Physically Aware Routing and Wavelength Assignment (RWA) Algorithms for Next Generation Transparent Optical Networks

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Abstract

This paper is a proposal of my Ph.D. thesis research on physically aware Routing and Wavelength Assignment (RWA). The paper includes a lengthy discussion of background information relevant to my topic. This paper also includes a presentation of the progress I have made in this area and my plans for future research.

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Chapter 1

Introduction

This paper is a proposal of my Ph.D. thesis research. The proposal includes background information on my proposed area of research, some results from my existing research, and a plan of action to further research this problem.

1.1 Context and motivation

Optical networks form the foundation of today's information infrastructure. Optical networks were first employed on a large scale in the 1980s. In the last 25-30 years, optical networks have changed drastically.

Current generation optical networks consist mainly of point-to-point links which switch between nodes and repeaters. All intermediate nodes convert the incoming optical signal into an electric one, process it, and then convert it back into an optical signal. This processes is called an OEO conversion. Networks which use OEO conversions are called *opaque*.

Optical networks are capable of broadcasting multiple channels on a single fiber using a technique known as Wavelength Division Multiplexing (WDM). Transmission systems using up to 160 wavelengths, each running at 10 Gbps are becoming standard. This gives each optical fiber a capacity of 1.6 Tbps. [1]

There is a trend in optical networking to move from opaque networks towards *transparent* networks. Transparent networks use optical switches to eliminate the need for OEO conversions. The reason for this transition is simple: electronics capable of handling Terabits of data per second are prohibitively expensive. Transparent networks are also more flexible, as they can handle multiple modulation formats and data rates.

Unfortunately, the movement towards transparent networks creates a new problem. Traditionally, optical networks had bit error rates so low that link error performance was never a large concern. Networks could depend upon the periodic OEO conversions to restore the signal quality. With transparent optical networks, the signal stays in the optical domain for the entire lightpath. This distinction allows physical impairments to accumulate along the lightpath.

For this reason, future networks absolutely must consider signal quality when choosing a route and wavelength assignment (RWA). However, minimizing the blocking probability is also important. Algorithms which consider signal quality are said to be *physically aware*. Most of the RWA algorithms used today do not consider signal quality. The few algorithms which do consider signal quality are relatively simple. New physically aware RWA algorithms are necessary to efficiently manage future optical networks.

1.2 Contents

The rest of this paper is organized as follows. Chapter 2 presents additional background on optical networks and the approaches used to manage network connections. Chapter 3 presents a summary on research already conducted by myself on this topic, including the presentation of a network simulation program to analyze existing and future algorithms. Chapter 4 presents goals of this research and some ideas to meet these goals.

Chapter 2

Background

The chapter presents a summary of the background information relevant to physically aware Routing and Wavelength Assignment (RWA). It begins with a section on optical networks and impairments. The RWA problem is then defined formally. The rest of the chapter summarizes approaches to solving the RWA problem.

2.1 Optical Networking Fundamentals

Optical fibers consist of two main layers, a core and cladding. The inside layer is called the core, while the outside layer is called the cladding. The refractive index of the core is slightly lower than the cladding. This distinction causes a optical phenomenon known as total internal reflection, resulting in extremely low signal attenuation. For this reason, optical fibers are available today with loss rates of 0.2 dB per km in the 1.55-μm waveband. A buffer and jacket are added to the fiber for protection.

Optical fibers are fabricated using pure silica glass synthesized by fusing SiO_2 molecules. The refractive index difference required for total internal reflection is accomplished using dopants such as GeO_2 and P_2O_5 which increase the refractive index and materials such as boron and fluorine which decrease the refractive index.

