HEURISTIC APPROACHES FOR OPTIMIZED REGENERATOR PLACEMENT WITH HYBRID FIBER AMPLIFICATION (HFA) IN OPTICAL NETWORKS

By

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DEDICATION

I dedicate this thesis to my parents who always loved and encouraged me. I am also dedicating this thesis to my beloved daughter and husband. Thank you so much for always been there for me. I am so grateful for their support.

ACKNOWLEDGEMENT

At foremost, I express my gratitude to Almighty Allah for blessing me with wisdom, healthiness, and power.

I am also grateful to my supervisor Dr. Arsalan Ahmad for giving me the opportunity to work under his supervision. I am thankful for his guidance, availability, and resourceful supervision.

Finally I am obliged to my family members for their support, belief, and prayers.

ABSTRACT

Exponential increase in the requirements of resources from internet users causes proliferation in the internet traffic. In this regard, the optical network offers data transmission between sender and receiver through optical fibers which is faster and reliable than any other network i.e. wireless network and copper wired network. Due to such efficiency optical network is known as backbone of the internet.

Although, optical networks are very optimistic solution to fulfill demands of internet traffic but there are some optical layer constraints and physical impairments which should be taken under consideration to cope with increasing demands. Some of these impairments are signal degradation, inappropriate modulation scheme and inefficient algorithm scheme etc. When signal propagates over a link from sender to receiver, this signal degrades with the time and distance covered. Therefore, to reach on its final destination that signal must be regenerated. Optical signal can be regenerated by placing optical regenerator on the optical link where the signal starts to degrade. However, adding these regenerators in the network is not a very efficient approach. So it is required to upgrade the network. In this thesis, the optical network is enhanced by selectively upgrading the optical line amplifiers.

The outcome shows that this approach can provide a great reduction in number of regenerators which are placed in the network topologies and makes network more transparent and efficient.

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Acronyms

CWDM Coarse Wavelength Division Multiplexing.

DeMUX Demultiplexer.

DWDM Dense Wavelength Division Multiplexing.

EDFA Erbium dopped fiber Amplifier.

ENF Equivalent Noise Figure.

HFA Hybrid Fiber Amplification.

LP Lightpath.

MPR Multi Path Routing.

MUX Multiplexer.

OEO Optical-Electrical-Optical.

OSNR Optical Signal to Noise Ratio.

QoT Quality of Transmission.

RP Regenerator Placement.

RR Regenerator Reduction.

RWA Routing and Wavelength Assignment.

SOA Semiconductor Optical Amplifier.

SPR Shortest Path Routing.

ULP Underperforming LP.

WDM Wavelength Division Multiplexing.

Chapter 1

Introduction

1.1 Introduction to Optical Networks

With the advancement in technology, exponentially grown internet traffic has been putting enormous load on the internet. Therefore, there is need of a network which has higher speed as well as longer bandwidth so it can accommodate all the requirements of user demands. One of the solutions which can fulfill such needs of client is **Fiber Optic Communication**. In fiber optic communication, optical fibers are used to send and receive high volume data between nodes with high flexibility and accuracy over any geographical area. Due to such benefits, optical network works as backbone of the internet. Basic network elements are optical fiber, regenerators, reconfigurable optical add drop Multiplexer (MUX), amplifiers etc.

Although optical network is highly beneficial network among all of the other networks, regarding its high volume data transmission, network flexibility, and data accuracy, there are some impairments which lessens its efficiencies i.e. signal degradation, in appropriate modulation scheme, optical noise etc. If the optical reach is less than the distance between two nodes then one of the main cause can be inappropriate modulation scheme. Optical reach is the distance that signal can travel before degradation of its quality to a level where this signal requires regeneration [1]. High modulation scheme (i.e. 16-QAM, 32-QAM, or 64-QAM etc.) can transfer data for small geographical area and vice versa for low modulation scheme (i.e. BPSK, QPSK etc.—). Available modulation formats with their transmission rate and optical reach are listed in table 1.1.

Table 1.1: Available Modulation Formats

-	**BPSK**	**QPSK**	**8QAM**	**16-QAM**	**32-QAM**	**64-QAM**
Transmission Rate (GB/s)	12.5	25	37.5	50	62.5	75
Optical reach (in km)	4000	2000	1000	500	250	125

When high modulation scheme is used for large area, optical reach is inadequate to catch the intended destination. And when low modulation scheme is used for small geographical area, data transfer is too slow for even small amount of data that may cause shortage of resources. To cope with this type of impairments regenerator is a very first solution which can be used. Regenerator is used to regenerate an attenuated and distorted optical signal. It does not add noise in regenerated signal as in an amplifier which amplifies the noise as well of the distorted optical signal. It is also known as optical communication repeater. It extends the optical reach of the signal in optical networks. Optical system with and without regenerators are shown in figure 1.1[1].

Regenerators regenerate the optical signal by converting it to electrical signal, and then signal is processed, at the end, signal is again converted into optical signal which is transmitted from regenerator's transmitter to the intended receiver. Due to this property, regenerator are also called OEO (Optical-Electro-Optical) device.

[1]fig 1.1 source: https://www.grotto-networking.com/BBOpticalGMPLS.html

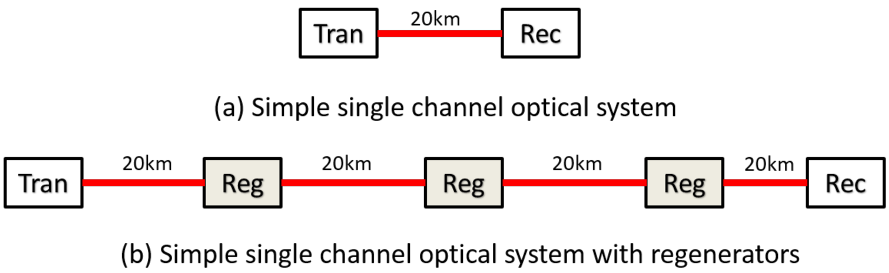

Figure 1.1: Optical system with and without regenerators

Regenerators regenerate signal to increase its optical reach. which allows the sender to transmit its data over a large geographical area. But regenerators can't be installed in any network randomly as it increases the cost of equipment and results in less return over investment. There are three types of optical networks shown in figure 1.2[2]named as,

1. Opaque network
2. Translucent network
3. Transparent network

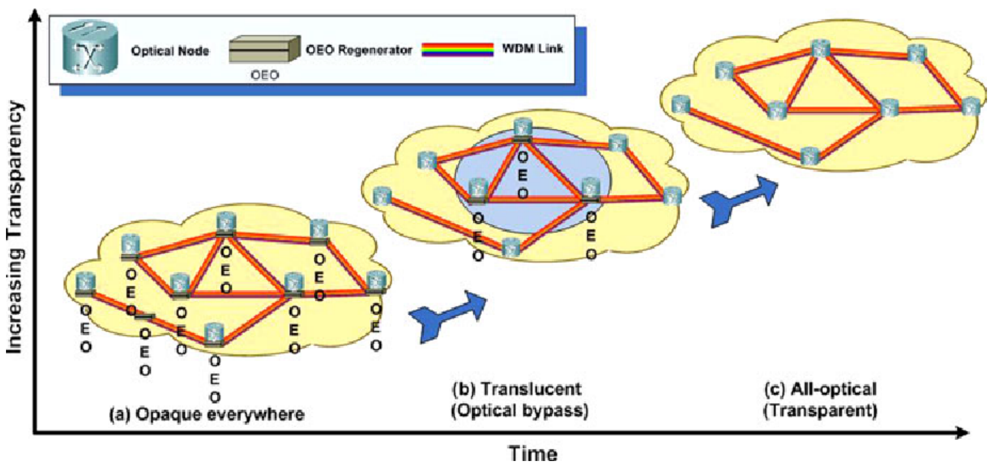

Figure 1.2: Evolution of networks from Opaque to Transparent

Each type varies from one to another in Regenerator Placement (RP). In opaque network, regenerator is placed at every intermediate node. Its power consumption and cost is increased

[2]fig 1.2 source:DICONET NPOT: An impairments aware tool for planning and managing dynamic optical networks

at very high rate. In translucent network,OEO conversions are not required on each node, but only when the signal is too degraded [2]. In this network, OEO is placed at selected node and divides a Lightpath (LP) into fragments [3, 4]. It can be applicable on any size of the network. Each node is selected by some criteria using some appropriate technique or algorithm. In this type cost and power consumption is manageable and network is flexible and scalable. In the third type of network, regenerator is not used. Transparency in the sense of end to end communication, this communication should be supported by network which independent of signal format or bit rate[5]. This limits the flexibility of network as there are very small numbers of nodes which can send and receive data from each other due to finite optical reach of sender node.

Translucent network is very economical and it is an attractive alternative as compared to other type of networks. It is a green solution for core networks where long distance communications are executed. But choosing the optimal number of regenerators in translucent network is the main issue which can be resolved by using some criteria or technique or heuristic approach. There are many algorithms which are used for above mentioned problem.

