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IMPAIRMENT AWARE DYNAMIC ROUTING AND WAVELENGTH ASSIGNMENT IN WDM NETWORKS

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By

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ABSTRACT

Optical networks play a major role in supporting the traffic in backbone computer networks. Routing and Wavelength Assignment (RWA) is the technique used to establish a light-path from a source node to a destination node in a Wavelength Division Multiplexed (WDM) optical network. As an optical signal propagates through the network, the quality of the signal degrades due to physical layer impairments. To address this problem, in translucent WDM networks, the signal is regenerated at intervals. The main objective of this research is to propose a fast heuristic for dynamic lightpath allocation in translucent WDM networks and to compare the heuristic with an optimal algorithm that was proposed recently.

DEDICATION

To my loving MOM and DAD

Shantha Surya

Shyam Sunder Surya

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Suchet Krishna Surya

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LIST OF ACRONYMS

OEO	OPTICAL ELECTRONIC OPTICAL
RWA	ROUTING AND WAVELENGTH ASSIGNMENT
WDM	WAVELENGTH DIVISION MULTIPLEXING
QoT	QUALITY OF TRANSMISSION
PLI	PHYSICAL LAYER IMPAIRMENT
SLE	STATIC LIGHTPATH ESTABLISHMENT
DLE	DYNAMIC LIGHTPATH ESTABLISHMENT
RPP	REGENERATOR PLACEMENT PROBLEM
RRP	ROUTING AND REGENERATOR PROBLEM
PMD	POLARIZATION MODE DISPERSION
ASE	AMPLIFIER SPONTANEOUS EMISSION
CD	CHROMATIC DISPERSION
FWM	FOUR WAVE MIXING
BFS	BEST FIRST SEARCH
ILP	INTEGER LINEAR PROGRAM

CHAPTER 1

1 INTRODUCTION

1.1 Overview of Optical Networks

In the past 20 years, there have been many changes in the telecommunication industry. The growth in internet traffic, including high bandwidth video and voice transmissions, and the availability of inexpensive and high-speed computers has led to a tremendous increase in demands for high-speed communication [11].

Before the emergence of optical networks, the information was transmitted through the electrical cables. Optical networks transmit data in the form of light, which allows higher capacity due to its higher carrier frequency [5]. Since 1960s lot of research has been carried out on optical communication [11]. Optical fibers are immune to electromagnetic interference; they are very secure, lightweight and smaller in size. They have a low transmission loss [25] and high bandwidth compared to copper cables [5]. These features have made them attractive candidates for high capacity wide-area networks.

Wavelength division multiplexing (WDM) is a technique where multiple signals from the transmitter are combined together and are sent on single fiber to a receiver in an optical network [25]. A *lightpath* is an optical level connection between two end-nodes in an optical network. Each lightpath is characterized by a route over the network topology and a wavelength on each edge of the route [11]. The problem of finding a suitable route and wavelength(s) for each established lightpath is known as the *routing and wavelength assignment* (RWA) problem. RWA is of two kinds: static RWA and dynamic RWA [25].

In static RWA [11], all lightpath requests are known in advance at the time of network setup. In dynamic RWA [11], a lightpath has to be setup as each connection request arrives and should be taken down after a specified period of time. When a lightpath is taken down, the resources allocated for that lightpath are released and can be reused to service another lightpath request.

1.2 Translucent Networks

The first generation of optical networks was *opaque* networks where the signal undergoes optical-electronic-optical (OEO) conversion at each intermediate node. Recently, the architecture is moving from standard opaque networks to *transparent* all-optical networks. In such networks the signal is carried entirely in the optical domain, and does not undergo any opto-electronic conversion until it reaches the destination node. Due to physical layer impairments (PLIs), the quality of transmission (QoT) decreases as the signal travels over a fiber. The *optical reach* is the maximum distance an optical signal can travel before the signal quality degrades to a level that requires regeneration at a particular node. The optical reach depends on a number of factors including modulation formats, and interference from other signals, and values of 2500km -3000km have been reported in the literature [27]. Signal regeneration typically involves re-amplification, reshaping and re-timing - known collectively as *3R regeneration* [27]. Although 3R regeneration can be completely carried out in optical domain, electrical 3R regenerators are economically much more feasible; so, 3R regeneration normally implies OEO conversion as well.

The cost of signal regeneration is determined by a number of factors such as, the cost and number of regenerators required, power consumption, increased heat dissipation and additional space requirements. Translucent networks were introduced to address the problem of signal degradation in transparent networks and high cost of opaque networks. In translucent networks 3R regenerators are scattered in a network, such that only some node will have the 3R regenerators instead of all the nodes. With this the cost will be reduced as the signal is maintained in the optical domain for longer time and OEO conversion is eliminated at every node [27]. This thesis mainly focuses on translucent networks.

1.3 MOTIVATION

In Wavelength Division Multiplexing (WDM) networks, lightpaths are established from a source node to a destination node through the multiple fiber links. Given a set of lightpath requests and the constraint on the number of wavelengths, routing and wavelength assignment must be done intelligently, in order to achieve lower lightpath blocking probability. RWA is known to be a difficult problem even for transparent optical networks [25]. Taking the effect of physical layer impairments into consideration makes the problem even more intractable. For the dynamic RWA case, the routing and wavelength assignment decisions for each connection request must be determined in real time. Based on the complexity of the problem, it is not feasible to generate optimal solutions within the required time frame. Therefore, it is extremely important to develop fast and efficient algorithms that can be used to establish lightpaths quickly, while still maintaining an acceptable blocking probability.

The main objective of this thesis is to propose a fast heuristic for dynamic lightpath establishment (DLE) in translucent optical networks, considering physical layer impairments. There are two main problems associated with RWA in translucent optical networks. These are briefly outlined below.

1.3.1 Regenerator Placement Problem (RPP):

In a translucent network where dynamic PLI-RWA is used, before the network is in operation, a minimum number of nodes has to be equipped with 3R-regeneration capability, so that each node in the network can communicate with any other node, using either a transparent or a translucent lightpath. The problem of identifying such a minimum number of nodes to be designated as regenerator nodes is called the *Regenerator Placement Problem* (RPP) [27]. The RPP problem is known to be NP-complete and heuristics are often used to solve this problem [27] for relatively larger networks.

1.3.2 Routing with Regenerator Problem (RRP):

In a network with 3R regeneration capable nodes, RRP tries to route a transparent or translucent *lightpath* using a minimum number of 3R regenerators [27]. The regenerators are deployed first during RPP phase and IA-RWA is performed afterwards during RRP phase. [30]

The main objective of the thesis is to propose a fast heuristic for dynamic lightpath allocation in translucent optical networks, to be used during the RRP phase.

1.4 Solution Outline

Given a network and the optical reach, the RPP phase gives the list of 3R regeneration capable nodes for the given network. In this thesis, we have utilized the approach proposed by Rahman et al. 2015 [27], in order to complete the RPP phase. This approach finds a minimum number of nodes, where regenerators should be placed, so that it is possible to establish a feasible translucent lightpath between any two nodes.

Once the regeneration capable nodes have been determined, the next step is to compute *k* shortest paths between each node pair, such that a feasible (possibly translucent) lightpath can be established using each potential path. The existing traffic on the network is simulated by randomly designating each channel on a fiber link as 'busy' or 'available', based on a specified probability. Finally, an A* algorithm [30] is used to select a good route for each connection request, based on the current traffic. In order to validate our approach, we have run simulations on different network topologies and with different traffic conditions on each topology.

1.5 Thesis Outline

The remainder of the thesis is organized as follows. In chapter 2, we discuss about the fundamentals of the optical networks and review the relevant literature on RWA in translucent networks. In chapter 3, we proposed our "fast heuristic for dynamic lightpath allocation" and explain each step with a clear example. In chapter 4, we present and discuss the results of our simulations and in chapter 6, we present our conclusions and outline some possible directions for future work.

Chapter 2

2 Review

In this chapter we will introduce some of the fundamental concepts and basic terminology used in optical networking. We will also identify different types of physical layer impairments that lead to signal degradation and review the current literature on impairment-aware RWA (IA-RWA) techniques.

2.1 Optical Fiber

An optical fiber is a thin high quality extruded glass (Silica) cylinder, slightly thicker than the human hair [8]. Optical fibers support transmission of signals in the optical domain (in the form of light) and are capable of carrying high bandwidth data over longer distance, compared to electrical transmission [5]. An optical fiber consists of two main layers - *core* and *cladding*. The inner layer is known as core and the outer layer as cladding, as shown in Figure 2.1. The cladding has slightly lower refractive index than the core [30], which allows light to travel using total internal reflection. Optical fibers have a loss rate of 0.2 dB per kilometer in 1.55-μm waveband. Each fiber is protected by two outer layers, known as *buffer* and *jacket*.

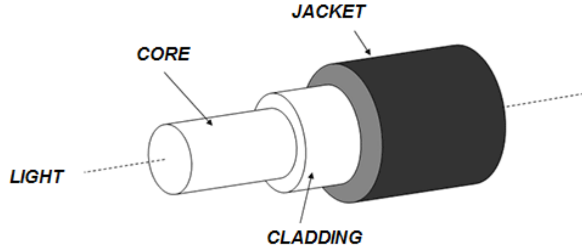

Figure 2.1: Optical Fiber

A single fiber can support transmission of multiple wavelengths (channels), which are used to send different streams of data simultaneously over the fiber. This is referred to as *wavelength division multiplexing* (WDM) [25].

2.2 Optical Networks

Based on the physical technology, three generations of networks have been developed [25]. First, a network based on copper wire or microwave radio technology. Second, a network that uses optical fibers, where the fiber simply replaces the copper because of its advantages in terms of bandwidth, signal quality and cost. But the performance of such networks is limited by the maximum speed of electronics deployed in switches and at the end nodes. Finally, all-optical networks, which carry information in the optical domain until it reaches the destination [25].

The traffic load on an optical network can be characterized in terms of a set of *demands* or connection requests, which must be routed over the network using the available resources. A demand can represent a request for a single (or multiple) lightpath(s). Alternatively, a demand can be at the *sub-wavelength* level, such that multiple demands can be combined on to a single lightpath. In the remainder of this thesis, we consider the granularity of a demand to be at the *lightpath* level, so each demands represents a request for a single lightpath to be setup.

2.2.1 WDM Networks

The encoded optical signals in the optical networks are carried by optical fibers for communication between the end-nodes. There have been lots of improvements in technology in last 20 years [30]. In order to utilize the high bandwidth (50 tera-bits per second) of an optical fiber, concurrency among transmissions is required, which can be achieved by *Wavelength Division Multiplexing* (WDM) [25]. A multiplexer (MUX) is used to combine multiple signals on different channels (wavelengths) prior to transmission. Similarly, at the receiver, a demultiplexer (DEMUX) is used to separate the combined signal into different channels [8].

