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Impairment – Aware Static Route and Wavelength Assignment in WDM Networks

by

Sebastian Christian Zawada

A Thesis
Submitted to the Faculty of Graduate Studies
Through the School of Computer Science,
in Partial Fulfillment of the Requirements for
the Degree of Master of Science, at the
University of Windsor

Windsor, Ontario, Canada

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Impairment – Aware Static Route and Wavelength Assignment in WDM Networks

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ABSTRACT

Routing and Wavelength Assignment (RWA) is a fundamentally important aspect of WDM optical network design. RWA is performed to determine a route and wavelength for each demand requesting resources between a given source and destination node. Classic RWA has only been concerned with determining a route while only taking into account network layer wavelength availability constraints. In recent years the size of WDM optical communication networks has exponentially increased in size. Resulting in the use of very long fibers for interconnecting nodes. On these modern WDM networks, researchers have identified at the physical layer, linear and non-linear impairments. Impairment occurs during the propagation of optical signals across a fiber cable and within the optical switching fabric of routing equipment. These impairments have the potential to either, greatly reduce the efficiency of WDM optical networks, or to completely render lightpaths unusable. Impairment-aware routing and wavelength assignment (IA-RWA) takes different types of impairments of lightpaths into account, while performing the RWA. The use of IA-RWA improves the quality of transmission among lightpaths as well as reduce the blocking ratio. A new heuristic for IA-RWA has been reported in this thesis for use in WDM optical network planning and design. This heuristic takes both linear and non-linear impairments into account during the RWA process. The heuristic uses existing techniques from graph theory, operations research, and optical network design, to determine an IA-RWA in an efficient manner.

DEDICATION

I dedicate this thesis to my family, which has always supported me in my endeavours.

ACKNOWLEDGEMENTS

I would like to thank my supervising professor, Dr. Subir Bandyopadyhay for his continuous support and advice making this research and thesis possible. I would also like to thank the University of Windsor Optics Research Team for their assistance in developing the needed tools and simulation software needed for my work.

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CHAPTER I

INTRODUCTION

Overview

In the last couple of decades, the global communications industry has seen exponential growth. With the advent of the World Wide Web (WWW), otherwise known as the Internet, the need for a reliable high-speed communication has shifted from being a luxury to a basic necessity. For an individual or an organization to be connected to the Internet, they must connect to an Internet Service Provider (ISP). An ISP facilitates the basic infrastructure and equipment needed to communicate with the internet. The range of usable frequencies over a medium is called *bandwidth*. While *bandwidth capacity* refers to the maximum amount of data that can be transmitted over a network at any one point in time. Heavily utilized networks are considered *congested*. Congestion refers to a network state where there is a large amount of data being transmitted. It may be difficult or impossible to transmit additional information over a congested network. Economic forces such as the continued growth of corporations, international trade, and logistical automation, have forced individuals, governmental institutions, and companies to maintain an ever increasingly important online presence. Organizations use their digital presence to integrate and streamline business units such as, commercial transactions, marketing, management, inventory control, and to facilitate end user sales and support.

Historically information on the Internet was presented in plain text, with few graphics. There weren't many options for website formatting and use was dominated by business and academic institutions. End users started to account for a larger percentage of Internet usage at the advent of what is known as Web 2.0. Web 2.0 allowed for websites to contain video and audio media, social media, and user created and driven content. The new media driven Internet requires significantly more data compared with the traditional content that was present on the Internet. The exponential increase in the number of users, coupled with the increase in bandwidth required to provide each website has created a need for a reliable and most importantly a faster communication medium for use by networks and ISP's.

Networks come in many different forms; a common pseudonym for the Internet is a "network of networks". Each ISP is responsible for maintaining and operating its own network, while interfacing and communicating with other ISP's using a set of well known and defined protocols, ports, and standards. Each user, corporate, or government entity is also able to maintain and a network for their own use, some of the common networks include local (LAN), metropolitan (MAN), and wide area networks (WAN) among others. LAN's are used to locally interconnect a set of computers and network-enabled devices such as smartphones and tablets located within a single building or floor. MAN networks are used to interconnect multiple LAN's owned by an organization within a city or small geographic area. WAN's are used to connect different business units located at different locations around the country or globe. WAN networks allow for seamless communication and information sharing between different individuals within an organization irrespective of the physical location of the office. To facilitate these different networks, a wide range of media exist, traditionally, copper cabling or satellites were used as the preferred medium to transmit information across networks. Some of the problems with these mediums include:

- Lack of bandwidth capacity,

- Sensitive to environmental noise,
- Low distance propagation,
- High latency.

Because of these restrictions, it was evident that a new medium for data communication would have to be used if the Internet was going to continue its exponential growth in both user count, and as an avenue for media consumption.

Fiber optics have been seen as the solution to problems plaguing traditional physical communication media such as copper cables. The use of fiber optic cabling and equipment within telecommunications has grown exponentially in the last couple decades. In this time, there have been vast strides in technological innovation resulting in immense performance increases as well as cost reductions. These innovations have also led to the increase of the amount of data that can be transmitted across an optical fiber while maintaining an exceptionally low number of errors and impairments in the signal. As optical networks are used more commonly within industry, and signals are propagated across greater distances, new challenges emerged. It has been observed that, optical signals degrade as the length of the fiber increases resulting in *Bit Errors* (BE), measured in *Bit Error Rates* (BER) at the destination.

Wavelength Division Multiplexing (WDM) is an innovation within optical networks that allows multiple communication streams called *lightpaths* to simultaneously propagate across an optical link. Each lightpath is capable of operating at speeds of 2.5Gbps or greater and each optical link is able to support between 4 and 64 distinct bi-directional lightpaths. In order for optical networks to operate efficiently, BE must be strictly monitored and minimized.

Optical networks consist of optical cables, optical cross-connect switches, and other amplification devices. Optical cables are used as the primary physical medium for sending information from the source to the destination. Pulses of optical light represent information where each pulse constitutes a 1 or 0. Optical switches are responsible for routing lightpaths by demodulating each wavelength on an incoming fiber connected to an ingress port, by doing so separating each lightpath and then re-modulating a final signal on an output fiber connected to an egress port. Amplification devices are used to strengthen the optical carrier signal (light pulse) so that it can propagate a further distance on a single optical cable. Electronic equipment can also be used within optical networks, but these devices represent a bottleneck, as the most powerful electronic devices operate slower compared to optical devices. The reason electronic devices are used is because when a signal is transmitted across long distances, the signal will deteriorate beyond amplification and must be regenerated. Only electronic devices are capable of performing this service at this time. Optical regenerators are currently in research and are prohibitively expensive for commercial deployment.

An optical network is usually represented by a graph $G=(N, E)$ where N is a set of nodes and E is a set of edges of the graph. Here each optical link is represented by an edge e, and each end point device is represented as a node n; each source and destination node on the physical network is denoted as $(s, d) \in E$ where $s \in N$ and $d \in N$. In optical networking, in many situations it is common for the traffic demands to be known during the design of the network. The list of connection requests is denoted by a set of source and destination nodes known as a demand set. The challenge in optical networks is to efficiently allocate lightpaths, to each of the source and destination requests. This is known as the *Routing and Wavelength Assignment* (RWA) problem.

Given the high performance nature of optical networks, failure to take account of errors could lead to massive amounts of lost data, or grievous inefficiency as information that is corrupted during transmission is usually repeated by the source node. This has resulted in the development of new *Impairment-Aware Routing and Wavelength Assignment algorithms* (IA-RWA).

Motivation

In recent years the deployment of optical networks has experienced exponential growth within telecommunications and corporate networks. Within these networks, the use of very high performance long haul optical cabling has become more common. State-of-the-art optical networks use technologies such as WDM that are capable of sending between 32 and 64 simultaneous streams of communication across an optical fibre. As the size and utilization of optical networks increases, researchers have noticed a rise in both linear and non-linear impairments of the optical signals. Unfortunately classic RWA algorithms do not take physical layer impairment into consideration. These impairments have the potential to cause devastating corruptions to the signal, resulting in corrupted lightpaths that are unusable. This makes the IA-RWA invalid. In order to sustain the exponentially increasing demand for traffic, a new class of IA-RWA algorithms must be developed. These algorithms take physical layer impairment into consideration while performing the RWA. IA-RWA is expected to yield significant improvements in network utilization, and to minimize impairment of the lightpaths that are established. This will result in increased capacity and potential for significant cost savings by service providers as the useful life of infrastructure is increased.

Problem Statement

Through innovations such as WDM in optical networking and the increasing distances of fiber cabling, impairments have been observed as a major limiting factor. Linear and non-linear impairments result in signal noise and corruption. Classic RWA is not concerned with impairment, as this was not observed at the time. A new class of IA-RWA algorithms must be developed in order to efficiently utilize network resources and to minimize the impairment experienced by each lightpath.

A new IA-RWA heuristic is being proposed that is capable of efficiently assigning network resources to a set of demands. The proposed heuristic takes both linear class 1 and non-linear class 2 impairments into consideration, when performing the RWA. The heuristic iteratively assigns network resources to an offline demand set. The ordering of the demands is done dynamically based on the current network state. The heuristic also implements an ILP solution that is used to avoid assigning too many lightpath through any single fiber on the network. With the intelligent prioritization of demands, ILP optimization, and selective wavelength assignment, an IA-RWA heuristic has been developed which outperforms comparable modern heuristics.

Organization of Thesis

Chapter two of this thesis contains a brief overview of related topics in fiber optics and a survey of work on IA-RWA. Chapter three provides a detailed overview of the proposed *Smart Priority Selection Impairment Aware Routing and Wavelength Assignment* (SPS-IA-RWA) heuristic. Chapter four covers the implementation details of the proposed heuristic. Chapter five provides a comparative analysis of the results that have been gathered from large scale testing of the performance of the proposed heuristic. Chapter six contains conclusions and future work.

CHAPTER II

REVIEW OF LITERATURE

Fundamentals of Optical Networks

Traditional networks based on twisted-pair copper cables operate by oscillating analogue electronic signals in order to represent digital data in the form of 1's and 0's. At the receiving end, the node would read the electronic signal and determine the binary value. Unlike traditional networks, optical networks do not transmit signals using electronic methods, instead uses pulses of light to represent binary values of 1 or 0. In order to use optical signals a special kind of cable is needed. A cable capable of transmitting optical signals is called an optical cable. Referring to figure 2.1, these cables consist of three primary components, a core, cladding, and coating. Both the core and the cladding are made entirely of glass and a single optical fiber is approximately the thickness of a human hair. Optical cables used in telecommunications bundle many optical fibers together in order to form a single cable as can be seen in figure 2.2 from [35]. The optical signal is transmitted within the core of the cable. The light pulses representing data never leave the core as that would result in a loss of

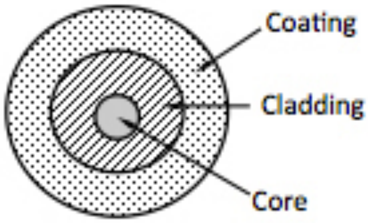


Figure 2.1 – Cross-Section of an Optical Fiber

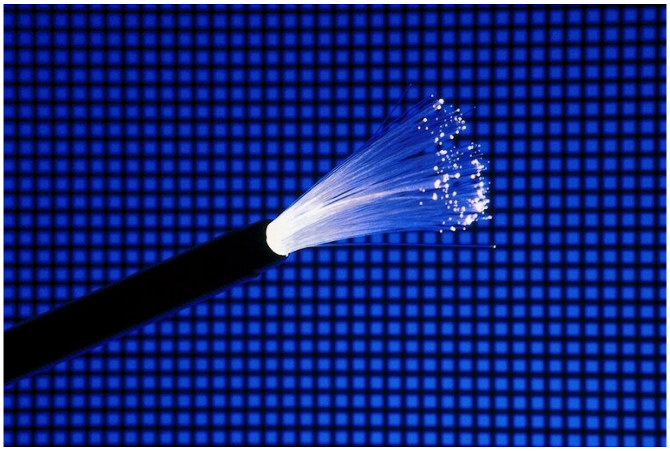


Figure 2.2 – Fiber Optic Cable

information. Since optical cables are not perfectly straight, the light pulse continually reflects off the cladding layer portion of the cable in order for the signal to bend with the cable. Within optics, surfaces have an index of refraction, this dictates how light propagates across the medium. The core of an optical cable has a high refractive index, while the cladding has a lower one. This creates the potential for the light to reflect from the cladding and stay enclosed within the core. Depending on the angle of the light being sent across the cable, there are three potential outcomes:

- The light breaks through the cladding and is therefore lost.
- The light propagated within the border between the cladding and core rendering the signal lost as well.
- The light reflects from the cladding, leaving the signal within the core.

The critical angle is defined within optics as the angle that results in the light pulse travelling along the border in-between the core and cladding ($\theta_c\ in\ figure$ 2.3). This angle is determined based on the refractive index of the core and cladding. Signals being transmitted below the critical angle will break through the cladding and will be irrecoverable. In order for

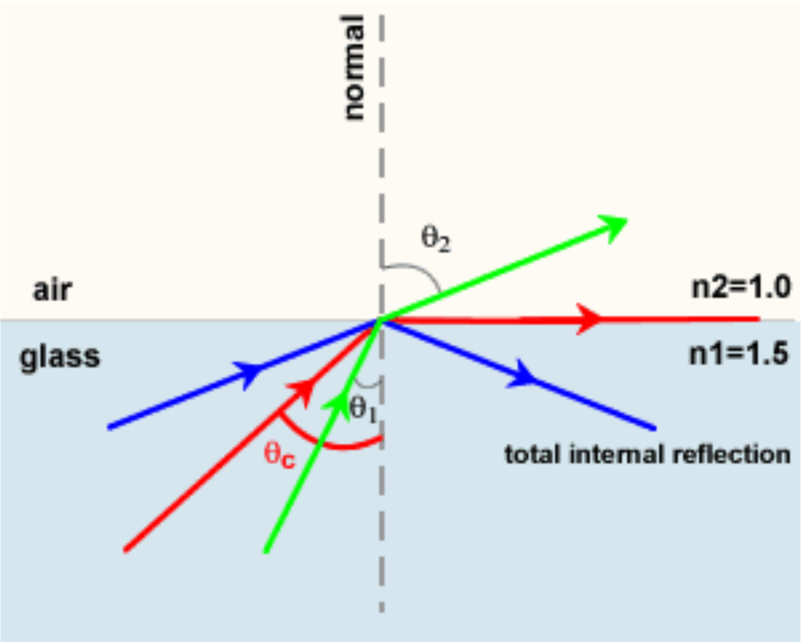


Figure 2.3 from [36]– How Light Propagates Along an optical Fiber

communication to be possible, the signals must be sent at an angle above the critical angle, at which point, the light is contained within the core until it reaches the destination. Due to manufacturing imperfections of the optical cables, light pulses will lose strength as they propagate along the cable. This results in the possible need for amplification or regeneration of the signal at some point along the route. The coating portion of the cable is used for physical protection of the cable. Depending on the environmental factors, requirements for the coating may vary and therefore is made from different materials. There are two common types of optical cables in use, multi and single mode fiber cable. The main difference between the two cables is that the multi-mode fiber cable has a thicker core compared to the single-mode variant. Multi-mode optical cables are generally cheaper as result and are used mostly for short distance communication. Single-mode optical cables are used almost exclusively for very long distance communication and are not only more expensive but also require more expensive equipment at the sending and receiving ends.

When the network receives a request for communication between an arbitrary source and destination node, it must perform two fundamental tasks:

- Determine a route on the physical network between the source and destination nodes.
- Determine which available wavelength should be used by the route.

Once a route is determined and a carrier wavelength selected, the lightpath may be setup and a stream of bits can be transmitted across the optical network. In the scope of optical networks, a lightpath is a connection at the optical layer, between the source and destination, where the communication is taking place entirely within the optical domain.

Each demand must have a lightpath established for the communication to be possible on the optical network. If two or more lightpaths share an optical fiber along the network, each of the lightpaths must operate on a different carrier wavelength. Once a wavelength is selected, it must be used along the entirety of the route that the lightpath is following, this is called the *wavelength continuity constraint*. Due to technological limitations and cost, the carrier wavelength is not allowed to change along the route of a lightpath. With IA-RWA networks, each lightpath must meet certain quality requirements before it is added to the network.

Each type of optical cable in modern communications is capable of utilizing WDM technology. WDM is a technology that allows multiply simultaneous communication streams to be transmitted at one point in time. Each communication stream operates at it's own carrier wavelength within the optical cable. As can be seen on figure 2.4 from [34], at the source, there are four unique signals.

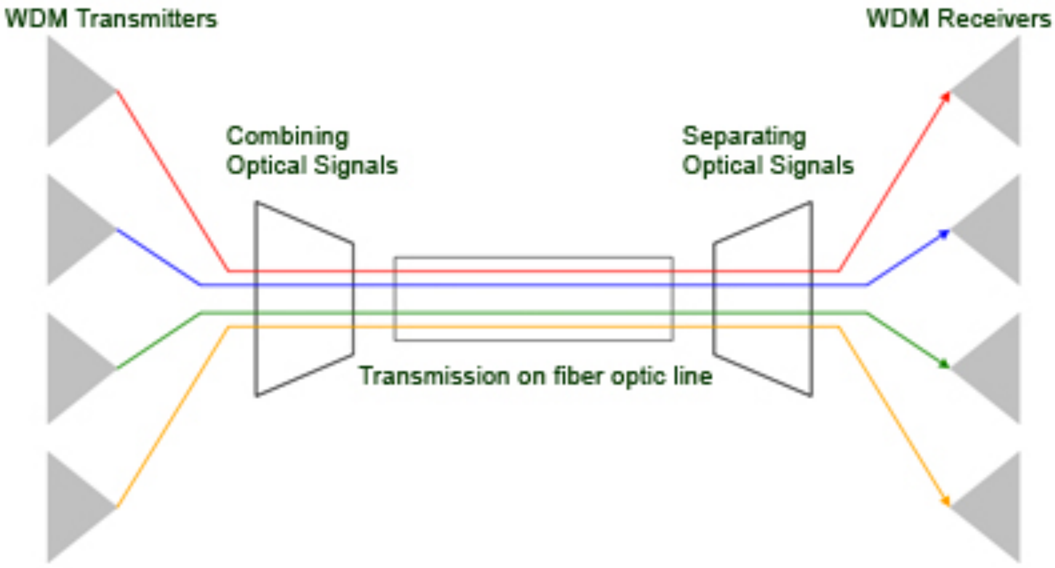


Figure 2.4 – Illustration of WDM

These signals are combined using a coupling device and the signal is transmitted along an optical fiber. At the destination a decoupling device separates each individual signal and routes it to output ports as needed. Depending on the equipment in use, current technology can support between 32 and 64 usable wavelengths, while current research is pushing over 120 in a laboratory environment. The primary limiting factor is the impairment of optical signals, as more lightpaths share fibers, greater interference is caused in-between wavelengths. This interference is referred to as non-linear, class 2 impairment, where a lightpath is impairing the *Quality of Transmission* (QoT) of other lightpaths that are using the same optical cable. QoT is a measure of quality at which a signal is being transmitted on.

Within an optical network, there are many different devices used in order to make communication between a source and destination using an optical medium possible. Within optical WDM networks there are three primary components:

- Amplifiers
- Regenerators
- Optical switches.

Due to the manufacturing imperfections of optical cables, the signals being propagated over a long distance must be re-amplified so that the light pulses are of sufficient strength for the receiving device to be able to interpret. Without amplification, the optical signal could be weakened to the point of the receiving device not recognizing it as a valid input and the information being transmitted would be lost. While amplifiers are necessary in most networks, care must be taken to only use as many as are needed, because during the amplification process a new type of impairment is introduced into the signal. In addition to injecting impairment into the signal, amplifiers do not filter impairment already present, resulting in both, the signal and noise being amplified. Regenerators are used within optical networks to recreate the optical signal being propagated along an optical fiber. Regenerators reshape, retime, and reamplify the optical signals. By performing these activities, the regenerator is capable of removing all impairment from the incoming signal. There are two types of WDM regenerators, electronic and optical that are used within optical networks. Electronic regenerators perform what is known as 3R conversion (re-time, re-transmit, re-shape) by an OEO process. OEO refers to the process of converting the received optical signal into electronic form and then converting it back into the optical domain as it is transmitted along the next optical fiber. Optical regenerators are able to retrieve a optical signal, remove impairment, and perform routing logic entirely within the optical domain without the need for electronic conversion.