There are different types of multiplexing techniques which are used to multiplex and transfer data from source to destination on multiple channels in a single fiber. These multiple multiplexing techniques are wavelength division multiplexing, frequency division multiplexing, and time division multiplexing. Wavelength Division multiplexing is frequently used technique in optical networks because it allows to increase the network capacity without diffusing more fibers and rebuilding the core network.

In optical network, signal is attenuated and dispersed in optical fiber with the time due to some physical impairment. Optical line amplifiers are used to amplify signal. These amplifiers are also called signal repeaters in long-haul communication. There are many types of optical amplifiers like laser amplifiers, semiconductor optical amplifier, and Raman amplifier etc.

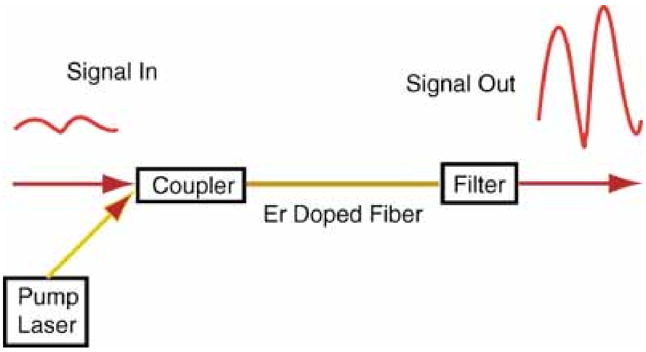

Figure 1.3: EDFA Working Principle

Erbium dopped fiber Amplifier (EDFA) is a type of laser amplifier shown in figure 1.3 [3]. This amplifier is widely used in DWDM transmission systems. In EDFA, there is no conversion of signal from electrical to optical or optical to electrical. This optical amplifier gives high gain and low noise in output but this advantage is limited because EDFA is non uniform in amplifier gain [6] . Whereas, Semiconductor Optical Amplifier (SOA) made up from the semiconductor material of group III and group V. Its noise figure is greater than remaining both types. On the other hand, it is economical and used for optical switching and low cost applications. The working principle of semiconductor amplifiers are shown in figure 1.4 [3].

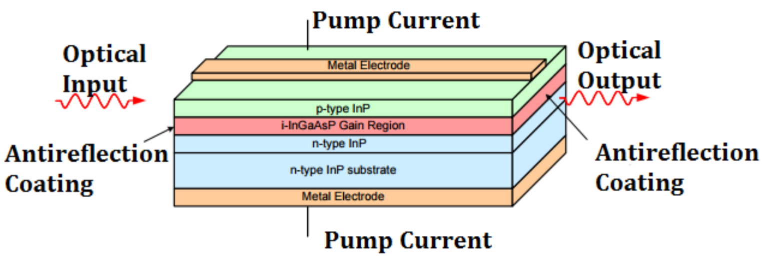

Figure 1.4: Semiconductor Amplifier Working Principle

In Raman Pumping, pumping method is used to increase the intensity of amplification of signal in optical fiber. Pumping method and signal are interacted nonlinerly to get amplification of signal. The working principle of raman amplifier is shown in figure1.5 [3].

In optical fiber communication hybrid amplification techniques are used to get distributed

[3]fig 1.3 source: http://www.fiber-optic-tutorial.com/introduction-of-optical-amplifier.html

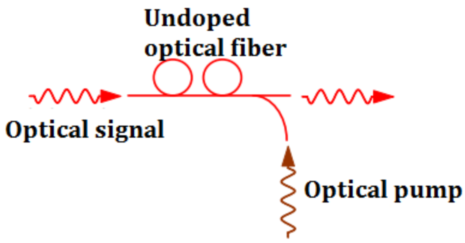

Figure 1.5: Raman Amplifier Working Principle

gain. This technique is counter-propagating Raman Pump which enables the distributed amplification and used as a complement of EDFA gain [7] . It affects WDM channel comb on the whole. The distributed gain of this technique is used to decrease Equivalent Noise Figure (ENF) of amplifier and improves Quality of Transmission (QoT) of data [8].

1.2 Objectives

We aim to propose the optimized RP in optical network with a heuristic approach. Heuristic approach calculates the number of regenerators required and reduced them from network using amplification scheme in order to create lightpath between different nodes in the optical networks transparently. This scheme is used in long haul networks where optical reach is less than the distance of lightpath from sender node to receiver node.Therefore, main objective of this thesis is as follows

1. Cost reduction.

2. Complexity reduction.

3. Reduced power consumption.

1.3 Problem Statement

With the exponential increase in traffic, user needs more resources for data transmission over large geographical area. Internet providers tried to upgrade the networks by using new optimized approaches and by installing upgraded equipments. This requires upgradation of devices and installation of higher number of devices since demands are increasing day by day which is directly associated with cost. Therefore, to reduce cost and power consumption a technique is proposed in this thesis.

1.4 Organization of Thesis

The organization of this thesis is as follows:

In chapter 1, optical networks and placement of regenerators in optical networks is introduced. Modulation schemes are discussed. Different approaches of multiplexing and amplification are also described in this chapter. Chapter 2 summarizes the literature on WDM in optical networks, RP in optical networks and algorithms for RP in optical networks. Different Amplification applications for different scenarios are discussed. In chapter 3 reduction in RP in optical network and a sequence in usage of enabling technologies is proposed. In chapter 4, results of proposed approach are provided and the very last chapter comprises on conclusion and future work.

Chapter 2

Literature

2.1 Fundamentals of Optical Networks

With the advancements in social networking, bandwidth hungry applications have increased their requirements by several times. Internet providers predict the explosive growth of internet traffic in couple of years [9]. In this situation, there is a need of such network that can deal with increasing demands of internet users in future. Optical network is a promising solution of this issue as it offers greater bandwidth amount. It uses different types of multiplexing techniques to manage growing internet traffic and their increasing demands and Wavelength Division Multiplexing technique is one of them. Optical networks use optical fiber to transmit and receive data and each fiber can carries standard independent number of channels. Each bandwidth channel of a single fiber (transmitting data from one end to anothe) contains a different wavelength and this wavelength is assigned by **Wavelength Division Multiplexing**. In a single fiber two channels are separated by guard bands to avoid interference between two wavelengths. But these guardbands shown in 2.1[1]may cause underutilization of spectrum [10, 11].

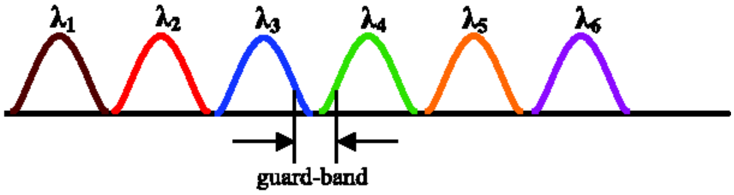

Figure 2.1: Guardband in Optical Spectrum

With WDM technology, 100GB/s or higher wavelength is supported by each fiber [12, 13]. When a connection is set up between two nodes (source and destination), LPs in figure 2.2[2]are established between these nodes, and data transmission is done without any disturbance by using intermediate devices.

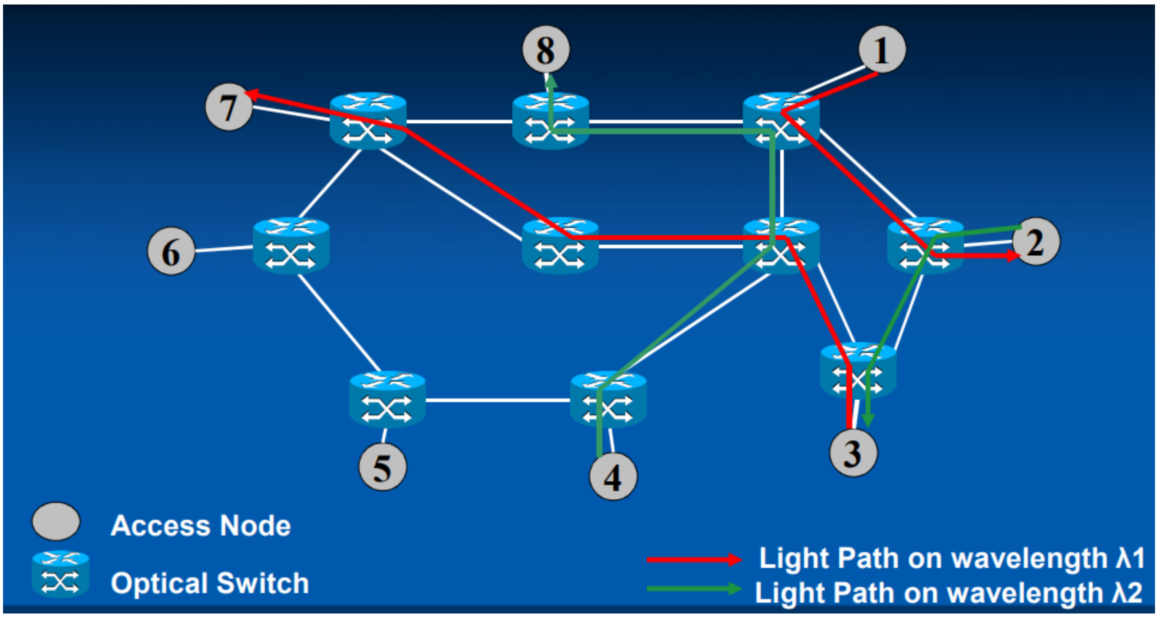

Figure 2.2: Lightpaths in WDM

A lightpath is all optical for data transmission between source destination pair. In all-optical networks, traffic is carried end-to-end in the optical domain, without any intermediate optical-electrical-optical (O-E-O) conversion. [14] A unique wavelength and route is assigned to each lightpath using Routing and Wavelength Assignment (RWA) algorithms.

