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Impairment Aware Routing in Translucent Optical Networks

by

Naseer Ansari

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Impairment Aware Routing in Translucent Optical Networks

by

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DECLARATION OF CO-AUTHORSHIP

I hereby declare that material in this thesis is the result of joint research. This thesis incorporates information obtained as a result of joint collaboration with Mr. Quazi Rahman under the supervision of Dr. Subir Bandyopadhyay and Dr. Arunita Jaekel. The author was responsible for developing a new approach to solve the impairment aware routing and wavelength assignment problem. In all cases, the primary contributions such as the main ideas, algorithm design, implementation, and result analysis were performed by the author. The co-authors contributed mainly through their constructive comments.

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ABSTRACT

Optical networks are ideally suited to meet today's rapidly increasing bandwidth demands due to the large fiber bandwidth capacity, low attenuation, low distortion and low cost. When an optical signal propagates along the fiber links, its quality degrades due to physical layer impairments such as optical noise, chromatic dispersion, polarization mode dispersion and nonlinear effects. As a result, bit error rate (BER) may become so high that signal may not be properly detected at the receiver. In order to address this problem, we have developed an impairment aware dynamic routing and wavelength assignment algorithm. Our algorithm not only takes into account the physical layer impairments but also resolves any wavelength conflict if there is a cycle in the path from a source to a destination. Our results indicate that the proposed algorithm significantly reduce the blocking probability in dynamic lightpath allocation if the impact of physical layer impairments is compensated by the use of regenerators.

DEDICATION

This thesis is dedicated to my beloved wife Shagufa Banu and my kids Kabir, Jakir and Amir.

ACKNOWLEDGMENT

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LIST OF SYMBOLS

ASE   - Amplifier Spontaneous Emission

CD   - Chromatic Dispersion

CWDM - Coarse Wavelength Division Multiplexing

DWDM - Dense Wavelength Division Multiplexing

EDFA - Erbium-Doped Fiber Amplifier

FF   - First Fit

FWM - Four Wave Mixing

IA-RWA - Impairment Aware Routing and Wavelength Assignment

OADM - Optical Add-Drop Multiplexer

PMD - Polarization Mode Dispersion

QoT   - Quality of Transmission

Regn - Regenerator

RF   - Random Fit

RWA - Routing and Wavelength Assignment

SPM - Self-Phase Modulation

WDM - Wavelength Division Multiplexing

XPM - Cross Phase Modulation

XT   - Crosstalk

Chapter 1

INTRODUCTION

1.1 Overview

An optical network is a system for data communication between two or more nodes using optical signals, instead of electronic signals. Optical signals propagate along the fiber optic cables and carry data from one node to another at the speed of light. Since the fiber cable has unprecedented bandwidth capacity, it provides users very fast communication [1].

In the real world, the entire bandwidth capacity of an optical fiber may not be used by a single user or a single application, creating the need to share the bandwidth among multiple users. Wavelength Division Multiplexing (WDM) technology is widely used to perform bandwidth sharing. This technology allows a single fiber to carry multiple optical signals with different carrier wavelengths. A lightpath in a WDM network is a unidirectional optical connection between a source node and a destination node, which carries data in the form of encoded optical signals and may span multiple fiber links and use one or multiple wavelengths [2]. Different lightpaths in WDM networks can use the same wavelength,

as long as they do not share any common links. Due to the WDM technology, multiple lightpaths can be established on the same fiber using different carrier wavelengths. The key network elements that enable the WDM optical networking are optical transmitters and receivers, optical amplifiers, add/drop multiplexers, and optical switches. These optical devices are connected by a set of optical fibers, defining an optical network. Details about network components will be discussed in Chapter 2.

A lightpath may pass through any number of intermediate nodes using optical cross connect switches (OXCs), which are able to switch signals from one port to another and may incorporate wavelength conversion capabilities. A lightpath is assigned the same channel on all the links that it traverses, if a wavelength conversion device is not used in WDM optical networks [3]. This is referred to as the *wavelength continuity constraint* [4]. This constraint tends to reduce the wavelength utilization, which results in degrading the network performance. However, it is used since wavelength converters are expensive. In WDM optical networks, the data is communicated from one node to another through lightpaths. To establish a lightpath for a connection request, a physical route from the source node to the destination is first determined and then an available wavelength on each link of the route is assigned. This problem of routing and assigning a wavelength to establish a lightpath is known as the *routing and wavelength assignment* (RWA) problem.

The main objective of the RWA problem is to establish as many lightpaths as possible, keeping resource limitations in mind, which minimizes the network operation cost and increases the network performance [2]. For the RWA problems, many algorithms have been proposed in the literature [5], [6], [7] and [8]. In translucent WDM optical networks, the problem of minimizing the number of regenerators on each translucent lightpath to reduce the use of regenerator resources is known as the *routing and regenerator placement* (RRP) problem [9].

As the optical signal propagates through the fiber links or passes through the OXCs, the signal quality degrades and the bit error rate (BER) rises due to physical layer impairments [10] and [11]. Existing lightpaths in the network also cause the signal degradation of the candidate lightpath or vice versa. This behavior of optical devices and the existing lightpaths may cause incorrect signal decoded by the receiver. Hence, it is very important to consider the impact of impairments on the signal quality while solving the routing and wavelength assignment problem. In order to compensate for the loss due to the impairments, 3R regenerators (re-shaping, re-timing, re-amplifying) are used at some selected nodes in any translucent WDM optical network, allowing signals to travel for long distances. Since regenerators are costly, the RWA algorithms are needed to allocate the lightpaths utilizing the minimum number of regenerators.

The impact of physical layer impairments on the signal quality has been a critical issue for routing in translucent optical networks. In recent years, this issue has drawn the attention of the researchers in [12], [13],[14], [15], [16], [17], [18], [19], [20] and [21]. However, the above researchers did not handle a situation where there is a cycle on the path from the source to the destination. The main reason of motivation for this work is to address this deficiency and study the impact of impairments on the lightpaths.

1.2 Problem Statement

In our work, the impairment due to the adjacent channel and the intra-channel crosstalk is referred to as the *Quality of Transmission* (QoT) value. The *optical reach* is defined as maximum distance that an optical signal can travel without requiring 3R regenerator. The QoT value and the optical reach are the major factors which must be considered to establish a connection request in a given WDM optical network. The problem is to design an algorithm to establish

a lightpath which satisfies the following conditions:

- The lightpath must satisfy the optical impairment requirements,

- The existing lightpaths in the network must not be disrupted,

- If there is a cycle in the route, it should be handled properly,

- The proposed algorithm must use the existing algorithm to determine the location of regenerators in the network.

1.3 Work Reported in This Thesis

In this thesis, we propose a heuristic algorithm for impairment aware dynamic routing and wavelength assignment. In addition to selecting the path with acceptable quality limit, our algorithm resolves the wavelength conflict, in case there is a cycle in the route from the source to the destination. The *blocking probability* is the ratio of total blocked requests and total connection requests. The experimental results shows that the proposed algorithm significantly reduces the blocking probability due to the fact that the impairments are compensated by the sparsely placed regenerators in the network.

1.4 Thesis Organization

The rest of the thesis has been organized as follows. In Chapter 2, we have reviewed some relevant topics in WDM networks and physical layer impairments that affect the quality of the light signal. In Chapter 3, we have presented our heuristic algorithm for impairment aware routing and wavelength assignment and

discussed the implementation details of the heuristic. In Chapter 4, we have presented the experimental results on some realistic networks and analyzed the results. Finally, in Chapter 5, we have concluded the thesis with some suggestions for future research work in this area.

Chapter 2

LITERATURE REVIEW

2.1 Overview

In this chapter, we review some relevant material about optical networks including WDM technology, routing and wavelength assignment problem, major physical layer impairments and their effects on routing in translucent optical networks.

2.2 Optical Networks

With continuing advancement in optical technology, the demand for optical network based services is growing. Optical networks provide better performance at lower costs compared to the traditional networks [2]. In optical networks, the data is transmitted in the optical domain over fibers whereas in the traditional networks data is transmitted in the electronic domain over copper cables [22]. Just a single strand of fiber has a potential bandwidth of nearly 50 terabytes per second [23]. However, the huge bandwidth of optical fiber is un-

likely to be utilized by single client or application. Hence, it drives the need of bandwidth sharing among multiple traffic sources by means of multiplexing.

2.2.1 Overview of WDM Networks

Wavelength Division Multiplexing is a technique that allows a single fiber to transmit many separate signals simultaneously at different wavelengths of light [24]. This is similar to broadcasting many radio and television signals through the air at different frequencies.

In order to share huge bandwidth among multiple clients, three major multiplexing approaches have been adopted in optical networks [24].

- Time division multiplexing (TDM): The TDM is a process of dividing up one communication time slot into smaller time slots. The users transmit data using their own time slot while utilizing only a part of their channel capacity [24].

- Space division multiplexing (SDM): In this technique, multiple users can be served on the same time slot/frequency slot; however, it is costly to implement [25].

- Wavelength division multiplexing (WDM): It is a process of combining multiple signals at various wavelengths for transmission along the same fiber optic media [24].

Since TDM technique is not able to fully utilize the enormous bandwidth of optical fibers and SDM is costly to implement, WDM technology is widely used in optical networks. As per WDM technology, the huge bandwidth of the optical fiber is

divided into a number of non-overlapping optical channels and each channel has a different wavelength [26]. It allows multiple channels to transmit on a single fiber simultaneously. At the transmitter node, a multiplexer combines wavelengths onto a common outgoing fiber link and at the receiver node, a demultiplexer separates the wavelengths and forwards each wavelength to a separate receiver. There are three categories of WDM [24]:

- WDM : 2 to 4 wavelengths per fiber

- CWDM : 4 to 8 wavelengths per fiber

- DWDM : 8 or more wavelengths per fiber

WDM, DWDM and CWDM all use multiple wavelengths of light on a single fiber, but they differ in the spacing of the wavelengths, number of channels, and the ability to amplify the multiplexed signals in the optical space. In WDM technology, the channel spacing is greater than 100GHZ whereas in CWDB, it is greater than 200 GHZ. The DWDM technology has spacing less than 100 GHZ and can allow transmission rates of up to 10 GB/s per channel [27].