2.2.2 Wavelength Conversion

WDM Networks can be classified into three categories, based on their wavelength conversion capabilities [5], as outlined below.

- **Full wavelength convertible networks:** In this type of network, every node has the capability, to convert any incoming wavelength to any other wavelength. Thus, a lightpath can be assigned a different channel on each link in its path.

- **Sparse wavelength convertible networks:** In this type of network, only some nodes have the wavelength conversion capacity. This allows some flexibility in assigning wavelengths to lightpaths, but the cost is lower compared to the previous category.

- **Wavelength continuous networks:** In this type network there are no wavelength converters available, so each lightpath must use the same wavelength along its entire path [5]. This may lead to increased blocking probability, since there is less flexibility in assigning wavelengths to lightpaths.

2.3 Routing and Wavelength Assignment

Due to technological and constraints, wavelength convertible networks are typically not feasible for current networks. In our work, we also assume that wavelength converters are not available at intermediate nodes. Therefore, when performing RWA, the following two constraints must be satisfied.

i. *Wavelength clash constraint*: Two lightpaths that traverse the same link at the same time must be assigned two different wavelengths.
ii. *Wavelength continuity constraint*: A lightpath must use the same wavelength along each link in its path.

The RWA problem has been widely researched in the last two decades and both optimal and heuristic approaches have been proposed to solve this problem. In *static* RWA, all requests known in advance [25], i.e., the demand set is known and fixed. In the *dynamic* RWA, a lightpath is set up as each connection request arrives (assuming sufficient resources are available), and released after a finite time [30].

If all connection requests are known in advance, this information can be used to determine which node requires the 3R regeneration capability [5] in translucent networks. In such cases, the regenerator placement problem and the impairment aware routing and wavelength assignment (IA-RWA) can be done parallel.

2.4 3R Regeneration

The quality of the optical signal degrades while traveling through the network. In order to restore the lost quality of the signal 3R regeneration technique can be used [27]. Figure 2.2 shows that every signal coming to a 3R regenerator is first converted from optical to electronic form (O/E) at the receiver. After the signal comes in, three operations called re-amplification, re-shaping and re-timing are performed [27]. Then at the transmitter, signal is again converted back to optical domain from electronic form (E/O) [27]. The wavelength assigned to the outgoing optical signal (C2) may or may not be the same as the incoming signal (C1). So, 3R Regenerator is also capable of performing wavelength conversion on the optical signal.

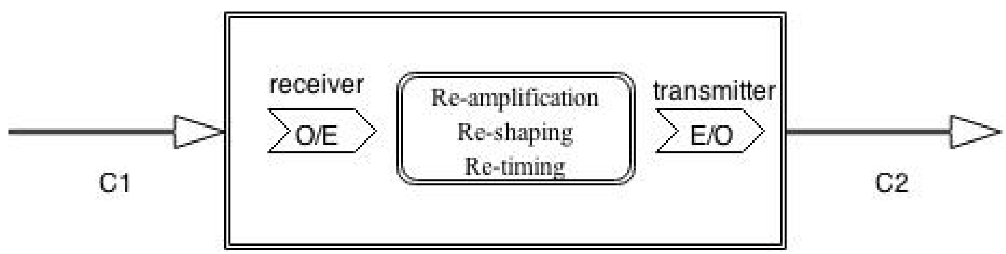

Figure 2.2: 3R Regeneration

In Figures 2.4 – 2.5, nodes which are capable of 3R regeneration are shaded in blue. Based on the availability of regenerators, 3 types of networks are possible.

Transparent: This type of network is also referred to as *all-optical* network, since the signal carried on a lightpath remains in the optical domain from the source to the destination. This is depicted by Figure 2.3, where none of the nodes can perform 3R regeneration along a lightpath.

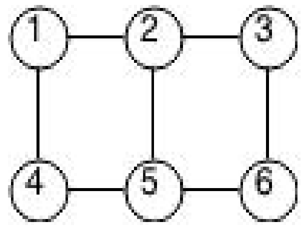

Figure 2.3: Transparent network

Translucent: This type of network has a few nodes with 3R regeneration capability, which are scattered in the network. This is depicted in Figure 2.4, where nodes 2 and 5 have regeneration capability. A lightpath which passes through these nodes *may* undergo 3R regeneration at these nodes.

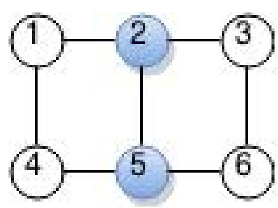

Figure 2.4: Translucent network **Opaque:** This type of network will have 3R regeneration capability at every node present in the network. This is depicted in Figure 2.5, where all nodes are shaded in blue. In opaque networks the signal undergoes OEO conversion at every intermediate node along its path. This increases cost and reduces performance, but can result in higher signal quality.

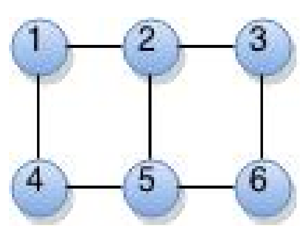

Figure 2.5: Opaque network

2.5 Physical Layer Impairments

The quality of signal degrades due to the physical layer impairments (PLI) along the fiber, which affects the overall performance and increases the bit error rate (BER) [5].

PLIs can be classified into two categories: Linear and Non-Linear impairments. [12]

2.5.1 Linear Impairments

These impairments affect the individual lightpaths, without affecting the existing lightpath. Some examples are given below, [8]

Polarization Mode Dispersion (PMD): "Anywhere along a fiber-span, fiber could be non-circular, contain impurities, or be subject to environmental stress such as local heating or movement. These irregularities present obstacles to an optical pulse along its path. These obstacles cause different polarizations of the optical signal to travel with different group velocities resulting in pulse spread in the frequency domain, known as PMD. PMD becomes a major limiting factor for WDM systems designed for longer distances at higher bit-rates." [28]

Amplifier Spontaneous emission (ASE): "The primary source of additive noise in optically amplified systems is due to the ASE produced by the optical amplifiers used as intermediate repeaters and as preamplifiers at the receiver end. This noise is often quantified with noise figure (NF). In optical amplifiers, ASE limits the achievable gain of the amplifier and increases its noise level. ASE effects may be mitigated by increasing the input laser intensity, decreasing the amplifier facet reflectivities, or tuning the master oscillator so that it is resonant with the amplifier." [28].

Chromatic dispersion (CD): "CD brings about pulse broadening, thereby affecting the receiver performance by reducing the pulse energy within the bit slot and spreading the pulse energy beyond the allocated bit slot leading to inter-symbol interference (ISI)." [27]

2.5.2 Non Linear Impairments

These impairments not only affect the lightpath under consideration but also affects the other existing lightpaths [11].

Self-Phase Modulation (SPM): "The non-linear phase modulation of an optical pulse caused by its own intensity in an optical medium is called SPM. The primary effect of SPM is to broaden the pulse in the frequency domain, keeping the temporal shape unaltered." [28]

Cross Phase Modulation (XPM): "The non-linear refractive index seen by an optical pulse depends not only on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses, i.e., the non-linear phase modulation of an optical pulse caused by fluctuations in intensity of other optical pulses is called XPM." [28]

XPM is illustrated in figure 2.6, where L0, L1 and L2 are three different signals which are using three different channels (c0, c1 and c2). On link 4 → 5, all three signals share the link which creates interferences between them. [30]

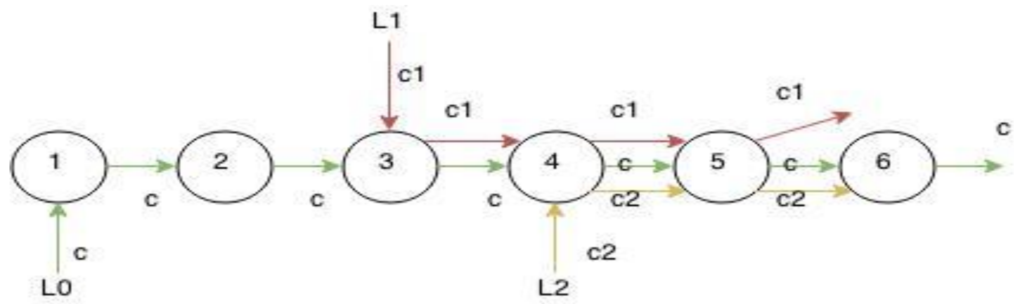

Figure 2.6: Cross Phase Modulation [30]

Four Wave Mixing (FWM): "FWM originates from third order non-linear susceptibility ($\chi^{(3)}$) in optical links. If three optical signals with carrier frequencies ω1, ω2 and ω3, co-propagate inside a fiber simultaneously, ($\chi^{(3)}$) generates a fourth signal with frequency ω4, which is related to the other frequencies by ω4 = ω1 ± ω2 ± ω3. In general for W wavelengths launched into a fiber, the number of FWM channels produced is M = W^2 (W −1)/2)." [28]

2.6 YEN'S Algorithm

Yen's algorithm is a very well-known algorithm which is used to compute the k shortest paths from a source to a destination [34]. I have implemented this algorithm and will use it in my thesis for computing k distinct shortest paths between each possible node pair in a given topology. In this section, we will give a brief overview of Yen's algorithm

The algorithm maintains two lists:

- L1, which contains the m (m < k) shortest paths found so far

- L2, which contains potential shortest paths that have been generated by applying small ‘deviations’ to one of the paths in L1.

Initially, L1 contains a single shortest path, which can be generated using *Dijsktra* algorithm [34] or any other appropriate algorithm. Starting with the first shortest path in L1, all deviations from this path are computed and the resulting paths are added to L2. The path *p* with lowest cost in L2 is then moved from L2 to L1. The next iteration continues in a similar fashion by calculating deviations from path *p* [34]. The process terminates when the desired number of shortest paths have been found (in L1), or no new paths can be generated. The following example is used to illustrate the steps in Yen’s algorithm.

