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Optimal Regenerator Placement for Dedicated Path Protection in Impairment-Aware WDM Networks

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by

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Abstract

Building resilient Wavelength Division Multiplexed (WDM) optical networks is an important area of research. This thesis deals with the design of reliable WDM networks where physical layer impairments are taken into account. This research addresses both the regenerator placement problem (RPP) and the routing with regenerator problem (RRP) in impairment-aware WDM networks, using dedicated path protection. Both the problems have been tackled using linear Integer formulations which can be implemented, using a solver such as the CPLEX. For solving RPP, two solutions have been proposed i) a formulation that gives optimal solutions which works only for small networks, and ii) a highly effective heuristic which given an optimal solution in 97.5 to 99% of cases for networks having a size up to 60 nodes.

Dedication

Dedicated to my wife, Geeta

and my two sons, Davin and Arvin.

Acknowledgement

Sincere thanks to my supervisors, Dr. Subir Bandyopadhyay and Dr.Yash Aneja, for their patience and support. This work could not have been achieved without their help and guidance.

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List of Acronyms

ALD - Ad hoc Lightpath Demands

ASE - Amplified Spontaneous Emmission

BER - Bit Error Rate

CD - Chromatic Dispersion

DLD - Dynamic Lightpath Demands

DPP - Dedicated Path Protection

FC - Filter Concatenation

FWM - Four Wave Mixing

IL - Insertion Loss

ILP - Integer Linear Programming

OSNR - Optical Signal-to-Noise Ratio

PDM - Polarization Dependent Loss PLI - Physical Layer Impairments

PMD - Polarization Mode Dispersion

QoT - Quality of Transmission

RPP - Regenerator Placement Problem

RRP - Routing with Regenerator Problem

RWA - Routing and Wavelength Assignment

SBS - Stimulated Brillouin Scattering

SLD - Static Lightpath Demands

SPM - Self Phase Modulation

SRS - Stimulated Raman Scattering

O/E/O - Optical-Electrical-Optical

WDM - Wavelength Division Multiplexing

XPM - Cross Phase Modulation

XT - Cross Talk

1 Chapter 1 - Introduction

1.1 Preamble

Optical networks are used to transfer large amounts of data, at high speed, over a wide geographical area. However, the quality of an optical signal degrades as the signal propagates through an optical network. As a result, reliable communication of an optical signal is limited to a certain distance. To overcome this limitation, certain techniques are used, so that networks can operate over a large geographical area. Another important aspect of backbone network design is the high volume of data (of the order of terabits per second) communicated by any fiber in an optical network. If this communication is interrupted, due to faults within the network, the results can be disastrous. We therefore need to design networks in a way that they:
i) take account of the degradation of optical signals proagating through a network, and
ii) handle faults, which will inevitably occur.

In this thesis, we focus on optical networks in which the nodes are sparsely populated over a wide geographical area. The main objectives of this thesis are as follows:

- design a network that will be able to be fully functional, taking account of the effects of signal degradations, and
- include sufficient redundancies, so that it will continue to operate even if any of the most common faults occur.

To define the problem and the methodologies we will use, we briefly discuss some of the terminologies that are used.

1.1.1 Wavelength Division Multiplexing (WDM) Networks

Wavelength Division: The range of frequencies that is available for data transmission is referred to as the *bandwidth* (e.g. the C-band is the range of frequencies used in optical networks). In the first generation optical networks, the entire bandwidth was utilized by a single carrier frequency (commonly referred to as a *carrier wavelength* in optical networks using the C-band) for data transmission. However, *wavelength division multiplexing* (WDM) provides a more efficient way to utilize this vast bandwidth. In WDM networks, the bandwidth is divided into non-overlapping ranges of frequencies, called *channels*, where each channel corresponds to a different carrier wavelength and is capable of transmitting data independently of the other channels. Figure 1 below, illustrates the division of the available bandwidth.

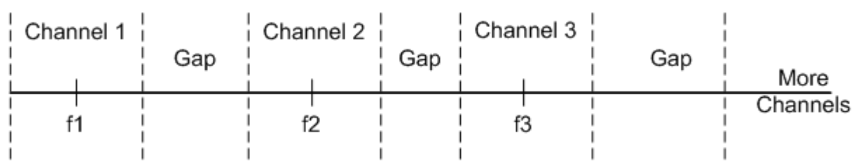

Figure 1: Channels and interchannel gaps

Lightpath: Signals travel through optical fibers in the form of laser beams (light). A source node S communicates with a destination node D, using an optical signal propagating from S to D through the fiber network. A connection in the optical domain from a source to a destination is called a *lightpath*. A lightpath from S to D is characterised by a *path*, from S to D through the physical topology, and a carrier wavelength, λ, which is used for communication through each link of the path. Figure 2 shows a four-node network with two lightpaths, L1 and L2. Here we assume that each link consists of only two optical fibers (one in each direction). For instance, lightpath L2, uses a physical path having two links, the link from node 1 to node 2 and the link from node 2 to node 4, using wavelength λ_2 on each link. Several lightpaths can be transmitted on a single fiber, provided they are transmitted using different carrier wavelengths.

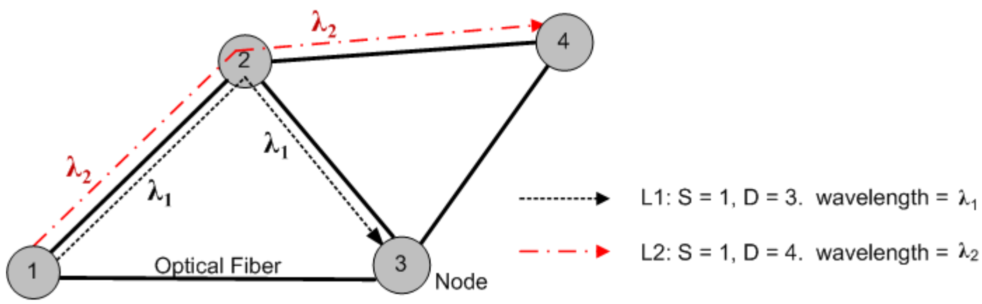

Figure 2: Concept of a lightpath

Routing and Wavelength Assignment: *Routing and wavelength assignment* (RWA) is used to provision each lightpath within an optical WDM network. A lightpath must be routed through a physical path within the network, from a source node to a destination node and an available carrier wavelength must be assigned for each link of the physical path. Each request for communication must be handled by at least one lightpath. The main objective is to handle as many requests for connection as possible. According to [Jue, 2001], the objective is to choose a route and a wavelength which maximizes the probability of setting up a given connection, while at the same time attempting to minimize the blocking of future connections.

1.1.2 Impairments

As stated earlier, in optical networks, the quality of a signal degrades as the signal propagates through a fiber network [30]. These degradations are caused by physical layer impairments (PLI). As the distance increases, the effects of PLI are more pronounced and the signal degrades even more. In other words, the distance a signal can travel along an optical fiber is limited and the maximum distance it can travel and still be useful for communication is called the *optical reach*. If a signal propagates beyond the optical reach, it will become so degraded that it cannot be used for reliable communication.

1.1.3 3R-Regeneration

To extend the range of an optical signal beyond the optical reach, special devices called regenerators, are used to Re-shape, Re-time and Re-amplify the signal. This process is known as *3R-regeneration*. After 3R-regeneration, a signal is restored to its original strength, so that it is able to travel another distance up to the optical reach. This process can be repeated indefinitely. Regenerators are thus used to extend the range of a signal to any geographical distance. A *regenerator-capable node* is a node that is equipped with one or more regenerators.

1.1.4 Network Faults and Failures

Failures: A network may fail for various reasons, but the most common type of failure is link failure. In a *link failure*, the communication between two adjacent nodes is disrupted due to a fault in the fiber connecting the two nodes. A failed link may be as simple as a slack connection, a fiber cut or the result of noise, introduced by the optical components. As mentioned earlier, each fiber in a WDM network uses many channels, where each channel carries data at 10 – 100 Gb/sec. As a result, a link failure may lead to huge data loss. Thus, it is very important that, during the design phase, the possibility of such faults be taken into account.

Fault-Management: Fault management is necessary to ensure network resilience and survivability. That is, a network should remain fully functional even when certain failures occur. One way to address link failures is to set up two lightpaths for each request for communication, say from a source node, S to a destination node, D. A working lightpath, called the *primary lightpath*, is used to establish the communication from S to D. At the same time provision is made for a second lightpath, called the *backup ligthpath*, which will be used to re-establish communication from S to D in the event of a failure of any link used in the primary lightpath. To ensure that the primary lightpath and the backup lightpath do not fail at the same time, the primary path and the backup path must not share a common link. This type of fault management scheme is known as *dedicated path protection* (DPP).

1.1.5 Impairment-aware RWA with DPP

In *impairment-aware RWA*, there are two main problems to consider, the impairments and the assignment of a route for each communication and the carrier wavelength. To mitigate against impairments, selected nodes are identified for the installation of regenerators, at design time. Here, we want to select a minimum number of nodes, at which regenerators should be placed, such that a signal from any source node, S, to any destination node, D, will not be required to propagate, without being regenerated, beyond the optical reach. In other words, before the signal is communicated over a distance that exceeds the optical reach, a regenerator must be available to regenerate the signal. This problem is known as the *regenerator placement problem* (RPP) [7], [26] - [29].

Once the regenerators are in place, the network can start operating. In response to requests for communication, lightpaths have to be set up. When a communication is over, resources devoted to the communication have to be reclaimed for future use. If there is a request for a communication from a source node, S, to a destination node, D, the problem is to make provisions for an impairment aware RWA from S to D. This is referred to as the *routing with regenerator problem* (RRP) [2] - [4], [11], [23], [38], [42] - [43].

RPP for DPP: In this thesis, we consider RPP for DPP. This aspect of the work is carried out during the design phase. Given an impairment-aware network, we want to find the minimum number of regenerator-capable nodes such that, for every request for communication from a source node S to a destination node D, it is always possible to find a primary path and a backup path from S to D with regenerators available, when needed [27].

RRP for DPP: Once the regenerators are placed at the selected nodes, the network can start operating. During this phase, requests for communication are processed as and when they arrive. In response to a communication from a source node S to a destination node D, the RWA algorithm has to allocate resource for a pair of light-paths, both from S to D, to establish the primary lightpath, and to make provisions for the backup lightpath. If two or more pairs of feasible paths are available, we want to choose a pair of paths, such that the total number of regenerators used (one at each regenerator-capable node for each lightpath) is minimum. A request for communication is satisfied, if a pair of lightpaths can be provisioned. If such lightpaths cannot be provisioned, the request is blocked and is deemed to be unsuccessful.

Example of RPP and RRP: Figure 3 illustrates the process involved in RWA with DPP. Here, we are initially given an impairment-aware optical WDM network. To avoid the situation of an optical signal degrading to an unacceptable level and to ensure reliable communication, regenerators are placed at selected nodes so that there will always be two edge-disjoint paths from every node to every other node (RPP with DPP). We then use the RWA algorithm to allocate two edge-disjoint lightpaths to satisfy a request for communication (RRP with DPP).

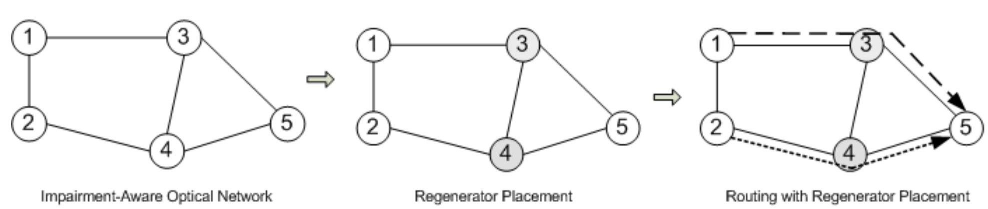

Figure 3: RPP and RRP with DPP

1.2 Scope of the thesis

In this thesis we have investigated the following problems (RPP and RRP):

1. We have proposed two approaches for RPP using dedicated path protection.

    - The first approach gives an optimal regenerator placement scheme. This works only for small networks (networks having at most 11 nodes), due to the complexity of the algorithm.
    - The second approach uses a heuristic that may be used for practical-sized networks. This does not guarantee an optimal solution but our experiments reveal that, in most cases, it does give the optimal solution.

2. We have proposed a scheme for RRP using dedicated path protection.

Both approaches for RPP and the algorithm for RRP use formulations based on Integer Linear Programs [35] and can be solved using a commercial solver such as CPLEX.