[1]figure 2.1 source:Towards elastic and fine-granular bandwidth allocation in spectrum-sliced optical networks
[2]figure 2.2 source: http://drzaidi.seecs.nust.edu.pk/lectures/Lec-8%20RWA%20Survey(10-04-2007)%20.pdf

2.1.1 Wavelength Division Multiplexing

Today's mostly used technique in optical communication is Wavelength Division Multiplexing. Through this technique a single fiber can pass multiple wavelengths from itself simultaneously. In optical spectrum the huge bandwidth spectrum is divided into number of small slots or channels and each channel has an individual wavelength to transmit data to other end. Both ends of a connection (i.e. Transmitter and receiver) have multiplexers (MUX) and demultiplexers (DeMUX) at their sides. These MUX and DeMUX can multiplex multiple wavelengths at transmitter end and demultiplex these multiple wavelengths at receiver end as shown in figure 2.3[3]. In optical networks, transmitter contains laser and modulator which is used to modulate the signal and to convert the electrical signal into optical signal, while, at receiver end there is a photodiode detector which converts back the optical signal into electrical signal [15].

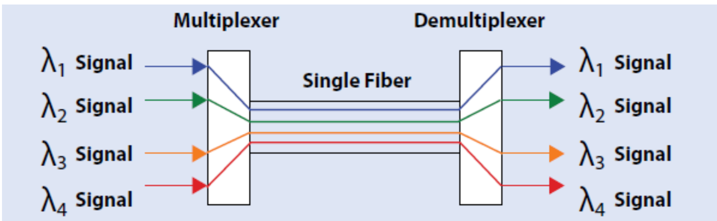

Figure 2.3: Multiplexer and Demultiplexer

The main advantage of the multiplexing technique is boosting up the network capacity many times without using more optical fibers. This gives us the secure and fast communication system as compared to other systems [16].

There are two main types of Wavelength Division Multiplexing shown in figure 2.4[4]. One is Coarse Wavelength Division Multiplexing (CWDM)) and the other one is Dense Wavelength Division Multiplexing (DWDM)).

[3]figure 2.3 source: http://www.fiber-optic-equipment.com/wdm-multiplexer-is-an-ideal-component-optimized-for-wdm-aplications.html

[4]figure 2.4 source: https://community.fs.com/blog/do-you-know-all-these-terminologies-of-wdm-technology.html

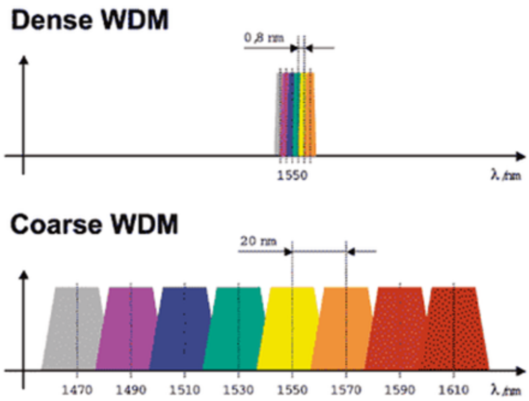

Figure 2.4: CWDM and DWDM

There are 16 active wavelengths in CWDM as compared to DWDM where active number of wavelengths are upto 160. CWDM is designed for short span whereas DWDM is designed for long haul communication.

A brief comparison between CWDM and DWDM is as listed in table 2.1 below:

Table 2.1: Comparison between CWDM and DWDM

Name	**CWDM**	**DWDM**
Active Wavelengths	16	160
Channel spacing	20nm	0.8nm
Geographical span	Short span of 80km	Large span upto 3000km
Channels	16	160 with 50GHz
Cost	Cost Effective	Expensive
Amplifiers	Nil	EDFA
Data rate	2.5Gbps-10Gbps	upto 100Gbps

2.1.2 Advantages of WDM Networks

Wavelength Division multiplexing technology is the base of core optical networks. The features which make it preferable over other techniques are as follows:

1. **Capacity Upgrade**: Due to multiplexing, multiple wavelengths passing through a single fiber simultaneously.
2. **Transparency**: Multiple bit rates and fewer constraints make it transparent.
3. **Wavelength Re-usability**: One wavelength is used multiple times for different links.
4. **Reliability**: Re-routing is possible in case of link failure make network reliable.
5. **Scalability**: It is possible to add more devices in the network on requirement.

2.1.3 Network Design

To design a network in optical domain some steps are given to follow:

Step 1: Logical Topology design

Step 2: Routing and Wavelength Assignment

In first step, LPs are established with the help of traffic matrix or/and physical topology. In second step, connections are established upon these lightpaths between source and destination pair. After finding routes, wavelengths are assigned to these lightpath. This process is called Routing and Wavelength Assignment [17].

After designing, a network data is started to transmit over established routes from sender to receiver.

2.1.4 WDM Algorithms

New technologies or new algorithms are based upon existing WDM algorithms. Some of these algorithms are as follows:

1. Random Fit Algorithm
2. First Fit Wavelength Algorithm
3. Mostly Used Wavelength Algorithm
4. Least used Wavelength Algorithm etc.

2.1.5 Constraints

To assign a wavelength there are two constraints which should be followed:

Wavelength Continuity Constraint: Same wavelength used all over the lightpath from source to destination.

Distinct Wavelength Constraint: On the same link there should be different wavelengths assigned to lighpaths.

2.1.6 Basic Elements of WDM technology

1. **Regenerators:**

   Regenerator has three main functions for an attenuated signal. First of all regenerator re-amplifies the signal, then function of re-timing is done within the regenerator and atlast, it reshapes the signal. When signal looks like the original signal then regenerator transmits the signal from the transmitter to the intended destination. The 3R functionality of regenerator is shown below in figure 2.5[5].

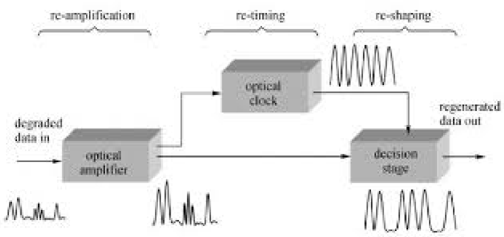

Figure 2.5: Re-amplifying, Re-shaping, Re-timing

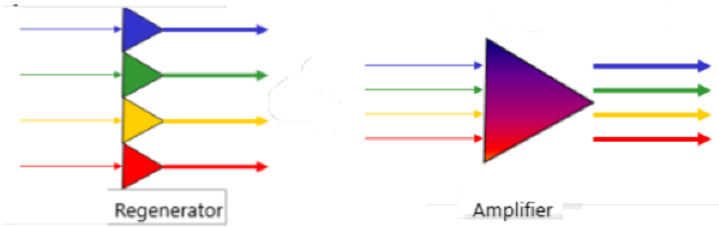

Figure 2.6: Difference between Regenerator and Amplifier

2. **Optical Amplifiers:**

   Optical amplifiers functionality is based upon stimulated emission principle. The attenuated signal in optical fiber is amplified using this principle. Optical amplifier functionality is known as 1R functionality as it works for amplification only unlike regeneratoror which is 3R functional device. The main difference between regenerator and amplifier is that one regenerator is used for only one wavelength out of many wavelengths per fiber, whereas, one amplifier is enough to amplify all wavelengths passing through single optical fiber. Difference is shown in figure 2.6 [6]

   These amplifiers are effective for some specific range of wavelengths[18]. Laser diodes are used for fiber amplification. For gain machanism, population inversion is created through pumping method. The sum of stimulated emission and spontaneous emission make the signal amplified. Spontaneous emission can cause noise along with the gain in optical fiber amplification. There are some applications of optical amplifiers, shown in figure 2.7[7], which are as follows[6]:

[5] figure 2.5 source:All-optical signal processing based on semiconductor optical amplifiers
[6] figure 2.6 source:https://slideplayer.com/slide/4984691/
[7] figure 2.7 source: http://www.fiber-optic-tutorial.com/introduction-of-optical-amplifier.html

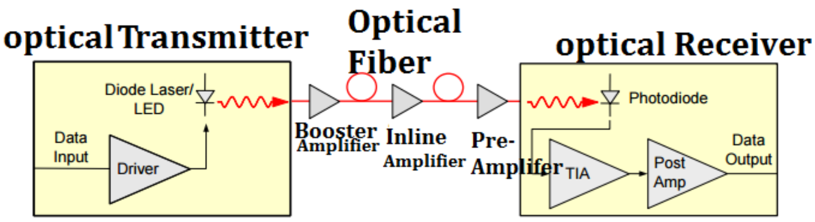

Figure 2.7: Optical Amplifiers in Optical Communication System

(a) **In-Line amplifier:**These are installed on intermediate points along the link to extend the distance and for compensation of loss during transmission of data. These amplifiers are also known as repeaters.

