Investigations on Routing and Wavelength Assignment Algorithms in WDM Optical Networks

THESIS

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PARAMJEET SINGH

Under the Supervision of

Prof. Ajay K. Sharma

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
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BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI (RAJASTHAN)

CERTIFICATE

This is to certify that the thesis entitled **Investigations on Routing and Wavelength Assignment Algorithms in WDM Optical Networks** and submitted by **PARAMJEET SINGH** ID No **2003PHXF006** for award of Ph. D. Degree of the Institute embodies original work done by him under my supervision.

Signature in full of the Supervisor:………………
Name in capital block letters: **AJAY K SHARMA**
Designation: **Professor**

Date:

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(PARAMJEET SINGH)

ABSTRACT

There is continuing and relentless need for more transmission capacity in the networks. It is due to various major factors e.g. one factor is the growth of the Internet. It has not only increased the number of users, but also the required bandwidth by each user. The major technology that guarantees to meet this high bandwidth demand of networks is optical networking. Optical networks use optical fibers as transport medium and can exploit the huge bandwidth provided by the optical fiber. The capacity of a single fiber is nearly 50 Tb/s, which can be used by dividing it into smaller bands or channels, and using these channels concurrently. This is accomplished by Wavelength Division Multiplexing (WDM), where each channel operates at a different wavelength. Also the transmission speed is very high in optical fibers.

A lightpath must be established between a pair of source and destination nodes before data can be transferred. The Routing and Wavelength Assignment (RWA) algorithms select routes and assign wavelengths to the connections. Due to the limitation in the number of wavelengths available on each fiber link as well as the wavelength-continuity constraint (in the absence of wavelength converters), the RWA problem has been a crucial issue for achieving good network performance. New RWA algorithms and approaches are covered in this thesis for improved performance. The performance is compared with the algorithms available in the literature. The investigations have been carried out with the following objectives:

1. To study and analyze the issues, concepts and techniques of existing RWA algorithms in WDM optical networks.

2. To analyze and compare the existing RWA algorithms.
3. To develop, investigate and simulate the effective RWA algorithms to optimize the objective function i.e. performance metric such as number of wavelengths required, blocking probability and number of attempts to find a free wavelength.
4. To investigate the improvement of the developed algorithms and comparison with existing algorithms in terms of the objective function.

Proposed RWA algorithms aim at the optimization of the performance. The thesis shows the use of alternate path to reduce the blocking probability with the given resources. Six RWA algorithm variations are then presented that use the shortest path, alternate shortest path, first-fit (FF) wavelength assignment algorithm and give more priority to shortest path as compared to alternate shortest path. These differ in the combinations of the RWA steps to establish the connections. This difference results in performance variations in terms of blocking probability.

Two wavelength assignment (WA) algorithms are also proposed. The objective of these algorithms is to reduce the number of attempts to search a free wavelength for lightpath establishment. First WA algorithm: Minimum Connection Count (MCC) assigns the wavelengths according to minimum number of lightpaths. The performance of this algorithm is compared with the commonly used FF WA algorithm. The results show that MCC algorithm is much better than FF algorithm. The problem with the MCC algorithm is maintaining the record for each wavelength and also the extra time required to calculate the wavelength with minimum connection count. The second proposed algorithm: Circular Sequential (CS) WA algorithm alleviates the problems available with MCC algorithm. The wavelengths are assigned according to circular sequential organization. Results prove that the number of attempts is less than commonly used WA algorithms.

Three dynamic RWA strategies to reduce the blocking probability are also presented. These strategies behave according to the network state. New weight is assigned to each link according to the demand/utilization of link to distribute the load. The performance of proposed strategies and existing trend has been evaluated. The simulation results show that all the three proposed strategies give better results than existing trend. The third proposed strategy which assigns the new weights to the links according to link utilization is the best out of these three.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AIS	Alarm Indication Signal
APS	Automatic Protection Switching
ATM	Asynchronous Transmission Mode
BER	Bit Error Ratio
BLSR	Bidirectional Line-Switched Ring
BSN	Broadcast-and-Select Network
CRCE	Channel Requirement for Connection Establishment
CRSP	Channel Requirement for Shortest Path
CS	Circular Sequential
CU	Channel Utilization
DCS	Digital Cross-Connect System
DLE	Dynamic Lightpath Establishment
DP	Diverse Protection
DPS	Diverse Protection Switching
EDFA	Erbium Doped Fiber Amplifier
EON	European Optical Network
FAR	Fixed Alternate Routing
FDDI	Fiber Distributed Data Interface
FDM	Frequency Division Multiplexing
FF	First-Fit
FR	Fixed Routing
HEC	Header Error Check

ICMP	Internet Control Message Protocol
ILP	Integer Linear Program
IP	Internet Protocol
LAN	Local Area Network
LCPR	Least Congested Path Routing
LOF	Loss of Frame
LOS	Loss of Signal
LUW	Least Used Wavelength
MCC	Minimum Connection Count
MUW	Most Used Wavelength
NSFNET	National Science Foundation Network
NWCC	Non Wavelength Continuity Constraint
OLA	Optical Line Amplifiers
OLT	Optical Line Terminals
OSPF	Open Shortest Path First
OXC	Optical Cross-Connect
PSC	Passive Star Coupler
RWA	Routing and Wavelength Assignment
SD	Signal Degrade
SDH	Synchronous Digital Hierarchy
SF	Signal Failure
SLE	Static Lightpath Establishment
SONET	Synchronous Optical Networks
TDM	Time Division Multiplexing
TRS	Tree Topology Strategy

UPSR	Unidirectional Path Switched Ring
VP	Virtual Path
VPN	Virtual Private Network
WA	Wavelength Assignment
WADM	Wavelength Add/Drop Multiplexer
WAN	Wide Area Network
WC	Wavelength Converter
WCC	Wavelength Continuity Constraint
WDM	Wavelength Division Multiplexing
WRN	Wavelength Routed Network
WRS	Wavelength Routing Switches
WWW	World Wide Web

SYMBOLS

p_{sd}	Represents the total number of edges along the route for *s*-*d* connection
s	Indicates the source for a connection request
d	Indicates the destination for a connection
G	graph of network
V	Set of vertices or nodes
E	Set of edges or links
L	Set of weights associated with the edges
C	Set of connection requests
W	Total number of wavelengths
A	Set of wavelengths
I	Total number of connection requests

λ	Represents the wavelength
R_{ij}	The route for *s-d* connection based on shortest path algorithm
z_{ij}	The wavelength assigned to the *s-d* connection.
acconn	Represents the number of accepted connections
rejconn	Represents the number of rejected connections

CHAPTER 1

INTRODUCTION

Various applications such as the World Wide Web (WWW) that require transfer of text data, video clips and voice data etc. are demanding high bandwidth at reasonable price. This high bandwidth requirement needs investments and advances in the technology. The estimates for traffic demand in the future however, show no signs of decrease. To satisfy the enormous demand in bandwidth, enormous capacity is needed. Optical networking is one such technology that addresses this problem very well.

1.1 Optical Networks

Optical networks that employ wavelength division multiplexing (WDM) are promising candidates for meeting the high bandwidth requirements of emerging communication applications. These networks (in which data is converted to photons and then transmitted over fiber) are faster than traditional networks (in which data in the form of electrons travel through copper cable). It is because photons weight less than electrons. Also photons do not affect one another when they move (because they bear no electric charge) and are not affected by photons outside the fiber. Further, light has higher frequencies and hence shorter wavelengths, and therefore more information can be transmitted through a length of fiber versus the same length of copper. The speed of electronics components restrict the advantages provided by fiber. All-optical-networks are those networks in which the data always remains in the optical domain during transmission. The routers and switches used are optical so that faster speed can be achieved.

In optical networks, each end-user is connected to an optical active switch via a fiber link. The combination of an end-user and its corresponding optical active switch is referred to as a network node. Each network node is equipped with a set of transmitters and receivers. A transmitter at a node sends data into the network and a receiver receives data from the network.

1.2 Optical Fiber Principle

The size of the optical fiber is very small. Optical fiber consists of cylinder of glass through which the light propagates. It is called core and is surrounded by a concentric layer of glass known as cladding. The core has a higher refractive index than the cladding. These layers are enclosed in a protective jacket of polymer protective coating. The optical fiber works on the principle of total internal reflection. Once light signal starts to reflect down the fiber, it will continue to do so. The ratio of the refraction indices of the core and the cladding defines the critical angle. Light injected into the core and striking the core to cladding interface at less than the critical angle will be completely reflected back into the core. The light signal propagates through a series of reflections off the cladding, back into the core, then to the cladding, then back into the core, and so on as shown in figure 1.1. As any light signal incident on the core cladding surface at an angle less than the critical angle is completely reflected internally, so many light signals will be reflected internally if they are incident at different angles. All the angles of incident should be less than critical angle. Each ray of light has a different mode and a fiber with this property is known as a multimode fiber. In multiple mode fibers, the light rays may interfere with each other, so the transmission capacity is limited. If the diameter of the core is very narrow, then the light signal can travel in a straight line along the center axis of the fiber as shown in figure 1.2. The fiber acts as a waveguide and is known as a single-mode fiber. Light striking the core cladding surface at greater than the critical angle will pass into the cladding and get dissipated by the protective jacket.

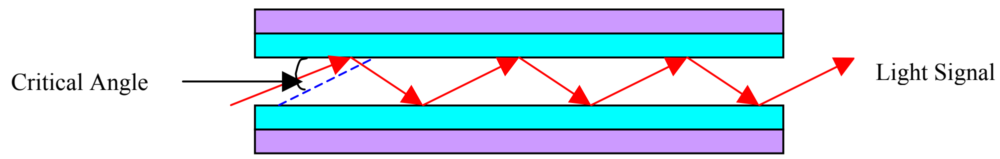

Figure 1.1 Transmission in optical fiber

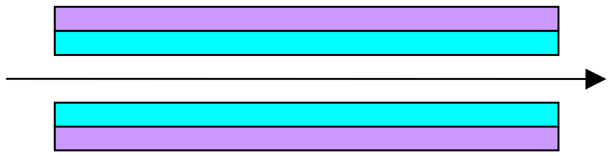

Figure 1.2 Single mode fiber

1.3 Evolution of Optical Networks

In literature, optical networks are categorized by dividing their evolution into two phases: first generation optical networks in which the optical fiber was used as a mode of communication while all the processing happens at the electronic level, and second generation optical networks in which some of the decisions take place in the optical domain. These are described below.

1.3.1 First Generation Optical Networks

First generation optical networks employ fiber only as a transmission medium. These networks involved replacing copper cables by optical fibers as the medium of transmission as optical fibers had better physical characteristics for transmission requirements than copper cables. The raw bandwidth offered by optical fibers is huge. Hence the copper cables in core telecom networks, which face loads more than perhaps any other networks, were first replaced by optical fibers. The switching and processing of bits were, however, handled in the electronic domain as before. Optical fibers were preferred for bit rates greater than 10 Mbps that were needed to be transmitted over a distance of more than a kilometer.

First generation optical networks have been widely deployed in public as well as private enterprise networks. The public network standard for transmission and multiplexing incorporated is Synchronous Optical Networks (SONET) in North America and Synchronous Digital Hierarchy (SDH) in Europe. The private enterprise network standards include fiber interconnects, such as High-Performance Parallel Interface (HIPPI), and metropolitan area networks, such as Fiber Distributed Data Interface (FDDI) [1] and Gigabit Ethernet [2].

Among first generation networks, SONET networks probably are the most popular. They incorporate a wide variety of functions. For example, they provide point-to-point connections between different node pairs in the network. Also, they provide add/drop functionalities, such that only a part of the streams are dropped at a node, and the rest can pass through. Also, SONET networks consist of cross-connects, which can switch multiple traffic streams.

From a network layering point of view, the impact of the first generation optical networks was felt primarily in the physical layer. From hereon, there were primarily two fundamental ways of increasing the speeds in the networks; either increase the electronic processing speeds by improved time division multiplexing (TDM) techniques or increase the capacity by using multiple carrier wavelengths in the fiber at the same time. The latter technique is similar to frequency division multiplexing (FDM) techniques in radio systems and offers the flexibility of working at the maximum state-of-the-art electronic speeds.

1.3.2 Second Generation Optical Networks

An increasing realization that optical networks are capable of providing more functions than just point-to-point transmission led to the emergence of second generation optical networks. These networks use WDM technology to split the huge bandwidth provided by a fiber into multiple wavelength channels that can be used to support multiple transmissions simultaneously.

The primary improvement of second generation optical networks over their first generation counterparts from technological point of view was in incorporating the switching and routing functionality in the optical domain and allowing for transparency of data format, protocol and bit rates. It thus allowed for lesser electronic load on a node by ensuring the need to terminate the traffic intended only for that node while allowing the other traffic to cut right through the node in the optical domain. In the first generation networks, a node would have to terminate all the optical signals (irrespective of whether they are intended for itself or not), convert them to electronic signals, process them and then regenerate the traffic not intended for itself into optical signals and send them on the appropriate outgoing links. The second generation optical switches are called the optical cross-connects. These switches may be configured to switch the optical signals between any incoming port to any outgoing port.

The role of the second generation optical networks is defined by the services that can potentially be offered to users [3, 4]. These networks were designed in a way so that the optical layer offers a lightpath service to the layers above. Lightpaths are connections (circuits) that are set up between two nodes [5-7]. They are established by setting up a wavelength along each link in the path from the source node to the destination node. However, the chosen wavelength need not be the same in all links. It depends on the wavelength conversion capability of an intermediate node along the path. When none of the nodes in the network have that capability, the constraint of having to choose the same wavelength along all the links in the path is referred to as the *wavelength continuity constraint (WCC)* [5, 8]. The granularity of bandwidth made available by a lightpath service to the layers above is in terms of a full wavelength. One wavelength can offer transmission capacity in the order of a few Gb/s. Moreover, second generation optical networks offers transparency, i.e. they are insensitive to the nature of the coding or modulation techniques used over the lightpaths.

1.3.3 Point-to-Point WDM Systems

WDM point-to-point communication systems are being deployed by several telecommunication companies due to the increasing demands on communication bandwidth. Figure 1.3 shows a three-channel point-to-point WDM transmission system.

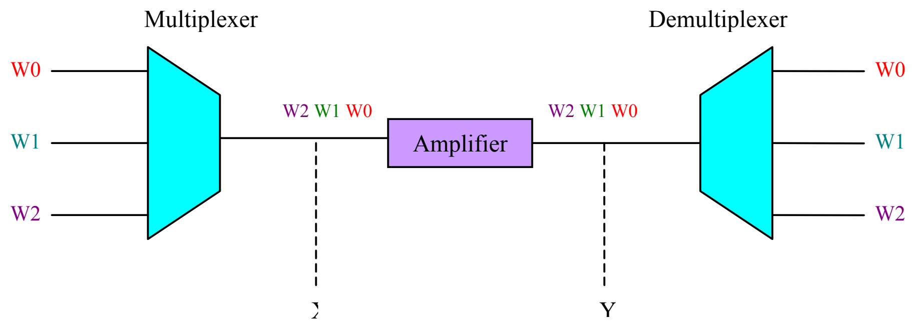

Figure 1.3 WDM point-to-point link

The capacity of the fiber link X→Y is now increased by a factor of 3, the number of wavelength channels used. These links are more cost-effective, when the demand exceeds the capacity in existing fibers, compared to installing new fiber.

WDM multiplexer/demultiplexer in point-to-point links with 64 channels are currently available [9]. However, these systems are not optical networks by themselves but a convenient multiplexing scheme.

1.4 WDM Technology in Optical Networks

Fiber has extremely high bandwidth in the order of Tb/s, in the 1.55 low-attenuation band. Traditionally only a small portion of the bandwidth in the order of Gb/s can be used, because the fiber is used as a single high-capacity wavelength channel. The speed of this channel is restricted by the speed at the end nodes, which is in the order of Gb/s due to electronic bottleneck. WDM systems provide more bandwidth capacity for use over optical fiber networks. It allows multiple channels within a single fiber to fully utilize the bandwidth. WDM is feasible solution in many cases because it is expensive to install new fibers especially in densely populated areas like cities, where fibers must be dug under streets. The possibility to use the existing fibers more efficiently makes WDM a very attractive alternative commercially. WDM practically allows terahertz transmission bandwidth in optical networks by fully utilizing the bandwidth provided by the fiber.

The above advantages of WDM systems encourage their use in Optical Wide Area Networks. The transport capabilities of such a network would enable the transport of large amounts of data, in varying formats (like Internet Protocol (IP) datagrams, Asynchronous Transfer Mode (ATM) cells, Synchronous Optical Network

(SONET) frames and others) directly on different channels (wavelengths) between different nodes of the network [10]. WDM systems thus allow the use of both traditional layered architectures, as well as transparent transport of different services without the intermediate layering. This feature of multiwavelength systems, as well as the add-drop capabilities provided, motivates the development of service-independent access at the network nodes.

It makes a single fiber look like multiple virtual fibers. Each virtual fiber can carry the data independently. So, several different independent wavelengths can transmit the data simultaneously through a fiber. Different data streams are modulated into the optical fiber with a unique wavelength. Each wavelength can be used to carry data independently with the transmission speed required by the application without bothering for other applications. Also different wavelengths can carry the data corresponding to the applications supporting different data formats. The bandwidth provided is partitioned into channels on different wavelengths. Channel space should be provided to avoid interference of the channels with each other. The total practical bandwidth supported by the fiber is the sum of the bandwidths of all the data channels. WDM also provides add drop capabilities. With it, the part of the total signal required by a node can be dropped at the node. The whole signal needs not to be terminated as was done in traditional systems. So, WDM technology has been recognized as one of the key components of the future networks. The commercialization of WDM technology is progressing rapidly.

1.5 Components of Optical Networks

There are various essential components that comprise all-optical networks [11]. A brief description of some of the components follows:

1.5.1 Light Source

The light source is an essential source in the optical networks because through it, the data for transmission is generated. It should consume low power for its operation. It should also be able to work with different wavelengths. There are many types of light sources available which differ in various parameters. The light source may be selected depending on the requirement of the application.

Below is a list of various types of light sources [11, 12]:

- Acousto-optically and electro-optically tuned lasers
- Mechanically tuned lasers
- Switched sources
- Injection current tuned lasers
- Array sources

1.5.2 Tunable Filter

A tunable optical filter is another important component. It can be of various types: Fabry-Perot, acousto-optic, electro-optic and liquid crystal [11, 12]. The type of the filter to be used depends upon the requirement of the application depending on the parameters: tuning range and tuning time.

1.5.3 Optical Cross-Connect

Optical cross-connect (OXC), is a component used to connect specified input ports to the specified output ports. It is also known as optical switch [13]. It can be dynamically configured to fulfill the demand. These can be categorized as non-blocking switch, wide-sense non-blocking switch, strict-sense non-blocking switch

[14] on the basis of flexibility. The higher flexibility makes the switch more complex. OXC perform a similar function as OADM but at much larger sizes, having a large number of ports, large number of wavelengths and complex topologies. These can also be categorized based on the type of routing supported. Static switches have *static* routing patterns. The switches that support dynamic behavior are called *dynamic* switches.

1.5.4 Wavelength Converter

Wavelength converter (WC) is an optional component in the network. Its purpose is to shift the data from one wavelength to another. These help in bypassing the wavelength-continuity constraint. So, more efficient use of the resources can be done to accept more number of connection requests. If there are free channels available in every link along the route, although on different wavelengths, the connection may be established with wavelength converters. The wavelength conversion can either be done in fully optical domain or with the help of electronic elements. A survey on wavelength conversion can be found in [15].

1.5.5 Optical Amplifier

The attenuation of optical signals is low in comparison with electrical signals. Still long-distance links may need amplifiers in order to operate properly. The traditional way to solve the problem is to convert the signal back to electrical domain for amplification and retransmit it optically. This approach, however, requires knowledge of the used bit rate and modulation. A new solution is to use amplifiers operating totally in the optical domain.

Also, the attenuation of signals during transmission is undesirable. This problem is less with optical networks as compared to with traditional networks. The optical networks require the amplifiers for long distance transmission for the sake of quality and to avoid data loss. Optical amplifiers can be used for this purpose because of their high speed. The erbium doped fiber amplifier (EDFA) operating at 1540 nm region is an example of the amplifier that has good results. A new technology that uses a circuit of EDFAs is known as *ultra wide-band* EDFA [7]. The amplifier is transparent to coding and bit-rate used, so it can be used for all-optical framework. Also a similar amplifier for the 1300 nm region has been built using praseodymium instead of erbium.

1.5.6 Optical Line Terminal

Optical Line Terminal (OLT) is relatively simple element from architectural prospective. OLTs are used at both ends of a point-to-point WDM link. They multiplex many wavelengths into a single fiber and demultiplex a set of wavelengths on a single fiber into separate fibers. One very important element in OLTs is transponder. The purpose of the transponder is to adapt the signals from the client and convert these into the form required by the optical network. The transponder does the reverse also i.e. it takes the optical signals from the optical network and converts them into the form required by the client. The interface between the client and the transponder may vary according to the transmission rate required by the user, the loss of the data and the distance between the client and the transponder.

1.5.7 Coupler

Coupler is a device used to combine and split signals in an optical network. The most commonly used couplers are made by fusing two fibers together in the middle. These are called fused fiber couplers. Couplers have many applications. One application is to distribute an input signal equally among multiple output ports. These can also be used to tap off a small portion of the power associated with a light signal for monitoring purposes.

1.5.8 Wavelength Add/Drop Multiplexer

Wavelength Add/Drop Multiplexers (WADM) enables a small number of contiguous wavelengths to be added and dropped without demultiplexing the entire wavelength bundle. Using a wavelength add/drop multiplexer, which can be "inserted" on a fiber link as shown in Figure 1.4, one can add/drop necessary wavelengths at the WADM location. WDM point-to-point links provide very high capacity between two terminals.

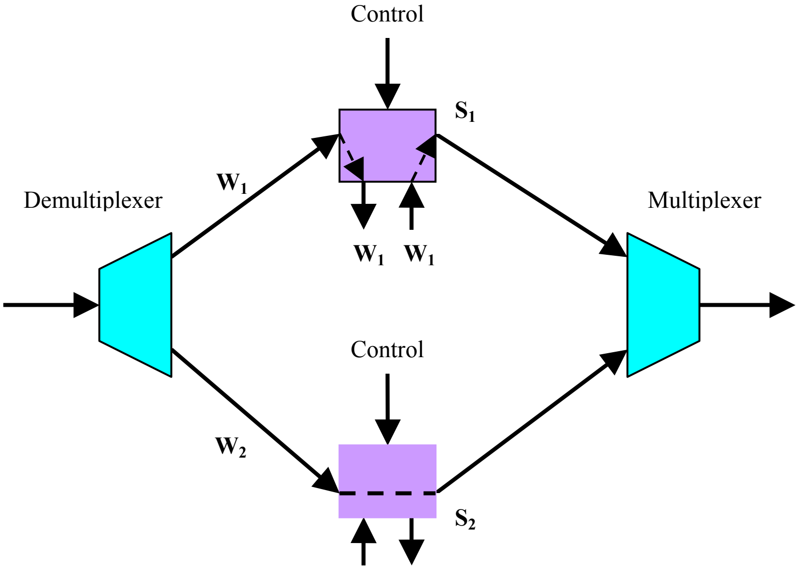

Figure 1.4 Wavelength add/drop multiplexer

If the terminals are widely spaced, in many networks it is necessary to drop some traffic at intermediate points along the route between the end points. A WADM can be realized using a demultiplexer, 2 × 2 switches, one switch per wavelength, and a multiplexer. If a 2 × 2 switch S_2 is in “bar” state, then the signal on the corresponding wavelength passes through the WADM. If the switch S_1 is in “cross” state, then the signal on the corresponding wavelength is “dropped” locally, and another signal can be “added” on the same wavelength at this WADM location.

1.6 WDM Network Architecture

WDM-based optical networks are designed for spanning local, metropolitan, and wide geographical areas. There are following popular architectures [16, 11] used in WDM optical networks:

1.6.1 Broadcast-and-Select Networks

A Broadcast-and-Select Network (BSN) consists of a passive star coupler connecting the nodes in the network [17-19]. Each node in such a network is equipped with one or more optical transceivers (transmitter and receiver). A bi-directional fiber runs between each node and a passive-star coupler (PSC). All nodes in the system send information to the passive star on distinct wavelengths. These wavelengths are optically merged by the passive star and then forwarded to each of the nodes. Each node can listen to one of the wavelengths by tuning its receiver to one of the wavelength channels. This architecture is appropriate for a local area network (LAN). Figure 1.5 shows a broadcast and select network.

However, these networks are limited by the number of nodes they can support because wavelengths cannot be reused in the network (at a time, a specific wavelength can be used by only one node in the network,) and also because the transmitted power from a node must be split among all the receivers in the network. In these networks, routing is provided to all nodes by default, and hence, no routing function is provided by the network. This is one of the features that differentiates broadcast and select networks from the wavelength routed networks, in which, as the name implies, the network provides the routing functionality.

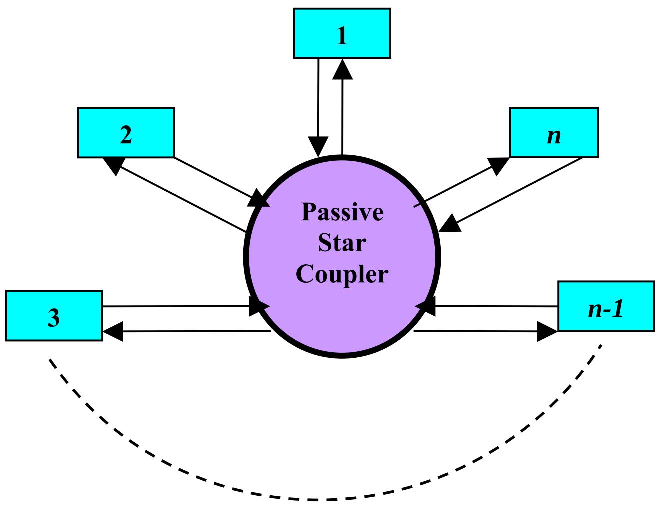

Figure 1.5 Broadcast-and-select network

1.6.2 Wavelength-Routed Networks

The broadcast-and-select architecture is inadequate for a wide area network (WAN) due to power limitations and the lack of wavelength reuse. This can be overcome by introducing wavelength routing. Wavelength routing allows the same wavelength to be reused in spatially disjoint parts of the network. The combination of an end-user access station and its corresponding switch is referred to as a network node. Figure 1.6 shows a wavelength routed network (WRN). In such networks, each access station is connected to a photonic switch [20], which is capable of routing a signal based on its input and wavelength.