1.3 Organization of thesis

The rest of this thesis is organized as follows: Chapter 2 provides a review of some of the concepts and terminologies that are related to this work and provides more details of the areas related to this research. It also includes a review of some of the related work by other researchers. In Chapter 3, we formally define the problem and present the proposed algorithms for RPP and RRP. In chapter 4, we present the results of the experiments we carried out. In Chapter 5, we present some future work and conclude the thesis.

2 Chapter 2 - Review

In order to make this thesis a self-contained document, so that readers can gain a better appreciation of the problem and the proposed solution, we provide a review of the essential topics that are of interest. However, these explanations are not exhaustive in any way and only serve as a guide for this thesis.

2.1 Optical Networks

A network has often been characterized by the communication medium it uses. For example, if we are using wireless medium for communication (radio waves, micro waves, etc), we talk about wireless networks. This parallelism is also applicable to optical networks in that an optical network uses fiber optics cable (a bundle of one or more optical fibers, held in a single jacket) as the medium of communication. Figure 4 below, shows a picture of a fiber optic cable, consisting of several bundles of optical fibers [Image taken from http://www.google.ca].

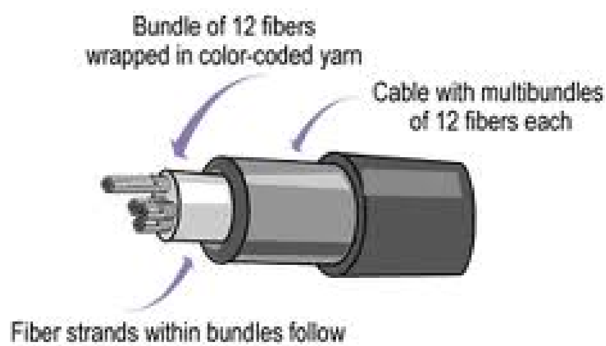

Figure 4: Fiber Optics Cable

There are many variants of optical fibers (single mode, multimode, step index, graded index, etc), but in its simplest form an optical fiber consists of a thin inner cylindrical core, made of high-quality glass (or plastic), a cladding, (also made of the same material), that surrounds the core and two protective layers (buffer coating and jacket), as shown in Figure 5. [Image taken from http://www.cablewholesale.com]

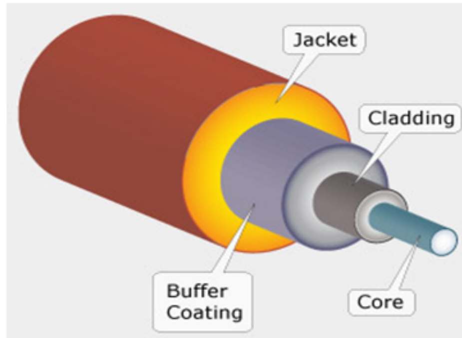

Figure 5: Cross section of an Optical Fiber

The main focus is on the inner core and the cladding. Signals travel through the core in the form of light (laser beams) and these signals are guided by the cladding, resulting in very low attenuation or loss of energy. The general principle involves the concepts of refraction and total internal reflection. When light is incident on a surface that is of lower refractive index, it bends away from the normal (the line in the plane of the incident ray and reflected ray that is perpendicular to the surface). As the angle of incidence, θ, increases the angle of refraction increases, until for some value of θ, the angle of refraction is 90 degrees. This angle is know as the critical angle, c. For angles of incidence greater than the critical angle, there will be no refracted ray and almost all the light will be internally reflected. This phenomenn is know as *total internal reflection*. Figure 6 illustrates the concepts of refraction and total internal reflection.

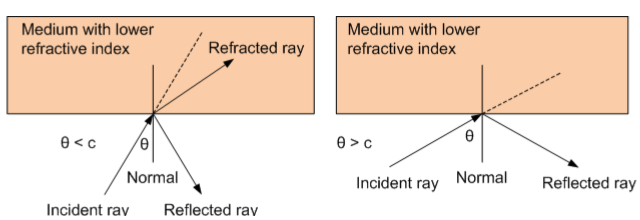

Figure 6: Refraction and Total Internal Reflection

Although both the inner core and the cladding are made of the same material, their optical densities are different. In this case, the cladding is less optically dense. As such, when light incident on the cladding, through the core, at an angle greater than the critical angle, almost all the light will be internally reflected by the cladding back into the core (a very small percentage will be absorbed). This causes the signals to remain inside the core and to be propagated by a series of total internal reflections as shown in Figure 7. It is this optical signal, inside the core of an optical fiber, that facilitates data transmission.

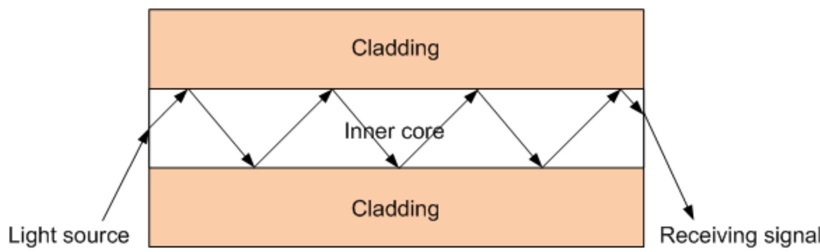

Figure 7: Propagation through total internal reflection

2.2 Data Transmission

In an optical network, data communication is achieved by the use of transmitters and receivers at the source and destination of the lightpath, respectively. The main component of a transmitter is a laser diode (used to provide a beam of light), while the main component of a receiver is a photodetector (used to detect a beam of light). Laser diodes use a wide range of frequencies of light to produce a coherent light source that can be considered as a single wavelength of light. However, in reality it has a very small range of different wavelengths. The terms wavelength and freqency can be used interchangebly, due to their relationship in the equation $c = f\lambda$, where f is the frequency, λ is the wavelength and c is a constant, the speed of light within the medium.

The frequency of this light source is referred to as the carrier frequency and it is this frequency that is modulated to transmit the data. The digital data is used to modulate the carrier frequency. This is, the carrier signal is combined with the digital signal to produce a modulated signal. This modulation may be very complex or as simple as *On/Off keying*, where a 1 (one) may be represented by the amplitude of the carrier frequency and a 0 (zero) may be represented by a peak amplitude of zero. Figure 8 shows an example of a carrier frequency, the digital data and the modulated signal, using on/off keying.

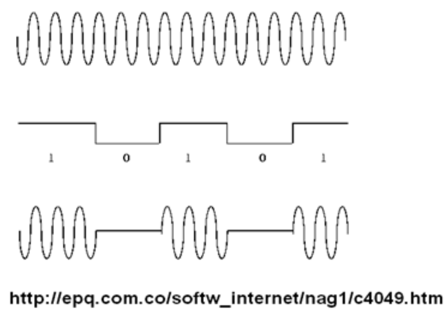

Figure 8: Modulation - On/Off Keying

At the receiving end, the receiver detects the optical signal (via the photodetector) and converts the detected signal into an electrical signal, after which the data can be stored. It is worth mentioning that the detected signal may not be the same as the original signal sent, due to physical layer impairments (PLI). as described in Section 2.4. It is also interesting to note that data cannot be stored in optical form.

2.3 Wavelength Division Multiplexing (WDM)

The range of frequencies that is available for data transmission is referred to as the bandwidth. Traditionally, the entire bandwidth uses a single carrier frequency for data transmission. However, Wavelength Division provides a more efficient way to utilize this bandwidth. Using this technique, we divide the entire range of frequencies into non-overlapping subsets of frequencies, called channels, with each channel used to transmit data using an appropriate carrier frequency.

The channels are separated by suitable inter-channel gaps to avoid inter-channel interference and disturbances. However, the gaps are also chosen to obtain as many channels as possible. Figure 9 shows a schematic diagram of the channels, carrier frequencies and inter-channel gaps. To avoid certain types of interference, the channels are unevenly spaced. That is, the sizes of the inter-channel gaps are not necessarily the same.

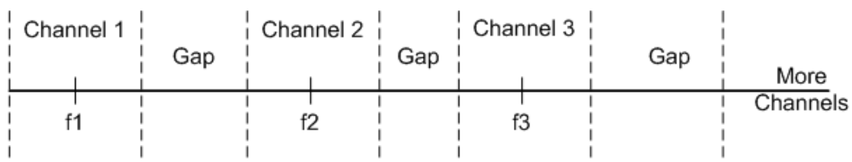

Figure 9: Channels and interchannel gaps

In WDM networks, the signals are generally referred to by the different wavelength of each channel, instead by the carrier frequency. Using WDM systems, the optical signals (of different wavelengths) are combined together as one composite signal (multiplexed) and propagated along the fiber. At the receiving end, this composite signal is separated (demultiplexed) into the original signals. As such, by using WDM systems, we can transmit data on multiple channels, using a single fiber. Figure 10 shows a schematic diagram of a WDM system with five channels (having wavelengths λ_1 to λ_5) that are multiplexed, transmitted and demultiplexed.

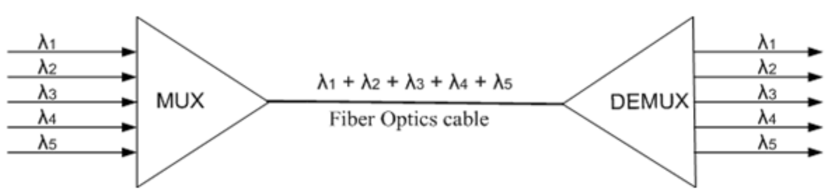

Figure 10: WDM System

As such, Wavelength Division Multiplexing allows us to transmit multiple signals using a single fiber. Typically a single fiber can have several hundreds of channels.

Each channel is capable of transmitting at a rate of 10, 40 or even 100 gigabits per second. This has been the main contributing factor for the high speed of data communication in optical networks. In fact, in 2012, NEC, Corning recorded an effective speed of 1.05 Petabits per second, using WDM channels on a 12 core cable.

2.4 Physical Layer Impairments (PLI)

It is worthwhile to mention here that light is not susceptable to electromagnetic interference or indeed, any outside influence. It is also important to understand that PLI are not necessarily defects, but characteristics of the fiber. A nonuniform fiber with chinks (irregularity in its cylinderical geometry) can also lead to certain impairments.

As an analogy, when we speak, our voices will not always be heard clearly. It is dependent on the amount of noise around us and on how far the listener is away. The facts that noise and loss of energy will corrupt our voice is not a defect of the air around us. In the same way, as an optical signal is transmitted and propogated across an optical network, it encounters many impairments, both in the fiber links and in the optical components (such as optical amplifiers and optical cross connects), that affect the characteristics of the signal. The further a signal travels through an optical network, the more pronounced are the effects of these impairments. After a certain distance, the signal will lose its configuration and becomes too degraded to be correctly decoded by the receiver, resulting in errors in transmission. As such, the overall effect of PLI affects the signal quality and hence, determines the feasibility of the lightpath [2], [30], [37] - [38].

The *Quality of Transmission* (QoT) is an indication of how feasible a lightpath is, for data communication. There are several indicators that are used to measure the QoT, such as the Optical Signal-to-Noise Ratio (OSNR) and the Q Factor. These are used to calculate the bit error rate. The *bit error rate* (BER) is the ratio of the number of bits that have been received incorrectly, due to errors in transmission to the total number of bits transmitted, over a period of time.

OSNR: The *optical signal-to-noise ratio* is the ratio of the signal power to the noise power. OSNR may be monitored or estimated using analytical models. For linear impairments, these values can be measured for different lengths of the optical fiber. In particular, the OSNR at the sourse and the OSNR at the destination can be measured. The OSNR can also be used to calculate the bit error rate. Ideally we want the OSNR to be high. That is, high signal power and low noise power.

Q Factor: The *Q Factor* (Quality Factor) is also an analytic measure of certain linear impairments and can also be used to calculate the BER. It combines the separate OSNR for the two signals used to indicate a 0 or a 1.

As can be seen, the desired measure of the QoT is the BER. If the BER is fairly low, we can use certain techniques to recover from the few errors and the QoT will still be acceptable, despite the presence of these errors. However, if the BER is so high that we canot adequately recover from these errors, we say that the QoT is unacceptable and that the lightpath is not feasible for data communication [17].

We usually fix an acceptable average BER and then determine the maximum length of fiber over which data can be transmitted such that the amount of degradation will not go beyond this BER and the signal will not be allowed to lose its configuration. However, this is not as easy as it sounds due to the varying effects of some of these impairments.

There are three main causes of physical layer impairments:

1. *Attenuation*, which is the loss of signal strength,
2. *Distortion*, which occurs when there are multiple signals combined together to form a composite signal that results in the combined signal changing its form and shape, and
3. *Noise*, which are unwanted signals that corrupts the desired signal.

We can also classify physical layer impairments as linear or nonlinear impairments.