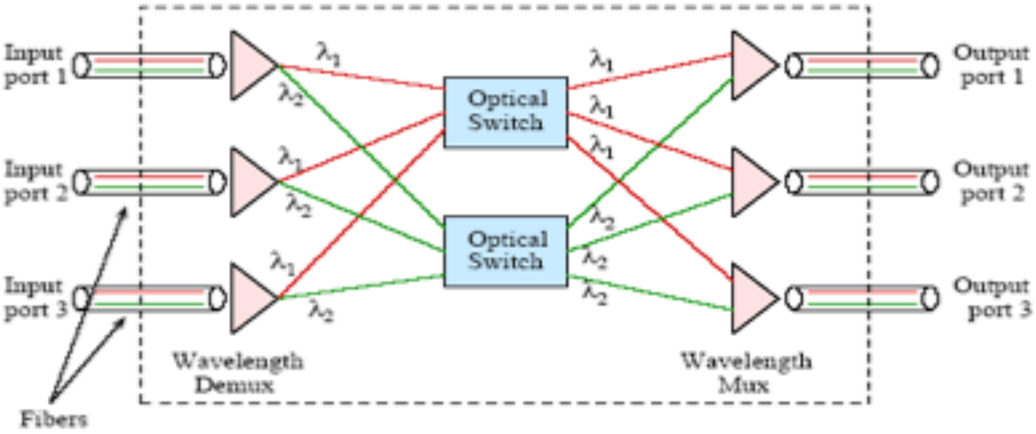


Figure 2.5 – WDM Enabled Optical Switch

Optical regenerators are currently prohibitively expensive for commercial applications and are almost exclusively used in research and development. Optical switches and cross-connects are used for routing lightpaths along the network. Optical switches and cross-connects operate entirely within the optical domain and do not rely on electronic processes for performing routing. Optical switches and cross-connects are capable of having many incoming and outgoing optical cables. Basic optical switches simply transmit a signal from one optical cable to another; while more sophisticated cross-connects utilize WDM. As can be seen in figure 2.5, there are three incoming optical fiber cables each with two lightpaths. On WDM enabled cross-connects and switches such as in figure 2.5, each incoming optical cable has its signal DE-multiplexed into individual lightpaths based on wavelengths used. Internally, the optical switching fabric is responsible for routing decisions. On the incoming cables, each usable wavelength is separated and aggregated into a pool with other such wavelengths. Based on the configuration, each wavelength is then aggregated onto a specific outgoing port. Each incoming port has a predefined number of wavelengths and the same number of wavelengths must be present on the outgoing ports. Each of the wavelengths are then multiplexed back onto the designated outgoing optical cable. It is important to note, that a lightpath must maintain its wavelength as it is propagated across the optical switch. This means that the wavelength assigned to the lightpath on the incoming optical cable will be the wavelength used on the out-going cable as well. Optical switches can be seen as source and destination nodes on the network, as these devices are responsible for physical layer routing within the network. With this variety of optical equipment current in use, there are three categories of optical networks:

- Opaque
- Translucent
- Transparent

The category of the network is dictated by the use of electronic devices such as regenerators. Opaque networks consist of optical to electronic to optical regenerating devices at each node on the network. Impairments are not accumulated as the optical signal is recreated at each switching node. On opaque networks, the wavelength continuity constraint on lightpaths can also be relaxed as the signal only propagates across a single optical fiber before undergoing OEO. These networks are commonly used in current communications networks. Opaque networks are costly to implement and perform very inefficiently compared to the alternatives. Translucent networks are a hybrid between opaque and transparent networks. A small subset of switching/routing nodes performs electronic conversion while the remainder operate entirely in the optical domain. Request routing is generally performed in such a way to maximize the use of optical nodes. Ideally the electronic nodes are reserved for longer requests that experience greater impairment.

Transparent networks operate entirely within the optical domain. Within these networks wavelength continuity is an operating requirement as optical wavelength reassignment is not commercially feasible. These networks experience the greatest amount of impairment as there is no possibility of electronic regeneration. All impairments are accumulated over the distance of the lightpath from the source to destination nodes. Given that transparent networks are the most efficient and cost effective solution, a new type of network has been developed, bridging the gap between translucent and transparent networks. This new type of network, contains "islands"[20] of transparent networks that are interconnected by electronic regenerating devices. Within the "island" [20] the network is entirely transparent, meaning that all of the devices used are entirely optical in nature. When a node within one island needs to send information to another, the lightpath must pass through an electronic device where optical to electronic to optical conversion is performed before the signal reaches it destination. When communicating in-between islands, the wavelength continuity constraint is usually relaxed, as the regenerators are capable of assigning a new wavelength as the information passes into a different optical island. Lightpaths operating entirely within a single island are restricted to using a single uninterrupted wavelength on the route.

The optical network consists of a number of optical devices called nodes that are interconnected by either unidirectional or bi-directional optical cables. With unidirectional cabling optical signals only propagate a single direction. While bi-directional optical cables allow information to flow both ways simultaneously across a single line.

An optical network can be represented by two different topologies:

- Physical
- Logical.

A physical topology is used to represent the physical devices and fibers current deployed on the network. It does not take lightpaths, traffic or any other information into consideration. The physical view is used primarily for determining routes for optical connection requests. The physical topology of the network is modeled by a graph G, where optical switches and routers of the physical topology are specified as nodes of graph G, and if there is a fiber on the physical topology from node x to y, there is a directed edge from node x to node y on graph G that includes a label specifying the length of the fiber. Each node has a label attached to it denoting a distinct node number. Nodes are numbered sequentially from zero to *N*, where *N* represents the number of nodes in the physical topology. The logical topology shows each of the lightpaths currently operating on the network. This view can be used to visualize the current network state. A logical topology can be represented by a graph *LG*, where each physical node, *N* on the network is a node of graph *LG*. A directed edge between node *x* and *y* exists only if there is a lightpath established on the network, going from node *x*, to node *y*. Much like the physical topology, each of the nodes is also labeled from 0 to *N*, where *N* is the number of nodes on the physical network.

A demand set is a list of source and destination nodes requesting resources on the network. It is represented by a list D. A demand that is successfully accepted needs to meet the following requirements; it must have a route selected and a unique wavelength for the lightpath to use. In the event one of the above requirements is not met, the demand is blocked. Demands come in two flavors:

- Dynamic, sometimes called online.
- Static, sometimes called offline.

Some optical network algorithms are capable of establishing both static and dynamic requests.

Dynamic (often called online) demand sets have to be processed when there is no priori knowledge of the complete list of source and destination nodes. Each request for resources arrives at random intervals and the duration of communication is unknown. These requests must be processed (RWA) very quickly when they arrive. As the requests arrive a route from the source node to the destination node must be found, and a valid wavelength must also be available along that route for a lightpath to be established on the network. The period of time that the lightpath is active is determined by the amount of data that is to be transmitted. The data transmission rate and the available bandwidth for each lightpath is constant as this is determined during network design. Once a lightpath is established, it is kept on the network for a period of time sufficient to communicate the data. The lightpath is torn down and resources are made available for new requests. During the tear down process the lightpath is removed from the network, during which the wavelength used by the lightpath is freed on each optical fiber along the route. Once the wavelength has been freed the lightpath is no longer existent and the resources are available for new connections.

A set of demands is called static, often referred to as an offline demand set when there is detailed priori knowledge of all demands that will be operating on the network. An offline demand set is represented by a complete list, D of source and destination nodes where each entry i is a single demand from some source node x, to some destination node y. This list is available during the network design phase. As the demand list is known during design, the RWA is not time sensitive as the network is not operational at the time the RWA is performed. Considering the lack of time sensitivity, algorithms responsible for the RWA are generally expected to return a more efficiently designed network compared to online networks. Offline RWA algorithms are able to implement larger scale ILP optimizations, detailed impairment calculations, and state of the art routing algorithms to carry out the RWA. The offline RWA, much like the online version, is expected to determine a route for the lightpath corresponding to each demand, and select an appropriate wavelength for the lightpath to utilize. Once the RWA is complete, the lightpaths that are established are considered semi-permanent. Semi-permanent can be defined as a period of time not governed by the amount of data that needs to be transferred across a lightpath for a single demand. Static lightpaths are usually only taken down when the network is being redesigned, or there are major changes in user demand.

Hybrid online and offline demand set networks are uncommon, but operate at different phases. During the network design phase, the offline component of the RWA is performed. When the network is deployed, the offline lightpaths are semi-permanently established, while the network online RWA algorithm implements all the online demands coming in. The online demands would work in conjunction with the offline lightpaths. As is typical with online demands, once the lightpath has concluded the requested data transfer, the lightpath is torn down.

Modern day IA-RWA algorithms, are expected to take impairment into consideration on both, online and offline demand sets. Given that the time sensitivity of online demand sets, it is common to use heuristic estimates, or constant worst-case values when calculating impairment of a lightpath. Many online IA-RWA also disregard certain impairments that are complex to estimate. Offline IA-RWA algorithms are capable of calculating impairments more accurately and generally take most well known impairments into consideration when performing RWA.

Wavelength Division Multiplexing (WDM)

WDM is a state of the art technology used for optical communication. Optical cables and switches are capable of transmitting optical signals at almost any frequency across the optical fibers. Research and practical applications have demonstrated that signals utilizing wavelengths within the “C-band” [29] are commercially usable. Optical lightpaths that are transmitted outside of the “C-band” [29] will experience considerable impairment and therefore are not practical for WDM or optical network applications. The “C-band” [29] is usually between 12.5nm and 15.5nm. Optimal wavelengths for use are between 12.5nm and 13.5nm and again between 14.5nm and 15.5nm. Within these wavelengths noise and optical impairment is minimized making communication viable. Within WDM, each usable wavelength is enumerated from 0 to W. Where W is the maximum number of wavelengths the network is able to accommodate on a single optical fiber.

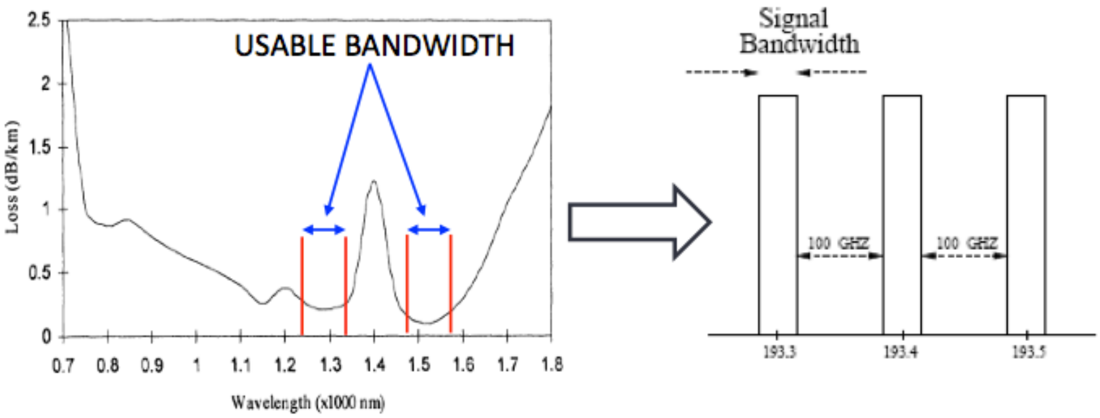


Figure 2.6 – Usable Wavelength Spectrum

As seen in figure 2.6, from [37], each enumerated lightpath corresponds to a 10GHZ (typical value) wide optical spectrum. This enumerated 10GHZ space is available for use by a lightpath and is referred to as channel $w \in W$. Within the usable wavelength spectrum, WDM is able to modulate individual signals into channels of width 10GHZ or less (depending on modulation technology used). To avoid significant impairments, channels are spaced at 100GHZ or less from other channels this is called channel spacing. Channel spacing and width is predetermined and must be consistent across the entire optical network. At the source node, all available wavelengths are combined together onto a single signal using an optical coupling device. When the optical signal reaches any node on the network, a de-coupling device separates each of the wavelengths and appropriately routes each individual lightpath. Lightpaths continuing on a route are modulated back onto an optical fiber carrying all channels.

Routing and Wavelength Assignment (RWA)

Classically RWA algorithms have only been concerned with routing and wavelength assigned between source and destination nodes of a given demand set. RWA algorithms perform two functions; they find a route for the lightpath on the physical topology of the network and then assign a wavelength $w \in W$ or channel on the optical medium for the lightpath to use. This is performed for each request in the demand set. These algorithms assumed a perfect communication medium (optical links, switches and routers) where impairment and signal degradation do not exist. This was a valid model until recently when propagation distances were minimized and each switching device along the route performed optical to electronic to optical conversion. This mechanism, while inefficient has prevented impairments from accumulating along the route resulting in a significant BER. Recently through cost reductions and availability of equipment, there has been a new trend in telecommunications to move from opaque networks to transparent networks. In a and transparent network, signals may not be converted into the electronic domain until the destination is reached, resulting in impairments accumulating over the physical route followed. In addition to impairments accumulating, the optical devices that replaced regenerators inject their own impairments into the signal.
IA-RWA algorithms have been developed in response to the shortcomings of the classic approach. Algorithms classified as impairment aware take many different forms and use

varying techniques to measure or estimate the impairment. There are two primary techniques for impairment modeling:

- Direct approach.
- Indirect approach.

The direct model uses complex formulations in an attempt to accurately measure the current impairment on the candidate lightpath. Some algorithms only measure linear impairments, and others take non-linear impairments into account as well. Non-linear model measure the both classes of impairment for each lightpath on the topology in conjunction with other already establish lightpaths. Accurate impairment calculations are usually very time consuming to calculate [11] and are generally only viable with off-line demand sets.

The indirect approach attempts to simplify the formulations and estimate what the impairment is believed to be. Estimations can be based on link/wavelength weights [3], offline simulation runs [3], or can be as simple as assigning a static worst-case impairment penalty to each lightpath. Most indirect approaches attempt to estimate what the impairment is by predicting what the load is expected to be on the network, and based on the utilization, the heuristic formulations attempt to determine if a lightpath has sufficient QoT. In some cases indirect impairments are added onto lightpaths using a worst-case value. Depending on the assumptions used the indirect approach can yield relatively accurate results as long as the underling assumptions about network load, congestion and utilization are valid. The impairment estimate is significantly faster compared to the direct approach resulting in its viability for online demand sets.

The classic RWA is an NP-Complete problem [30]. Adding impairment analysis makes the problem even more intractable. As a result, many algorithms separate the routing portion of the RWA from the wavelength assignment. This way the IA-RWA problem becomes more manageable on larger networks. Classically a lightpath was only blocked due to a network layer constraints when the optical network ran out of usable wavelengths.

Current generation of IA-RWA algorithms that perform impairment analysis are able to block lightpaths due to physical layer QoT constraints due to impairment on individual lightpaths. When algorithms consider non-linear impairments, it is possible to be in a situation where a newly established lightpath will cause adverse impairment on a lightpath that was established at an earlier time; resulting in the lightpath having an unsatisfactory QoT. In a situation such as this the algorithm has the following options:

- Block the newly established lightpath,
- Block the already established lightpath,
- Tear down, and attempt to reroute the newly created lightpath,
- Tear down, and attempt to reroute the impaired lightpath.

Depending on the RWA, impairments can be considered at different phases. Most algorithms perform impairment analysis during the routing [3] or wavelength [2] assignment phases of the RWA. Other algorithms perform cross-layer impairment aware optimization [10]. This way, if the route is deemed invalid, there is no need to continue onto further phases and therefore a new route must be found or the demand has to be blocked. Depending on the algorithm, final impairment verification may take place once a candidate lightpath has been determined. This is done for two reasons:

- Verify the lightpath impairment is acceptable when operating with established lightpaths.
- Verify that the candidate does not adversely affects any of the implemented lightpaths.

Impairments

Impairments are caused by a variety of reasons such as, diminishing optical signal strength, optical amplification, and physical phenomenon. Optical cabling and switches also possess manufacturing imperfections resulting in propagation impairments. Signal strength deteriorates as the distance travels along a fiber. It is estimated that the signal must be amplified on average between 75km and 100km using Erbium Doped Fiber Amplifiers (EDFA) otherwise the destination node would receive a signal that is too faint to be recognized as a valid input. The challenge posed by EDFA's is that these amplifiers operate entirely within the optical domain and are not capable of separating the signal from the noise. During the amplification process, EDFA's will also inject Amplified Spontaneous Emission (ASE) [21] noise into the optical cable carrying many lightpaths. In addition to injecting ASE noise, impairments already present on a fiber are amplified as well. Impairments within optical networking can be organized into two broad categories [21]:

- Linear – Class 1 impairments.
- Non-linear – Class 2 impairments.

The classification of impairments is determined by whether the impairment on a specific lightpath is caused by interference from a different lightpaths operating on the same fiber on different wavelengths, or if the impairment is caused by physical phenomenon, which affects each lightpath on a fiber individually.

Linear class 1 impairments affect each lightpath on a fiber link individually. The number of established lightpaths on a single optical fiber has no affect on impairments classified as linear. The impairment caused by optical cabling, switches, nodes, and routers is static and consistent across the network. Because of the static nature, these impairments are relatively simply to calculate accurately. Some common linear class 1 impairments are:

- ASE - Amplified Spontaneous Emission.
- PMD – Polarized Mode Dispersion.
- CD - Chromatic Dispersion.

Manufacturing imperfections within optical equipment causes the majority of the linear impairments listed, PMD and CD. ASE noise is injected onto an optical fiber during the signal amplification process by EDFAs. Manufacturing imperfections within the core of an optical fiber can result in certain wavelengths propagating at varying speeds, this is known as CD [39]. PMD is a result of CD, “birefringence” [38] within the optical fiber, and other phenomenon. PMD impairment occurs when lightpaths with different polarizations separate and overlap [38].

Non-Linear impairments are caused by interference between lightpaths. These impairments can occur when two lightpaths are propagating on two adjacent or second-adjacent wavelengths on a single fiber, or within the optical switching fabric of a node or optical cross-connect. The current load on a fiber and node dictate the intensity of these impairments. Since load isn’t perfectly evenly distributed across the network, these impairments are very difficult to calculate because the state of each link and node must be uniquely computed. Adding an additional lightpath onto a network may also have an adverse affect on one or more lightpaths that have already been established. Nonlinear class two impairments are classified as follows:

- SPM – Self-phase modulation.
- XPM – Cross-Phase Modulation.
- FWM – Four-wave Mixing.

SPM is impairment that occurs when the frequency of a lightpath changes due to a change in the refractive index of the core and cladding of the optical fiber. The change in the refractive index happens due to natural phenomenon known as the optical Kerr effect [38]. XPM is caused when one-lightpath induces a phase change within another lightpath on a different wavelength propagating along a fiber [32]. FWM occurs when the interference between two different lightpaths along a fiber causes the creation of two additional lightpaths that contain noise [31]. Each O-E-O node must then filter out the faulty lightpaths that were created when processing lightpath signals.

One of the strategies to minimize the effect of these impairments is use intelligent routing and wavelength assignment decisions. This includes load balancing the network, reducing congestion, and assigning non-consecutive wavelengths to lightpaths if alternatives exist. Increasing the spacing in-between lightpath channels reduces the effect of non-linear impairments. Other strategies include using amplifiers and electronic regenerators within the network.

Impairment Models

Each research group is responsible for developing their own version of an impairment verification or computation tool that will be run on the IA-RWA test system. The European DICONET project has developed proprietary optical impairment tool known as the "Q-Tool"[10]. The DICONET "Q-tool" [10] is a very well known impairment model because it is able to directly translate impairment computed into a per lightpath bit-error rate. This tool uses the direct approach for computing both, linear and nonlinear impairments. While the tool is very accurate, it is computationally expensive and takes a long time to run. Another direct method of computing the impairment is through the use of ILP optimizations as done in [10][11].

Tools that estimate the impairment of a lightpath may follow one of these broad approaches:

- Accurately measure class 1 impairments while estimating the effect of class 2 impairments,
- Accurately measure class 1 impairments while adding the worst-case effect of class 2 impairments,
- Estimate both class 1 and class 2 impairments,
- Use worst-case impairment for all lightpaths.

The goal of indirect tools is rarely to compute an accurate BER, noise, or impairment value. These tools simply need to determine if the operating lightpaths on a network meet minimum QoT requirements. Another alternative is to measure impairment by computing the Optical Signal To Noise Ratio [15] (OSNR) of lightpaths. The OSNR model represents the QoT as a signal power to noise power ratio at the destination node of the lightpath. Depending on the model selected, the tools have the ability to be developed such that all impairments are taken into consideration or only a small sub-set depending on the expected usability of the tool. In all cases, a minimum QoT or maximum impairment has to be set for an IA-RWA to be performed.

Related Works

Classic RWA algorithms assumed a perfect communication medium, meaning that impairments were not taken into consideration when establishing lightpaths. While considering only network layer wavelength constraints on a network, the RWA has the potential to establish lightpaths that are heavy impaired resulting in unacceptable BER. All modern optical RWA must take physical layer impairment into consideration. RWA that takes impairment into consideration at some point during the RWA is called IA-RWA. There are two common approaches used for computing impairment, i) direct [1] [2] [7] [9] [10] [11] [12] [16], where the impairment is accurately computed and ii) indirect [3] [5] [6] [8] [10] [11] [17] [19], where the impairment is estimated. In [4] a hybrid approach is taken where the linear impairments are computed and nonlinear impairments are estimated using a worst-case scenario static cost. In [26] a study is performed evaluating the benefit of direct impairment calculation. In papers [10] and [11] a comparison was made between direct and indirect impairment computation. Papers [3], [8], and [18] implement simulations in order to estimate impairment cost on each optical link. IA-RWA can be used for solving online [11] [12] [13] and offline [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [16] [17] [25] demand sets. Many different papers use a variation of ILP [1][2][4][10] relaxation and solving techniques to assist or to solve the IA-RWA. Hyper-Heuristics have also been proposed to solve the IA-RWA in [5] and [6]. Paper [9],

[19], [20], [22], [23], [24], and [14] assume a translucent network where the goal of the IA-RWA is to not only minimize blocking but to also minimize the use of regenerators. In [11] [12] and [13] the authors have assumed an online demand set.