Example:

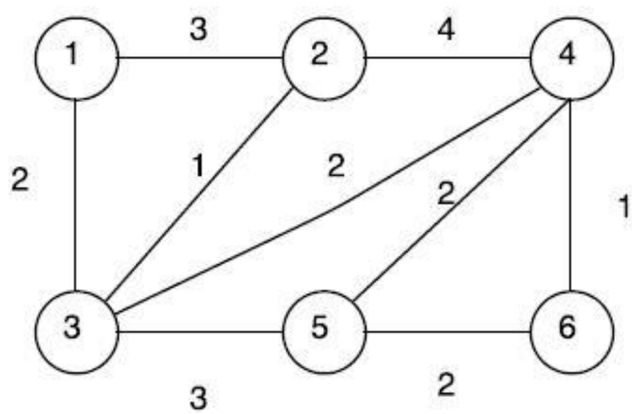

Figure 2.7: Sample 6 Node Network

We consider the topology of Fig 2.7, with node 1 as source and node 6 as destination. Using Dijkstra’s algorithm a best path from node 1 to 6 is been calculated i.e. 1-3-4-6 with total cost 5. Now this path is added into list L1, which is first of *k* shortest path in $L1^1$. Node 1 in $L1^1$ is selected and the edge 1-3 will be set to infinity which becomes unreachable, this is done because it coincides with the root path and with the path in the list L1. Now again the Dijkstra's algorithm is used to get shortest path from 1 to 6 by deleting an edge 1-3. We get 1-2-4-6 with cost 8. This is the first deviation from the shortest path and is added to L2 as a potential candidate for being one of the *k* shortest paths. Next node 3 is chosen from $L1^1$ and the edge 3-4 is set as infinity. Again the Dijkstra's algorithm is used to get shortest path from 1 to 6 after deleting an edge 3-4. We get 1-3-5-6 with the cost 7, which is added in list L2. Finally, node 4 chosen from $L1^1$ and the edge 4-6 is set to infinity; using Dijkstra's algorithm we get a shortest path 1-3-4-5-6 with the cost 8 (after deleting an edge 4-6), which is added in list L2 as a possible shortest path. Now from the three paths in list L2, we select the least cost path (that is 1-3-5-6 with the cost 7), move it to L1 and call it $L1^2$. This completes one iteration, and we continue until we have found *k* shortest paths or no new paths are available.

2.7 Literature Review

In the previous sections, we have explained some fundamental concepts and based terminology related to translucent WDM optical networks. In this section, we review some current literature dealing with IA-RWA in such networks.

In [2] the authors argue that traditional RWA solutions that do not consider PLIs are not sufficient for future photonic networks. In this paper the authors propose two new algorithms, MCP- D2 and MCP-S [2], to support the critical services in Wavelength Routed Photonic Networks. The main objectives of these two algorithms are to protect with assured QoT and to minimize the resource allocation. The first algorithm uses on-the-fly multipath RWA based on Dijkstra Algorithm and the second algorithm uses Suurballe algorithm. The results are compared with IA-RWA survivable algorithm Markidis et al. [09]. The authors stated that this algorithm strictly provides either 1+1 or 1:1 protection. The main aim of these algorithms is to guarantee QoT and survivability in single link failure case. The complexity of these algorithms is lower and setup delay of the lightpath is reduced.

In [13], the authors Hirata, K., et al. consider multi-fiber WDM networks, where every link consists of multiple fibers and can establish multiple lightpaths with the same wavelength in the same link using different fibers. The authors propose a new scheme for RWA in multi-fiber networks [13], with sparse and full wavelength conversion. A suitable path is selected from the set of pre-defined routes between each sender and receiver node. Then each path is divided into segments between nodes with wavelength conversion capabilities and a suitable wavelength is assigned for each segment. This approach can be adapted for IA-RWA as well.

In [14] the authors, Hirata, K et al. state that the probability of blocking is high in wavelength routed WDM networks, due to the coarse granularity and wavelength continuity constraint for establishment of lightpaths. The paper presents a new Dynamic RWA scheme [14] by signaling the backward reservation for multi-fiber WDM networks. This scheme helps in reducing the blocking probability in establishing the light-path.

In this paper [21], the authors Pachnicke, S et al. address the problem that quality of transmission (QoT) goes down with the network load and change of channel. In large translucent optical networks (pan-European Networks) the quality of the signal is very important in transparent paths. Due to the high cost of 3R regenerations, limited regeneration sites are deployed. The authors present a novel online constraint-based routing (CBR) algorithm [21], which uses the present channel load to properly model the inter-channel effects, guarantee connections and give the minimum signal quality when new connection is established. This CBR algorithm considers both linear and non-linear impairments. The authors compare their CBR algorithm to a commonly used shortest path routing with high transparent reach. The results show that shortest path routing results in higher blocking probability compared to offline and online CBR algorithms.

In this paper [10], the authors Christodoulopoulos, K., et al. point out that signal interference will affect an existing lightpath when new lightpaths are added; similarly the QoT of a new lightpath is affected by already existing lightpaths. The authors propose two multi-cost algorithms which consider interference effects and physical effects to create a cross layer optimization between network and physical layers. The first algorithm evaluates the quality of the candidate lightpath. In the second algorithm the physical models are used to define noise variance, which is related with the cost parameters for calculating the Q-factor of the candidate lightpath.

Varanasi et al. 2014 [30] in his Master's thesis, states that due to the physical layer impairments the quality of optical signal degrades in the optical fiber and effects the RWA. In order to restore the lost signal 3R regeneration technique has been used. The work in [30] tries to lower both the capital and operational costs by sparsely using 3R regenerators in translucent networks. A new A* best first search algorithm is proposed, which guarantees that a feasible RWA using a minimum number of regenerators will be found if such a path exists.

For every dynamic connection request, from source to destination, a search tree is constructed with the source node as the root node in the search tree. All the nodes connected to the source node are explored and an estimated cost to reach the destination from each node is calculated. The node with the lowest cost is selected for further exploration. This process continues in each iteration, where the lowest cost node is expanded, until the destination is reached or no more feasible paths exist. In chapter 3, the algorithm is clearly explained with and example.

Chapter 3

3 Algorithm for Dynamic Route and Wavelength Assignment in Translucent WDM Networks

We have proposed a fast heuristic algorithm for dynamic lightpath allocation in translucent optical networks. We have used the A* best first search algorithm for finding the IA-RWA solution. We have constructed a search tree for finding a feasible path for any request from source to destination. We have precomputed *k* shortest paths from every node to every other node within optical reach in the network, which helps the algorithm to search the destination using a segment by segment search.

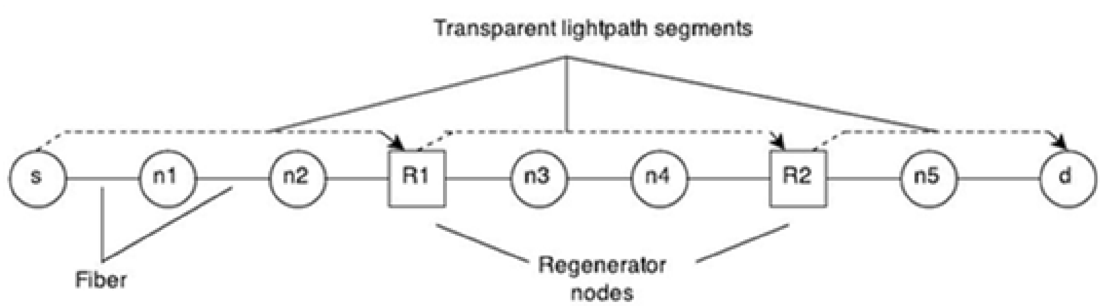

Figure: 3.1 Translucent Network

The main aim is to reach the destination without degrading the quality of the signal to an unacceptable level. Here in figure 3.1, to set up a lightpath from a source to destination, three transparent lightpath segments are used. The regenerators are fixed in the network and, we find a good path to reach the destination using regenerators as needed. As the destination is beyond the optical reach, we cannot find a transparent path to the destination. So we first establish a transparent path to a regenerator R1, where the signal undergoes a 3R regeneration process. We then establish a transparent path to a regenerator R2, where the signal again undergoes a 3R regeneration process. This process is repeated until the signal reaches the destination. Each transparent lightpaths in known as a segment and concatenating all segments give us the translucent lightpath.

3.1 Notations

Topology	→	is a graph $G = (V, E)$ with a set of nodes V, a set E of edges (i, j), each denoting a fiber from i to j,
s	→	Source of request in communication
d	→	Destination of request in communication
T	→	Search tree created by the Best First Search
q	→	A node in the physical topology
t^n	→	A node n in the search tree t
t^r	→	Root node in the search tree
(s, d)	→	Source and Destination of a request.
R	→	A set of nodes which are equipped with regenerators. It is assumed that each node equipped with regenerators have an infinite number of regenerators

P_q → A set of a set of paths from q, each set of paths denotes possible routes from q to a regenerator.

P_q^b → A set of paths from node q to node b in the physical topology

p_q^b → A path from node q to node b in the physical topology

A_b^s → Actual cost from source s to node b in the physical topology

H_d^b → Heuristic cost from node b to destination d in the physical topology

c^{t^n} → Total cost from source s to destination d in the physical topology through node n

r → Optical reach

$\mathfrak{z}_y^x$ → Set of paths from node x to node y such that

a) The length of each path is <= optical reach r,
b) The number of paths in any given set does not exceed k,
c) Any path from x to y not included in $\mathfrak{z}_y^x$ has a length >= the longest path in $\mathfrak{z}_y^x$

$\boldsymbol{Z}$ → Set of all non-empty sets $\mathfrak{z}_y^x$ for all pairs x and y

Ł → RWA solution from source s to destination d

create_root(s)	→	this function creates root node in the search tree which corresponds to the source node for the communication.
create_node(t^n, b)	→	this creates a node t^b in the search tree corresponding to node b in the physical topology, node t^n becomes the parent of node t^b.
*select_eligible_paths_from_**Z**(q)*	→	returns all the paths from a node *q* in the physical topology, to every regenerator node
select_best_leaf(T)	→	returns a node to explore in *T*
find_node_in_physical_topology(t^n)	→	returns the node in the physical topology corresponding to node t^n in the search tree *T*
actual_cost(q,b)	→	returns the actual cost to go from the previous node *q* to the present node *b*.
heuristic_cost(b,d)	→	returns the heuristic cost to go from the present node *b* to the destination *d*.
create_path_from_s_to_d (s,d)	→	returns the *RWA solution*

NoPath	→	Communication Request is Blocked
light_path_feasible (p_q^b)	→	checks whether the lightpath is feasible in this path from node *b* to *q*
delete_path(p_q^b)	→	if no lightpath is feasible, the path is deleted and is not explored in the future.

3.2 Actual Cost and Heuristic Cost

The main objective of the BFS-RWA is to minimize the number of regenerators used, the actual and the heuristic costs are calculated according to the number of regenerators needed. [30]

$$A_{T^n} = R^n + \frac{distance\ from\ the\ source\ or\ the\ last\ regenerator\ \ to\ the\ present\ node}{Optical\ reach} \quad (1)$$

$$H_{T^n} = \frac{distance\ of\ shortest\ route\ from\ node\ to\ destination}{Optical\ reach} \quad (2)$$

This heuristic is admissible, as the actual route chosen to go from a node to the destination will never exceed the distance of the shortest route from the node to the destination. We have used the optical reach to determine when regeneration is needed and have omitted the Non-linear impairments.