2.4.1 Linear Impairments

Linear impairments are independent of the signal power and affect the channels individually. These are caused by Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Attenuation, Filter Concatenation (FC), Crosstalk (XT), Amplified Spontaneous Emission (ASE), Insertion Loss (IL) and Polarization Dependent Loss(PDL). Some of the key causes of linear impairments are discussed below:

Amplified Spontaneous Emission: In laser amplifiers, energy excites the electrons in a laser crystal and these electrons get to a higher state. However, because of their desire to return to their original state, these electrons give up the energy by emiting a photon (a particle of light). The stimulated emission of photons are used to amplify a signal. However, in this process of amplification, there are uncontrolled spontaneous emissions (light) that goes in all directions and some of this light gets into the core of the fiber. More so, this unwanted light wave does not correspond with the phase and timing of the desired signal. Nonetheless, they are also amplified with the desired signal, resulting in noise (unwanted signals) that corrupts the desired signal. This type of impairment is known as *Amplified Spontaneous Emission* (ASE) Noise. Also, even when a signal is not present, ASE may produce an unwanted signal that may lead to data communication errors. ASE noise weakens the signal gain from laser amplifiers and impact negatively on the OSNR and hence the QoT.

Chromatic Dispersion: *Chromatic Dispersion* (CD) has to do with the fact that the different wavelengths of light do not propagate with the same velocity. In a fiber, each component (individual wavelength within a small range) of the light source will propagate at a different velocity. When these velocities are sufficiently different, the signal may become corrupted, due to interference between these wavelengths. The main problem is that of timing. In a signal, the different wavelengths of the light source will arrive at the destination at different times, resulting in degradation of the signal. CD is dependent on the actual wavelength of the light used and increases with distance. It is considered a significant cause of linear impairment.

Polarization Mode Dispersion: *Polarization* is the plane in which the electrical signal is travelling. When light is emitting from a laser it is polarised in the same way, for coherence. However, as the signal travels further, the range of angles increases and the coherence of the polarization broadens, leading to distortions.

In reality, due to the non-uniformity of the fiber, light components which normally travels at the same speed, willl travel at different speeds. This results in the loss of coherency (spreading of the light due to increase in the range of angles) and distorts the signal. PMD has a similar effect to that of CD, but PMD is not dependent on the wavelingth used, but on the polarized dispersion from the plane in which the signal is travelling.

2.4.2 Nonlinear Impairments

Nonlinear impairments are significantly more complex than linear impairments and can be considered as dynamic in nature, as they not only affect the channels individually but also cause disturbance and interference between them. More so, the different types of fibers (standard single mode fiber, dispersion shift fiber, dispersion compensated fiber) have varying effects as a result of nonlinear impairments. Nonlinear impairments are caused by Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four Wave Mixing (FWM), Stimlated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS). Although SBS and SRS are present, they have little effect on the QoT. Two of the key nonlinear impairments are discussed below.

Self Phase Modulation: Laser beams are susceptable to what is called the *AC Kerr effect*. That is, when a beam of light travelling in a fiber undergoes a phase shift, due to the variation in the refractive index. This effect causes the different components of light to travel at different velocities, resulting in distortions.

Cross Phase Modulation: *Cross Phase Modulation* (XPM) occurs when the optical intensity of one lightpath produces a phase change in another lightpath. It is similar to SPM except that the effect is not triggered by the lightpath itself but a different lightpath. This leads to channel cross-talk and produces amplitude and timing jitters.

2.5 Optical Reach - Maximum distance Constraint

From the above examples, we can recognize that optical signals that are transmitted suffers from PLI which negatively impact the QoT, especially as the distance increases. More so, in WDM networks, increasing the number of WDM channels or decreasing the inter-channel gaps leads to higher interference and poorer signal quality. It is therefore important to mitigate these constraints. One such technique is to use a single constraint, known as the maximum distance constraint [33].

As an optical signal travels along a fiber, we can analytically measure the effects of linear impairments. One such measure is the OSNR for a given BER. However, a more practical way is to measure the QoT based on the distance the signal will have to travel through the fiber. As the signal degrades sufficiently over distance, the effect on the QoT will be felt. After a certain distance, the signal will lose its configuration, causing the BER to become unacceptable and beyond that distance the signal will not be useful for data communication. This is known as the maximum distance constraint and is the maximum distance the signal can travel to facilitate communication. Figure 11 shown a schematic diagram of this measure. First, we fix an average acceptable BER and instead of measuring the signal quality (e.g. OSNR), we measure the distance and the BER. If the BER is below the accepted BER, we increase the distance progressively. Beyond a certain distance, the BER will not be acceptable.

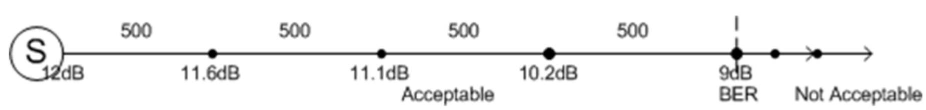

Figure 11: Measuring Linear Impairments

However, since the nonlinear constraints are dynamic in nature they may not always be pressent and thus cannot be readily measured. More so, the amount of disturbance and interference may vary considerably. To compensate for these constraints, we limit the transmission distance to an estimated distance called the optical reach. The optical reach is therefore defined as the maximum distance a signal can travel before it loses its configuration and requires 3R-regeneration, described below. This distance is treated as an engineering standard for a particular type of optical cable.

2.6 3R-Regeneration

Regenerators are used to solve the problem that arise as a result of the maximum distance constraint. The question is, if we cannot propagate a signal beyond the optical reach, how can we extend the area covered by a network for data communication beyond that distance? The answer lies in regenerating the signal at or before distance covered that exceeds the optical reach. 3R-regeneration is normally used to re-shape, re-time and re-amplify the signal. After 3R-regeneration, the signal is restored to its original strength and configuration. The signal is thus able to travel along the fiber until it again is “close” to the optical reach, after which it can be regenerated again, indefinitely. As such, regenerator are used to extend a signal to accommodiate data communication across a network over any geographical distance.

2.6.1 Regenerator Placement and Usage

The use of regenerators has invoked a very interesting problem, which is a central part of this thesis. That is, which nodes are we going to place these regenerators, so that every source node can communicate with every destination node? This problem looks simple and innocuous, but it is in the class of NP complete problems [14], [26] - [29]. We discuss this problem in detail in Chapter 3.

It is important to understand, not only the placement of regenerators, but when to use these regenerators. Just because we have a regenerator-cabable node (a node equipped with regenerators) we don’t have to regenerate every light signal that will pass through that node. As an example, let us consider a network, with nodes A, B, C and D with the distances, in km, as shown in Figure 12 below. Let us say that the optical reach of 2000 km.

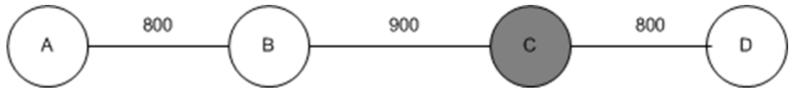

Figure 12: Regenerator Placement and Usage

If we want to communicate from node A to Node D, since this distance is more than the optical reach, the signal must be regenerated, Say, we have a regenerator-capable node at C. The signal will be regenerated at node C before it is transmitted to node D. However, if we wish to communicate between node B and node D, the optical reach will not be exceeded, so we do not have to regenerate the signal at node C. We tend to avoid using regenerators, not only because they are expensive, but regenerating a signal causes a significant delay, as it takes place in the electrical domain. That is, in order to undergo 3R-regeneration, the signal must first be converted from the optical domain to the electrical domain, where regeneration occurs, and then be converted back to the optical domain for transmission. This is referred to as *optical-electrical-optical conversion* (O/E/O). O/E/O takes up a lot of time when compared to the speed at which signals are propagated.

2.6.2 Regenerator-capable node

When designing or operating a network we have to determine two things about a lightpath passing through a regenerator-capable node:

1. if the signal needs to undergo 3R-regeneration or it should by-pass the regenerators, and

2. if regeneration is required, whether a regenerator is available for that lightpath.

A regenerator-capable node has only a limited number of regenerators and if the number of signals, which requires 3R-regeneration, exceeds the number of regenerators at that node, some of the requests for lightpaths will be blocked for lack of regenerators. Figure 13, below, illustrates this process.

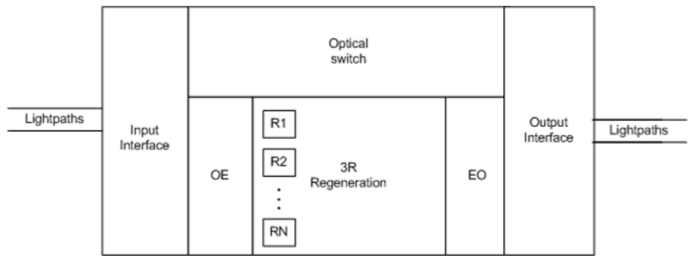

Figure 13: A Regenator-capable node

An optical signal will enter a regenerator-capable node at the input interface. If regeneration is required, the signal will be converted from the optical domain to the electrical domain, regenerated and then be converted back to the optical domain and transmitted through the output interface. However, if regeneration is not required, the signal will remain in the optical domain and switched to the output interface. That is, if the lightpath does not require 3R-regeneration then the optical switch is used. However, if 3R-regeneration is required and there is a regenerator available, then the lightpath undergoes 3R-regeneration.

2.7 Transparent vs. Translucent Lightpaths

As we said before, optical signals are used in optical network for data communication. The presence of regenerators has been used to not only determine the type of optical networks (transparent, opaque and translucent), but also the types of lightpaths. These regenerators can be viewed as dividing a lightpath, from a source to a destination, into sections, called segments. A *segment* may be defined as the path a lightpath is allowed to travel before it will loose its configuration and has to be regenerated.

A segment starts from a source of a lightpath or from a regenerator-capable node and ends at the destination of the lightpath or at another regenerator-capable node. For instance, in Figure 14, there are three segments:

1. $S \rightarrow n_1 \rightarrow r_1$,
2. $r_1 \rightarrow n_2 \rightarrow n_3 \rightarrow r_2$, and
3. $r_2 \rightarrow D$.

Each segment of the lightpath (from source to the first regenerator-capable node, from one regenerator-capable node to the next nearest regenerator-capable node, or from the last regenerator-capable node to the destination) is referred to as a transparent lightpath and must obey the *wavelength continuity constraint.* That is, it must use the same wavelength on each link within a segment. The reason for this is that we are not considering optical wavelength converters and as such wavelengths cannot be changed. However, when a lightpath is regenerated, the wavelength can be changed for the new segment.

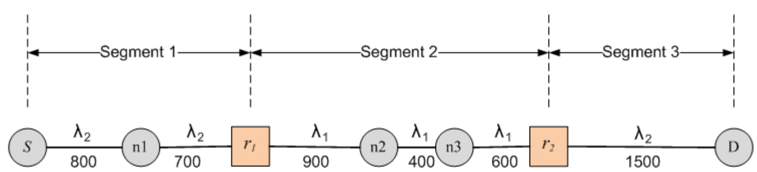

Figure 14: A translucent lightpath

The circles represent nodes that are not regenerator-capable nodes, while the rectangles represent nodes that are regenerator-capable nodes. λ_1 and λ_2 represent the wavelengths used on each edge. The indicated distances are in km and the optical reach is assumed to be 2000 km.

A *translucent lightpath* can thus, be defined as a sequence of two or more transparent lightpaths that undergo 3R regeneration. It is characterised by, a path from a source node, S, to a destination node, D and a wavelength for each edge on the path, as shown in Figure 14.

2.8 Lightpath-demand Schemes

Although requests for communication are processed individually, the requests are considered as an ordered list of requests. Such a list of requests is referred to as a traffic demand. Traffic demands or lightpath allocations can be categorised as either static lightpath demands (SLD) or dynamic lightpath demands (DLD). The main difference between SLD and DLD is the duration of the lightpaths. In *static lightpath demands* (SLD), once set up, the lightpath will continue to exist for months or even years, if the demand on the network has not changed. If the traffic demand changes, the old lightpaths that are not needed will be taken down and new lightpaths that are required will be set up. With SLD, the lightpaths are known before hand and each source-destination pair uses the same lightpath for data communication.

However, with *dynamic lightpath demands* (DLD), lightpaths are set up when required and torn down when the communication is over. As such, a different lightpath must be established in response to each request for connection. Sometimes, with DLD it is required that the lightpath be set up at a scheduled time and for a specific duration. This type of DLD is known as scheduled lightpath demand. However, very often, neither the arrival time nor the duration of the traffic demands are known. These type of demands are known as *ad hoc lightpath demands* (ALD) [5], [41].

ALD usually follow some natural probability distributions for the arrival time and duration of these requests. In this thesis, the arrival rate is generated based on the Poisson distribution while the duration is generated based on a negative exponential distribution.