An optical network can be classified as opaque, transparent or translucent optical network [21]. In an *opaque* network the optical signal is regenerated at each intermediate node via optical-electronic-optical (O-E-O) conversion [21] and [28]. Normally, this conversion is done using a 3R regenerator, which is deployed at network nodes to provide signal regeneration capability in the network [2]. Since 3R regenerators are expensive, the design of such a network could be so costly that it may not be feasible to implement [29]. In a *transparent* network the signal along a lightpath remains in the optical domain from the source node to the end node of the lightpath. A lightpath in such a network is called *transparent*

lightpath. This type of network is less expensive but it covers only a relatively small geographical area, since the maximum length of a lightpath cannot exceed a specified limit. A *translucent* network [21] can be viewed as a combination of opaque and transparent networks, where only a subset of nodes has the capacity to regenerate the signal. A *translucent lightpath* is a lightpath in a translucent network, which consists of multiple lightpath segments. As shown in Figure 2.1, the lightpaths L_1 and L_2 are transparent lightpath segments. A route $0 \rightarrow 1 \rightarrow 2$ is called a segment [30], where the same wavelength is used, hence maintaining the wavelength continuity constraint (please refer section 2.5).
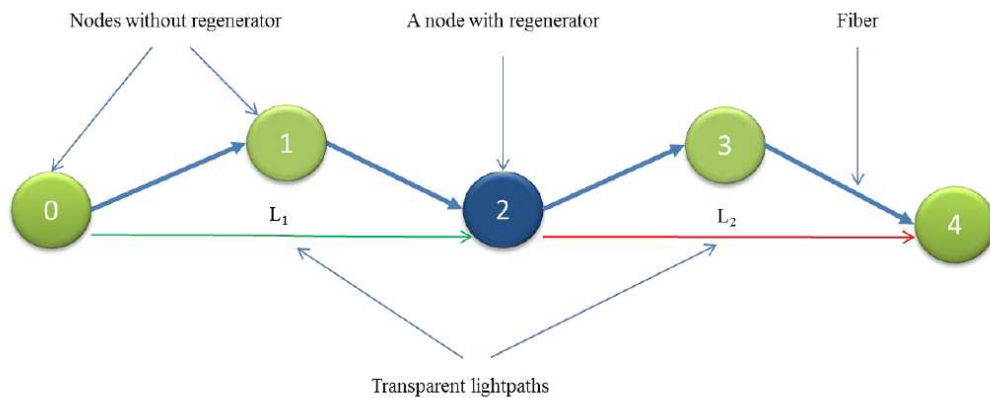
Figure 2.1: A translucent lightpath from 0 to 4

Since it is not necessary to have regenerators at every node, it is far less costly than opaque networks [21]. However, the presence of sparsely placed regenerators allows a translucent network to span over a large geographical area.

2.2.2 Faults in WDM Networks

In a WDM network, different types of failures such as link failures, node failures, channel failures and software failures occur in network components [23]. One relatively common scenario is when fiber is cut in the process of digging by

backhoe [23] or some other physical damage to the fiber occurs due to human error. Similarly, at the nodes, the transmitter and the receiver may malfunction or due to software issues or physical damage. In any case, disruption of traffic could be serious because the data transfer rate of each lighpath is typically from 2.5 GB/s to 10 GB/s [31], and a single fiber can carry multiple lightpaths.

2.3 Optical Networking Components

The main components of optical networks include fiber optic cables, optical transmitters, optical receivers, optical amplifiers, optical switches and Optical Add-Drop Multiplexers (OADM) [32] and [23].

2.3.1 Fiber Optic Cable

The fiber optic cable is the basic building block of optical networks and carries signals from node to node, with switches directing the signals to their destination. A typical fiber cable is shown in Figure 2.2 taken from [33].
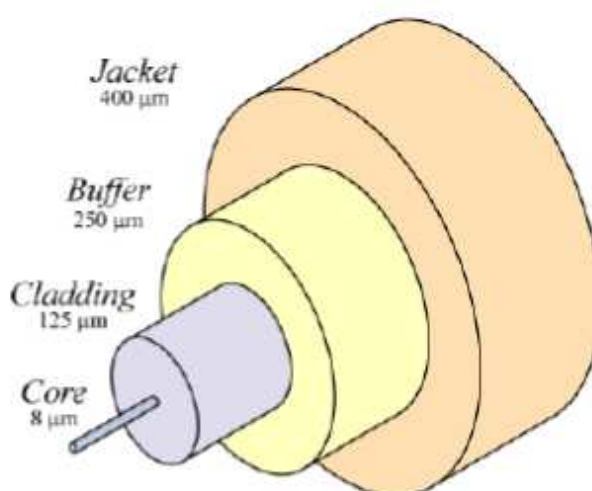
Figure 2.2: A typical optical fiber cable

A fiber optic cable consists of a thin strand (about the size of a human hair) of very pure glass, called the core, through which the light travels [31]. The material outside the core is called the cladding. When the light launched into the core strikes the cladding, the light is reflected from the core to cladding interface and all the light remains in the core because of total internal reflection [34]. The index of refraction for the cladding must be less than the index of refraction for the core to limit the light within the core of an optical fiber. A buffer which surrounds each cladding protects the fiber from damage and moisture. A single fiber cable which contains hundreds or thousands of fiber strands is finally protected by outer jacket.

2.3.2 Optical Transmitter and Receiver

An optical transmitter is a device which converts an electrical input signal into the corresponding optical signal and then launches it into the optical fiber to create a communication channel. Most optical transmitters use laser (Light Amplification by Stimulated Emission of Radiation) [35], which produces intense high-powered beams of coherent light. In order to transmit data across an optical fiber, the data has to be encoded into a laser signal. This is usually done by a technique called on-off keying (OOK) which sends a bit by turning the light off (on) if the bit is a 0 (1) [23].

The optical receiver converts the incoming optical stream at the destination back into a digital stream and recovers the data transmitted by the source. The major component of the optical receiver is a photo detector that converts an optical signal to electronic signal through the photoelectric effect [35].

2.3.3 Optical Amplifier

As an optical signal propagates through an optical fiber, the optical power

level decreases. In order to receive the signal properly at the destination, it is necessary to amplify the signal at regular intervals. Optical amplifiers can serve this purpose at lower cost compared to electronic regenerators since it can amplify several communication channels simultaneously [26].

Erbium-Doped Fiber Amplifier (EDFA) is a commonly used optical device to amplify a weak optical signal so that the signal can be detected and extracted correctly by the receiver. A pump laser, typically working at a wavelength of 980 nm or 1480 nm, is used to pump an input optical signal [26]. The input signal and the pump laser are coupled by a wavelength-selective coupler and the resulting signal is sent into the fiber. The pump signal is separated from the amplified signal at the receiver. Using EDFAs in the optical network, a signal gain of 25 DB or 30 DB and a bandwidth gain of 35 nm can be achieved. The EDFAs can facilitate spans up to 800 km without the use of electronic regenerators [26] and [24].

2.3.4 Optical Switch

An optical switch is used to switch signals on a wavelength from an input fiber to the correct output fiber. A diagram of a simple switch which has two inputs and two outputs is shown in Figure 2.3.
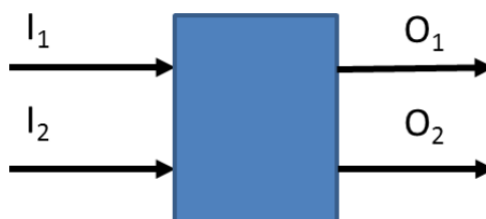
Figure 2.3: A 2 x 2 switch

This type of switch is called a 2 x 2 switch. The switch can be adjusted in such a way that either input I_1 or I_2 can be sent out to either output O_1 or

O_2 [23]. On the basis of this simple switch, a large switch with many inputs and outputs can be designed and built.

2.3.5 Optical Add-Drop Multiplexer (OADM)

An Optical Add-Drop Multiplexer is a device that has the ability to add and drop channels in the network [36]. It consists of a pair of a multiplexer and a demultiplexer [23]. A schematic diagram of an OADM is shown in Figure 2.4 taken from [24].
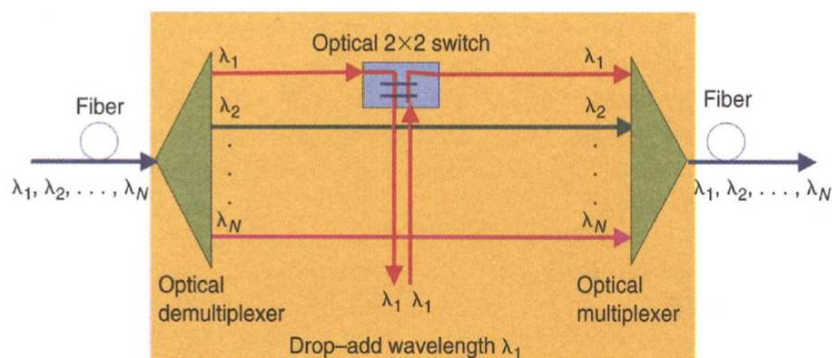
Figure 2.4: An optical add-drop multiplexer

As shown in Figure 2.4, the signal using channel λ_1 is dropped, which means that this signal is not connected to the multiplexer; instead it is connected to a receiver. The OADM then adds in the same direction of data flow the same wavelength, but with different data content. This added signal with same wavelength comes from a transmitter.

2.4 Physical Layer Impairments

The quality of the transmission degrades as the optical signal propagates through the physical media such as optical fiber. The farther the signal travels from the source, the higher bit error rate (BER) it generates [14]. At the receiver,

the BER value may be so high that the message cannot be received correctly. This phenomenon occurs because of the physical layer impairments (PLI). The PLIs are classified into linear and non-linear impairments.

2.4.1 Linear Impairments

Linear impairments affect each of the wavelengths individually [37]. The important linear impairments are:

- **Amplifier Spontaneous Emission (ASE):** Amplifier spontaneous emission is produced by the optical amplifiers used as intermediate repeaters along the fiber and as pre-amplifiers at the receiver end. The ASE mixes with the optical signal and dissipates some of the signal power [37].

- **Chromatic Dispersion (CD)**: Chromatic dispersion is the impairment that causes pulse broadening. It also reduces the pulse energy, which affects the receiver performance at the end [24].

- **Polarization Mode Dispersion (PMD)**: The PMD is the broadening of a pulse due to the time delay of one of the two pulse components. The effect of PMD is noticeable for most type of fibers at 40 Gbps or higher rates [38].

- **Crosstalk (XT)**: Optical components such as OADMs, multiplexer/demultiplexers, and optical switches cause the linear crosstalk , which is the effect of signal power leakage from other WDM channels on the desired channel [37].

2.4.2 Non-linear Impairments

Non-linear impairments depend on the current status of allocated light-paths. They affect not only each optical channel individually but also cause disturbance and interference between them. The important non-linear impairments are:

- **Self-Phase Modulation** (**SPM**): The SPM is broadening of the frequency i.e. the change in the optical phase of a light signal caused by its own intensity. In DWDM systems, when ultra-short optical pulse travels in a non-linear medium, it induces a time varying refractive index of the medium, resulting in phase change of the signal [37] and [26].

- **Cross Phase Modulation** (**XPM**): The XPM is the nonlinear effect which is generated when the intensity of one light signal causes the phase change of another light signal. It influences the system more than SPM, particularly when the number of channels is large. The effect of XPM reduces as the wavelength spacing between individual channels increases [37].