3.3 Algorithm

Input: Request for communication from *s* to *d*, *Topology*, ***R***, ***Z***

Output: RWA path, *NoPath*

1. t^r ← *create_root(s)*
2. c^{t^n} ← *heuristic_cost*(t^r, *d*)
3. *while termination condition not satisfied*
4. t^n ← *select_best_leaf(T)*
5. *q* ← *find_node_in_physical_topology*(t^n)
6. P_q ← *select_eligible_paths_from_**Z**(q)*
7. *for* each P_q^b in P_q *repeat step 8 to 20*
8. *for* each p_q^b in P_q^b *repeat step 9 to 20*
9. *if* (*light_path_feasible* (p_q^b)) *then*
10. {
11. t^m ← *create_node*(t^n, *b*)
12. A_b^s ← *actual_cost(q, b)*
13. H_d^b ← *heuristic_cost(b,d)*
14. c^{t^n} ← $A_b^s + H_d^b$
15. *break out of the for loop from step 8 to 19*
16. *else*
17. *delete_path*(p_q^b)
18. end_*if*
19. end *for*
20. end *for*
21. end *while*
22. *if (path to destination is found) then*
23. *Ł* ← *create_path_from_s_to_d(s,d)*
24. return path
25. *else*
26. return *NoPath* // request is blocked
27. end *if*

The above algorithm takes a new request for communication from source node *s* to destination node *d*, the topology, the set of regenerators and the set of paths ***Z*** as its inputs. The algorithm generates either the RWA solution or returns a flag NoPath if the request cannot be handled. When the request arrives, the algorithm creates, from the source, a root node t^r in the search tree (see line 1). As the value of the actual cost always remains 0 at the source node, only the heuristic cost is calculated for t^r. Lines 3-21 shows the exploration of the search tree. The while loop (lines 3-21) is executed until the termination i.e. until the destination is found or until there are no more paths to explore in P_q.

Line 4, using the best first search approach, finds the best leaf node in the search tree to explore, initially the root node is chosen to explore as it is the only node present in the search tree. Later the leaf node, which has the lower value of total cost, will be explored chosen to explore. Line 5, *find_node_in_physical_topology(*t^n*)* returns a node *q* in the physical topology corresponding to node t^n in search tree. In line 6, the list of valid paths from node *q* to the regenerators will be selected from a set of sets of paths (***Z***) and saved in P_q. P_q contains the set of set of paths from *q*, each set of paths denote possible routes from *q* to a regenerator. Line 7-20 is an iterative process where every path in every set of paths P_q is checked to determine whether the lightpath is feasible or not.

The function *light_path_feasible(*p_q^b*)*, checks whether the light path may be set up . If the lightpath is feasible for a particular path then in Line 11, the algorithm creates a node as a child *b* to the explored node t^n in the search tree. In lines 12-14, the actual cost, the heuristic cost and the total cost is calculated for the node b. Line 15, breaks out of the inner loop and checks for lightpath feasibility for each and every path in P_q^b.

If the lightpath is not feasible, for any path p_q^b in the set P_q^b, that particular path p_q^b will be deleted from the set P_q^b. The while loop is executed until the termination i.e. until the destination is found or until there are no more paths to explore inP_q. Once the destination is found in line 23, *create_path_from_s_to_d(s,d)* generates the RWA solution and returns the path, and if the destination was not found the request will be blocked.

3.4 Example

We consider a network with 9 nodes, shown in Figure 3.2. In this figure, each edge represents a fiber, and has a label denoting the distance of the fiber. Here each fiber can accommodate up to 4 channels. We assume that the optical reach is 1000 km. We also assume that we have already run a regenerator placement algorithm to identify regeneration-capable nodes and that nodes 4 and 5 are equipped with regenerators (shown as shaded nodes for convenience). Table 3.1 shows the list of channels available on different fibers. The edges not included in Table 3.1 do not have any available channel. Table 3.2 is the list of k or fewer shortest paths, using k = 3, for selected source-destinations pairs, as samples of set $\boldsymbol{Z}$. For instance, if the source is 0 and the destination is 4, we have included path 0-3-4 having a length of 500 and path 0-1-2-3-4 having a distance of 800. Since we used k = 3, the next path is

0-1-3-4 which we have not included in the table, since the length of the path is 1100, which exceeds the optical reach.

We now consider the problem of finding a valid path from node 0 to node 8. We will use the optimal algorithm given in Varanasi et al. 2014 and the heuristic that we have proposed above to discuss the two approaches to find a valid path for communication. We recall that in Varanasi et al. algorithm, the search is carried out fiber-by-fiber. In our algorithm we carry out a limited search for possible paths of each segment. We indicated in Figure 3.2 that the heuristic cost of a node is the ratio of the length of the shortest path of the node to the destination and the optical reach.

Source: 0, **Destination:** 8

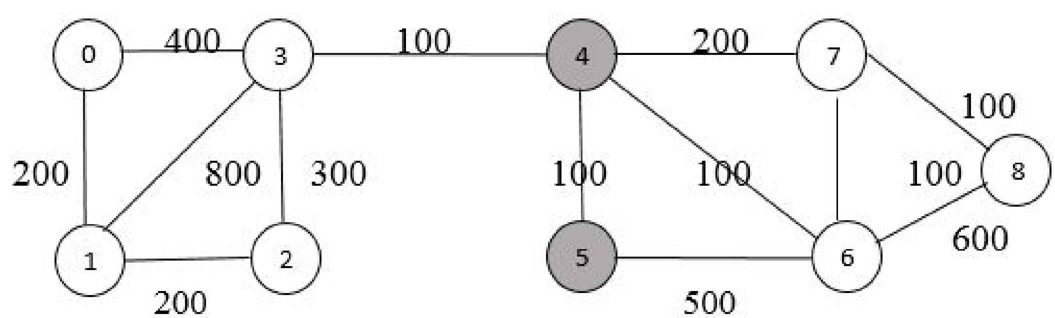

Figure 3.2: 9 Node Network

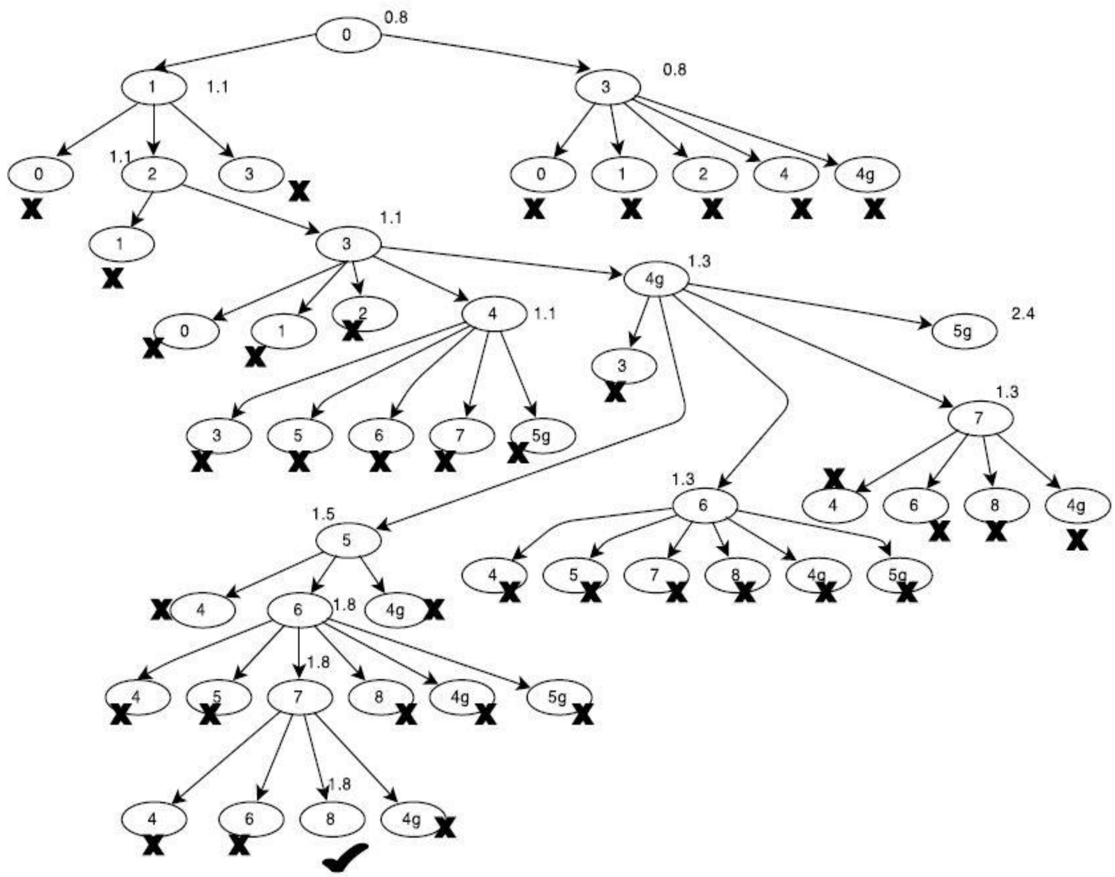

Figure 3.3: Varanasi et al. 2014, search tree exploration

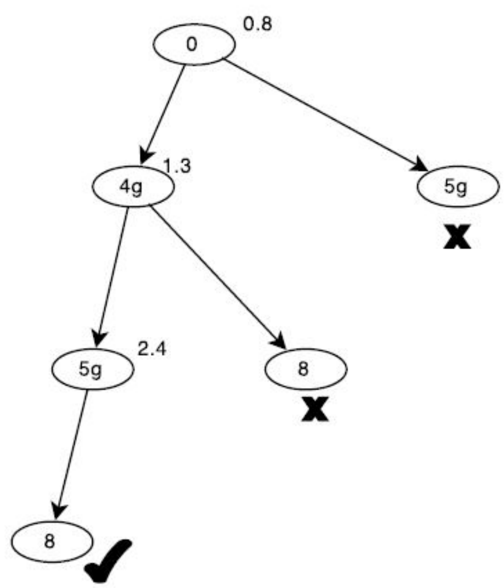

Figure.3.4: Our search tree exploration

Edges	No. Of Channel	Available Channel List
0-1	3	C1,C2,C3
0-3	2	C2,C3
1-2	3	C1,C2,C3
1-3	2	C1,C3
2-3	3	C0,C1,C3
3-4	2	C0,C1
4-5	2	C0,C3
4-6	1	C2
4-7	2	C0,C2
5-6	2	C2,C3
6-7	2	C1,C3
6-8	3	C0,C1,C3
7-8	2	C1,C3

Table 3.1: List of available Channels

source	Destination	*k* shortest paths
0	4	0-3-4
		0-1-2-3-4
	5	0-3-4-5
		0-1-2-3-4-5
	8	0-3-4-7-8
		0-3-4-6-7-8
4	5	4-5
		4-6-5
		4-7-6-5
	8	4-7-8
		4-6-7-8
		4-6-8

Table 3.2: List of *k* shortest paths

3.4.1 Search tree using Varanasi Algorithm

Figure. 3.3 represents the search tree for this problem using the algorithm proposed in Varanasi et al. 2014. In the search tree we included the letter ‘g’, if we used a regenerator in that particular node of the search tree. The total cost is shown beside every node in the search tree. **X** indicates that the node cannot be explored any more due to any one of the following reasons:

a. No channel is available for communication in the segment corresponding to that node in the search tree,

b. The length of the segment corresponding to that node in the search tree exceeds the optical reach,

c. If the node in the search tree is already occurred before in the same path of search tree.