Present generation optical networks are characterized by low-attenuation single-mode fibers (SMF) or dispersion shifted fibers (DSF) as the transmission medium. Erbium doped fiber amplifiers (EDFAs) are used to compensate for the attenuation while DSF is used to compensate for dispersion. With a single fiber, multiple wavelengths can be used to transmit data simultaneously using Wavelength Division Multiplexing (WDM). Each wave-

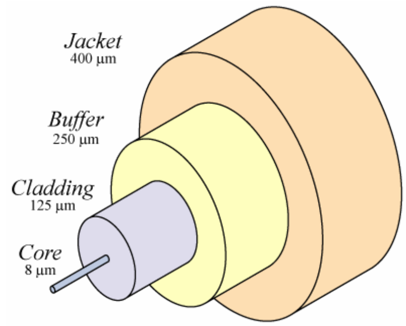


Figure 2.1: Optical Fiber [2]

length is called a channel. Such networks are used as the backbone of today's networks.

Optical networks are undergoing a transition from electronic switching to optical switching. Electronic switches perform an optical-electrical-optical (OEO) conversion. It is necessary to convert the incoming optical signal into an electric one using a photo detector so that the data in the header can be processed to determine the correct output port. Once processed, this data is converted back into an optical signal using an optical transmitter. There is an implicit retiming, reshaping, and reamplifying (3R) of the optical signal that allows the signal to maintain a high level of quality. In other words, physical impairments such as Amplified Spontaneous Emission (ASE), Polarization Mode Dispersion (PMD), Four Wave Mixing (FWM), Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Stimulated Brillouin Scattering (SBS), and Stimulated Raman Scattering (SRS) are not a large concern.

Optical switches are capable of switching data from an input fiber to the correct output fiber entirely in the optical domain. There is no need to perform the OEO conversions. The first step in this process is demultiplexing the incoming signals. Each signal is then connected to a wavelength routing switch (WRS) which chooses the correct output port. The signals are then combined using a coupler and transmitted out of the switch. The WRS can be configured dynamically as connections are added/dropped on the network.

Optical switches reduce network delay by eliminating the need for OEO conversions and any switch queuing delay. The electronic devices required for OEO conversions are very expensive at higher bit rates, so optical switches can significantly reduce the cost of the network. They also reduce the network complexity, as they can operate without the details of the optical signal (bit rate, bit encoding, network protocol).

A major disadvantage of optical switches is the physical impairments enumerated above accumulate across the signal path. These impairments can reduce the signal quality to a level which either blocks the connection completely or reduces the maximum bit rate of the connection to an unacceptable level. Bit error rates (BER) are a great concern in these networks. [3, 4]

It is possible to perform wavelength conversion in an optical network. Wavelength converters are capable of doing this entirely in the optical domain, but they are prohibitively expensive. Another approach is to perform an OEO conversion, using a different wavelength on the output port than the input port. Unfortunately, this is also too costly. Unless stated otherwise, the algorithms defined in the following section assume that no wavelength converters are available.

Mainly for these economic reasons, next generation optical networks are moving towards all optical networks. Such networks are called *transparent* networks. This is a requirement for optical networks with higher data rates. An unfortunate side effect of this shift requires that future networks be physically aware, as the effects of impairments increase with the bit rate.

There are two types of physical impairments: linear and nonlinear. Linear impairments, such as Amplified Spontaneous Emission and Polarization Mode Dispersion, are caused by physical properties of optical fibers and are not dependent upon the presence of other wavelengths. They tend to be relatively simple to estimate. Nonlinear impairments, on the other hand, are caused by separate wavelengths when the total light power reaches a certain threshold. Examples of nonlinear impairments are Four Wave Mixing, Self Phase Modulation, and Cross Phase Modulation. These effects tend to be more difficult to estimate.

Amplified Spontaneous Emission is caused by Erbium Doped Fiber Amplifiers (EDFAs) due to the spontaneous emission of atoms in the exited state. The power spectral density of ASE noise is

$$S(f) = 2n_{sp}(G-1)hf \tag{2.1}$$

where n_{sp} is the spontaneous emission factor, h is Planck's constant, f is the frequency, and G is the amplification gain. ASE noise is usually treated as white noise. [5]

Polarization Mode Dispersion (PMD) is caused by random imperfections in optical fiber. These imperfections cause the different polarizations of the optical signal to travel at different speeds. The mean time differential can be calculated by

$$\sigma_T \approx \Delta\beta_1\sqrt{2l_cL} \equiv D_p\sqrt{L} \tag{2.2}$$

where D_p is the PMD parameter, typically in the range of 0.1 to 1 $ps/\sqrt{km}$. [6] PMD can become a limiting factor for high speed optical networks over long distances. [7]