- **Four Wave Mixing** (**FWM**): Four Wave Mixing can occur if two or more different frequency components travel together in a nonlinear medium such as an optical fiber cable. When three signals of frequencies f_0 , f_0 - u and f_0, $f_0 + u$ propagate along a fiber simultaneously, the FWM leads to the generation of some new frequencies such as f_0 - 3u, f_0 - 2u, $f_0 + 2u$ and $f_0 + 3u$ [39]. The effects of the FWM can be reduced by decreasing the channel spacing [37].

2.4.3 Adjacent Channel Interference

The effect of inter-channel crosstalk and nonlinear impairments such as FWM and XPM is very severe between adjacent channels [14] and [21]. The Figure 2.5 shows how a lightpath is influenced by adjacent channels.
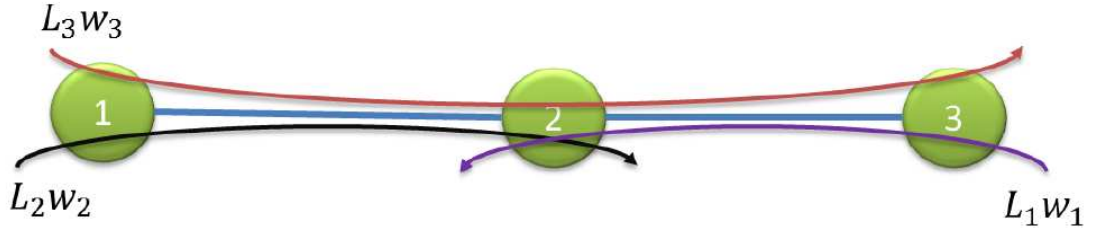
Figure 2.5: Adjacent channel interference on (L_3w_3) by (L_2w_2) and (L_1w_1)

Suppose we need to establish a lightpath L_3 from node 1 to node 3 that uses a wavelength w_3 at the moment when L_1 and L_2 are existing lightpaths using adjacent channels w_1 and w_2 respectively. In such a situation, L_1 and L_2 will affect the quality of the optical signal that establishes L_3. Conversely, L_3 will affect L_1 and L_2 as well.

2.4.4 Intrachannel Crosstalk

The impairment due to intrachannel crosstalk is related to optical cross connect switch [40]. This type of impairment is generated because of power leakage between lightpaths crossing the same cross connect switch and using the same wavelength. The Figure 2.6 shows the effect of intrachannel crosstalk.
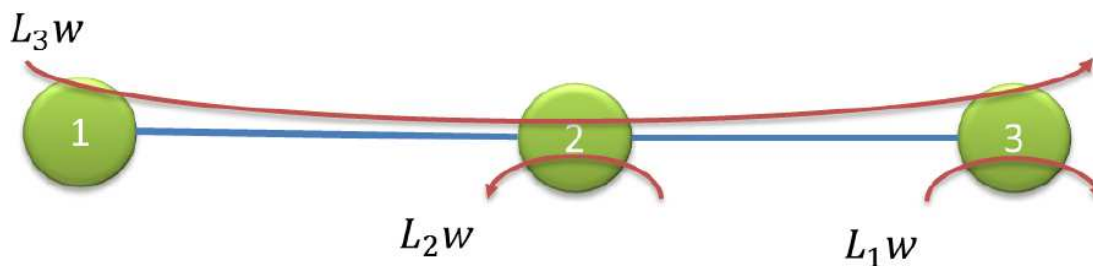
Figure 2.6: Intrachannel interference on (L_3w) by (L_2w) and (L_1w)

Let L_3 be a candidate lightpath from node 1 to node 3 using the wavelength w. L_1 and L_2 are existing lightpaths using the same wavelength w crossing nodes 1 and 2 which are located along the path L_3. The existing lightpaths L_1 and L_2 will affect the signal quality of L_3 and vice versa.

2.5 Routing and Wavelength Assignment Problem

One of the major problems in WDM optical networks is the Routing and Wavelength Assignment (RWA) [41], [42] and [43]. Each connection request must be associated with a route and a wavelength. To establish a lightpath, it is required that the same wavelength should be allocated on all the links in the absence of wavelength conversion. The problem in RWA consists of two sub-problems: Routing and Wavelength Assignment.

2.5.1 Routing

The routing means finding a path between a source and destination pair whereas wavelength assignment (WA) assigns a wavelength along that path. There are normally three types of routing approaches used [44].

1. Fixed Path Routing

2. Fixed Alternate Routing

3. Adaptive Routing

The simplest approach for finding a feasible route for a lightpath is *Fixed Path Routing.* In this approach, the lightpath route is computed ahead of time using a shortest path algorithm, such as Dijkstra's algorithm [45]. Even though this approach is very simple, the network performance is not very good. If any link along the fixed paths is unavailable, the incoming connection requests will not be established even though other paths may exist. The next approach is an extension of Fixed Path Routing. Instead of having just one fixed route for a given source and destination pair, several routes are stored [44] and [2]. Since *Fixed Alternate Routing* allows fixing several routs for a single pair of source and destination, it is more efficient than Fixed Path Routing. When a connection request arrives, one of the available paths is used. If all of the paths fail, the connection is blocked. The disadvantage of these routing techniques is that neither one takes into account the current state of the network. A connection will be blocked if the predetermined paths are not available even though other paths may exist. In order to overcome this problem, an approach called Adaptive Routing [46], [47] and [2] is used. In this approach, there is no limitation on route selection. Any available route based on the current network state information is selected for a connection request, which reduces the blocking probability compared to fixed alternate routing and provides better fault tolerant capability. This technique is widely used for the research work today.

2.5.2 Wavelength Assignment

There are several wavelength assignment algorithms for wavelength as-

signment problem in the literature. However, the most common algorithms are First-Fit and Random-Fit [2].

2.5.2.1 Random-Fit (RF)

The *Random-Fit* algorithm selects the wavelength randomly. In this algorithm, the wavelengths available on each link of a route are determined first and then a wavelength from a list of available wavelengths is chosen [48] and [49].

2.5.2.2 First-Fit (FF)

The *First-Fit* algorithm explores the wavelengths in a fixed order. In this approach, all the wavelengths are indexed first and then the wavelengths are searched in the order of their index numbers. It selects the first available wavelength [49], [2] and [48].

2.5.3 Routing and Wavelength Assignment

Normally, routing and wavelength assignment sub-problems are solved jointly. Hence, it is called RWA problem. The RWA problem is classified into static RWA [16] and [14] and Dynamic RWA [5] and [50]. They are also called offline and online RWA. The following are the properties which distinguish static RWA from dynamic RWA.

Static RWA

- A set of connection requests is known in advance.

- It is executed in planning phase.

- Optimal solution is intractable.

Dynamic RWA

- Connection requests come randomly and are served one by one.

- It is used when network is in operation.

- The RWA is done based on current information only.

- A lightpath is setup on demand and taken down after the communication is over.

2.6 A Property of the Translucent Networks

If a translucent lightpath consists of two segments (please refer section 2.2.1 for definition of translucent lightpath and segment) that share one or more fiber link(s), each segment must be assigned with different wavelengths [5]. This property of the translucent lightpath is shown in Figure 2.7 taken from [30]. Let the optical reach be 2000 km and a lightpath from A to H is to be established. Since the distance from A to H through B and C is more than optical reach, the candidate lightpath can't be established directly; instead it should go through the regenerator node D where the signal is regenerated for further traversal.
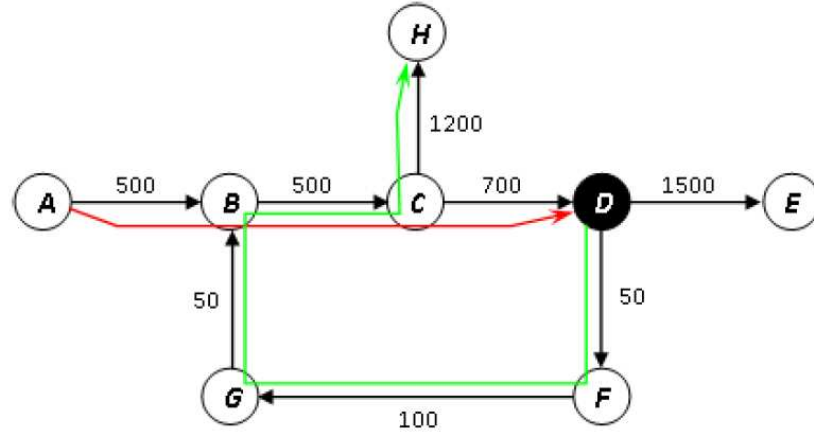
Figure 2.7: Loop $B - C - D - F - G - B$ for lightpath A to H

As shown in Figure 2.7, when an optical signal passes through the regenerator node and reaches the destination H, a loop $B - C - D - F - G - H$ is formed. Obviously, there is a common edge $B - C$ shared by both segments $A - B - C - D$ and $D - F - G - B - C - H$. In this situation, both segments $A - B - C - D$ and $D - F - G - B - C - H$ must not have the same wavelength. In general, the lightpaths that share one or more common links must be assigned different wavelengths using list coloring algorithm. This restriction is known as *cyclic constraint.*

2.7 Wavelength Conversion

In addition to considering the impact of physical layer impairments, we need to consider the impact of wavelength continuity constraint imposed on the RWA problem in optical networks [51]. This restriction may affect both the network performance and the complexity of RWA algorithms since establishing of a new lightpath depends on the availability of the same wavelength in a number of links. The limitation caused due to wavelength continuity constraint can be removed by using wavelength conversion, which is usually carried out by means of an optical-electrical-optical (O-E-O) signal regenerator. The (O-E-O) regenerator

first converts an input wavelength to an electronic signal and then converts it back onto another wavelength. Although this is the expensive process, it improves the network performance and reduces the blocking probability.

2.8 Impairment-Aware RWA (IA-RWA)

As physical layer impairments accumulate along a lightpath, the signal quality of transmission (QoT), normally measured in terms of the bit-error rate (BER), may drop beyond a predefined threshold, as a result the signal does not provide meaningful information to the receiver [37]. The most common way to mitigate the effect of physical layer impairments at network operation time is to develop routing and wavelength assignment (RWA) algorithms taking physical layer parameters into account. Normally, a QoT estimator, which models (approximately) the effect of different impairments on network layer, is used to design IA-RWA algorithms. The goal of IA-RWA algorithms is to ensure that viable lightpaths can be established, even in the presence of physical layer impairments [52].

During last decade, a number of researchers [53], [54], [55] and [56] have considered the effect of physical layer impairments, when solving the RWA problem. Impairment Aware RWA (IA-RWA) was discussed by Saleh [57], who proposed an algorithm to logically divide a large optical network into several islands of transparency. Each island is viewed as a transparent optical network, in which communication occurs in all-optical domain. Ramamurthy et al. [58] studied the effect of physical layer impairments on the tele-traffic performance of wavelength routed optical networks. Many researchers then proposed their algorithms to solve impairment aware RWA problems. The majority of them have focused on online RWA problem [8], [13], [59] and [55], since it is easier to account the interference among lightpaths. However, several papers [7], [60], [21] and [6] have

discussed the offline RWA problem as well.