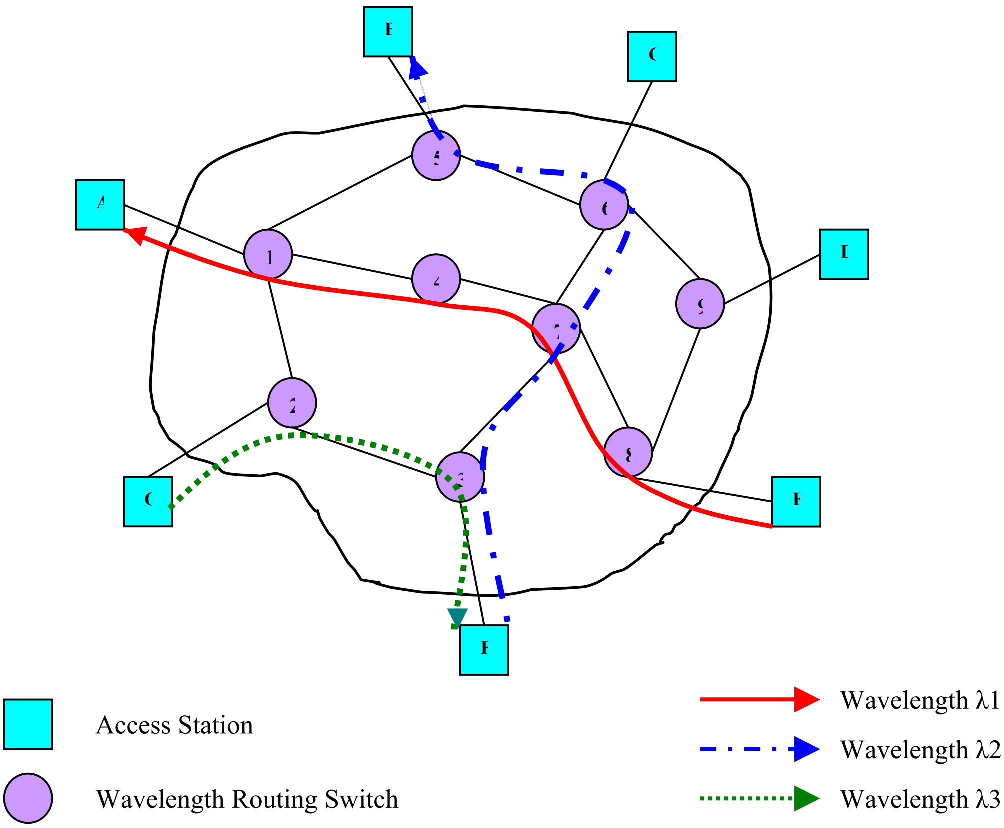

Figure 1.6 Wavelength routed network

In WRN, a message is transfer from one node to another node using a wavelength continuous path called a *lightpath* without requiring any optical-electronic-optical conversion at the intermediate nodes [21-23]. This process is also known as *wavelength routing*. Thus lightpath is a high-bandwidth pipe, carrying information up to several gigabits per second and is uniquely identified by a physical route and a wavelength. The two lightpaths can not be assigned the same wavelength on any fiber [24]. This requirement is known as *distinct wavelength assignment constraint*. However, two lightpaths can use same channel if they use disjoint sets of links. This characteristic is known as *wavelength reuse*. This important property in wavelength routed networks makes them more scalable than broadcast-and-select networks. Another important property in wavelength routed networks which enables them to span long distances is that the transmitted power invested in the lightpath is not split to irrelevant destinations.

Since the active components are generally used in the WRN architecture [8], the WRN architecture does not suffer from the splitting losses that always associated with the passive optical components in BSNs. Therefore, the network capacity and reliability can be improved by using wavelength routing and switching technologies.

1.6.3 Linear Lightwave Networks

In WRNs, the available bandwidth is divided in wavelengths as shown in figure 1.7. The usable portion of the optical spectrum is divided into many wavebands [14] in these networks. Each waveband can be further decomposed into a number of wavelengths as shown in figure 1.8 for the same bandwidth as for WRN. Two level partitioning is used in these types of networks. Many wavelengths are multiplexed on a waveband. Many wavebands are multiplexed on a fiber. It is done to make the things simple. The routing nodes do not deal with wavelengths, but deal with wavebands. So, the number of switches required in a node is equal to the number of wavebands. In it, the wavelengths in a waveband cannot be separated during transmission.

The wavelengths in a waveband are separated at the optical receivers. Guard bands are required between the wavelengths for transmission. These are required to avoid the problems from the imprecision of transmitter tuner and intermixing of signals.

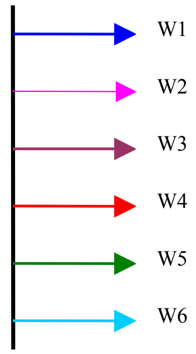

Figure 1.7 Wavelength partitioning

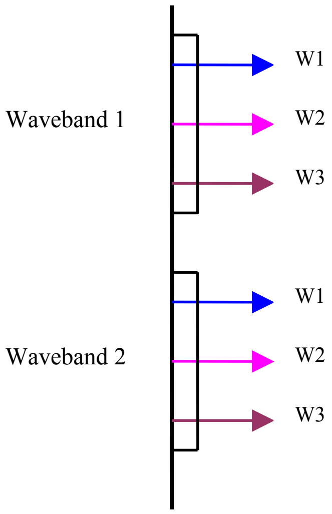

Figure 1.8 Waveband partitioning in linear lightwave networks

The wavelength continuity and distinct wavelength assignment constrains applicable to wavelength routed networks also apply to linear lightwave networks. Further, there are two routing constraints unique to linear lightwave networks: *inseparability*, that is, channels belonging to the same waveband when combined on a single fiber cannot be separated within the network; and *distinct source combining*, that is, on any fiber, only signals from distinct sources are allowed to be combined.

1.7 Routing and Wavelength Assignment Problem

The routing and wavelength assignment consists of carefully choosing a specific route for a given connection request and assigning it a wavelength along the links in its route from the possible set of wavelengths [25-29] without violating the wavelength continuity constraint such that a given performance metric is optimized (i.e. minimum total number of wavelengths used or minimum blocking). The RWA algorithm employed can significantly influence the network efficiency as it deals with the resources.

The RWA problem for static traffic is known as the static lightpath establishment (SLE) problem. For dynamic traffic, the RWA problem is referred to as the dynamic lightpath establishment (DLE) problem, which is aimed at setting up a lightpath in a manner so as to reduce the network blocking probability when a connection request arrives [22, 30, 31]. To establish a lightpath, an optical network normally requires a common wavelength to be assigned on all the links on the route. This requirement is known as the *wavelength-continuity constraint* and such a network is called wavelength-continuous network. The wavelength continuity constraint is eliminated, if the data arriving on a wavelength at an input port can be transferred on another wavelength at the output port at an OXC node. Such a technique is referred to as wavelength conversion [32-35] and wavelength converters are the devices to operate wavelength conversions. Optical switches embedded with wavelength converters can provide wavelength conversion capability to a network [32]. Such a network is called a wavelength-convertible network. Wavelength conversion is beneficial particularly when designing networks with high connectivity, and networks with additional capacity for future traffic growth. It seems that the best strategy for obtaining a high utilization is to place wavelength converters at few selected nodes [36].

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

WDM allows the same fiber to carry many signals independently as long as each uses a different wavelength. Optical networks using WDM technology have emerged as an attractive solution for meeting rapidly growing demands for bandwidth. It has been discussed in the previous chapter that the RWA [1, 37, 38] routes and assigns wavelengths to the connections such that no two connections use the same wavelength on the same link. This chapter reviews the issues in the literature dealing with the problem of RWA in optical networks. Within the framework of this thesis, we study, analyze and propose RWA algorithms to enhance the network throughput with respect to the algorithms reported in the literature.

2.2 Routing and Wavelength Assignment

The RWA problem is defined as follows: Given a network topology and a set of lightpaths demands to be set up and given a constraint on the number of wavelengths, we need to determine the paths and the wavelengths that should be assigned to the lightpath demands so that a certain optimality criterion (performance metric) is achieved [4, 39, 40]. The RWA algorithms available in the literature [1, 2, 8, 28, 37, 41] differ in their performance metrics and traffic assumption. The performance metrics used generally fall under one of the following three categories:

- Number of wavelengths required for accommodating the connection requests [4, 42].
- Blocking probability which is defined as the ratio of the number of rejected lightpath requests and the total number of lightpath requests [14].
- Number of attempts to find a free wavelength along a route to establish the lightpath. It directly affects the connection establishment time.

The RWA problem can be considered under three different traffic assumptions: static, incremental, and dynamic [43, 44].

- In the case of static traffic [1, 45], a set of connection requests is given and the connections will be established such that a certain performance measurement e.g. carried traffic is optimized. Two commonly used objectives of performance measurements are minimizing the wavelength requirement and maximizing the network throughput [1, 20, 46-48]. Static traffic assumes that the set of connections is known in advance, and the problem is then to set up lightpaths for these requests in a global fashion. Alternatively, one may attempt to set up as many of these permanent connections as possible for a given fixed number of wavelengths per fiber-link. The RWA problem for static traffic is known as the Static Lightpath Establishment (SLE) problem [8, 20, 49, 50].

- In the incremental-traffic case, connection requests arrive sequentially, a (the) lightpath(s) is (are) established for each connection, and the lightpath(s) remains in the network indefinitely [43, 44].

- In the case of dynamic traffic [37, 51-53], connection requests will arrive and leave randomly. For a given sequence of requests, the dynamic RWA problem is to route the lightpath in order to optimize network performance. In this case, the performance measurement is typically the lightpath blocking probability. Moreover, in the dynamic traffic model, the lightpaths are generally established according to the current state of the WDM network.

The objective in the incremental and dynamic traffic cases is to set up lightpaths and assign wavelengths in a manner which minimizes the amount of connection blocking (or maximizes the number of connections that are established), or the total (weighted) number of blocked connections over a given period of time. This problem is known as the Dynamic Lightpath Establishment (DLE) problem [8, 20, 49, 50]. In this thesis, we survey the different approaches to solve both the SLE and the DLE problems.

A number of studies have investigated the RWA problem for setting up a static set of lightpaths [1, 5, 20]. These studies often formulate the SLE problem as an integer linear program (ILP) [54, 55], or rely on heuristic approaches in an attempt to minimize the number of wavelengths required to establish a given set of lightpaths. The ILP formulations may only be solved for very small systems [5]. For larger systems, heuristic methods must be used. To make the problem more tractable, the SLE problem can be partitioned into two problems namely the routing problem and the Wavelength Assignment (WA) problem. The two problems are solved separately [20, 45].

The DLE problem is more difficult to solve, and therefore, heuristics methods are generally employed [56]. As lightpaths are established and torn down dynamically, routing and wavelength assignment decisions must be made as lightpath requests arrive to the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. The connection may also be blocked if there is no common wavelength available on all of the links along the chosen path. Thus, the objective in the dynamic situation is to choose a path and a wavelength(s) which maximizes the probability of setting up a given connection, while at the same time attempting to minimize the blocking for future connections. Similar to the case of static lightpaths, the dynamic RWA problem can also be decomposed into a routing problem and a corresponding wavelength assignment problem.

Approaches to solve the routing problem can be broadly classified into four types: Fixed Routing (FR), Fixed Alternate Routing (FAR), Adaptive Routing (AR) and Least Congested Path Routing (LCR) [51, 57-60]. Among these approaches, fixed routing is the simplest while adaptive routing yields the best performance. Alternate routing offers a trade-off between complexity and performance. These approaches will briefly be discussed in the following subsection 2.2.1.1. For the wavelength assignment sub problem, a number of heuristics have been proposed [24, 45, 61-68]. Some of the more significant heuristics are described in subsection 2.2.1.2.

2.2.1 Separate Route-Wavelength Selection Approach

2.2.1.1 Route selection algorithms

In this section, a description of the commonly used route selection algorithms available in the literature is given.

Fixed routing: Fixed routing is the simplest algorithm. A single fixed path is predetermined for each source-destination pair. When a lightpath demand is to be set up, the network will attempt to establish a lightpath along the fixed path. It checks whether some wavelength is free on all the links on the path. If none is free on this fixed route, then the connection request is blocked. If more than one wavelength is available, a wavelength selection algorithm can be used to select the best wavelength.

A fixed routing approach is simple to implement and has a short set up time; however, it is very limited in terms of routing options and may lead to a high level of blocking. In order to minimize the blocking in fixed routing networks, the predetermined paths need to be selected in a manner which balances the load evenly across the network links.

Fixed alternate routing: Fixed alternate routing [32, 58, 63, 69] is an extension of the *FR* algorithm. For every node pair in the network, a set of *K*-alternate shortest paths ($K > 1$) is provided. These paths are computed offline. When a lightpath request is to be set up, its candidate *K*-alternate shortest paths are searched in a fixed order and the first path with as many path-free wavelengths as the number of requested wavelengths is selected. The order according to which the *K*-alternate candidate paths are considered is typically based on either path length or path congestion or path delay or any other cost function. If no path can be found with as many path-free wavelengths as the requested number of wavelengths, then the lightpath demand is blocked. If more than one wavelength is free on the selected shortest path, a wavelength assignment algorithm can be used to choose the best wavelengths. Although this algorithm is slightly more complex than the *FR* algorithm, it has also the advantage of simplicity and shorter connection set-up time. It also has better performance than the *FR* algorithm as a choice among multiple shortest paths has to be done [70]. However, the candidate paths for a node pair may not include all the possible paths. As a result, the performance of the algorithm is not the best achievable.

Adaptive routing**:** Adaptive routing algorithm also called unconstrained routing algorithm [8, 32, 37, 58, 63, 69, 71-73]. Adaptive routing does not predetermine the candidate paths for any node pair. When a new lightpath demand is to be set up for a source destination pair, it chooses the best path (based on some cost criterion) among all the possible paths. Thus, by exploring all possible paths, it attempts to increase the acceptance rate of connection requests. In order to choose the optimal path, a cost is associated with each route in the network depending upon the performance metric under consideration. A least-cost routing algorithm is then executed to find the least cost path. The cost varies with each lightpath. The algorithm has longer setup times than the *FR* and *FAR* algorithms as the cost information needs to be changed with every lightpath. Moreover, this algorithm is made for centralized implementation and can not be used with distributed control.

While many emerging systems are almost static, with lightpaths being established for long periods of time, it is expected that, as network traffic continues to scale up and become more bursty in nature, a higher degree of multiplexing and flexibility will be required at the optical layer. Thus, lightpath establishment will become more dynamic in nature, with connection requests arriving at higher and unpredictable rates, and lightpaths being established for shorter time durations. In such situations, maintaining complete and up to date global information may become impossible. The alternative is to implement routing schemes which rely only on local information.

A number of adaptive routing schemes exist which rely on local information rather than global information. The advantage of using local information is that the nodes do not have to maintain a large amount of state information; however, routing decisions tend to be less optimal than in the case of global information. One of the local information based adaptive routing schemes is the least congested path routing algorithm.

***Least congested path routing*:** Least congested path routing [51] chooses the path with least congestion among the possible paths connecting a source node and a destination node in the network. The congestion of a path is determined from the number of free wavelengths available on the entire path. The greater the number of free wavelengths, the less congested is the path.

For every node pair in the network, a set of K alternate shortest paths are computed offline. When a lightpath demand between a source node and a destination node in the network is to be set up, the cost of each of the K alternate shortest paths is computed. The cost of a path is determined by the wavelength availability (congestion) along the path. If more than one path has the same cost, then the path with shorter hop count is preferred. Once the path is selected, a wavelength assignment algorithm is then used to select the wavelength(s). By selecting the least congested path, the algorithm tries to keep as many path-free wavelengths as possible in order to help satisfying many of future lightpath demands.

2.2.1.2 Wavelength selection algorithms

If there are multiple wavelengths along the route from a source node to a destination node, then a wavelength assignment (selection) algorithm is required to select a wavelength for a given lightpath [38, 45, 66-68, 74, 75]. The wavelength selection may be performed either after a route has been determined, or in parallel when finding a route. The same wavelength must be used on all links in a lightpath (to observe the wavelength continuity constraint). The wavelength assignment algorithm should be such that it chooses the wavelength to optimize certain performance metric. A review of wavelength assignment strategies is given in [8, 67, 76].

The commonly used wavelength assignment algorithms are: First-Fit (FF), Random (RA), Most Used Wavelength (MUW), Least Used Wavelength (LUW) and strategy with Tree Topology (TR) algorithms. These differ in the sequence in which the wavelengths are tried for connection establishment.

In *FF* algorithm, the wavelengths are indexed. The network will attempt to select the wavelength with the lowest index for lightpath establishment before attempting to select a wavelength with a higher index. By selecting wavelengths in this manner, existing connections will be packed into a smaller number of total wavelengths. It will result in non symmetric distribution of data over different wavelengths. If multiple connections are attempting to set up a lightpath simultaneously, then it may be the case that all lightpaths will choose the same wavelength, leading to one or more connections being blocked due to non availability of the free wavelength on any of the links along the route. It does not consider the wavelength usage factor, so does not require the complete connection information. It can be used both with centralized and distributed control.

Another approach for choosing between different wavelengths is to simply select one of the wavelengths randomly. There is no criterion for picking up the wavelength. It is called Random wavelength assignment algorithm. It can be used with both centralized and distributed control. This approach first searches the wavelengths to find the set of all wavelengths that are available on the required lightpath. Among the available wavelengths, one is chosen randomly.

In *MUW*, the wavelength which is used by most of the connections is tried firstly [57]. Then the wavelength with second highest connections is tried. This algorithm attempts to provide maximum wavelength reuse in the network, leaving maximum wavelengths underutilized.

The *LUW* algorithm attempts to spread the load evenly across all wavelengths by selecting the wavelength which is the used by minimum connections in the network [57]. This approach ends up breaking the long wavelength lightpaths quickly; hence, only connection requests that traverse a small number of links will be serviced in the network. This approach requires additional storage and computation cost. *LU* is the opposite of *MU* in that it attempts to select the least-used wavelength in the network.

Wavelength assignment strategy with Tree Topology (TR) [77] picks up any node randomly. Now, construct tree taking this node as root using breadth first search algorithm. Take all the one hop count connections and assign the first free wavelength to this connection. Repeat this process for all the nodes and establish all the other remaining connections with first fit strategy.

If more than one wavelength comes out with the same link usage count, then first-fit algorithm can be used for these wavelengths in *MUW* and *LUW* algorithms. Both algorithms require complete knowledge of the connections and the allocated resources to select the wavelength. So, these can only be used with centralized control and not with distributed control.

Many papers have analyzed the results in terms of blocking probability under various approximations for commonly used wavelength assignment algorithms such as *FF* [37, 58, 61, 65, 78] and the *R*A wavelength assignment [41, 79-83]. *FF* performs better than random wavelength assignment strategy [63]. The studies show that the performance of *FF* and *MUW* is almost same.

2.2.2 Simultaneous Route-Wavelength Selection Approach

All the algorithms discussed so far select the path and wavelength(s) independently in two separate steps. The joint wavelength-path selection algorithms consider the cost of selecting every wavelength-path pair and choose the least cost pair. The cost functions that may be used for wavelength-path pair selection take into account factors such as the wavelength availability in the network, the hop length of the path, and the congestion (or, equivalently, the number of path-free wavelengths) on the path. Simultaneous wavelength-path selection algorithms use alternate routing approach: The path for a lightpath demand is selected among *K* candidate alternate shortest paths computed online [84]. A detailed description of Simultaneous wavelength-path selection algorithms can be found in [9].

2.3 Centralized and Distributed Control Mechanism

In wavelength routed networks, the control of lightpath set-up can be broadly classified into centralized or distributed approaches.

2.3.1 Centralized Control

In centralized control, a master router keeps all the information about the paths and the wavelength usage of the entire network. Since every node has to make a request to the master node to acquire permission to set a lightpath, the master node, with the global information, can efficiently manage all the resources in the network. However, if the master node crashes, the whole network will collapse. Furthermore, a centralized approach does not scale well, as the centralized entity would need to maintain a large database to manage all nodes, links, and connections in the network. One approach to adaptive routing with global information is alternate-path routing. Alternate-path routing relies on a set of predetermined fixed routes between a source node and a destination node [63, 85]. When a connection request arrives, a single route is chosen from the set of predetermined routes, and a lightpath is established on this route. The criterion for route selection is typically based on either path length or path congestion. An example of a routing algorithm based on path length is the *K*-shortest paths algorithm [85, 86], in which the first *K* shortest paths are maintained for each source-destination pair, and the paths are selected in order of length, from shortest to longest. A connection is first attempted on the shortest path. If resources are not available on this path, the next shortest path is attempted. A path selection policy based on path congestion examines the available resources on each of the alternate paths, and chooses the path on which the highest amount of resources is available.

Choosing the shortest-path route consumes less network resources, but may lead to high loads on some of the links in the network, while choosing the path with the least congestion leads to longer paths, but distributes the load more evenly over the network.

Another adaptive routing approach utilizing global information is unconstrained routing which considers all possible paths between a source node and a destination node. In order to choose an optimal route, a cost is assigned to each link in the network based on current network state information, such as wavelength availability on links. A least-cost routing algorithm is then executed to find the least-cost route [71, 72]. Whenever a connection is established or taken down, the network state information is updated.

2.3.2 Distributed Control

In a distributed control, each node in the network must maintain complete network state information [71]. Each node may then find a route for a connection request in a distributed manner. Whenever network state changes, all nodes must be informed. Therefore, the establishment or removal of a lightpath in the network may result in the broadcast of update messages to all nodes in the network. The need to broadcast update messages may result in significant control overhead. Furthermore, it is possible for a node to have outdated information, and for the node to make an incorrect routing decision based on this information. A distance-vector approach to routing with global information is also possible [72]. This approach doesn't require that each node maintains complete link-state information at each node as in [71], but instead has each node maintain a routing table which indicates for each destination and on each wavelength, the next hop to the destination and the distance to the destination. The approach relies on a distributed Bellman-Ford algorithm to maintain the routing tables. Similar to [71], the scheme also requires nodes to update their routing table information whenever a connection is established or taken down. This update is accomplished by having each node send routing updates to their neighbors periodically or whenever the status of the node's outgoing links changes. Although each node maintains less information than in [71] and the updates are not broadcast to all nodes, the scheme may still suffer from a high degree of control overhead.

In the case of large networks or under the condition of rapidly changing availability of resources, the distributed approach becomes more suitable due to a low latency required in the lightpath establishing stage. However, one apparent disadvantage in distributed control networks where each node establishes its own lightpaths is that collisions frequently occur when two or more simultaneous requests are trying to reserve the same wavelength on the same link (this problem rarely occurs in centralized control networks due to the control of the master node)

2.4 Selection of Study Area

The rapid evolution of telecommunication networks is always driven by the ever-increasing demands of the Internet as well as continuous advances in communication systems. When the physical network and required connections are given, Routing and wavelength assignment is the problem to select a suitable path and wavelength among the many possible choices for each connection such that no two paths using the same wavelength pass through the same link. In the absence of wavelength conversion, a lightpath must use the same wavelength on all fiber links that it spans. In optical networks, there is need to optimize the network performance. The network optimization problem that must be addressed is to minimize the number of wavelengths required to accommodate all the connection requests, blocking probability, number of attempts and connection establishment time. Blocking probability is defined as the ratio of the number of rejected lightpaths demands to the total number of lightpaths demands arriving at the network. Number of attempts is a measure which gives number of searches done to find a free wavelength along the selected route to establish the lightpath. It directly affects the connection establishment time. Connection establishment time is the time taken to establish the connection from source to destination.

RWA is the fundamental control problem in optical WDM networks. Since the performance of a network depends not only on its physical resources (e.g., OXCs, converters, fibers links, number of wavelengths per fiber, etc.) but also on how it is controlled, the objective of an RWA algorithm is to achieve the best possible performance within the limits of physical constraints. In order to practically establish a new optical network or extend existing optical network performance in economic way, it is crucial to consider RWA problem in WDM networks.

This has caused a resurgence of my interests in investigations on RWA algorithms in WDM optical networks. Therefore the focus of this research has been to develop the effective RWA algorithms in wavelength routed optical networks, by tackling the limitations of existing algorithms.

2.5 Main Objectives of Study

Research has been carried out with the following main objectives:

- To Study and analyze the issues, concepts and techniques of existing RWA algorithms in WDM optical networks.

- To analyze and compare the existing RWA algorithms.
- To develop, investigate and simulate the effective RWA algorithms to optimize the objective function i.e. performance metric such as number of wavelengths required, blocking probability and number of attempts to find free wavelength.
- To investigate the improvement of the developed algorithms and comparison with existing algorithms in terms of the objective function.

2.6 Outline of the Thesis

Chapter 1 serves as an introduction to some of the technical contents related to WDM optical networks. Chapter 2 provides an insight into the previous work done related to the RWA problem. It also discusses the major categorization of the problem: Separate wavelength-route selection and simultaneous wavelength-route selection. Chapter 3 presents the problem mathematically. In this chapter, a model is given for the RWA problem.

Chapter 4 presents the use of alternate shortest path to reduce the blocking probability with the given resources. It presents six variations for RWA algorithm. Although all the proposed variations for RWA algorithm use the shortest path, alternate shortest path and first-fit wavelength assignment algorithms and give more priority to shortest path as compared to alternate shortest path; yet differs in the combinations of these routing and wavelength assignment algorithms to establish the connections. This combination difference leads to variation in the performance.

Chapter 5 gives two wavelength assignment algorithms: *Minimum Connection Count (MCC)* and *Circular Sequential (CS)* algorithms. *MCC* assigns the wavelengths according to number of connections already established on the wavelengths. It reduces the number of attempts to find a free wavelength for connection establishment and hence reduces the connection establishment time. The performance comparison is done with the commonly used *FF* wavelength assignment algorithm. The main problem with the *MCC* algorithm is maintaining the record (how many connections are using the wavelength currently) for each wavelength. The second proposed algorithm i.e. circular sequential wavelength assignment algorithm avoids this record keeping and maintaining problem. In *CS* algorithm, each wavelength has equal importance. It uniformly assigns the wavelengths according to circular sequential organization. Results show that the number of attempts required to find the free wavelength is less than commonly used algorithms and hence the connection establishment time reduces.

The RWA algorithms given in chapters 4 and 5 are static in nature. The routes with minimum weight are selected and the link having lower weight is over utilized. The links with higher weights become underutilized. The resources are not used efficiently as links are not used symmetrically.

Chapter 6 presents three dynamic algorithms that consider the utilization of links. These algorithms try to distribute the data symmetrically over the links and balance the load on the links. The simulation results show that all the proposed algorithms give better.

Chapter 7 gives the overview of the work done in the form of conclusions and specific contributions. It also presents the further directions for extending the work done in this thesis in the form of future scope of the work.

CHAPTER 3

PROBLEM DEFINITION

3.1 Introduction

Previous work shows that RWA is very important problem and also presents the issues related with this problem. This chapter gives the problem definition to define the RWA problem with the associated constraints and the objectives. Whenever any connection request arrives, a connection needs to be established from the source to the destination to accommodate the request. For establishing a connection, a route needs to be selected from source node to destination node. It is called routing problem. Then a wavelength is required along this route to carry the data. The problem is known as the wavelength assignment. Together these problems are called RWA problem. There are various metrics which affect the network performance, and the objective function is to optimize any of the metrics.

In WDM optical networks, there are two main constraints related with wavelength assignment: *wavelength continuity constraint* (if no wavelength converters are available in the network) and *distinct channel assignment constraint.* In wavelength continuity constraint, the same wavelength must be used on all the edges along the route. This constraint may be broken i.e. the different wavelengths can be used on the edges along the route but the nodes should have wavelength conversion capability. But several studies have reported that the cost of adding wavelength conversion is significantly high as compared to the advantages offered by it [87, 88]. In distinct channel assignment constraint, two lightpaths cannot be assigned the same channel on any fiber.

3.2 Problem Formulation

Given is a network with physical topology represented by a graph *G (V, E, L)*. Here *V* is the set of vertices or nodes in the network. Total number of nodes in the network are $|V|=n$, and are numbered from 0 to n-1. *E* is the set of edges or links in the network. These are the physical edges connecting the vertices. Single fiber system is assumed i.e. there is one fiber along any link. The edges are assumed to be undirected. *L* is the set of weights associated with the edges. This weight is used for computing the route with shortest path algorithm. The set of connection requests is *C*. $|C|=I$ indicate the total number of connection requests. These connection requests are numbered from 0 to I-1. *A* represents the set of wavelengths. $|A|=W$ is the total number of wavelengths numbered from 1 to *W*. Equal number of wavelengths per fiber has been assumed.