Four Wave Mixing (FWM) generates a spurious wavelength due to the presence of three other wavelengths. The incident photons scatter and produce a fourth photon. Given three inputs, the system will produce a range of frequencies given by

$$f_1 \pm f_2 \pm f_3 \tag{2.3}$$

If the spurious wavelength is close to another signal channel, the FWM will cause crosstalk and increase the noise. The effects of Four Wave Mixing on RWA are discussed in [8].

Self Phase Modulation (SPM) occurs because the refractive index of a signal channel has a component which is intensity-dependent, due to the optical Kerr effect. The nonlinear refractive index creates a phase shift, causing a chirping or modulation of the carrier frequency. This can cause a spreading of the pulse by dispersion.

Cross Phase Modulation (XPM) arises because the refractive index of a signal channel is influenced by the intensities of other active channels. This causes a phase shift and chirping of the signal. This also causes a spreading of the pulse by dispersion.

Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) result from stimulated inelastic scattering where the optical field transfers a portion of its energy to the nonlinear medium. Photons participate in SRS, while phonons participate in SBS. [6]

The listing of physically impairments presented here is by no means exhaustive. EDFA transients are discussed in [9, 10]. Intersymbol interference, amplifier noise, and node crosstalk are discussed in [11]. The impairments discussed here, however, do represent the most significant impairments in a WDM network.

Given the transformation to transparent networks, it is important for optical connections to consider these physical impairments. Algorithms which consider physical impairments are said to be physically aware.

Traditionally, signal quality was measured by the Optical Signal to Noise ratio (OSNR) or the Bit Error Rate (BER). BER and OSNR measurements are not sufficient for optical networks, as optical networks have BERs below 10^{-12}. A measurement of nearly error-free BER can take hours or even days.

[12] In optical networks, quality is usually measured via the Q-factor. The Q-factor can be calculated as

$$Q = 10 \log_{10} \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{2.4}$$

where I_0 and I_1 are the photo-current received at the destination and σ_0 and σ_1 is the standard deviation at the destination when a "1" and "0" are transmitted. [13]

Once the Q-factor is calculated, the BER can be approximated. This formula makes a Gaussian noise assumption. [14]

$$BER \approx 0.5erfc(\frac{Q}{\sqrt{2}}) \tag{2.5}$$

Connection request delay, or the difference between the connection request receipt time and the time a response is received, is also becoming an increasingly important consideration. Complex quality calculations can have a negative impact upon the blocking probability due to extended request delay. [15]

2.2 RWA Problem Definition

The general objective of the Routing and Wavelength Assignment (RWA) problem is to maximize the number of established connections. Each connection request must be given a route and wavelength. The wavelength must be consistent for the entire path, unless the usage of wavelength converters is assumed. Two connections requests can share the same optical link, provided a different wavelength is used.

The RWA problem can be formally defined in a Integer Linear Program (ILP). The ILP formulation given here is taken from [16].

$$\textbf{Maximize} : C_0(\rho, q) = \sum_{i=1}^{N_{sd}} m_i \tag{2.6}$$

subject to

$$m_i \geq 0, integer, i = 1, 2, ..., N_{sd} \tag{2.7}$$

$$c_{ij} \in 0, 1, i = 1, 2, ..., P, j = 1, 2, ..., W \tag{2.8}$$

$$C^T B \leq 1_{W \times L} \tag{2.9}$$

$$m \leq 1_W C^T A \tag{2.10}$$

$$m_i \leq q_i \rho, i = 1, 2, ..., N_{sd} \tag{2.11}$$

N_{sd} is the number of source-destination pairs, while m_i is the number of connections established for each source-destination pair. L is the number of links and W is the number of wavelengths. P is the set of paths to route connections. $A : P \times N_{sd}$ is a matrix which shows which source-destination pairs are activate, $B : P \times L$ is a matrix which shows which links are activate, and $C : P \times W$ is a route and wavelength assignment matrix.