Pointurier et al. [12] found that it was possible to consider the effect of physical layer impairments in the network layer during routing and wavelength assignment process. They proposed new algorithms that account for impairments in their design and increase fairness among users in all optical (transparent) networks. Marsden et al. [13] designed a dynamic routing and wavelength assignment (RWA) algorithm that takes into account one of the impairments called Four Wave Mixing (FWM) [61], which produces interference between WDM channels and imposes a severe limitation on the maximum launched power of individual WDM channel. Their algorithm evaluates the effect of FWM not only on wavelength assignment but also on routing process. Christodoulopoulos et al. [59] also considered the effect of interferences and proposed an algorithm to ensure that a new path is not affected by existing paths or vice versa. Shen [15] proposed an algorithm to account for impairments in design of translucent optical network. The proposed methodology divides a large network into several small transparent networks and places a regenerator between two networks. However, its low scalability limits future work on this approach. Pachnicke et al. [16] presented an online constraint-based routing (CBR) algorithm that considers a minimum quality of transmission (QoT) as a constraint and takes into account both linear and nonlinear impairments. This approach accounts for more impairments than previous works and establishes only those lightpaths which have at least minimum required signal quality. Hence it reduces the blocking probability significantly. Chaves et al. [17] proposed an algorithm to indirectly consider impairments by solving the regenerator placement problem. Kokkinos et al. [18] proposed a multi-parametric approach in which each link is assigned with a vector of cost parameters. This approach introduces a different way of handling impairments. Cost parameters include impairment generating sources such as the path length, the number of hops, the number of crosstalk sources etc. While exploring the route of a candidate path, the authors calculate its cost vector and

determine if the path is feasible. Zhao et al. [19] proposed an algorithm to improve the network performance and resolve the problem of duplicate resources by considering the physical layer effect on the network layer (cross layer). Keles et al. [20] proposed a heuristic to solve RWA problem with proper consideration of impairments. Recently, Christodoulopoulos et al. [55] have proposed multi-cost algorithms that account for the actual current interference among lightpaths and establish the lightpath which has the best cost. Azodolmolk et al. [52] proposed an IA-RWA algorithm that considers the impact of physical layer impairments on RWA using QoT estimators. The proposed algorithm also accounts for the inaccuracy of the QoT for first time. However, above research works have not considered the scenario where a single lightpath may travel along the same link twice to reach the destination.

Chapter 3

DESIGN AND METHODOLOGY

3.1 Introduction

In this chapter, we first define the problem and then describe our new approach to solve impairment-aware dynamic RWA problem in WDM translucent optical network. Our approach incorporates the well-known A* algorithm [62] for path finding and the List Coloring algorithm [63] to resolve the wavelength conflict problem if there is a cycle during the process of exploring the best path from the source to the destination.

Our algorithm is to carry out dynamic impairment-aware RWA. The objective of the algorithm is to find a "good" path between the source and the destination pair if it exists and a channel for every edge in the path. The lightpath determined by our algorithm must have acceptable QoT value which measures the impact of the physical layer impairments on an optical signal. In our work, we measure the linear impairment using the optical reach and the impairment due to adjacent channels and intrachannel crosstalk (nonlinear impairment) by a QoT value. If the search is successful, the new lightpath, when deployed, must

not adversely affect the existing lightpaths.

3.2 Problem Definition

Prior to defining the problem, we consider the following important points.

- If the length of the path is less than the optical reach and the QoT requirements or the cyclic constraint are not violated (section 2.6), no 3R regenerator is used along the path.

- If there are a number of available wavelengths, the first available wavelength is selected while searching a path for the given source and destination pair.

- Fiber links are bidirectional i.e. communication occurs in both directions of a single fiber.
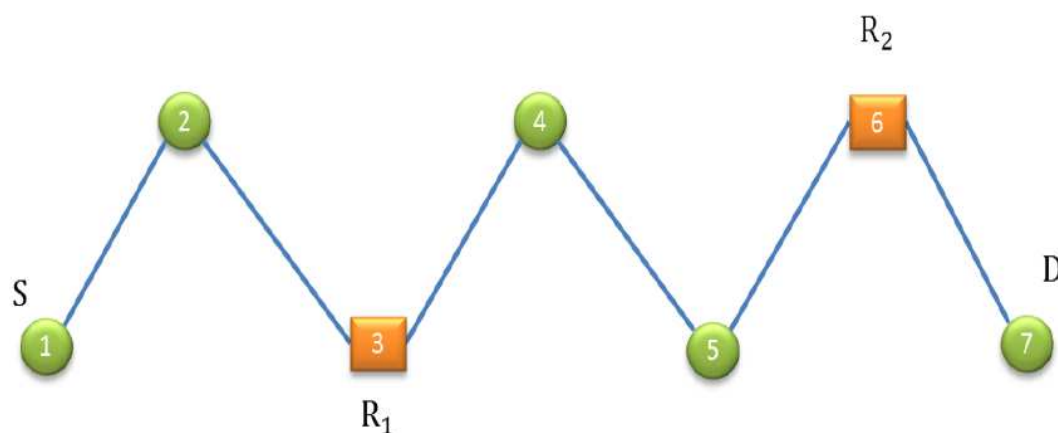
Figure 3.1: A lightpath from S to D

Let us consider a path from a given source S to a destination D as shown in Fig. 3.1, in which nodes 3 and 6 are capable of regenerating optical signals, also called regenerator nodes $R1$ and $R2$ respectively. The rest of the nodes are

called regular nodes which can't regenerate the optical signal even if it is required. Each node in the network is connected by optical fibers that can handle a fixed number of wavelengths. The problem is to establish a translucent lightpath from S to D, if possible, through the intermediate nodes 2, 3, 4, 5, and 6 such that the following statements hold true.

- The optical reach and the given QoT threshold must not be violated at any intermediate node from S to D.

- The lightpath from S to D must not violate the property of the translucent lightpath (cyclic constraint) as described in the section 2.3.5.

- The lightpath from S to D must use the minimum number of regenerators.

- The lightpath from S to D must not affect the feasibility of existing lightpaths in the network.

3.3 A* Algorithm

A* algorithm [62] is a greedy search algorithm which is usually used for finding a path from a source to a goal. One of the A* search strategies is to minimize the cost of the path. The cost computing function is represented by the following equation:

$$f(n) = g(n) + h(n)$$

In this function, $g(n)$ represents the path cost from the start node to node n, $h(n)$ represents the estimated cost of the cheapest path from n to the goal. The function $f(n)$, the sum of $g(n)$ and $h(n)$, represents the total cost of the

cheapest path passing through node n. The cheapest path is not discovered until the A* algorithm terminates. If the heuristic function $h(n)$ never overestimates the cost to the destination, it is said to be admissible. If $h(n)$ is admissible, then $f(n)$ always produces the best actual cost which finally gives the optimal solution.

3.4 List Coloring Algorithm

Given a graph $G(V, E)$ and given a list of colors $L(V)$ for each vertex V, list coloring algorithm assigns every vertex a color from the list $L(V)$ such that no two adjacent vertices are assigned the same color [63]. Suppose there are two vertices 1 and 2 as shown in Fig 3.2.
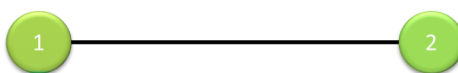
Figure 3.2: Two vertices with a list of colors

Let a list of colors $[0, 1, 2, 3]$ be available at the vertex 1 and a list of colors $[1, 2, 3]$ be available at the vertex 2. If the vertex 1 is assigned a color 1 from its own list, the vertex 2 must not be assigned the same color; instead it should have either the color 2 or the color 3 from the list of colors at vertex 2.

3.5 Description of the New Heuristic

In this section, we present a new dynamic IA-RWA heuristic algorithm. Our new heuristic is for finding a path between a given source and a destination in a given network without violating any constraint that has been imposed to meet the requirements of a valid path. This new heuristic is referred to as *findPath*. We evaluate the cost of the node along the path according to the A*

algorithm. The current node is a node along the route, which would possibly lead towards the destination. In our algorithm, the actual cost represents the number of regenerators required to reach the current node from the source node and the heuristic cost is an estimate of the minimum number of regenerators required to reach the destination from the current node. The sum of the actual cost and the heuristic cost is the total cost. We use Dijkstra's algorithm [45] to compute the shortest distances from a node to all nodes in a network. The heuristic cost which is the shortest distance from the current node to the destination divided by the optical reach, is always less than or equal to the actual cost. Our algorithm never overestimates the cost of reaching the goal. Our algorithm is therefore an admissible heuristic and provides an optimal solution, if it exists.

After computing the cost, we also compute the QoT value at each node and compare it with the threshold of the QoT due to adjacent channel and same channel interference as we search for a path. We also check whether there is a cycle on the path from the source node to the current node. If a cycle is found along the path, wavelengths on the segments are assigned using the list coloring algorithm (refer section 3.4). A flowchart of our proposed heuristic is shown in Figure.3.3.
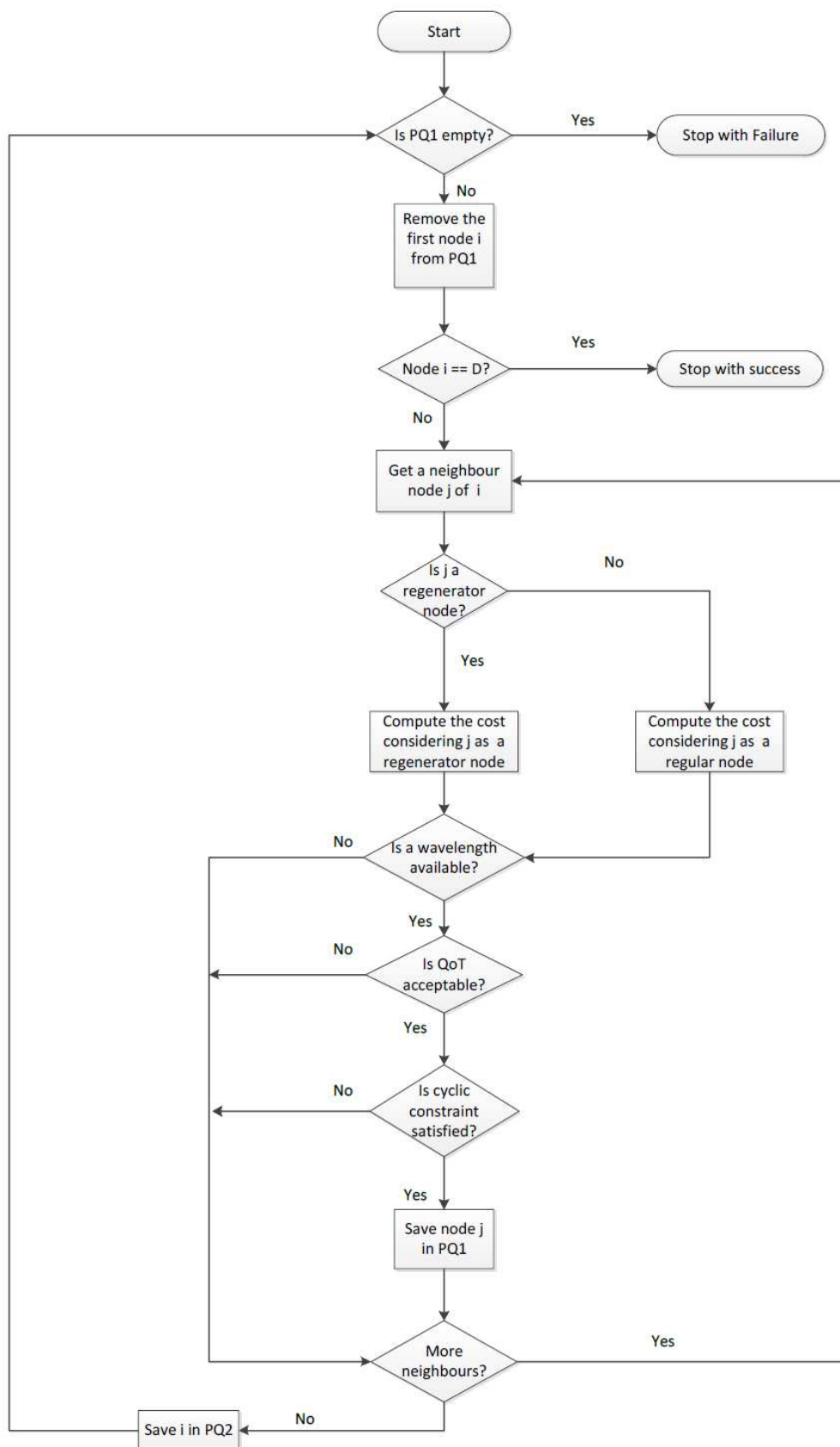
Figure 3.3: Flowchart of findPath algorithm