In [4] the “ROLE” algorithm has been proposed. It is divided into three phases, where phase one is responsible for routing and wavelength assignment, phase two attempts to reroute demands that were blocked, phase three will initialize phase one over again with a reordered demand list. Phase one computes k-shortest paths for each demand in the demand list. The shortest of the k-shortest paths determines each demands length measured by the number of hops from the source node to the destination node. Each optical link on the physical topology counts as a hop. The demands are then ordered from shortest to longest. Multiple route assignment methods are tested, shortest-path first, shortest widest-path first, and widest-shortest path first. Wavelength assignment is performed by the following methods, first-fit with BER, maximum BER, and maximum-minimum BER. Phase two separates the blocked paths into two categories, paths that have been blocked due to a lack of wavelengths (network layer constraint) and paths that have been blocked due to impairment (physical layer constraint). “ROLE”[4] will attempt to assign lightpaths to demands that have been blocked due to BER first. For these demands a variety of alternative routes are tested. Next demands blocked due to wavelength constraints are processed. For these, “ROLE”[4] attempts to tear an active lightpath down and make resources available if possible. Phase three starts phase one over again where the demand that was the first to be blocked in phase two is assigned a lightpath first. The impairments are commuted using the Q-Factor formulations, which take the following impairments into account, signal cross talk, ASE, shot noise, and thermal noise. The authors have ignored the calculation of non-linear impairments; instead have implemented a static worst-case penalty on all lightpaths when computing the final Q-factor.

In [8] a simulation based heuristic called “least variance” is developed. The impairment model applies a “cost metric”[8] to each edge on the network. Linear impairments are accurately measured, while non-linear are simply estimated based on the current load on the edge. An adjustable impairment weight is also assignment to each edge. The greater the cost the greater is the impairment that will be experienced by the lightpaths. The weight is dynamically changed as additional lightpaths are added onto the network. The algorithm then proceeds to use a shortest path algorithm such as Dijkstra’s algorithm for routing. Routing will avoid heavily congested links and therefor the network load will be relatively even across all links. Wavelength assignment is performed by either first fit or random pick.

The authors of [7] have proposed three algorithms, “quality path selection algorithm” [7], “Worst Quality Path Selection Algorithm” [7], and “Shortest Worst Quality Algorithm” [7]. The impairment model takes into consideration, CD, PMD, non-linear phase shift and OSNR. The Q-Factor is also using “Eye-opening penalties”[7] for better calculation. It is noted that this is the first paper to take these impairments into consideration simultaneously when determining impairment of a lightpath. Each of the routing algorithms presented follow an iterative approach towards processing demands. The first phase is also common across all of the algorithms where a number of k-shortest paths are determined for each demand. An initial trimming takes place where paths without an available wavelength are discarded. During phase two, “quality path selection" [7] algorithm will select the first available path, and assign a wavelength to it on a first fit basis. "Worst quality path selection algorithm" [7] and "Shortest Worst Quality Algorithm" [7] will compute the Q-Factor for each available wavelength on each of the k-paths for the remaining demands. "Worst quality path selection algorithm" [7] will assign the path and wavelength combination resulting in the worst Q-Factor of each demand with the intention that better paths will be available for other demands. "Shortest Worst Quality Algorithm" [7] initially orders each of the demands based on the length of the path from shortest to longest.

The authors of [5] have implemented an Ant Based Hyper Heuristic for solving the IA-RWA problem. The impairment analysis attempts to estimate basic linear impairments while ignoring non-linear ones such as FWM. In order to compute impairment first the Q-Factor is estimated after which the result is converted into a BER. The "Max-Min Ant System"[5] version of the "Ant Colony optimization"[5] problem is used in this paper. At the initialization phase, each edge has an equal pheromone value. During phase two, a number of virtual ants are placed at random locations on the network. At each increment the ants will traverse across one edge on the network. The number of times a path is traversed the greater its pheromone level making it more desirable. After incrementing a number of times, a set of paths will be determined. At this time the topology is reset and the incremental traversing by ants begins over again. The best result from all runs is used as the final IA-RWA.

[6] Proposes an alternative hyper heuristic to [5] using Tabu Search instead of Ant Colony Optimization. Similarly to [5], [6] takes a very simplified approach towards impairment. It considers only ASE, and cross-talk with no additional compensation for

ignoring non-linear impairments. The hyper heuristic will be selecting from the following low level heuristics, shortest path, k-shortest paths, least congested path, and lowest BER path. The shortest path heuristic finds the shortest path on the physical topology between two nodes. The k-shortest paths heuristic will select a random path from k paths. Least congested path will select the path from k-shortest paths with the greatest number of available wavelengths. Lowest BER path selects the path that has the lowest BER from k-shortest paths. A hyper heuristic approach is only followed during the routing phase of IA-RWA. Wavelength assignment is performed on a first fit basis. The algorithm will perform an iterative IA-RWA a number of times where the blocking ratio is recorded at the conclusion of each iteration. While performing the IA-RWA, the hyper heuristic selects a random low level heuristic for the routing of each demand. The order at which the demands are processed is constant. At the conclusion the IA-RWA resulting in the lowest blocking is selected.

The authors of [3] propose a new “analytical”[3] model for the estimation of impairment on a lightpath. The goal of this model is to reduce the complexity of direct computation of impairment. Each link is assigned a cost based on “Q-penalties”[3] that are computed using the network state, topology, and optical characteristics of the equipment in use. For each demand, three shortest paths are determined. There were two different wavelength assignment methodologies used, Impairment Aware Wavelength Assignment and Pre-Specified Wavelength Assignment. Impairment Aware Wavelength Assignment computes the impairment of all available wavelengths on a given route and selects the one with the highest quality. In Pre-Specified Wavelength Assignment each available wavelength along an optical link is ordered, based on its expected quality. The first available wavelength that is expected to yield the best result is selected for use by a lightpath. A final Q-Factor verification is performed to ensure that all lightpaths are valid.

In [2] an algorithm called “Rahyab”[2] is proposed that not only performs IA-RWA but also provides each established lightpath with dedicated redundant protection. The impairment tool used takes into consideration all common linear and non-linear impairments. Each of the demands are established at a predefined sequence. During the pre-processing phase, all of the demands are ordered from the shortest to longest, based on their path length. Once the demands been ordered, a network layer graph is created for each demand. Each layer represents an optical wavelength on the physical topology. On each of these layers a routing algorithm is run. The goal is to determine a set of diverse routes that are edge disjoint. Once a set of paths have been found, each is run through the Q-tool to determine the impairment. The potential lightpath that results in the highest quality is selected for use. In addition to proposing “Rayhab”[2] the authors have also implemented an additional ILP based algorithm for use as comparison. The ILP results in an optimal IA-RWA solution but because of the complexity it is only viable on small-scale topologies. The ILP algorithm supports impairment through the use of constraint-based formulations.

In [10] much like [2], the authors have implemented an ILP based IA-RWA. There are three algorithms that have been developed; a classic ILP based RWA, direct ILP IA-RWA, and indirect ILP IA-RWA. The classic ILP RWA will establish lightpaths onto a given network with no consideration of physical layer impairments. The direct ILP uses a series of formulations that allow the ILP formulation to accurately measure the impairment of each lightpath. These formulations are part of the constraints portion of the

ILP. While this impairment model takes both linear and non-linear impairments into account, it applies some “simplifying assumptions”[10]. The indirect approach also computes the impairment on each lightpath but it uses estimations instead of direct calculations. Each of the algorithms follows a four-phase process where phase one computes a set of k-shortest paths for each demand in the offline set. The k-shortest paths algorithm attempts to locate both disjoint and non-disjoint paths. Phase two executes one of the ILP algorithms (classic/direct/indirect). Phase three performs “random permutations” [10] and “iterative fixing” [10] to ensure that the solution provided by the ILP is valid. Phase four is executed only when phase three fails to find a solution. Phase four will iteratively add additional wavelengths until a valid solution is found. Demands occupying the excess wavelengths are then blocked.

The ILP based algorithm proposed in [1] is similar to the work done in [10]. The ILP algorithm implements a hybrid approach towards calculating the Q-Factor. The Q-Factor is used as a measurement of the impairment experienced by a potential lightpath. In order to simplify the computation of non-linear impairments, FWM is applied as a constant worst-case variable. To further reduce the complexity, the algorithm ignores any impairment generated by signal 0 [1]. The ILP Q-Factor formulation is divided into two parts the first part computes the impairment on a specific route, followed by non-linear calculations. The algorithm begins by computing k-shortest paths for each demand. The ILP is then called to select an optimal route and wavelength combination for each demand. The goal of the ILP is to evenly distribute the load across the entire network by minimizing the congestion on specific optical links. The ILP result is then run though a series of fixing and rounding to ensure that that result is valid. If a lightpath fails to be established by the ILP it is blocked permanently.

CHAPTER III

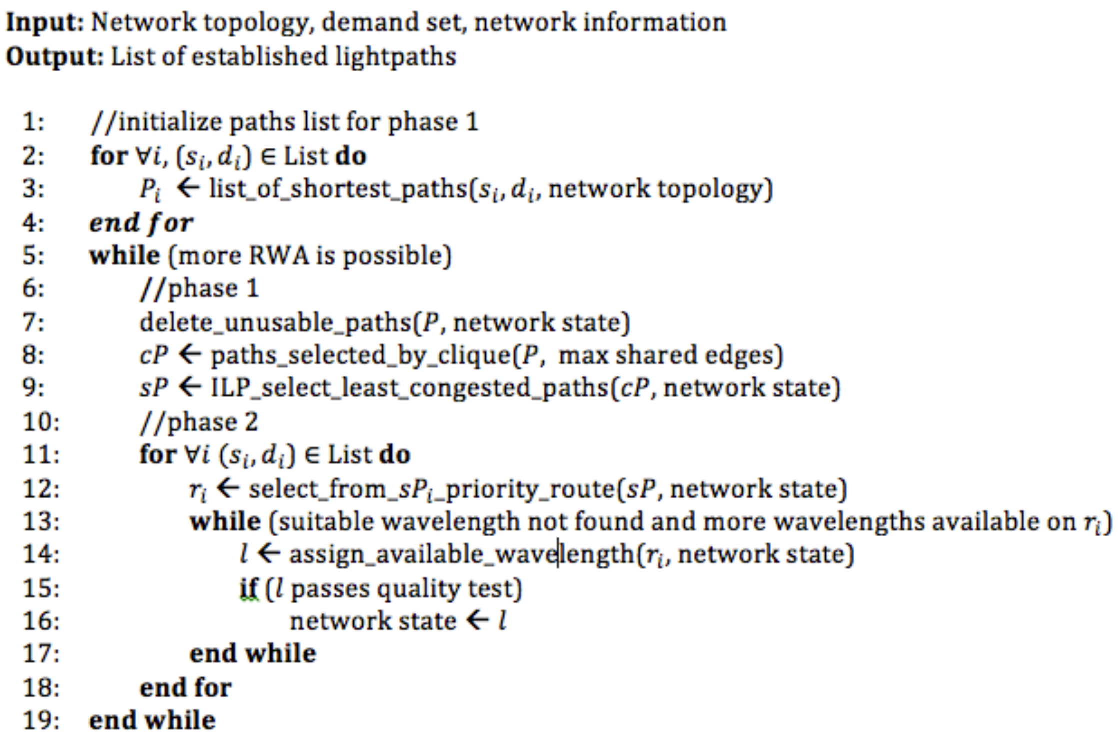
SPS-IA-RWA HEURISTIC ALGORITHM

Introduction

The objective of this algorithm is to carry out static route and wavelength assignment (RWA) for a list of requests for data communication, where each request is denoted by a pair of nodes (*x, y*), taking into consideration both linear and non-linear physical layer impairments. If RWA is successful for the pair (*x, y*), it means that a transparent lightpath may be deployed from node *x* to *y,* using a route from node *x* to node *y* and a channel that is currently not being used by any edge on the route.

The algorithm takes an iterative approach to RWA where in a given iteration lightpaths are assigned to as many source and destination pairs as possible. In a given iteration, the algorithm considers each request in the demand list that has not yet been assigned a lightpath successfully and

- Determine, if possible, an appropriate route *R* on the physical layer, for the request being considered,
- Compute the best channel *c* for the request,
- If the quality of transmission for a lightpath deployed using route *R* and channel *c* are both within acceptable limits and does not cause an unacceptable impairment to lightpaths that are already established, the request is deemed to be successfully handled in this iteration. It is included in the list of established lightpaths and removed from the demand list. Otherwise, the request is retained in the demand list for subsequent iterations.



Input: Network topology, demand set, network information
Output: List of established lightpaths

```
//initialize paths list for phase 1
for $\forall i$, $(s_i, d_i) \in$ List do
    $P_i$ ← list_of_shortest_paths($s_i$, $d_i$, network topology)
end for
while (more RWA is possible)
    //phase 1
    delete_unusable_paths($P$, network state)
    $cP$ ← paths_selected_by_clique($P$, max shared edges)
    $sP$ ← ILP_select_least_congested_paths($cP$, network state)
    //phase 2
    for $\forall i$ $(s_i, d_i) \in$ List do
        $r_i$ ← select_from_$sP_i$_priority_route($sP$, network state)
        while (suitable wavelength not found and more wavelengths available on $r_i$)
            $l$ ← assign_available_wavelength($r_i$, network state)
            if ($l$ passes quality test)
                network state ← $l$
        end while
    end for
end while
```

Figure 3.1: IA-RWA Heuristic Algorithm

Figure 3.1 provides an algorithmic overview of the heuristic. Symbol P is used to denote a list of paths for all source and destination requests. The variables s_i and d_i represent an individual demand for resources between a source node s_i and a destination node d_i. Network state contains the network topology, a list of active lightpaths and their corresponding routes and wavelengths. The list cP contains all of the paths for each source and destination requests that have been selected by the function paths_selected_by_clique from figure 3.1. The symbol sP represents a list that contains a single path for each outstanding request. The variable r_i contains the route for the selected demand i. The variable l denotes a candidate lightpath for demand i.

The algorithm consists of three phases. Phase one is responsible for the routing portion of the IA-RWA. For each demand the heuristic algorithm will retrieve k-shortest paths, from the source to the destination for some relatively large k. It is believed that generating a relatively large number of k-shortest paths for each demand increases the probability of successfully locating a path where a valid lightpath has the potential to be established. In order to achieve RWA within a reasonable time, the entire set of paths for each demand cannot be considered by the algorithm and therefore a subset must be chosen. For a path to be considered valid, it must have a minimum of one available wavelength that may be used by a lightpath using this path and the distance must also be less than the OR. If any one of the two conditions is not met, the path is automatically invalid, by definition, as the requirements for a lightpath to be established are not satisfied. These paths are removed from the k-shortest paths list. While the remaining paths satisfy the basic requirements for a lightpath, some may be more “preferred” than others. If two or more k-shortest paths between a source and destination share a large portion of edges on the physical topology, these paths are considered “less desirable”, compared to the paths that share relatively few edges. While edge-disjoint paths are optimal, as they do not share any edges, a vast majority of demand sets will not meet this criterion. Most paths will share one or more edges with alternative paths, so that the less edges shared, the more desirable the path becomes. A record is kept of the number of shared edges for each path. If the number of shared edges is acceptably small, it will be referred to as, a *partially disjoint* path. Selecting disjoint or partially disjoint paths is beneficial because it has the ability to significantly reduce the list of shortest paths, while retaining the paths that are more likely to result in a network state where the utilization of edges is relatively evenly distributed across the topology, this is referred to as a balanced network load. Balancing the load of a network is strongly beneficial as it avoids popular routes while alternative resources are available. The RWA algorithm has two objectives:

- Minimize the congestion,
- Balance the load on the network.

A network load is balanced when the traffic is relatively evenly distributed across all of the available edges on the physical topology. Congestion is defined as an edge that is utilized by a significantly disproportionate number of lightpaths. By minimizing the congestion and balancing the load on a network, longer paths that are more sensitive to impairments have the ability to utilize the shortest route on the network, while other demands requiring shorter paths can be guided using alternative routes and by doing so, it is possible to reduce the overall blocking ratio. Given this benefit, a final path for each demand will be selected such that the resulting network has minimized congestion and relatively evenly balanced load. At the conclusion of phase one, each outstanding request will be tentatively assignment a single path for use.

Phase two will attempt to assign a single wavelength to each of the routes that have been selected in phase one. A wavelength must be assigned to each route such that:

- The impairment for the lightpath is below a maximum threshold.
- Already established lightpaths are not adversely affected.

In order to meet the core quality consideration for a lightpath, not all wavelengths may be deemed acceptable, and therefore an iterative search has to be performed over the entire spectrum of unassigned wavelengths available to the selected path. Given the iterative nature of the algorithm, the SPS-IA-RWA heuristic must first determine the order at which it will attempt to assign wavelengths to the paths. Since the heuristic is utilizing an offline-demand set, a first-in approach cannot be followed, as all demands are known at the time of execution of the heuristic. In order to maximize the number of demands that can be established, the network must make efficient use of its resources by effectively minimizing the impact of each lightpath that is added on the overall network. In order to determine the priority of paths that will be selected for wavelength assignment, the primary factor is the number of wavelengths available for use. Given that the lightpaths are established on an iterative basis, a path with less wavelengths available to it, should be given priority over paths with an abundance of wavelengths available for use because different demands may share edges in common on the physical topology and therefore establishing a lightpath adds a restriction where that wavelength can no longer be used on any edge occupied by the lightpath. This restriction could result in a situation where a lightpath's route is left with no available wavelengths, and is therefore blocked. Therefore to maximize the number lightpaths established, routes with less available wavelengths are given priority for wavelength assignment. Another consideration for prioritizing wavelength assignment is to determine the impact the lightpath would have on other demands. Paths that share edges with many different demands have a very high impact rate as establishing the lightpath would restrict the wavelength from being used by many different demands. Therefore, to effectively utilize network resources, paths that are either independent (where they do not share an edge with any other demand), or share an edge with a small number of other demands will be given priority. Paths can also be prioritized based on the length. It has been shown that longer paths have a lower probability of being assigned a wavelength [28], and therefore if given priority over shorter paths for wavelength assignment, the overall blocking ratio may be increased. Once a path is selected, there may be more than one available wavelength for use. Each optical link, represented as an edge on the physical topology has a finite number of wavelengths available for use. Each lightpath that is established will use up one wavelength along its' route. The selected wavelength is then no longer available for any other demand that may share an edge with an already established lightpath. A modified list colouring algorithm is used to determine the wavelengths that are to be used by each path. List colouring is primarily used within graph theory, where the goal of the algorithm is to colour an entire graph with the least number of colours while following these conditions:

- Each node has a variable list of available colours for use,
- If a colour *y* is selected for node *X*, no other node that is connected to node *X* through an edge *E* can use colour *y*.

This classical problem shares many characteristics of the wavelength assignment problem of the overall RWA. In order to apply a list colouring algorithm, demands must be represented as nodes of a graph. Therefor a path intersection graph is created, where each demand is a node, an edge exists between two nodes, if the path of the demand, shares one or more edge(s) on the physical topology with the path of another demand. Instead of assigning each node with a list of available colours, the modified algorithm assigns a list of available wavelengths to each path of a demand that is represented by a node on the path intersection graph. The list colouring algorithm will now attempt to efficiently select a wavelength to be used by each path where the number of possible assignments is maximized.

In order to select the best wavelength for use, the heuristic should determine the impact each lightpath would have on the network. The wavelength that results in the least amount of impact should be assigned to the path. Network impact is defined as the number of paths belonging to other demands that share both, an edge with the current path and the available wavelength currently being considered.

In the event some paths have been rejected from phase two, due to lack of wavelength availability, or a failure to meet minimum quality requirements by the lightpath, phase three attempts to locate alternative routes to be used. From the initial shortest paths list, each demand that has been rejected, the path used by this iteration of the heuristic is removed. The heuristic continues onto the next iteration, where phases one and two are repeated until one of two conditions is met. The first condition for stopping is that lightpaths have been established for all demands. The second condition is that a defined number of iterations have been carried out, and it is determined that a certain number of demands cannot be established.

At the conclusion of the heuristic, the number of successfully established lightpaths is returned to the network simulator for comparative analysis against other offline heuristics.

Phase 1 – Routing

Phase one of the IA-RWA heuristic is responsible for the following fundamental tasks:

- Determining *k* or less valid paths for each demand *i*,
- To select a single path from k paths such that, if a lightpath is established using the path, the network does not experience excess congestion.

A valid path is defined as a path whose distance is less than the optical reach, and that a minimum of one wavelength is available for use. Once a set of *k* or less paths for each demand *i* is determined, a clique algorithm is run to select a small subset of paths where the number of edges shared between any two is less than a predefined amount. A subset of k paths must be selected because using the entire set for each demand *i* would either be computationally in-feasible or overly time consuming due to the NP-Complete nature of the RWA problem. A clique algorithm is used to select a set of paths that are partially disjoint. Using partially disjoint paths for each demand has two benefits, it reduces the set of *k* and the resulting paths are diversified, therefore offering many options for the ILP algorithm to properly balance the load on the network. Once the subset of paths is selected for each demand *i*, an ILP file is created and executed by CPLEX to find the optimal path from the list of available paths for use by each demand *i*.