The source node 0 in the physical topology is used to create root node in the search tree shown in Figure 3.3. We recall that the heuristic cost of a node is the ratio of the length of the shortest path of the node to the destination and the optical reach. Thus, the root node has an estimated total cost of 0.8, since the shortest path between source node 0 and destination node 8 is 0-3-4-7-8 with the total distance 800 so that by dividing this total shortest path distance, 800 by the optical reach 1000 gives 0.8.

Then, 0 has two neighbors, nodes1 and 3. The search explores both neighbors and calculates the total costs of both the nodes. Node 1 has a cost of 1.1 and node 3 has the cost of 0.8. As node 3 has the least total cost, it is explored first. But due to the lack of availability of channels or exceeding the optical reach, all the neighbor nodes of 3 cannot be explored as discussed below

Edges	**Reason**
3-0	Node 0 is already visited
3-1	No channel is available
3-2	No channel is available
3-4	No channel available for a segment from 0-4
3-4g	No channel available for a segment from 0-4

Table 3.3: Sample of exploration at node 3

Hence we will explore node 1, the remaining child node of 0. Node 1 has three neighbors - node 0, node 1 and node 3. Node 0 and node 3 cannot be explored as node 0 is already visited and the segment 0-1-3 to node 3 exceeds the optical reach. When we explore node 2, which has neighbors 1 and 3, node 1 is already visited, so we explore node 3. Node 3 has 4 neighbors – nodes 0, 1, 2 and 4. Node 0, 1 and 2 are already visited nodes. Node 4 has to be considered twice – once when we use node 4, without using any regeneration, and when we use node 4 for regeneration. We have shown the case when we use node 4 for regeneration as '4g' in Fig. 3.3. We explore the node with the least total cost. In this case we will explore node 4 with a total cost of 1.2. However, the neighbors (nodes 3, 5, 6, 7,5g) cannot be explored further, for reasons similar to those given above. We next choose node 4g with a total cost 1.3. Since this is a regenerator node, the path 0-1-2-3-4g forms one segment and we can use channel C1 for the segment. Exploring 4g, we get node 5, 5g, 6, and 7, but due to the lack of channels or repetition of nodes or since the optical reach is exceeded, nodes 5g, 6 and 7 cannot be explored. Only node 5 with total cost 1.4 is available for further exploration. In a similar way, we get a path 4g-5-6-7-8 to the destination. This translucent lightpath contains two transparent paths as shown below.

Segment	Path	Channels
S1	0-1-2-3-4g	C1
S2	4g-5-6-7-8	C3

Table 3.4: *BFS-RWA-SV* Transparent segments

3.4.2 Search tree using our algorithm

In Step 1 of my algorithm, the source node 0 in the physical topology is used to create root node t^r in the search tree shown in Figure 3.4. In Step 2, t^r has an estimated total cost of 0.8, since the shortest path between source node 0 and destination node 8 is 0-3-4-7-8 with the total distance 800. When we divide this total shortest path distance, 800, by the optical reach 1000, we get 0.8 as the total cost of the node. Since the node in the physical topology corresponding to node t^r in the search tree is not the destination node, the termination condition is not satisfied. Therefore we enter the *while* loop (line 4 – 20).

Now in Step 4, we choose the best node in the search tree to explore, where the best node is the leaf node in the search tree with the least total cost. Initially, there will be only one node present in the search tree i.e., node t^r. Hence we will choose node t^r in the search tree for exploration. The node in the physical topology corresponding to node t^r in the search tree is 0. Therefore q is 0 in Step 5. Since node 0 has no path in $\boldsymbol{Z}$ to the destination node 8, in Step 6 the paths from node 0 will be to the regenerators. Since both 4 and 5 are within the optical reach of node 0, in Step 6 the list of *k* shortest paths will be as follows:

Set 1 (P_q^4)	0-3-4
	0-1-2-3-4
Set 2(P_q^5)	0-3-4-5
	0-1-2-3-4-5

Table 3.5: set of set of possible paths (P_q)

In lines 7 to 20, we will consider each path from each set of paths and check whether the lightpath is feasible or not. If the lightpath is not feasible, we will not explore the path, else we will create a node in search tree as a child to the node 0 (Line 11). In the first iteration of the *for* loop in lines 7-20, b = 4. In line 8-19 we will examine paths from 0 to 4. In the first iteration of the *for* loop from lines 8 to 19, we consider the path 0-3-4. In Line 9 we find that no channel is available for this segment. In the next iteration we consider the path 0-1-2-3-4. As shown in Fig 3.4, channel C1 is available for this segment. Therefore in line 12 the value of the actual cost becomes 1 since one regenerator is used so far. In line 14 we calculate the total cost and create a node in the search tree corresponding to node 4 (Fig 3.4)

In line 15 we break out of the loop since we don't need to consider any other path to node 4. In a similar way we have to explore paths to regenerator node 5 in the next iteration of the *for* loop in lines 7-20. Both the paths 0-3-4-5 and 0-1-2-3-4-5 have to be processed in successive iterations of the *for* loop in lines 8-19. Both paths are rejected when executing line 9 since no channel exists for any of these paths.

This concludes one iteration of the while loop in lines 3-21. Since node 4 is not the destination, the termination condition is not satisfied. We enter the next iteration of the while loop in lines 3-21.

There is only one leaf node (the node in the search tree corresponding to physical node 4 in Fig. 3.4). Therefore in line 4, t^n is the node in the search tree corresponding to physical node 4 in Fig. 3.4. In line 5, the node q is 4. This time we note that the destination is within the optical reach of node 4, in Step 6 the paths from node 4 will be to the regenerator node 5 and to the destination node 8. Since both 5 and 8 are within the optical reach of node 4, in Step 6 the list of *k* shortest paths will be as follows:

Set 1 (P_q^5)	4-5
	4-6-5
	4-7-6-5
Set 2 (P_q^8)	4-7-8
	4-6-7-8
	4-6-8

Table 3.6: set of set of possible paths (P_q)

In lines 7 to 20, we will consider each path from each set and check whether the lightpath is feasible or not. If the lightpath is not feasible, we will not explore the path, else we will create a node in search tree as a child to the node 4 (Line 11). In the first iteration of the *for* loop in lines 7-20, *b* = 5. In line 8-19 we will examine paths from 4 to 5. In the first iteration of the *for* loop from lines 8 to 19, we consider the path 4-5. In Line 9 we find channel C0 is available for this segment (Fig 3.4). Therefore in line 12 the value of the actual cost becomes 2, since two regenerators are used so far. In line 14 we calculate the total cost and create a node in the search tree corresponding to node 5 (Fig 3.4.) In line 15 we break out of the loop since we don't need to consider any other path to node 5. In a similar way we have to explore paths to destination node 8 (*b* = 8) in the next iteration of the *for* loop in lines 7-20. All the paths 4-7-8, 4-6-7-8 and 4-6-8 have to be processed in successive iterations of the *for* loop in lines 8-19. All the paths are rejected when executing line 9 since no channel exists for any of these paths. This concludes one more iteration of the while loop in lines 3-21. Since node 5 is not the destination, the termination condition is not satisfied. We enter the next iteration of the while loop in lines 3-21.

Now we have only one leaf node (the node in the search tree corresponding to physical node 5). In line 4, t^n is the node in the search tree corresponding to physical node 5 (Fig. 3.4). In line 5, the node q is 5. Here, we see that the destination is within the optical reach of node 5, in Step 6 the paths from node 5 will be to the destination node. In Step 6 the list of *k* shortest paths will be as follows:

Set 1 (P_q^8)	5-4-7-8
	5-4-6-7-8
	5-6-7-8

Table 3.7: set of set of possible paths (P_q)

In lines 7 to 20, we will consider each path from the set and check whether the lightpath is feasible or not. If the lightpath is not feasible, we will not explore the path, else we will create a node in search tree as a child to the node 5 (Line 11). In the first iteration of the *for* loop in lines 7-20, b = 8. In line 8-19 we will examine paths from 5 to 8. In the first iteration of the *for* loop from lines 8 to 19, we consider the path 5-4-7-8 and in line 9 we find that node 4 is already visited in the path so we ignore it (not shown in figure). Again we consider the next path 5-4-6-7-8 in next iteration, similarly we find that node 4 is already visited in the path so we even ignore it. We consider 5-6-7-8, this time we find (Line 9) that channel C3 is available for this segment (Fig 3.4). Therefore in line 14 we calculate the total cost and create a node in the search tree corresponding to node 8 (Fig 3.4.) In line 15 we break out of the loop. Since node 8 is the destination, the termination condition is satisfied and we exit out of the loop and move to next line 22, as the destination is found the algorithm returns the whole translucent path (0-1-2-3-4g-5g-6-7-8) from source node to the destination node. If we fail to find a path to destination we have to block the request.

The path 0-1-2-3-4g-5g-6-7-8 contain three transparent segments.

Segment	Path	Channel
S1	0-1-2-3-4g	C1
S2	4g-5g	C0
S3	5g-6-7-8	C3

Table 3.8: *BFS-RWA* Transparent segments

Comparing both the approaches we can observe that the number of node visited in each search tree are different. The number of nodes visited in Varanasi et al. is more, compared to number of nodes visited in my approach. Comparing both the search tree, figure 3.3 explored using a fiber by fiber search, where as in Figure 3.4 explored using segment by segment search, resulting in a decrease of the number of node visit.

Chapter 4

4.1 Simulation

In this section we will be presenting the experimental setup and the results of the proposed approach (*BFS-RWA*). We will discuss, in detail, each aspect of our experiment. We evaluated all the results by comparing them with the results using Varanasi's approach (*BFS-RWA-SV*) outlined in [30]. Simulation is a very well-known technique used to study the performance of network, and we have used it to study our algorithm as well as that in [30].