Our algorithm takes several parameters as input to compute a "good" path between a given source and destination pair. The important parameters are as follows:

- A physical topology of a network,

- A source node S,

- A destination node D,

- A Priority Queue $PQ1$ initially containing the source node S,

- An empty Priority Queue $PQ2$ to store evaluated nodes,

- A fixed set of wavelengths,

- A database of existing lightpaths.

As shown in Figure 3.3, our algorithm starts exploring a lightpath from the source node which is initially placed in $PQ1$. The $PQ1$ is a priority queue that maintains a queue of nodes to be traversed. One complete iteration of our algorithm is described below (steps 1 to 10).

1. We always remove the first node from $PQ1$ which is sorted in ascending order. The first node in the $PQ1$ is considered as the current node. Each node in the $PQ1$ contains the following pieces of information.

    - A node number

    - Node type i.e. if it is a regenerator node or a regular node

- Actual cost, determined by the number of regenerators used so far

- Heuristic cost, determined by the estimated number of regenerator to reach goal

- Distance from last regenerator, set to zero at the source node or regenerator node

- Parent information i.e. which node is the parent of the current node?

- A channel list c_1, carries a list of wavelengths that can be used to reach the current node from the source node. All the wavelengths are available at the source node.

- A channel list c_2, carries a list of wavelengths that can be used to reach the destination from the current node. All the wavelengths are available at the source node and at each regenerator node.

- An adjacent channel list ac_1 which contains a list of the QoT values due to adjacent channel for each wavelength to reach the current node.

- An adjacent channel list ac_2 which contains the same information as the adjacent channel list ac_1 except it is initialized to zero at each regenerator node.

2. If the current node is not the destination, we expand it, meaning that each node adjacent to the current node is evaluated. The process of expanding a node is illustrated below using the Figure 3.4.
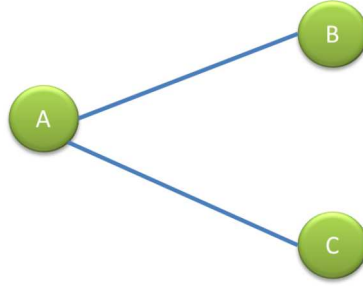
Figure 3.4: Node A with two adjacent nodes B and C

We consider a situation where we need to expand a node A which has two adjacent nodes B and C. We interchangeably use the terms adjacent node and neighbor node. The cost for each neighbor node is computed using the heuristic function given below. The value of the parameters such as the actual cost, the heuristic cost, the distance from last regenerator varies according to the type of the adjacent node (regular or regenerator node). If adjacent node B is a regular node, the distance from the last regenerator is d_1, the distance between A and B is d_2, the distance from destination is d_3, then the parameters at B can be computed by the equations (3.1), (3.2) and (3.3).

$$heuristic\ cost\ at\ B = (d_1 + d_2 + d_3)/optical\ reach \qquad (3.1)$$

$$distance\ from\ last\ regenerator\ at\ B = (d_1 + d_2)/optical\ reach \qquad (3.2)$$

$$actual\ cost\ at\ B = actual\ cost\ at\ A \qquad (3.3)$$

The distance from destination (d_3) is the estimated distance from the node B to the destination, which we compute using Dijkstra's algorithm.

3. We check whether at least one wavelength is available on the edge $A{\rightarrow}B$. A wavelength is available on the edge $A{\rightarrow}B$ only when it is available at the channel list c_2 and it is not used by any existing lightpath using the edge $A{\rightarrow}B$. If there is more than one wavelength available on the edge $A{\rightarrow}B$, the first wavelength is usually selected for the new connection. Since node B is a regular node, both the channel list c_1 and the channel list c_2 contains the same information. The QoT value due to adjacent channels corresponding to each wavelength available on the edge $A{\rightarrow}B$ is computed by taking into account 1.25 units for each first adjacent channel and 1.0 unit for each second adjacent channel. The sum of the QoT value at the node A and the computed QoT value at node B is stored in the adjacent channel list ac_1 and the adjacent channel list ac_1 at node B. Both the adjacent channel list ac_1 and the adjacent channel list ac_2 contain the same information at a regular node. If B is a regeneration node, the channel list c_2 is set to have all the wavelengths available and the adjacent channel list ac_2 is initialized to zero. There must be at least one channel available on the edge $A{\rightarrow}B$, which does not exceed the given threshold of the QoT.

4. Since the most of the linear impairments vary according to the length of the fibers, they are taken into account by computing the sum of distance from last regenerator and distance between A and B. If the computed distance is greater than the optical reach, the node B violates the constraint imposed by the linear impairments. Hence, the current node is abandoned and the other adjacent nodes are processed.

5. The QoT value due to the intrachannel crosstalk is computed by adding up the QoT value at each node from the current node to the regenerator node. The computed value must not exceed the given threshold of the QoT.

6. The QoT value of the existing lightpaths due to adjacent channels and

intrachannel crosstalk is updated. The new QoT values of the existing lightpaths must not exceed the given QoT threshold, otherwise it will cause the severe impairments to the data communication.

7. We check if there is a cycle to reach the node B from the source. This is done by checking whether the edge $A{\to}B$ is shared by all the previous segments along the path from the source to the node B. If the edge $A{\to}B$ is shared by any previous segment, we use the list coloring algorithm to assign different wavelengths to the segments which share the edge $A{\to}B$ as described in section 2.6. If any one condition from steps 3 to 7 violates the requirement, it is immediately abandoned and we start processing the next neighbor node.

8. If all the conditions from steps 3 to 7 are satisfied, the node B is inserted into priority queue $PQ1$, indicating that the node B could lead towards the goal if it has the lowest cost compared to its siblings.

9. If B is a regenerator node, it is not only evaluated as a regular node but as a regenerator node as well. The parameters at the node B are computed by the equations (3.4), (3.5) and (3.6).

$$heuristic\ cost\ at\ B = d_3/optical\ reach \tag{3.4}$$

$$distance\ from\ last\ regenerator\ at\ B = 0 \tag{3.5}$$

$$actual\ cost\ at\ B = actual\ cost\ at\ A + 1 \tag{3.6}$$

The steps from 3 to 8 are repeated for the node B again; as a result of which, a copy of node B as a regenerator node is also stored in $PQ1$. In another words, if the node B is a regenerator node, there are two copies of

it in $PQ1$ (one as a regular node and another as a regenerator node).

10. All the neighbor nodes are processed and at the end of the expanding process, the node A is stored into priority queue $PQ2$, which keeps record of the evaluated nodes.

Then, we again start the process by removing the first node from $PQ1$. This process continues until the destination is found or the $PQ1$ is finally empty. In either case, our algorithm terminates. If the destination is found, it terminates with success otherwise it terminates with failure. In another words, the lightpath is *blocked*.

Since our algorithm is based on the A* algorithm, the complexity of our algorithm depends on the heuristic function. For A* algorithm, in the worst case, the search space is exponential in the length of the solution [64]. The A* algorithm is polynomial if the following conditions are satisfied.

- The search space is a tree,

- There is single goal state,

- The heuristic function satisfies the condition of sub-exponential growth, which is a $|h(n) - h * (n)| \leq O(log\ h * (n))$, where $h * (n)$ is the true cost of getting from n to the goal [64].

Our algorithm satisfies all these conditions, it is therefore polynomial.

3.6 An Example With a 5-Nodes Network

Let's consider a network as shown in Figure 3.5 to illustrate how a new lightpath is established. Each edge has the unique identifier, which is assigned as follows:

Edge #	Node #	Node #
0	0	1
1	1	2
2	2	3
3	2	4
4	3	1

Each link in the network can support three channels λ_0, λ_1 and λ_2. We assume that there are two existing lightpaths L_1 and L_2 as shown in Table 3.1. Rows and columns in the table represent wavelengths and edges respectively and the value in the cell represents the lightpaths. A channel and a link corresponding to the negative value in the cell are available for the new lightpaths.