Path Determination

For the i^{th} request, say from node *x* to node *y*, the routing portion of the heuristic will run a "*k*-shortest path" [27] algorithm to compute a number of routes from node *x* to node *y*. It is entirely possibly, that *k* alternate paths do not exist between source node *x*, and destination node *y*. In this event the "*k*-shortest path" [27] algorithm will return the paths that it was able to successfully route. Therefore the number of paths for request *i* maybe less than or equal to *k*. The RWA heuristic receives the paths for request *i* in the form of a matrix with *N* columns, and *k* rows. The path data will be represented as such, each row will contain a route *j* between source node *x*, and destination node *y*. Each column will represent a node, denoted by its' label, on the j^{th} route, where the first element of the row is the source node *x*, and last valid element is the destination node *y*, in-between a set of nodes are listed in sequential order that are traversed by the route. Paths that are shorter than *N* use the value "-1" to indicate the end of the route. The j^{th} route for request *i* will be denoted by $K_{ji,}$. Each route must meet the following criteria:

1. The distance between the source node *x* and destination node *y* on the physical topology must be below the OR.
2. Each K_{ji} path must have at least one available wavelength, say wavelength *c*, for use from the source node *x* to the destination node *y* on the physical topology.

Condition one is enforced to save the computation time as a path that exceeds the optical reach, by definition will be rejected, as the BER value will be unacceptable. Condition two ensures that, on every edge on the path $K_{ji,}$ a channel *c* is available for use to set up a lightpath. This constraint does not ensure that a lightpath using path K_{ji} and wavelength *c* will have an acceptable *BER* value. In our approach, we will use a standard algorithm for finding the *k*-shortest paths. If a paths' length exceeds the *OR* (above condition one), or a continuous channel *c* is not available for use between the source node *x* and destination node *y* (above condition two), the path will be removed from the list of paths to be considered for demand *i*.

The two conditions are established in order to select a subset of the K_{ji} paths that are feasible at accommodating request *i*. Condition one is enforced by the "*k*-Shortest Paths"[24] algorithm, while condition two is iteratively applied to the paths returned. For each *i*, the number of paths failing to meet condition one and two is variable and therefore it is possible that no two demands will have the same number of K_{ji} paths. Each rejected path is removed from the paths matrix by filling the j^{th} row with the value "-1", this signals the heuristic that this path has been rejected.

Next, the SPS-IA-RWA heuristic will iteratively run a "clique" algorithm for each demand *i* consisting of *k* or less paths. A Clique Value (*CV*) must be defined. This represents the maximum number of shared edges between path k_{ji} and K_{j+1i} paths of demand i. Graph CG, is defined by a set of N nodes and E edges. Each node represents a path j of demand i such that $(N) \in K_{ji}$. An edge $(s, d) \in E$ denotes a relationship between two paths represented by a source node $s \in N$ and destination node $d \in N$ where the number of shared edges on graph G is less than CV. The graph CG is defined by a kxk matrix where a value of "1" represents an edge between node $N \in K_{ji}$ and $N \in K_{ji}$. A clique is defined as the largest set of nodes $N \in K_{ji}$ within a graph CG that form a complete sub-graph. With the goal of finding a set of partially disjoint edges; the clique algorithm will select a set such that no two paths share more than CV edges. The algorithm exhaustively searches for the largest clique in the graph CG. For each N_i node, the clique algorithm will iteratively add a single node, $N \in K_{ji}$ to a clique set, where an edge on graph CG exists between node N and node $N \in K_{ji}$. For each iteration the current clique set is run through a verification function to ensure that the nodes contained form a complete sub graph within CG. If node $N \in K_{ji}$ fails to form a complete graph with the other nodes it is removed from the clique set. The algorithm then continues onto the next iteration seeking a node such that an edge exists on graph CG. For each i the largest clique is stored and compared against the results from other nodes $N \in K_{ji}$ on the graph CG. The final clique represents the set of partially disjoint paths for demand i. These paths must now be added into a Reduced Paths (RP) matrix $(D*K)$xE matrix. The process of creating CG and selecting the largest clique will be repeated for each demand i. The RP matrix will contain for each demand, a set of paths as selected by the clique algorithm. The RP matrix must have $D*K$ columns as the number of final paths selected is variable in-between demands, a worst-case approach is used to prevent an array overflow. In the likely event demand *i* does not contain *K* paths, a value of "-1" is used to indicate that a path does not exist on the i^{th} element of the RP matrix.

Integer Linear Programming

An ILP algorithm will be used to determine the actual path to use for each demand *i* in the current iteration. The goal of the ILP is to minimize the congestion on each of the directed edges representing optical links between nodes on the physical topology. The objective is to ensure that the number of lightpaths using any edge of the physical topology is minimized. Excessively loading a select few optical links can result in higher *BER* for all lightpaths that are assigned the specific link in question or alternatively problems may arise when assigning a wavelength at the network layer. Additionally non-linear impairments, such as Four-Wave Mixing (*FWM*) will have a much bigger effect when more lightpaths share the same fiber. For each demand *i*, the ILP will select a single route to use out of the list of potential K_{ji} paths. The ILP will return a single path for each demand *i* in the form $C_{NE.}$ C_{NE} is represented by an *N*x*E* matrix, where *N* represents the number of nodes $N_i \in N$ and *E* represents the number of edges between $(s, d) \in E$ where $s \in N_i$ and $d \in N_i$ on the physical topology graph *G*.

Notation Used

Variables:

Λmax : A variable denoting the maximum number of lightpaths that can simultaneously share an edge n_ch

$$e^i : \begin{cases} 1\ if\ the\ lightpath\ for\ demand\ i\ can\ be\ established\ without\ exceeding\ N_{ch} \\ 0\ otherwise \end{cases}$$

$$x_p^i : \begin{cases} 1\ if\ path\ p\ is\ selected\ for\ demand\ i \\ 0\ otherwise \end{cases}$$

Constants:

N_{ch} : A constant denoting the maximum number of wavelengths per fiber

P_i : A constant denoting the potential number of alternative paths per demand i

$N_{commodity}$: A constant denoting the number of demands being considered. i ∈ d

a_e^p : A constant where, $\begin{cases} 1 \; if \; path \; p \; is \; using \; edge \; e \\ 0 \; otherwise \end{cases}$

E : The set of all edges on the physical topology.

Formulations

Objective Function:

Minimize:

$$\Lambda\text{max} - \text{M} * \sum_{i=1}^{Ncommodity} e^i$$

Subject to:

1. $\sum_{p=1}^{P_i} x_p^i = e^i, \forall i, 1 < i \le N_{commodity}$
2. $\sum_{p=1}^{P_i} \sum_{i=1}^{I} x_p^i * a_e^p \le \Lambda\text{max}, \forall \text{e} \in \text{E}$
3. $\Lambda\text{max} < N_{ch}$

Description

As described, the ILP is responsible for selecting a single path for each demand *i*, such that the network congestion is minimized. The *objective function* of the ILP has two components responsible for:

1. Maximizing the number of paths selected.
2. Minimizing network congestion.

While these requirements may seem contradictory, objective 1 is present to ensure that if it is feasible, a path is selected for each demand i. Objective 2, minimizes the congestion experienced on the network by selecting paths for each demand i, that follow either disjoint or partially disjoint routes on the physical topology from other demands and lightpaths. Combined, the two components form the final ILP objective function that is used to select, if possible, a path $p \in P_i$ for each demand i.

Constraint formulation 1 ensures that for each demand, at most one path can be selected. It works by summing the variable x_p^i over each demand i, forcing the result to equal e^i. Where e^i, having a binary value of 1|0 represents the feasibility that a potential lightpath can be established for demand i. If a lightpath is feasible, the value is 1, therefore forcing CPLEX to select at most one x_p^i as it also contains a binary 1|0 value, for the demand i.

Constraint formulation 2 will be called the wavelength availability constraint as it is used to ensure that an edge is not utilized beyond capacity. Since each optical link can only support a finite number of wavelengths, the number of potential paths that use it, must be less than or equal to $\Lambda max.$ The number of demands i, that are utilizing an edge is determined by a binary value 1|0 for the variables $x_p^i \ and \ a_e^p$. If, path $p \in P$ is selected for demand i, and demand $p \in P$ is using edge $e \in E$ the value is 1.

Constraint 3 ensures that Λmax is less than or equal to N_{ch}. N_{ch} is a constant representing the maximum number of wavelengths a single fiber can accommodate, notwithstanding impairment considerations.

Phase 2 – Wavelength Assignment

Phase two, is responsible for selecting the wavelength for use by each of the outstanding demands. Some of the fundamental tasks include:

- Determine the order of demands that will be used for assigning network resources.
- Select wavelength for use by a route for demand i such that network impact is minimized.
- Test impairment ensuring that the proposed lightpath and all other lightpaths on the network meet minimum impairment (quality) requirements.

Valid criteria will have to be developed to effectively select the order of demands that will be assigned wavelengths. Once a demand i is selected, if more than one available wavelength exists, it must be analysed which wavelength results in the least impact to the network. The goal is to efficiently utilize the finite number of wavelengths, resulting in the ability to establish more demands on the network. The criteria used for path selection includes, the number of available wavelengths, the effect, and length (measured by hop count) of the demand. In order to prevent paths from being blocked due to an unavailability of wavelengths, demands with less available wavelengths are given assignment priority. Second, a demand with the least network effect will be prioritized, where network effect is modeled by a path intersection graph. The degree of each demand will be used as an accurate indicator of the potential disruption to the network. Therefore demands that have the smallest degrees will be given assignment priority. Finally as a final indicator of priority, the path length is used. It has been shown that longer paths are more difficult when assigning wavelengths to the path. Therefore in order to minimize blocking ratio, shorter paths will be given priority. Once a path is selected, the wavelength resulting in the least impact on the network is selected for use if it meets impairment requirements. Impact is modeled by the path intersection graph as well with an additional requirement, the route of two or more demands must not only share an edge in common, but the wavelength currently being tested must also be available as well. This way, the number of available wavelengths for other demands that have not yet been established is maximized and therefore the wavelength with the least impact should be selected. At the conclusion of phase two, demands that have been granted network resources are active as lightpaths, and blocked demands proceed on to phase three.

At the conclusion of phase II, for each demand *i,* we will assign, if possible, a channel number to each demand. We have to make sure that:

1. Each lightpath is assigned a channel number.
2. If two paths share a fiber they are assigned different channels.

The first requirement is known as the wavelength continuity constraint. This constraint is applied to optical networks where wavelength reassignment is not possible. Considering only a finite number of W wavelengths are available, it is imperative to efficiently assign a wavelength C ∈ W to each demand *i*. The heuristic will use a list colouring algorithm for channel assignment. List colouring is used because the algorithm ensures that on a graph with a set of nodes and edges, no two nodes that are connected by an edge share a colour in common. Each node on the graph has a list of potential colours it can choose from, and the goal is to colour the entire graph with the least amount of colours. The heuristic will apply a modified version of the classic list colouring algorithm, where each colour attached to a node represents an available channel number C where $C \in W$.

First a path intersection graph G_{PIG} is created, where G_{PIG} is defined by a set of N nodes and E edges. Each node, N, on graph G_{PIG} represents a demand i, where $(N_i) \in D$. An edge $(s, d) \in E$ indicates that the demand i, denoted by source node $s \in N_E$ and demand j, denoted by destination node $d \in N_E$ on graph G_{PIG} share at least one common edge on the physical topology denoted by graph G. G_{PIG} is represented by a DxD matrix, where a value of "1" indicates an edge exists between nodes D_i and D_j. For example, if a route D_1 is as follows (1 -> 3 -> 4 -> 5) and a route D_2 is (2 ->3 ->4) an edge would exist on the graph G_{PIG} between D_1 and D_2, as the two share a common link (3->4).

The SPS-IA-RWA heuristic performs an iterative selection process where it attempts to prioritize the demands that will be served followed by the wavelength selection. At each iteration a temporary demand set represented by a DxN matrix where D is the number of demands and N is the number of nodes on the physical topology is created. This set is initialized with the value of "-1". For each demand i, a path that has not been assigned a wavelength $C \in W$ is iteratively added into this temporary set. Once the temporary set is created, for each demand i it will contain either, a path that is requesting wavelength $C \in W$ assignment, or a value of "-1" indicating that the path has already been added to the network or has been blocked and can therefor be disregarded. For each demand i in the temporary set, an iterative priority is attached to it. There are three categories for demand priority in the order from highest to lowest:

1. The number of unoccupied channels along the path for demand *i.* The lower the number, the higher the priority.
2. The length, by hop count of the path for demand *i*. The lower the number, the higher the priority.
3. The degree of the demand *i* where degree is defined as the number of demands represented by nodes $N_j \in D$ on graph G_{PIG} that share a common edge with demand *i* denoted as N_i on the graph. The lower the number, the higher the priority.

The three prioritization categories are applied to the demands iteratively starting with the calculation of the number of available wavelength $C \in W$ for each *i*. The available wavelengths for a path belonging to demand *i* are computed by analyzing the network topology taking into consideration already established lightpaths. The demand with the least amount of available wavelengths $C \in W$ is selected for assignment. In the event more than one demand *i* ranks the same, all the paths with a lower ranking are eliminated from the temporary set, leaving only the high priority demands. At this time, a second iteration is started ranking the remaining demands based on the length of the path by hop count. The shortest demand *i* is selected for wavelength $C \in W$ assignment. In the event more than one high priority demand exists with the same length, longer demands will be eliminated from the temporary set, and a third and final prioritization phase takes place. At this time, the remaining demands, are iteratively prioritized based on the nodes edge degree. This information is retrieved from the graph G_{PIG}, where each node *N* represents a specific demand *i*. The degree is defined as the number of outgoing edges from node N_i. In the event, two or more remaining demands have the same degree; the final elimination takes place and the selection takes place on a first-selection (FS) basis. FS picks the first remaining demand i, in the temporary set for channel $C \in W$ assignment. This process is repeated D times.

For each demand i, a function is run to determine what wavelength /s $C \in W$ are available. In situations where only one wavelength $C \in W$ is available, the channel is selected by default as no others are available. When more than one wavelength $C \in W$ is available, the algorithm will assign a wavelength $C \in W$ on a Lowest-Degree (LD) methodology. LD is defined as a channel $C \in W$ on graph G_{PIG}, where the number of affected nodes N_j that are connected to node N_i via a directed edge are minimized. An affected node is defined as a node N_j that shares both, a common available wavelength $C \in W$ and a directed edge with node N_i. The algorithm iteratively tests each available channel $C \in W$ on demand i to determine the number of affected nodes. The channel resulting in the least affected nodes is temporarily selected as a candidate wavelength $C \in W$. Both, the candidate channel and demand i path are then submitted into the impairment model for analysis. If the wavelength and path combination fall below a maximum BER and fail to impair any establish lightpaths, demand i, is established as a lightpath on the network topology on the candidate channel. In the event the impairment test fails, the next available wavelength $C \in W$ with the second lowest number of affected nodes is tested. This iterative process is repeated until a wavelength, which passes the impairment test is found or the available wavelengths has been exhausted, in which case the demand is blocked on this iteration of the heuristic.

Demands D, that are successfully assigned a wavelength $C \in W$, have their representative node N_i removed from the graph G_{PIG}.

Phase 3 – Blocked Requests

Phase three attempts to find alternative paths for demand requests that have been blocked in phase two. The fundamental tasks that must be performed include:

- Removing rejected path from the k-shortest paths list,
- Starting a new iteration of the heuristic.

Each route of the demands that have been blocked must be removed from the k-shortest paths set. Doing so prevents phase one of the next iteration of the heuristic from selecting a path that has already been tested during a previous run. Once the k-shortest paths set has been updated for each blocked demand *i*, phase one is called again, and the heuristic attempts to find an alternate route and wavelength combination for the blocked demands.

The heuristic has to now deal with the demands that have been blocked due to excessive *BER* or lack of wavelength availability. Using the list *D*, the algorithm iterates a number of times from phase one over again. Iteration will terminate if one of two conditions is met, the heuristic will attempt to establish demands, a maximum of *H* times, or if during the previous iteration all the demands have been granted a wavelength $C \in W$. For each demand *i* the algorithm will flag the route that has been selected by the ILP during phase two of the previous iteration. This will prevent the same route from being selected as a candidate twice. Phase one begins over again, where each demand *i* has a set of K_{ji} paths, an ILP will select what it believes to be the path that results in the least congestion on the physical topology. This will take into consideration already established lightpaths on the network. With the route selected, the algorithm now starts phase 2, the list coloring process over again. Given the demand list *D*, it will create a graph G_{PIG} that contains a node for each demand D_i. Edges between nodes on graph G_{PIG} will be placed where the routes of demand i and demand j share a common link on the physical topology. The algorithm will then attempt to assign a wavelength $C \in W$ to each node N_i ensuring that non-disjoint edges have unique assignments while maintaining an acceptable BER. The paths that are accepted will be added to the network topology; otherwise blocked requests stay in the demands list where assignment is attempted again during the next heuristic iteration.

CHAPTER IV

DESIGN AND METHODOLOGY

Introduction

In order to fairly and effectively evaluate the performance of optical IA-RWA heuristics, a suite of tools with a well-known interface must be developed. Running the same tools with the same configuration across multiple heuristics will allow for accurate and reliable performance comparison. For the tools to be useful by offline IA-RWA heuristics, the following components must be present:

- It must be able to generate synthetic topologies and store databases of real-life topologies,
- It must generate a set of demands,
- It must calculate class one and two impairments on proposed lightpaths using some tool for evaluating impairments,
- It must record and store results from each heuristic.

The primary benchmark for offline IA-RWA algorithms is the ratio of established lightpaths divided by the total number of requests. This will be used as the variable that compares the effectiveness of different heuristics. The number of blocked demands divided by the total number of demands is known as the blocking ratio.

After a thorough and exhaustive search it has been concluded that a set of tools that meet the above needs does not exist. In order to rectify this Ghosh [33] has developed a Network Simulator. Varanasi Sriharsha implemented a PLI Tool based on [15]. The Network Simulator is responsible for generating topologies and demands, providing a framework for pluggable offline IA-RWA heuristics, and recording results.

The PLI tool is an independently functioning piece of the Network Simulator. This tool is responsible for measuring the impairments experienced by the lightpaths on the topology that have been generated. The two tools will form the foundation of the testing framework for the heuristic proposed in this thesis and any future algorithms that may be developed.

While surveying related literature, an observation has been made that many IA-RWA heuristics utilize a k-shortest paths algorithm [27] for routing between source and destination nodes on a given topology. Given the common nature of this algorithm, an additional KSP tool has been developed by Ghosh [33] for use. The KSP Tool has been implemented within the Network Simulator for any heuristic to use. The benefit of this is that if the need for k paths exists, the set of paths generated will be consistent for all of the heuristics being tested.

All of the software has been developed using the C language. The work was compiled using the GCC on Ubuntu 12.04 operating system. CPLEX Studio 12.4 by IBM is used to solve the ILP optimization problem that is generated by the SPS-IA-RWA heuristic.

Implementation

In order to fairly compare the performance of the SPS-IA-RWA heuristic with other IA-RWA algorithms, the Optical Network Group at the University of Windsor has developed a set of tools that provide a framework for executing a series of IA-RWA algorithms with consistent parameters. The Network Simulator calls a PLI Tool, which uses an OSNR [15] based impairment test for all IA-RWA algorithms being executed. For fair results, each heuristic must use the tools provided by the Network Simulator.

This way, all parameters, related to the demand set and topology are globally controlled and consistent. With this implementation, the performance of the heuristic is entirely dependent on the design.

The Network Simulator provides an interface for developers to easily "plug-in" IA-RWA algorithms. The SPS-IA-RWA heuristic is utilizing the following tools provided by the Network Simulator:

- Test bed
- k-shortest paths generator
- PLI tool

In addition to the tools, the SPS-IA-RWA heuristic must follow a set of communication and data structure standards known as protocols that have been setup by the Network Simulator. If any of the IA-RWA algorithms do not follow these protocols, the Network Simulator will not be able to transfer or receive, all or a partial amount of data, to and or from the algorithm in question. As a result, a heuristic could potentially have incomplete data to process or would not be able to return results back to the Network Simulator, either way, the heuristic is void and not comparable.

The following requirements must be followed by any IA-RWA heuristic to be successfully plugged-into the Network Simulator:

- Must be developed in the C language,
- Must use the provided *NT* structure for physical topology and demand data,
- Must use provided *Result* structure for returning RWA results,
- Must use global network configurations,

- Must use PLI Tool if needed.

These requirements are mandated by the Network Simulator for each algorithm to be able to properly work within the testing environment. The C language must be used, as it is the language in which the simulator has been developed. Using other languages would result in complications and compatibility issues. The Network Simulator is currently running on the Ubuntu operating system. The heuristic must in one way or another retrieve the physical topology and set of demands from the *NT* structure that is provided by the Network Simulator. In order to return the blocking ratio back to the Network Simulator the *Result* structure must be used. Each IA-RWA algorithm must also use the global configurations of the network as this provides important information such as the number of wavelengths, the number of nodes, the demands. If an IA-RWA algorithm utilizes any of the following components, the tools provided by the Network Simulator must be used:

- QoT impairment Test,
- k-shortest paths .