Figure 15 below, shows the lightpath allocation schemes used.

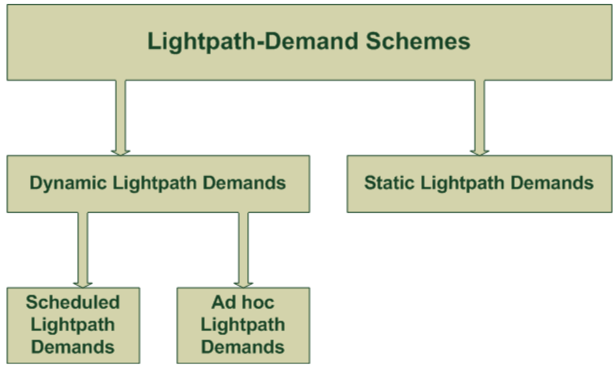

Figure 15: Lightpath-Demand Schemes

2.9 Network vs. Physical Layer Blocking

In DLD, there are several arbitrary requests for communication. A request for communication may not always be successful in networks handling ALD. That is, we may not be able to establish communication, from a source node to a destination node, for every request. When this happens, we say the request is blocked. A request may be blocked either as a result of physical layer impairments or due to lack of network resources. This is illustrated in Figure 16, below.

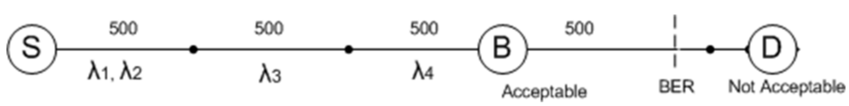

Figure 16: Network and Plysical Layer Blocking

For example, depending on the state of the network, a request for communication from node S to node B may be blocked due to unavailability of network resources, say, the unavailability of channels (all the channels, λ_1 to λ_4 are in use). On the other hand, a request from node S to node D may be blocked as a result of physical layer impairments. In this example, the optical reach is 2000 km, the indicated distances are in km and there are no regenerator-capable nodes.

2.10 Network Survivability Schemes

Failures: A network may fail for various reasons. There may be software failures as well as hardware failures. Hardware failures include link failures, node failures and even channel failures. Failures may also occur as a group and are typical when a group share a common physical property. This can be as simple as disruption of a set of cables running in the same conduit or as extensive as a group of components (e.g. nodes) being destroyed as a result of being in the same disaster area [31], [43]. However, the most common type of failure is link failure, where the communication between two adjacent nodes is disrupted due to a fault in the fiber connecting the nodes. As such, in this work, we consider link failures only. A failed link may be as simple as a slack connection or a fiber cut or as a result of noise, introduced by optical components. Whatever the cause of failure, it is very important that failures be managed to prevent possible dire consequences. For example, optical WDM networks use many channels, with each channel capable of carrying very high volume of traffic, as such, link failure may lead to huge data loss.

There are two main fault-management schemes,that are used to handle faults, protection and restoration but there are many variants of these schemes [1], [6], [22]. Protection schemes include dedicated path protection (DPP), shared path protection, dedicated link protection and shared link protection while restoration schemes include path restoration and link restoration. An organizarion of these schemes are shown in Figure 17, below.

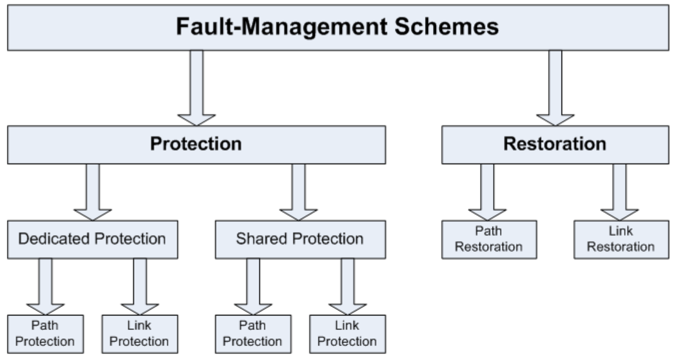

Figure 17: Fault-management Schemes

The two main functions of these schemes are detection of failures and the re-routing of traffic, as a result of a failure. However, the challenge is how quickly these can be done. This is highlighted with path and link management. The difference between path and link management is that, with link management, the failed link must first be identified before remedial action is taken, whereas with path management, a backup path is reserved for the rerouting of traffic in the event of any link failure along the path. There is no need to identify the point of failure. Path management schemes therefore has a faster response time than link management schemes.

2.10.1 Dynamic Restoration

According to Kamal, [Kamal, 2006], “In *Dynamic Restoration*, when a failure occurs spare capacity is discovered, and is used to re-route the traffic affected by the failure”. That is, restoration is done after the failure. With restoration, there is only one path identified for data communication when there is no fault in the network. In the event of a failure, the system then seeks to set up an alternative fault-free path to redirect the failed traffic [25]. Two things should be noted:

1. There may not be an alternative path due to unavailability of resources, and

2. The time needed to find an alternative fault-free path may vary considerably.

There is no guarantee that the restoration scheme will always recover from a failure, as there may not be enough network resources to accommodate an alternative path. This will be dependent on the congestion of the network as a result of resource utilization at the time of failure.

2.10.2 Dedicated Path Protection

With dedicated path protection, two paths are identified at the time of setting up the lightpath, a primary path and a backup path. Bandwidth capacity is reserved or concurrently used (in the case where both lightpaths are set up) for failures. In the event of a failure on the primary path, the entire path is discarded and the backup path identified earlier is guaranteed to re-route the failed traffic. This scheme is very fast when compared to the restoration scheme, as there is no need to identify the point of failure. Although 50% of the resource will be idle if there is no failure, this redundancy is necessary when compared to the potential consequences. There are two techniques that are used to implement dedicated path protection, 1+1 and 1:1, [20] - [21].

1+1 Technique: In 1+1 technique, the bandwidth is concurrently used, as both the primary and backup paths are lit up. That is, two link-disjoint lightpaths are established and simultaneously used to process a request for communication. According to [Kamal, 2006], in 1+1 technique, the traffic of a circuit is transmitted on two link-disjoint lightpaths, and the receiver selects the stronger of the two signals.

1:1 Technique: The 1:1 technique is similar to the 1+1, except that traffic is not transmitted on the backup path until a failure occurs. That is, the backup path is unlit and the bandwidth is reserved. If a failure occurs on the primary path, the backup lightpath is established and is used to re-route the traffic. Although this technique is a little slower, the resources used in the backup path may be used for carrying lower priority traffic.

2.10.3 Shared Path Protection

Because of the amount of resources that will be idle, if a network is robust and does not have a history of regular failures, researchers have proposed a scheme that focuses on the utilization of network resources at the expense of guaranteed protection from single link failures, called *shared path protection* [8] - [11], [14], [18]. In shared path protection, the M:N (M less than N) technique is used and is discussed below. However, there are certain additional constraints required for shared path protection. For example, not only the backup path must be edge disjoint from the primary path, but in the event of a backup path protecting two primary lightpaths, the primary paths must also be edge-disjoint. Otherwise, if they (the two primary paths) share a common edge and that edge fails, the backup path will not be able to protect both of the primary lightpaths.

M:N Technique: M:N technique is used for shared path protection, where M backup paths are designed to protect N working paths. For example, in 3:7 protection, 3 backup paths are designed to protect 7 primary paths. This form of protection focus on the sharing of resources and utilizes the bandwidth more effeciently, but at the expense of guaranteed protection.

2.10.4 Branch-and-Cut Algorithm

The *branch-and-cut technique* is used to solve a wide variety of integer linear programming (ILP) problems. is is a combination of the ctting-plane nethod with a branch-and-bound algorithm that provides an optimal solution is a solution is feasible.

In the *branch-and-bound method* the problem is divided into two sub-problems, by splitting on a variable. The optimal solution will be the better of the two solutions. Here there may be severa layers of splitlitting, resulting in multiple sub problems (two in each split on a variable).

With branch-and-cut technique, we use a *cutting-plane approach*, where we add a cut by using an inequality in the plane. This is done after solving the linear programming relaxation of the ILP. The general idea is to either start with all the variables, and use reduce costs to remove variables or to work wth an initial subset of the variables and then add the other variables, if necessary [24].

The algorithm that is used in the heuristic is base on the branch-and-cut approach and is described in the work of Rahman, et al in [29].

2.11 Literature Review

In this section, we review three papers describing research that attempts to solve the problem by methods which use traffic grooming equipment and/or regenerator. Traffic grooming equipment can be used to groom the traffic as well as regenerating a signal. The methods used are traffic grooming and/or regenerator placement under shared path protection, traffic grooming and/or regenerator placement with dedicated path protection and traffic grooming and/or regenerator placement with connection-level protection.

2.11.1 Traffic Grooming under Shared Path Protection

The problem addressed

Yang et al [2005] address the problem of protecting impairment-aware WDM networks against failures by assigning wavelengths and optical-electrical-optical (O/E/O) modules along the working and protection paths.

The new algorithm

The researchers developed three approaches to solve the problem. An integer linear program (ILP) approach that formulates the problem into a single IPL problem, and two heuristic solutions approaches (LOH and TSH) that first find an initial solution by employing the divide-and-conquer and greedy principles. A directed graph is used to represent the network, with each vertex representing a network node and each edge representing a fiber link that has a fixed number of wavelengths. The objective is to minimize the number of O/E/O modules and wavelength links consumed by all the connection requests. In this approach k-shortest paths are chosen as candidates for the working path of each connection. Given the working path, another set of k-shortest paths is chosen as candidates for the protection path. A greedy wavelength and O/E/O assignment algorithm is then used to assign wavelengths and O/E/O modules along the working and protection paths.

The LOH (local optimization heuristic) approach is used to improve the initial solution, based on a reconfiguration evaluation procedure while the TSH (tabu-search heuristic), which the authors claim further optimize the solution, is based on a meta-heuristic for solving hard combinatorial optimization problems.

2.11.2 Traffic Grooming with Dedicated Path Protection

The problem addressed

Patel et al [2010] address the problem of protection of impairment-aware traffic-grooming WDM networks against single failures by focusing on efficient placement of equipment.

The new algorithm and architecture

The authors developed a ROADM architecture that places a traffic grooming equipment or a regenerator at each node. They also developed a heuristic algorithm that is based on an auxiliary graph that consists of physical links (physical network topology), auxiliary links (routes that satisfied the impairments constraints) and virtual links (established lightpaths with sufficient spare capacity for the request).

A new backup lightpath is established by finding the shortest path on the auxiliary graph that is a link disjoint from the working path. Regenerators are then placed at all intermediate nodes along the backup path. Also, if there is spare capacity, the algorithm establishes a separate working lightpath and a separate disjoint backup lightpath.

2.11.3 Traffic Grooming with Connection-level Protection

The problem addressed

The problem identified by Gao et al [2012] is protection of impairment-aware optical WDM networks against failures by focusing on improving utilization of network resources.

The new architecture and algorithms

The authors developed a reconfigurable optical add-drop multiplexer (ROADM) node architecture. They state that this architecture has an all-optical wavelength switch fabric coupled with an electrical backbone, which together connects the various grooming and regenerator equipment.

The authors present two algorithms (a dedicated connection-level protection algorithm and a shared connection-level protection algorithm) that use auxiliary graphs that take into consideration the weight and residual capacity of each type of link. They note that, in each algorithm, the auxiliary graph is first generated and used to select the solution that generates the minimum network cost.

2.11.4 Summary of related work

A summary of the three papers that are closely related to this work is shown in the table below.

Year	Title	Authors	Major contribution
2005	Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints	Yang, X., Shen L., and Ramamurthy, B.	Equipment placement and Shared path protection
2010	Survivable impairment-aware traffic grooming with dedicated path protection dedicated path protection	Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Naito, T.	Equipment placement and Dedicated path protection
2012	Survivable impairment-aware traffic grooming and regenerator placement with connection-level protection	Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M.	Equipment placement and Connection-level protection

3 Chapter 3 - The Proposed Algorithms

In this chapter, for solving the RPP with dedicated path protection (DPP), we present two solutions, an optimal solution (SOL-O) and a heuristic solution (SOL-H). As indicated earlier, RPP with DPP is done during the planning phase. After the regenerator placement phase is over, we solve the RRP for DPP. RRP is needed in the operational phase. To solve both RPP with DPP and RRP, we propose integer linear program (ILP) formulations [35].