4.1.1 Experimental Setup

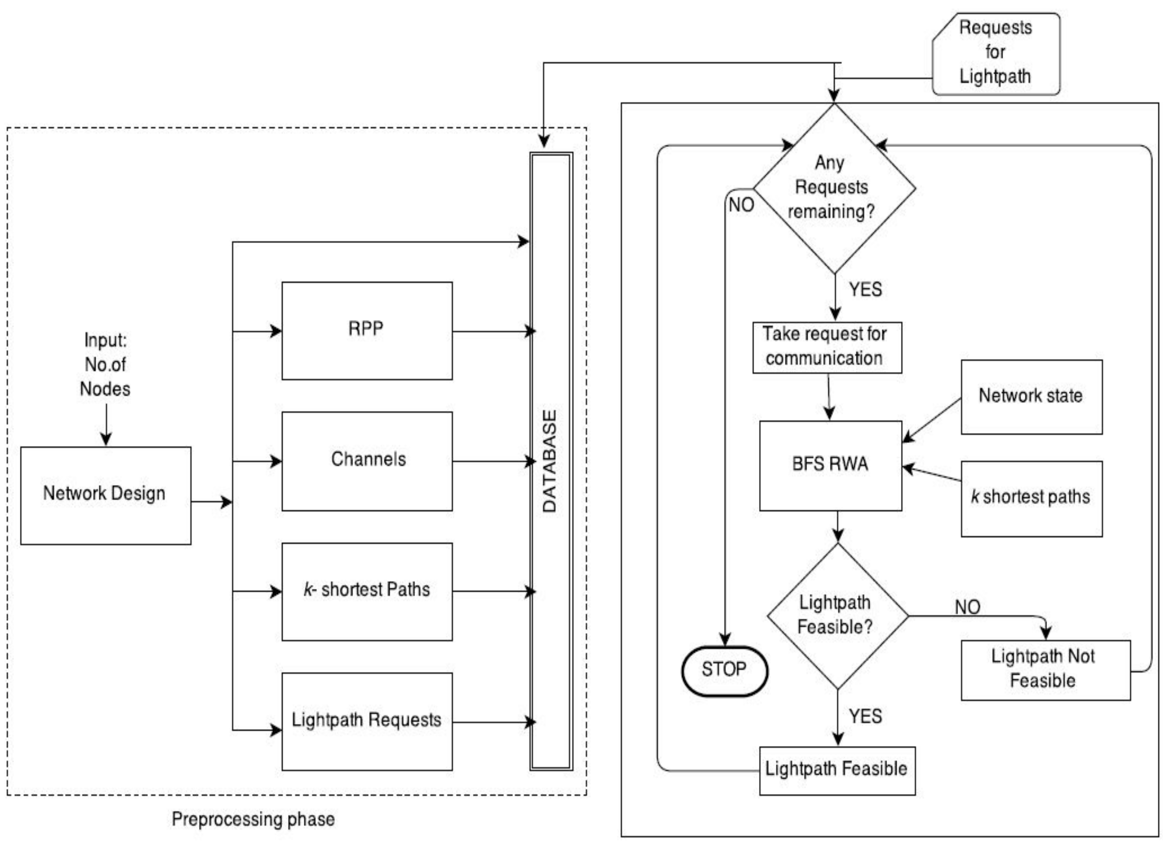

Figure 4.1 Simulator

Components in the setup:

Network Design	:	This component generates the network topology, when number of nodes is given as input.
RPP	:	This finds the regenerator node in network.
Channels	:	This component randomly make some channels busy and gives available channels
***k* shortest Paths**	:	This component generates k shortest paths between every pair of nodes in the network
Lightpath Request	:	This generates the dynamic connection requests.

In the simulator (Figure 4.1), the network design component takes "Number of nodes" as input from the user, which gives the network topology as an output. The network topology is given as an input to each component in the experiment i.e. RPP, Channels, *k* shortest paths and Lightpath Requests. All the information generated by the each component is stored as individual files in the database, in the preprocessing phase. Then the simulator looks for a request from "Requests for Lightpath" file. If there exists a request, that request is given to BFS-RWA algorithm (discussed in Chapter 3). The simulator outputs a file which contains the IA-RWA solution for each connection request, the number of nodes visited, the number of regenerators used in every path used by the lightpath corresponding to a successful request for communication, and the success rate. We have carried out many simulations. For a given number of nodes and the number of requests for communication, the database created in the preprocessing phase contains 5 topologies with n nodes and 5 sets of requests. Our simulation considers 25 cases, one for each topology and request file. The simulation was repeated with Varanasi approach i.e. *BFS-RWA-SV* component instead of *BFS-RWA* component.

The detailed description of each component is discussed below:

4.1.2 Network Design

This component generates a network topology, where the user inputs the number of nodes. Here, the term "degree" mean the number of edges connected to a node in the network, and we specify the minimum and the maximum value of the degree. The minimum and the maximum distance between the nodes can be altered. All the edges in the network are bi-directional. A sample 9 node network topology is shown in Figure 4.2, where the maximum degree is 4, the minimum and the maximum distance between the nodes is 100 and 800 respectively. The optical reach is 1000.

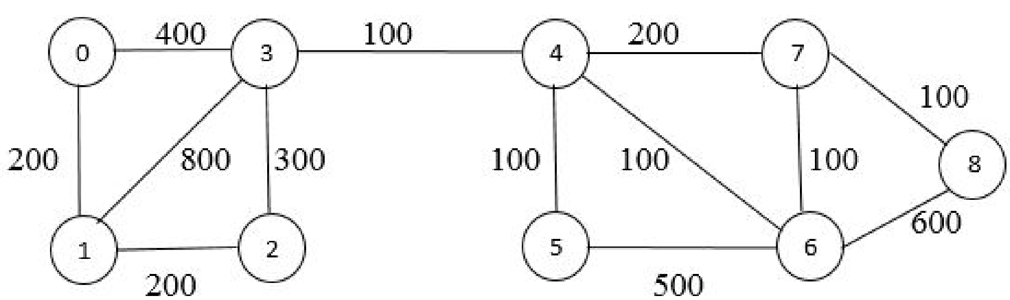

Figure 4.2 Sample Network topology

4.1.3 RPP Component

Given a network and the optical reach, the RPP phase gives the location of possible 3R regeneration capable nodes for a network as solution. This RPP phase is based on the work done by Rahman et al. 2015 [27]. Non-linear impairments have not been considered in [27] RPP approach. The physical topology with the optical reach, is given as inputs to RPP component which finds the nodes which are capable for 3R regeneration, such that for any source destination pair from the source to the destination it can establish a translucent lightpath. For a given network topology and a value for the optical reach, the approach constructs an Integer Linear Program (ILP) and solves the problem using the software called IBM ILOG CPLEX [27].

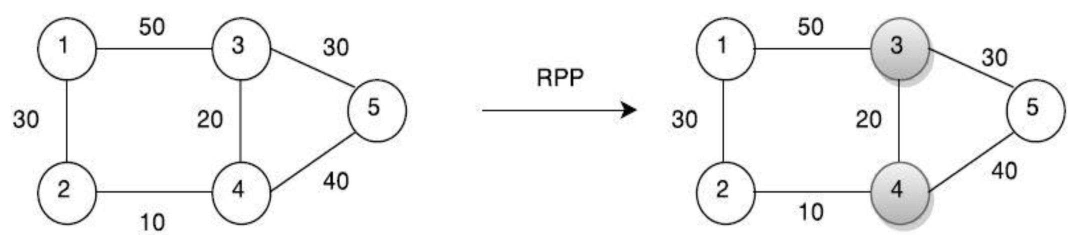

Figure 4.3 Network topology with regenerator nodes

Figure 4.3, shows a randomly generated network topology with 5 nodes having an optical reach of 50. This is given as input to RPP phase and we obtain a corresponding regenerator placement. The shaded nodes in the above figure are the regenerator capable nodes.

4.1.4 Channels

Given a network, this component gives us a list of free channels available on every edge in the network. The fiber joining any pair of nodes in the network has a limited number of channels, where some channels will be free to accommodate the lightpath while the remaining channels are already carrying signals. For an example given below there are 4 channels available for each fiber, this component takes the given network as input and will designate some channels on each fiber as busy in the network. This is done by picking a random number between 0-4 for each edge, which says how many channels are free, suppose we got 3, that means 3 channels are free for a particular edge and then we will randomly pick which 3 channels are free like C0, C2, and C3. Finally we output the list of free available channels on each edge. In this thesis, we consider three kinds of traffics - low, medium and high, where low indicates 0% – 30% channels are busy between the edges, medium means 30% – 60% channels are busy and high indicates 60% – 100% are busy in the network.

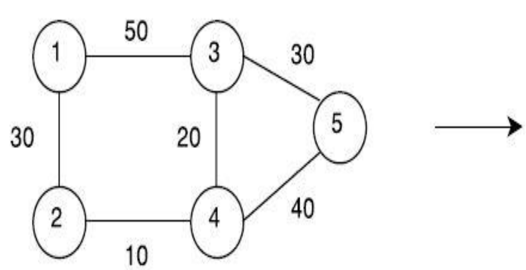

Figure 4.4 Sample Network

Edges	**Channels available**
1-2	C1, C2
1-3	C0
2-4	C3, C2
3-4	C0, C1
3-5	C1, C2, C3
4-5	C2

Table 4.1 Channels Available

Table 4.1 show a typical list of available channels on every edge for a given 5 node network topology. Each fiber on the network can support 4 channels available (namely C0, C1, C2, and C3).

4.1.5 *k* shortest paths

This component takes the network topology as input and outputs the list of *k* shortest paths from every node in the network to the every other node. Yen's algorithm is a very well-known algorithm which is used to compute the *k* shortest paths from a source to a destination [33]. Yen's algorithm uses *Dijsktra's algorithm* or any other shortest path algorithm to start computing the shortest path from source to destination. The algorithm is divided into two parts, solving the first *k*-shortest path and others [33]. We have presented a brief descripting of Yen's algorithm with an example in Chapter 2. We have consider *k* = 3, where we find, if possible, three shortest paths from a node to every other node in the topology.

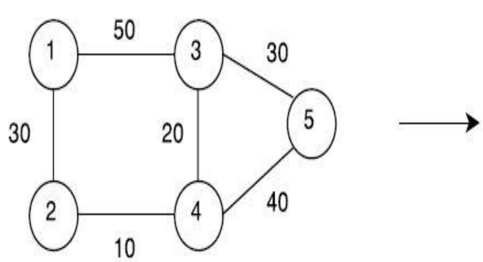

Figure 4.5 Sample Network

1-2	2-4-3-1
1-3-4-2	2-4-5-3-1
1-3-5-4-2	2-4-3
1-3	2-4-5-3
1-2-4-3	2-1-3
1-2-4-5-3	2-4
1-2-4	2-1-3-4
1-3-4	2-1-3-5-4
1-3-5-4	...
2-1	...