This final requirement is in place, not because of software compatibility considerations, but so that the performance results of each IA-RWA heuristic can be compared.

Network Simulator

The Network Simulator is the primary tool that is used for the execution and evaluation of the IA-RWA algorithms. The modules present in the simulator can be seen in figure 4.1. While it has been designed with the intent of evaluating impairment-aware algorithms, it is also compatible with classic RWA heuristics that are not impairment-aware. The simulator is responsible for:

- Generating or loading a network topology,
- Generating a complete demand set containing source and destination nodes,
- Retrieving blocking ratio from each IA-RWA algorithm executed.

The operator of the simulator has the ability to control a wide variety of variables that are used in the creation of the topology and demand sets.

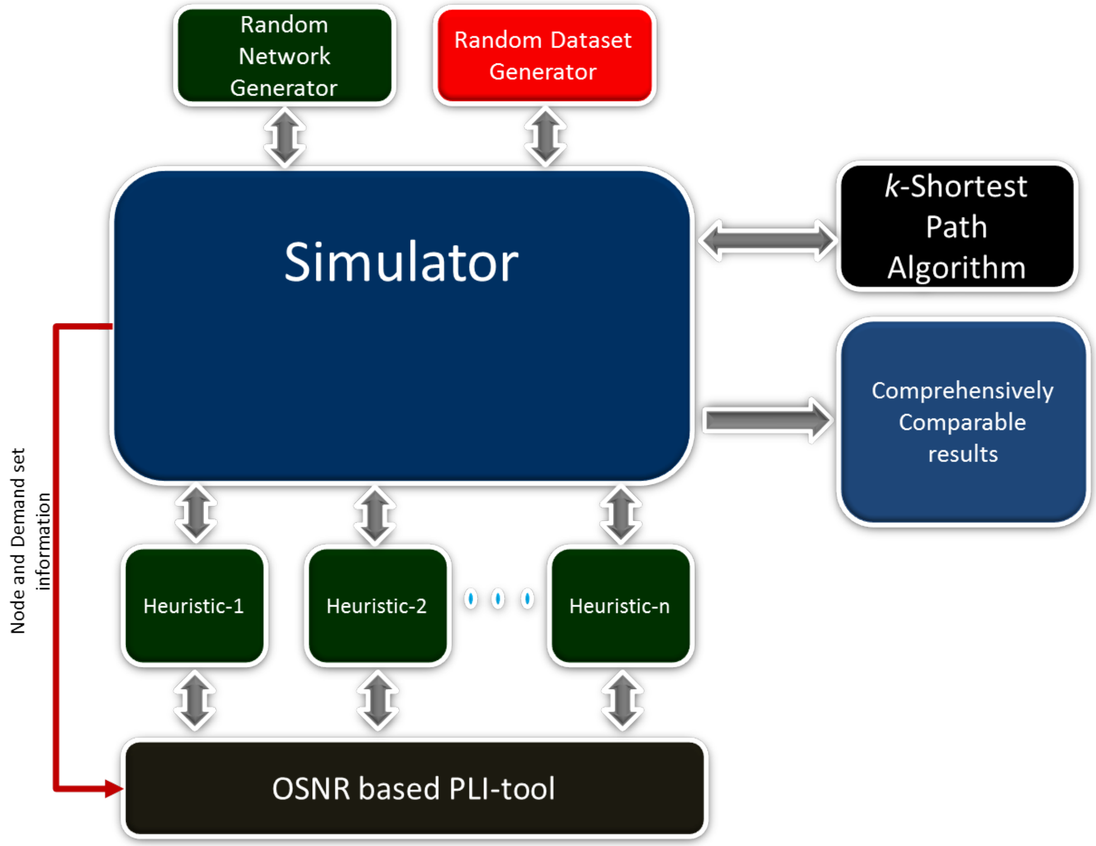


Figure 4.1 – Network Simulator

Figure 4.1 provides an overview of the network simulator taken from [33]. It supports any number of independently functioning IA-RWA/RWA heuristics. The fundamental task of the network simulator is to create network topologies on which IA-

RWA/RWA algorithms will be tested. For the successful creation of a topology, the user must define the following variables:

- Number of nodes in the topology,
- Maximum Node degree,
- Percentage of Optical Reach Lower/Upper Limit,
- Number of Wavelengths.

The number of nodes in the topology represents the network size, where each node on the graph is capable of being either a source or a destination node for any number of demands. The node degree cap represents the maximum number of allowable incoming and outgoing fibers to each node on the network. In addition to the maximum node degree, an additional constraint is in place where each node must have a minimum of two degrees. This means that each node will have at least two incoming fibers and two out going fibers. The optical reach upper and the lower limit define the maximum and minimum lengths between any two nodes on the topology. Specified as a percentage fraction of the optical reach. Based on the optical reach computed by the impairment model, the minimum and maximum distances of any edge on the topology will be:

- $OR * Optical\ Reach\ Lower\ Limit$
- $OR * Optical\ Reach\ Upper\ Limit$

With these settings in place, the Network Simulator will generate a random topology that meets the provided specifications. In the event a random topology is not desired, it is possible to load a standard topology such as the NSF Net from a database. In addition to controlling the topology design, the user is able to configure the number of available wavelengths. The number of available wavelengths is consistent across the whole topology.

The second task that must be executed for the Network Simulator is to create a demand set containing a list of source and destination nodes that are requesting network resources. These resources are allocated through the IA-RWA/RWA process, where the objective is to establish a lightpath between a source and destination node. The following configuration options may be specified for the creation of a demand set:

- Number of source and destination demands in the set,
- Percentage Lower Limit,
- Percentage Upper Limit.

The variable controlling the number of source and destination nodes represents the size of the demand list. The percentage upper and lower limit variables define a range of acceptable distances that can be used by routes between any source and destination node. This restriction is in place to have better control over the distances that paths follow. If a greater lower limit is set, the average path length will increase and therefore will experience greater impairment as well as increase the load on the network.

The Network Simulator has an additional module available for use by RWA/IA-RWA heuristics, the k-shortest paths generator. The k-shortest paths algorithm is based on [27]. The number of paths generated for each source and destination request is determined by a global variable set by the Network Simulator. The list of paths generated ranges from the shortest to the k^{th} shortest path. An additional built-in constraint is that the paths, which exceed the optical reach, are automatically rejected. Since the algorithm finds paths in order of their length, if a path exceeds the optical reach, all of the paths that follow will be rejected as well. Therefore the algorithm can generate *k* or less shortest paths for each source and destination in the demand list. The default setting for *K* is 4, where for each source and destination, 4 potential alterative paths are found ordered from the shortest to the longest.

The network simulator also saves and displays information related to the blocking ratio of each IA-RWA/RWA algorithm that has been executed, this is done by saving the result from each algorithm into an array data structure. At the conclusion the results are saved into a file and the output is displayed on the screen.

PLI Tool

The PLI Tool that has been developed by the University of Windsor Optical Network Team and is based on the OSNR [15] impairment model. The tool is able to account for linear (class 1) and non-linear (class 2) impairment types. The following class 1 impairments are included in the impairment calculation, ASE, Noise Induced by Optical Amplifiers, and Optical Switch Loss. The following class 2 impairments are included in the computation, cross-talk (XT) and XPM. The model calculates the impairment present on a lightpath as a ratio between optical signal and noise, which can be defined as the total optical signal power to the total noise power at any given node on the network. If a certain threshold is crossed, the lightpath is deemed to be impaired and is therefore rejected. It is important to note that the PLI tool does not block any lightpaths. The Network Simulator allows each IA-RWA algorithm to call the PLI Tool as needed and pass the proposed lightpaths for testing. The PLI Tool then returns a binary result indicating whether each of the lightpaths passed or failed the impairment. Each IA-RWA algorithm must implement its own mechanisms for dealing with blocking. In order that the IA-RWA algorithms be able to use the PLI tool, the protocols outlined by the Network Simulator must be followed. The PLI tool must have two separate arrays passed into it, one array contains the paths, while the second array contains the corresponding wavelengths. The PLI tool also needs the topology, the number of demands, and the number of nodes initialized. Prior to executing any IA-RWA algorithms the Network Simulator will initialize the needed variables for the PLI tool.

For testing purposes it is also possible to configure the PLI tool by defining the maximum allowable impairment. The combined impairment from class 1 and class 2 sources may not exceed 23dB.

SPS-IA-RWA Heuristic

The SPS-IA-RWA heuristic was developed in the C programming language and meets all of the operating requirements that have been outlined by the Network Simulator. The SPS-IA-RWA heuristic has been developed as a plug-in for the Network Simulator. Using the *NT* structure provided by the Network Simulator, the SPS-IA-RWA heuristic will read the network topology and demand list, and perform pre-processing tasks such as determining the number of edges, create the current operating network topology, edge graph, and initialize any other needed variables. The SPS-IA-RWA heuristic uses the following tools provided by the Network Simulator:

- k-shortest paths tool
- PLI tool

Once the pre-processing step has been completed the SPS-IA-RWA heuristic will call the k-shortest paths tool and retrieve up to k-paths for each demand from the Network Simulator. During phase 1 of the SPS-IA-RWA heuristic, the clique algorithm will select a set of candidate paths for each demand from the k-shortest paths. Frank Luo has developed the software used to generate the ILP formulation file to be used by CPLEX 12.4 by IBM. During phase two as each route is assigned a temporary wavelength, the PLI Tool is called to evaluate how the candidate lightpath will function within the network with already established lightpaths. Once the IA-RWA is completed by the SPS-IA-RWA heuristic, the results are returned to the Network Simulator via the provided *Results* structure.

There were three version of the SPS-IA-RWA heuristic implemented with the following configurations:

1. Default values: As presented in chapter 3
2. Path selection changed from shortest path first to longest path first
3. Wavelength selection changed from lowest PIG (path intersection graph) degree to random

The generic configuration (configuration 1) does not deviate from the theoretical algorithm design presented in chapter 3. The following configurations only modify a single component of the generic SPS-IA-RWA heuristic. The second configuration amends the demand prioritization during phase 1. It changes the second prioritization criterion that is based on the length of the route from the original configuration, which is from the shortest to the longest path, to the new configuration giving longer paths priority. The goal of this change was to observe, keeping all other variables constant, to observe the effect that length based prioritization has on the final blocking ratio. The third configuration modifies the wavelength assignment during phase 2 of the SPS-IA-RWA heuristic. On the generic SPS-IA-RWA heuristic, wavelengths were assigned on the basis of the least PIG degree; the modification removes the degree test and replaces it with random assignment. In the event the wavelength fails the impairment test, an alternative wavelength that is both available and randomly selected is assigned to the candidate lightpath and the impairment is tested over again. This process continues until all available wavelengths are exhausted and the demand is blocked or, a wavelength is found on which a successful lightpath can be established. The goal of this modification is to see the effect wavelength assignment has on the overall blocking ratio of the SPS-IA-RWA heuristic. The initial algorithm takes care to select the wavelength that has the least impact to the network, while the random version simply selects a wavelength from the pool of available wavelengths where the first selection to pass impairment is used for the lightpath.

Comparative Heuristics

Aside from the SPS-IA-RWA heuristic, additional algorithms were needed for demonstration and testing purposes. An additional problem is that each research team uses proprietary tools and heuristics, therefore comparing performance of the SPS-IA-RWA heuristic to externally published results of alternative modern algorithms is not possible. An additional problem with externally run experiments is that the RWA variables such as paths, routes, and topologies would be different from the experiments run at the University of Windsor. To address this, the University of Windsor Optical Network Group has developed the following RWA and IA-RWA algorithms to be used as a benchmark for the SPS-IA-RWA heuristic and to test the Network Simulator:

- Classic RWA (cRWA) [9],
- Simple Lightpath Establishment with Regenerator Placement (sLERP) [9],

- Shortest Longest Path First (SLPF) [28],
- Longest Shortest Path First (LSPF) [28].

The Classic RWA (cRWA) algorithm is not impairment aware and is used as an illustration of the maximum theoretical limit on the number of lightpaths that may be set up with only network layer constraints. The algorithm is divided into the following components:

- Generate k-shortest paths for each demand,
- Select path and wavelength for each demand.

The cRWA [9] algorithm begins by generating k-shortest paths for each demand. The next phase is responsible for assigning network resources to each demand. This is done iteratively; the demands are processed as they appear in the initial demand list generated by the Network Simulator. During processing, the cRWA [9] algorithm will start at the shortest path, determine if any wavelengths are available, and if so assign a wavelength on a first-fit basis. In the event a path does not have an available wavelength, the next path is tested. This continues until all K paths have ben exhausted in which case the demand is blocked.

sLERP [9] was initially designed to be used on translucent networks with optical to electronic to optical conversion capabilities. Since the Network Simulator is only capable of simulating transparent networks, this algorithm was modified so that an IA-RWA is possible without the use of regenerators. This algorithm begins by running the k-shortest paths algorithm on each demand, these demands are then randomly ordered. Once the demands have been randomized, each demand will be incrementally selected for wavelength assignment. During wavelength assignment, the first k-shortest path is selected for a sequential search for the first available wavelength along the route. Once a wavelength is found, the candidate lightpath is added to the network and an impairment test is performed by the PLI Tool. If the lightpath passes the impairment test it is established and the next demand in the list is processed. In the event that the impairment exceeds the allowable threshold, the next path from the k-shortest paths list is selected. Wavelength assignment once again finds the first available wavelength along the route and the new candidate lightpath is evaluated for QoT. This process continues until all K alternative routes have been exhausted for a demand at which time it is blocked. sLERP [9] will repeat this IA-RWA process a finite number of times. During each iteration the demands list is randomized and the process of IA-RWA is repeated. The iteration with the best (lowest) blocking ratio is preserved and reported back to the Network Simulator.

Similarly to sLERP [9] and cRWA [9], SLPF [28], and LSPF [28] will run the k-shortest paths algorithm for each demand to retrieve a list of potential routes that a lightpath can follow. The Shortest Longest Path First (SLPF) heuristic then proceeds to order each of the demands, from the shortest to the longest, based on the shortest path obtained from the k-shortest paths algorithm. The ordered demands are then sequentially processed one after another. During processing, wavelengths are assigned on a first fit basis. Once a wavelength is selected, the candidate lightpath is added to the network and an impairment test is performed. If passed, the lightpath is established, otherwise the Shortest Longest Path First algorithm attempts to find an alternative wavelength. If all wavelengths are exhausted, the next route from k paths for the demand is tested. This is continued until all paths and their available wavelengths have been exhausted at which time the demand is blocked. Once all demands have been sequentially processed, the results are returned to the Network Simulator.

LSPF [28] is a derivative of SLPF [28]. Initially the algorithm runs the k-shortest paths algorithm for each source and destination request in the demand list. The heuristic then orders the demands from the longest to the shortest based on path length, which is retrieved from the shortest of k paths. The rest of the RWA is identical to that of SLPF [28] heuristic. During wavelength assignment, the first available wavelength along the path is selected, and the candidate lightpath undergoes a QoT test. In the event the impairment exceeds a predefined threshold, the next available wavelength is tested. If all available wavelengths fail along the path, the next path from the K paths is selected. If all paths fail the impairment test, the demand is blocked. Otherwise the demand is assignment a lightpath and is added to the list of lightpaths in use on the network.

CHAPTER V

SIMULATION RESULTS

Network Configurations used for Simulation Studies

The Network Simulator has been configured to run a variation of experiments to test the performance of the SPS-IA-RWA heuristic with that of other modern IA-RWA algorithms. The experiments will be divided into primary categories:

- Synthetic Topology
- Real Network Topology

Synthetic topologies refer to networks that are randomly generated. These topologies can have any number of nodes and wavelengths. In addition to controlling the number of nodes on the topology, it is also possible to configure a variable bound on the lengths for each edge. Another potential configuration is the minimum and maximum degree of each node. Given the flexibility of synthetic topologies, it is possible to test a wide variety of configurations. Real Network Topologies represent networks that are already in existence. Some of the popular networks to model are as follows:

- AT-14
- USA-24
- ARPA-21

In order to evaluate the performance of the SPS-IA-RWA heuristic, it will be tested on both synthetic and real world topologies. Given the flexibility of synthetic environments, a greater number of tests will be performed using randomly generated topologies.

The Network Simulator's configuration can be seen in Table 1. The minimum number of paths generated for each demand is denoted by k-shortest paths. The Node

Degree Cap is used for the creation of synthetic networks and controls the maximum incoming and outgoing degree of each node. The Lower and Higher Edge Distance Bounds are also used to generate synthetic networks. These two values represent the maximum and minimum lengths of each edge on the network. The Lower and Upper Demand Distance represents the minimum and maximum path length for any demand. Each experiment was run a number of times. The number of demand sets, represents the number of different lists of demands. Each demand list was executed by the heuristics being tested. Depending on the test being performed, each demand list has the same number of source and destination pairs. The number of Network Sets represents the number of different randomly generated topologies that was used for each test. Each topology conforms to the specifications of the test, meaning that each different topology will have the same number of wavelengths on fibers, nodes, node degree, etc.

Constant Values	
K-Shortest Paths	4
Node Degree Cap	3
Lower Edge Distance Bound	20%
Higher Edge Distance Bound	40%
Lower Demand Distance Bound	20%
Higher Demand Distance Bound	80%
Number of Demand Sets	15
Number of Network Sets	3

Table 1 – Network and Demand Specifications

Each comparative test that is run on a synthetic network use a number of different randomly generated topologies. In addition to the different topologies, each topology was tested with a number of different demand sets by the different IA-RWA heuristics being evaluated. Each synthetic test for each IA-RWA heuristic was run $Number\ of\ Demand\ Set\ *\ Number\ of\ Network\ Sets$ times. The results reported will be the cumulative average of each of these tests.

The PLI Tool configuration is shown in Table 2. The Optical Fiber Amplifier Noise refers to the impairment created by an EDFA. This impairment is only generated during amplification. Fiber Loss Coefficient is measured in dB/Km propagated by an optical signal. Optical Switches within the network are responsible for routing the optical signals, within the optical switching fabric of the device. Leakage occurs causing Switch Loss. Optical MUX and DeMUX loss occurs as the optical signal is modulated and demodulated at the ingress and egress ports of switches within the network. Switch Isolation Factor was used for computation of node cross talk. The XPM loss is a constant value representing the impairment caused by XPM. The OSNR threshold is the minimum acceptable signal QoT.

PLI Tool Configuration in dB	
Fiber Amplifier Noise	5
Fiber Loss Coefficient	0.2
Optical Switch Loss	3
Optical MUX Loss	3
Optical DeMUX Loss	3
Switch Isolation Factor	-40
XPM Loss	-28
Starting OSNR	30
OSNR Threshold	23

Table 2 – PLI Tool Configuration

The PLI Tool configuration will be the same for all synthetic and real network tests that will be performed. These values were taken from [15].

All graphs presented in this chapter will follow an identical format.

Synthetic Topologies

All of the tests performed was done on synthetically topologies that are randomly created. Each test was performed on three different topologies with identical specifications. The topologies were different as a result of randomization. For each topology there will also be fifteen different data sets. The following tests were divided into two categories:

1. SPS-IA-RWA was compared against other RWA/IA-RWA heuristics
2. Variations of SPS-IA-RWA Heuristic were compared against the generic algorithm

The first category used the generic SPS-IA-RWA heuristic and was compared against other RWA heuristics such as cRWA [9], sLERP [9], SLPF [28], and LSPF [28]. The second category evaluated the effect of wavelength assignment and path length prioritization on the SPS- IA-RWA heuristic. Both these categories were tested on a variety of topologies with different numbers of nodes and available wavelengths. Tests were performed with different demand sets to evaluate different network conditions varying from low to high congestion.

The first set of tests compared the IA-RWA heuristics, SPS-IA-RWA, sLERP[9], SLPF [28], and LSPF [28]. The configurations were as follows. Each test was run with 8 followed by 16 channels with 10, 15, 20, and 25 nodes. Figures 5.1 to 5.8, follow the same pattern comparing the performance of each of the heuristics. The X-axes shows how each group of heuristics performes with a set of demands, while the Y-Axes shows the percentage of demands that were successfully established onto the network as lightpaths.