A computer network is often modelled by a connected graph $G = (N, E)$ (where N is the set of nodes in G, and E is the set of edges in G, where each edge represents a fiber). A *connected graph* is a graph in which there is a path from any node to any other node. A *weighted network* can be represented by a pair, (G, w), consisting of a connected graph G and a non-negative weight function $w : E \rightarrow [0, \infty)$ which assigns a weight to each edge of E. Here we use the length of a fiber connecting any two nodes, i and j, as the weight for the edge. The *distance*, $d(i, j)$, from node i to node j in a network is the length of the shortest path from i to j. (The length of a path is just the sum of the weights of the edges of the path). The optical reach, d_{max}, of an optical signal is the maximum distance the optical signal can travel in the optical medium without unacceptable degradation.

Let a lightpath from node S to D in graph $G = (V, E)$, involve a route $S \rightarrow n_1 \rightarrow n_2 \rightarrow \ldots \rightarrow D$. If the total length of this route does not exceed the optical reach d_{max}, then a transparent lightpath can be set up from S to D. Such a route, will be called a *valid route*, where nodes n_1, n_2, $\ldots$ can be any node in the network.

If the route for a lightpath from node S to node D exceeds d_{max}, the route must include one or more regenerators. Let $S \rightarrow n_1 \rightarrow n_2 \rightarrow \ldots \rightarrow r_1 \rightarrow n_m \rightarrow \ldots \rightarrow$

$r_2 \rightarrow \ldots \rightarrow r_p \rightarrow \ldots \rightarrow D$ be such a route. Here r_1, r_2 ..., r_p are regenerators in the route from S to D. Such a route is a *valid route* for a translucent lightpath if the length of every segment[1] in such a path must not exceed d_{max}. For instance, the path from S to D in Figure 18 is $S \rightarrow n_1 \rightarrow r_1 \rightarrow n_2 \rightarrow n_3 \rightarrow r_2 \rightarrow n_4 \rightarrow n_5 \rightarrow D$. If this is a valid path, the length of segments $S \rightarrow n_1 \rightarrow r_1$, $r_1 \rightarrow n_2 \rightarrow n_3 \rightarrow r_2$ and $r_2 \rightarrow n_4 \rightarrow n_5 \rightarrow D$ must not exceed d_{max}. In general, there may be many valid paths from S to D.

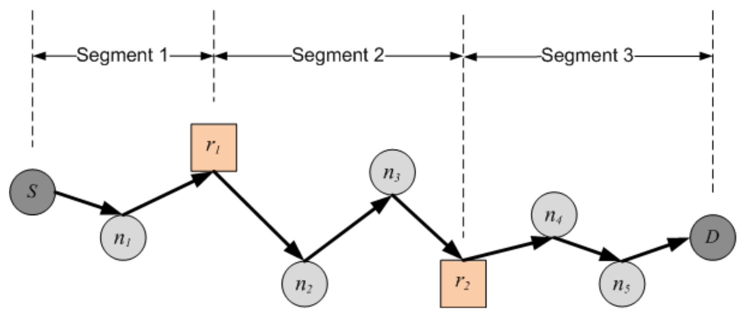

Figure 18: Valid Path for a Translucent Lightpath

3.1 The Regenerator Placement Problem (RPP)

3.1.1 RPP without Protection

To simplify the explanations, we start with a definition of RPP without protection. Given a weighted graph (G, w), where $G = (V, E)$, a set of regenerator capable nodes R ($R \subseteq V$) is a *valid placement of regenerators* if, for all node pairs (S, D), there exists a valid route from S to D. A set of regenerator capable nodes R is an *optimum solution to the RPP problem*, if no other valid placement of regenerators R' exists, such that $|R'| < |R|$.

[1]segment is defined in Section 2.7

3.1.2 RPP with protection

To incorporate dedicated path protection, we now define RPP with protection as follows.

Given a weighted graph (G, w), let R be a valid placement of regenerators. If this is a *valid placement of regenerators to achieve dedicated path protection* then, for all node pairs (S, D), there exists a pair of valid paths P_1 and P_2 which are edge disjoint.

This ensures that, if any link on the primary path fails, the network G will still be fully operational. However, this resiliency is only applicable to the failure of a single link between a pair of nodes and does not extend to node failures. If any node x fails, for whatever reason, the surviving network will not be guaranteed to function properly.

Figure 19 shows two translucent lightpaths, P_1 and P_2 (both from S to D), using edge-disjoint paths:

$S \rightarrow n_1 \rightarrow r_1 \rightarrow n_2 \rightarrow n_3 \rightarrow r_2 \rightarrow n_4 \rightarrow D$, with regenerators at r_1 and r_2, and

$S \rightarrow r_3 \rightarrow n_5 \rightarrow n_6 \rightarrow r_4 \rightarrow n_3 \rightarrow n_7 \rightarrow r_5 \rightarrow D$, with regenerators at r_3, r_4 and r_5.

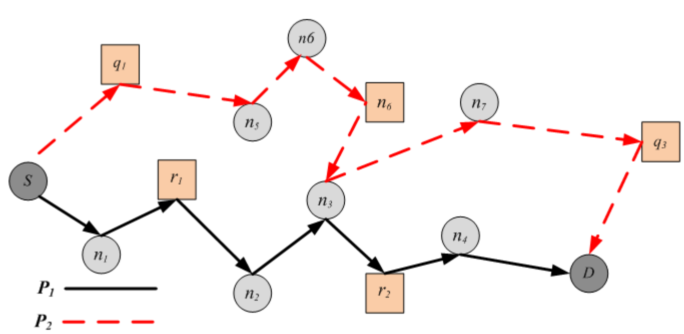

Figure 19: Two Translucent lightpaths using edge-disjoint paths

3.1.3 Formulation of RPP with DPP

We view the RPP with dedicated path protection as a network flow programming problem [35] as follows. Here each *commodity* in our network flow problem is characterized by its source (S) and its destination (D). To simplify the work, we first eliminate all source-destination pairs (S, D), such that there exists two edge disjoint paths from S to D, both with a length less than d_{max}. For such commodities, we do not need any regenerator and hence they need not be considered when solving RPP with DPP. For all other commodities, the problem is to find valid paths as defined above, so that it is possible to ship one unit of each commodity from their sources to their respective destinations. To present the formulation we have described below our notation, the objective function, the constraints and an explanation for each constraint.

Notation

G : a connected graph that represents the network, defined by a set of node N and a set of edges E.

N : a set of nodes in the network.

E : a set of physical edges in the network, each representing a fiber

(i, j) : an edge in the network, that represents a fiber from node i to node j, where $i, j \in N$ and $(i, j) \in E$

w : a weight function that determines the length of each edge, $(i, j) \in E$.

K : a set of commodities, each specified by a source and a destination.

x_{ij}^k : a binary variable, where

$$x_{ij}^k = \begin{cases} 1, & \text{if edge } (i, j) \text{ is in the primary path for commodity } k, \\ 0, & \text{otherwise.} \end{cases}$$

y_{ij}^k : a binary variable, where

$$y_{ij}^k = \begin{cases} 1, & \text{if edge } (i,j) \text{ is in the backup path for commodity } k, \\ 0, & \text{otherwise.} \end{cases}$$

r_j : a binary variable, where

$$r_j = \begin{cases} 1, & \text{if node } j \ (j \in N) \text{ is identified to be a regenerator-capable node,} \\ 0, & \text{otherwise.} \end{cases}$$

d_{max} : the optical reach for the network.

d_{ij} : the distance from node i to node j, where $i, j \in N$.

v_i^k : a continuous non-negative variable, $k \in K$, $i \in N$, denoting the distance of node i from the last regenerator (or from the source), for the primary path.

w_i^k : a continuous non-negative variable, $k \in K$, $i \in N$, denoting the distance of node i from the last regenerator (or from the source), for the backup path.

$O(k)$: the source node of commodity k.

$D(k)$: the destination node of commodity k.

Objective Function:

Our objective is to identify nodes that must be equipped with regenerators (i.e.,regenerator-capable nodes), such that there will always be two edge-disjoint paths defined by variables $\{x_{ij}^k : (i,j) \in E\}$ and $\{y_{ij}^k : (i,j) \in E\}$ for each commodity, $k \in K$.

The objective function seeks to minimize the number of regenerator-capable nodes and is defined as follows:

$$minimize \sum_{j:j \in N} r_j$$

subject to:

(a) Flow balance equations for the primary and the backup path must be satisfied by all commodities k, $k \in K$ and all nodes $i, j \in N$.

$$\sum_{j:(i,j)\in E} x_{ij}^k - \sum_{j:(j,i)\in E} x_{ji}^k = \begin{cases} 1 & \text{if } i = O(k), \\ -1 & \text{if } i = D(k), \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

$$\sum_{j:(i,j)\in E} y_{ij}^k - \sum_{j:(j,i)\in E} y_{ji}^k = \begin{cases} 1 & \text{if } i = O(k), \\ -1 & \text{if } i = D(k), \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

(b) For each commodity, the primary path and the backup path must be edge-disjoint.

$$x_{ij}^k + y_{ij}^k \le 1 \quad \forall k \in K,\ \forall (i,j) \in E. \tag{3}$$

(c) Both the primary path and the backup path must obey the optical reach requirement. To ensure this we use distance labels v_i^k and w_i^k as follows:

$$v_i^k + d_{ij} \,.\, x_{ij}^k - d_{max}(1 - x_{ij}^k + r_j) \le v_j^k \quad \forall k \in K,\ \forall (i,j) \in E, j \ne D(k). \tag{4}$$

$$v_i^k + d_{ij} \,.\, x_{ij}^k \le d_{max} \quad \forall k \in K,\ \forall (i,j) \in E. \tag{5}$$

$$v_i^k \le d_{max}(1 - r_i) \quad \forall k \in K,\ \forall i \in N, i \ne D(k). \tag{6}$$

$$v_i^k = 0 \quad \forall k \in K,\ \forall i \in N, i = O(k). \tag{7}$$

$$w_i^k + d_{ij} \,.\, y_{ij}^k - d_{max}(1 - y_{ij}^k + r_j) \le w_j^k \quad \forall k \in K,\ \forall (i,j) \in E,\ j \ne D(k). \tag{8}$$

$$w_i^k + d_{ij} \,.\, y_{ij}^k \le d_{max} \quad \forall k \in K,\ \forall (i,j) \in E. \tag{9}$$

$$w_i^k \le d_{max}(1 - r_i) \quad \forall k \in K,\ \forall i \in N, i \ne D(k). \tag{10}$$

$$w_i^k = 0 \quad \forall k \in K,\ \forall i \in N, i = O(k). \tag{11}$$

3.1.4 Justification of the RPP with DPP Formulation

Constraints (1) and (2): Constraints (1) and (2) deal with flow conservation. Let us define the total amount of commodity, k entering a node i as the $inflow(i,k)$ and the total amount of the commodity k leaving a node i as the $outflow(i,k)$. Then, the net flow of commodity k through node i is given by:

$netflow(i,k) = outflow(i,k)$ - $inflow(i,k)$.

Our objective in constraints (1) and (2) is that it must be possible for commodity k to flow from its source, $O(k)$, to its destination, $D(k)$, using both the primary and the backup paths. In other words, we wish to send 1 unit of commodity k from $O(k)$ to $D(k)$. This means that at node $O(k)$, the $inflow(O(k),k)$ must be 0 and the $outflow(O(k),k)$ must be 1, hence the $netflow(O(k),k)$ is 1. At node $D(k)$, the $inflow(D(k),k)$ must be 1 and the $outflow(D(k),k)$ must be 0, hence the $netflow(D(k),k)$ is -1. At all intermediate nodes i, the $inflow(i,k) = outflow(i,k)$, so the $netflow(i,k)$ must be 0. This must be true for both the primary path and the backup path.

Constraint (3): To explain constraint (3), we consider the following three scenarios:

(i) edge (i,j) is not used by both the primary and the backup path for commodity k.

(ii) edge (i,j) is used by either the primary path or the backup path (but not both) for commodity k.

(iii) edge (i,j) is used by both the primary path and the backup path for commodity k.

In scenario (i), both x_{ij}^k and y_{ij}^k are 0, so $x_{ij}^k + y_{ij}^k = 0$. In scenario (ii) only one of x_{ij}^k and y_{ij}^k is 1, so $x_{ij}^k + y_{ij}^k = 1$. Scenario (iii) is not possible, since we require the primary path and the backup path to be edge-disjoint, so $x_{ij}^k + y_{ij}^k$ cannot be 2.

Constraints (4) to (11): Constraints (4) to (11) implements the optical reach constraint for the primary and the backup lightpaths. We recall that, for any commodity k, a valid translucent lightpath is such that the length of each segment is $\leq d_{max}$.