(b) **Pre-Amplifier:** It is used at the receiver to boost the weak signal before photo detector in order to make photo detector more sensative.

(c) **Post-Amplifier:** It is used at the end of transmitter to enhance the power of signal and to make the span larger. The transmission distance can increased from 10 to 100 km.

2.2 Literature Reveiw

In optical communication, high volume data can be transmitted over a large area from source to destination but data quality can be degraded during transmission which results in degradation of information for the intended receiver [19, 20]. In this regard, there are multiple techniques for RP or optical amplifier upgradation in order to increase the optical reach of a signal in the network.

In [4], the researchers worked on Minimal-cost placement algorithm (MCPA) using heuristic approaches. which minimized the blocking of lightpath establishment due to wavelength and transceiver shortcomings. MCPA outperforms other traditional heuristics and gives better results in blocking performance according to number of transceivers, wavelengths, and lightpath spans.

In [21], a heuristic REPARE (Regenerator Placement And Route Establishment) and an ILP solution is proposed. REPARE is proposed for long area networks as ILP does not perform well in this situation. The Pacific Bell network topology is used here. Although proposed ILP solution is realistic but outperforms by heuristic approach in time efficiency, increasing traffic matrix size (size of traffic matrix is directly proportional to number of regenerators required), and wavelength blocking probability.

Synergies between Regenerator Placement (RP) and Regenerator Reduction (RR) are discussed in [22]. In this paper four algorithms are tested for RP purpose and two algorithms are used for RR purpose. Combination of different RP and RR algorithms are examined to minimize request blocking probability and to minimize no, of regenerator. In the result, trade off is observed between number of regenerators saving and spectrum saving. According to this paper, each combination of RP algorithm with RR algorithm gives different results so synergy between algorithm should be chosen wisely.

Impact of different optical fibers and Raman pumping is studied in [7]. Here network is transparent and based on DWDM with 20 nodes random topology. Benefit of Raman Pumping on three different fiber types is evaluated. It results in better performance of NZDSF as compared to other fiber types when used with Hybrid Fiber Amplification (HFA).

In [23],regenerators are minized by using ISC-DBP (Ideal Single Channel- Digital Back Propagation) and lightpath regeneration. Here, three real topologies are considered named as German, Pan-EU, USNET. DBP gives better results for short geographical area but when geographical span is increased DBP fails to remain better. By using HFA, regenrators reduced in a significant percentage from the topologies for large geographical area. In this paper, comparison of DBP (Digital back propagation) and HFA in contrast to lightpath regeneration is done to enable underperforming lightpaths with less number of OEOs.

Chapter 3

Proposed Methodology

This thesis addresses the problem of regenerator reduction and placement from optical LPs by taking optimal number of regenerator into account. For this purpose different modulation schemes and a heuristic approach will be used. This thesis proceeds in three steps.

(i) Path OSNR

(ii) Shortest Path Routing (SPR) / Shortest Path Routing (SPR)

(iii) Heuristic algorithms usage.

3.1 Proposed Technique

In the proposed technique, all links between sender-receiver pair are considered. First of all, the paths are established after routes computation in the topology There are two types of routing algorithms for computing routes which are as follows:

1. Shortest Path Routing (SPR)

2. Multi Path Routing (MPR)

After computing routes of topology path OSNR is calculated using IGN model [17, 24] for each route or link. When a new request arrived, If the path OSNR is above threshold then such link does not require any regenerator. So check availability of the wavelength and allocate the available wavelength to user request considering First-Fit wavelength assignment technique [24]. If wavelength is not available for that user request then follow the proposed procedure. In the second case, when Path OSNR is less than threshold then that lightpath is underperforming lightpath (ULP). The main objective of this thesis is to cope with the problem of ULPs. Therefore, proposed procedure is followed when there is an underperforming lightpath is present in the topology. The procedure to find ULPs from topology for applying proposed techniques is showed by following flow diagram (figure 3.1).

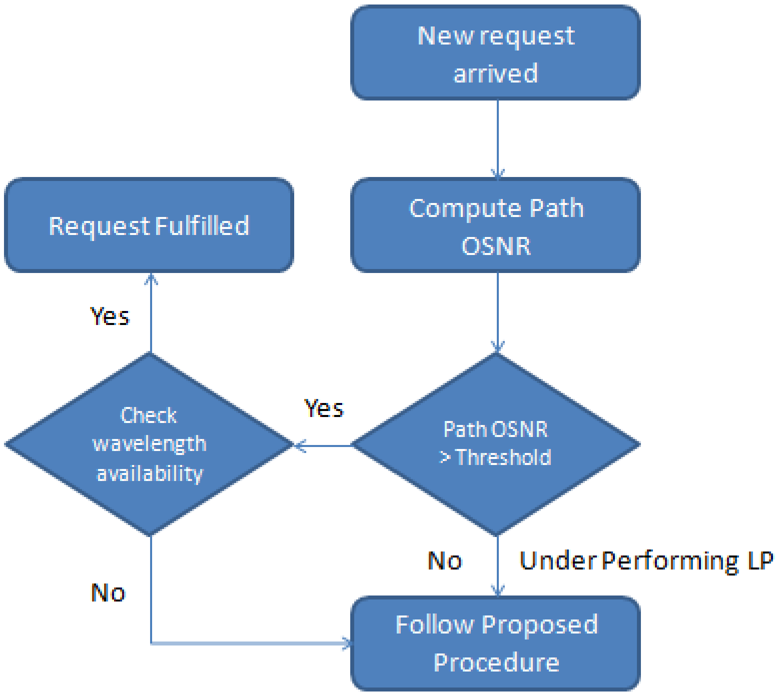

Figure 3.1: Flow Diagram

The steps of proposed techniques are Regenerator Placement (RP) and Regenerator Reduction (RR) Which are done using following algorithms:

3.1.1 Regenerator Placement

1. Compute routes for which # of regenerators are calculated.
   - SPR - Dijkstra Algorithm
   - MPR - K-Shortest Paths Algorithm
2. Calculate # of regenerators for each path and place them at optimal position for each route
   - Min-Stop Algorithm

3.1.2 Regenerator Reduction

1. Reduce number of regenerators using proposed Algorithm
   - Reduced-OEO Algorithm (R-OEO Algorithm)
2. Reduce number of regenerators using amplification
   - Introducing HFA Amplifiers

First of all shortest routes are computed using Yen's Algorithm. The first step of this algorithm is implementation of Dijkstra Algorithm. After computing paths, OEOs are calculated for each shortest path using Path OSNR using Minimum-stop Algorithm. Then apply our proposed algorithm R-OEO Algorithm to pick one of the shortest path while considering the cost (cost due to # of OEOs). The last step of our methadology is using HFAs in our technique.

The Flow Digram of our technique is as shown in Figure 3.2.

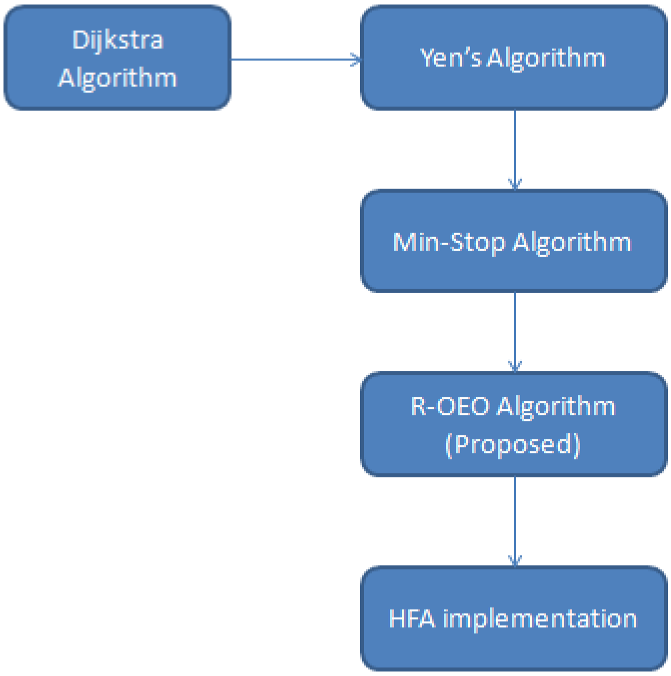

Figure 3.2: Flow Digram of Methadology

3.2 Methadology

In methadology, steps listed in the above section are followed:

3.2.1 Dijkstra Algorithm

Dijkstra algorithm is used to get one shortest path or route from the number of routes based upon cost of that route in any scenario. For example, in the given scenario there are six nodes 0, 1, 2, 3, 4, and 5. Source is node 1 and the intended destination is node 0. Cost of each path between two consecutive nodes is mentioned along the path in given figure 3.3.

Calculate cost of all paths from source node 1 to destination node 0 and pick the shortest route by considering cost. All possible paths along their costs are shown in figure 3.4.

The costs from shortest path to largest path are 65, 78, 109, and 174. So the shortest path out of these four paths picked on the basis of cost is shown in figure 3.5.