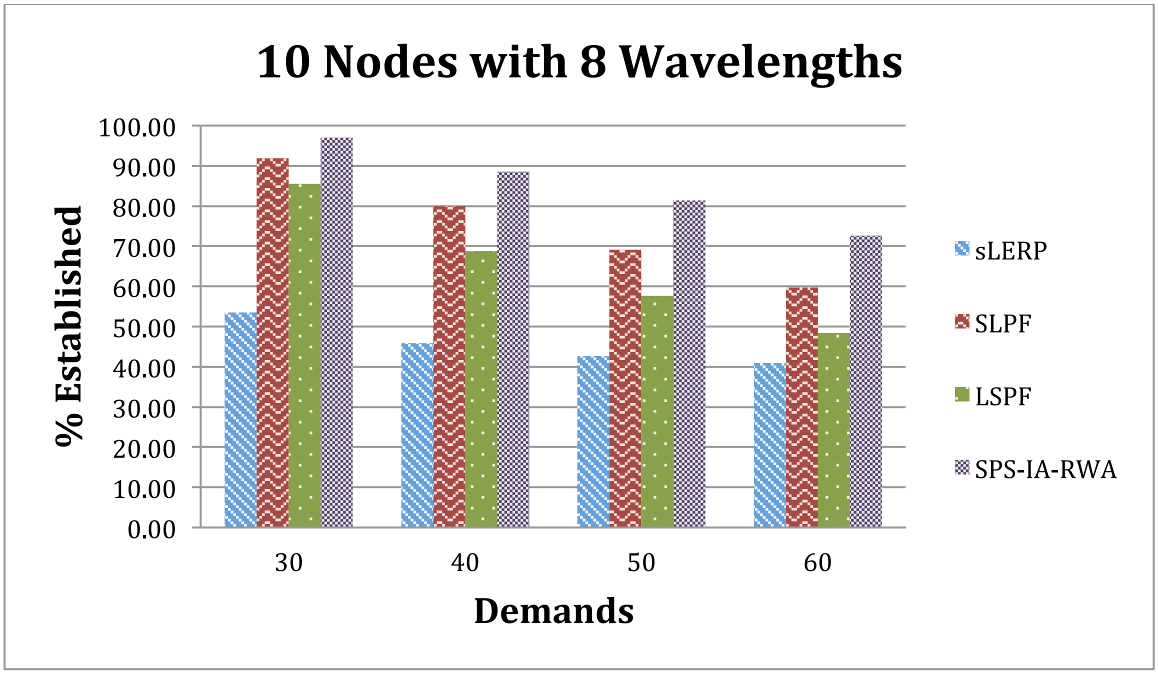


Figure 5.1 – Experimental Results – Synthetic 10N 8W

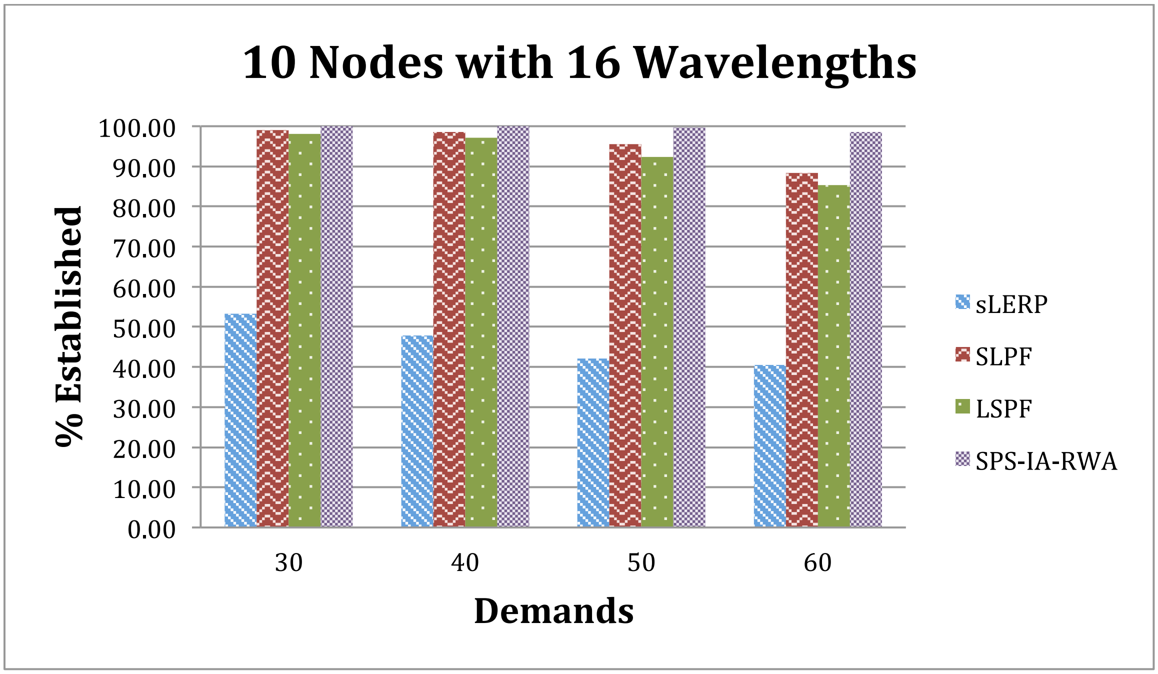


Figure 5.2 - Experimental Results – Synthetic 10N 16W

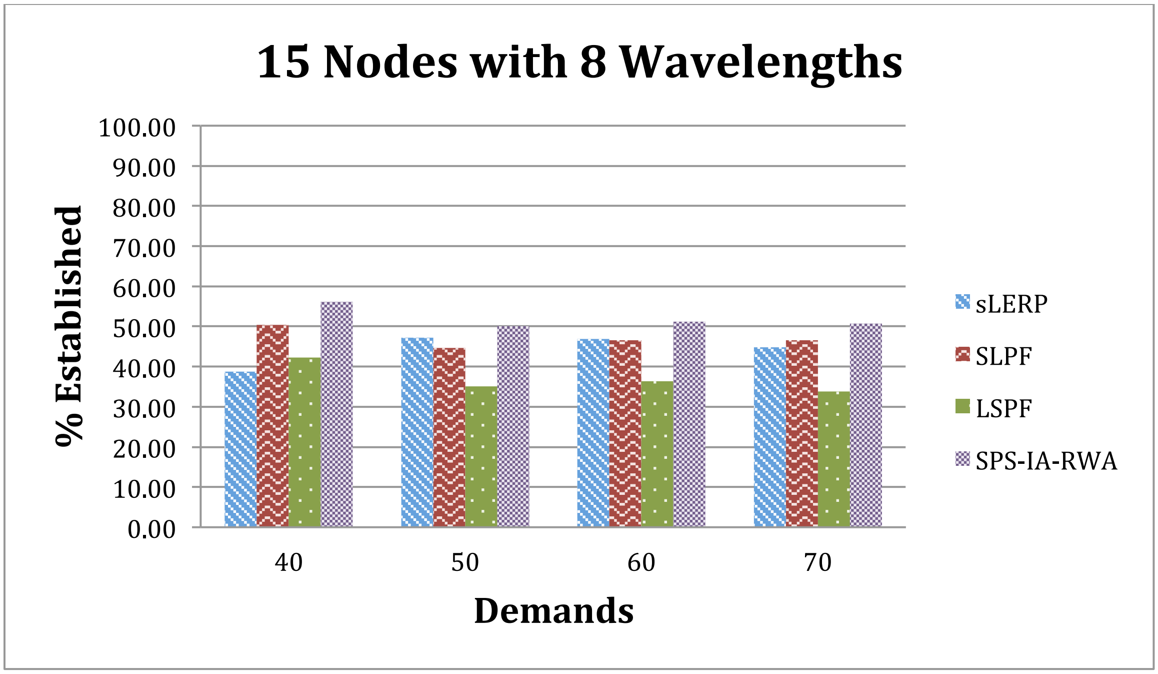


Figure 5.3- Experimental Results – Synthetic 15N 8W

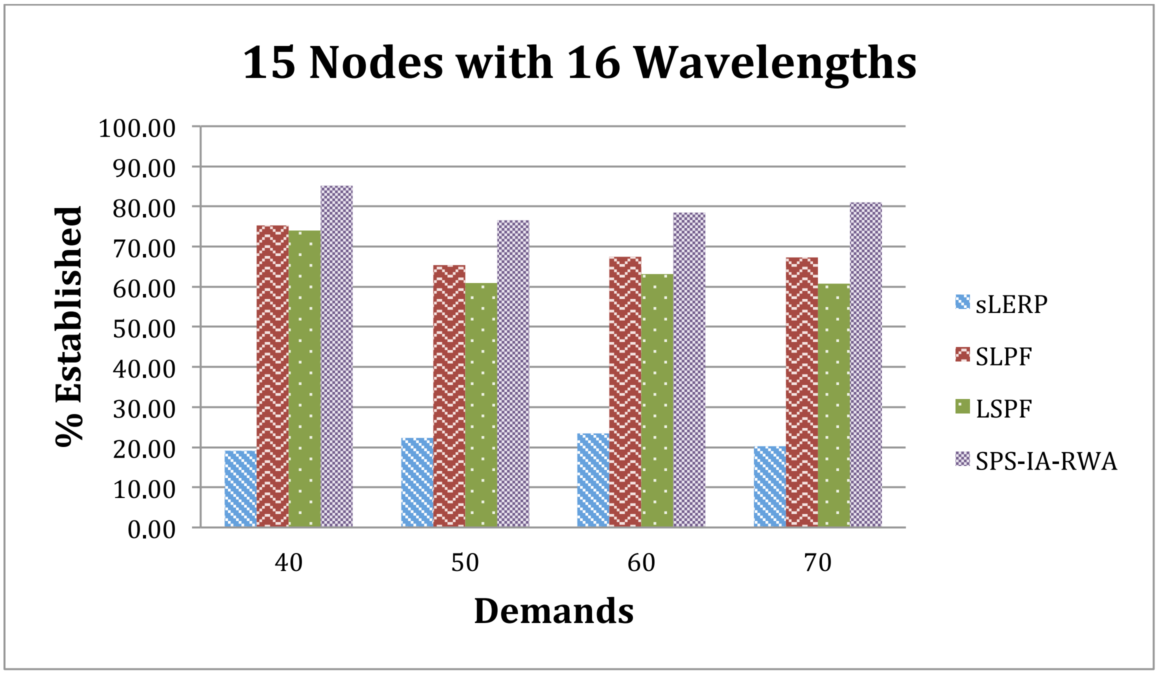


Figure 5.4- Experimental Results – Synthetic 15N 16W

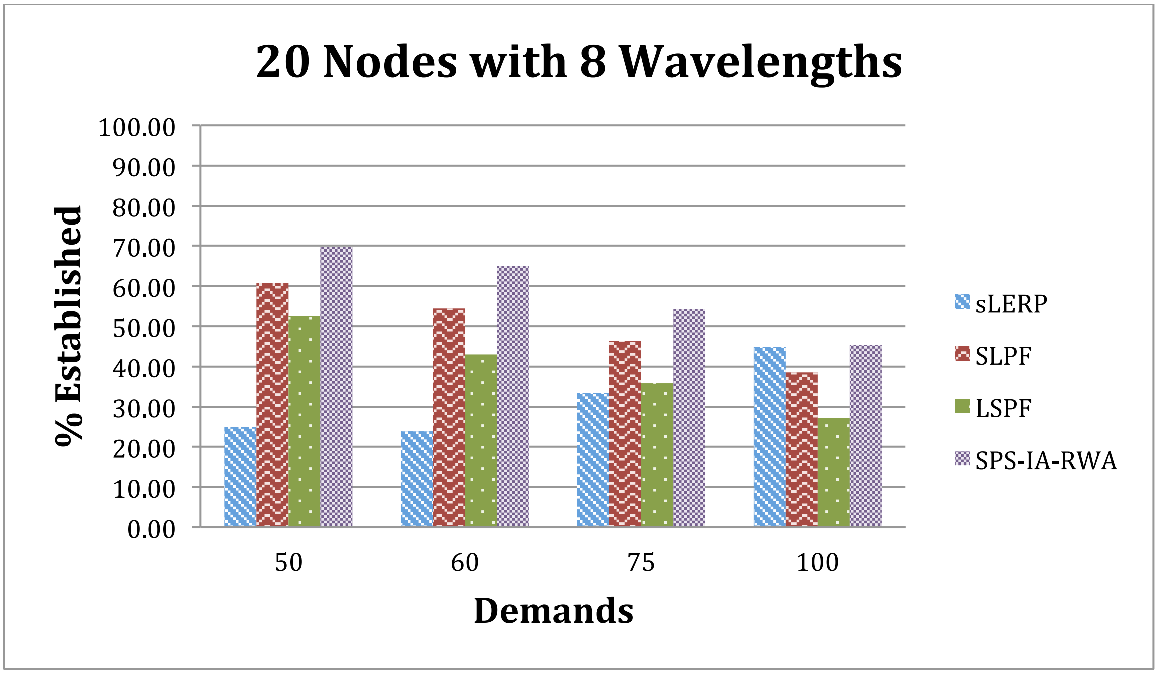


Figure 5.5- Experimental Results – Synthetic 20N 8W

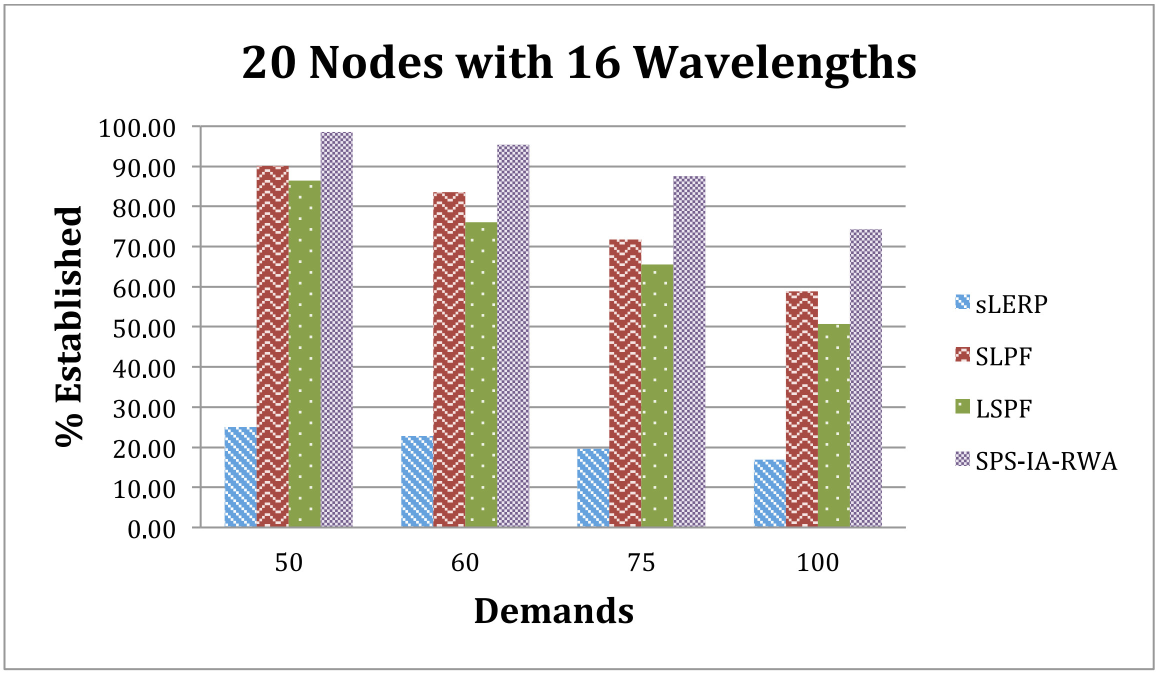


Figure 5.6- Experimental Results – Synthetic 20N 16W

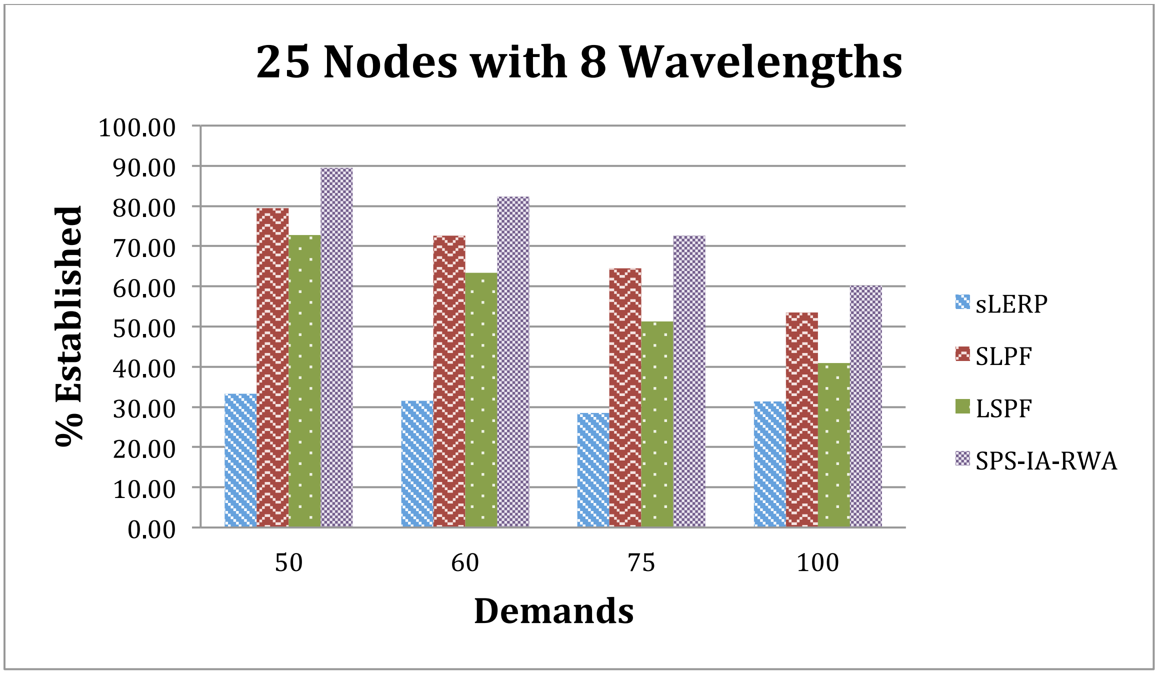


Figure 5.7- Experimental Results – Synthetic 25N 8W

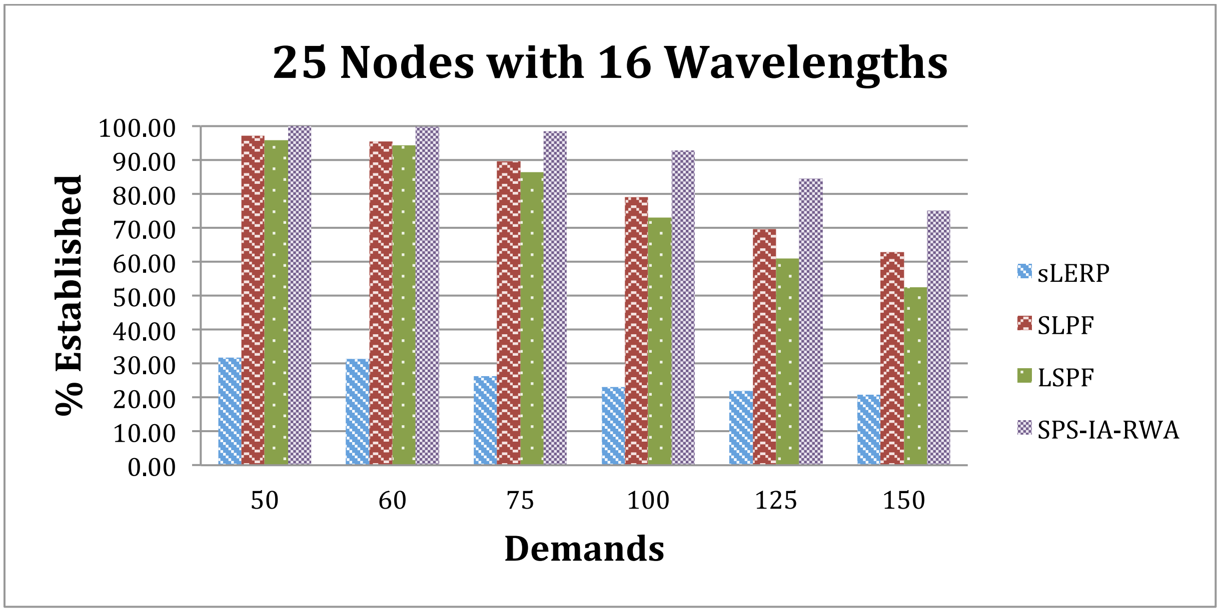


Figure 5.8- Experimental Results – Synthetic 25N 16W

As it can be seen from figures 5.1 to 5.8, SPS-IA-RWA performs consistently better compared to other modern IA-RWA heuristics. The performance increase on average compared against sLERP [9] ranges from as low as 5% to as high as 60% in some tests. When comparing SPS-IA-RWA with SLPF [28] and LSPF [28], the performance increase is subtler ranging from only 5% to about 15%. The poor performance of sLERP [9] can be attributed to the lack of iterative or randomized wavelength assignment. Wavelength assignment is performed on a first fit basis; if the proposed lightpath fails the impairment test, the demand is blocked. This is the reason why increasing the number of available wavelengths makes little to no difference on the performance of sLERP [9]. When a number of initial lightpaths are established on an optical link, the impairment generated, if adjacent wavelengths are used will be significant. Therefore the primary limiting factor for sLERP [9] is the physical layer impairment. This is especially evident on tests with relatively low network loads with many available wavelengths eg, figure 5.2. An additional observation that can be made is that LSFP [28] performs consistently worse compared to SLPF [28]. This can be attributed to the fact that longer paths experience greater impairment by definition, as the optical signal must propagate a longer distance. This makes the lightpaths on the network more fragile, as there is a smaller tolerance for additional impairment. This additional impairment is caused by newly established lightpaths due to nonlinear class 2 impairments. Referring to figures 5.8 and 5.1 among others, it can also be seen that in most tests, as the network congestion increases, the margin of lead between SPS-IA-RWA and SLPF [28] and LSPF [28] increases. This is attributed to the intelligent prioritization of path and wavelength selection that was used. As the network becomes more congested, the prioritization of paths and wavelengths becomes more important as the available resources are becoming used up.