Table 3.1: Details of channels and links

Edges → Channels ↓	0	1	2	3	4
λ_0	L_1	L_1	-1	-1	-1
λ_1	-1	-1	L_2	-1	-1
λ_2	-1	-1	-1	-1	-1

We notice, from Table 1, that lightpath L_1 utilizes the edges 0 and 1 along with a channel λ_0 and the lightpath L_2 utilizes the edge 2 and the channel

λ_1. Suppose a connection from the node 0 to the node 4 is to be established. We start by finding a path between 0 and 4 from expanding the node 0. Let 1500 km be the optical reach, the node 3 be the regenerator node and the QoT threshold due to adjacent channels and the same channels is 5 units.
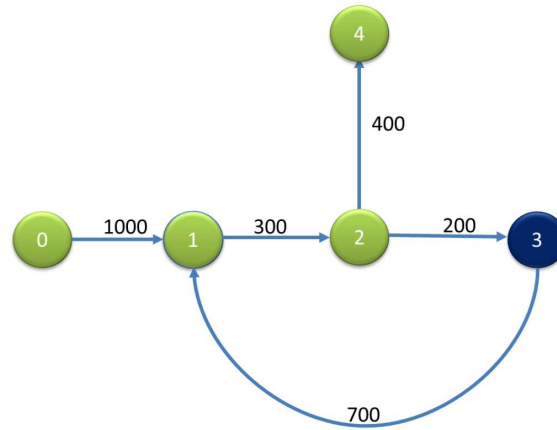
Figure 3.5: A typical network diagram

Before we start our *findPath* algorithm, we update the information at the source node 0 as follows:

$node\# = 0$

$nodet\ type = 0$

$actual\ cost = 0$

$heuristic\ cost = 1$

$distance\ from\ last\ regenerator = 0$

$parent \rightarrow NULL$

$channel\ list\ c_1 : [1\,,1\,,1]$

$channel\ list\ c_2 : [1\,,1\,,1]$

adjacent channel list ac_1 : $[0.0\,,0.0\,,0.0]$

adjacent channel list ac_2 : $[0.0\,,0.0\,,0.0]$

If a node type is 0 (1), it represents a regular node (regenerator node). For the channel list c_1 and channel list c_2, 1 represents the wavelength is available and 0 represents the wavelength has been used. After updating the information at the source node, let us call it n_0 and place in the $PQ1$ as shown below.

$PQ1$: n_0

Now we start exploring the path.

Expand the node 0

The first node n_0 is taken out of $PQ1$ and expanded. The node 0 has one neighbor node which is node 1. The following information at node 1 is updated.

node# $= 1$

nodet type $= 0$

actual cost $= 0$

heuristic cost $= 1$

distance from last regenerator $= 1000$

parent$\rightarrow$0

channel list c_1 : $[0\,,1\,,1]$

channel list c_2 : $[0\,,1\,,1]$

adjacent channel list ac_1 : $[0.0\,,1.25\,,1.0]$

adjacent channel list ac_2 : [0.0 , 1.25 , 1.0]

Let us call this node n_1.

The QoT values due to the existing lightpaths are shown in Table 3.2.

Table 3.2: The QoT due to the cross-connect switches

Channels → Nodes ↓	λ_0	λ_1	λ_2
0	1.25	0	0
1	1.25	0	0
2	1.25	1.25	0
3	0	1.25	0
4	0	0	0

Since the node n_1 satisfies all the conditions (steps 3 to 7) as described in section 3.3, it is inserted into $PQ1$ as shown below.

$PQ1$: n_1

$PQ2$: n_0

Expand the node 1

Node n_1 from $PQ1$ is removed and expanded because it is not the destination. Since links in Figure 3.5 are directional, only node 2 is adjacent to node 1. We update all the information at node 2. This node satisfies the conditions (steps 3 to 7), it is therefore renamed as n_2 and inserted into $PQ1$.

$PQ1$: n_2

$PQ2$: $n_{1,}n_0$

$PQ1$ is sorted in ascending order as soon as all the neighbor nodes are processed, so that the least cost node is selected in next iteration.

Expand the node 2

Node n_2 is the least cost node, so it is removed from $PQ1$ for expansion. It has two neighbors 3 and 4 but the neighbor 4 is unreachable from 0 because it exceeds the optical reach. Hence, only the node 3 is processed for the path. The node 3 is a regenerator node, so it is expanded as a regular and as well as a regenerator node. Let n_{31} and n_{32} be two types (regular and regenerator) of node 3 and the both nodes satisfy the requirements. They are inserted into $PQ1$ as follows:

$PQ1$: n_{32}, n_{31}

$PQ2$: $n_2, n_{1,}n_0$

Expand the node 3

Similarly, the node n_{32} is expanded. Since the node 1 comes across second time along the path, let us call it n_1'.

$PQ1$: n_1', n_{31}

$PQ2$: n_{32}, n_2, n_1, n_0

Expand the node 1

$PQ1$: n_2', n_{31}

$PQ2$: $n_1', n_{32}, n_2, n_1, n_0$

When we expand node 2 second time, we find a cycle $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 1 \rightarrow 2$, in which the edge $1 \rightarrow 2$ is used twice. Since the channel λ_0 is already

used by lightpath L$_1$ and the channel λ_1 is used by L_2. The segment along this path would use some other channels determined by list coloring algorithm. In this case, the channel λ_2 is assigned on the segment $0 \rightarrow 1 \rightarrow 2 \rightarrow 3$ and the channel λ_1 is assigned on the segment $3 \rightarrow 1 \rightarrow 2 \rightarrow 4$ avoiding the same wavelength on both segments.

Expand the node 2

$PQ1$: $n_4, n'_{32}, n'_{31}, n_{31}$

$PQ2$: $n'_2, n'_1, n_{32}, n_2, n_1, n_0$

The destination 4 is found while checking the node 4 removed from the $PQ1$. Once the destination is found, we back track the path from the destination and record the edges and wavelength(s). If the current lightpath number is $L3$, the Table 3.1 is updated as below.

Table 3.3: Updated details of channels and links

Edges $\rightarrow$ Channels $\downarrow$	0	1	2	3	4
λ_0	L_1	L_1	-1	-1	-1
λ_1	-1	L_3	L_2	L_3	L_3
λ_2	L_3	L_3	L_3	-1	-1

3.7 Simulation

In order to carry out experiment and analyze the result, we have developed a simulator which executes our algorithm *findPath* and outputs the blocking probability for the given input. Our simulator handles a list of communication

requests and maintains the network status up to date. It takes the following inputs:

- A given network topology $G(V, E)$,

- The optical reach **r**,

- An event list L of source and destination pairs along with the start time and the duration of requests,

- The locations of the regenerators (we use an existing program developed by Mr. Quazi Rahman to find the location of the regenerator),

- Maximum allowable QoT value.

The event list L is generated by the event List Generator, developed by Mr. Quazi Rahman, to carry out the simulation. It takes a physical topology of the translucent network which needs to be simulated and the total time for which the simulation is to be carried out. In the event list, event start time, event stop time, source and destination pair are generated randomly.

The event list L contains information about the requests for communication such as event number, event type (establish or terminate a connection), time when communication starts, source and destination. An example for an event list is illustrated in Table 3.1.

Table 3.4: An example of event list

Event Number	Time	Event Type	Source	Destination
0	5	1	0	4
0	115	0	0	4
1	10	1	0	2
1	125	0	0	2
2	15	1	0	1
2	75	0	0	1
3	25	1	1	3
3	25	1	1	3
4	86	1	0	4
4	86	1	0	4

Event Number: It represents a unique sequential number of the event. Both new communication request and the termination request carry the same event number.

Event Type: **1** means a new request to serve a connection for communication whereas **0** means a request to terminate an existing path.

Time: Time corresponding to Event Type 1(0) means starting (terminating) a request.

Source: The node at which a communication request originates.

Destination: The node at which a termination request terminates.

The simulator takes communication requests from the event list and handles each request sequentially. If the event type is 1, a path between source and destination pair using findPath is searched. If a path and a channel number

is found for a request, the lightpath is established and the network state information is updated using an algorithm *createConnection*. The *createConnection* algorithm is given below.

Algorithm: *createConnection*

Input: network topology, Lightpath number, a 2-dimension list which contains the channel(s) and the link(s) associated with the lightpath number, a list of regenerators by a lightpath

Output: creates a lightpath and updates the network state information

Begin:

1. Assign the wavelengths to each segment on the route

2. Update the network state information

End:

The number of successful lightpaths is counted to evaluate the network performance. If a path is not found, the simulator counts it as a blocked path. If an event type is 0, the corresponding lightpath is deleted and resources used by it are released, making them available to serve other requests for communication. This is done by the algorithm *deleteConnection* which is given below.

Algorithm:	*deleteConnection*
Input:	network topology, lightpath number, a double dimension list which contains channel(s) and link(s) associated with the lightpath number, a list of regenerators by a lightpath
Output:	Release the wavelengths used for a path and updates network state information
Begin	

1. Free each wavelength assigned to each segment on the route

2. Update the network state information

End

The algorithms createConnection and deleteConnection work in conjunction with our Simulator algorithm. The *Simulator* algorithm is given as follows:

Algorithm: *Simulator*

Input: *A* given network topology $G(V, E)$, the optical reach r,

An event list L, locations of the regenerators,

maximum allowable QoT value

Output: Finds blocking probability

Begin

For each communication request

{

  IF the event type is 1 THEN

    1. Get the source destination pair from the event list

    2. Find the path using *findPath* algorithm

    IF the path is found THEN

       a. Call *createConnection*

       b. Increase the successful path number

    ELSE

       Mark it as an unsuccessful path

    ENDIF

  ELSE

   Call *deleteConnection*

  ENDIF

}

End

Chapter 4

ANALYSIS OF RESULTS

In this chapter, we present the experimental results to evaluate the performance of our proposed algorithm. We analyze the results and study the variation of the blocking probability in different scenarios. The experiment is performed on three networks - the 14-node NSF network, 21-node ARPA network and 24-node USA network as shown in Figure 4.1, Figure 4.2 and Figure 4.3 respectively. The NSF network is taken from [65], where the link distances vary from 300 km to 2800 km. The link distances in the ARPA network and the USA network are shorter, as given in [66].
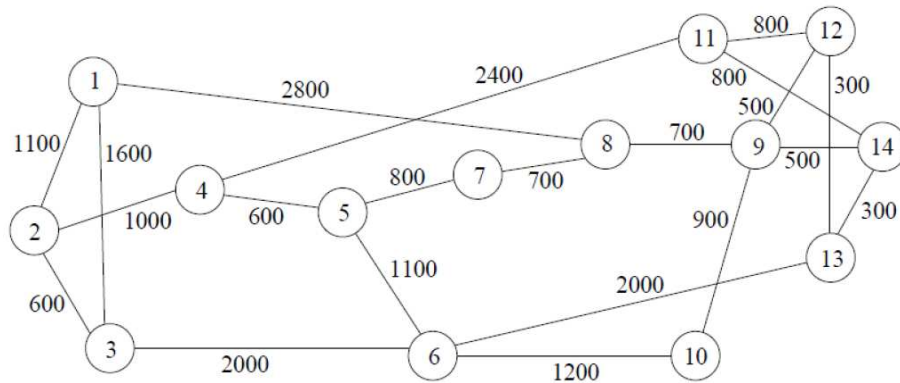