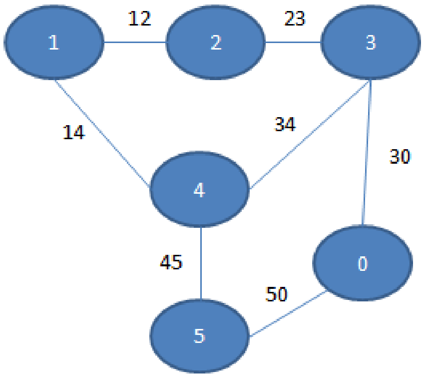

Figure 3.3: 6- node Topology

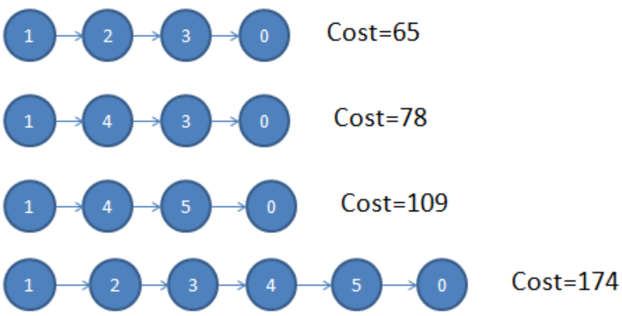

Figure 3.4: All possible Paths

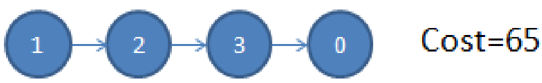

Figure 3.5: Shortest Path

3.2.2 K-shortest paths (yen's) algorithm

Introduction: Yen's algorithm gives K number of shortest loopless paths from source to intended destination. It consists of two parts. One is root path and the other one is spur path. The loopless spur path is obtained by removing the vertices from root path. There are two lists of paths. First list named "A"contains shortest paths and the second list named "B"contains candidate path as in figure 3.6. Candidate path consists of root path in addition with spur path shown in figure 3.7.

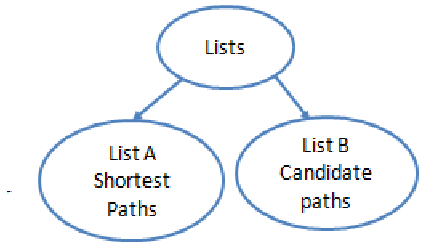

Figure 3.6: Lists in Yen's Algorithm

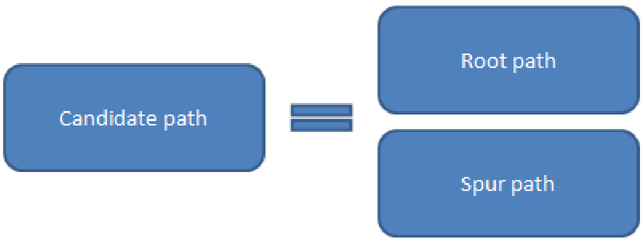

Figure 3.7: Candidate path in Algorithm

Working of Algorithm: According to the 6-node network topology shown in the figure 3.3, where node 1 is the source node and node 0 is the destination.

All possible paths of this scenario are shown in figure 3.8 below:

1. Firstly applying Dijkstra to get shortest path we get path

$$<1, 2, 3, 0>$$

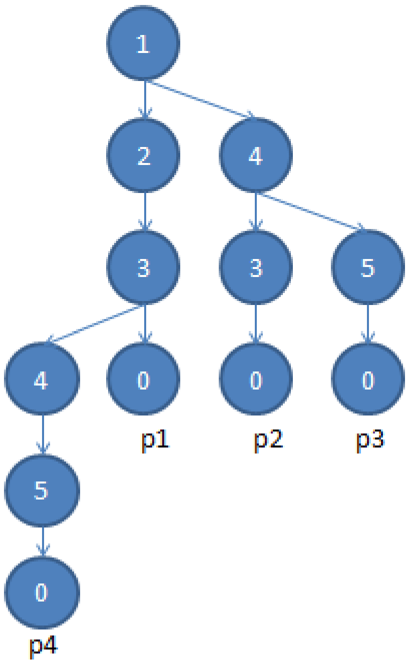

Figure 3.8: All possible Paths

2. Second step is to make node 1 as root and spur at the same time and link between node 1 and node 2 will be removed. This step will give us the candidate path as

$$<1, 4, 3, 0>$$

3. In third step, after making $<1, 2>$root path and node 2 as spur, link between node 2 and node 3 will be removed. This spur path from node 2 to node 0 gives null as there is not any other link between node 2 and node 0.

4. In step four, $<1,2,3>$is root path and node 3 to node 0 is spur path by making node 3 spur and removing direct link between node 3 and 0. Then spur path will be

$$<3, 4, 5, 0>$$

And candidate path will be

$$<1, 2, 3, 4, 5, 0>$$

Now there are 2 candidate entries in list B and 1 shortest path entry in list A as shown in figure 3.9.

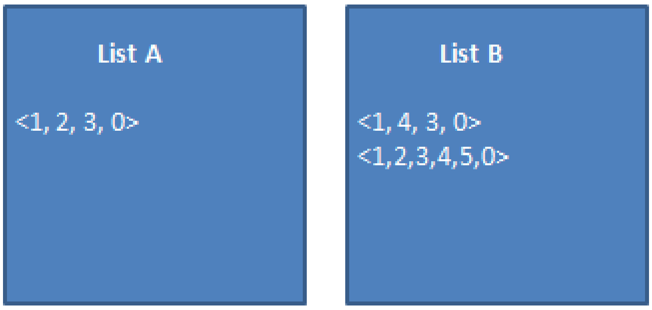

Figure 3.9: Enteries of both Lists

5. The cost of first entry is 78 by adding cost of each vertex between two nodes of candidate entry $<1, 4, 3, 0>$. And the cost of second entry $<1, 2, 3, 4, 5, 0>$is 164.

   As cost of $<1, 4, 3, 0>$is less than cost of $<1, 2, 3, 4, 5, 0>$, so $<1, 4, 3, 0>$will be moved to list A. Now k-shortest paths after execution of Yen's algorithm are shown in figure 3.10

   We get two shortest paths after applying yen's algorithm on above scenario.

Figure 3.10: Shortest Paths

Above algorithms are used to route data from source to destination. Now, Min-stop Algorithm is used to find the number of regenerators required and to find the optimal position to place the regenerator.

3.2.3 Min-stop Algorithm

If any lightpath cannot be reached at its final destination due to OSNR less than threshold then this lightpath is called underperforming lightpath. In this situation, there is a need of placing one or more regenerators on intermediate nodes. The Path OSNR is computed to calculate the number of regenerators required for a lightpath from source to destination. For this purpose, Minimum-Stop- Algorithm [25] is used. This strategy is a greedy strategy as it place regenerator greedily on all of the required nodes.

In Min-Stop Algorithm, firstly we compute the OSNR of the complete lightpath from source to destination. For example, considering the six node path 3.11 from the topology shown in figure 3.3 where nodes are named as 0, 1, 2, 3, 4, and 5 with node 1 as source and node 0 as destination.

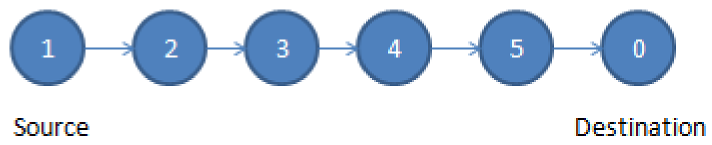

Figure 3.11: 6-node Path

There will be two cases in this situation which are as follows:

Case 1: If OSNR of LP is greater than threshold, then the LP does not need any regenerator and only one lightpath transfers data from source to destination without any regenerator as in figure 3.12.

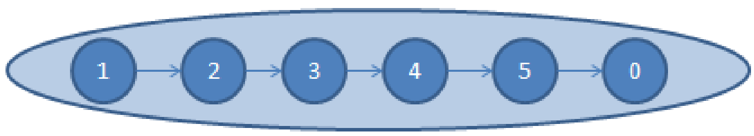

Figure 3.12: OSNR >Threshold

Case 2: If OSNR of LP is below threshold, then find the best node to place regenerator. For this purpose, Path OSNR is calculated from node 1 to node 4 shown in figure 3.13 and from 4 to 0 as in figure 3.14.

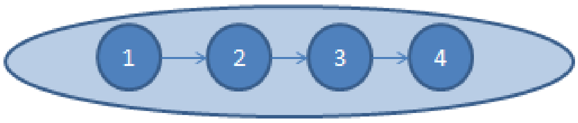

Figure 3.13: Lightpath from 1 - 4

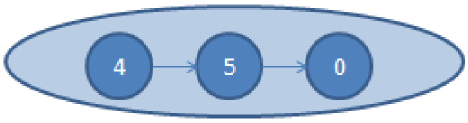

Figure 3.14: Lightpath from 4 - 0

If OSNR of both sections of LP are above threshold, then this underperforming lightpath (ULP) needs only one regenerator at node D.

Above mentioned example shows how to place a regenerator if OSNR of a path is less than threshold. For reduction of OEOs, an algorithm named as R-OEO Algorithm is proposed. This algorithm picks the shortest path with least cost according to number of regenerators and availability of the wavelength in a network topology.