The second set of tests that have been performed was to compar the performance of the generic SPS-IA-RWA heuristic to the cRWA [9] non-impairment aware RWA algorithm. The goal of this experiment is to evaluate the network utilization of the SPS-IA-RWA heuristic and to determine the impact impairment awareness makes on the potential load of a network. The cRWA [9] is assumed to utilize the network to its maximum potential as it only takes the network layer wavelength availability constraint into consideration. The experiment was run with topologies consisting of 10, 15, 20, and 25 nodes with 8 wavelengths. The experiment was run with demand sets having 60 source and destinations. Each topology had 3 variations with 15 different demand sets. The performance is evaluated using the percentage of successful lightpaths established by each heuristic. The percentage of successful established lightpaths is determined by the following formula, $(\# \; of \; lightpaths \; established \; / \; number \; of \; demands) * 100$.

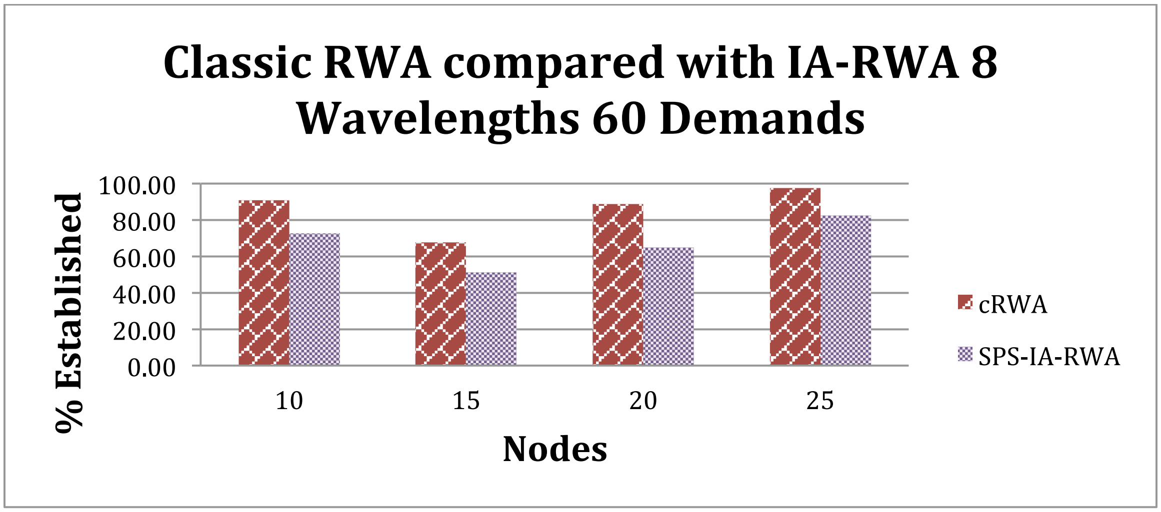


Figure 5.9- Experimental Results – Synthetic RWA – IA-RWA

The results show cRWA [9] outperforming SPS-IA-RWA as expected because it does not take impairment into consideration and is therefore able to utilize the network to its potential with the only constraint being network layer wavelength availability. As can be seen by figure 5.9, cRWA [9] outperforms SPSIA-RWA on the average by approximately 20%. IA-RWA heuristics have been developed because classic RWA was not sufficient to meet today's needs. The results show that on a synthetically generated network topology, approximately 20% of the established lightpaths would be unusable due to impairment.

The third test that has been performed using synthetic networks compares the performance of the of the generic SPS-IA-RWA compared to the modified versions:

- With Random Wavelength Assignment,
- With Longest to Shortest Path prioritization.

Each modified SPS-IA-RWA heuristic only modifies one aspect of the generic heuristic. Random wavelength assignment replaces the intelligent wavelength selection based on availability, and Longest to Shortest Path prioritization modified the demand selection prioritization from Shortest to Longest. The goal of this experiment was to observe the performance difference resulting from:

- Prioritizing longer paths first,
- Random wavelength assignment.

The randomization of wavelengths may show the benefit or the lack there of from intelligent wavelength assignment as this process is computationally expensive. From earlier tests it has also been observed that assigning longer paths first results in consistently lower performance as demonstrated by the LSPF [28] algorithm. It was interesting to see if this trend is consistent with the SPS-IA-RWA heuristic.

This test was run with 15, 30, and 50 node topologies with 8, 16, 32, and 64 wavelengths each. On The 15 node topology 150 demands were tests, on the 30 and 50 node topology there were 400 demands. As with the earlier tests, there were 3 variations of each topology with 15 different demand sets. The percentage of successfully established lightpaths is the measure of performance for each heuristic. The percentage of successful established lightpaths is determined by the following formula, $(\# \, of \, lightpaths \, established \, / \, number \, of \, demands) * 100$. Figures 5.10 to 5.12 show the results from these tests.

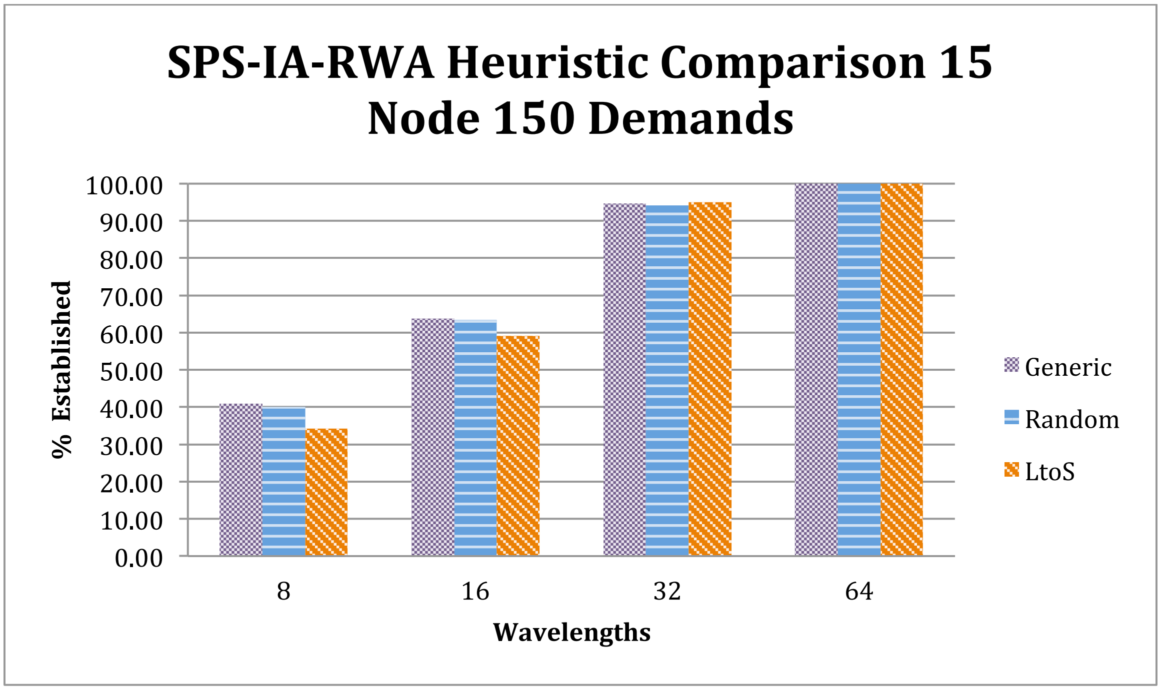


Figure 5.10- Experimental Results – Synthetic 15N 150D

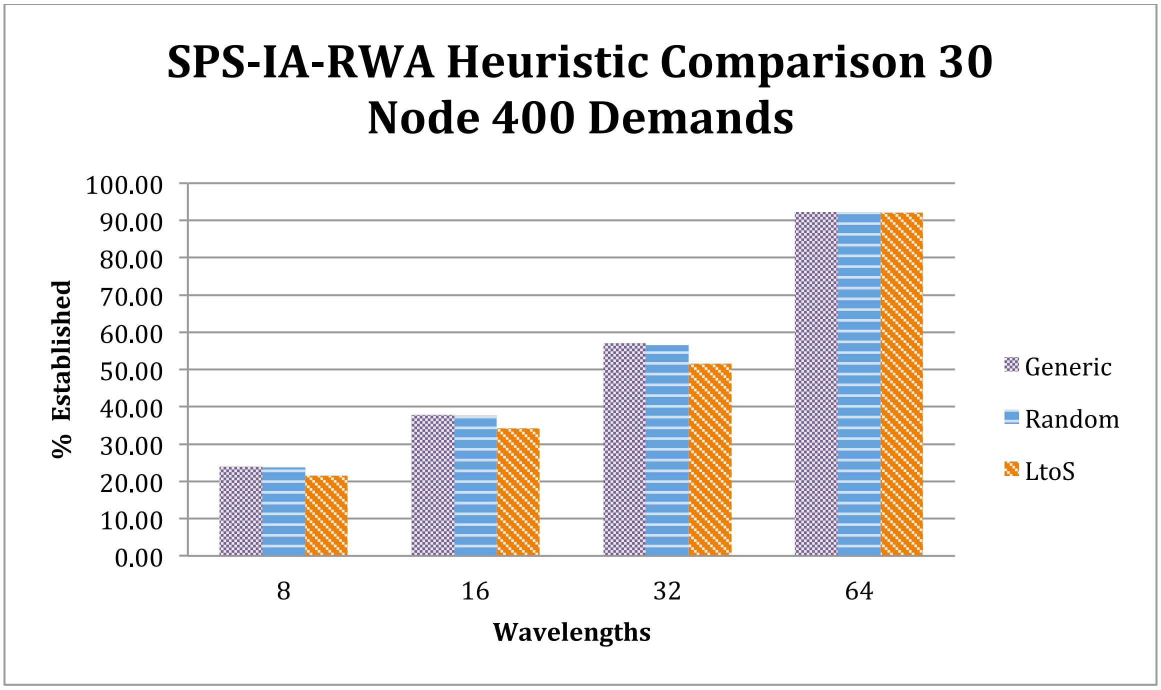


Figure 5.11- Experimental Results – Synthetic 30N 400D

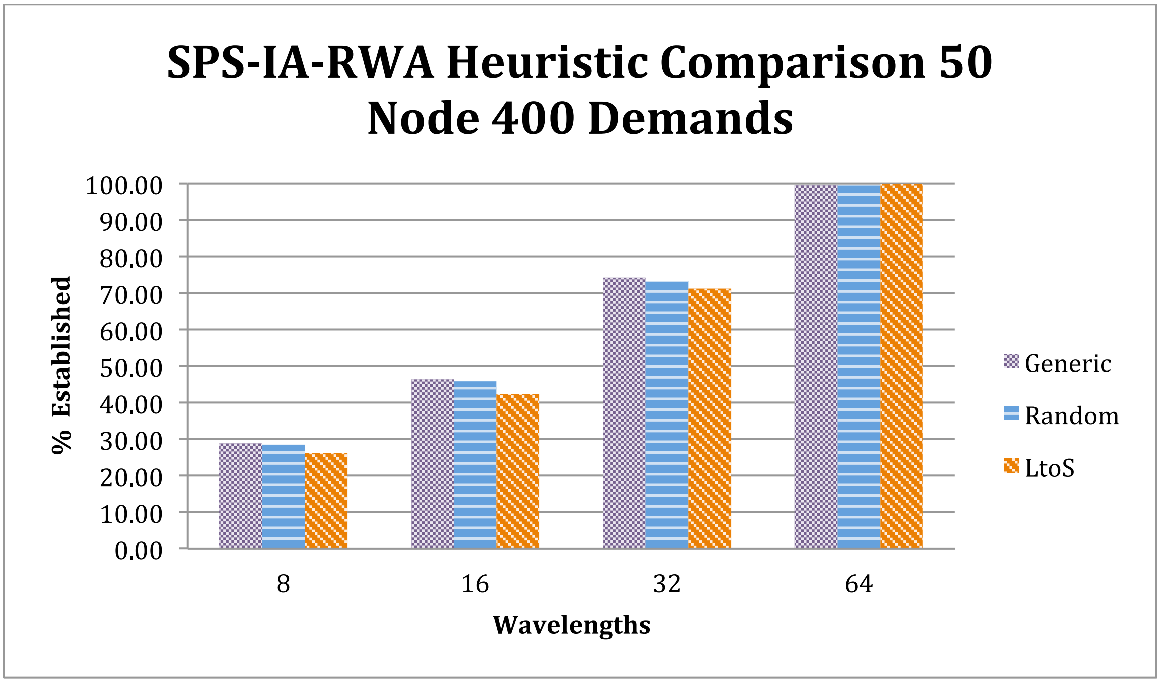


Figure 5.12- Experimental Results – Synthetic 50N 400D

As expected, the Longest to Shortest variant of the SPS-IA-RWA performs noticeably worse, compared to the generic and randomized wavelength assignment heuristics. Similarly as was discussed with LSPF [28] the main reason for this behaviour is that longer lightpaths, by definition, experience a greater amount of impairment as the optical signal must propagate through a greater distance. Since the first few lightpaths to be established have greater impairments compared to shorter paths, the tolerable QoT variance is reduced and therefore the lightpaths are more sensitive to non-linear class 2 impairments. This sensitivity increases as the network becomes more congested and as a result, less lightpaths are established. In most cases, random wavelength assignment performs marginally worse than the generic heuristic. This was surprising as the SPS-IA-RWA heuristic took great care to select the wavelength resulting in the least impact, which was originally expected to improve the efficiency of the network significantly. The success of the random algorithm can also be attributed to the iterative nature of wavelength assignment, where, in the event a single wavelength fails the QoT impairment test, the next available random wavelength was tried until no more available wavelengths existed for a path. Another benefit of random assignment is that the wavelengths that are assigned to lightpaths will be relatively evenly distributed across the available wavelength spectrum. This reduces first and second adjacency impairment that may be affecting lightpaths established by the generic heuristic.

The fourth test was run to evaluate the effect of varying the number of iterations on the overall performance of the SPS-IA-RWA heuristic. The number of iterations refers to the number of times the heuristic attempts to find alternative paths for demands that have been blocked in the previous iteration as part of the third phase. The experiment was performed on topologies with 20 and 40 nodes each with 8 and 16 available wavelengths. These experiments were performed on the generic SPS-IA-RWA heuristic. The number of iterations begins at 1 and goes up to 5. Each instance of the heuristic will be tested on 3 different topologies with 15 different demand sets for each topology. The 20 node topology has 150 demands while the 40 node variant has 200. The number of demands was increased in this case to ensure the topology will be congested and therefore a 100% establishment won't be possible as the goal is to see the gains at each increment.

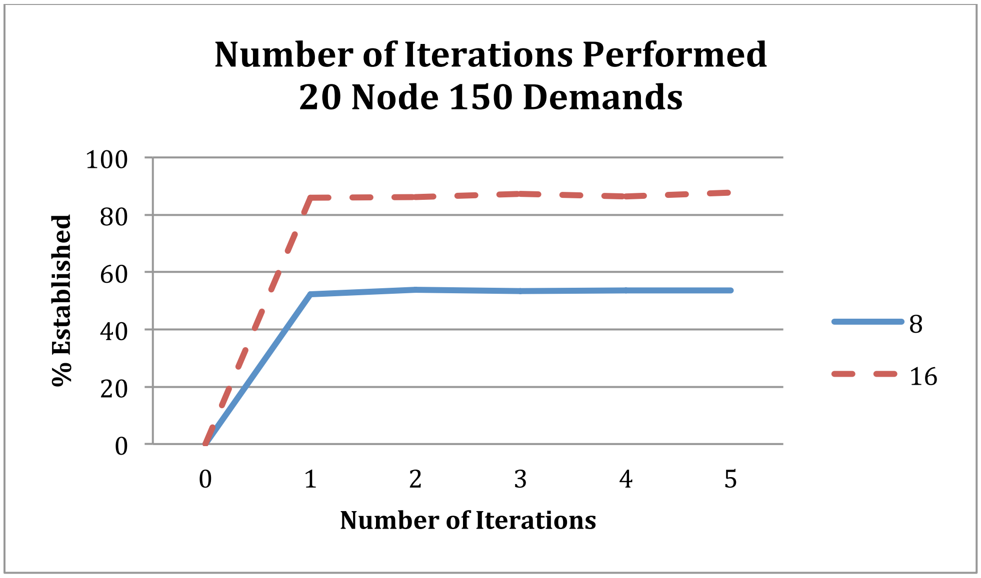


Figure 5.13 - Experimental Results – Synthetic 20N 150D

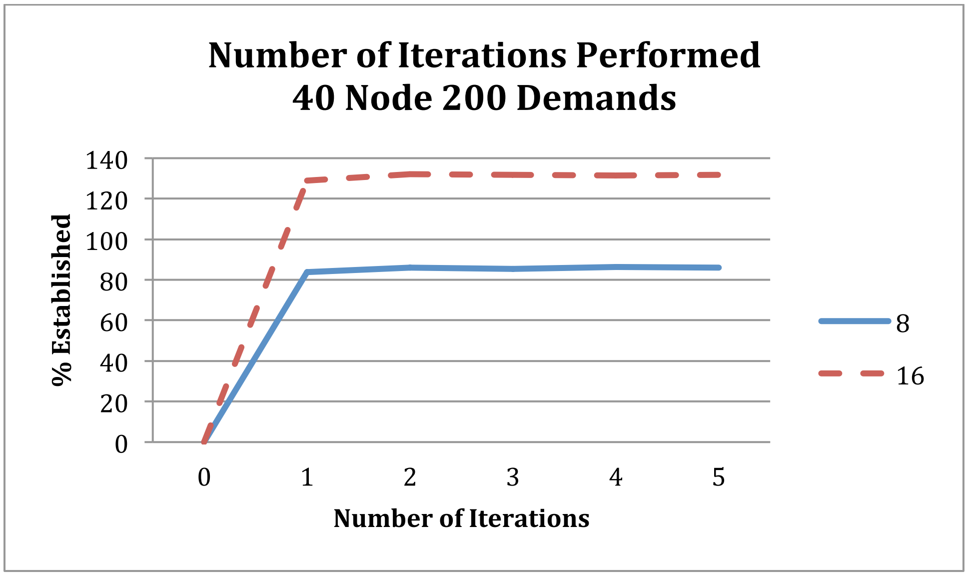


Figure 5.14 - Experimental Results – Synthetic 20N 200D

The results of the experiment indicate that the performance gains after the first iteration are marginal at best. In all cases the gain was between 1 and 2 additional lightpaths at the second and third iterations. This can be attributed to the network being heavy congested during the first phase. Many lightpaths fail to be established because of either i) a lack of wavelengths, ii) network layer constraint, or iii) the available wavelengths are heavy impaired and therefore unusable. This network state leaves very little room for additional improvement and therefore any additional iteration beyond 3 would yield no benefit. Since this is an offline RWA there are no time constraints and therefore it can be inferred that 3 iterations is the best setting to use as the experiments show an occasional additional lightpath being established. If the computation time is a variable, the number of iterations should be capped at 1 as almost all lightpaths are established. This trend has been consistent across all tests that have been performed on 20 node, figure 5.13, and 40 node, figure 5.14 topologies.

Real World Topologies

The tests were performed on the following real world topologies:

- NSF-14,
- ARPA-21,
- USA-24.

The network simulator was configured to retrieve these topologies from a database. Since these are real world topologies, the user did not have any control over the length of edges and therefore some of the features of the network simulator associated with generating random topologies are not applicable in this section. The demand set was still generated at random with one modification. The configuration variable, lowest/highest demand distance bound is set between 1% and 100%.

The tests that were performed will be comparing the performance of the following heuristics SLPF[9], LSPF[28], sLERP[28], and SPS-IA-RWA. As was done during the synthetic tests, the performance metric was the percentage of successfully established lightpaths. This was calculated with the following formula, $(Number\ of\ Established\ Lightpaths\ /\ Number\ of\ Demands) * 100$. Each topology was tested on two different wavelength capacities, 8 and 16. Each topology was run on 20 different demand sets. The results presented was the average result from each of the tests.