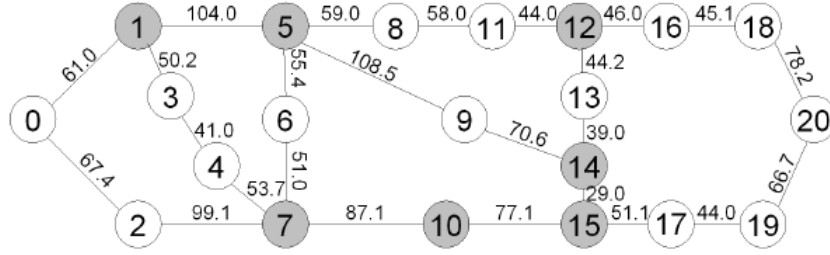Figure 4.1: 14-Node NSF network topology

Figure 4.2: 21-Node ARPA network topology
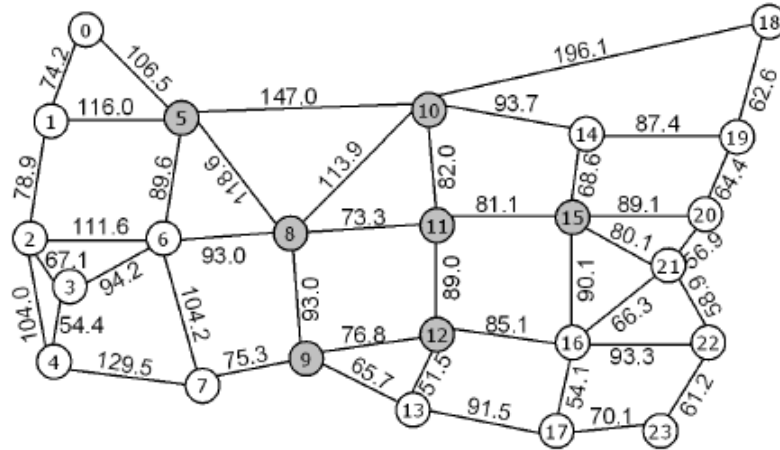
Figure 4.3: 24-Node USA network topology

Before we run our experiment, we determine the location of the regenerators in the networks, which varies according to the optical reach. For each topology, the minimum value for the optical reach is always selected to be greater than the longest link distance. This ensures that no physical link in the topology becomes unusable. Also, the value of the optical reach should not be so high that there is no need for regeneration at all, which will result in a transparent network. Based on these criteria, the values of optical reach used in our simulations are specified in Table 4.1, for each topology.

Table 4.1: Location of regenerators

NSF network		ARPA network		USA network	
Optical reach	Regn node #	Optical reach	Regn node #	Optical reach	Regn node #
3000	0, 7	110	0, 2, 7, 10, 11, 13, 16	200	6, 11, 20
3500	6	160	4, 10, 13, 17	300	8, 11
4000	3	210	5, 12	400	8
4500	3	260	5, 10	500	3

In order to conduct our experiments, we have randomly generated a number of connection requests for the above mentioned networks with varying traffic loads as shown in Table 4.2. The traffic load is expressed in Erlangs, which represents the density of the network traffic in a fixed duration of time. The Erlang is computed by the following formula [9]:

$$Erlang = \frac{\sum \lambda_i}{\tau}$$

In this formula, τ is the maximum duration of time and λ_i is the duration of each call (event) i. The value of λ_i is defined by a *start time* and an *end time*. Start time represents the time when an event starts and the end time represents the time when an event ends. If the end time is smaller than τ, then λ_i is randomly generated. Otherwise, λ_i is computed by the following formula:

$$\lambda_i = \tau - start\ time$$

In our experiments, we are defining the duration of time by the number of iter-

ations that our algorithm runs. For our experiment, the total number of iterations are 500. For example, if τ is 60 minutes, the number of calls is 30, each call has an average duration of 5 minutes, then the traffic load in one hour is $150/60 = 2.5\ Erlangs.$

Table 4.2: Number of requests vs. Erlangs

Traffic load (Erlangs)	10	20	30	40	50
No. of requests in NSF network	104	222	333	410	534
No. of requests in ARPA network	103	210	318	446	507
No. of requests in USA network	103	220	330	427	541

4.1 The Effect of the QoT

In this section, we study how the nonlinear impairments affect dynamic lightpath allocation. Figure 4.4 shows the variation of the blocking probability with different loads, as the QoT value changes, for the NSF network topology with optical reach of 3000 km, 16 wavelengths per fiber, and 999 regenerators (i.e. no constraints on the number of regenerators per site) available at each regenerator site. The QoT threshold values represent the amount of non-linear interference that can be tolerated by each lightpath. We observe that as the QoT threshold increases, i.e. the impact of non-linear impairments is reduced, the blocking probability decreases. This is because it is possible that a lightpath which would be blocked at a lower QoT threshold can be allocated at higher threshold. If the QoT threshold increases beyond some specific limit, the effect on the blocking probability is negligible. This is because for high QoT threshold values, lightpaths are blocked primarily due to unavailability of wavelengths. Therefore, further increasing the QoT threshold, without changing the number of available channels per fiber will not reduce the blocking probability.
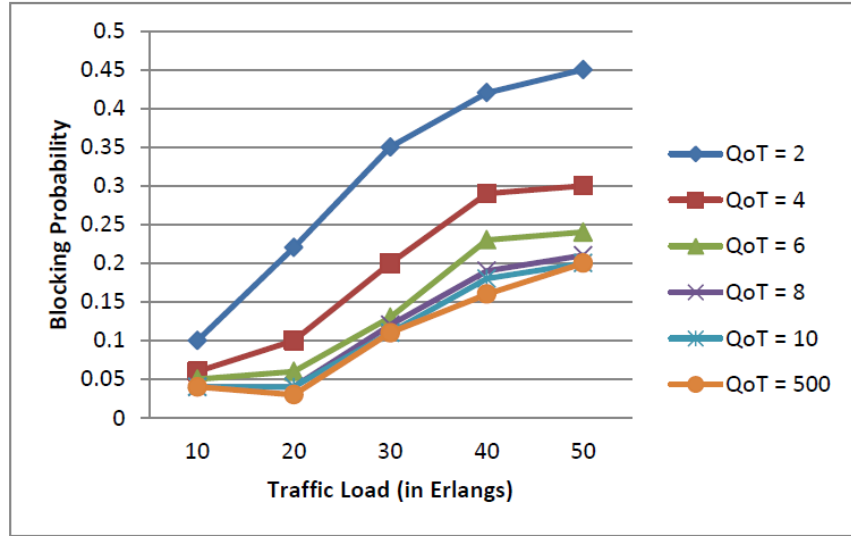
Figure 4.4: Blocking probability v/s traffic load for NSF network when the QoT value varies.

4.2 The Effect of the Optical Reach

In this section, we study the effect of the optical reach on the blocking probability. Figures 4.5, 4.6 and 4.7 show the results for the NSF network, ARPA network and USA network topologies respectively. For these experiments, we used 16 channels per fiber, the QoT value of 2, and 999 regenerators per node. For all three topologies the blocking probability increases with load, as expected. For a given QoT value, the lower the impact of linear impairments, the higher the values of optical reach that can be used. So, we expect that for higher values of optical reach (indicating lower level of linear impairments) the blocking probability will decrease. However, that is not always the case. For example in Figure 4.5, the blocking probability decreases as the optical reach (r) is increased from 3500 km to 4500 km, but the blocking probability for $r = 3000$ km, is actually lower than that for $r = 3500$ km. At first this appears anomalous. However, we note that for $r = 3000$ km, there are two regenerator sites, as opposed to only one site for $r = 3500$ km. This increase in regenerator availability helps reduce the blocking probability; even though the impact of impairments is higher. So, it is apparent

that the locations and number of regenerator sites can have a significant effect on the overall blocking probability. In order to eliminate the effect of regenerator availability, we conducted the above experiments with fixed regenerator sites (based on the regenerator placement for r = 3000 km in Table 4.1), for all values of optical reach. The corresponding results for the NSF network topology are shown in Figure 4.8. We note that in this case the blocking probability for $r = 3500$ km is lower than that for $r = 3000$ km, and the blocking probability decreases consistently with increasing optical reach, as expected.
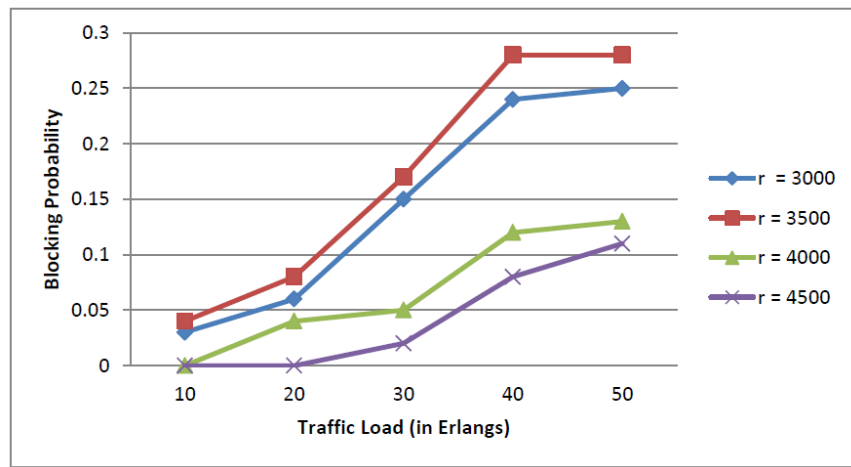

Figure 4.5: Blocking probability v/s traffic load for NSF network
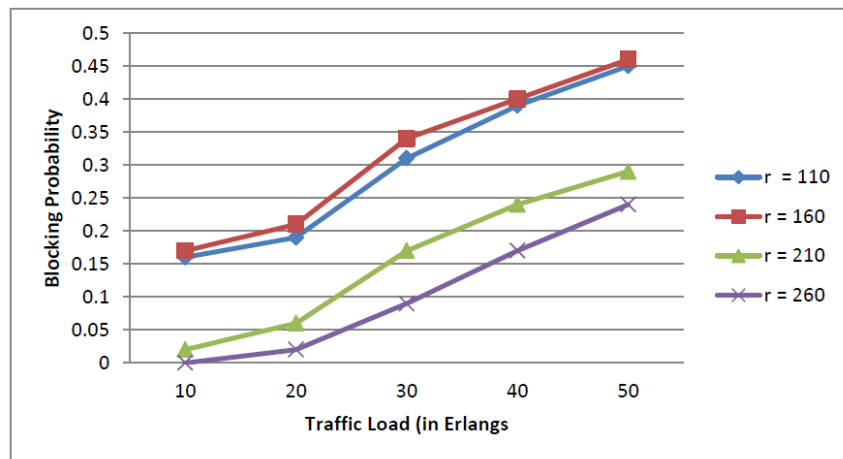

Figure 4.6: Blocking probability v/s traffic load for ARPA network

Figure 4.7: Blocking probability v/s traffic load for USA network

Figure 4.8: Blocking probability v/s traffic load for NSF network when the location of regenerators is fixed

4.3 The Effect of Number of Channels per Fiber

In this section, we study the effect of the number of channels that a fiber can support on the blocking probability in different networks. Figure 4.9 shows the results for the NSF network topology, with $r = 3000$ km, a QoT value of 2 and 999 regenerators per site. We observe that the blocking probability decreases significantly, as the number of channels is increased. This is due to two factors, as follows:

- With more available channels, lightpaths with common links/nodes can be spaced farther apart, resulting in lower interference from non-linear impairments. This reduces blocking due to QoT issues.