3.2.1 Notations

p_{sd} Represents the total number of edges along the route for *s*-*d* connection

s Indicates the source for a connection request

d Indicates the destination for a connection

R_{ij} The route for *s*-*d* connection based on shortest path algorithm

z_{ij} The wavelength assigned to the *s*-*d* connection.

acconn Represents the number of accepted connections

rejconn Represents the number of rejected connections

$w_{ij}^{sd} = 0$, $if\ s-d$ connection does not use any wavelength on edge ij

$= 1$, $otherwise$

$m_{ij,k}^{sd} = 0,\ if\ \ s-d$ connection does not use wavelength k on edge ij

$= 1,\quad otherwise$

$Q_{sd}^{k} = 1,\ if\ \ s-d$ connection uses wavelength k

$= 0,\quad otherwise$

3.2.2 Objective Function

Minimize the blocking probability for given resources.

Or

Minimize number of searches to find free wavelength

Or

Minimize wavelengths required (*W*) to accommodate all the connections (*I*)

A feasible RWA solution is required which optimizes any of the objective function according to the requirement. First and third objective functions are related to each other. Both will be optimized, only if resources are used efficiently.

3.2.3 Mathematical Formulations

Total number of connections (I) with permutation routing (If connections when $(s = d)$ included), $\forall\ (s, d \in V)$

$$= (n(n-1)/2) + n,\quad if\,(R_{ij} = R_{ji}\ \ and\ \ z_{ij} = z_{ji})\ \ \forall\ i, j \in V$$

$$= n \times n,\quad otherwise$$

Total number of connections (I) with permutation routing (If connections when $(s = d)$ excluded), $\forall\ (s, d \in V)$

$$= n(n-1)/2,\quad if\,(R_{ij} = R_{ji}\ \ and\ \ z_{ij} = z_{ji})\ \ \forall\ i, j \in V$$

$$= n(n-1),\quad otherwise$$

3.2.4 Constraints

1. $\sum_{sd} w_{ij}^{sd} <= W \quad \forall \; sd \in C \quad and \quad \forall \; ij \in E$

   Wavelengths assigned on a link for all the connections should not exceed the total number of wavelengths on a link i.e. *W*. It is because; no two or more lightpaths can use a wavelength simultaneously on an edge to observe distinct channel constraint.

2. $\sum_{ij}^{sd} m_{ij,k} = P_{sd}, \quad if \; Q_{sd}^{k} = 1$

   $= 0, \quad otherwise \quad \forall \; sd \in C, \quad \forall \; ij \in E \quad and \quad \forall \; k \in A$

   For any wavelength k and for the $s-d$ connection, left side of the equation represents the number of channels with wavelength k used by the lightpath. If the lightpath uses wavelength k, then the total number of channels used will be equal to the total number of edges along the route R_{sd} i.e. p_{sd}. If the $s-d$ connection does not use the wavelength k then the number of channels on wavelength k used will be zero.

3. $m_{ij,k}^{sd} = 1, \; if \quad w_{ij}^{sd} = 1 \; and \quad Q_{sd}^{k} = 1$

   $= 0, \quad otherwise \quad \forall \; sd \in C, \quad \forall \; ij \in E \quad and \quad \forall \; k \in A$

   The left side of the equation shows whether the wavelength k on edge ij is used by the $s-d$ connection or not. It will be 1, only if the lightpath for the $s-d$ pair is using this channel i.e. the lightpath uses the edge ij and also the lightpath is established on wavelength k.

4. $m_{ij,k}^{sd} \times m_{yv,x}^{sd} = 1 \quad if \;\; k = x \;\; and \;\; w_{ij}^{sd} = 1 \;\; and \;\; w_{yv}^{sd} = 1 \;\; and \;\; Q_{sd}^{k} = 1$

$= 0, \quad otherwise$

It is assumed that there are no wavelength converters in the network. So, w*avelength continuity constraint* is to be observed.

CHAPTER 4

RWA ALGORITHMS WITH VARIATIONS IN IMPLEMENTATION

4.1 Introduction

Blocking probability is very important metric to measure the network performance as discussed in the previous chapters. Existing RWA algorithm is given in next section. The proposed variations for RWA algorithm are presented in section 4.3. The performance comparison is done in terms of blocking probability. Results are given and evaluated in section 4.4. Section 4.5 gives the summary of the findings.

4.2 Existing RWA Algorithm (RWA 1)

In this section, commonly used RWA algorithm [37, 58, 61, 65, 78, 89-91] is presented. In this algorithm, shortest path algorithm is used for routing and first-fit wavelength assignment algorithm is used for wavelength assignment. For each *s-d* pair, first of all, a trial is made to establish the connection on first wavelength using shortest route. If unsuccessful, then connection is tried on second wavelength and so on up to the last wavelength.

Algorithm

1. *For j=0 to I-1*
2. *Find the route for sd[j] using dijkstra's shortest path algorithm*
3. *End loop for j*
4. *rejconn=0*
5. *For j=0 to I-1*

6. *For k=1 to W*
7. *Try to establish the connection for sd[j] on wavelength k using the shortest route*
8. *If connection established in step 7, then go to step 11*
9. *End loop for k*
10. *rejconn ++*
11. *End loop for j*
12. *Blocking probability=rejconn/I*
13. *End*

4.3 Proposed Variations for RWA with Alternate Route

Mostly all the networks employ shortest path for connection establishment. Alternate path is used to establish the connection in the proposed variations for RWA algorithm, if the connection could not be established with shortest path. It is because; the connections not established with shortest path may get established with alternate path with the available resources, to reduce the blocking probability. Alternate paths are more weighed than their corresponding shortest paths, so are given lower priority in the variations for RWA algorithm. The alternate route information is stored at the buffers available at the nodes. The algorithms in this section show the different possible variations of using shortest path with alternate shortest path for first-fit wavelength assignment strategy. These implementation variations are general and can be used with other routing algorithms and wavelength assignment strategies also. Although these are simple to understand and use, yet gives different performance in terms of blocking probability.

4.3.1 RWA 2

In this algorithm, an attempt is made to establish the connection for first *s-d* pair using shortest route starting from first to last wavelength. Now the connection for second *s-d* pair is tried in the similar way and so on this process is repeated for all *s-d* pairs. The connection for first *s-d* pair is tried using alternate route starting from first to last wavelength if connection not established earlier. This step is executed for all other *s-d* pairs in sequence.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*
4. *rejconn=0*
5. *For j=0 to I-1*
6. *For k=1 to W*
7. *Try to establish the connection for sd[j] on wavelength k for shortest path*
8. *If connection established in step 7, then go to step 11*
9. *End loop for k*
10. *rejconn ++*
11. *End loop for j*
12. *For j=0 to I-1*
13. *If connection for sd[j] established with shortest path, go to step 20*
14. *For k=1 to W*
15. *Try to establish the connection for sd[j] on wavelength k for alternate shortest path*

16. *If connection established in step 15, then*

    (i) *rejconn --*

    (ii) *Go to step 19*

17. *End loop for k*

18. *Connection not established*

19. *End loop for j*

20. *Blocking probability=rejconn/I*

21. *End*

4.3.2 RWA 3

In this algorithm, firstly the connections are tried for all the connection requests in sequence using shortest route on first wavelength. Now the similar attempt is made for all the connection requests on all the wavelengths according to their position in indexing. The above mentioned steps are again executed in the same sequence but with alternate route instead of shortest route.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*
4. *rejconn=I*
5. *For k=1 to W*
6. *For j=0 to I-1*
7. *If connection for sd[j] not established with lower wavelength(s), then try to establish the connection for sd[j] on wavelength k for shortest path else go to step 9*

8. *If connection established in step 7, then rejconn --*
9. *End loop for j*
10. *End loop for k*
11. *For k=1 to W*
12. *For j=0 to I-1*
13. *If connection for sd[j] not established with lower wavelength(s), then try to establish the connection for sd[j] on wavelength k for alternate route else go to step 15*
14. *If connection established for sd[j] in step 13, rejconn--*
15. *End loop for j*
16. *End loop for k*
17. *Blocking probability=rejconn/I*
18. *End*

4.3.3 RWA 4

First of all, first connection request is tried using shortest route on the wavelength starting from first to last wavelength. If unsuccessful, the same connection is tried using alternate route on all the wavelengths. The same process is repeated for all the connection requests.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*
4. *rejconn=0*
5. *For j=0 to I-1*

6. *For k=1 to W*
7. *Try to establish the connection for sd[j] on wavelength k for shortest path*
8. *If connection established in step 7, then go to step 15*
9. *End loop for k*
10. *For k=1 to W*
11. *Try to establish the connection for sd[j] on wavelength k for alternate shortest route*
12. *If connection established in step 11, go to step 15*
13. *End loop for k*
14. *rejconn ++*
15. *End loop for j*
16. *Blocking probability=rejconn/I*
17. *End*

4.3.4 RWA 5

On first wavelength, all the connection requests are tried using their shortest routes. Now the same wavelength is again tried for all the connection requests but with their alternate routes. The above steps are followed for all the wavelengths.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*
4. *rejconn=I*
5. *For k=1 to W*
6. *For j=0 to I-1*

7. *If connection for sd[j] not established with lower wavelength(s), then try to establish the connection for sd[j] on wavelength k for shortest path else go to step 9*
8. *If connection established in step 7, then rejconn --*
9. *End loop for j*
10. *For j=0 to I-1*
11. *If connection for sd[j] not established with lower wavelength(s), then try to establish the connection for sd[j] on wavelength k for alternate shortest route, else go to step 13*
12. *If connection established in step 11, then rejconn --*
13. *End loop for j*
14. *End loop for k*
15. *Blocking probability = rejconn/I*
16. *End*

4.3.5 RWA 6

The connection establishment for first *s-d* pair is tried on first wavelength using shortest route. If unsuccessful, the same connection is tried on same wavelength using alternate route. The same procedure is followed for all the other wavelengths. All the other connection requests are also tried in the same way as the connection establishment for first *s-d* pair is tried.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*

4. *rejconn=0*
5. *For j=0 to I-1*
6. *For k=1 to W*
7. *Try to establish the connection for sd[j] on wavelength k for shortest path*
8. *If connection established in step 7, then go to step 13*
9. *Try to establish the connection for sd[j] on wavelength k for alternate shortest route*
10. *If connection established in step 9, then go to step 13*
11. *End loop for k*
12. *rejconn ++*
13. *End loop for j*
14. *Blocking probability=rejconn/I*
15. *End*

4.3.6 RWA 7

It tries for maximum utilization of resources, so that more connections can be established. In this algorithm, first of all the attempt is made to establish the connection for first *s-d* pair using shortest route on first wavelength. If unsuccessful, the same connection request is tried using alternate shortest route on the same wavelength. Now second *s-d* pair is tried on same wavelength, firstly with shortest route and then with alternate shortest route and so on for all the *s-d* pairs. In this way, the attempt is made for maximum utilization of first wavelength for connection establishment. It tries to establish maximum connections using the wavelength under consideration. If there is any connection that could have been established using first wavelength either with shortest route or alternate shortest route, it is established. The procedure is followed for all the wavelengths according to the indexing sequence. The attempt of connection establishment is made on any wavelength only if all the wavelengths previous to it in indexing have been tried for all the connection requests with both routes. This algorithm gives better results because it utilizes the resources very efficiently.

Algorithm

1. *For j=0 to I-1*
2. *Find the shortest and alternate shortest route for sd[j]*
3. *End loop for j*
4. *acconn=0*
5. *For k=1 to W*
6. *For j=0 to I-1*
7. *If connection for sd[j] not established with lower wavelengths, then try to establish the connection for sd[j] on wavelength k for shortest path else go to step 11*
8. *If connection established in step 7, then*
    - *(i) acconn ++*
    - *(ii) Go to step 11*
9. *Try to establish the connection for sd[j] on wavelength k for alternate shortest route*
10. *If connection established in step 9, then*
    - *(i) acconn ++*
    - *(ii) Go to step 11*
11. *End loop for j*

12. *End loop for k*
13. *Blocking probability=I-acconn/I*
14. *End*

4.4 Results and Discussions

We have applied proposed variations for RWA algorithm and existing algorithm to a realistic example of a backbone network, namely, the NSFNET [87, 92] irregular topology shown in Figure 4.1. The nodes are connected together with undirected links. The route from node *t* to node *u* will traverse the same links as traversed by the route from node *u* to node *t* but in the reverse direction.

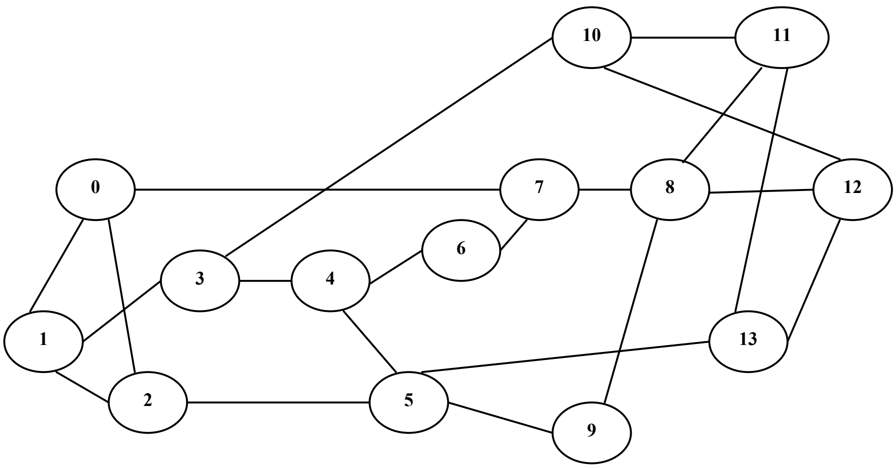

Figure 4.1 NSFNET network

Permutation routing [93-95] has been taken for finding out the sample source destination pairs in which every node in the network acts as the source to every other node in the network simultaneously. Static traffic is assumed and each connection request is numbered. The algorithms work in the greedy way. If a connection request can be accommodated at any stage, it is accommodated immediately by reserving the resources and the algorithms do not try the connection on any other wavelength. Any connection request is first tried using shortest route. The connection could not be established if the wavelength considered is not free on any of the links along the route.

The alternate route taken is the route with minimum weight out of all the possible routes which are node and link disjoint with the shortest route so that no link or intermediate nodes are common with the shortest route. The node disjoint route is taken to control the congestion as nodes have to store the information. With the alternate route, there are chances of connection establishment because the link, on which the wavelength was not free with shortest route, does not come in the route. Table 4.1 stores the link information of the network in terms of their weight.

Table 4.1

Link weight information for NSFNET

Link	Weight
0-1	1
0-2	2
0-7	8
1-2	2
1-3	3
2-5	4
3-4	2
3-10	9
4-5	1
4-6	1
5-9	4
5-13	7
6-7	1
7-8	1
8-9	6
8-11	1
8-12	2
10-11	1
10-12	5
11-13	6
12-13	4

Table 4.2 shows the comparison of existing RWA algorithm and proposed variations for RWA algorithm in terms of blocking probability. The first column of table 4.2 shows the number of wavelengths taken. Column 2 gives the blocking probability for the commonly used existing algorithm. Columns 3 to 8 give the

blocking probability for various proposed variations for RWA algorithm for comparison purpose.

Table 4.2

Blocking probability comparison table

No. of λs	**Blocking probability**						
	RWA1	RWA 2	RWA 3	RWA 4	RWA 5	RWA 6	RWA 7
1	0.813187	0.802198	0.791209	0.846154	0.802198	0.846154	0.857143
2	0.714286	0.681319	0.670330	0.747253	0.681319	0.725275	0.758242
3	0.659341	0.604396	0.593407	0.637363	0.604396	0.637363	0 .648352
4	0.604396	0.560440	0.549451	0.571429	0.549451	0.538462	0.549451
5	0.549451	0.494505	0.483516	0.494505	0.483516	0.483516	0.483516
6	0.505495	0.428571	0.417582	0.406593	0.417582	0.417582	0.406593
7	0.461538	0.373626	0.362637	0.351648	0.351648	0.362637	0.362637
8	0.428571	0.307692	0.307692	0.318681	0.307692	0.318681	0.318681
9	0.406593	0.274725	0.274725	0.285714	0.274725	0.252747	0.263736
10	0.384615	0.252747	0.252747	0.241758	0.241758	0.197802	0.208791
11	0.373626	0.230769	0.230769	0.219780	0.208791	0.164835	0.164835
12	0.340659	0.197802	0.197802	0.186813	0.186863	0.142857	0.131868
13	0.318681	0.175824	0.175824	0.164835	0.153846	0.120879	0.098901
14	0.307692	0.164835	0.164835	0.153846	0.142857	0.087912	0.065934
15	0.296703	0.131868	0.131868	0.131868	0.131868	0.065934	0.043956
16	0.285714	0.131868	0.131868	0.131868	0.109890	0.043956	0.032967
17	0.274725	0.109890	0.109890	0.109890	0.087912	0.032967	0.010989
18	0.252747	0.098901	0.098901	0.098901	0.065934	0.010989	0
19	0.230769	0.098901	0.098901	0.098901	0.043956	0	0
20	0.219780	0.098901	0.098901	0.098901	0.021978	0	0
21	0.197802	0.098901	0.098901	0.098901	0	0	0
22	0.186813	0.098901	0.098901	0.098901	0	0	0
23	0.175824	0.098901	0.098901	0.098901	0	0	0
24	0.164835	0.098901	0.098901	0.098901	0	0	0
25	0.142857	0.098901	0.098901	0.098901	0	0	0
26	0.131868	0.098901	0.098901	0.087912	0	0	0
27	0.120879	0.076923	0.076923	0.065934	0	0	0
28	0.098901	0.076923	0.076923	0.065934	0	0	0
29	0.076923	0.076923	0.076923	0.065934	0	0	0
30	0.065934	0.076923	0.076923	0.065934	0	0	0
31	0.054945	0.076923	0.076923	0.065934	0	0	0
32	0.043956	0.054945	0.054945	0.043956	0	0	0
33	0.032967	0.032967	0.032967	0.021978	0	0	0
34	0.010989	0.032967	0.032967	0.021978	0	0	0
35	0	0.010989	0.010989	0	0	0	0
36	0	0	0	0	0	0	0

The blocking probability comparison graph in figure 4.2 shows the results given in table 4.2 graphically. X-axis represents the number of wavelengths and the Y-axis represents the blocking probability with permutation routing. The combination difference of the shortest path algorithm, alternate shortest path algorithm and first-fit WA algorithm among the proposed variations for RWA algorithm leads to variation in the performance as shown by the results given in the columns 3 to 8 of table 4.2.

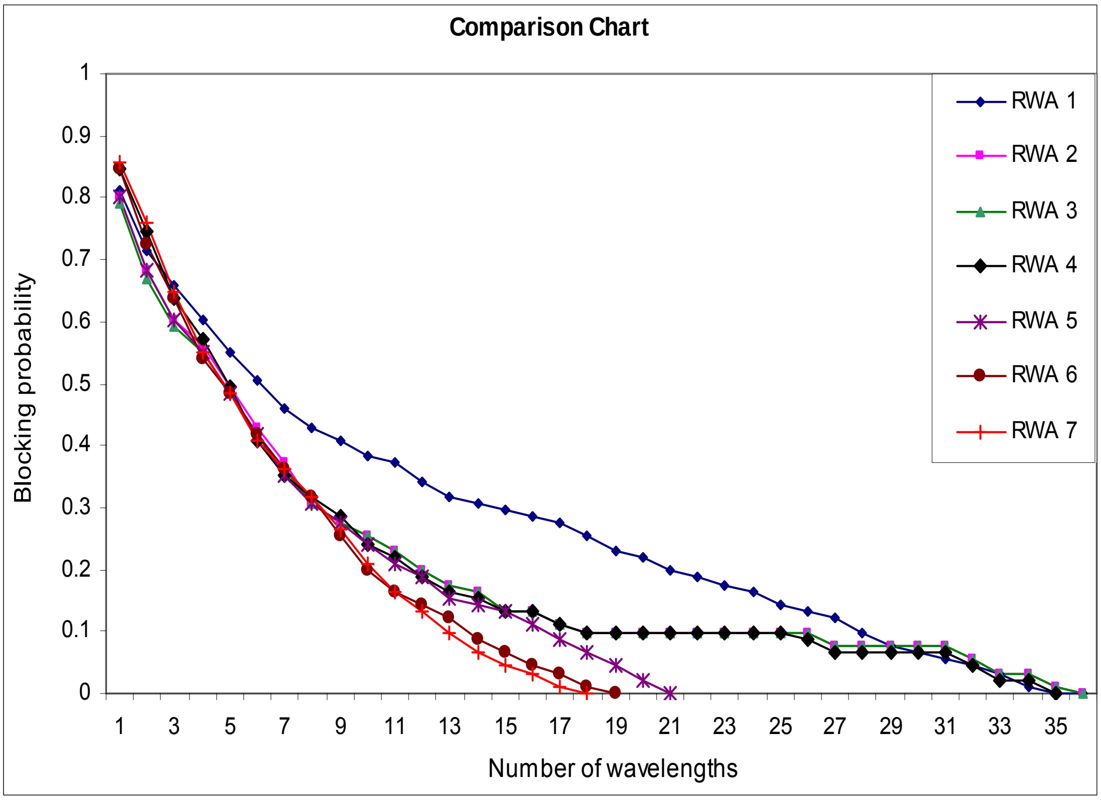

Figure 4.2 Blocking probability comparison graph

Out of these proposed variations, RWA7 gives the best performance because it efficiently utilizes the wavelengths. Simulation results show that the performance of all the proposed variations for RWA algorithm is much better than the existing algorithm because proposed variations use alternate shortest route for connections not established with shortest route.

4.5 Conclusions

In this chapter, we first discussed routing and wavelength assignment problem in WDM optical networks, then the focus was on commonly used RWA algorithm in the optical networks. We have proposed some variations for RWA algorithm which reduces the blocking probability by reducing the number of connections rejected. Although all the proposed variations use the shortest path, alternate shortest path and first-fit WA algorithm giving more priority to shortest path as compared to alternate shortest path, yet differs in the combinations of the three to establish the connections. Each possible combination has been considered. This difference leads to variation in the performance as shown by the results. Out of these proposed algorithms, RWA7 gives the best performance because it efficiently utilizes the resources. The performance of proposed variations for RWA algorithm and most commonly used RWA algorithm have been evaluated in terms of blocking probability by applying on the sample network. Simulation results show that the performance of all the proposed variations for RWA algorithm is much better than the existing algorithm.

CHAPTER 5

MODIFIED WAVELENGTH ASSIGNMENT ALGORITHMS

5.1 Introduction

The previous chapter gives the RWA algorithms which use the *FF* (commonly used wavelength assignment) algorithm. Wavelength assignment algorithm decides the order in which the wavelengths will be tried for a lightpath establishment and greatly affects the performance. This chapter covers two wavelength assignment algorithms in sections 5.2 and 5.3. The presented algorithms try to reduce the number of attempts required to find a free wavelength for a lightpath. If fewer attempts are required, less time will be taken to find the free wavelength which directly means low connection establishment time. Performance evaluation is done in section 5.4 with the help of results. The chapter ends with the conclusions in the last section.

5.2 Minimum Connection Count (MCC) Algorithm

The route gives the sequence of links starting from source node to destination node. A wavelength is required to be reserved over these links to carry the data. This wavelength is selected by the wavelength assignment algorithm. As it deals with resource allocation and establishment of connections, it is critical issue and affects the performance of the network.

5.2.1 Existing Algorithm (First-Fit Algorithm)

This algorithm is implemented by predefining an order of the wavelengths. The wavelength search is made according to this order. The first free wavelength found on the links along the route is reserved for connection establishment. It does not take into consideration the usage factor of the wavelengths i.e. how heavily loaded a wavelength is. The wavelengths are searched starting from the first wavelength for all the connections, so the wavelengths earlier in the list are tried before the wavelengths later in the list [90, 91]. The algorithm for *FF* wavelength assignment algorithm is given below:

Algorithm

For each s-d pair, do the following:

1. *ptr1 = 1*
2. *Take node pointer ptr2 initially pointing to s*
3. *If wavelength ptr1 is not free on link from node pointed by ptr2 to next node on the route, then*
   - *(i) If ptr1 = W, then go to step 8*
   - *(ii) ptr1= ptr1+1*
   - *(iii) Go to step 2*
4. *Advance node pointer ptr2 to next node on the route*
5. *If ptr2 != d, then go to step 3*
6. *Reserve wavelength ptr1 on all the links on the route from s to d to establish the connection*
7. *Go to step 9*
8. *Reject the connection request*
9. *End*

5.2.2 Proposed Algorithm (Minimum Connection Count Algorithm)

In this, whenever any connection request arrives, the wavelength which is used by minimum number of connections out of all the wavelengths is attempted for connection establishment. If this wavelength is free on all the links along the route for the *s-d* pair under consideration, it is reserved along the route for *s-d* connection establishment. If wavelength is not free, then from the remaining wavelengths again the wavelength with minimum connection count is attempted and so on till the connection gets established or all the wavelengths are tried. If more than one wavelength has minimum connection count, then first fit is used to choose the wavelength.

When number of wavelengths is initially very less and there are unestablished connections, if the wavelengths are increased, the number of attempts will increase. It is because the resources are very less and connection requests are more. Due to the availability of lesser resources than required, the connections will be attempted on mostly all the wavelengths including the added wavelengths resulting in increase in the number of attempts. If wavelengths are further increased, then as more resources become available, there are more connection establishment chances with the earlier attempted wavelengths, as these are least loaded wavelengths. The number of wavelengths searched reduces as more resources are available. Even if all the connections get established and number of wavelengths are further increased then as it tries least loaded wavelength so the number of attempts may decrease as the chance of wavelengths to be free will be more and the connection request can get free wavelength from earlier wavelengths. For a connection request, chances of getting a free wavelength from the wavelengths attempted earlier are more as more resources lead to less load on wavelengths. The *MCC* wavelength assignment algorithm is given below:

Algorithm

For each s-d pairs, perform the following:

1. *ptr1=1*
2. *Find a wavelength from all the wavelengths in the list with minimum connection count. Let it be e*
3. *Delete e from the list*
4. *Take node pointer ptr2 initially pointing to s*
5. *If wavelength e is not free on the link from node pointed by ptr2 to next node along the route, then*
   (i) *If ptr1=W, then go to step 9*
   (ii) *ptr1=ptr1+1*
   (iii) *Go to step 2*
6. *Advance node pointer ptr2 to next node on the route*
7. *If ptr2!=d, then go to step 5*
8. *Reserve wavelength e on all the links on the route from s to d to establish the connection, go to step 10*
9. *Reject the connection request*
10. *End*

The disadvantage of first-fit algorithm is that for every *s-d* pair, the search for free wavelength starts from the first wavelength in the index. Initially the lower indexed wavelengths may be available for connection establishment. But after some connections get established, the lower indexed wavelengths are more heavily used as compared to others because whenever a connection request arrives, wavelength search starts from lowest indexed wavelength. Lower indexed wavelengths are heavily used so there is less probability of connection establishment on these wavelengths. So number of attempts to find wavelength for connection establishment increases leading to higher connection establishment time.

In *MCC*, the wavelength which is tried first for any *s-d* pair is the wavelength which is used by minimum connections. So, this wavelength is least loaded and the chance of getting the wavelength free on the links along the route is high. It will lead to more connection establishment chances on the earlier attempted wavelengths, directly reducing the number of attempts and time to find a free wavelength. Also, *MCC* is different from existing least used wavelength assignment strategy because in least used strategy the calculation is done according to the number of links [9] but in *MCC* the calculation is done according to number of connections. *MCC* strategy is simple as compared to least used strategy.

5.3 Circular Sequential (CS) Algorithm

The wavelength assignment algorithm proposed in the previous section results in less number of attempts to find a free wavelength. But it requires the number of connections using the wavelength counter to be associated with each wavelength. Also time is wasted in calculating the wavelength with minimum connection count. A wavelength assignment algorithm is proposed in this section that overcomes these two problems and provides the advantage of less number of attempts. In it, a circular list of wavelengths is taken instead of taking a linear list as in first-fit. If *W* numbers of wavelengths are available, then they are arranged as in figure 5.1.