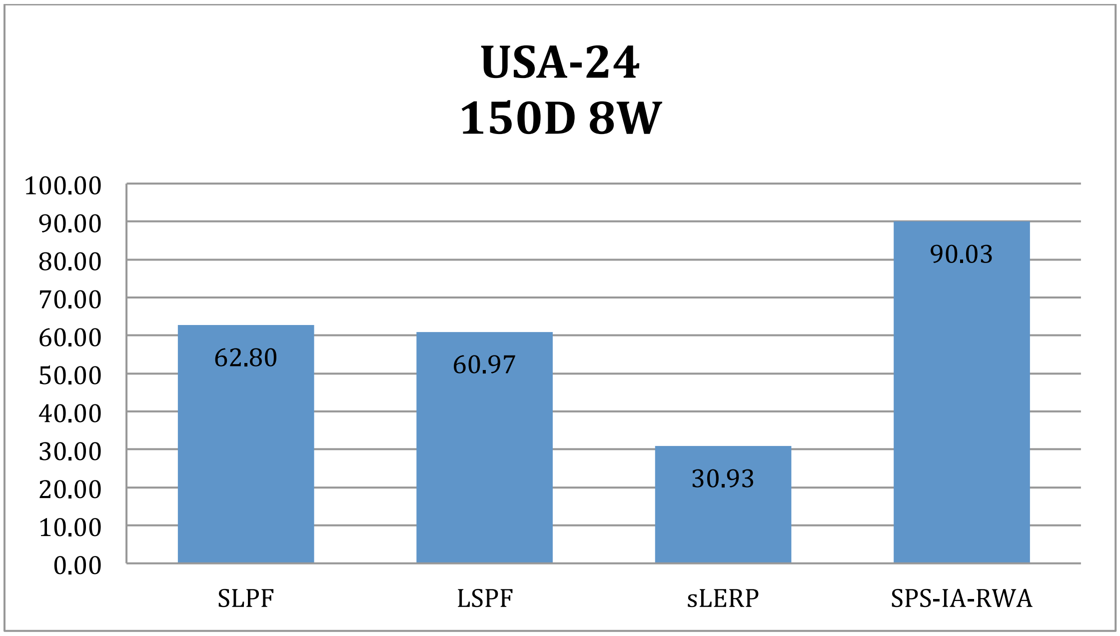


Figure 5.15 – Experimental Results - USANET - 24N 150D 8W

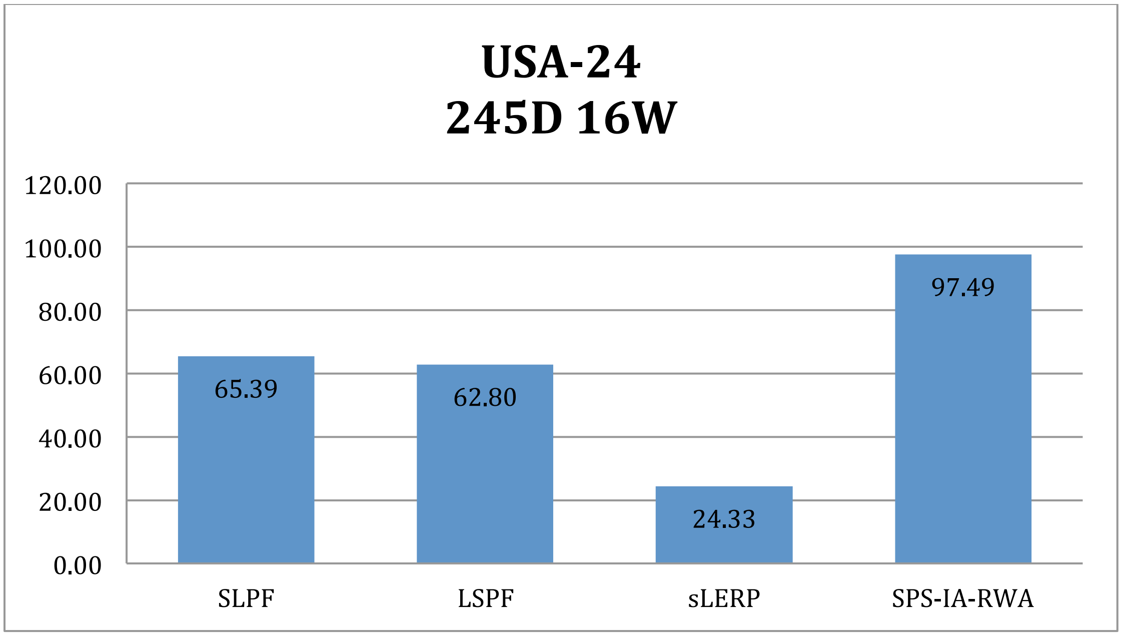


Figure 5.16 – Experimental Results - USANET – 24N 245D 16W

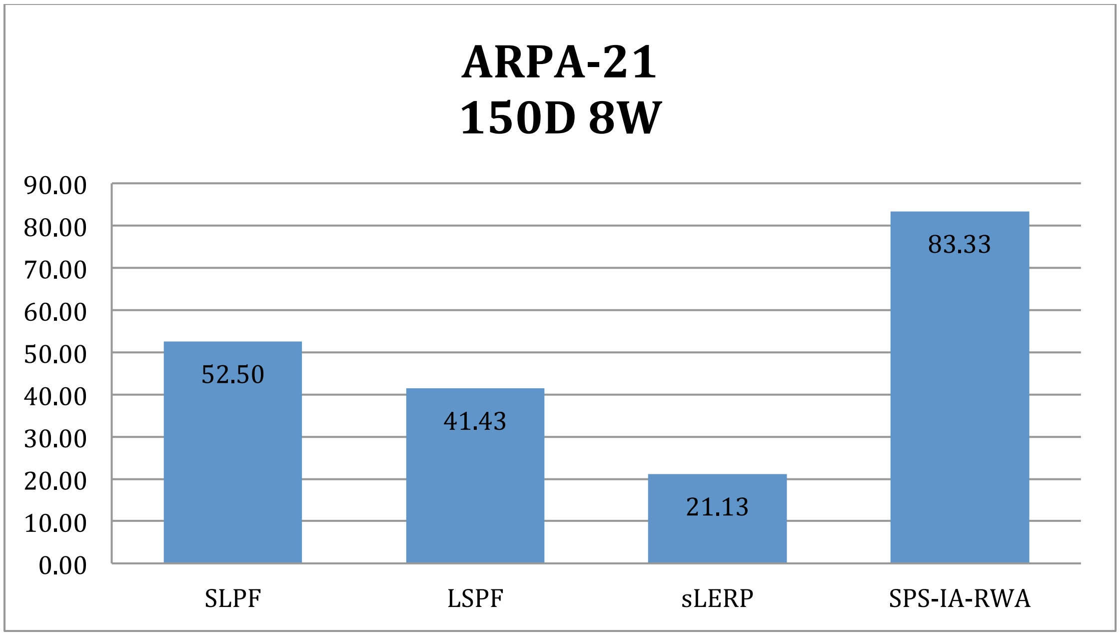


Figure 5.17 – Experimental Results - ARPANET – 21N 150D 8W

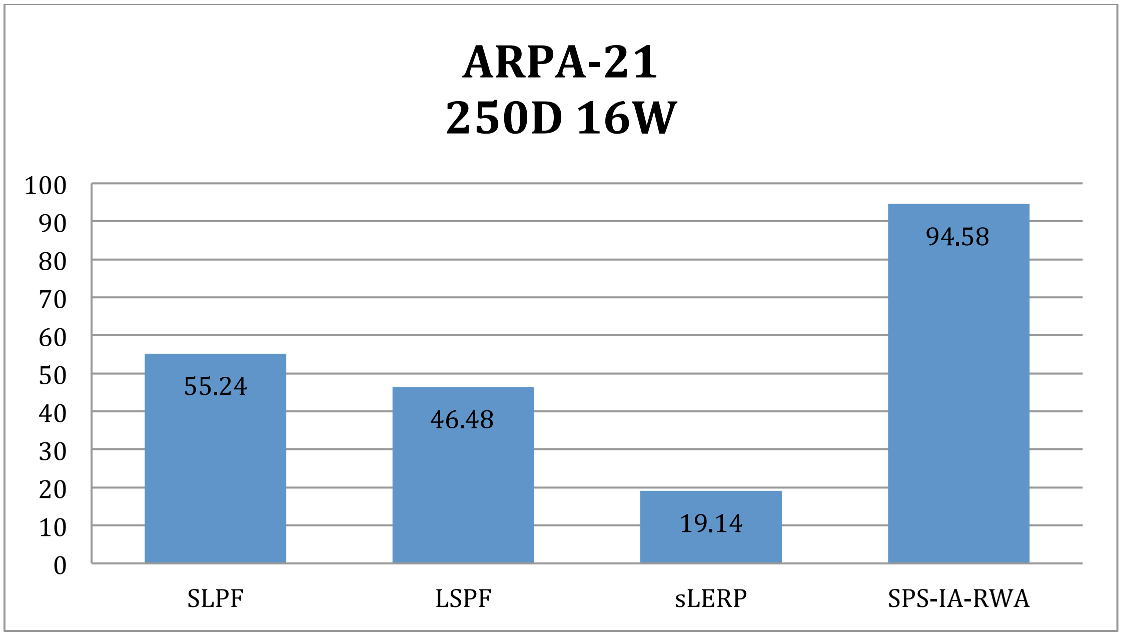


Figure 5.18 – Experimental Results - ARPANET – 21N 250D 16W

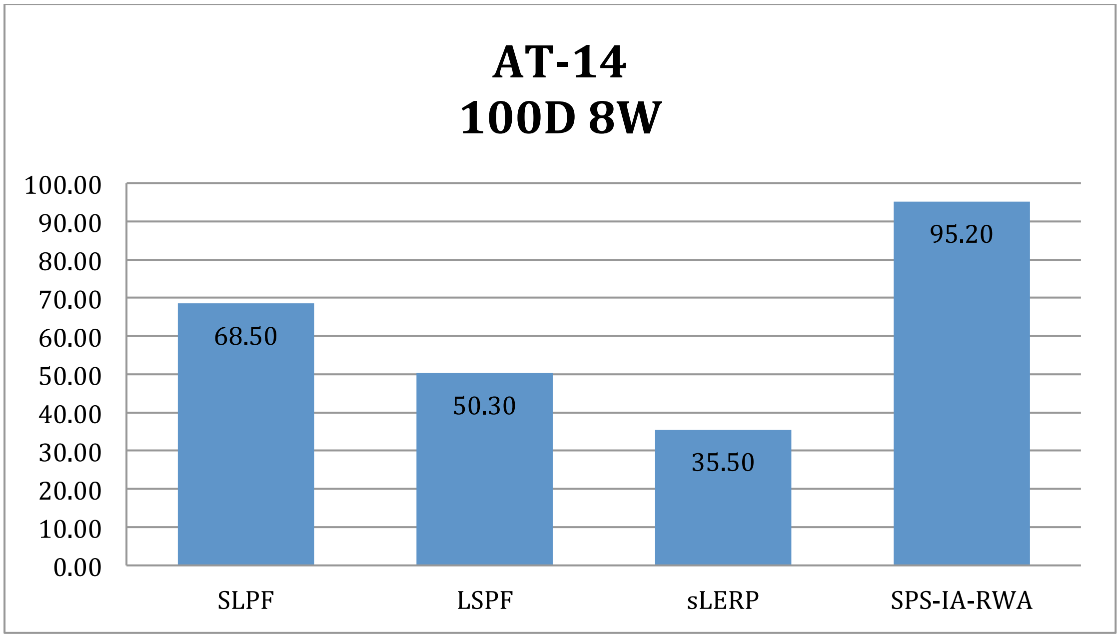


Figure 5.19 – Experimental Results - AT – 14N 100D 8W

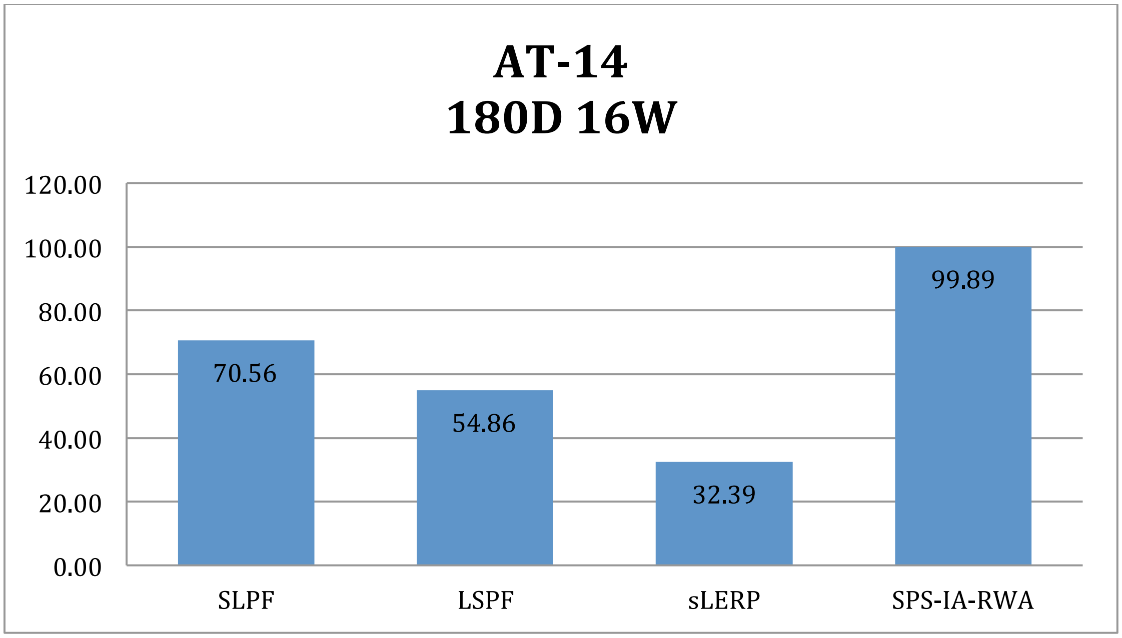


Figure 5.20 – Experimental Results - AT – 14N 180D 16W

Figures 5.15 to 5.20 show the results for the real world topology experiments that were performed. As can be seen, the proposed SPS-IA-RWA heuristic outperformed comparable modern heuristics. On the real world topologies the performance of the heuristic appears to have increased as more lightpaths are able to be established compared to tests performed on synthetic networks. This is attributed to the distribution of demands that were generated. As was mentioned, the demands were generated with route distances between 1% and 100% compared to 20% and 80% as was done previously. As there were additional shorter paths, the network load was not as great and therefore additional paths could be established. Otherwise the findings were consistent as expected with the tests performed on synthetic topologies. As can be seen prioritizing longer paths (LPF) [28] over shorter once (SPF) [28] yielded a lower performance as can be seen in figure 5.20.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

Conclusions

Since its inception, the Internet has experienced an exponential growth in both users and content availability. In order to sustain this growth, new technologies must be developed in order to provide a reliable form of high performance communication. Considering the commercial and governmental reliance on the communications infrastructure, the new technology must not only provide high bandwidth but also exceptional reliability. In the last few decades fiber optics have emerged as the optimal technology to use at the foundation of the telecommunications infrastructure, which powers phone, network, and Internet systems worldwide. Fiber optics provides a medium of transmission that relies on modulated pulses of light through a fiber cable. With the discovery of WDM, the telecommunications industry has been able to drastically increase the capacity of data that each optical fiber is able to carry at any one point in time. As new discoveries are made, new problems emerge. Industry has moved from opaque to translucent networks, with research being done on transparent networks; issues of impairment resulting in information corruption have risen. With transparent networks a single pulse of light is transmitted from the source to the destination node with no regeneration. Classic RWA algorithms disregarded impairment as the algorithms were designed for smaller scale opaque networks. Considering modern and next generation networks have grown in size and no longer rely on regenerators, a new class of algorithms needs to be developed in order to solve the RWA problem while taking impairment into account, this class is called IA-RWA.

The proposed SPS-IA-RWA heuristic has been designed to work on next generation all optical transparent networks. The heuristic is impairment aware and uses the OSNR [15] model for computing impairment. The IA-RWA is performed on the offline demand set. The heuristic has three phases, during phase one it finds a number of k-shortest paths for each demand, followed by an ILP optimization that selects a single path for each demand that results in the least amount of congestion. This results in load being evenly distributed across the network. Once each demand has a path selected, the heuristic will iteratively select which demand to prioritize for wavelength assignment. Demand prioritization is based on three factors:

- Number of available channels,
- Path Length,
- Degree of each path (determined by path intersection graph).

After a demand has been selected, phase two wavelength assigning begins. Wavelengths are prioritized, based on the properties of PIG (path intersection graph) as follows. Each outstanding demand is part of the path intersection graph, the degree is the number of paths joined by an edge to the path undergoing wavelength assignment that share an available wavelength in common. The lower the degree the higher the prioritization. Once a wavelength is selected, the candidate lightpath is added to the network and the impairment is tested. If any lightpath fails the QoT test, the candidate lightpath selects the next available wavelength and the test is repeated. If all available wavelengths are exhausted, the demand is temporarily blocked for this iteration. This process repeats for each unallocated demand in the list. For each blocked demand, phase three removes the path that has been tested and starts the heuristic from phase one over again. This process will repeat a specific number of times.

The SPS-IA-RWA heuristic was implemented within a network simulator that was used as a testing framework for RWA/IA-RWA algorithms. The network simulator currently considers only transparent networks and offline demand sets. The simulator provides each of the RWA/IA-RWA algorithms with the following tools:

- PLI tool,
- k-shortest paths tool.

In order to provide a fair testing base, all implemented algorithms must utilize these tools if needed. The PLI tool is based on the OSNR [15] model. This impairment model measures the optical signal to noise ratio at each destination node. The k-shortest paths tool is based on the algorithm by [27] and will generate a number of paths for each source and destination demand.

The results show that the SPS-IA-RWA heuristic consistently outperforms algorithms such as SLPF [28], LSPF [28], and sLERP [9]. Performance of each heuristic is measured by the percentage of successfully established lightpaths. The average gain in performance by the SPS-IA-RWA heuristic is approximately 10% compared against SLPF [28] and LSPF [28]. In some experiments SPS-IA-RWA has been able to outperform sLERP [9] by approximately 60%. This gain in performance has been attributed to the iterative wavelength selection mechanic in SPS-IA-RWA, SLPF [28], and LSPF [28]. Additional tests have been performed comparing SPS-IA-RWA to cRWA [9]. These experiments were run to better understand the effect of attaching impairment awareness to an RWA algorithm. The tests have shown that on average 20% of the lightpaths established by the cRWA algorithm would exceed the impairment tolerance and therefore would be unusable. Other tests have also been run with modified versions of the SPS-IA-RWA heuristic. These tests have been run to understand the impact of path length prioritization and wavelength assignment. It has been observed that prioritizing longer paths first results in a lower number of successfully established paths by a few percent. This finding is consistent with what was seen with the performance of LSFP [28] being worse than SLPF [28]. Surprising results have come out of testing randomized wavelength assignment. This scheme performs very closely to the initial priority based wavelength assignment. These results may be attributed to the lightpaths being assigned non-adjacent wavelengths on a single fiber and therefore experiencing less class two impairments during the early iterations of the SPS-IA-RWA heuristic.

Overall, the newly proposed SPS-IA-RWA heuristic outperforms other comparable modern IA-RWA algorithms. The newly proposed SPS-IA-RWA heuristic can be implemented by network operators for use in provisioning offline demands on transparent networks. This implementation will increase the current networks utilization by optimizing the load while maintaining a certain a minimum QoT. Research in fiber optic networking is currently ongoing and with the advent of optical regenerators and very high density fibers (over 62 available wavelengths per fiber) the need for intelligent lightpath provisioning with QoT considerations will only increase. Optical technology has been the solution to the ever-increasing demand for high-speed network communication. With the challenges currently faced, the proposed SPS-IA-RWA heuristic, among others can be used to further the growth of current and next generation networks.

Future Work

While the proposed Smart Priority Selection Impairment Aware Routing and Wavelength Assignment (SPS-IA-RWA) heuristic is able to perform very well, there is still potential for further improvement. The fundamental strength of the SPS-IA-RWA heuristic is the intelligent path selection based on a set of criteria. Given this statement, further improvements may be possible by either:

- Modifying the prioritization criteria,
- Re-ordering the prioritization.

Modifying the prioritization criteria results in changes to the performance. As can be seen by the experiments, figures 5.10 to 5.12, changing the criteria from shortest path first, to longest path first, resulted in a noticeable drop in performance. What has not been analysed is the effect of the degree each path in the path intersection graph. Prioritizing paths that share many edges with other demand paths may increase the performance as these paths more likely to experience network layer blocking as a result of demands with more disjoint paths taking up all the resources. The tests that have been performed all use the same general prioritization categories in the following order:

- Wavelength Availability,
- Path Length,
- Demand degree.

Future implementations should modify the ordering of the prioritization and evaluate the results.

The experiments that have been performed show a near indistinguishable benefit of the intelligent wavelength assignment compared to generic random selection. This implies that the criterion used for iteratively selecting wavelengths is inefficient as the net benefit is marginal. An alternative to the current form of iterative wavelength assignment is an ILP based solution. The goal would be to maximize the number of available channels on each fiber. Since the ILP based solution would yield an optimal solution for the given iteration it may improve the over all performance of the SPS-IA-RWA heuristic.

The SPS-IA-RWA heuristic is designed to currently work exclusively on next generation transparent optical networks. The current trend within the telecommunications industry is to implement translucent networks, in order for the SPS-IA-RWA heuristic to function effectively on these networks it would require the addition of OEO regenerator placement. Given the success in transparent networks, the prioritization based SPS-IA-RWA heuristic may prove equally powerful in translucent network.

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