3.2.4 Reduced-OEO (R-OEO) Algorithm

In R-OEO Algorithm, k-shortest paths algorithm is used to get more than one shortest path. After placing regenerators on these paths where required, calculate the cost of each path with regenerators. In the end, pick up the path with the least cost.

The Flow diagram of this algorithm is shown in figure 3.15.

The steps pseudo code will be as follows:

1. Compute k-shortest loopless paths

2. Compute number of regenerators for every path

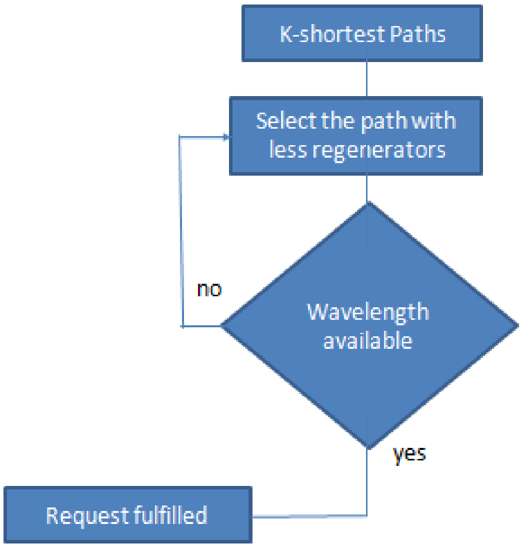

Figure 3.15: Flow diagram of Algorithm

3. Assign costs to the paths according to the regenerators

4. Select the path with the least cost

5. Assign wavelength if available otherwise goto the step 4.

This algorithm shows the improvement in the result of K-shortest algorithm by reducing number of regenerators from topology. But the number of reduced regenerators from topology is too small. Therefore, by applying HFA technology on the results of R-OEO, we get a noticeable reduction in number of regenerators.

Chapter 4

Results

We have use Single mode fiber for the transmission of data where 80 wavelengths are passing from a single fiber. In this setting, QPSK, 8-QAM and 16-QAM modulation schemes are considered in two network topologies named USNET and Pan-EU. Here K=0, K=4, K=6 and K=8 are used. Simulation parameters are as in table 4.1.

Results are checked in three steps. These steps are following:

Step1:

- Each OEO enabled LP is upgraded with HFA without using OEO.
- For each upgraded LP check either LP can be routed transparently or not. If LP is routed transparently then recompute OSNR of these paths, otherwise, goto step 2.

Step 2:

- If LP can be routed with HFA + reduced number of OEOs then this LP is operated through combination of these two technologies, otherwise, goto step 3

Step 3:

- In the last step, LP is operated through only OEOs.

Table 4.1: Simulation Parameters

Simulation Parameters	Values
Fiber type	SMF
Wavelengths	80 /fiber
Dispersion	16.7 ps/nm/km
Attenuaton	0.2 db/km
Modulation Schemes	QPSK, 8-QAM, 16-QAM
Data Rates	100Gbps, 200Gbps
OSNR threshold	8.5 db ,15.1 db
Gross symbol rate	32 GBaud
Equivalent Noise Figure	5 db for EDFA, 0 db for HFA
Topologies	USNET,Pan-EU

4.1 Pan-EU Topology

There are 28 nodes with 41 links in Pan-EU network topology [26] with average link length 637 km. Pan-EU is the European topology of optical inter-networking. The topology of Pan-EU is shown in figure 4.1. Simulation parameters listed in Table 4.1.

In fact, nodes in Pan-EU topology are cities of the Europe. These nodes are named as 0,1,2,3,....., and 27 in this topology. Each node behaves as a source, destination or intermediate node in the topology. Internet traffic volume passed through any node varies from one another.

This results in diversity in Number of OEOs installed on each node. Some of these nodes in this network topology require large number of OEOs (upto 80 OEOs) to be installed on them to make ULP operational. These nodes are located at the center of topology and most of the traffic is passed through these nodes. On the other hand, some nodes does not require any

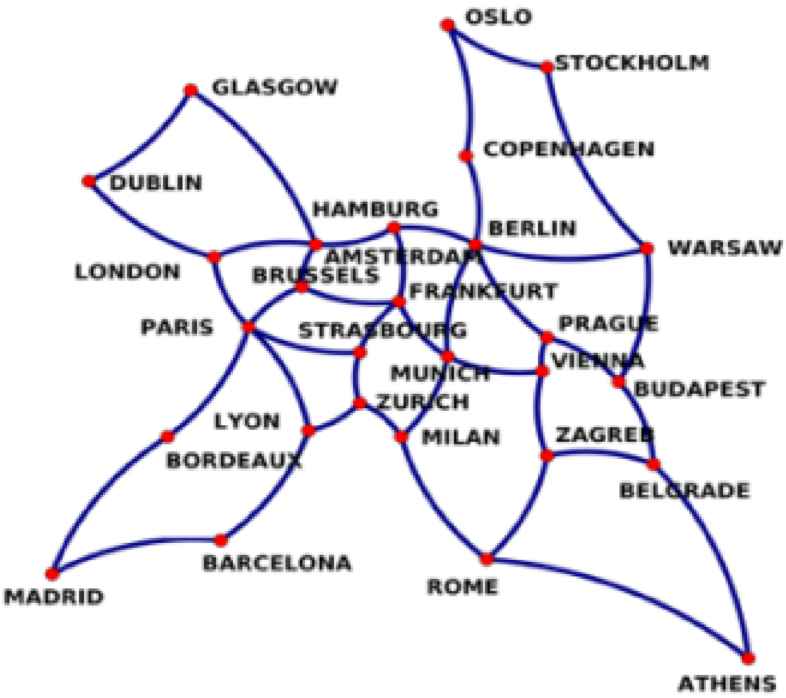

Figure 4.1: Pan-EU topology

OEO. These nodes are located at the corners of the topology so there is a negligible chance that any traffic can pass through it. These nodes are either source node or destination node, however, these corner nodes can not be an intermediate node. Therefore, number of required OEOs depends upon location of that node and the internet traffic volume passing through that node.

4.1.1 Results of yen's Algorithm

After applying yen's Algorithm results of Pan-EU topology for underperforming lightpaths are listed in Table4.2.

In this scenario, K=0 shows the results for SPR or Dijkstra Algorithm while K=4, K=6, and K=8 show the result for MPR i.e., yen's Algorithm for all of these three modulation schemes. In this case shortest paths are picked considering cost of the path. Here, total number of request are 756, these requests can be operational or un-operational according to their need. If all of the requirements are fulfilled in the topology then request will be operational with or

Table 4.2: Results of SPR and MPR for QPSK,8-QAM and 16QAM in Pan-EU Topology

-	QPSK				8-QAM				16-QAM			
-	K=0	K=4	K=6	K=8	K=0	K=4	K=6	K=8	K=0	K=4	K=6	K=8
Operational requests	710	747	755	756	710	747	755	756	680	743	755	756
Un-operational requests	46	9	1	0	46	9	1	0	76	13	1	0
Number of OEOs	0	0	0	0	168	188	197	198	869	1046	1103	1108
Underperforming LPs	0	0	0	0	167	187	195	196	496	559	571	572

without regenerators otherwise requests will be un-operational. There are number of routes which require regenerators to establish LP between source-destination pair. Therefor, LPs with regerators are called Underperforming LP. Number of required regenerators are also listed in Table 4.2.

In QPSK modulation format, there are number of requests which are un-operational in SPR but with the increase in the value of K (in MPR)un-operational requests are decreased and at K=8, there are 0 un-operational requests. In this modulation format, there is no need to install regenerator as there is not any underperforming LP.

In 8-QAM modulation format, there are many LPs which are underperforming in addition with un-operational requests. Like QPSK, number of un-operational requests are reduced to 0 in 8-QAM but by installing regenerator for each ULP in the topology. As there are number of ULPs so regenerators must be installed on each ULP. With the increase in the value of K, number of ULPs are also increased as at K=0 number of ULPs are 167 while at K=8 number of ULPs are 196. On averge, each ULP needs only 1 regenerator.

The case of 16-QAM modulation format is same like 8-QAM modulation format. There are some un-operational requests as well as huge amount of regenerators are also installed in the topology due to ULPs. Un-operational request are decreased to 0 with the increment in the value of K but with the increment in number of regenerators with more number of ULPs. On average, 2 regenerator required for each ULP. There is not any major difference between the trend of 8-QAM and 16-QAM modulation format.

Figure 4.2 shows the number of OEOS required by each node in SPR of 16-QAM for Pan-EU topology at this stage.