Constraints (4) to (7) are related to the primary lightpath and define the distance of any node from the start of the segment that contains the node. The objectives of these constraints are as follows:

1. In constraint (4), $(1 - x_{ij}^k + r_j)$ has a value 0, 1 or 2. If $(1 - x_{ij}^k + r_j)$ is 1 or 2, constraint (4) is clearly satisfied, since constraint (5) guarantees that $v_i^k + d_{ij} \cdot x_{ij}^k \leq d_{max}$, so that the LHS is negative. The value of $(1 - x_{ij}^k + r_j)$ can be 0 only if $x_{ij}^k = 1$ and $r_j = 0$. In that case, constraint (4) becomes $v_i^k + d_{ij} \leq v_j^k$. In other words, if node j is not used for regeneration and is not the destination node, $D(k)$, constraint (4) computes the value of v_j^k, where i is the node proceeding j, in the primary path from $O(k)$ to $D(k)$.

2. Constraint (5) ensures that length of a segment that passes through node i never exceeds d_{max}.

3. Constraint (6) ensures that, if node i is used for regeneration (i. e., $r_i = 1$), $v_i^k = 0$, so that the length of the segment starting node i is 0.

4. Constraint (7) ensures that, if node i is the source node, $O(k)$, $v_i^k = 0$, so that the length of the segment starting at the source node is 0.

We stipulate the constraints for the backup path similarly, using constraints (8) to (11). Hence, if constraints (4) to (11) are satisfied, then the length of each segment, in both the primary and the backup path, will not exceed the optical reach.

3.2 The Routing with Regenerator Problem (RRP)

As mentioned above, RRP phase is carried out when the network is operating. At this time, all sites for regenerators have been identified and regenerators are available at these sites, so that a translucent network (G, w, R), where $R \subseteq N$ is a set of regenerator-capable nodes, is available. Since the network is in operation, at any given point in time, a number of lightpaths are in existence. Each lightpath requires requisite resources from the network. For instance, let an existing lightpath use a channel, say channel c, on the fiber from node i to node j. While this lightpath is in existence, any request for a new lightpath must not use channel c on the fiber from node i to j.

We note that, if a lightpath undergoes regeneration at node m, one regenerator at node m is dedicated to regenerate the optical signal corresponding to this lightpath. While this lightpath is operational and the signal is regenerated, this regenerator cannot be used to regenerate any other optical signal. To simplify our discussions, we assume that each regenerator-capable node has an infinite number of regenerators, so that the lack of regenerators does not pose a problem. We can easily extend the formulation given below, so that we start with a specified number of regenerators at each regenerator-capable node. When all regenerators at a regenerator-capable node have been allotted, the node will no longer be considered to be regenerator-capable.

3.2.1 Problem definition for RRP with DPP

As explained in Section 1.1.5, the RRP problem is to handle, if possible, a request for communication, say from S to D. Since we are using dedicated path protection, if we are successful in handling a request for communication from S to D, the RRP algorithm should identify a pair of edge-disjoint routes (P_p, P_b), both from S to D, to set up the primary and the backup lightpaths, respectively. In our discussions below, we assume that 1+1 dedicated path protection is used, so that both the primary and the backup lightpath are deployed if the algorithm determines that the request can be handled. If 1:1 dedicated path protection is used, only the primary lightpath will be deployed, using route P_p. Resources will be reserved for the backup lightpath, using route P_b, but the backup lightpath will not be deployed until there is a link failure in the primary route.

If the RRP algorithm is successful, routes P_p and P_b must satisfy the following conditions:

1. P_p (P_b) can only use channel k on edge $(i, j) \in E$, if the channel k is available.
2. Each segment of P_p and P_b must obey the wavelength continuity constraint. In other words, for each segment of a translucent lightpath, the same channel must be used on each link within that segment. However, different segments may use different wavelengths.
3. Both P_p and P_b must satisfy the optical reach requirement.
4. A minimum number of regenerators should be used to set up the primary and the back-up lightpaths.

3.2.2 Formulation to solve the RRP problem with DPP

Notation

G : a connected graph that represents the network, defined by a set of nodes N and a set of edges E.

N : the set of nodes in the network.

E : the set of physical edges in the network.

(i, j) : an edge in the network, representing a fiber from node i to node j, where $i, j \in N$ and $(i, j) \in E$.

w : a weight function that determines the length of each edge, $(i, j) \in E$.

d_{ij} : the distance from node i to node j, where $i, j \in N$ are nodes in the same segment in the route from S to D, using the path currently under consideration.

K: the set of channels.

b_{ij}^k : a constant to specify whether channel k is available on edge (i, j), where

$$b_{ij}^k = \begin{cases} 1, & \text{if channel } k \text{ is available on edge } (i,j), \\ 0, & \text{otherwise.} \end{cases}$$

S : the source node for the request for communication.

D : the destination node for the request for communication.

d_{max} : the optical reach for the network.

R : the set of regenerator-capable nodes ($R \subseteq N$), identified during the RPP phase.

r_j : a binary variable, where

$$r_j = \begin{cases} 1, & \text{if } j \in R \text{ and is used for regeneration of the primary or backup lightpath for} \\ & \text{the request under consideration,} \\ 0, & \text{otherwise.} \end{cases}$$

x_{ij}^k : a binary variable, where

$$x_{ij}^k = \begin{cases} 1, & \text{if edge } (i,j) \text{ uses channel } k \text{ for the primary route,} \\ 0, & \text{otherwise.} \end{cases}$$

y_{ij}^k : a binary variable, where

$$y_{ij}^k = \begin{cases} 1, & \text{if edge } (i,j) \text{ uses channel } k \text{ for the backup route,} \\ 0, & \text{otherwise.} \end{cases}$$

P_i : a continuous variable $i \in N$, for the primary lightpath, such that

$$P_i = \text{distance of node } i \text{ from} \begin{cases} \text{source } S, \text{ if node } i \text{ lies on the first segment,} \\ \text{last regenerator, otherwise.} \end{cases}$$

B_i :a continuous variable $i \in N$, for the backup lightpath, such that

$$B_i = \text{distance of node } i \text{ from} \begin{cases} \text{source } S, \text{ if node } i \text{ lies on the first segment,} \\ \text{last regenerator, otherwise.} \end{cases}$$

Objective Function:

$$minimize \sum_{j:j \in R} r_j$$

Subject to:

(a) Flow constraints for both the primary and backup paths must be satisfied:

$$\sum_{j:(i,j)\in E} \sum_{k:k\in K} x_{ij}^k - \sum_{j:(j,i)\in E} \sum_{k:k\in K} x_{ji}^k = \begin{cases} 1 & \text{if } i = S, \\ -1 & \text{if } i = D, \\ 0 & \text{otherwise.} \end{cases} \tag{12}$$

$$\sum_{j:(i,j)\in E} \sum_{k:k\in K} y_{ij}^k - \sum_{j:(j,i)\in E} \sum_{k:k\in K} y_{ji}^k = \begin{cases} 1 & \text{if } i = S, \\ -1 & \text{if } i = D, \\ 0 & \text{otherwise.} \end{cases} \tag{13}$$

(b) The primary and the backup lightpaths can only use channel k on edge $(i,j) \in E$, if the channel is available.

$$x_{ij}^k \leq b_{ij}^k \quad \forall k \in K, \forall (i,j) \in E. \tag{14}$$

$$y_{ij}^k \leq b_{ij}^k \quad \forall k \in K,\ \forall (i,j) \in E. \tag{15}$$

(c) The primary path and the backup path must be edge disjoint.

$$\sum_{k:k \in K} x_{ij}^k + \sum_{k:k \in K} y_{ij}^k \leq 1 \quad \forall (i,j) \in E. \tag{16}$$

(d) Each transparent segment of the primary and the backup lightpath must satisfy the wavelength continuity constraint[2].

$$(1 - r_j) \cdot (\sum_{i:(i,j) \in E} x_{ij}^k - \sum_{i:(j,i) \in E} x_{ji}^k) = 0 \quad \forall k \in K,\ \forall j \in N - \{S, D\}. \tag{17}$$

$$(1 - r_j) \cdot (\sum_{i:(i,j) \in E} y_{ij}^k - \sum_{i:(j,i) \in E} y_{ji}^k) = 0 \quad \forall k \in K,\ \forall j \in N - \{S, D\}. \tag{18}$$

(e) Each segment of the primary path and the backup path must obey the optical reach requirement. To ensure this, we use the distance labels P_i and B_i as follows:

$$P_i + d_{ij} \,.\, \sum_{k:k \in K} x_{ij}^k \ - \ d_{max}(1 - \sum_{k:k \in K} x_{ij}^k + r_j) \leq P_j \quad \forall (i,j) \in E, j \neq d. \tag{19}$$

$$P_i + d_{ij} \,.\, \sum_{k:k \in K} x_{ij}^k \leq d_{max} \quad \forall (i,j) \in E. \tag{20}$$

$$P_i \leq d_{max}(1 - r_i) \quad \forall i \in N - \{D\}. \tag{21}$$

$$P_s = 0 \tag{22}$$

$$B_i + d_{ij} \,.\, \sum_{k:k \in K} y_{ij}^k \ - \ d_{max}(1 - \sum_{k:k \in K} y_{ij}^k + r_j) \leq B_j \quad \forall (i,j) \in E, j \neq D. \tag{23}$$

$$B_i + d_{ij} \,.\, \sum_{k:k \in K} y_{ij}^k \leq d_{max} \quad \forall (i,j) \in E. \tag{24}$$

$$B_i \leq d_{max}(1 - r_i) \quad \forall i \in N - \{D\}.. \tag{25}$$

[2]We have used two non-linear constraints to specify this. We will discuss later how these constraints may be replaced by a set of linear constraints for use in a solver, such as CPLEX.

$$B_s = 0. \tag{26}$$

3.2.3 Justification of the RRP Formulation

Constraints (12) and (13): Constraints (12) and (13) are flow balance equations for the primary and backup paths, respectively and similar to constraints (1) and (2).

Constraints (14) and (15): Constraints (14) and (15) deal with the availability of channels. They ensure that a channel can only be assigned if it is available.

Constraint (16): As with constraint (3), we consider the following three scenarios:

(i) edge (i, j) is not used by both the primary and the backup lightpath to process the request,

(ii) edge (i, j) is used by either the primary path or the backup lightpaths (but not both) to process the request,

(iii) edge (i, j) is used by both the primary lightpath and the backup lightpath to process the request.

We note that only one channel can be assigned to an edge $(i, j) \in E$, for a lightpath. So, $\sum_{k:k\in K} x_{ij}^k$ is either 0 or 1 (and likewise $\sum_{k:k\in K} y_{ij}^k$). Thus in (i), $\sum_{k:k\in K} x_{ij}^k =$ 0 and $\sum_{k:k\in K} y_{ij}^k = 0$. So, $\sum_{k:k\in K} x_{ij}^k + \sum_{k:k\in K} y_{ij}^k = 0$. In (ii), either $\sum_{k:k\in K} x_{ij}^k$ $= 1$ or $\sum_{k:k\in K} y_{ij}^k = 1$ (but not both). So, $\sum_{k:k\in K} x_{ij}^k + \sum_{k:k\in K} y_{ij}^k = 1$. Scenario (iii) is not possible, since the lightpaths are edge-disjoint. Thus, So, $\sum_{k:k\in K} x_{ij}^k +$ $\sum_{k:k\in K} y_{ij}^k$ cannot be 2.

Constraints (17) and (18): We will discuss Constraint (17), dealing with the case of the primary lightpath in detail. Our objective is to ensure that, for the primary lightpath, if node j appears in the path from S to D and is not a regenerator

node (i.e., $r_j = 0$), the lightpath coming into j must use the same channel k as the lightpath coming out of j. Using network flow terminology, if j is not a regenerator node, and there is an inflow into node j, corresponding to some channel k, using some edge (i, j), there must be a corresponding outflow from j, also corresponding to the same channel k, using some edge (j, p). If $r_j = 1$, regeneration is taking place at node j, so that there is no relationship between the channel used by the incoming lightpath and the channel used by the outgoing lightpath. We note that node j is not the source node or the destination node.
Constraint (18), dealing with the case of the backup lightpath, is similar.

Constraints (19) to (26): Constraints (19) to (26) ensure that the optical reach requirement is obeyed and are similar to constraints (4) to (11). However, instead of having a commodity k on an edge (i, j), defined by variables x_{ij}^k (y_{ij}^k), we have a channel that is used on the edge (i, j) that is defined by $\sum_{k:k \in K} x_{ij}^k$ ($\sum_{k:k \in K} y_{ij}^k$). Also, the distance labels, v_i^j (w_i^j) are now defined by variables P_i (B_i) for the primary (backup) lightpaths that are used to process the request for communication.