Table 4.2 Sample *k* shortest path list

Table 4.2, shows part of a list of *k* shortest paths from every node to every other node for a given 5 node network topology using k=3. We have shown only a few paths in the table.

4.1.6 Lightpath Request

This component generates dynamic connection requests i.e. the source destination pairs for which our algorithm has to generate, if possible, the RWA solution. We generate all possible source destination pairs i.e. every node to every other node in the request file, this file is given as input to the algorithm. Given a network, the location of the regenerators, *k* shortest paths and a dynamic connection request as an input to A* algorithm, it gives a good RWA solution. In this chapter, we have presented many experiments comparing my solution to that obtained by Varanasi approach considering different size of networks

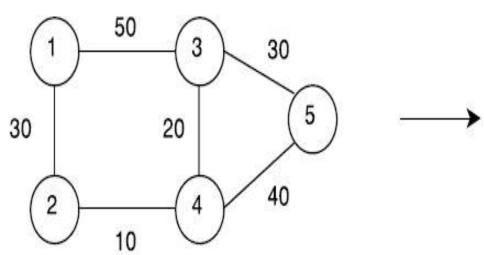

Figure 4.6: Sample network

Source	Destination
1	2
1	3
1	4
1	5
2	...

Table 4.3: Dynamic Requests

4.2 Results

This section reports the simulation results for our proposed *BFS-RWA* approach. We have tested our approach on a number of different topologies and with different traffic distributions for each topology. We assumed there are 8 available channels on each fiber link in the physical topology. We considered three network sizes, with 10, 20 and 30 nodes in the network. For each network size, 5 random topologies were generated and each of these was simulated with different traffic distributions. The traffic demand sets were classified into 3 categories: i) Low traffic load, ii) Medium traffic load and iii) High traffic load, depending on the number of available channels on each link. A high (respectively medium and low) traffic load has 0 to 2 (respectively 2 to 4 and 5 to 8) channels available on each link in the network. We generated 5 demand sets for each type of traffic load. So, the results reported in the remaining sections represent the average of 25 simulation runs for each case. We have compared our approach with *BFS-RWA-SV* as reported in [30], by using the same data sets to generate solutions with *BFS-RWA-SV*.

4.2.1 Success Rate

Table 4.4 shows the average number of successful connections that could be established using *BFS-RWA-SV* and *BFS-RWA* respectively. The total number of connection requests for each network size is indicated in column 1 of the table. Overall both approaches achieved very high success rates (98.1% and 92.5%) for low and medium traffic loads. Even with a high traffic load, the success rates were 96.6% and 86%. We observed some variations in success rates with the network size as well.

For the 10 node network, the performance of the two approaches were very similar, resulting in 98.7% success rate in *BFS-RWA-SV* approach, and 97.8% success rate in *BFS-RWA.* The difference in performance was more noticeable in the larger networks. In the 20 node (30 node) networks, the average success rates were 96.4% (98.8%) and 80% (90%) using the *BFS-RWA-SV* and *BFS-RWA* respectively. The slight decrease in performance for *BRS-RWA* is expected, since it only searches *k* (=3) pre-computed routes for establishing a lightpath; whereas *BFS-RWA-SV* searches all possible paths over the topology, when trying to establish a connection.

TABLE 4.4: Success rate with *BFS-RWA-SV* and *BFS-RWA* approach

Network Size	**Traffic Load**	**Number of Successful Connections**		**Percentage of Successful Connections**	
		BFS-RWA-SV	***BFS-RWA***	***BFS-RWA-SV***	***BFS-RWA***
10 Node 90 requests	**Low**	90	89.8	100%	99.7%
	Medium	90	89.6	100%	99.5%
	High	86.6	84.8	96.2%	94.2%
20 Node 380 requests	**Low**	379	315.8	99.7%	83.1%
	Medium	379	313.8	99.7%	83%
	High	341.4	273.6	89.8%	73%
30 Node 870 requests	**Low**	869.8	802	99%	93.1%
	Medium	870	800.6	100%	92%
	High	840.6	747.6	96.6%	86%

Fig 4.7 shows how the success rate varies with traffic load for a given network size. The results shown are for the 10 node networks, but the other network sizes follow a similar pattern. As expected, we observe that the success rate decreases consistently, as the network load increases. This is because there are fewer available channels to route the new connection request, as more channels become 'busy'.

Figure 4.7 Success rate in 10 Node Network

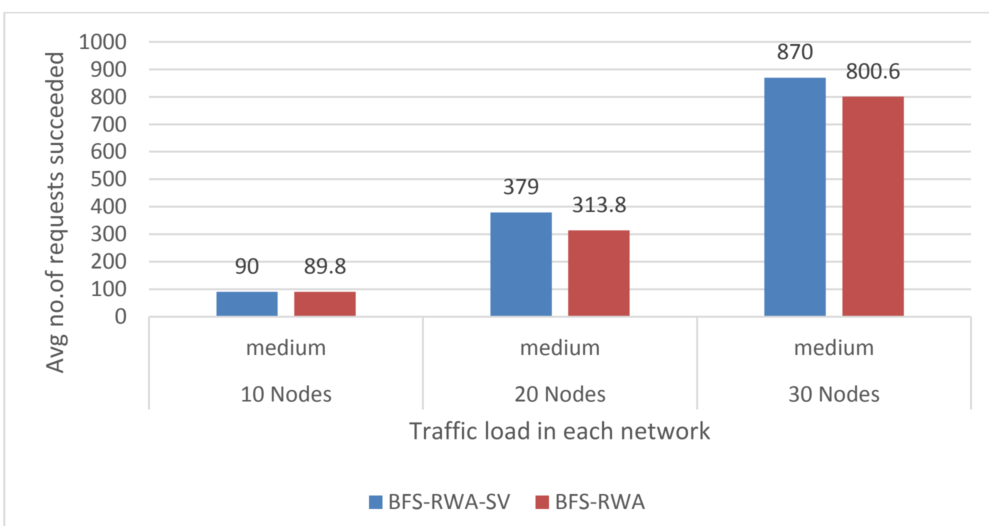

Figure 4.8 Success rate with Medium Traffic load

Figure 4.8, shows the variation in success rate, with different network sizes, for a given type of traffic load. In all the 3 network we got nearly 2% difference between Varanasi and my approach with medium traffic.

4.2.2 Average Nodes Visited

The main motivation for the proposed *BFS-RWA* approach was to develop a fast, efficient strategy for dynamic impairment-aware RWA that can generate 'good' solutions in a reasonable amount of time. The *BFS-RWA* algorithm creates a search tree, and the number of nodes visited (n_v) in the search process gives a good estimate of the amount of computation required to find a solution. This in turn is directly related to time needed to generate a solution. Therefore, we have used this metric (n_v) in the following discussions. Table 4.5 shows the average number of nodes of the search tree that are explored before a solution is reached using the two approaches, for different network sizes and traffic loads. We see from Table 4.2 that, as the network size increases n_v increases fairly quickly for *BFS-RWA-SV*. This means that the approach will become computationally intractable for networks of larger size. In fact, this has been observed to be the case, as reported in [30]. On the other hand, for *BFS-RWA*, we do not observe a steady increase in the value of n_v, with network size.

Figure 4.9 and Figure 4.10 show how n_v varies with traffic and load network size respectively. We see from Fig 4.5 that there is relatively little change in n_v with the traffic load. Also, there seems to be no consistent pattern. For the 10 node network, n_v increases very slightly with traffic load. However, for the 20 and 30 node networks, the high traffic load case actually has smaller values of n_v compared to medium traffic. This is true for both *BFS-RWA-SV* and *BFS-RWA*.

Table 4.5: Number of nodes visited with *BFS-RWA-SV* and *BFS-RWA* approach

Network Size	Traffic Load	Number of nodes visited (n_v)	
		BFS-RWA-SV	***BFS-RWA***
10 Node 90 requests	**Low**	5.288	3.892
	Medium	5.368	3.894
	High	6.276	4.246
20 Node 380 requests	**Low**	21.224	9.11
	Medium	22.078	9.076
	High	18.05	8.556
30 Node 870 requests	**Low**	31.804	5.578
	Medium	31.226	5.496
	High	25.332	4.474

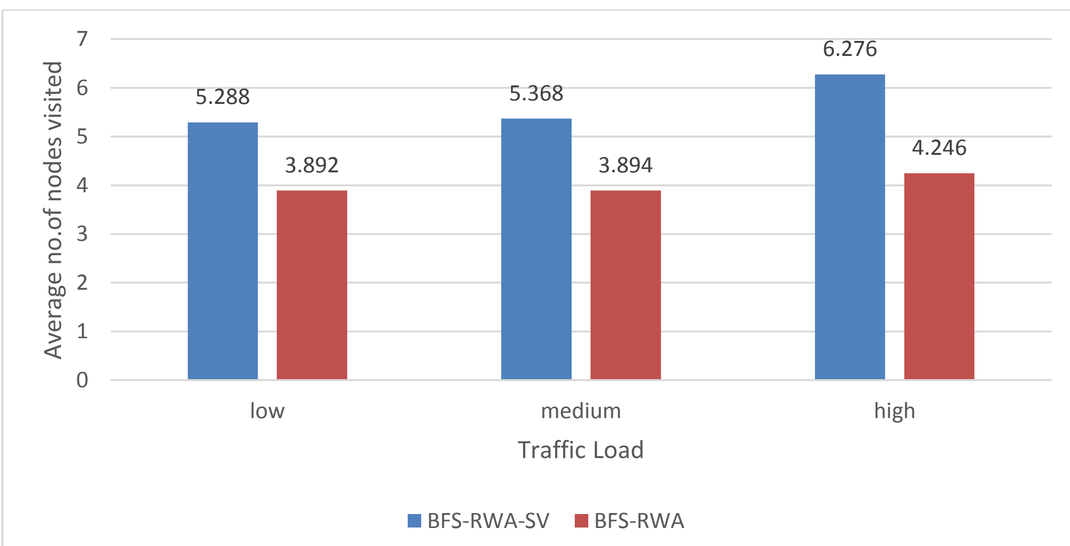

Figure 4.9: Average nodes visited in 10 node network

Fig 4.10 on the other hand clearly demonstrates that the network size has a significant effect on the value of n_v for *BFS-RWA-SV*. The results shown are for medium traffic load, but the same pattern is observed for low and high traffic as well. For *BFS-RWA* the change in n_v, with network size, is much less significant. Also, the difference in n_v values between the two approaches become more pronounced as the network size increases. This means that computations required to generate a solution will be significantly higher in larger networks for *BFS-RWA-SV*, resulting in a higher solution time.