There is one pointer pointing to one wavelength. Whenever a connection request arrives, wavelength assignment is tried starting from the wavelength pointed by the pointer. After the assignment of the wavelength, the pointer points to the next wavelength.

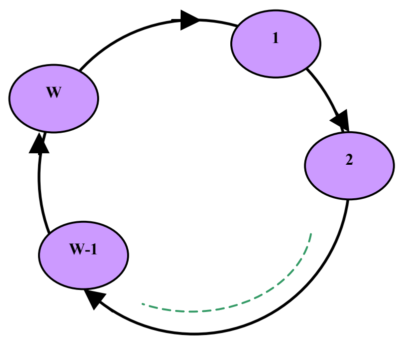

Figure 5.1 Arrangement of wavelengths in circular sequential algorithm

Algorithm

1. *ptr = 1*
2. *For each s-d pair, do the following*
3. *i = ptr*
4. *Take node pointer j initially pointing to s*
5. *If wavelength i is not free on link from j to next node on the route, then*
   - *(i) If (i =((ptr + W-2) modulus W) + 1), then go to step 11*
   - *(ii) i = ((i + W) modulus W) + 1*
   - *(iii) Go to step 4*
6. *Advance node pointer j to next node on the route*
7. *If (j != d), then go to step 5*
8. *Reserve wavelength i on all the links from s to d on the route to accept the connection request*
9. *ptr = ((i + W) modulus W) + 1*

10. *Go to step 12*

11. *Reject the connection request*

12. *Go to step 2 for new s-d pair till end*

5.4 Results and Discussions

Case A: Minimum Connection Count Algorithm

To determine the optimality of proposed algorithm, we tested it on various standard networks. The NJ LATA network [96, 97] shown in figure 5.2, COST239 network [98] shown in figure 5.3 and NSFNET shown in figure 4.1 are the sample networks. The nodes are connected together with undirected links. Let *t* and *u* are two different nodes in the network. Due to undirected links, the routes for *t* (source) to *u* (destination) and *u* (source) to *t* (destination) will be same.

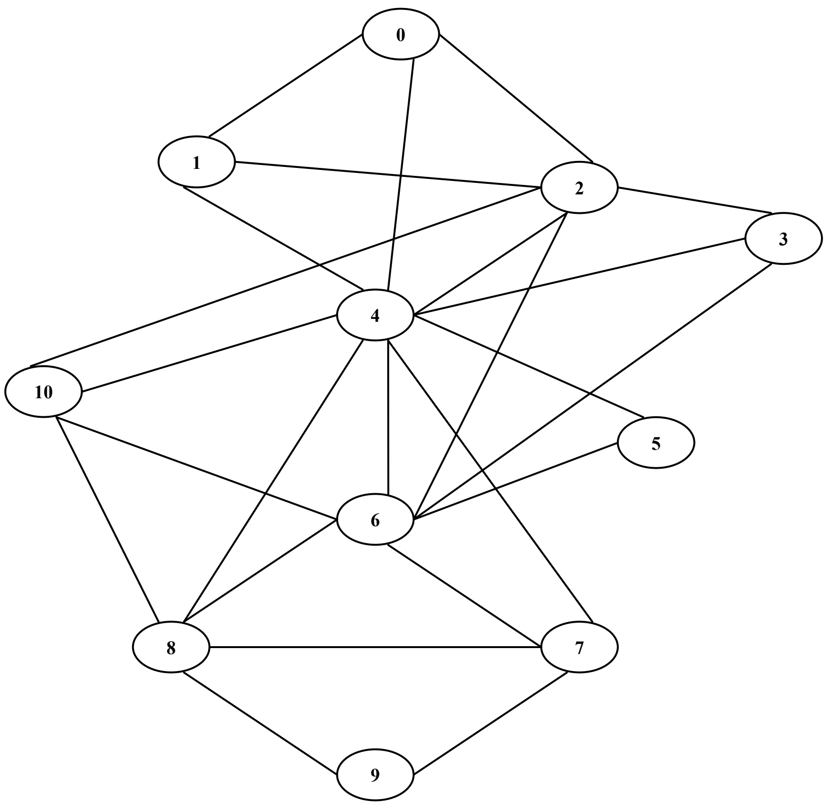

Figure 5.2 NJ LATA network

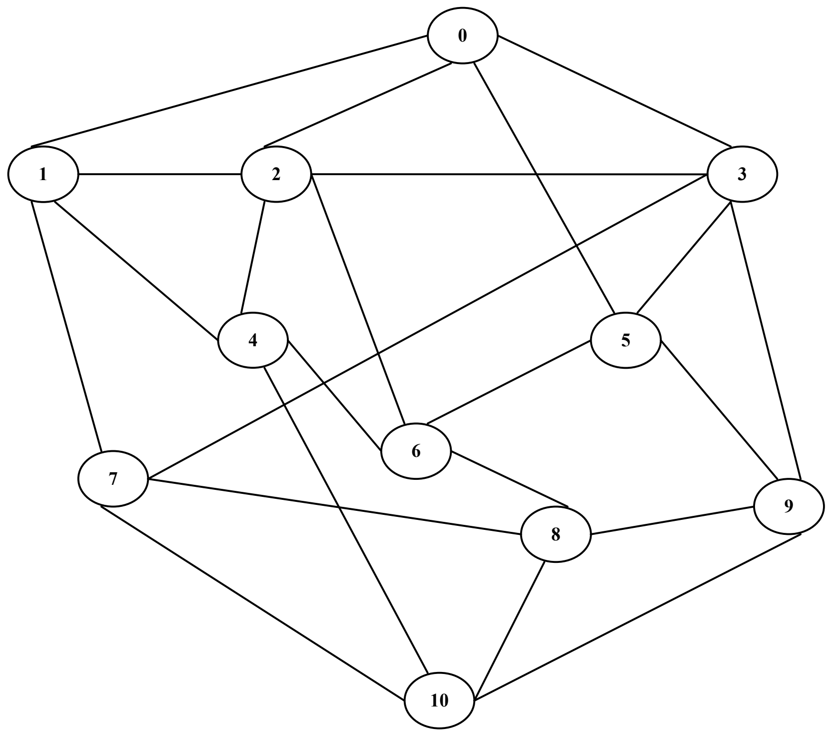

Figure 5.3 COST239 network

Permutation routing has been taken for finding out the sample *s-d* pairs. Total number of *s-d* pairs in permutation routing depends upon the number of nodes. It is assumed that if a node has to send some data to it, the data is sent internally and no external links are used for the transfer. So the *s-d* pairs, when *s=d* are not included during the simulation as they do not require the wavelength and do not affect the number of attempts.

The weight taken for each link in the network is same and shortest path algorithm is applied to find the route because it efficiently utilizes the resources. Equal number of wavelengths per fiber has been assumed and *wavelength continuity constraint* is observed. Greedy approach is used while wavelength selection for a connection i.e. the first free wavelength found along the route is reserved for the connection.

Figure 5.4, 5.5 and 5.6 show the performance comparison in terms of number of attempts for *FF* and *MCC* wavelength assignment algorithms when applied on NJ LATA, COST239 and NSFNET networks respectively. The X-axis represents the number of wavelengths and Y-axis represents the number of attempts done to find the free wavelength for the connection requests.

Simulation results show that *MCC* algorithm performs better than *FF* algorithm because it tries the wavelengths according to their reservation for various connections. In *MCC*, the least loaded wavelength is tried first as there are more chances of connection establishment over it, leading to reduced number of attempts.

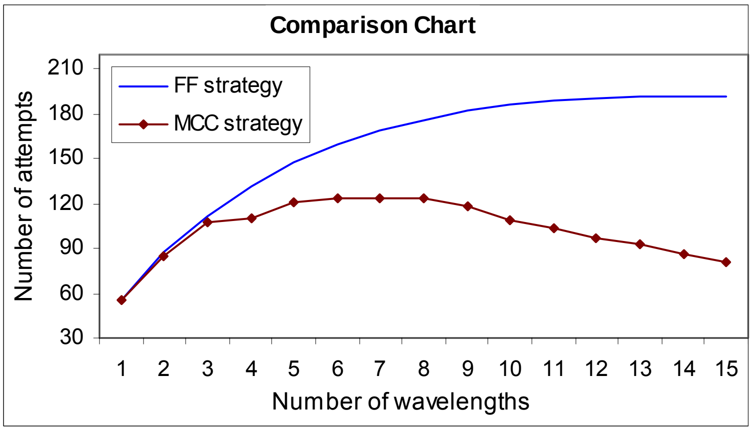

Figure 5.4 Performance comparison of *FF* and *MCC* for NJ LATA network

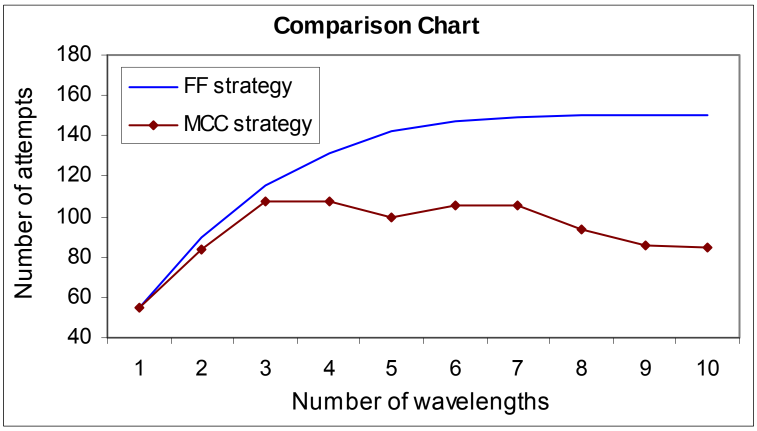

Figure 5.5 Performance comparison of *FF* and *MCC* for COST239 network

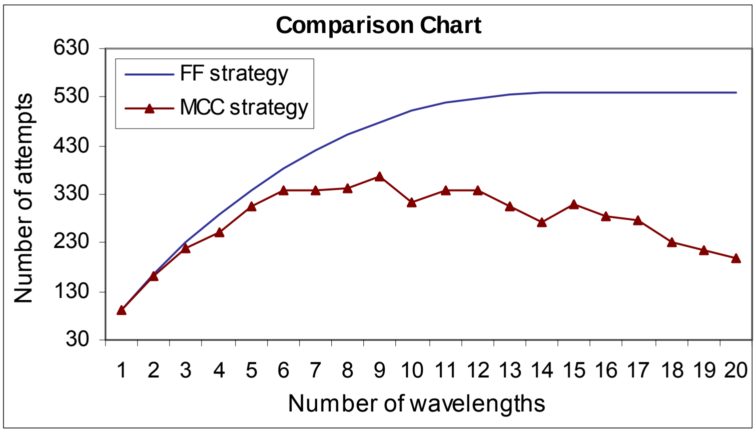

Figure 5.6 Performance comparison of *FF* and *MCC* for NSFNET

Case B: Circular Sequential Algorithm

The networks shown in Figure 4.1 and Figure 5.7 are NSFNET and unidirectional ring network respectively taken as the sample networks. The paths are wavelength continuous. The routes have been selected by applying shortest path algorithm for NSFNET.

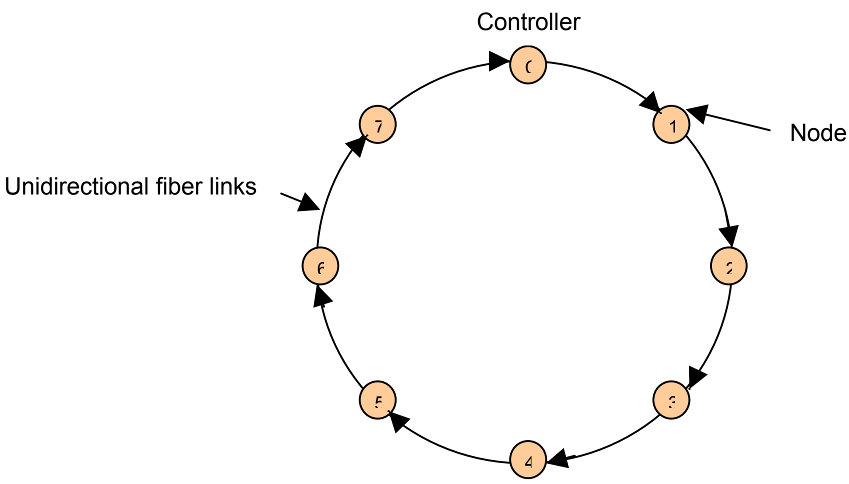

Figure 5.7 Unidirectional ring with 7 nodes

The following *s*-*d* pairs for connection establishment have been taken for NSFNET with two wavelengths:

(0 - 8), (7 - 13), (1 - 5), (11 - 13), (1 - 6), (0 - 1), (0 - 6), (5 - 12), (2 - 8), (3 - 5), (10 - 13), and (3 - 12).

Then, the following *s-d* pairs for connection establishment have been taken for unidirectional ring with three wavelengths:

(2 - 5), (4 - 6), (1 - 3), (5 - 7), (6 - 1), (4 - 7), (2 - 4), and (3 - 4).

The following *s-d* pairs are also considers for NSFNET with four wavelengths:

(0 - 8), (7 - 13), (1 - 5), (11 - 13), (1 - 6), (0 - 1), (0 - 6), (5 - 12), (2 - 8), (3 - 5), (10 - 13), (3 - 12), (5 - 2), (2 - 4), (3 - 6), (9 - 7), (4 -13), (7 - 1), (4 - 1), and (7 - 4).

By applying the commonly used wavelength assignment strategies *(LU, MU, FF, RA and Tree Topology(TR) Strategy*[77]*)*, and the *CS* strategy on the above mentioned networks and the *s-d* pairs, the results are tabulated in tables 5.1, 5.2, and 5.3 for NSFNET with two wavelengths, Ring with three wavelengths and NSFNET with four wavelengths respectively.

Table 5.1

Comparison for NSFNET with 2 wavelengths

(s-d) Pair	Shortest route	Commonly used wavelength assignment algorithms										Proposed algorithm	
		Least used		Most used		First-fit		Random		Strategy with tree topology		Circular sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
0-8	0-7-8	1	1	1	1	1	1	2	1	1	1	1	1
7-13	7-8-11-13	2	1	2	2	2	2	1	2	D	2	2	1
1-5	1-2-5	1	1	2	1	1	1	1	1	1	1	1	1
11-13	11-13	1	1	1	2	1	1	2	2	2	1	1	2
1-6	1-3-4-6	2	1	2	1	1	1	1	1	1	1	2	1
0-1	0-1	1	1	2	1	1	1	1	1	2	1	1	1
0-6	0-7-6	2	2	2	1	2	2	1	2	2	2	2	1
5-12	5-13-12	1	1	2	1	1	1	2	1	1	1	1	1
2-8	2-5-9-8	2	2	1	2	2	2	2	2	2	2	2	1
3-5	3-4-5	1	1	1	2	2	2	2	1	2	2	1	1
10-13	10-12-13	2	2	1	2	2	2	1	2	2	2	2	1
3-12	3-10-12	1	1	2	1	1	1	2	1	1	1	1	1
Total no. of attempts		15		17		17		17		17		13	

Table 5.2
Comparison for ring network with 3 wavelengths

(s-d) Pair	Shortest route	Commonly used wavelength assignment algorithms										Proposed algorithm	
		Least used		Most used		First-fit		Random		Strategy with tree topology		Circular sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
2-5	2-3-4-5	1	1	1	1	1	1	1	1	2	2	1	1
4-6	4-5-6	3	1	2	2	2	2	3	1	1	1	2	1
1-3	1-2-3	2	1	2	2	2	2	2	2	1	1	3	1
5-7	5-6-7	1	1	1	2	1	1	2	2	2	2	1	1
6-1	6-7-1	2	1	1	2	2	2	3	2	1	1	2	1
4-7	4-5-6-7	*D*	3	3	3	3	3	*D*	3	3	3	3	1
2-4	2-3-4	3	1	3	3	3	3	3	2	3	3	2	2
3-4	3-4	2	2	2	3	2	2	2	3	1	1	3	1
Total no. of attempts		11		18		16		16		14		9	

Table 5.1, 5.2 and 5.3 show the comparison in terms of number of attempts to find the wavelength for connection establishment of the commonly used and the *CS* wavelength assignment algorithms. Column 1 shows the *s-d* pairs, column 2 gives the shortest route from source to destination, column 3, 5, 7, 9, 11, and 13 show the wavelength reserved for connection establishment for *LU, MU, FF, RA, TR*, and *CS* strategies respectively. The '*D*' in these columns indicates that the connection could not be established due to unavailability of free wavelength. Column 4, 6, 8, 10, 12, and 14 show the number of attempts to find a free wavelength along the route for *LU, MU, FF, RA, TR*, and *CS* algorithms respectively. There is one row in the table corresponding to each *s-d* pair. The last row indicates the total number of attempts for all the *s-d* pairs for various wavelength assignment algorithms. The tables clearly show that the proposed algorithm results in less number of attempts to establish the connection as compared to commonly used algorithms in most of

the cases. Table 5.3 shows equal number of attempts for *LU* and *CS* algorithms but table 5.1 and 5.2 show the better results for *CS* as compared to *LU*. Moreover, in case of *LU* algorithm whenever a connection request arrives the system have to calculate the uses of each wavelength but *CS* algorithm is very simple and does not require this overhead.

Table 5.3
Comparison for NSFNET with 4 wavelengths

(s-d) Pair	Shortest route	Commonly used wavelength assignment algorithms										Proposed algorithm	
		Least used		Most used		First-fit		Random		Strategy with tree topology		Circular sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
0-8	0-7-8	1	1	1	1	1	1	2	1	1	1	1	1
7-13	7-8-11-13	2	1	2	2	2	2	4	1	2	2	2	1
1-5	1-2-5	3	1	2	1	1	1	3	1	2	2	3	1
11-13	11-13	4	1	1	2	1	1	2	1	1	1	4	1
1-6	1-3-4-6	4	1	2	1	1	1	3	1	1	1	1	1
0-1	0-1	1	1	2	1	1	1	3	1	1	1	2	1
0-6	0-7-6	3	1	2	1	2	2	1	1	2	2	3	1
5-12	5-13-12	1	1	2	1	1	1	4	1	1	1	4	1
2-8	2-5-9-8	2	1	1	2	2	2	1	1	3	3	1	1
3-5	3-4-5	3	1	1	2	2	2	2	2	2	2	2	1
10-13	10-12-13	4	1	1	2	2	2	2	2	2	2	3	1
3-12	3-10-12	1	1	2	1	1	1	1	1	1	1	4	1
5-2	5-2	4	3	3	3	3	3	4	2	1	1	2	2
2-4	2-5-4	1	3	4	4	4	4	*D*	4	4	4	4	2
3-6	3-4-6	2	1	4	3	3	3	4	2	3	3	3	3
9-7	9-8-7	3	1	4	3	3	3	3	3	4	4	4	1
4-13	4-5-13	4	1	3	4	3	3	3	3	3	3	1	1
7-1	7-0-1	2	1	4	3	3	3	4	3	3	3	4	3
4-1	4-3-1	1	2	3	4	4	4	1	4	4	4	3	3
7-4	7-6-4	1	4	1	2	4	4	2	4	4	4	4	1
Total no. of attempts		28		43		44		36		42		28	

Figure 5.8 shows the comparison of the commonly used and proposed algorithms in the form of bar graph. The X-axis represents the sample networks and the number of wavelengths considered. The Y-axis represents the total number of attempts.

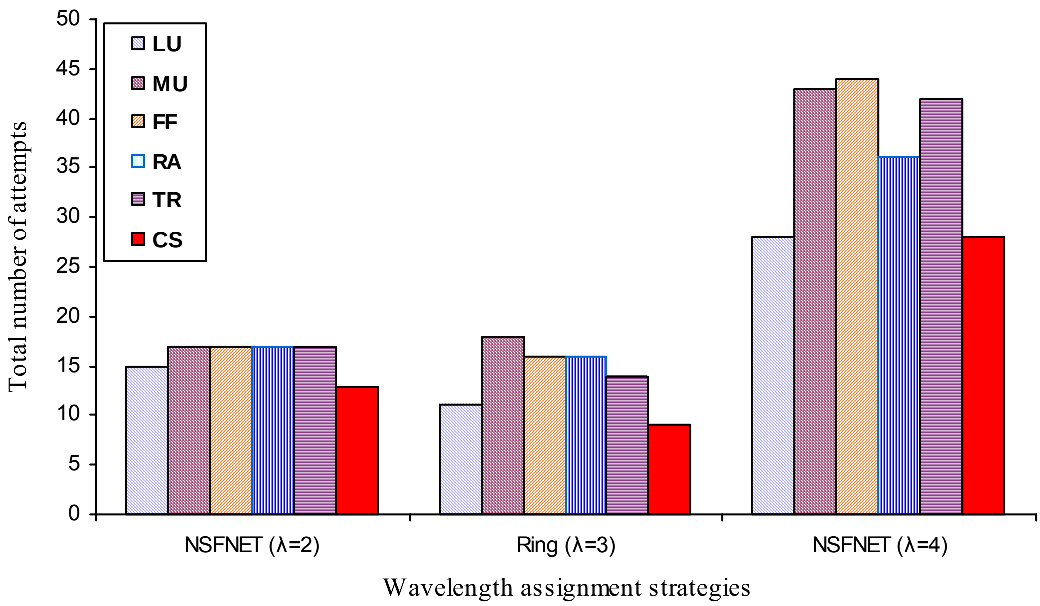

Figure 5.8 Performance evaluation of *CS* for NSFNET and ring networks

5.5 Conclusions

Wavelength assignment problem is covered in this chapter. Two wavelength assignment algorithms have been proposed. First WA algorithm (*MCC*) assigns the wavelengths according to minimum connection count. It reduces the number of attempts to find a free wavelength for connection establishment and hence reduces the connection establishment time. The performance of *MCC* algorithm is compared with the commonly used *FF* wavelength assignment algorithm in terms of number of attempts to find a free wavelength for connection establishment. The simulation is done using different network models. The simulated results show that the *MCC* algorithm is much better than existing algorithm in terms of number of attempts. It is because, the disadvantage of *FF* algorithm is that the lower indexed wavelengths are much more heavily used as compared to others, because whenever a connection request arrives; wavelength search is started from lowest indexed wavelength. Lower indexed wavelengths are heavily used, so there is less probability of connection establishment using these wavelengths. So, number of attempts to find wavelength for connection establishment increases.

The problem with the *MCC* algorithm is maintaining the record for each wavelength and also the extra time required to calculate the wavelength with minimum connection count. The second proposed *WA* algorithm i.e. *CS* algorithm gives good results and avoids the problems available with *MCC* algorithm. In *CS* algorithm, each wavelength has equal importance. It uniformly assigns the wavelengths according to definite approach. Results show that the number of attempts required to find the free wavelength is less than commonly used algorithms.

CHAPTER 6

COMPARATIVE INVESTIGATIONS ON DYNAMIC RWA STRATEGIES

6.1 Introduction

The RWA algorithms covered in the previous chapters were static in nature. The disadvantage of this approach is that the network state is not considered while computing the route. The routes selected are always the routes with minimum weight and the link with lower weight is over utilized. It might lead to the situation where some links on the network are over utilized, while other links are underutilized. Now although the free resources are available along the underutilized links, but the new routes may try for the routes with over utilized links. It is because the network state is not considered and so utilization of links does not affect the routing decision. It will result in rejection of many connection requests. Section 6.2 of this chapter presents the dynamic strategies that consider the utilization of links in the next section. These strategies try to symmetrically distribute the data over the links to efficiently utilize the resources and will lead to reduced blocking probability. Section 6.3 gives and analyzes the results. Conclusions are given in section 6.4.

6.2 Dynamic RWA Strategies

There is a central controller that keeps track of all the information. Mostly all the networks employ shortest path for connection establishment. In all the four strategies discussed, first of all the connection establishment corresponding to all the connections is tried on shortest path because shortest path helps to utilize the resources efficiently. Alternate shortest path is then used to establish the connection, if the connection could not be established with shortest path. It is because the connections rejected with shortest path may be established with alternate shortest path without requiring additional resources as given in section 4.3. As it is node and link disjoint so it will not cover the overloaded link/node in the shortest path and there are chances of connection establishment. As alternate shortest paths are more weighed than shortest paths, so are given lower priority. Always first of all lightpaths on shortest routes are tried before lightpaths on alternate shortest paths as given in section 4.3. In all the strategies first-fit wavelength assignment technique is used.

6.2.1 Existing Strategy

The network with the given link weight is taken and all the connections are established according to these link weights. The link weights do not change according to the connection requests, the number of wavelengths, the resource requirement/utilization, and resource availability [87, 99].

The disadvantage of this approach is that the routing decision is not made based on the current state of network. It might lead to the situation where some links on the network are over utilized while other links are underutilized.

6.2.2 Channel Requirement for Shortest Path (CRSP) Strategy

The new weight assigned to a link is equal to the number of channels required on that link if all the connections are to be accepted with shortest path with the existing strategy. It gives higher weight to the links which are required more number of times, so that they are less preferred for connection establishment leading in reduction of traffic over these links. Similarly the links which were less demanded earlier are given low weight so the traffic on these links increases. In this way, the load gets balanced on the links so that more connections can be accepted reducing blocking probability. It is independent of the total number of channels on the link i.e. the resources available. The connection requests and the resources required for those is very important factor and it was not considered in the strategy discussed in the previous sub section. *CRSP* strategy changes the link weights according to the connection requests and the resources required for the connection establishment, so gives better results than the existing strategy.

6.2.3 Channel Requirement for Connection Establishment (CRCE) Strategy

The new weight assigned to a link is equal to the total number of channels required on that link if the shortest as well as alternate shortest light paths are to be established for all the connection requests with the existing strategy. The load balancing on the links is done according to the resources required and it leads to more number of connections established. In the four strategies discussed, the connection is tried on alternate shortest path if not established on shortest path. So the resources required for alternate shortest path are also equally important as that for the resources required for shortest path and needs consideration which is done in this strategy. This consideration was not done in the earlier two discussed strategies, so this strategy performs better than the existing and *CRSP* strategies. It is independent of the number of wavelengths on the links.

6.2.4 Channel Utilization (CU) Strategy

In this strategy, the new weight assigned to a link is equal to the total number of channels that will be used on that link for the establishment of all the connections for the given number of wavelengths with the existing strategy. All the links have equal number of channels, but some links are more demanded, so more number of channels is used on those links and some links are less demanded, so less number of channels is used on those links. If all the links are equally used then more number of connections can be established. The new link weight assigned tries to give the more priority to the links that were earlier less demanded so that they can be more used by the connections. It also gives less priority to the links that were earlier more demanded so that they are less demanded now. In this way, the traffic gets symmetrically distributed over the links to some extent thus reducing the blocking probability. It gives best results out of all the four strategies discussed in this chapter because it takes into consideration the utilization factor of each link if each link has same resources i.e. number of channels which was not taken are of in the other three strategies.

6.3 Results and Discussions

The skeleton of the NSFNET shown in figure 4.1 is the sample network. The nodes are connected together with undirected links. We have applied presented strategies on this network. Permutation routing has been taken for finding out the sample source destination pairs.

Table 6.1 stores the link information of the network in terms of their weight. Table 6.2 shows the comparison of existing strategy and proposed strategies in terms of blocking probability. The first column of table 6.2 shows the number of wavelengths taken. Column 2 gives the blocking probability for the commonly used strategy. Columns 3 to 5 give the blocking probability for comparison purpose for proposed *CRSP*, *CRCE* and *CU* strategies respectively.