3.2.4 A procedure to handle nonlinear constraints in the formulation for RRP

Since constraints (17) and (18) are not linear, these constraints may not be used in a solver such as the CPLEX. We have replaced constraint (17) by linear constraints (27) to (33) and constraint (18) by linear constraints (34) to (40). We have described below constraints (27) to (40). These constraints need additional symbols as follows.

Notation

IP_j^k : a continuous variable $\forall j \in N$ and $k \in K$ for the primary route, which *will be constrained to have a value of 0 or 1*, where

$$IP_j^k = \begin{cases} 1, & \text{if } r_j = 0 \text{ and there exists an edge } (i,j) \text{ using channel } k \\ & \text{for the primary path,} \\ 0, & \text{otherwise.} \end{cases}$$

OP_j^k : a continuous variable $\forall j \in N$ and $k \in K$ for the primary path, which *will be constrained to have a value of 0 or 1*, where

$$OP_j^k = \begin{cases} 1, & \text{if } r_j = 0 \text{ and there exists an edge } (j,i) \text{ using channel } k \\ & \text{for the primary path,} \\ 0, & \text{otherwise.} \end{cases}$$

IB_j^k : a continuous variable $\forall j \in N$ and $k \in K$ for the backup path, which *will be constrained to have a value of 0 or 1*, where

$$IB_j^k = \begin{cases} 1, & \text{if } r_j = 0 \text{ and there exists an edge } (i,j) \text{ using channel } k \\ & \text{for the backup path,} \\ 0, & \text{otherwise.} \end{cases}$$

OB_j^k : a continuous variable $\forall j \in E$ and $k \in K$ for the backup path, which *will be constrained to have a value of 0 or 1*, where

$$OB_j^k = \begin{cases} 1, & \text{if } r_j = 0 \text{ and there exists an edge } (j,i) \text{ using channel } k \\ & \text{for the backup path,} \\ 0, & \text{otherwise.} \end{cases}$$

We claim that constraint (17) is equivalent to constraints (27) to (33).

$$IP_j^k \leq (1 - r_j) \quad \forall k \in K, \forall j \in N. \tag{27}$$

$$IP_j^k \leq \sum_{i:(i,j)\in E} x_{ij}^k \quad \forall k \in K. \tag{28}$$

$$IP_j^k \geq \sum_{i:(i,j)\in E} x_{ij}^k - r_j \quad \forall k \in K. \tag{29}$$

$$OP_j^k \leq (1 - r_j) \quad \forall k \in K, \forall j \in N. \tag{30}$$

$$OP_j^k \leq \sum_{i:(j,i)\in E} x_{ji}^k \quad \forall k \in K. \tag{31}$$

$$OP_j^k \geq \sum_{i:(j,i)\in E} x_{ji}^k - r_j \quad \forall k \in K. \tag{32}$$

$$IP_j^k - OP_j^k = 0 \quad \forall k \in K, \forall j \in N - \{S, D\}. \tag{33}$$

We also claim that constraint (18) is equivalent to constraints (34) to (40).

$$IB_j^k \leq (1 - r_j) \quad \forall k \in K,\ \forall j \in N. \tag{34}$$

$$IB_j^k \leq \sum_{i:(i,j)\in E} y_{ij}^k \quad \forall k \in K. \tag{35}$$

$$IB_j^k \geq \sum_{i:(i,j)\in E} y_{ij}^k - r_j \quad \forall k \in K. \tag{36}$$

$$OB_j^k \leq (1 - r_j) \quad \forall k \in K,\ \forall j \in N. \tag{37}$$

$$OB_j^k \leq \sum_{i:(j,i)\in E} y_{ji}^k \quad \forall k \in K. \tag{38}$$

$$OB_j^k \geq \sum_{i:(j,i)\in E} y_{ji}^k - r_j \quad \forall k \in K. \tag{39}$$

$$IB_j^k - OB_j^k = 0 \quad \forall k \in K, \forall j \in N - \{S, D\}. \tag{40}$$

To establish our claims, we note that constraint (17) is equivalent to the following nonlinear constraint,

$$(1 - r_j) \cdot \sum_{i:(i,j)\in E} x_{ij}^k = (1 - r_j) \cdot \sum_{i:(j,i)\in E} x_{ji}^k. \tag{41}$$

We now show that linear Constraints (27) - (33) is equivalent to the nonlinear constraint (41). This constraint is true for intermediate nodes only and is not applicable for the source and the destination nodes. There are three cases to consider:

(i) node j is not used by the primary lightpath. In this case, both $\sum_{i:(i,j)\in E} x_{ij}^k$

and $\sum_{i:(j,i)\in E} x^k_{ji}$ are 0.

(ii) node j is used by the primary lightpath, for regeneration. In this case, both $\sum_{i:(i,j)\in E} x^k_{ij}$ and $\sum_{i:(j,i)\in E} x^k_{ji}$ are 1 and $r_j = 1$.

(iii) node j is used by the primary lightpath, but is not used for regeneration. In this case, both $\sum_{i:(i,j)\in E} x^k_{ij}$ and $\sum_{i:(j,i)\in E} x^k_{ji}$ are 1 and $r_j = 0$.

It may be readily verified that, in each case, the left hand side of constraint (41) becomes 1(0) when the value of IP^k_j is 1 (0). Similarly the RHS of constraint (41) becomes 1(0) when the value of OP^k_j is 1 (0). In other words, constraints (27) - (33) is equivalent to nonlinear constraint (41).

Similarly, constraints (34) - (40) is used to replace constraint (18) for the backup lightpath.

3.3 Heuristic solution for RPP with DPP

As we mentioned earlier, the formulation for an optimum solution of RPP with DPP described in Section 1.2 works only for networks with no more than 11 nodes. In this section we describe SOL-H - a heuristic which can be used for networks of practical size (with up to 60 nodes). A key component for SOL-H, is an algorithm[3] developed by [Rahman et al, 2014] which finds an optimal solution that guarantees that restoration is possible in the event of single-link failures.

Lemma 1 *Any regenerator placement that satisfies the requirements for RPP with DPP is a regenerator placement which guarantees that restoration is possible in the event of single-link failures.*

Proof: As outlined in Section 3.1.2, a RPP for DPP gurantees that, for every source-destination pair (S, D), there is a valid primary path and a valid backup path that

[3] Section 2.10.4 has a brief review of this algorithm.

are edge disjoint. Let $S \to a_1 \to a_2 \ldots \to a_m \to D$ be the primary path when RPP with DPP was solved for the commodity characterized by the pair (S, D). Also let $S \to b_1 \to b_2 \ldots \to b_p \to D$ be the corresponding backup path. If this is a valid scheme for restoration, then for every single link failure in the primary path, a path from S to D must exist that does not involve the failed edge. This is guaranteed, since the backup path $S \to b_1 \to b_2 \ldots \to b_p \to D$ is edge-disjoint with respect to the primary path and can be used for failure in *any* link in the primary path. ∎

Lemma 2 *Any regenerator placement, which guarantees that restoration is possible in the event of single-link failures,* ***does not necessarily*** *give a regenerator placement that satisfies the requirements for RPP with DPP.*

Proof: Let $P_1 = S \to a_1 \to a_2 \ldots \to a_m \to D$ be the path used for fault-free operations, when solving RPP to guarantee that restoration is possible. This means that, in the event of failure of any single edge in the path, P_1, there is another valid path, P_2 from S to D that avoids the failed edge. For instance, consider a fault scenario where there is the failure of edge $a_p \to a_{p+1}$ in path P_1. If $a_p \to a_{p+1} \neq S \to D$, then there are two subpaths whose edges are fault-free: $Q_1 = S \to a_1 \to a_2 \ldots \to a_p$, and $Q_2 = a_{p+1} \to a_{p+2} \ldots \to D$.

We note that if $a_p = S$ and $a_{p+1} \neq D$, then subpath Q_1 will be empty. Likewise, if $a_p \neq S$ and $a_{p+1} = D$, then subpath Q_2 will be empty.

The scheme to solve RPP for restoration guarantees that there is a path $P_2 = S \to c_1 \to c_2 \ldots \to c_r \to D$ which avoids the failed edge $a_p \to a_{p+1}$. However, an edge, $a_q \to a_{q+1}$, in either of the subpaths Q_1 or Q_2, can be an edge in path P_2. There is no restriction for including a fault-free edge or fault-free edges from the path P_1 in the path P_2. In other words, the RPP for restoration does not mean that, for a primary path $S \to a_1 \to a_2 \ldots \to a_m \to D$ there exists a valid backup path $S \to b_1 \to b_2 \ldots \to b_p \to D$ that is edge-disjoint with respect to this primary path.

∎

Lemma 3 *If an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures, gives a regenerator placement that satisfies the requirements for RPP with DPP, then the placement is also optimal for RPP with DPP.*

Proof: Let this claim be false. Let R_1 be a placement for a weighted network (G, w) such that:

- R_1 is an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures, but
- R_1 is not an optimal regenerator placement, which guarantees that dedicated path protection is possible in the event of single-link failures.

This means there exists a better placement R_2 (meaning that $|R_2| < |R_1|$) which guarantees that dedicated path protection is possible. By Lemma 1, R_2 is also a regenerator placement which guarantees that restoration is possible in the event of single-link failures. This means that placement R_1 for graph (G, w) is not an optimum regenerator placement, which guarantees that restoration is possible in the event of single-link failures (since $|R_2| < |R_1|$). This is a contradiction, hence the claim is true. ∎

3.3.1 Algorithm for heuristic

In this section we will describe a heuristic solution for the RPP using DPP. The heuristic uses the branch-and-cut approach for optimal RPP, satisfying the requirements for restoration, described in [29] to generate R_1, an initial placement of regenerators. As discussed in Lemma 2, this initial placement does not necessarily give a regenerator placement for RPP with DPP. To check whether the requirements for RPP with DPP are fulfilled by R_1, we have taken all distinct-source pairs (S, D), and checked whether it is possible to establish two edge-disjoint viable paths from S to D using R_1. Our experiments, reported in Chapter 4, show that, in an overwhelming number of cases, R_1 does fulfill the requirements for RPP with DPP. Using Lemma 3, we see that, in all such cases, R_1 is an optimal placement of regenerators for DPP. In cases where an edge-disjoint pair of viable paths cannot be established for all distinct source-destination pairs (S, D), we have augmented R_1 with additional nodes, so that all distinct-source pairs (S, D) can be handled.

Notation

R_1 : an initial placement of regenerators, satisfying the requirements of restoration.

R : a placement of regenerators that satisfies the requirements of RPP with DPP.

$placementForRestoration(G, w)$: a function that invokes the branch-and-cut algorithm in [29] to generate an initial placement of regenerators. The argument needed for the function is the weighted graph (G, w) representing the network, where $G = (N, E)$.

$\mathbb{B}$: a set of source-destination pairs (S, D), such that two edge-disjoint viable paths cannot be established from S to D.

$currentCommodity$: a source-destination pair (S, D) that is currently under consideration.

$\mathbb{S}$: a set of source-destination pairs (S, D) which have not been considered yet.

$allCommodities$: a set of all possible source-destination pairs (S, D) for graph $G = (N, E)$.

$removeNextCommodity(\mathbb{S})$: a function that deletes one element from set $\mathbb{S}$ and returns the deleted element.

$commodityCannotBeHandled(G, w, R_1, currentCommodity)$: a function that returns true if it is not possible to establish two edge-disjoint viable paths from S to D when there is no lightpath in the network. Otherwise it returns false.

$augmentRegeneratorSites(G, w, R_1, \mathbb{B})$: a function that computes a minimum augmentation of the regenerator placement R_1, such that the weighted graph (G, w), with this augmented set of regenerators, allows every source-destination pair in set $\mathbb{B}$ to establish two edge-disjoint viable paths from S to D.

The steps for SOL-H are shown below.

Require: A connected graph (G, w), *allCommodities* - a set of all pairs of source-destinations for graph $G = (N, E)$.
Ensure: A set of regenerator-capable nodes R, that is a solution for RPP with DPP.
1: $R_1 \leftarrow placementForRestoration(G, w)$
2: $\mathbb{S} \leftarrow allCommodities$
3: $\mathbb{B} \leftarrow \emptyset$
4: **while** $(\mathbb{S} \neq \emptyset)$ **do**
5:     $currentCommodity \leftarrow removeNextCommodity(\mathbb{S})$
6:     **if** $(commodityCannotBeHandled(G, w, R_1, currentCommodity))$ **then**
7:         $\mathbb{B} \leftarrow \mathbb{B} \cup \{currentCommodity\}$
8:     **end if**
9: **end while**
10: **if** $(\mathbb{B} \neq \emptyset)$ **then**
11:     $R \leftarrow augmentRegeneratorSites(G, w, R_1, \mathbb{B})$
12: **else**
13:     $R \leftarrow R_1$
14: **end if**
15: **return** R

Algorithm 1: Heuristic for RPP with DPP

3.3.2 Implementing the heuristic

The inputs for the heuristic consists of:

(i) a connected graph (G, w) representing the network and

(ii) *allCommodities* - a set of all node pairs, each representing a commodity to be considered.