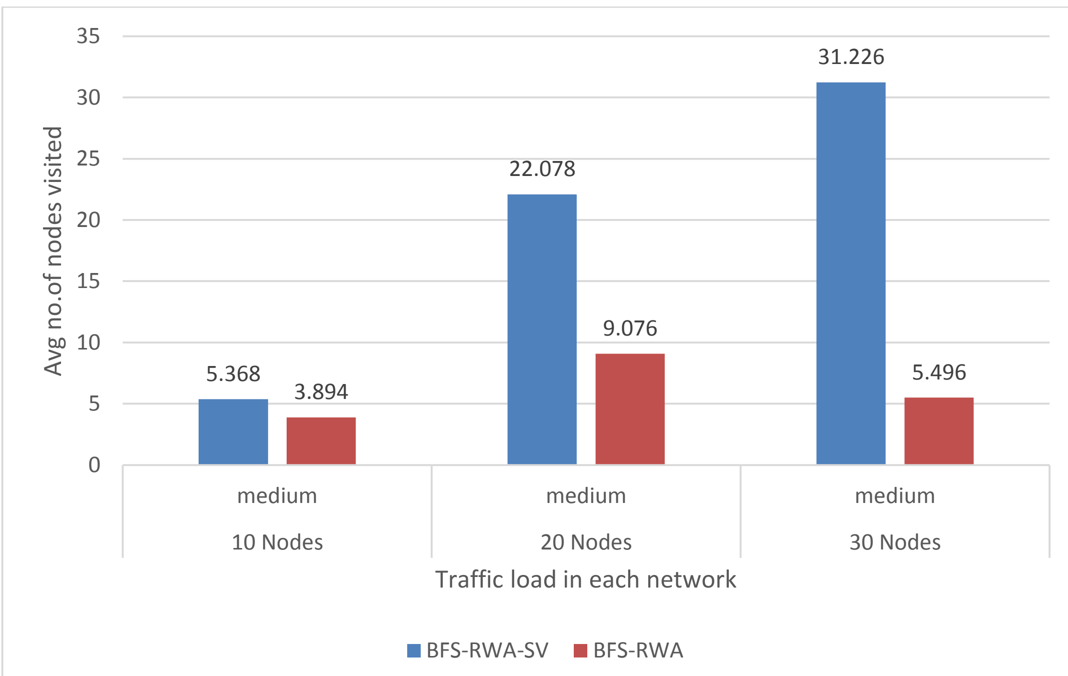

Figure 4.10: Average Number of nodes visited in each Network

4.2.3 Regenerator Usage

An important metric in evaluating the performance of an impairment-aware RWA algorithm is the average number of regenerators required to establish a connection. This is important because regenerators are expensive components in optical networks and it is desirable to use as few regenerators as possible, in order to reduce the overall network cost. Table 4.6 shows the average number of regenerators needed to establish a lightpath, using the two approaches under consideration. We note that Table 4.6 gives the number of regenerators required per *successfully established* connections. Connections which were blocked are not counted. This also means that the total number of regenerators needed increases with network size. So, even though the values *per connection*, for the 30 node networks are higher than the corresponding values for the 20 node networks, the 30 node topologies still use significantly more regenerators overall.

Table 4.6: Average Number of Regenerator used with *BFS-RWA-SV* and *BFS-RWA* approach

Network Size	**Traffic Load**	**Avg. Number of Regenerators Needed**	
		BFS-RWA-SV	***BFS-RWA***
10 Node 90 requests	**Low**	1.686	1.536
	Medium	1.736	1.6
	High	1.806	1.4825
20 Node 380 requests	**Low**	2.752	2.036
	Medium	2.768	2.028
	High	2.898	2.016
30 Node 870 requests	**Low**	3.448	1.874
	Medium	3.43	1.862
	High	3.626	1.952

Table 4.6 shows that the number of regenerators required for the two approaches are fairly close particularly smaller networks. However, *BFS-RWA* does require fewer regenerators on average, and the difference becomes more noticeable for larger networks. As reported in [30], *BFS-RWA-SV*, is designed to find the feasible path requiring the *minimum* number of regenerators for each connection, if such a path exists. But, Table 4.6 seems to show that *BFS-RWA* requires fewer regenerators. This apparent anomaly can be explained by considering that the number of connections actually established using *BFS-RWA-SV* is higher. Often, these extra connections are established using very long paths, which require a higher number of regenerators. This is why *BFS-RWA* seems to require fewer regenerators on average. Fig 4.11 shows that the traffic load does not have a significant impact on regenerator usage, for both approaches. Figure 4.12 shows that while regenerator usage increases steadily with network size for *BFS-RWA-SV*, network size appears to have relatively little impact on regenerator usage for *BFS-RWA*.

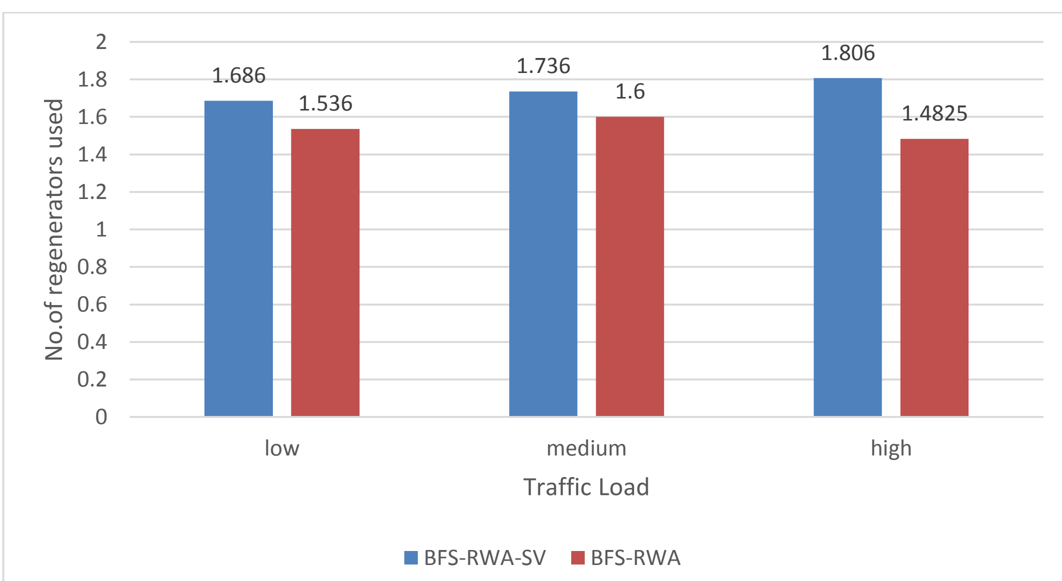

Figure 4.11 Number of Regenerators used in 10 Node network

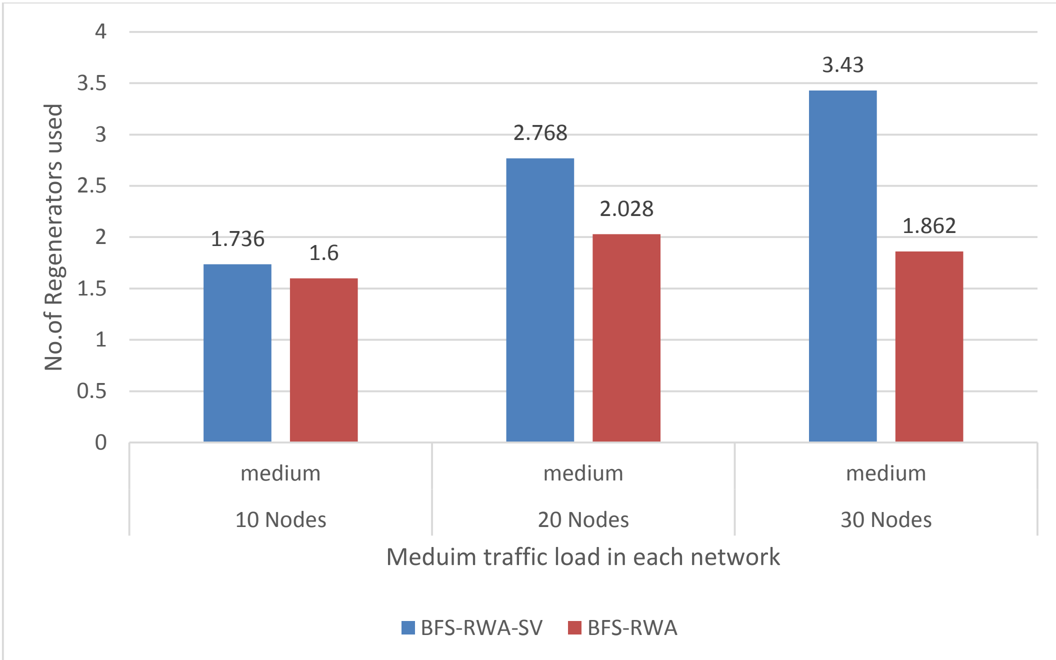

Figure 4.12 Number of Regenerators used in each network

Chapter 5

5 Conclusions and Future Work

5.1 Conclusions

In this thesis, we have proposed a fast heuristic for dynamic lightpath allocation in translucent networks and have compared the heuristic with an optimal algorithm proposed by Varanasi et al. 2014 [30]. An existing regenerator placement strategy is used prior to the network operation, to determine the regeneration capable nodes. We have used an A* best first search algorithm for finding the IA-RWA solution. Our algorithm selects a route (from a set of pre-defined routes) for every source destination pair, using least possible number of regenerators. We constructed a search tree for finding a feasible path for any request from any source to any destination. Pre-computing *k* shortest paths between every node pair (within optical reach) helps the algorithm to reach the destination quickly, using a segment by segment search.

We have performed simulations with 10, 20 and 30 nodes in the network, in chapter 4, to study the performance of the BFS-RWA. We have discussed the advantages and disadvantages of our scheme compared to the scheme recently proposed in Varanasi et al. [30], where a fiber by fiber search approach was used.

5.2 Future Work

The results achieved in our work are promising leaving more to be explored for further research. We feel that fast heuristics should be explored, using techniques such as genetic algorithms, simulated annealing or tabu search. These approaches could use the framework described in this thesis as well as the optimal results using the approach proposed by Varanasi et al. 2014 [30].

Currently our work only considers fault-free networks. It would be useful to extend this approach so that it is capable of handling faults in the network. The relative effectiveness of both protection and restoration based schemes should be evaluated and compared.

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