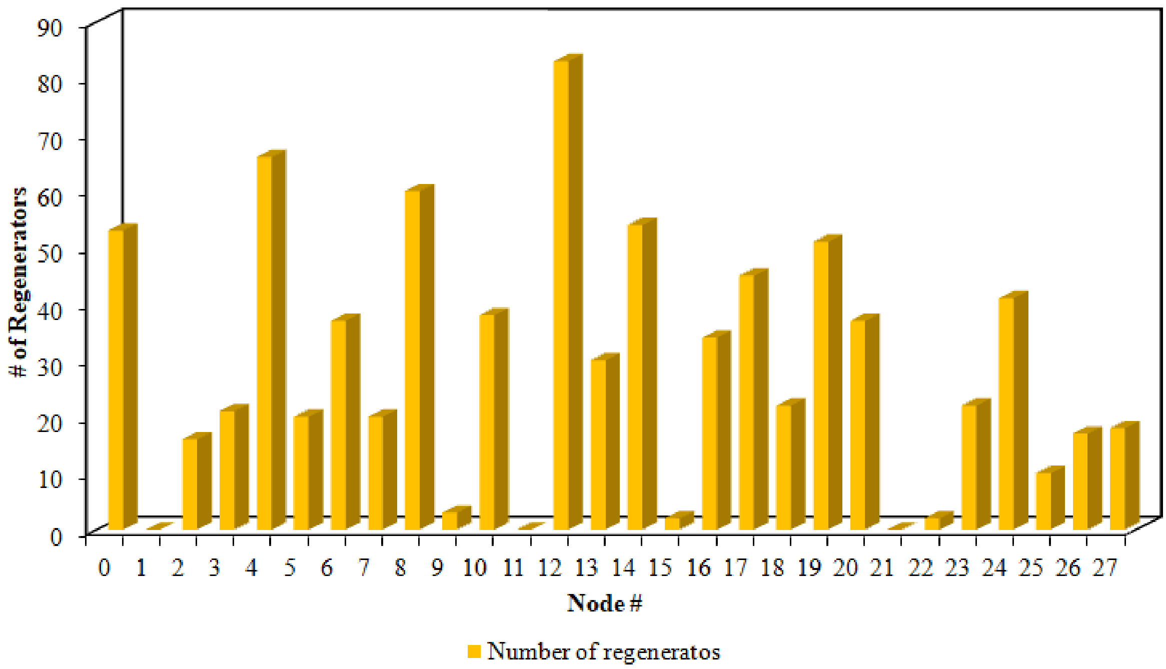

Figure 4.2: # of Required OEOs vs. Node #

4.1.2 Results of R-OEO Algorithm

After applying R-OEO Algorithm on 16-QAM results for underperforming lightpaths are listed in Table4.6

After applying propsed R-OEO Algorithm, it is reviled that some LPs are transparent and does not need any regenerators while other nodes requires OEOs to be installed on them.

Table 4.3: Results of R-OEO

Pan-EU Topology	-
Total LPs or requests	756
Underperforming LPs	572
Required OEO	1056
Average OEO per LP	1.84

According to this result, on average, each node requires 2 OEOs to be installed on them.In Pan-EU topology, results are listed in Table 4.6.

4.1.3 Results of HFA

After using enabling technology of HFA on our proposed algorithm, number of regenrators are reduced upto 75% from topology. Following Table 4.4 depicts the results:

Table 4.4: Results of HFA

ENF	Pan-EU Results
5 db	100% OEO
4.5 db	75% OEO, 20% OEO+HFA, 5% HFA
3 db	40% OEO, 40% OEO+HFA, 20% HFA
0 db	0.35% OEO, 45% OEO+HFA, 55% HFA

In figure 4.3, x-axis depicts the ENF from 5 db to 0 db whereas y-axis shows the ULPs. When enabling technologies of HFA and HFA+OEO are applied upon these ULPs, OEOs are reduced in number which is our main objective. According to this figure, at 5 db ENF, scenario is 100% OEO enabled. With the decrease in ENF value, i.e., at 4.5 db ENF, scenario is 75% OEO enabled whereas 20% of ULPs are HFA+OEO enabled and 5% of these LPs are HFA enabled.

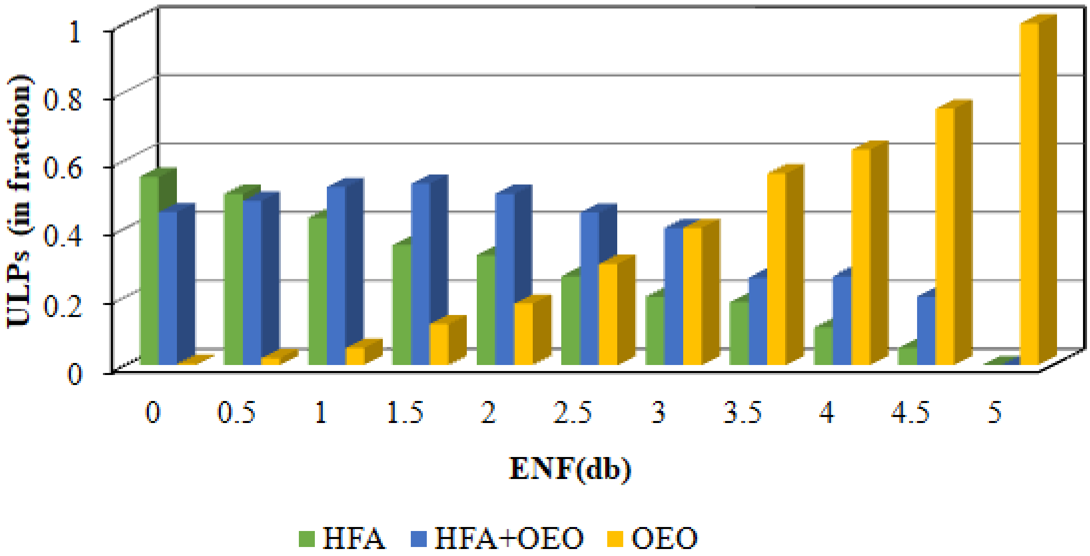

Figure 4.3: ULP vs. ENF

At 2db of ENF, OEOs are reduced in this scenario 20% by HFA only and 17% by HFA+OEO. At 0db ENF, scenario is enabled by OEOs upto 0.35% only, enabled by HFA + OEO upto 45%, and enabled by HFA only 55%. At this value of ENF, scenario is more HFA enabled than HFA+OEO.

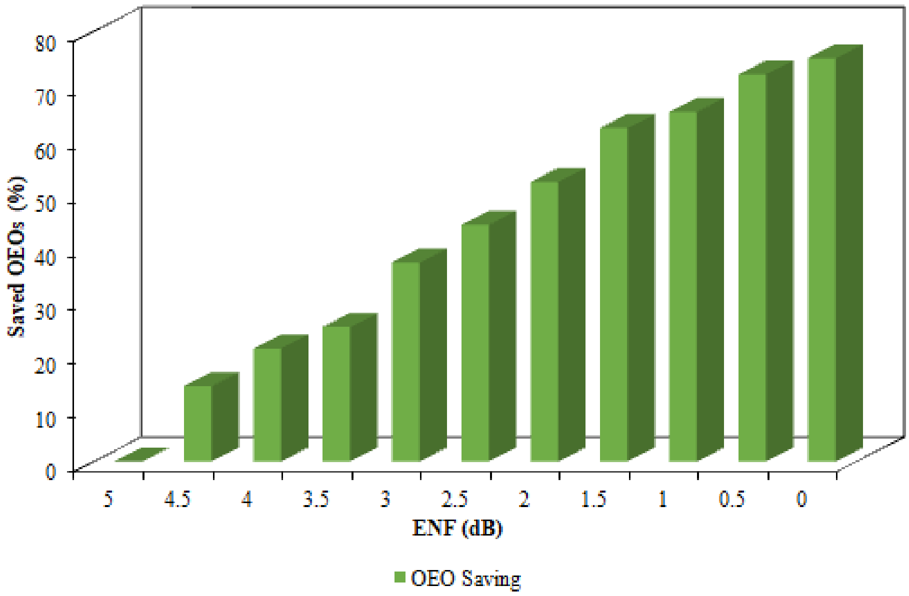

Figure 4.4: OEO saving vs. ENF

OEO savings in Pan-EU topology by introducing HFA in figure 4.4, where ENF is placed upon x-axis and saved OEOs by upgrading network to HFA is placed on y-axis. On average, 15% of OEOs are reduced per db ENF either with HFA + OEO or HFA only. At 2db ENF, there is

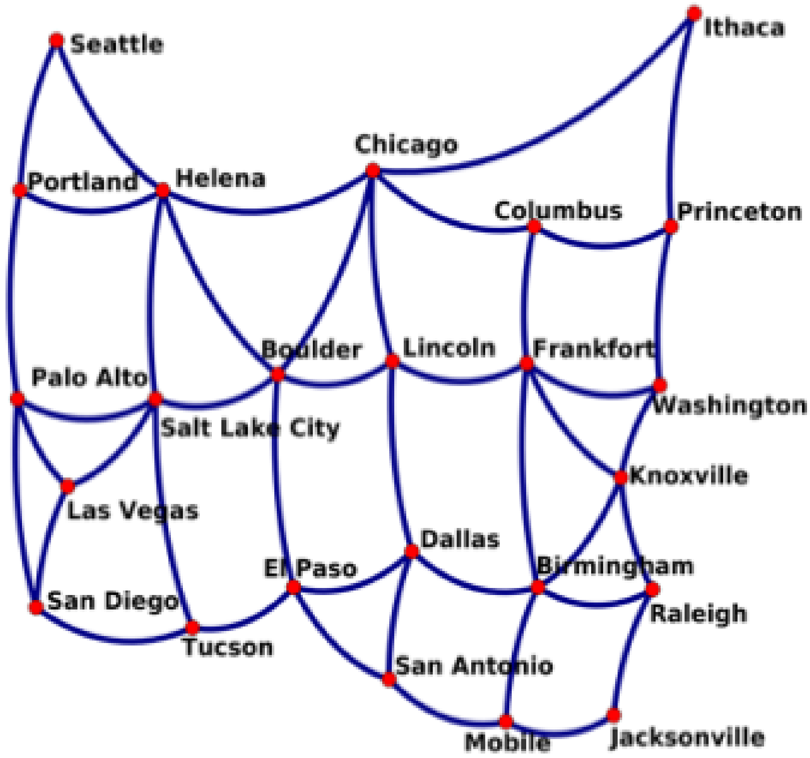

Figure 4.5: USNET TOPOLOGY

50% reduction in OEOs from the Pan-EU scenario. At 0db ENF, reduction in number of OEOs increased to 75%. This figure shows the approximate linear relation between OEO saving and ENF as with the decrease in ENF value, number of saved OEOs are increased.