- Since more channels are available, wavelength blocking due to unavailability of channels is reduced.

Figure 4.9: Blocking probability v/s traffic load for NSF network

The results for ARPANET and USA network topologies follow a similar pattern and are shown in Figures 4.10 and 4.11 respectively.

Figure 4.10: Blocking probability v/s traffic load for ARPA network
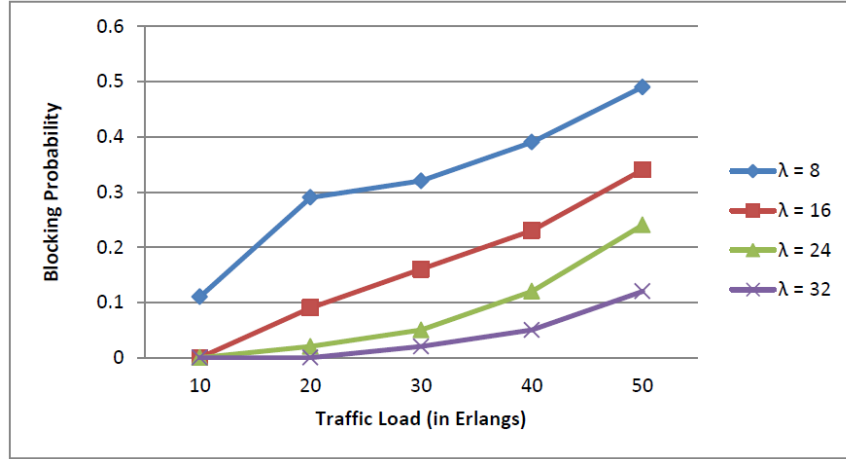
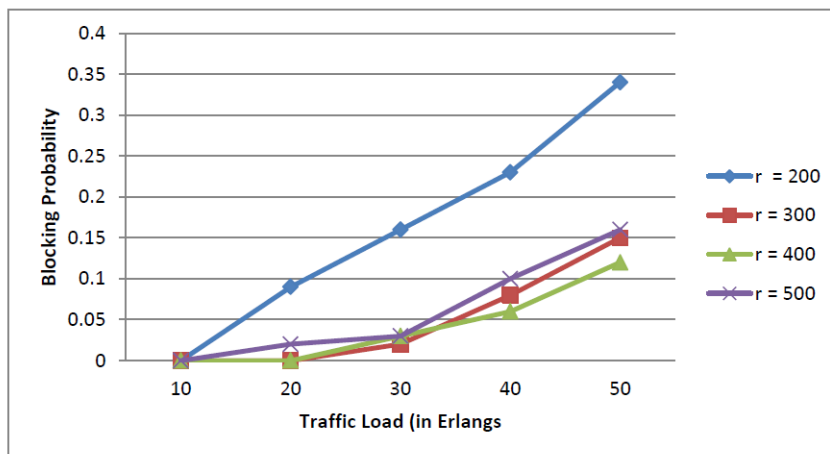Figure 4.11: Blocking probability v/s traffic load for USA network

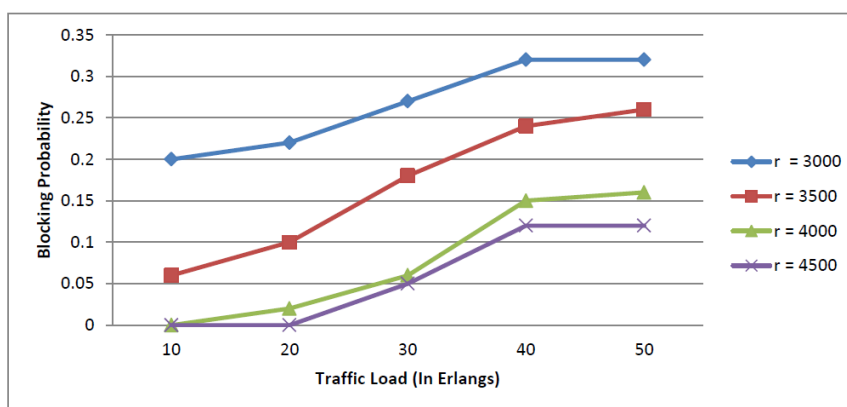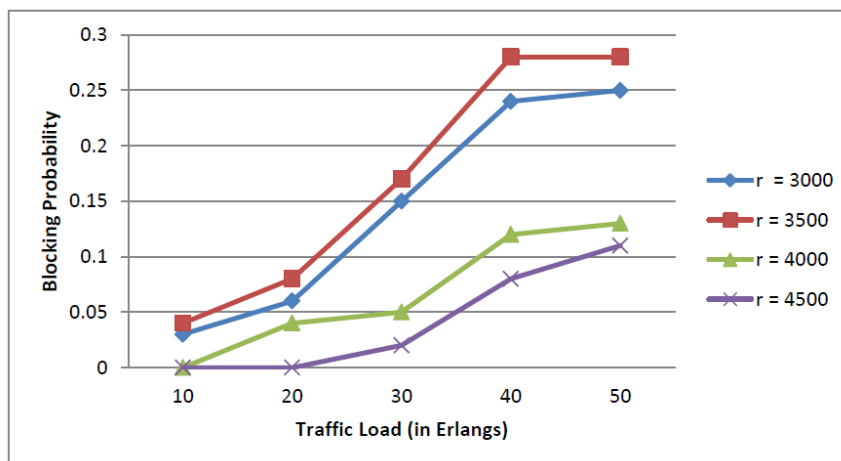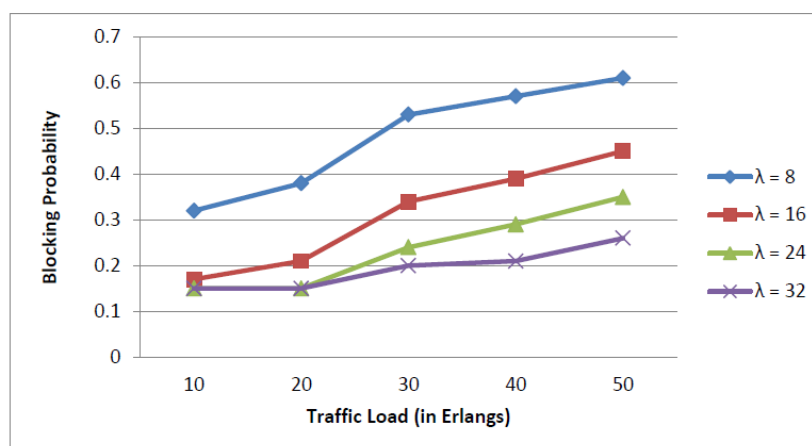## 4.4 The Effect of Regenerator Availability

In this section, we have reported the results of our experiments on the variation of the blocking probability with the number of available regenerators at the specified locations. The results for the NSF network, with 16 channels per fiber, $r = 3500$ km and a QoT threshold of 4, is shown in Figure 4.12. Initially, the blocking probability decreases as the numbers of regenerators per node increases while other network parameters remain the same. However, if the number of regenerators per node increases beyond a certain value, there are no increased benefits. This is because when the number of regenerators is sufficiently large, all the connections blocked due to impairments can be established. The remaining blocked connections are due to wavelength unavailability, and are not affected by any increase in the number of regenerators. Based on Figure 4.12, we note that a relatively small number of regenerators per node may be sufficient in most cases.
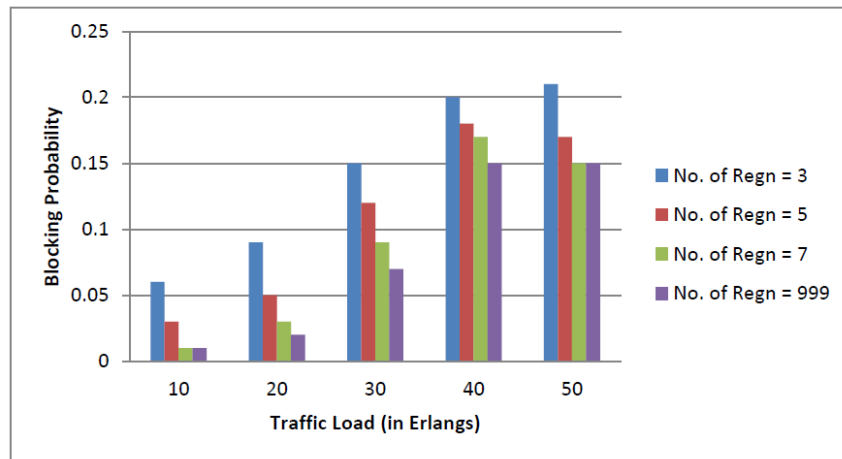
Figure 4.12: Blocking probability v/s traffic load for NSF network when the number of regenerators per node varies.

4.5 The Effect of Cycles

We have observed that the blocking probability is also affected due to the formation of a cycle in the path from a source to a destination. For the USA network, we have found seven lightpaths with cycles (out of 534) while running the experiment with load of 50 Erlangs. The RWA for these lightpaths would have been incorrect if this situation was not considered.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The objective of this thesis is to develop an impairment aware RWA algorithm for finding a valid route from a source to a destination and study the effect of impairments in different scenarios. An important constraint called "lightpath segments overlap", described by the authors of [30], has not been considered by the existing *impairment aware algorithms* for dynamic lightpath allocation. An example in section 2.3 shows that there may exist cycles in the path from a source to a destination, where the cycle includes a regenerator. If this happens, the existing algorithms may give invalid solutions. We have implemented A^* algorithm using an admissible heuristic for impairment aware dynamic lightpath allocation and shown that our algorithm can satisfactorily handle the constraint mentioned above using list coloring algorithm.

We have conducted simulation experiments on several realistic network topologies with different network parameters such as the traffic load, number of channels per fiber, the optical reach, the number of regenerators per node, and

the QoT threshold. The experimental results show that there is a significant reduction in the blocking probability when the effect of nonlinear impairments is compensated using regenerator. We observed the variation on blocking probability due to change in the value of a network parameter while keeping the values of other parameters the same. In all cases, the sparsely placed regenerators in the network have compensated the impairments, increasing the network performance.

5.2 Future Works

Our heuristic allocates the lightpaths considering the optical reach as a parameter to take into account the linear impairments. Our model of computing the nonlinear impairments is simply the count of adjacent channels and the intrachannel crosstalk along the path. We compute the linear and nonlinear impairments separately. This type of consideration gives us an approximate impact of the impairments. In order to compute the impact of the impairments with more accuracy, it is possible to design a QoT tool that considers the nonlinear impairments and the linear impairments simultaneously. The implementation of such a tool in our algorithm may increase its performance. We use a regenerator placement scheme developed by Mr. Quazi Rahman, which determines the location of the regenerators in the network, based on the optical reach. Hence, it is also possible to improve the proposed algorithm by using a new regenerator placement scheme that takes into account both linear and nonlinear impairments while determining the location of regenerators in the network.

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