Table 6.1

Link information for dynamic strategies

Link	Weight
0-1	1
0-2	2
0-7	8
1-2	2
1-3	3
2-5	4
3-4	2
3-10	9
4-5	1
4-6	1
5-13	7
6-7	1
7-8	1
8-9	6
8-11	1
8-12	2
10-11	1
10-12	5
11-13	6
12-13	4

The difference of the link weights among the existing strategy and the proposed strategies leads to variation in the performance as shown by the results given in the columns 2 to 5 of table 6.2, although rest everything i.e. the physical network topology *G*, the set of connection requests *C*, the routing technique (with shortest and alternate shortest path in this case) and the WA strategy (first fit in this case) is same for all the strategies. All the proposed strategies give better results than the existing approach, but out of all these proposed strategies, *CU* strategy gives the best performance. Simulation results show that the performance of all the proposed strategies is much better than the existing strategy. The comparison graph in figure 6.1 shows the results given in table 6.2 graphically. X-axis represents the number of wavelengths and the Y-axis represents the blocking probability for the sample network with permutation routing.

Table 6.2

Blocking probabilities for dynamic strategies

No. of λs	Blocking probability			
	Existing strategy	CRSP strategy	CRCE strategy	CU strategy
1	0.791209	0.846154	0.835165	0.835165
2	0.681319	0.714286	0.714286	0.725275
3	0.615385	0.626374	0.626374	0.637363
4	0.56044	0.549451	0.582418	0.538462
5	0.505495	0.472527	0.505495	0.450549
6	0.43956	0.428571	0.428571	0.395604
7	0.395604	0.384615	0.384615	0.307692
8	0.340659	0.351648	0.318681	0.263736
9	0.307692	0.285714	0.252747	0.21978
10	0.263736	0.252747	0.208791	0.153846
11	0.241758	0.208791	0.164835	0.131868
12	0.197802	0.186813	0.131868	0.076923
13	0.175824	0.175824	0.076923	0.065934
14	0.153846	0.153846	0.032967	0.021978
15	0.131868	0.10989	0.010989	0.010989
16	0.10989	0.098901	0	0
17	0.10989	0.087912	0	0
18	0.087912	0.087912	0	0
19	0.076923	0.087912	0	0
20	0.076923	0.054945	0	0
21	0.076923	0.043956	0	0
22	0.076923	0.032967	0	0
23	0.076923	0.032967	0	0
24	0.076923	0.021978	0	0
25	0.076923	0.021978	0	0
26	0.076923	0.010989	0	0
27	0.076923	0.010989	0	0
28	0.054945	0.010989	0	0
29	0.032967	0.010989	0	0
30	0.032967	0	0	0
31	0.032967	0	0	0
32	0.032967	0	0	0
33	0.032967	0	0	0
34	0.010989	0	0	0
35	0	0	0	0

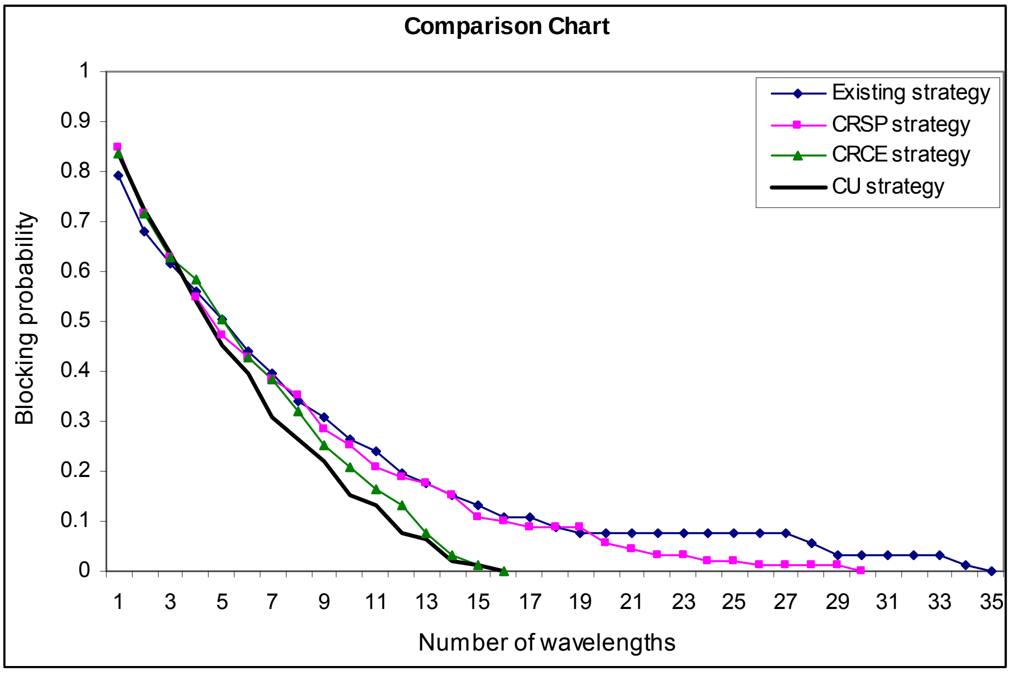

Figure 6.1 Performance evaluations of dynamic strategies

6.4 Conclusions

In this chapter, three strategies to reduce the blocking probability are presented. In first proposed strategy, the new link weight is equal to the number of channels required if shortest path corresponding to all s-d pairs are to be established as it assigns the link weight according to the demand of link, so balances the load. The second proposed strategy further improves the results by also considering the alternate shortest path because it is also equally important. The third proposed strategy gives the best performance by considering the link utilization of each link if each link has equal capacity. The performance of proposed strategies and existing trend has been evaluated in terms of blocking probability. The simulation results show that all the three proposed strategies give better results than existing trend. The third proposed strategy is the best out of all these.

CHAPTER 7

CONCLUSIONS, SPECIFIC CONTRIBUTIONS AND FUTURE SCOPE OF WORK

7.1 Conclusions

Wavelength routing, in conjunction with WDM, is the most promising mechanism for data transmission. Routing and wavelength assignment is very important issue. Efficient routing and wavelength assignment algorithms are presented in this thesis, which optimize the performance.

Chapter 4 shows the advantage of alternate shortest path to reduce blocking probability. It also gives the proposed variations for RWA algorithm, all of which use the shortest path, alternate shortest path, first-fit wavelength assignment algorithm and give more priority to shortest path as compared to alternate shortest path; yet differ in the combinations of the three to establish the connections. Each possible combination has been considered. This combination difference leads to different values of blocking probabilities as shown by the results. Out of all the algorithms, *RWA7* gives the best performance because it efficiently utilizes the resources.

Chapter 5 covers two wavelength assignment algorithms. Wavelength assignment algorithm decides the order in which the wavelengths are tried for a lightpath establishment and greatly affects the performance. The presented algorithms try to reduce the number of attempts required to find a free wavelength for a lightpath. If fewer attempts are required, less time is taken to find the free wavelength. First proposed algorithm *MCC* assigns the wavelengths according to connection count of the wavelengths. The performance of *MCC* algorithm is compared with the commonly used *FF* wavelength assignment algorithm in terms of number of attempts. The simulation is done using different network models. The simulated results show that the *MCC* algorithm is much better than *FF* algorithm in terms of number of attempts. It is because, the disadvantage of *FF* algorithm is that the lower indexed wavelengths are much more heavily used as compared to others; because whenever a connection request arrives, wavelength search is started from lowest indexed wavelength. Lower indexed wavelengths are heavily used, so there is less probability of connection establishment using these wavelengths. So, number of attempts to find wavelength for connection establishment increases.

The problem with the *MCC* algorithm is maintaining the record for each wavelength and also the extra time required to calculate the wavelength with minimum connection count. The second proposed algorithm *CS* wavelength assignment algorithm gives good results and avoids the problems available with *MCC* algorithm. In it, each wavelength has equal importance. It uniformly assigns the wavelengths according to a definite approach. Results show that the number of attempts required to find the free wavelength is less as compared to commonly used algorithms.

The RWA algorithms covered in chapters 4 and 5 are static in nature. The disadvantage of this approach is that the network state is not considered while computing the route. If the shortest path algorithm is used, the route with minimum weight is selected. The links having lower weights are over utilized. It leads to the situation where some links on the network are over utilized, while other links are underutilized. Now although the free resources are available along the underutilized links, but the new routes use over utilized links. It is because the network state is not considered and the utilization of links does not affect the routing decision. It results in rejection of many connection requests. Chapter 6 presents three dynamic strategies that consider the utilization/requirement of channels on links. These try to distribute the data over the links to efficiently utilize the resources. In first proposed strategy, the new link weight is equal to the number of channels required if shortest path corresponding to all *s-d* pairs are to be established. As it assigns the link weight according to the demand of link, so it distributes the load. The second proposed strategy further improves the results by also considering the alternate shortest path because it is also equally important. The third proposed strategy considers the link utilization of each link, if each link has equal channel capacity. The performance of proposed strategies and existing trend has been evaluated in terms of blocking probability. The simulation results show that all the three proposed strategies give better results than existing trend. The third proposed strategy is the best out of all these.

This thesis gives the RWA algorithm variations which reduce the blocking probability without any change in infrastructure. It also covers two wavelength assignment algorithms which try to reduce the number of attempts required to find a free wavelength for a lightpath. First proposed algorithm, *MCC* assigns the wavelengths according to minimum connection count. The simulated results show that the *MCC* algorithm is much better than existing algorithm. The problem with the *MCC* algorithm is maintaining the record for each wavelength and also the extra time required to calculate the wavelength with minimum connection count. The second proposed algorithm, *CS* wavelength assignment algorithm gives good results and avoids the problems available with *MCC* algorithm. Three dynamic link weight assignment strategies that consider the utilization/requirement of wavelengths on links, to distribute the data over the links are presented. The simulation results show that all the three proposed strategies give better results than existing trend. The third proposed strategy is the best out of all these.

7.2 Specific Contributions

Efficient routing and wavelength assignment algorithms are presented in this thesis. Six variations for RWA algorithm which use the shortest path, alternate shortest path and first-fit wavelength assignment algorithm and give more priority to shortest path as compared to alternate shortest path are given in chapter 4. These differ in the combinations of the three and result in different blocking probabilities. Two wavelength assignment algorithms have been presented, which try to reduce the number of attempts required to find a free wavelength. First wavelength assignment algorithm (*MCC*) assigns the wavelengths according to minimum connection count. The simulated results show that *MCC* algorithm is much better than existing algorithm in terms of number of attempts. The problem with *MCC* algorithm is the extra time required to calculate the wavelength with minimum connection count. The second proposed algorithm i.e. circular sequential wavelength assignment algorithm avoids this problem. It uniformly assigns the wavelengths in a circular manner.

Three dynamic strategies that try to distribute the data symmetrically over the links are also presented. In first strategy, the new link weight is equal to the number of channels required if shortest path corresponding to all *s*-*d* pairs are to be established. The second proposed strategy further improves the results by also considering the alternate shortest path. The third proposed strategy gives the best performance by considering the link utilization of each link, if each link has equal channel capacity.

7.3 Future Scope of Work

RWA problem is very important problem in WDM optical networks. Many research efforts have been devoted to this problem in this thesis. There is still more research required for RWA problem with various other related issues. Following are a few directions for the future research work:

- Interesting extension is the use of wavelength converters to improve the blocking probability by breaking *wavelength continuity constraint*. There are various points to be considered such as the conversion capacity of the wavelength converters and placement of wavelength converters in the network. The impact of full or limited range wavelength converters was not simulated in the thesis and can be a possible extension of this work.

- The main focus of the work presented in this thesis is based on centralized control. There are many cases where distributed control can be better choice than centralized control. So, new algorithms can be developed that work with distributed control. Also the algorithms that combine the good features of distributed and centralized control to have better results can be investigated.

- The algorithms proposed in this thesis are evaluated in terms of the parameters such as blocking probability, resource requirement and number of attempts to find a free wavelength. The algorithms were not compared in terms of computation complexity and space complexity. If more space is used, then computation complexity decreases. By increasing the computation complexity, the space complexity can be decreased. The algorithms may be further extended by providing trade-offs between computation complexity and space complexity. The trade-off may be selected depending on the requirement of the application.

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LIST OF PUBLICATIONS AND PRESENTATIONS

A. International Journals

Accepted/Published

1. **Paramjeet Singh**, Ajay K. Sharma, and Shaveta Rani, "Routing and Wavelength Assignment Algorithms in Optical Networks," *Int. Journal of Optical Fiber Technology,* Vol. 13, Issue 3, July 2007, pp. 191-197, Available at www.sciencedirect.com.
2. **Paramjeet Singh**, Ajay K. Sharma, and Shaveta Rani, "An Efficient Wavelength Assignment Strategy for WDM Optical Networks," *Int. Journal of Optical Engineering,* SPIE, Vol. 46, No. 8, Aug. 2007, Available at http://spiedigitallibrary.aip.org.
3. **Paramjeet Singh**, Ajay K. Sharma, and Shaveta Rani, "Routing and Wavelength Assignment in WDM Networks with Dynamic Link Weight Assignment," *OPTIK- Int. Journal for Light and Electron Optics,* Vol. 118, Issue 11, 2007, pp. 527-532, Available at www.sciencedirect.com.
4. **Paramjeet Singh**, Ajay K. Sharma, and Shaveta Rani, "Minimum Connection Count Wavelength Assignment Algorithm for WDM Optical Networks," *Int. Journal of Optical Fiber Technology,* 2007, Article in press, Available at www.sciencedirect.com.
5. Shaveta Rani, Ajay K. Sharma, and **Paramjeet Singh**, "Resource Allocation Strategies for Survivability in WDM Optical Networks," *Int. Journal of Optical Fiber Technology,* Vol. 13, Issue 3, July 2007, pp. 202-208, Available at www.sciencedirect.com.

6. Shaveta Rani, Ajay K. Sharma, and **Paramjeet Singh**, "Restoration approach in WDM optical networks" *OPTIK- Int. Journal for Light and Electron Optics*, Vol. 118, 2007, pp. 25-28, Available at www.sciencedirect.com.
7. Shaveta Rani, Ajay K. Sharma, and **Paramjeet Singh**, "Survivability strategy for large and scalable WDM optical networks," *Int. Journal of Optical Communications*, Vol. 28, Issue 1, 2007, pp. 43-45, Available at www.joc-online.schiele-schoen.de.
8. Shaveta Rani, Ajay K. Sharma, and **Paramjeet Singh**, "Provisioning for Restorable WDM Optical Networks" *OPTIK - Int. Journal for Light and Electron*, Germany, Elsevier, 2007, Article in press, Available at www.sciencedirect.com.

B. International Conferences/Workshops/Symposiums

9. **Paramjeet Singh**, Ajay K Sharma, Shaveta Rani and Neeru Bala, "Wavelength Assignment Strategy for Wavelength Routed Optical Networks," Presented and Published in the Proceedings of the Indo-UK workshop on *Recent Advances in Fiber Optics and Photonics* (RAFOP-2006), pp. 136-140, Aug. 25-27, 2006, IIT, Roorkee, India.
10. **Paramjeet Singh**, Ajay K. Sharma, Shaveta Rani, and Surinder Singh, "Routing and Wavelength Assignment in WDM Optical Networks," IEEE conference on *Wireless and Optical Communications Networks (WOCN)*, April 11-13, 2006, Banglore, India.
11. **Paramjeet Singh**, Ajay K. Sharma and Shaveta Rani, "Provisioning Strategy for Path based Survivability in WDM Optical Networks," IEEE

4th Symposium on *High Capacity Optical Networks and Enabling Technologies (HONET-2007)*, Nov. 18 - 20, 2007, Dubai, UAE.

12. Shaveta Rani, Ajay K Sharma, **Paramjeet Singh**, and Neeru Bala, "Survivability Approaches for Critical and Non-critical Traffic in WDM Optical Networks," Published in the Proceedings of the Indo-UK workshop on *Recent Advances in Fiber Optics and Photonics* (RAFOP-2006), pp. 131-135, Aug. 25-27, 2006, IIT, Roorkee, India.
13. Shaveta Rani, Ajay K. Sharma, and **Paramjeet Singh**, "Dynamic Survivability Algorithms in WDM Optical Networks," IEEE conference on *Wireless and Optical Communications Networks (WOCN)*, April 11-13, 2006, Banglore, India.
14. Shaveta Rani, **Paramjeet Singh**, and Ajay K. Sharma, "Distributed Control based Survivability Strategy for WDM Optical Networks," Seventh International Conference on *Optoelectronics, Fiber Optics and Photonics*, *(PHOTONICS-2004)* Organised by International School of Photonics, Cochin University of Science and Technology, Kochi, Kerala, India, during 9-11 Dec., 2004, p2.112, NET-P8.
15. Shaveta Rani, **Paramjeet Singh**, and Ajay K. Sharma, "Survivability Strategy with Congestion Control in WDM Optical Networks," IEEE 4th International Symposium on *High Capacity Optical Networks and Enabling Technologies (HONET-2007)*, Nov. 18 - 20, 2007, Dubai, UAE.

C. National Conferences/Symposiums

16. **Paramjeet Singh**, Ajay K Sharma, Shaveta Rani, and Surinder Singh, "Routing and Wavelength Assignment (RWA) With Fairness

Improvement in WDM Optical Networks," Presented and Published in the Proceedings of the National Symposium on *Emerging Trends in Networking and Mobile Communication*, Silver Jubilee Year, organized by IETE at PEC, Chandigarh, pp. 47, September 2003.

17. **Paramjeet Singh**, Ajay K Sharma, Shaveta Rani, and Surinder Singh, "Routing and Wavelength Assignment (RWA) in Wavelength-Routed WDM Optical Networks with Permutation Routing," National Seminar on *Cutting Edge Technologies in Electronics Communication (CETEC-2004)*, organized by ECE Dept. at SLIET Longowal, pp. 18-21, 14th March, 2004.
18. Shaveta Rani, Ajay K Sharma and **Paramjeet Singh**, "Issues in WDM Optical Networks", Presented and Published in the Proceedings of the National Symposium on *Emerging Trends in Networking and Mobile Communication*, Silver Jubilee Year, organized by IETE at PEC, Chandigarh, pp. 88, Sep. 2003.
19. Shaveta Rani, Ajay K Sharma, **Paramjeet Singh**, and Surinder Singh, "Survivability in Multi-Service Networks," National Seminar on *Cutting Edge Technologies in Electronics Communication (CETEC-2004)*, organized by ECE Dept. at SLIET Longowal, pp. 39-41, 14th March, 2004.

D. Presentations

1. Routing and Wavelength Assignment with Fairness in WDM Optical Networks.
2. Optimal Routing in Sparse Wavelength Convertible Optical Networks.

3. Round Robin Wavelength Assignment for Mesh WDM Optical Networks.
4. An Efficient Wavelength Assignment Strategy in WDM Optical Networks.
5. Wavelength Assignment Strategy for Wavelength Routed Optical Networks.

BRIEF BIOGRAPHY OF THE CANDIDATE

Paramjeet Singh received the B. Tech. in Computer Science and Engineering from Punjab Technical University, Jalandhar, Punjab, India, in 1998 and M. S. in Software Systems from Birla Institute of Technology and Science (BITS), Pilani, Rajasthan, India, in 2002.

He worked in Giani Zail Singh College of Engineering and Technology, Bathinda, Punjab, India as a Lecturer in the dept. of Computer Science and Engineering from September 1998 to May 2005. Presently, since May 2005 he is working as Assistant Professor in the Department of Computer Science and Engineering in the same college.

There are 19 research and review papers to his credit out of which 8 research papers in International refereed Journals, 7 publications in International refereed Conference proceedings, rest are in National Conferences. His research interest includes routing and wavelength assignment algorithms in optical networks, computer graphics, and software engineering.

BRIEF BIOGRAPHY OF THE SUPERVISOR

Ajay K Sharma received his BE in Electronics and Electrical Communication Engineering from Punjab University, Chandigarh, India in 1986, MS in Electronics and Control from Birla Institute of Technology (BITS), Pilani in the year 1994 and PhD in Electronics Communication and Computer Engineering in the year 1999. His PhD thesis was on "Studies on Broadband Optical Communication Systems and Networks". From 1986 to 1995, he worked with TTTI Chandigarh, DTE Chandigarh, Indian Railways New Delhi, SLIET Longowal and National Institute of technology (Erstwhile Regional Engineering College) Hamirpur (HP) at various academic and administrative positions. He has joined National Institute of Technology (Erstwhile Regional Engineering College) Jalandhar as Assistant Professor in the Department of Electronics and Communication Engineering in the year 1996. From November 2001, he has worked as Professor in the same department and presently, he is working as Professor and Head in Computer Science & Engineering Dept. in the same institute. His major areas of interest are broadband optical communication systems, dispersion compensation, fiber nonlinearities, optical soliton transmission, WDM systems and networks, Radio-over-Fiber (RoF) and wireless networks. He has published 166 research papers in the International/National Journals/Conferences and 12 books. He has supervised 8 PhD and 12 M.Tech theses. He has completed two R&D projects funded by Government of India and one project is ongoing. Presently he is associated to implement the World Bank project of 209 Million for Technical Education Quality Improvement programme of the institute. He is technical reviewer of reputed international journals like: Optical Engineering, Optics letters, Optics

Communication, and Digital Signal Processing. He has been appointed as member of technical Committee on Telecom under International Association of Science and Technology Development (IASTD) Canada for the term 2004-2007 and he is Life member of Indian Society for Technical Education (I.S.T.E.), New Delhi.

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Routing and wavelength assignment strategies in optical networks

Paramjeet Singh [a,*], Ajay K. Sharma [b], Shaveta Rani [a]

[a] *Department of Computer Science and Engineering, GZSCET, Bathinda, Punjab, India*
[b] *Department of Electronics and Communication Engineering, NIT, Jallandhar, Punjab, India*

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Abstract

We consider the routing and wavelength assignment (RWA) problem on wavelength division multiplexing (WDM) networks without wavelength conversion. When the physical network and required connections are given, RWA is the problem to select a suitable path and wavelength among the many possible choices for each connection such that no two paths using the same wavelength pass through the same link. In WDM optical networks, there is need to maximize the number of connections established and to minimize the blocking probability using limited resources. This paper presents efficient RWA strategies, which minimizes the blocking probability. Simulation results show that the performance of the proposed strategies is much better than the existing strategy.

Keywords: WDM; RWA; Optical networks; Wavelength continuity constraint; Shortest path

1. Introduction

Wavelength routing, in conjunction with WDM, appears to be the most promising mechanism for information transport in metropolitan and wide area networks [1]. An optical network based on WDM using the wavelength routing technique is considered as a very promising approach for the realization of future large bandwidth networks. To accommodate several wavelength channels on a fiber, WDM technology can be used as this could enhance the line capacity of the networks. WDM should be used in combination with wavelength routing to enhance the transmission line capacity and cross-connect node processing capability of the large bandwidth networks [2]. In wavelength routing, data signals are carried on single wavelength from source node to destination node.

In WDM optical networks, there are three main constraints related with wavelength assignment: wavelength continuity constraint (WCC), distinct wavelength assignment constraint (DWAC), and nonwavelength continuity constraint (NWCC). In WCC, the same wavelength should be used on all the links along the selected route. In DWAC, two lightpaths cannot be assigned the same wavelength on any fiber and in NWCC, different wavelengths can be used on the links along the selected route but the nodes should have wavelength conversion capability. Wavelength conversion is the ability to convert the data on one wavelength to another wavelength. Eliminating wavelength conversion significantly reduces the cost of the switch, but it may reduce network efficiency because more wavelengths might be required. But several studies reported that the increased efficiency by using wavelength conversion is small as compared to the cost increase [3,4].

In this paper, we have proposed efficient routing and wavelength assignment strategies, which reduce the blocking probability by reducing the number of connections rejected. The comparison of the proposed routing and wavelength assignment strategies with the commonly used strategy in terms of blocking probability has been presented. This paper is organized as follows. In Section 2, we describe RWA problem in optical networks. In Section 3, we present RWA strategies. Section 4 focuses on performance analysis which shows simulation results by taking an example of realistic NSFNET network. Conclusions are given in Section 5.

2. RWA problem in optical networks

In a wavelength-routed WDM optical network, pairs of access stations communicate with one another through a light-

* Corresponding author.
E-mail address: param2009@yahoo.com (P. Singh).

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path. Given a set of lightpaths that need to be set up, the RWA problem is to route each lightpath and find a wavelength for each. The RWA problem can be considered in two categories according to traffic pattern: static traffic (off-line) and dynamic traffic (on-line) [5]. In the case of static traffic, all lightpath requests are known in advance, thus a routing decision can be made based on the complete knowledge of the traffic to be served by the network. In the case of dynamic traffic, a lightpath request must be routed and wavelength is assigned independently of other lightpaths, which either have been assigned or will be assigned in the future. The objective is to minimize the number of used wavelengths and the call blocking probability and to maximize the number of connections established by the network, i.e., to accommodate maximum connection requests using minimum resources.

If the nodes along the route selected are incapable of converting wavelengths, then it must be assured that a wavelength chosen for the lightpath is available on all links along the chosen route. This is called the wavelength continuity constraint. The problem of selecting an optimal route and a wavelength for a lightpath such that the network throughput is maximized or minimize blocking probability is a tightly coupled problem. Since the tightly coupled RWA problem cannot be analytically solved, it is a general practice to de-couple the problem and try to solve the routing and wavelength assignment problems separately. It is often infeasible to solve the coupled RWA problem for large networks because of the size of the problem [6]. It is more realistic to solve it by decoupling the problem into two separate subproblems, routing subproblem and wavelength assignment subproblem. The objective functions in RWA problem are as follows:

- Given a set of lightpaths, minimize the required number of wavelengths to satisfy these lightpaths without blocking.
- Given a maximum number of wavelengths available, minimize the lightpath blocking probability.

When considered together, the RWA problem seeks to address the question: Given a set of lightpaths that need to be established, what is the best way to achieve it? It could be the minimum number of wavelengths needed to establish the given set of lightpaths or it could be to minimize the blocking probability.

2.1. Routing problem

It is to select an appropriate route from source to destination among all existing routes. If there is more than one choice to select the route, the controller can decide the route according to some heuristics as shortest path routing, load balancing routing, etc. Generally, the fixed shortest-path routing approach is used [7]. The shortest path for each source destination pair is computed off-line in advance using standard shortest-path algorithms, e.g., Dijkstra's algorithm or Bellman–Ford algorithm. The disadvantage of this approach is that the routing decision is not made based on the current state of network. It might lead to the situation where some links on the network are over utilized while other links are underutilized.

2.2. Wavelength assignment problem

Wavelength assignment is to assign the wavelength along the selected route on which data transmission can take place. Proper assignment of wavelengths can lead to reduced or no use of wavelength converters which can significantly reduce the cost. Whenever a call is generated by the source node, it sends the request to the controller. As controller has the knowledge about the network, it contains the information of free and busy wavelengths at that instant of time. Controller then selects a wavelength from the set of free wavelengths and assigns it to that call. To select a wavelength is the critical issues which affects the performance of the network. Mostly used wavelength assignment strategy is first-fit wavelength assignment strategy [2]. It is implemented by predefining an order of the wavelengths. The list of used and free wavelengths is maintained. The assignment scheme always tries to establish the connection using first wavelength, if that wavelength is free on all the links of selected route then connection establishment take place otherwise it will try to establish the connection by using next indexed wavelength and so on up to last wavelength. When the call is completed the wavelength is added back to the free wavelength set.

2.3. Problem formulation

2.3.1. Notations

A: Set of nodes in the network.

B: Set of links in the network.

C: Set of connections.

D: Set of wavelengths.

N: Total number of wavelengths numbered from 0 to $N-1$.

I: Total number of connection requests numbered from 0 to $I-1$.

n: Total number of nodes in the network numbered from 0 to $n-1$.