In Step 1 of Algorithm 1, the function $placementForRestoration(G, w)$ calls the branch-and-cut algorithm, developed by [Rahman et al, 2014] to return a set of regenerator-capable nodes, which is saved in set, R_1. In Step 6, we check, using function $commodityCannotBeHandled(G, w, R_1, currentCommodity)$, whether the current commodity, represented by source-destination pair, say (S, D), can be handled by the network using the regenerators in R_1. If the function returns true, an edge-disjoint pair of valid paths exist from S to D. We have implemented function $commodityCannotBeHandled$ using the RRP algorithm, described in Section 3.1.3, after setting $b_{ij}^k = 1$, for all edges $(i, j) \in E$. In other words, function $commodityCannotBeHandled$ checks if, in the absence of network layer constraints, it is possible to set up the paths that may be used by the primary lightpath and the backup lightpath. If the test in Step 6 fails, it means that we need one or more regenerators, at sites different from those in R_1, in order to handle the pair (S, D). Such (S, D) pairs are included in set $\mathbb{B}$ (Step 7). When Step 9 is over, set $\mathbb{B}$ contains all pairs (S, D) which cannot be handled by the regenerators in R_1.

In Step 10, if set $\mathbb{B}$ is empty, it means that the regenerators in R_1 is adequate to handle all source-destination pairs and R, the final set of regenerators, will be the same as the initial set of regenerators R_1 (Step 13) and the heuristic terminates. In Step 10, if set $\mathbb{B}$ is not empty, function $augmentRegeneratorSites(G, w, R_1, \mathbb{B})$ augments set R_1 with additional sites for regenerators, so that the requirements for path protection is satisfied by all commodities in $\mathbb{B}$. Function $augmentRegeneratorSites$ returns this augmented set and the heuristic terminates. Function $augmentRegeneratorSites$ uses a modification of the formulation for RPP described in Section 3.1.3 to augment the set of regenerators R_1. Details of this modification are given below.

The objective of the modified ILP for RPP with DPP is the same as that described in Section 3.1.3, except that we supply the ILP with $R_1 \subset N$, an initial set of regenerator-capable nodes. The ILP has to identify an additional set R_2 which have to be equipped with regenerators so that, for each commodity, say the pair (S, D), 2 edge-disjoint valid paths exist from S to D. To achieve this, we replaced constraints (4) and (8) by constraints (42) and (43) given below.

$$v_i^k + d_{ij} \, . \, x_{ij}^k - d_{max}(1 - x_{ij}^k + r_j) \leq v_j^k \quad \forall k \in K, \, \forall (i,j) \in E, j \neq D(k), j \notin R_1 \quad (42)$$

$$w_i^k + d_{ij} \, . \, y_{ij}^k - d_{max}(1 - y_{ij}^k + r_j) \leq w_j^k \quad \forall k \in K, \, \forall (i,j) \in E, \, j \neq D(k), j \notin R_1 \quad (43)$$

We also added the following two constraints.

$$v_i^k = 0 \quad \forall k \in K, \, \forall i \in R_1 \quad (44)$$

$$w_i^k = 0 \quad \forall k \in K, \, \forall i \in R_1 \quad (45)$$

Constraint (42) is similar to Constraint (4), except that if node j is already identified to be a site for regenerators (i.e., if $j \in R_1$), we do not calculate the value of v_j^k from the value of v_i^k. In such a case, constraint (44) forces the value of v_j^k to be 0. The discussions for constraints (43) and (45) are similar.

4 Chapter 4 - Experimental Results

In this chapter, we present results of the experiments that we carried out. We note that all the experiments were executed on a virtual server which is hosted on a personal computer having 2GB of RAM and two 2.66 GHz processors. The optimization problems were solved using CPLEX, a commercial solver that runs on this server. We also note that the resources on the virtual server is shared by many users and, as such, the execution time may vary considerably depending on the number of processes that is executing.

To verify our solutions and to give an idea of the execution time, several experiments were carried out. The rational and results of these experiments are given below.

4.1 Results of Execution time for Optimal solution

For networks with 11 or fewer nodes, we executed the RPP algorithm described in Section 3.1.3 10 times, using different networks. For networks with more than 11 nodes, the resources available on the virtual server were not sufficient to complete the process in a reasonable amount of time. Table 1, below, shows the average execution times.

# of Nodes in network	# of networks	Average run-time (seconds)
5	10	0.5
6	10	5.5
7	10	9
8	10	185
9	10	420
10	10	1518
11	10	13027

Table 1: Average Run-time for Optimal Solutions

This data is represented by the graph below, where the x-axis represents the number of nodes and the y-axis represents the log of the average time in seconds.

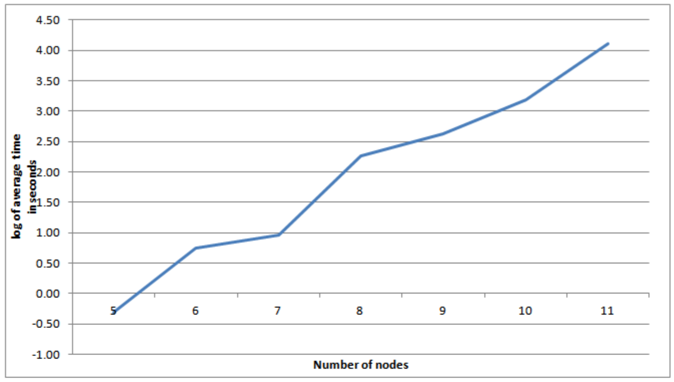

Figure 20: Graph showing log of average run-time

4.2 Results for Heuristic for RPP with DPP

We had the following two objectives for our experiments

- What is the largest network that the heuristic can handle?
- How good are the results obtained by the heuristic?

We executed the algorithm on networks having 30, 40, 50 and 60 nodes. For many larger networks, the branch-and-cut heuristic did not converge within a reasonable amount of time. For each size of the network, we generated 200 different network topologies. As discussed in Section 3.3, if the heuristic does not execute Step 11, it means we have obtained an optimal solution. We have reported below the number of times the heuristic algorithm determined optimal solutions. In each remaining cases, we noted how many additional regenerators were added in Step 11. We show the results of our experiments in Table 2 below.

Size of the network	Number of Networks	Number of optimal solutions
30	200	199
40	200	198
50	200	197
60	200	197

Table 2: Regenerator placement using heuristic SOL-H

We make the following interesting observations:

- In 98.5 - 99.5% of the networks, the heuristic provides optimal solutions. This is a remarkable result and establishes that this is a highly effective heuristic.
- In all cases, where the heuristic executed Step 11, only one (1) additional regenerator-capable node was necessary to obtain a solution for RPP with DPP. This does not necessarily mean that the regenerator placement we obtained is sub-optimal. The results obtained by the branch-and-cut algorithm is merely a lower limit on the number of regenerator-capable nodes needed in the network. We cannot prove that the solution we obtained was optimal and can only conclude that, in all cases where the heuristic executed Step 11, our solution may be sub-optimal and is only one node more than the lower limit for the optimal solution.
- Although the regenerator placement is carried out in the design phase, where the run-time is not very critical, it is worth noting that the average run-time was less than 5 minutes (300 seconds).

4.3 Results for RRP with DPP

In this section we have studied the performance of the RRP algorithm. The RRP algorithm will be used during the operational phase. At any given point, the network is already handling a number of communications. The RRP algorithm has to be invoked when there is a new request for communication, say from node S to node D. If the RRP algorithm succeeds in finding a route, from S to D, for both the primary lightpath and the backup lightpath, the request can be handled. Otherwise, the request has to be denied (or blocked). A request may be blocked due to two reasons:

- lack of available channels as a result of existing lightpaths, set up in response to earlier requests for communication. This is a network layer constraint. We note that our algorithm for RRP takes into account all possible pairs of edge-disjoint routes, from the source node to the destination node corresponding to the current request for communication - not just the pair of routes which was used in the RPP phase.

- lack of regenerators. This is a constraint due to network layer impairments that can happen if at least one pair of valid paths exist, with channels available to set up the lightpaths, but all the regenerators at the requisite regenerator-capable nodes are already allotted to existing lightpaths. To simplify our study, we have ignored this possibility by assuming that there is an infinite number of regenerator nodes at each regenerator-capable node.

If everything else remains the same, as the number of lightpaths in a network increases, the probability that a call may be blocked increases. For the same number of lightpaths in a network, if each fiber can accommodate more channels, the probability that a call may be blocked decreases. To study how the blocking probability changes with the number of lightpaths in the network and the number of channels on each fiber, we have used a practical-sized network, namely, the USAnet. This network has 24 nodes and 86 links, with the longest link being 196 km. We assume an optical reach of 200 km.

We measured the load on the network using Erlang values [40]. In our studies we have considered Erlang values of 10, 20, 30 and 40. We considered the cases where each fiber has 4, 8, 12 or 16 channels. An example of a data set is shown in Table 3, below. Here the Erlang value was 20 and five (5) sets of requests were generated for this Erlang value. In each run, we calculated the blocking probability as the ratio of blocked requests to the total number of requests. We then computed the average of the blocking probabilities, and expressed it as a percentage (rounded to the nearest percent).

Run	# of requests	Chnl = 4	Chnl = 8	chnl = 12	Chnl = 16
1	108	81	54	21	13
2	115	80	45	21	7
3	103	66	39	18	5
4	113	76	43	19	9
5	106	68	31	11	3
BP%		68	39	16	7

Table 3: Calculation of average blocking probability (Percentage)

Figure 21, below, shows the blocking probability for the various scenarios we considered. There were five (5) runs for each Erlang value and we have reported the average blocking probability (in percentage) for each Erlang value.

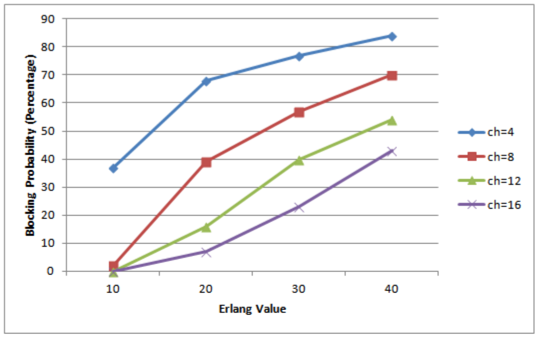

Figure 21: Graph showing Blocking Probability

Since the time to process a request for communication is critical in the operational phase, we measured the execution time to handle each request. We are reporting the worst scenario that we found. In other words, the execution time for the USAnet with Erlang value of 40 with 16 channels available. The execution time for each request is summarised in Table 4, below.

	Time (in Seconds)
minimum	0.22
maximum	2.20
average	0.39

Table 4: Minimum, maximum and average run-time per request

We note, that with a faster system and dedicated resources, the results will be even more attractive, facilitating faster execution times.

5 Chapter 5 - Conclusions and Future Work

5.1 Conclusion

In this thesis we have shown that it is possible to design impairment-aware optical WDM networks that guarantee protection against single-link failures. We developed an ILP formulation that may be used to obtain optimal solution for small networks (with size of 11 nodes or less) and a heuritic that works for medium to large scale back-bone networks. A remarkable feature of the heuristic is that for 60 node networks, in 98.5% of the 200 cases we tested , our heuristic does give optimal solutions. For 40 node networks in 99% of the cases we tested, we obtained optimal solutions. For the isolated cases where we did not obtain solution which is known to be optimal, our heuristic needed only one additional site more that the lower limit on the number of nodes needed in an optimal solution. Current back-bone networks require less than 30 nodes. For instance, the USAnet, although spanning a wide geographical area, has only 24 nodes. Therefore, our heuristic will remain viable for the foreseeable future.

5.2 Future Work

In this thesis, we have shown how to protect impairment-aware optical WDM networks from single-link failures by using optimal regeneration placement with dedicated path protection. Future work may include dual-link failures and/or SRLG failures. Also, because of the amount of resource which may be idle, if the network is not prone to many failures, future work may include optimal regeneraor placement with shared path protection for single and dual-link failures. we also note that an easy extension of this work is to control the number of regenerators required at each node. That is, in addition to the optimal placement of regenerators at selected nodes, we can also optimize the number of regenerators that should be placed at each node based on an acceptable blocking percentage.

We have proposed an optimal scheme for RRP. It is very likely that faster heuristics may be developed to obtain a fast solution to the RRP problem. Our optimal solution for the RPP will serve as a useful benchmark for such future investigations.

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