4.2 USNET Topology

There are 24 nodes with 43 links in USNET topology [27] with average link length 308km. USNET topology is shown in figure 4.5. This topology shows the inter-networking between the nodes of United States and the nodes in this topology showed the cities of US. According to simulation parameters listed in table 4.1, USNET topology results will be as in Table ??.

4.2.1 Results of yen's Algorithm

After applying yen's Algorithm results for underperforming lightpaths are listed in Table4.5.

Table 4.5: Results of SPR and MPR for QPSK,8-QAM and 16QAM in USNET Topology

-	QPSK				8-QAM				16-QAM			
-	K=0	K=4	K=6	K=8	K=0	K=4	K=6	K=8	K=0	K=4	K=6	K=8
Operational requests	552	552	552	552	552	552	552	552	552	552	552	552
Un-operational requests	0	0	0	0	0	0	0	0	0	0	0	0
Number of OEOs	0	0	0	0	0	0	0	0	29	29	29	29
Underperforming LPs	0	0	0	0	0	0	0	0	29	29	29	29

In USNET topology, Total number of requests are 552. For QPSK modulation format all of the requests are operational. This scenario does not require any regenerator to be istalled as there is not any underperforming lightpath. Same trend is shown in 8-QAM modulation format as there is not any ULP, nor any un-operational LP.

In 16-QAM modulation format, there is not any un-operational LP but the underperforming LPs are 29 in number. On average, each ULP requires one regenerator to be intalled on it.

4.2.2 Results of R-OEO Algorithm

After applying R-OEO Algorithm results for underperforming lightpaths are listed in Table4.6

After applying propsed R-OEO Algorithm, it is reviled that some LPs are transparent and

Table 4.6: Results of R-OEO

USNET Topology	-
Total LPs or requests	552
Underperforming LPs	25
Required OEO	25
Average OEO per LP	1

does not need any regenerators while other nodes requires OEOs to be installed on them. According to this result, on average, each node requires 2 OEOs to be installed on them.In Pan-EU topology, results are listed in Table 4.6.

4.2.3 Results of HFA

By using HFA on the results of our proposed algorithm, reduction in OEOs from USNET topology is upto 100% at 3 db ENF. Results are listed in Table 4.7.

Table 4.7: Results of HFA

ENF	Pan-EU Results
5 db	100% OEO
4.5 db	41% OEO, 0% OEO+HFA, 59% HFA
3 db	100% HFA

In figure 4.6, x-axis and y-axis showed ENF and technologies used by ULPs respectively. According to this figure, at 5db of ENF, scenario is fully OEO enabled. But with the decrease of only 0.5 db in ENF, at 4.5 db ENF, remaining OEOs in this topology are upto 41%. At 3 db ENF scenario of USNET becomes transparent as it is fully HFA enabled at this level.

OEO saving in USNET topology through HFA is shown in figure 4.7. Here x-axis shows

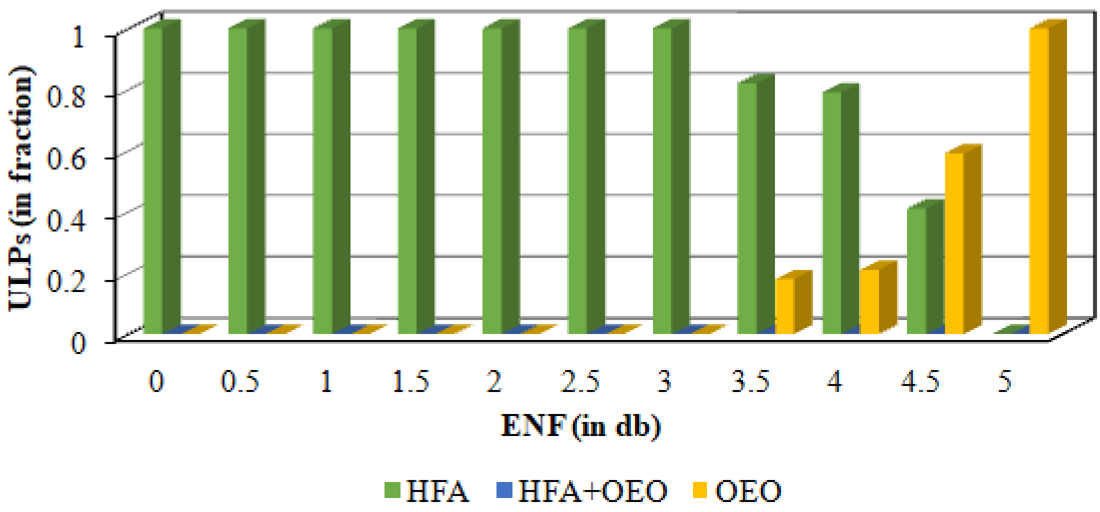

Figure 4.6: ULP vs. ENF

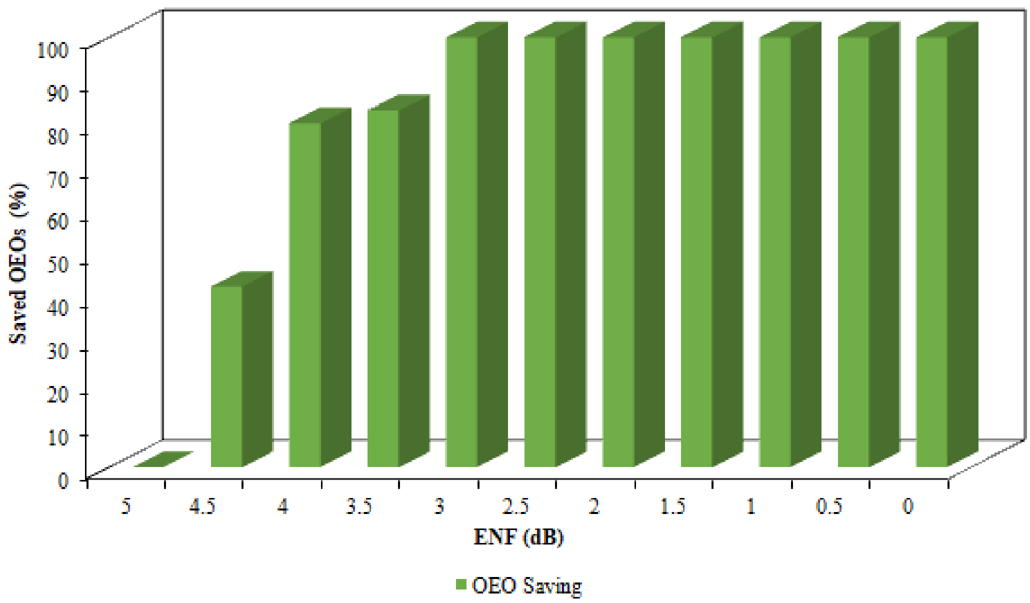

Figure 4.7: OEO saving vs. ENF

the ENF values while saved OEOs are showed by y-axis. In this figure, at 5 db of ENF value, network topology is 100% OEO enabled. With the decrement of .5 points in ENF value, i.e.,4.5 db ENF, saving of OEOs increased upto 59%. At 3 db ENF, topology is 100% HFA enabled. At this stage, this network topology becomes a transparent network. Therefore, no more HFAs are required in this topology after ENF reached to the value of 3db.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This thesis addresses the problem of underperforming lightpaths in a network topology. In case of placing OEOs in LPs, network topology costs alot. To reduce OEOs from LPs in Pan-EU and USNET topologies, Optical line amplifiers were upgraded to some extent. This upgradation in optical line amplifier (EDFA) enables HFA or OEO+HFA to reduce OEOs from topologies. In Pan-EU, reduction in OEOs is 75% at 0db ENF whereas in USNET, OEOs reduced to 100% at 3db ENF.

5.2 Future Work

The proposed technique is inversely proportional to the network size. This technique will become less effective with increase in the network size. Thus, there should be more efficient technique to remove OEOs to make network transparent.

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