P_{sd}: Total number of links along the route for sd connection.

s indicates the source.

d indicates the destination.

$sd[j]$ indicates jth connection.

R_{ij} represents the route for the connection when $s=i$ and $d=j$.

W_{ij} represents the wavelength assigned to the connection when $s=i$ and $d=j$.

rejconn is the variable used to store the number of connections rejected.

acconn is the variable used to store the number of connections accepted.

$$W_{ij}^{sd} = \begin{cases} 0, & \text{if } s\text{–}d \text{ connection does not use any wavelength on link } ij, \\ 1, & \text{otherwise.} \end{cases}$$

$$m_{ij,k}^{sd} = \begin{cases} 0, & \text{if } s\text{–}d \text{ connection does not use wavelength } k \text{ on link } ij, \\ 1, & \text{otherwise.} \end{cases}$$

$Q^k_{sd} = 1$, if s–d connection is established on wavelength k,
$= 0$, otherwise.

2.3.2. Mathematical formulations

Total number of s–d pairs (I), if s–d pairs when $s = d$ included, $\forall(s, d \in A)$,

$$= (n(n-1)/2) + n, \quad \text{if } R_{ij} = R_{ji} \text{ and } w_{ij} = w_{ji} \ \forall i,\ j \in A,$$
$$= nxn, \quad \text{otherwise.}$$

Total number of s–d pairs (I), if $s-d$ pairs when $s = d$ excluded, $\forall(s, d \in A)$,

$$= n(n-1)/2, \quad \text{if } R_{ij} = R_{ji} \text{ and } w_{ij} = w_{ji} \ \forall i, j \in A,$$
$$= n(n-1), \quad \text{otherwise.}$$

Blocking probability = rejconn/I = $(I - \text{acconn})/I$.

Objective function = minimize (blocking probability) for fixed number of wavelengths.

Or minimize (N) for zero blocking probability.

Constraints:

1. $\sum_{sd} w^{sd}_{ij} \leqslant N, \quad \forall sd \in C,\ \forall ij \in B.$
   Wavelengths assigned on a link for all the connections does not exceed N.
2. $\sum_{ij} m^{sd}_{ij,k} = P_{sd}, \quad \text{if } Q^k_{sd} = 1,$
   $= 0, \quad \text{otherwise} \quad \forall sd \in C,\ \forall ij \in B, \text{ and } \forall k \in D.$
3. $m^{sd}_{ij,k} = 1, \quad \text{if } w^{sd}_{ij} = 1 \text{ and } Q^k_{sd} = 1,$
   $= 0, \quad \text{otherwise} \quad \forall sd \in C,\ \forall ij \in B, \text{ and } \forall k \in D.$

3. Routing and wavelength assignment strategies

Mostly all the networks employ shortest path for connection establishment. Alternate path is used to establish the connection in the proposed RWA strategies, if the connection could not be established with shortest path. It is because the connections not established with shortest path may get established with alternate path with the available resources to reduce the blocking probability. Alternate paths are more weighed than their corresponding shortest paths, so are given lower priority in the algorithms. These algorithms show the different possible variations of using shortest path with alternate shortest path for first-fit wavelength assignment strategy.

3.1. Existing RWA strategy

3.1.1. RWA 1

In this strategy, shortest path algorithm is used for routing and first-fit wavelength assignment strategy is used for wavelength assignment. For each s–d pair, first of all, try is made to establish the connection on first wavelength using shortest route. If unsuccessful, then connection is tried on second wavelength and so on up to the last wavelength.

3.2. Proposed RWA strategies

3.2.1. RWA 2

In it, the attempt is made to establish the connection for first s–d pair using shortest route starting from first to last wavelength. Now the connection for second s–d pair is tried in the similar way and so on this process is repeated for all s–d pairs. The connection for first s–d pair is tried using alternate route starting from first to last wavelength if connection not established earlier. This step is executed for all other s–d pairs in sequence.

3.2.2. RWA 3

In it, firstly the connections are tried for all the connection requests in sequence using shortest route on first wavelength. Now the similar attempt is made for all the connection requests on all the wavelengths according to their position in indexing. The above mentioned steps are again executed in the same sequence but with alternate route instead of shortest route.

3.2.3. RWA 4

First of all, first connection request is tried using shortest route on the wavelength starting from first to last wavelength. If unsuccessful, the same connection is tried using alternate route on all the wavelengths. The same process is repeated for all the connection requests.

3.2.4. RWA 5

On first wavelength, all the connection requests are tried using their shortest routes. Now the same wavelength is again tried for all the connection requests but with their alternate routes. The above steps are followed for all the wavelengths.

3.2.5. RWA 6

The connection establishment for first s–d pair is tried on first wavelength using shortest route. If unsuccessful, the same connection is tried on same wavelength using alternate route. The same procedure is followed for all the other wavelengths. All the other connection requests are also tried in the same way as the connection establishment for first s–d pair is tried.

3.2.6. RWA 7

It tries for maximum utilization of resources, so that more connections can be established. In this strategy, first of all the attempt is made to establish the connection for first s–d pair using shortest route on first wavelength. If unsuccessful, the same connection request is tried using alternate route on the same wavelength. Now second s–d pair is tried on same wavelength, firstly with shortest route and then with alternate route and so on for all the s–d pairs. In this way, the attempt is made for maximum utilization of first wavelength for connection establishment. It tries to establish maximum connections using the wavelength under consideration. If there is any connection that could have been established using first wavelength either with shortest route or alternate route, it is established. The procedure is followed for all the wavelengths according to the indexing sequence. The attempt of connection establishment is made on any wavelength only if all the wavelengths previous to it in indexing have been tried for all the connection requests with both routes. This strategy gives better results because it utilizes the resources very efficiently.

4. Performance analysis

4.1. Simulation environment

No heuristics could be validated until they are supported by practical results. In order to demonstrate that our approach performs better than that reported in the literature and to investigate the performance of algorithms, we must resort to simulations. Not able to find a suitable simulator that could support our proposed heuristics, we designed and developed a simulator to implement routing and wavelength assignment in all-optical networks for regular and irregular topologies. The simulator is developed in C++ language. It accepts input parameters such as the number of nodes in the network, link information with weight, number of wavelengths per fiber, connection requests. Some of the calls may be blocked because of the unavailability of free wavelength on links along the route from the source to the destination. The ratio of the total number of calls blocked to the total number of lightpath requests in the network is defined as the blocking probability. The output of the simulator is the blocking probability for the specified parameters along with the detailed information of connections. All these parameters can be initialized before running the simulations to obtain results for a given selection of parameters. Extensive simulations are then carried out for every combination of parameters of interest and the obtained results are tabulated.

4.2. Performance evaluation

We have applied proposed RWA algorithms and existing strategy to a realistic example of a backbone network, namely, the NSFNET irregular topology shown in Fig. 1. The nodes are connected together with undirected links. The route from node t to node u will traverse the same links as traversed by the route from node u to node t but in the reverse direction. Permutation routing has been taken for finding out the sample source destination pairs in which every node in the network acts as the source to every other node in the network simultaneously with unicasting approach. Total number of source destination pairs in permutation routing depends upon the number of nodes. The strategies work in the greedy way. If a connection request can be accommodated at any stage, it is accommodated immediately by reserving the resources and the strategies does not try the connection on any other wavelength. Any connection request is first tried using shortest route. The connection could not be established if the wavelength considered is not free on any of the links along the route. The alternate route taken is the route with minimum weight out of all the possible routes which are node and link disjoint with the shortest route so that no link or intermediate nodes are common with the shortest route. With the alternate route, there are chances of connection establishment because the link on which the wavelength was not free with shortest route, does not come in the route.

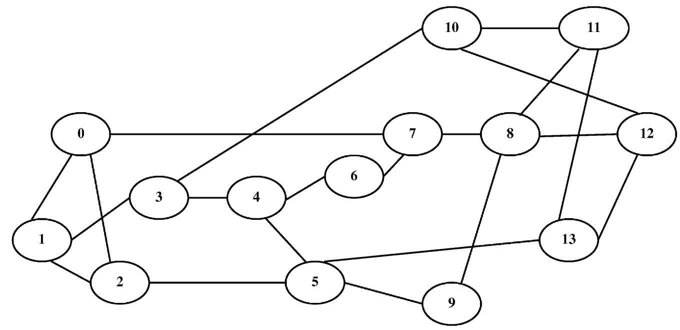

Fig. 1. NSFNET network.

Table 1
Link information table

Link	Weight
0–1	1
0–2	2
0–7	8
1–2	2
1–3	3
2–5	4
3–4	2
3–10	9
4–5	1
4–6	1
5–9	4
5–13	7
6–7	1
7–8	1
8–9	6
8–11	1
8–12	2
10–11	1
10–12	5
11–13	6
12–13	4

Table 1 stores the link information of the network in terms of their weight. Table 2 shows the comparison of existing RWA strategy and proposed RWA strategies in terms of blocking probability. The first column of Table 2 shows the number of wavelengths taken. Column 2 gives the blocking probability for the commonly used existing strategy. Columns 3–8 give the blocking probability for various proposed RWA strategies for comparison purpose. The comparison graph in Fig. 2 shows the results given in Table 2 graphically. X-axis represents the number of wavelengths and the Y-axis represents the blocking probability with permutation routing. The combination difference of the shortest path strategy, alternate shortest path strategy and first fit algorithm between the proposed strategies leads to variation in the performance as shown by the results given in the columns 3–8 of Table 2. Out of these proposed strategies, RWA7 gives the best performance because it efficiently utilizes the resources. Simulation results show that the performance of all the proposed strategies is much better than the existing strategy because proposed strategies use alternate route for connections not established with shortest route.

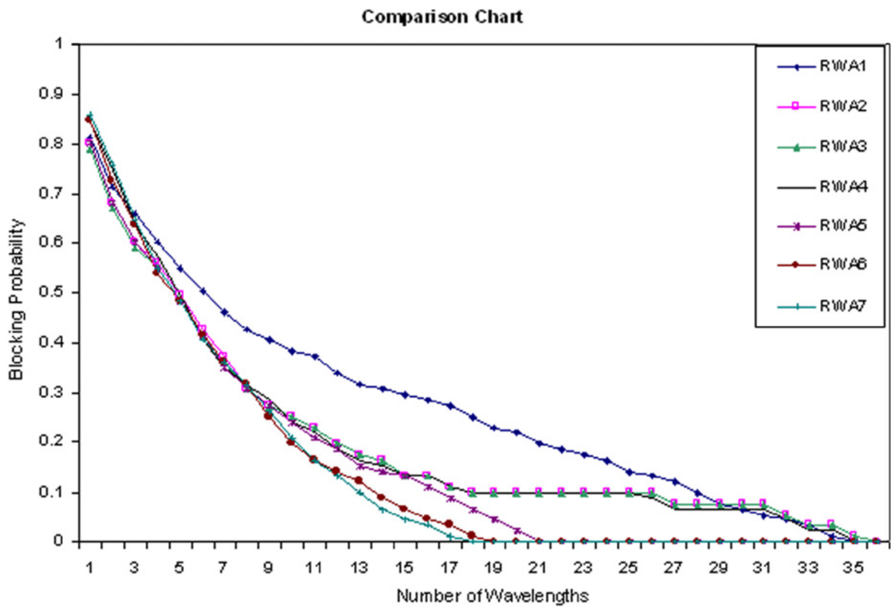

Fig. 2. Comparison graph.

Table 2
Blocking probability comparison table

Number of wavelengths	Blocking probability						
	RWA 1	RWA 2	RWA 3	RWA 4	RWA 5	RWA 6	RWA 7
1	0.813187	0.802198	0.791209	0.846154	0.802198	0.846154	0.857143
2	0.714286	0.681319	0.67033	0.747253	0.681319	0.725275	0.758242
3	0.659341	0.604396	0.593407	0.637363	0.604396	0.637363	0.648352
4	0.604396	0.56044	0.549451	0.571429	0.549451	0.538462	0.549451
5	0.549451	0.494505	0.483516	0.494505	0.483516	0.483516	0.483516
6	0.505495	0.428571	0.417582	0.406593	0.417582	0.417582	0.406593
7	0.461538	0.373626	0.362637	0.351648	0.351648	0.362637	0.362637
8	0.428571	0.307692	0.307692	0.318681	0.307692	0.318681	0.318681
9	0.406593	0.274725	0.274725	0.285714	0.274725	0.252747	0.263736
10	0.384615	0.252747	0.252747	0.241758	0.241758	0.197802	0.208791
11	0.373626	0.230769	0.230769	0.21978	0.208791	0.164835	0.164835
12	0.340659	0.197802	0.197802	0.186813	0.186863	0.142857	0.131868
13	0.318681	0.175824	0.175824	0.164835	0.153846	0.120879	0.098901
14	0.307692	0.164835	0.164835	0.153846	0.142857	0.087912	0.065934
15	0.296703	0.131868	0.131868	0.131868	0.131868	0.065934	0.043956
16	0.285714	0.131868	0.131868	0.131868	0.10989	0.043956	0.032967
17	0.274725	0.10989	0.10989	0.10989	0.087912	0.032967	0.010989
18	0.252747	0.098901	0.098901	0.098901	0.065934	0.010989	0
19	0.230769	0.098901	0.098901	0.098901	0.043956	0	0
20	0.21978	0.098901	0.098901	0.098901	0.021978	0	0
21	0.197802	0.098901	0.098901	0.098901	0	0	0
22	0.186813	0.098901	0.098901	0.098901	0	0	0
23	0.175824	0.098901	0.098901	0.098901	0	0	0
24	0.164835	0.098901	0.098901	0.098901	0	0	0
25	0.142857	0.098901	0.098901	0.098901	0	0	0
26	0.131868	0.098901	0.098901	0.087912	0	0	0
27	0.120879	0.076923	0.076923	0.065934	0	0	0
28	0.098901	0.076923	0.076923	0.065934	0	0	0
29	0.076923	0.076923	0.076923	0.065934	0	0	0
30	0.065934	0.076923	0.076923	0.065934	0	0	0
31	0.054945	0.076923	0.076923	0.065934	0	0	0
32	0.043956	0.054945	0.054945	0.043956	0	0	0
33	0.032967	0.032967	0.032967	0.021978	0	0	0
34	0.010989	0.032967	0.032967	0.021978	0	0	0
35	0	0.010989	0.010989	0	0	0	0
36	0	0	0	0	0	0	0

5. Conclusions

In this paper, we first discussed routing and wavelength assignment problem in WDM optical networks, then the focus was on commonly used routing and wavelength assignment strategy in the optical networks. We have proposed RWA strategies which reduces the blocking probability by reducing the number of connections rejected. Although all the proposed strategies use the shortest path, alternate shortest path and first-fit wavelength assignment strategies giving more priority to shortest path as compared to alternate shortest path, yet differs in the combinations of the three to establish the connections. Each possible combination has been considered. This difference leads to variation in the performance as shown by the results. Out of these proposed strategies, RWA7 gives the best performance because it efficiently utilizes the resources. The performance of proposed strategies and most commonly used RWA have been evaluated in terms of blocking probability by applying on the sample network. Simulation results show that the performance of all the proposed strategies is much better than the existing strategy.

Appendix A. Algorithms for the strategies

1. Existing RWA strategy

RWA 1

1. rejconn = 0.
2. for $j = 0$ to $I - 1$.
3. for $k = 0$ to $N - 1$.
4. try to establish the connection for $sd[j]$ on wavelength k for shortest path.
5. if connection established in step 4
   then go to step 8.
6. end loop for k.
7. rejconn ++.
8. end loop for j.
9. blocking probability = rejconn/I.
10. end.

2. Proposed RWA strategies

RWA 2

1. rejconn = 0.
2. for $j = 0$ to $I - 1$.
3. for $k = 0$ to $N - 1$.
4. try to establish the connection for $sd[j]$ on wavelength k for shortest path.
5. if connection established in step 4
   then go to step 8.
6. end loop for k.
7. rejconn ++.
8. end loop for j.
9. for $j = 0$ to $I - 1$.
10. if connection for $sd[j]$ established with shortest path
    then go to step 17.
11. for $k = 0$ to $N - 1$.
12. try to establish the connection for $sd[j]$ on wavelength k for alternate shortest path.
13. if connection established in step 14
    then (i) rejconn −−, (ii) go to step 17.
14. end loop for k.
15. connection not established.
16. end loop for j.
17. blocking probability = rejconn/I.
18. end.

RWA 3

1. rejconn = I.
2. for $k = 0$ to $N - 1$.
3. for $j = 0$ to $I - 1$.
4. if connection for $sd[j]$ not established earlier
   then try to establish the connection for $sd[j]$ on wavelength k for shortest path
   else go to step 6.
5. if connection established in step 4
   then rejconn −−.
6. end loop for j.
7. end loop for k.
8. for $k = 0$ to $N - 1$.
9. for $j = 0$ to $I - 1$.
10. if connection for $sd[j]$ not established earlier
    then try to establish the connection for $sd[j]$ on wavelength k for alternate path
    else go to step 12.
11. if connection established for $sd[j]$ in step 10
    then rejconn −−.
12. end loop for j.
13. end loop for k.
14. blocking probability = rejconn/I.
15. end.

RWA 4

1. rejconn = 0.
2. for $j = 0$ to $I - 1$.
3. for $k = 0$ to $N - 1$.
4. try to establish the connection for $sd[j]$ on wavelength k for shortest path.
5. if connection established in step 4
   then go to step 12.
6. end loop for k.
7. for $k = 0$ to $N - 1$.
8. try to establish the connection for $sd[j]$ on wavelength k for alternate shortest path.
9. if connection established in step 8
   then go to step 12.
10. end loop for k.
11. rejconn ++.
12. end loop for j.

13. blocking probability = rejconn/I.
14. end.

RWA 5

1. rejconn = I.
2. for $k = 0$ to $N - 1$.
3. for $j = 0$ to $I - 1$.
4. if connection for $sd[j]$ not established with lower wavelength(s)
   then try to establish the connection for $sd[j]$ on wavelength k for shortest path.
   else go to step 6.
5. if connection established in step 4
   then rejconn −−.
6. end loop for j.
7. for $j = 0$ to $I - 1$.
8. if connection for $sd[j]$ not established earlier
   then try to establish the connection for $sd[j]$ on wavelength k for alternate shortest path
   else go to step 10.
9. if connection established in step 8
   then rejconn −−.
10. end loop for j.
11. end loop for k.
12. blocking probability = rejconn/I.
13. end.

RWA 6

1. rejconn = 0.
2. for $j = 0$ to $I - 1$.
3. for $k = 0$ to $N - 1$.
4. try to establish the connection for $sd[j]$ on wavelength k for shortest path.
5. if connection established in step 4
   then go to step 10.
6. try to establish the connection for sd[j] on wavelength k for alternate path.
7. if connection established in step 6
   then go to step 10.
8. end loop for k.
9. rejconn ++.
10. end loop for j.
11. blocking probability= rejconn/I.
12. end.

RWA 7

1. acconn = 0.
2. for $k = 0$ to $N - 1$.
3. for $j = 0$ to $I - 1$.
4. if connection for $sd[j]$ not established with lower wavelengths
   then try to establish the connection for $sd[j]$ on wavelength k for shortest path
   else go to step 8.
5. if connection established in step 4
   then (i) acconn ++, (ii) go to step 8
6. try to establish the connection for $sd[j]$ on wavelength k for alternate path.
7. if connection established in step 6
   then (i) acconn ++, (ii) go to step 8.
8. end loop for j.
9. end loop for k.
10. blocking probability = I − acconn/I.
11. end.

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Efficient wavelength assignment strategy for wavelength-division multiplexing optical networks

Paramjeet Singh
Shaveta Rani
Giani Zail Singh College of Engineering and Technology
Department of Computer Science and Engineering
Dabwali Road
Bathinda, Punjab 151001, India
E-mail: Param2009@yahoo.com

Ajay K Sharma
Dr. B. R. Ambedkar National Institute of Technology
Department of Electronics and Communication Engineering
Jalandhar, Punjab 144011, India

Abstract. When a physical network and its required connections are given, the routing and wavelength assignment (RWA) is a problem. A suitable path and wavelength must be selected from among the many possible choices for each connection such that no two paths using the same wavelength pass through the same link. In the absence of wavelength conversion, a lightpath must use the same wavelength on all fiber links that it spans. In wavelength-division multiplexing (WDM) optical networks, there is a need to maximize the number of connections accepted and to minimize the number of connections rejected, i.e., the blocking probability. We propose a new strategy to assign the wavelength. Then we compare the performance of the proposed strategy with commonly used wavelength assignment strategies in terms of the number of attempts required to establish the given connection. The comparison shows that fewer attempts are required for the proposed strategy, leading to a reduced connection establishment time. [DOI: 10.1117/1.2771580]

Subject terms: WDM; RWA; optical networks; wavelength continuity constraint.

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1 Introduction

Wavelength-division multiplexing (WDM) is emerging as the dominant technology for next-generation optical networks.[1] It is the most important technique to expand the inherent great capacity of optical fibers. WDM modulates multiple information signals (optical signals) at different wavelengths, and the resulting signals are combined and transmitted simultaneously over the same optical fiber. In order to use WDM on an optical fiber connecting two network nodes, each optical channel is set up on one wavelength by an appropriate tuned laser at the transmitter. Afterward, all wavelengths of the used channels are combined on the fiber by a multiplexer. At the other end of the fiber, a demultiplexer again decodes lightwaves and transfers them to corresponding receivers. An optical network based on WDM using the wavelength routing technique is considered as a very promising approach to realize future large-bandwidth networks.[2] In wavelength routing, data signals are carried on a unique wavelength from a source node to a destination node passing through some intermediate nodes.

In this paper, the Dijkstra's shortest path algorithm is used to find the route from source to destination. A comparison of the performance of the proposed wavelength assignment strategy with the most commonly used existing strategy in terms of the number of attempts to find the wavelength for connection establishment has been presented. This paper is organized as follows. In Sec. 2, we describe the RWA problem in optical networks. In Sec. 3, we describe an existing wavelength assignment strategy. In Sec. 4, we propose an efficient wavelength assignment strategy that reduces the number of attempts required to establish a connection. In Sec. 5, we evaluate the performance of the proposed strategy by taking National Science Foundation NETwork (NSFNET) network. Conclusions are given in Sec. 6.

2 Routing and Wavelength Assignment Problem

In a wavelength-routed WDM optical network, a pair of access stations communicate with one another through a lightpath.[3] Given a set of connection requests, the problem of establishing lightpaths by routing and assigning a wavelength for each connection request is called the RWA problem.[4] The wavelength routed from the source to the destination depends on the availability of the wavelengths at the intermediate links. In a network with no wavelength converters, the lightpath must use the same wavelength from the source to the destination. This is called the wavelength-continuity constraint in wavelength-routed net-

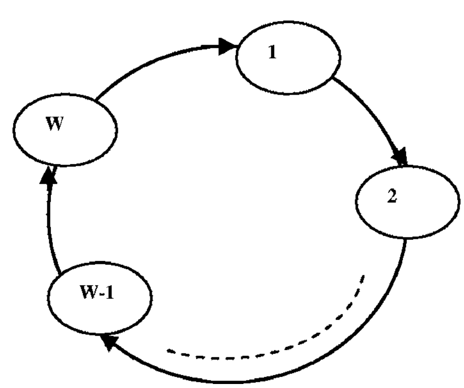

Fig. 1 Arrangement of wavelengths.

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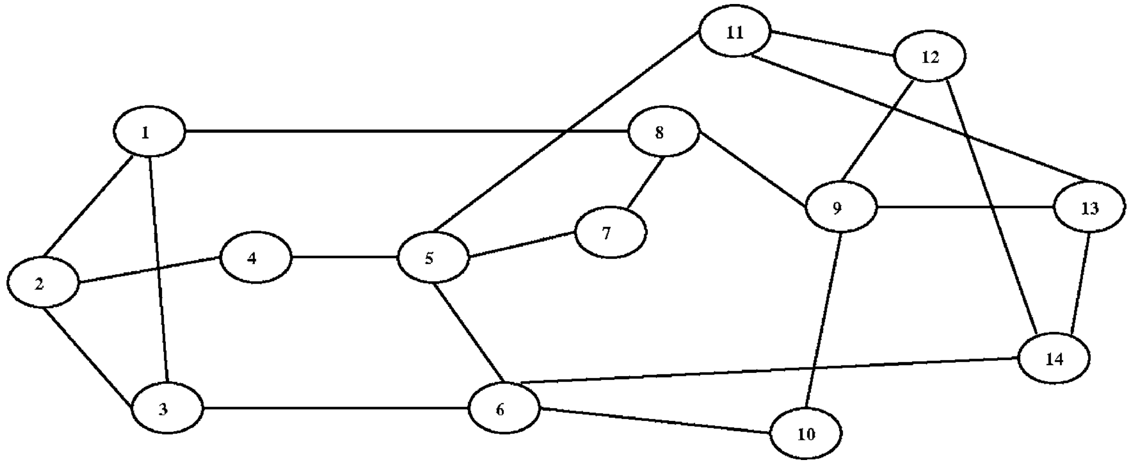

Fig. 2 NSFNET network.

works. The RWA problem deals with routing and assigning wavelengths at every hop in the path.[5,6] Whenever a call arrives at a wavelength router (WR), it will run a predefined algorithm and then select the outgoing port and a wavelength. The shortest-path algorithm can be used to find a route based on the hop count because it selects a route that uses the minimum number of links. When fewer links are used, resources are used more efficiently and the blocking probability is reduced.[7] The selection of the wavelength plays an important role in the algorithm performance and also on the overall blocking probability. Hence, a WR must find the route for the lightpath request and assign a wavelength that minimizes the blocking probability.

RWA schemes can be classified into two categories: static (off-line) or dynamic (on-line).[8] In a static RWA scheme, all the routes and wavelengths for the lightpaths to be set up are fixed initially. Whenever a lightpath request arrives, the RWA scheme assigns the preallocated route and wavelength for that request, so the routing procedure doesn't change with time. A dynamic RWA algorithm uses the current state of the network to determine the route for a given lightpath request. In WDM optical networks, there are three main constraints related with wavelength: wavelength continuity constraint (WCC), distinct wavelength assignment constraint (DWAC), and nonwavelength continuity constraint (NWCC).[9] In WCC, the same wavelength must be used on all the links along the selected route. In DWAC, two lightpaths cannot be assigned to the same wavelength on any fiber. And in NWCC, the different wavelengths can be used on the links along the selected route, but the nodes should have wavelength conversion capability. Wavelength conversion is the ability to convert the data on one wavelength to another wavelength. Eliminating wavelength conversion significantly reduces the cost of the switch, but it also may reduce network efficiency because more wavelengths might be required.

3 Commonly Used Wavelength Assignment Strategies

3.1 *First-Fit (FF) Strategy*

The FF strategy is implemented by predefining an order on the wavelengths.[10,11] A list of used and free wavelengths is maintained. The assignment scheme always chooses the lowest indexed wavelength from the list of free wavelengths and assigns it to the request. By selecting wavelengths in this manner, existing connections will be packed into a smaller number of total wavelengths, leaving a larger number of wavelengths available for longer lightpaths. When the call is completed, the wavelength is added back to the free-wavelength set. But in the FF algorithm, also called the fixed-order algorithm, if multiple connections attempt to set up a lightpath simultaneously, then all lightpaths may choose the same wavelength, leading to one or more connections being blocked due to the nonavailability of the free wavelength on any of the links along the route. This algorithm does not consider the wavelength usage factor, so it does not require the complete connection information. It can be used both with centralized and distributed control.

3.2 *Least-Used (LU) Strategy*

The LU strategy attempts to spread the load evenly across all wavelengths by selecting the wavelength that is the least used on links in the network.[10] This approach ends up breaking the long-wavelength lightpaths quickly; hence, only connection requests that traverse a small number of links will be serviced in the network. This approach requires additional storage and computation costs.

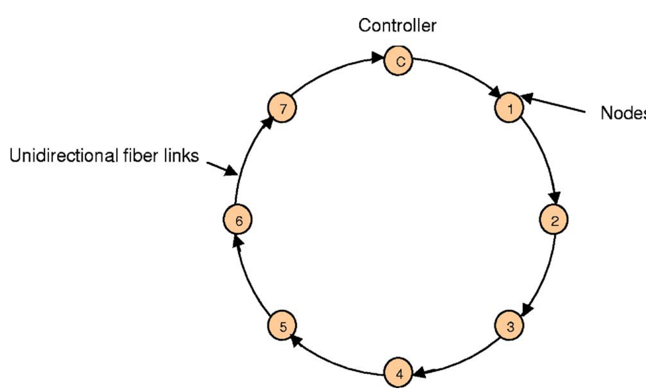

Fig. 3 Unidirectional ring with seven nodes.

Table 1 Comparison table for NSFNET with two wavelengths.

(*s-d*) Pairs	Shortest Route	Commonly Used Wavelength Assignment Strategies										Proposed Strategy	
		Least Used		Most Used		First-Fit		Random		Strategy with Tree Topology		Circular Sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
1-9	1-8-9	1	1	1	1	1	1	2	1	1	1	1	1
8-14	8-9-12-14	2	1	2	2	2	2	1	2	D	2	2	1
2-6	2-3-6	1	1	2	1	1	1	1	1	1	1	1	1
12-14	12-14	1	1	1	2	1	1	2	2	2	1	1	2
2-7	2-4-5-7	2	1	2	1	1	1	1	1	1	1	2	1
1-2	1-2	1	1	2	1	1	1	1	1	2	1	1	1
1-7	1-8-7	2	2	2	1	2	2	1	2	2	2	2	1
6-13	6-14-13	1	1	2	1	1	1	2	1	1	1	1	1
3-9	3-6-10-9	2	2	1	2	2	2	2	2	2	2	2	1
4-6	4-5-6	1	1	1	2	2	2	2	1	2	2	1	1
11-14	11-13-14	2	2	1	2	2	2	1	2	2	2	2	1
5-13	5-11-13	1	1	2	1	1	1	2	1	1	1	1	1
Total no. of attempts			15		17		17		17		17		13

Table 2 Comparison table for ring network with three wavelengths.

(*s-d*) Pairs	Shortest Route	Commonly Used Wavelength Assignment Strategies										Proposed Strategy	
		Least Used		Most Used		First-Fit		Random		Strategy with Tree Topology		Circular Sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
2-5	2-3-4-5	1	1	1	1	1	1	1	1	2	2	1	1
4-6	4-5-6	3	1	2	2	2	2	3	1	1	1	2	1
1-3	1-2-3	2	1	2	2	2	2	2	2	1	1	3	1
5-7	5-6-7	1	1	1	2	1	1	2	2	2	2	1	1
6-1	6-7-1	2	1	1	2	2	2	3	2	1	1	2	1
4-7	4-5-6-7	D	3	3	3	3	3	D	3	3	3	3	1
2-4	2-3-4	3	1	3	3	3	3	3	2	3	3	2	2
3-4	3-4	2	2	2	3	2	2	2	3	1	1	3	1
Total no. of attempts			11		18		16		16		14		9

3.3 *Most-Used (MU) Strategy*

In MU strategy, the wavelength that is used by most of the links in the network is tried first, then the wavelength with the second-highest number of connections is tried.[10] This algorithm attempts to provide maximum wavelength reuse in the network, leaving maximum wavelengths underutilized. The MU strategy is the opposite of the LU strategy in that it attempts to select the most-used wavelength in the network.

3.4 *Random (RA) Strategy*

Another approach for choosing between different wavelengths is to simply select one of the wavelengths randomly.[12,13] There is no criterion for picking up the wavelength. It can be used with both centralized and distributed control. This approach first searches the wavelengths to find the set of all wavelengths that are available on the required lightpath, and among the available wavelengths, one is chosen randomly.

3.5 *Strategy with Tree Topology (TR)*

This strategy picks up any node randomly, then constructs a tree by using this node as the root and using breadth first search algorithm. It takes all the one-hop count connections and assigns the first free wavelength to this connection.

Table 3 Comparison table for NSFNET with four wavelengths.

(*s*-*d*) Pairs	Shortest Route	Commonly used Wavelength Assignment Strategies										Proposed Strategy	
		Least Used Strategy		Most Used Strategy		First-Fit Strategy		Random Strategy		Strategy with Tree Topology		Circular Sequential	
		λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts	λ no.	No. of attempts
1-9	1-8-9	1	1	1	1	1	1	2	1	1	1	1	1
8-14	8-9-12-14	2	1	2	2	2	2	4	1	2	2	2	1
2-6	2-3-6	3	1	2	1	1	1	3	1	2	2	3	1
12-14	12-14	4	1	1	2	1	1	2	1	1	1	4	1
2-7	2-4-5-7	4	1	2	1	1	1	3	1	1	1	1	1
1-2	1-2	1	1	2	1	1	1	3	1	1	1	2	1
1-7	1-8-7	3	1	2	1	2	2	1	1	2	2	3	1
6-13	6-14-13	1	1	2	1	1	1	4	1	1	1	4	1
3-9	3-6-10-9	2	1	1	2	2	2	1	1	3	3	1	1
4-6	4-5-6	3	1	1	2	2	2	2	2	2	2	2	1
11-14	11-13-14	4	1	1	2	2	2	2	2	2	2	3	1
5-13	5-11-13	1	1	2	1	1	1	1	1	1	1	4	1
6-3	6-3	4	3	3	3	3	3	4	2	1	1	2	2
3-5	3-6-5	1	3	4	4	4	4	D	4	4	4	4	2
4-7	4-5-7	2	1	4	3	3	3	4	2	3	3	3	3
10-8	10-9-8	3	1	4	3	3	3	3	3	4	4	4	1
5-14	5-6-14	4	1	3	4	3	3	3	3	3	3	1	1
8-2	8-1-2	2	1	4	3	3	3	4	3	3	3	4	3
5-2	5-4-2	1	2	3	4	4	4	1	4	4	4	3	3
8-5	8-7-5	1	4	1	2	4	4	2	4	4	4	4	1
Total no. of attempts			28		43		44		36		42		28

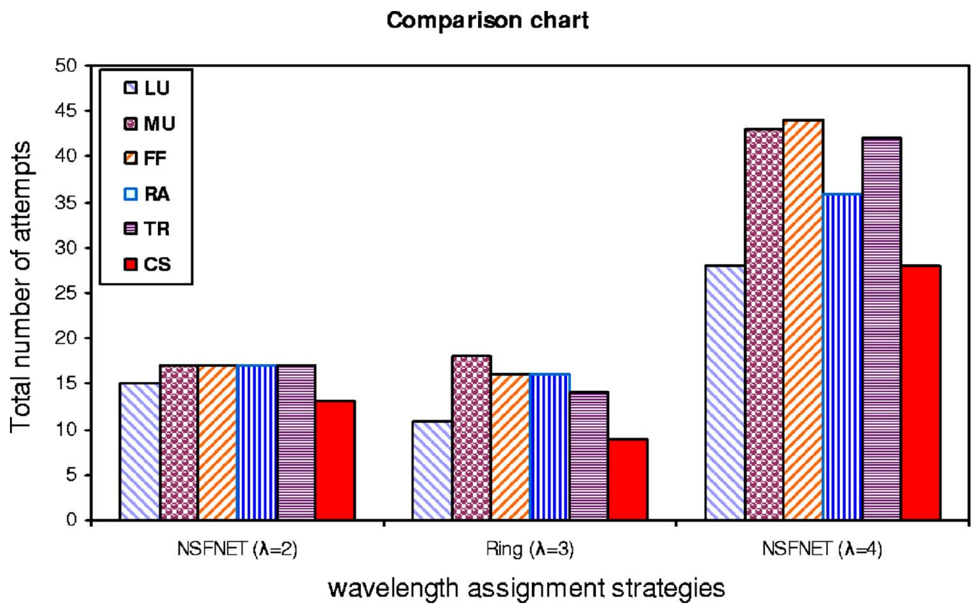

Fig. 4 Comparison chart.

This process is repeated for all the nodes. All the other remaining connections are established with the FF strategy.[14]

4 Circular Sequential (CS) Proposed Strategy

In our proposed CS strategy, a circular list of wavelengths is taken. If W number of wavelengths are available, then they are arranged as shown in Fig. 1. One pointer points to a wavelength. Whenever a connection request arrives, a wavelength assignment is tried starting from the wavelength pointed by the pointer. If the pointed wavelength is free on all the links along the route, a connection is established; otherwise, the pointer proceeds and the next wavelength is tried on the route specified for connection establishment. After the wavelength is assigned, the pointer points to the next wavelength.

The CS algorithm is as follows, where "ptr" means pointer:

1. ptr=1
2. For each source-destination (s-d) pair, do the following
3. i=ptr
4. Take node pointer j initially pointing to s
5. If wavelength i is not free on link from j to next node on the route, then

(i) if $i=[(\text{ptr}+W) \text{ modulus } W]+1$, then go to step 11
(ii) $i=[(i+W) \text{ modulus } W]+1$
(iii) go to step 4

6. Advance node pointer j to next node on the route
7. If $j\,!=d$, then go to step 5
8. Reserve wavelength i on all the links from s to d on the route to accept the connection request
9. $\text{ptr}=[(i+W) \text{ modulus } W]+1$
10. Go to step 12
11. Reject the connection request
12. Go to step 2 for new s-d pair till end

5 Results and Discussion

The networks shown in Figs. 2 and 3 are NSFNET[15,16] and unidirectional ring networks, respectively, taken as the sample networks. The paths are wavelength-continuous. The routes have been selected by applying the shortest-path algorithm for NSFNET. First, the following s-d pairs for connection establishment have been taken for NSFNET with two wavelengths: (1-9), (8-14), (2-6), (12-14), (2-7), (1-2), (1-7), (6-13), (3-9), (4-6), (11-14), and (5-13). Then the following s-d pairs for connection establishment have been taken for the unidirectional ring with three wavelengths: (2-5), (4-6), (1-3), (5-7), (6-1), (4-7), (2-4), and (3-4). The following s-d pairs are also considered for NSFNET with four wavelengths: (1-9), (8-14), (2-6), (12-14), (2-7), (1-2), (1-7), (6-13), (3-9), (4-6), (11-14), (5-13), (6-3), (3-5), (4-7), (10-8), (5-14), (8-2), (5-2), and (8-5).

The commonly used wavelength assignment strategies and the CS strategy were applied to the above-mentioned networks and the s-d pairs. The results are tabulated in Tables 1–3 for NSFNET with two wavelengths, for the ring network with three wavelengths, and for NSFNET with four wavelengths, respectively. These tables compare the number of attempts to find the wavelength for connection establishment for the commonly used and the CS wavelength assignment strategies. Column 1 shows the s-d pairs; column 2 gives the shortest route from source to destination; and columns 3, 5, 7, 9, 11, and 13 show the wavelengths reserved for connection establishment for the LU, MU, FF, RA, TR, and CS strategies, respectively. The "D" in these columns indicates that the connection could not be established due to the unavailability of a free wavelength. Columns 4, 6, 8, 10, 12, and 14 show the number of attempts to find a free wavelength along the route for the LU, MU, FF, RA, TR, and CS strategies, respectively. One row in the table corresponds to each s-d pair. The last row indicates the total number of attempts for all the *s-d* pairs for various wavelength assignment strategies. These tables clearly show that in most of the cases, the proposed strategy results in fewer attempts to establish a connection as compared to commonly used strategies. Table 3 shows an equal number of attempts for the LU and CS strategies, but Tables 1 and 2 show better results for CS as compared to LU. Moreover, in the case of the LU strategy, whenever a connection request arrives the system must calculate the uses of each wavelength; but the CS strategy is very simple and does not require this overhead.

Figure 4 compares the commonly used and proposed strategies in the form of a bar graph. The *X* axis represents the sample networks and the number of wavelengths considered. The *Y* axis represents the total number of attempts.

6 Conclusions

In this paper, we have proposed a wavelength assignment strategy that assigns the wavelength in a circular sequential manner. It gives good results because each wavelength has equal importance as it uniformly assigns the wavelengths. The results are taken in terms of the number of attempts to find a free wavelength along the route for connection establishment. The results clearly show that the proposed strategy performs better than commonly used strategies. The number of attempts directly affect the connection establishment time, so with the proposed strategy the connection establishment time is reduced.

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Paramjeet Singh received a B Tech degree in computer science and engineering from Punjab Technical University, Jallandhar, Punjab, India, in 1998, and a MS in software systems from Birla Institute of Technology and Science (BITS), Pilani, Rajasthan, India, in 2002. He is currently pursuing a PhD degree in optical networks from BITS. From September 1998 to May 2005, he was a lecturer at Giani Zail Singh College of Engineering and Technology, Bathinda, Punjab, in the dept. of computer science and engineering. Since May 2005, he has been an assistant professor in the department of computer science and engineering. There are 40 research and review papers to his credit, of which seven research papers were published in international refereed journals, and eight papers were published, in international refereed conference proceedings; the rest appeared in national conference proceedings. His research interests include routing and wavelength assignment algorithms in optical networks and computer graphics.

Shaveta Rani received a B Tech degree in computer science and engineering from Punjab Technical University, Jallandhar, Punjab, India, in 1998, and a MS in software systems from Birla Institute of Technology and Science (BITS), Pilani, Rajasthan, India, in 2002. She is currently pursuing a PhD in optical networks from BITS. From August 1998 to May 2005, she was a lecturer at Giani Zail Singh College of Engineering and Technology, Bathinda, Punjab, in the dept. of computer science and engineering. Since May 2005, she has been an assistant professor in the department of computer science and engineering. There are 41 research and review papers to her credit, of which seven research papers were published in international refereed journals and eight papers were published in international refereed conference proceedings; the rest appeared in national conference proceedings. Her research interests include survivability algorithms in optical networks and image compression.

Ajay K. Sharma graduated in electronics and communication engineering from Punjab University, Chandigarh, India, in 1986. He received a MS in electronics and control engineering from Birla Institute of Technology and Science, Pilani, in 1994, and earned his doctorate in electronics, communication and computer engineering in 1999 from Kurukshetra University, Kurukshetra. From 1986 to 1990 he held various teaching and research positions at Technical Teachers Training Institute and Directorate of Technical Education, Chandigarh; Indian Railways, New Delhi; and Sant Longowal Institute of Engineering and Technology, Longowal. In 1991 he joined the faculty of Regional Engineering College, Hamirpur, H.P. (now National Institute of Technology). From February 1996 to October 2001, he was an assistant professor in electronics and communication engineering at the National Institute of Technology (Deemed University), (erstwhile Regional Engineering College) Jalandhar, Punjab. Since November 2001, he has been a professor in the department of elec-

tronics and communication engineering in the areas of chromatic dispersion compensation and WDM systems and computer networks. There are 151 research papers to his credit published in international and national refereed journals, international refereed conference proceedings, and national conference proceedings. Currently, he is engaged in research in the areas of dispersion compensation for linear and nonlinear optical communication systems and networks, soliton transmission and WDM optical networks, and performance analysis and crosstalk evaluation in WDM systems and networks. He is a technical reviewer for *Optics Communication*, and *Digital Signal Processing*. He was appointed, as a member of the technical committee on telecom by the International Association of Science and Technology Development (IASTD), Canada, for the term 2004 to 2007. He is a life member of the Indian Society for Technical Education (ISTE).

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Minimum connection count wavelength assignment strategy for WDM optical networks

Paramjeet Singh [a,*], Ajay K. Sharma [b], Shaveta Rani [a]

[a] *Department of Computer Science and Engineering, GZSCET, Bathinda, Punjab 151001, India*
[b] *Department of Electronics and Communication Engineering, NIT, Jalandhar, Punjab, India*

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Abstract

In this paper, we have proposed one wavelength assignment strategy for optical networks which assigns the wavelength according to minimum connection count. The performance of proposed strategy is compared with the most commonly used strategy among the existing strategies in terms of number of searches to find the wavelength for connection establishment. The searching takes the time and directly affects the connection establishment time. The simulation is done using different network models. The results show that the proposed strategy is much better than existing strategy in terms of number of searches required to find a wavelength for establishing the connection and hence connection establishment time reduces.

Keywords: WDM; Wavelength assignment; Optical networks; Wavelength continuity constraint

1. Introduction

Optical networks employing wavelength division multiplexing (WDM) offer the promise of meeting the high bandwidth requirements of communication applications. It divides the huge transmission bandwidth of an optical fiber (∼50 terabits per second) into multiple communication channels with bandwidths (∼10 gigabits per second) compatible with the electronic processing speeds of the end users. In WDM optical networks, the lightpaths are the basic building block, so their effective establishment is crucial [1].

Given a network topology and a set of connection requests, determining a route and wavelength for each connection request is called routing and wavelength assignment (RWA) problem [2]. It is important because it provides a route for each connection request and assigns a wavelength on each of the links along this route among the possible choices so as to optimize a certain performance metric. Routing problem is to select an appropriate route from source to destination among all existing routes [3]. Generally, the shortest path routing approach is used. The shortest path for each source destination pair is computed off-line in advance using standard shortest-path algorithm, e.g., Dijkstra's algorithm or Bellman–Ford algorithm. Wavelength assignment problem is to assign the wavelength along the selected route on which data transmission can take place. The wavelengths assigned to different lightpaths should be such that no two lightpaths that share a physical link use the same wavelength on that link. In the absence of wavelength conversion, it is required that the lightpath occupy the same wavelength on all links it traverses. This requirement is referred to as the *wavelength continuity constraint*. A channel is a wavelength on a link and is reserved at any time for at most one lightpath [4].

The traffic assumptions generally have two categories: static or dynamic. In static models, it is assumed that the demand is fixed and known, i.e., all the connections that are to be set up in the network are known beforehand. The objective is typically to accommodate the demand while minimizing the connection establishment time. Connection establishment time is the time taken to establish the connection from source to destination.

* Corresponding author.
E-mail address: param2009@yahoo.com (P. Singh).

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In dynamic, it is assumed that connection requests for source–destination pairs can arrive at any time.

In this paper, one wavelength assignment strategy has been proposed which reduces the number of searches to find the wavelength for connection establishment and hence reduces the connection establishment time. The performance of proposed strategy is compared with commonly used wavelength assignment strategy. The simulated results show that the proposed strategy is much better than the existing strategy. This paper is organized as follows. In Section 2, we explain system model. In Section 3, we present wavelength assignment strategies in WDM networks. Section 4 focuses on performance evaluation, which shows simulation results by taking examples of standard NJ LATA, COST239 and NSFNET networks. Conclusions are drawn in Section 5.

2. System model

Given is a network with physical topology represented by a graph $G(A, B, L)$. Here V is the set of vertices or nodes in the network. Total number of nodes in the network is $|A| = n$; they are numbered from 0 to $n - 1$. B is the set of links in the network. These are the physical edges connecting the vertices. Single fiber system is assumed, i.e., there is one fiber along any link. The edges are assumed to be undirected. L is the set of weights associated with the edges. These weights are used for computing the route with shortest path algorithm. The set of connection requests is C. $|C| = I$ indicates the total number of connection requests. These connection requests are numbered from 0 to $I - 1$. D represents the set of wavelengths. $|D| = N$ is the total number of wavelengths numbered from $W1$ to WN. Equal number of wavelengths per fiber has been assumed.

Notations

p_{sd}: Total number of links along the route for s–d connection.
s: The source for a connection.
d: The destination for a connection.
$sd[j]$: jth connection.
R_{ij}: The route for the connection when $s = i$ and $d = j$.
z_{ij}: The wavelength assigned to the connection when $s = i$ and $d = j$.

$$w_{ij}^{sd} = \begin{cases} 0, & \text{if } s\text{–}d \text{ connection does not use any wavelength on link } ij, \\ 1, & \text{otherwise.} \end{cases}$$

$$m_{ij,k}^{sd} = \begin{cases} 0, & \text{if } s\text{–}d \text{ connection does not use wavelength } k \text{ on link } ij, \\ 1, & \text{otherwise.} \end{cases}$$

$$Q_{sd}^{k} = \begin{cases} 1, & \text{if } s\text{–}d \text{ connection is established on wavelength } k, \\ 0, & \text{otherwise.} \end{cases}$$

Mathematical formulations

Total number of s–d pairs (I) (if s–d pairs when $(s = d)$ included), $\forall(s, d \in A)$

$$= \begin{cases} (n(n-1)/2) + n, & \text{if } (R_{ij} = R_{ji} \text{ and } z_{ij} = z_{ji})\ \forall i, j \in A, \\ n \times n, & \text{otherwise.} \end{cases}$$

Total number of s–d pairs (I) (if s–d pairs when $(s = d)$ excluded), $\forall(s, d \in A)$

$$= \begin{cases} n(n-1)/2, & \text{if } (R_{ij} = R_{ji} \text{ and } z_{ij} = z_{ji})\ \forall i, j \in A, \\ n(n-1), & \text{otherwise.} \end{cases}$$

Objective function = Minimize (number of searches) for fixed number of wavelengths.

Constraints

1. $\sum_{sd} w_{ij}^{sd} \leqslant N \quad \forall s, d \in C \text{ and } \forall i, j \in B.$
   Wavelengths assigned on a link for all the connections do not exceed N.
2. $\sum_{ij}^{sd} m_{ij,k} = \begin{cases} P_{sd}, & \text{if } Q_{sd}^{k} = 1, \\ 0, & \text{otherwise } \forall s, d \in C, \\ & \forall i, j \in B \text{ and } \forall k \in D. \end{cases}$
   For any wavelength k and for any connection request for s–d pair, left side of the equation represents the number of channels with wavelength k used by the lightpath. If the lightpath use wavelength k, then the total number of channels used will be equal to the total number of links along the route, i.e., P_{sd}. If the lightpath does not use the wavelength k then the number of channels (on wavelength k) used for the connection under consideration will be zero.
3. $m_{ij,k}^{sd} = \begin{cases} 1, & \text{if } w_{ij}^{sd} = 1 \text{ and } Q_{sd}^{k} = 1, \\ 0, & \text{otherwise } \forall s, d \in C,\ \forall i, j \in B \text{ and } \forall k \in D. \end{cases}$
   The left side of the equation shows whether the wavelength k on link ij is used by the connection for s–d pair or not. It will be 1, only if the lightpath for the s–d pair is using this channel, i.e., the lightpath uses the link ij and also the lightpath is established on wavelength k.
4. $m_{ij,k}^{sd} \times m_{yv,x}^{sd} = \begin{cases} 1, & \text{if } k = x,\ w_{ij}^{sd} = 1, \\ & w_{yv}^{sd} = 1 \text{ and } Q_{sd}^{k} = 1, \\ 0, & \text{otherwise.} \end{cases}$
   This constraint represents the wavelength continuity constraint.

3. Wavelength assignment strategies

Wavelength assignment deals with selecting a wavelength to establish the connection along a given route for the connection request. Whenever data is to be transmitted, a route is selected by using routing algorithm over which data transmission is done. The route gives the sequence of links starting from source node to destination node. A wavelength is required to be reserved over these links to carry the data. This wavelength is

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selected by the wavelength assignment strategy. As wavelength assignment deals with resource allocation and establishment of connections, it is critical issue and affects the performance of the network.

3.1. First-fit (FF) wavelength assignment strategy (existing strategy)

This strategy is implemented by predefining an order of the wavelengths. The wavelength search is made according to this order. The first free wavelength found on the links along the route is reserved for connection establishment. This wavelength assignment strategy does not take into consideration the usage factor of the wavelengths, i.e., how heavily loaded a wavelength is. The wavelengths are searched starting from the first wavelength for all the connections, so the wavelengths earlier in the list are tried before the wavelengths later in the list [5,6]. Algorithm for this strategy is presented in Appendix A.

3.2. Minimum connection count (MCC) wavelength assignment strategy (proposed strategy)

In this, whenever any connection request arrives, the wavelength which is used by minimum number of connections out of all the wavelengths is attempted for connection establishment. If this wavelength is free on all the links along the route for the s–d pair under consideration, it is reserved along the route for connection establishment. If wavelength is not free, then from the remaining wavelengths again the wavelength with minimum connection count is attempted and so on till the connection gets established or all the wavelengths are tried. If more than one wavelength has number of connections equal to minimum connection count then first fit is used to choose the wavelength out of all these.

Initially the number of searches will increase with the increase in total wavelengths. It is because the resources are very less and connection requests are more. Due to less resources than required, the connections will be attempted on mostly all the wavelengths including the added wavelengths resulting in increase in the number of searches. If number of wavelengths is further increased then as more resources become available, there is more connection establishment chances with the earlier attempted wavelengths as these are least loaded wavelengths. The number of wavelengths searched reduces as more resources are available. Even if all the connections get established and number of wavelengths is further increased, then the number of searches may decrease. For a connection request, chances of getting a free wavelength from the wavelengths attempted earlier are more as more resources lead to less load on wavelengths. Algorithm for this strategy is presented in Appendix B.

The disadvantage of first-fit strategy is that for every s–d pair, the search for free wavelength starts from the first wavelength in the index. Initially the lower indexed wavelengths may be available for connection establishment. But after some connections get established, the lower indexed wavelengths are more heavily used as compared to others because whenever a connection request arrives, wavelength search starts from lowest indexed wavelength. Lower indexed wavelengths are heavily used so there is less probability of connection establishment on these wavelengths. So number of searches to find wavelength for connection establishment increases leading to higher connection establishment time. In MCC, the wavelength which is tried first for any s–d pair is the wavelength which is used by minimum connections. So this wavelength is least loaded and the chance of getting the wavelength free on the links along the route is high. The wavelengths which will be tried earlier are freer, so there are more connection establishment chances on the earlier attempted wavelengths which directly reduce the number of searches and time to find a free wavelength.

4. Performance evaluation

In order to evaluate the performance of strategies, simulations are performed. Not able to find a suitable simulator that could support the strategies, we designed and developed a simulator for WDM optical networks for regular and irregular topologies. The simulator is developed in C++ language. It accepts input parameters such as the number of nodes in the network, link weight information, number of wavelengths per link, connection requests, etc. All these parameters can be initialized either before running the simulations to obtain results for a given selection of parameters or at the run time. Whenever any connection is to be established, a wavelength is required for the connection which is free on all the links along the route (in case of *wavelength continuity constraint*). The wavelengths are tried one by one for the connection establishment according to the wavelength assignment strategies discussed. The number of searches gives the information how many wavelengths have been tried. One output of the simulator is the number of searches for the specified parameters along with the detailed information of connections for the given resources. Extensive simulations are then carried out to get the results.

To determine the optimality of proposed strategy, we tested it on various standard networks. Figures 1, 2 and 3 show the NJ LATA [7,8], COST239 [5,9] and NSFNET [10,11] standard networks, respectively, taken as sample networks. The nodes are connected together with undirected links and the information on links can flow in both directions. Let t and u be two different nodes in the network. Due to undirected links, the routes for t (source) to u (destination) and u (source) to t (destination) will be same. Permutation routing has been taken for finding out the sample source destination pairs in which every node in the network acts as the source to every other node in the network simultaneously with unicasting approach. Total number of source destination pairs in permutation routing depends upon the number of nodes. It is assumed that if a node has to send some data to it, the data is sent internally and no external links are used for the transfer. So the s–d pairs, when $s = d$ are not included during the simulation as they do not require the wavelength and do not affect the number of searches. The weight taken for each link in the network is same. Shortest path algorithm is applied to find the route because it efficiently utilizes the resources. Equal number of wavelengths per fiber has

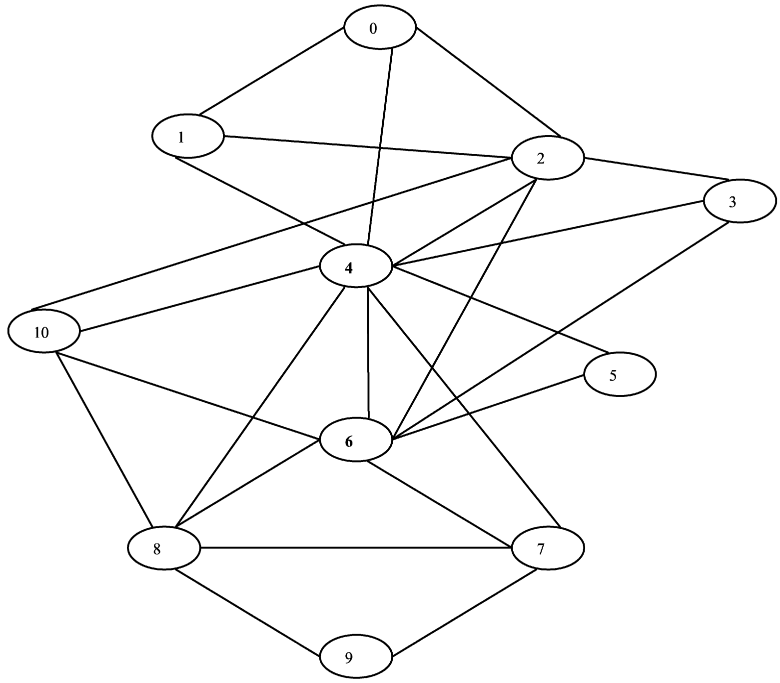

Fig. 1. NJ LATA (N: 11, L: 23) network topology.

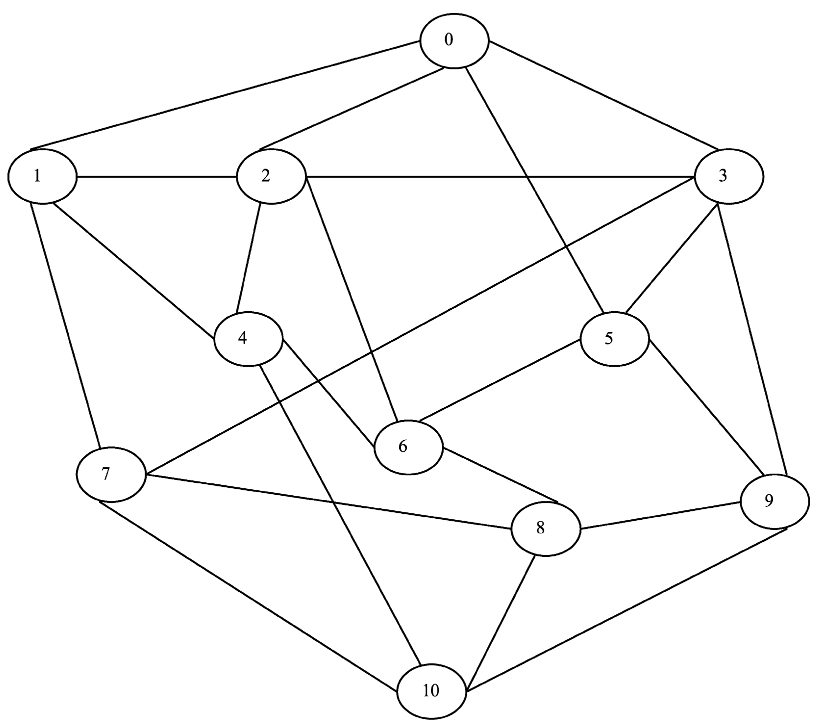

Fig. 2. COST239 (N: 11, L: 23) network topology.

been assumed. Wavelength continuity constraint is observed. Greedy approach is used while wavelength selection for a connection, i.e., the first free wavelength found along the route is reserved for the connection.

Figures 4, 5 and 6 show the comparison charts in terms of number of searches for FF and MCC wavelength assignment strategies when applied on NJ LATA, COST239 and NSFNET networks, respectively. The X-axis represents the number of wavelengths and Y-axis represents the number of searches done to find the free wavelength for the connection requests. Simulation results show that MCC strategy performs better than FF strategy because it tries the wavelengths according to their reservation for various connections. In MCC, the least loaded wavelength is tried first as there are more chances of connection establishment over it, leading to reduced number of searches and connection establishment time.

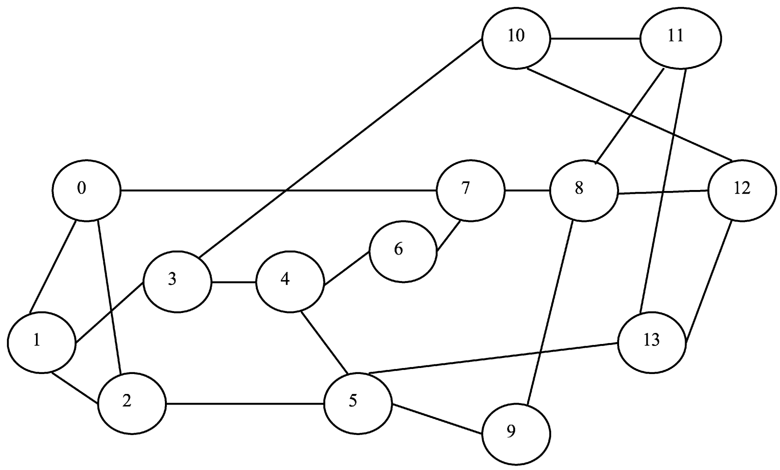

Fig. 3. NSFNET (N: 14, L: 21) network topology.

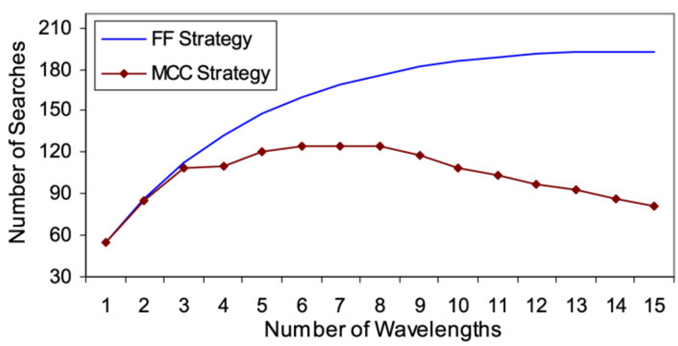

Fig. 4. Comparison chart for NJ LATA topology.

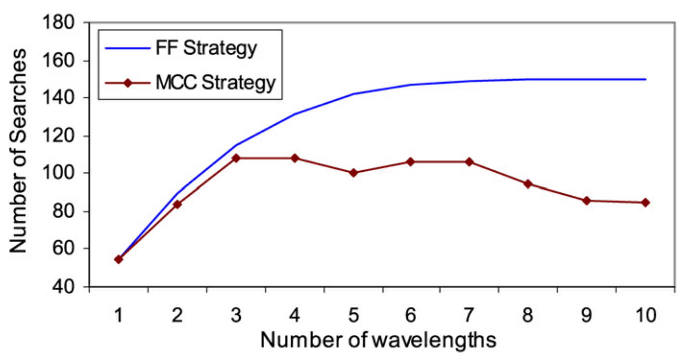

Fig. 5. Comparison chart for COST239 topology.

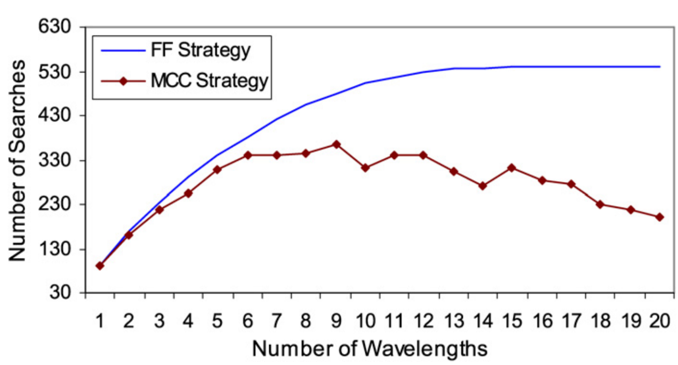

Fig. 6. Comparison chart for NSFNET.

5. Conclusions

In this paper, routing and wavelength assignment problem is discussed in WDM optical networks in general and wavelength assignment problem in specific. One wavelength assignment strategy has been proposed for optical networks which assigns the wavelengths according to minimum connection count. It reduces the number of searches to find the wavelength for connection establishment and hence reduces the connection establishment time. The performance of proposed (MCC) strategy is compared with the commonly used (FF) wavelength assignment strategy in terms of number of searches to find the free wavelength for connection establishment. The simulation is done using different network models. The simulated results show that the proposed strategy is much better than existing strategy in terms of number of searches required to find a wavelength for establishing the connection and hence connection establishment time reduces.

Appendix A. First-fit (FF) wavelength assignment strategy

For each s–d pair, do the following:

1. $\text{ptr}1 = W1$.
2. Take node pointer ptr2 initially pointing to s.
3. If wavelength ptr1 is not free on link from node pointed by ptr2 to next node on the route, then:
   (i) If $\text{ptr}1 = N$, then go to step 8;
   (ii) $\text{ptr}1 = \text{ptr}1 + 1$;
   (iii) Go to step 2.
4. Advance node pointer ptr2 to next node on the route.
5. If $\text{ptr}2! = d$, then go to step 3.
6. Reserve wavelength ptr1 on all the links on the route from s to d to establish the connection.
7. Go to step 9.
8. Reject the connection request.
9. End.

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Appendix B. Minimum connection count (MCC) wavelength assignment strategy

For each s–d pairs, perform the following:

1. ptr1 = 1.
2. Find a wavelength from all the wavelengths in the list with minimum connection count. Let it be e.
3. Delete e from the list.
4. Take node pointer ptr2 initially pointing to s.
5. If wavelength e is not free on the link from node pointed by ptr2 to next node along the route, then:
   (i) If ptr1 = N, than go to step 11;
   (ii) ptr1 = ptr1 + 1;
   (iii) Go to step 2.
6. Advance node pointer ptr2 to next node on the route.
7. If ptr2! = d, then go to step 5.
8. Reserve wavelength e on all the links on the route from s to d to establish the connection.
9. Go to step 11.
10. Reject the connection request.
11. End.

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Routing and wavelength assignment in WDM networks with dynamic link weight assignment

Paramjeet Singh[a,*], Ajay K. Sharma[b], Shaveta Rani[a]

[a]Department of Computer Science and Engineering, GZSCET, Bathinda, Punjab, India
[b]Department of Electronics and Communication Engineering, NIT Jalandhar, Punjab, India

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Abstract

We consider the routing and wavelength assignment problem on wavelength division multiplexing networks without wavelength conversion. When the physical network and required connections are given, routing and wavelength assignment (RWA) is the problem to select a suitable path and wavelength among the many possible choices for each connection such that no two paths using the same wavelength pass through the same link. In wavelength division multiplexing (WDM) optical networks, there is need to maximize the number of connections established and to minimize the blocking probability using limited resources. In this paper, we have proposed three dynamic link weight assignment strategies that change the link weight according to the traffic. The performance of the existing trend and the proposed strategies is shown in terms of blocking probability. The simulation results show that all the proposed strategies perform better than the existing trend.

Keywords: WDM; RWA; Optical networks; Wavelength continuity constraint; Shortest path

1. Introduction

Optical networks basing on wavelength division multiplexing (WDM) technique is obviously the most promising way to support the huge broadband traffic demand anticipated. Among the study fields related to such optical networks, the routing and wavelength assignment (RWA) of optical paths has been given great attention [1]. WDM should be used in combination with wavelength routing to enhance the transmission line capacity and cross-connect node-processing capability of the large bandwidth networks.

In WDM optical networks, there are three main constraints related with wavelength: *wavelength continuity constraint* (*WCC*), *distinct wavelength assignment constraint* (*DWAC*) *and non-wavelength continuity constraint* (*NWCC*). In WCC, the same wavelength must be used on all the links along the selected route, In DWAC, two light paths cannot be assigned the same wavelength on any fiber and in NWCC, the different wavelengths can be used on the links along the selected route but the nodes should have wavelength conversion capability. Wavelength conversion is the ability to convert the data on one wavelength to another wavelength. Eliminating wavelength conversion significantly reduces the cost of the switch, but it may reduce network efficiency because more wavelengths might be required. But several studies reported that the increased efficiency by using wavelength conversion is small compared to the cost increase [2,3]. The paper examines the case that no wavelength converters exist in the network.

*Corresponding author. Tel.: +98 8858 5202.
E-mail address: param2009@yahoo.com (P. Singh).

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Notations

N	total number of wavelengths numbered from 0 to $N-1$.
I	total number of connection requests numbered from 0 to $I-1$.
n	total number of nodes in the network and are numbered from 0 to $n-1$.
P_{sd}	total number of links along the route for sd connection.
s	indicates the source.
d	indicates the destination.
$sd\,[j]$	indicates jth connection.
R_{ij}	represents the route for the connection when $s=i$ and $d=j$.
W_{ij}	represents the wavelength assigned to the connection when $s=i$ and $d=j$
rejconn	is the variable used to store the number of connections rejected
acconn	is the variable used to store the number of connections accepted
$W_{ij}^{sd}=0$	if s–d connection does not use any wavelength on link ij.
$W_{ij}^{sd}=1$	otherwise
$m_{ij,k}^{sd}=0$	if s–d connection does not use wavelength k on link ij.
$m_{ij,k}^{sd}=1$	otherwise
$Q_{sd}^{k}=1$	if s–d connection is established on wavelength k
$Q_{sd}^{k}=0$	otherwise

In this paper, we have proposed three dynamic link weight assignment strategies that change the link weight according to the traffic, which reduces the blocking probability by symmetrically distributing the traffic to some extent so that more connections can be established. The comparison of the performance of proposed strategies with the existing trend [4–7] in terms of blocking probability has been presented. This paper is organized as follows. In Section 2, we describe RWA problem in optical networks. In Section 3, we present system model. In Section 4, we explain link weight assignment strategies. Section 5 focuses on performance analysis which shows simulation results by taking an example of realistic NSFNET network. Conclusions are given in Section 6.

2. RWA problem in optical networks

Given a network topology and a set of end-to-end light path requests, determine a route and wavelength(s) for the requests, using the minimum possible number of wavelengths is called RWA problem [8]. The problem of selecting an optimal route and a wavelength for a light path such that the network throughput is maximized or minimize blocking probability is a tightly coupled problem. Since the tightly coupled RWA problem cannot be analytically solved, it is a general practice to de-couple the problem and try to solve the RWA problems separately. It is often infeasible to solve the coupled RWA problem for large networks because of the size of the problem [9]. It is more realistic to solve it by de-coupling the problem into two separate sub problems, routing sub problem and wavelength assignment sub problem. The objective functions in RWA problem are as follows:

- given a set of light paths, minimize the required number of wavelengths to satisfy these light paths without blocking,
- given a maximum number of wavelengths available, minimize the light path blocking probability.

Routing problem is to select an appropriate route from source to destination among all existing routes. Generally, the fixed shortest-path routing approach is used [10]. The shortest paths for each source destination pair is computed off-line in advance using standard shortest-path algorithms, e.g. Dijkstra's algorithm or Bellman–Ford algorithm.

Wavelength assignment problem is to assign the wavelength along the selected route on which data transmission can take place. Proper assignment of wavelengths can lead to reduced or no use of wavelength converters which can significantly reduce the cost. Whenever a call is generated by the source node, it sends the request to the controller. As the controller has the knowledge about the network, it contains the information of free and busy wavelengths at that instant of time. The controller then selects a wavelength from the set of free wavelengths and assigns it to that call. The commonly used wavelength assignment strategy is the first-fit wavelength assignment strategy. It is implemented by predefining an order of the wavelengths. The list of used and free wavelengths is maintained. The assignment scheme always tries to establish the connection using the first wavelength, if that wavelength is free on all the links of selected route then the connection establishment takes place otherwise it will try to establish the connection by using the next indexed wavelength and so on up to a total number of wavelengths. When the call is completed, the wavelength is added back to the free wavelength set.

3. System model

The physical network topology is represented as $G(S, L, W)$, in which S represents the set of nodes in the network, L represents the set of links, and W represents the set of wavelengths on each link. A connection request of an s–d pair is served by setting up a light path that is a series of channels belonging to the immediate nodes along the path from the source s to the destination d. The physical topology and the set of connections (C) are given as input for the problem. Our objective is to maximize the number of light paths to be established from the given set of connections.

3.1. Mathematical formulations

Total number of s–d pairs (I) (If s–d pairs when ($s = d$) included), $\forall$ (s, $d \in S$),

$= (n(n-1)/2)+n$, if $R_{ij} = R_{ji}$ and $w_{ij} = w_{ji}$ $\forall i, j \in S$,

$= n \times n$, otherwise.

Total number of s-d pairs (I) (If s-d pairs when ($s = d$) excluded), $\forall$ (s, $d \in S$),

$= n(n-1)/2$, if $R_{ij} = R_{ji}$ and $w_{ij} = w_{ji}$ $\forall i, j \in S$,

$= n(n-1)$, otherwise.

Blocking probability = rejconn/I = (1−acconn)/I.

Objective function = minimize (blocking probability) for fixed number of wavelengths. Or minimize (N) for zero blocking probability.

Constraints:

1. $\sum_{sd} w_{ij}^{sd} <= N, \quad \forall sd \in C, \forall ij \in L.$

Wavelengths assigned on a link for all the connections does not exceed N.

2. $\sum_{ij}^{sd} m_{ij,k} = P_{sd}$, if $Q_{sd}^{k} = 1$.

$= 0$, Otherwise $\forall sd \in C, \forall ij \in L$ and $\forall k \in W$.

3. $m_{ij,k}^{sd} = 1$, if $w_{ij}^{sd} = 1$ and $Q_{sd}^{k} = 1$.

$= 0$, Otherwise $\forall sd \in C, \forall ij \in L$ and $\forall k \in W$

4. Link weight assignment strategies

Mostly all the networks employ the shortest path for connection establishment. In all the four strategies discussed, first of all the connection establishment corresponding to all the connections is tried on the shortest path because the shortest path helps to utilize the resources efficiently. The alternate shortest path is then used to establish the connection if the connection could not be established with the shortest path with the available resources to reduce the blocking probability in this paper because the connections rejected with shortest path may be established with the alternate path without requiring additional resources [11]. The alternate shortest path for a source destination pair is the path which is link and node disjoint with the shortest path and is least weighted out of all the alternative paths. As it is node and link disjoint, so it will not cover the congested link/node in the shortest path and there are chances of a connection establishment. As alternate paths are more weighed than shortest paths, so are given a lower priority. Always, light paths on shortest routes should be tried before light paths on alternate shortest paths [10]. In all the strategies, the first-fit wavelength assignment technique is used.

4.1. Existing strategy

The network with the given link weight is taken and all the connections are established according to these link weights. The link weights do not change according to the connection requests, the number of wavelengths, the resource requirement/utilization, and resource availability [4–7].

The disadvantage of this approach is that the routing decision is not made based on the current state of network. It might lead to the situation where some links on the network are over utilized while other links are underutilized.

4.2. Proposed strategies

4.2.1. Channel requirement for shortest path (CRSP) strategy

The new weight assigned to a link is equal to the number of channels required on that link if all the connections are to be accepted with the shortest path with the existing strategy. It gives higher weight to the links which are required more number of times, so that they are less preferred for connection establishment, leading in reduction of traffic over these links. Similarly, the links that were in less demand earlier are given low weight so that the traffic on these links increases. In this way, the load gets balanced on the links so that more connections can be accepted reducing the blocking probability. It is independent of the total number of channels on the link i.e. the resources available. The connection requests and the resources required for those are a very important factor and it was not considered in the above-discussed strategy. This strategy changes the link weights according to the connection requests and the resources required for the connection establishment, so gives better results than the existing strategy.

4.2.2. Channel requirement for connection establishment (CRCE) strategy

The new weight assigned to a link is equal to the total number of channels required on that link if the shortest as well as alternate shortest light paths are to be established for all the connection requests with the existing strategy. The load balancing on the links is done according to the resources required and it leads to more number of connections established. In the four strategies discussed, the connection is tried on the alternate shortest path if not established on the shortest path. So the resources required for the alternate shortest path are also equally important as that of the resources required for the shortest path and needs consideration, which is done in this strategy. This consideration was not done in the earlier two discussed strategies, so this strategy performs better than the existing and CRSP strategies. It is independent of the number of wavelengths on the links.

4.2.3. Channel utilization (CU) strategy

In it, the new link weight depends on the total number of channels on a link. The new weight assigned to a link is equal to the total number of channels that will be used on that link for the establishment of all the connections for the given number of wavelengths with the existing strategy. All the links have equal number of channels, but some links are more demanded, so more channels are used on those links and some links are less demanded, so less number of channels is used on those links. If all the links are equally used, then more number of connections can be established. The new link weight assigned tries to give the more priority to the links that were earlier less demanded so that they can be more used by the connections. It also gives less priority to the links that were earlier in more demand so that they are less in demand now. In this way, the traffic gets symmetrically distributed over the links to some extent, thus reducing the blocking probability. It gives best results out of all the four strategies discussed in this paper because it takes into consideration the utilization factor of each link if each link has same resources i.e. number of channels which was not taken care of in the other three strategies.

5. Performance analysis

5.1. Simulation environment

No heuristics could be validated until they are supported by practical results. In order to demonstrate that our approach performs better than that reported in the literature and to investigate the performance of algorithm we must resort to simulations. Not able to find a suitable simulator that could support our proposed heuristics, we designed and developed a simulator to implement RWA in all-optical networks for regular and irregular topologies. The simulator was developed in the C++ language. It accepts input parameters such as the number of nodes in the network, link information with weight, number of wavelengths per fiber, connection requests. Some of the calls may be blocked because of the unavailability of free wavelength on links along the route from the source to the destination. The ratio of the total number of calls blocked to the total number of light path requests in the network is defined as the blocking probability. The output of the simulator is the blocking probability for the specified parameters along with the detailed information of connections. All these parameters can be initialized before running the simulations to obtain results for a given selection of parameters. Extensive simulations are then carried out for every combination of parameters of interest and the obtained results are tabulated.

5.2. Performance evaluation

The skeleton of the NSFNET shown in Fig. 1 is a 14-node network with 21 edges. The nodes are connected together with undirected links. We have applied proposed strategies to this network. Permutation routing has been taken for finding out the sample source destination pairs in which every node in the network acts as the source to every other node in the network simultaneously with unicasting approach. Total number of source destination pairs in permutation routing depends upon the number of nodes.

Table 1 stores the link information of the network in terms of their weight. Table 2 shows the comparison of existing strategy and proposed link weight assignment strategies in terms of blocking probability. The first column of Table 2 shows the number of wavelengths taken. Column 2 gives the blocking probability for the commonly used existing strategy. Columns 3–5 gives the blocking probability for comparison purpose for proposed CRSP, CRCE and CU link weight assignment strategies, respectively. The comparison graph in Fig. 2 shows the results given in Table 2 graphically. The *X*-axis represents the number of wavelengths and the *Y*-axis represents the blocking probability for the sample network with permutation routing. The difference of the link weights among the existing strategy and the proposed strategies leads to variation in the performance as shown by the results given in the columns 2–5

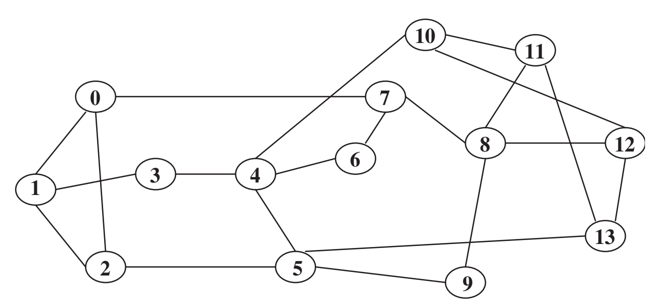

Fig. 1. NSFNET network.

Table 1. Link information table

Link	Weight
0–1	1
0–2	2
0–7	8
1–2	2
1–3	3
2–5	4
3–4	2
3–10	9
4–5	1
4–6	1
5–13	7
6–7	1
7–8	1
8–9	6
8–11	1
8–12	2
10–11	1
10–12	5
11–13	6
12–13	4

Table 2. Blocking probability comparison table

No. of λs	Existing strategy	CRSP strategy	CRCE strategy	CU strategy
1	0.791209	0.846154	0.835165	0.835165
2	0.681319	0.714286	0.714286	0.725275
3	0.615385	0.626374	0.626374	0.637363
4	0.56044	0.549451	0.582418	0.538462
5	0.505495	0.472527	0.505495	0.450549
6	0.43956	0.428571	0.428571	0.395604
7	0.395604	0.384615	0.384615	0.307692
8	0.340659	0.351648	0.318681	0.263736
9	0.307692	0.285714	0.252747	0.21978
10	0.263736	0.252747	0.208791	0.153846
11	0.241758	0.208791	0.164835	0.131868
12	0.197802	0.186813	0.131868	0.076923
13	0.175824	0.175824	0.076923	0.065934
14	0.153846	0.153846	0.032967	0.021978
15	0.131868	0.10989	0.010989	0.010989
16	0.10989	0.098901	0	0
17	0.10989	0.087912		
18	0.087912	0.087912		
19	0.076923	0.087912		
20	0.076923	0.054945		
21	0.076923	0.043956		
22	0.076923	0.032967		
23	0.076923	0.032967		
24	0.076923	0.021978		
25	0.076923	0.021978		
26	0.076923	0.010989		
27	0.076923	0.010989		
28	0.054945	0.010989		
29	0.032967	0.010989		
30	0.032967	0		
31	0.032967			
32	0.032967			
33	0.032967			
34	0.010989			
35	0			

of Table 2 although the rest i.e. the physical network topology G, the set of connection requests C, the routing technique (with shortest and alternate shortest path in this case) and the wavelength assignment strategy (first fit in this case) are the same for all the strategies. All the proposed strategies give better results than the existing approach, but out of all these proposed strategies, CU strategy gives the best performance. Simulation results show that the performance of all the proposed strategies is much better than the existing strategy.

6. Conclusion

In this paper, we discussed RWA problem in WDM optical networks. We have proposed three strategies that aim at load balancing to reduce the blocking probability. In the first proposed strategy, the new link weight is equal to the number of channels required if the shortest path corresponding to all s–d pairs are to be established as it assigns the link weight according to the demand of the link so balancing the load. The second proposed strategy further improves the results by also considering the alternate shortest path because it is also equally important. The third proposed strategy gives the best performance by considering the link utilization of each link if each link has equal capacity. The performance of proposed strategies and existing trend has been evaluated in terms of blocking probability by applying on the sample network. The simulation results show that all the three proposed strategies give better results than the existing trend. The third proposed strategy is the best of all these.

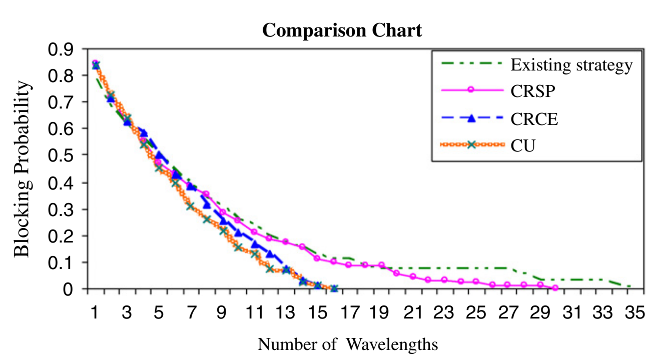

Fig. 2. Comparison graph.

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