Equation 2.6 represents the total number of connections in the network. Equation 2.7 ensures that the number of connections per source destination pair is a non-negative positive integer. Equation 2.8 limits the C matrix values to either 1 (active) or 0 (inactive). Equation 2.9 ensures that each wavelength is used only once. Equations 2.10 and 2.11 ensure that the number of established connections are less than or equal to the requested connections.

Note that the above formulation assumes that the traffic demands are known *a priori*. This type of problem is known as Static Lightpath Establishment (SLE). The above formulation also does not consider the signal quality. We are interested in solving the more complicated dynamic physically aware RWA problem, where the traffic demands are not known ahead of time and signal quality is considered.

It has been shown that the SLE RWA problem is NP-complete in [17]. The proof involves a reduction to the n-graph colorability problem. In other words, solving the SLE RWA problem is as complex as finding the chromatic number of a general graph. Given that dynamic RWA is more complex than static RWA, it must be the case that dynamic RWA is also NP-complete.

Another NP-complete proof is given in [18]. This proof involves a reduction to the integral multi-commodity Flow Problem.

The RWA problem is further complicated by the need to consider signal quality. Many of the optical impairments are nonlinear, so a standard shortest path algorithm can't be used to solve them optimally even if we know the exact state of the network. This is usually not a safe assumption, so solutions need to be efficient using only limited network information.

Given the complexity of RWA, there are two general methodologies for solving the problem. The first method is solving the routing portion first, and then assigning a wavelength second. Three types of route selection are Fixed Path Routing, Fixed Alternate Routing, and Adaptive Routing. The second approach is to consider both route selection and wavelength assignment jointly.

2.3 Fixed Path Routing

Fixed Path Routing is the simplest approach to finding a lightpath. The same fixed route for a given source and destination pair is always used. Typically this path is computed ahead of time using a shortest path algorithm, such as Dijkstra's Algorithm. While this approach is very simple, the performance is usually not sufficient. If resources along the fixed path are in use, future connection requests will be blocked even though other paths may exist.

The SP-1 (Shortest Path, 1 Probe) algorithm is an example of a Fixed Path Routing solution. This algorithm calculates the shortest path using the number of optical routers as the cost function. A single probe is used to establish the connection using the shortest path. The running time is the cost of Dijkstra's algorithm: $O(m + n \log n)$, where m is the number of edges and n is the number of routers. The running time is just a constant if a predetermined path is used.

Algorithm 1 Shortest Path Algorithm (SP)

1. Set the cost of each link L using $cost(L) = 1$
2. Return the minimal cost path using a shortest path(s) algorithm

This definition of SP-1 uses the hop count as the cost function. The SP-1 algorithm could be extended to use different cost functions, such as the number of EDFAs.

2.4 Fixed Alternate Routing

Fixed Alternate Routing is an extension of Fixed Path Routing. Instead of having just one fixed route for a given source and destination pair, several routes are stored. The probes can be sent in a serial or parallel fashion. For each connection request, the source node attempts to find a connection on each of the paths. If all of the paths fail, then the connection is blocked. If multiple paths are available, only one of them would be utilized.

The SP-p (Shortest Path, p Probes, $p > 1$) algorithm is an example of Fixed Alternate Routing. This algorithm calculates the p shortest paths using the number of optical routers as the cost function. The running time using Yen's algorithm [20] is $O(pn(m + n \log n))$ where m is the number of edges, n is the number of routers, and p is the number of paths. The running time is a constant factor if the paths are precomputed.

2.5 Adaptive Routing

The major issue with both Fixed Path Routing and Fixed Alternate Routing is that neither algorithm takes into account the current state of the network. If the predetermined paths are not available, the connection request will become blocked even though other paths may exist. Fixed Path Routing and Fixed Alternate Routing are both not quality aware. For these reasons, most of the research in RWA is currently taking place in Adaptive algorithms. Five examples of Adaptive Routing are LORA, PABR, IA-BF, IA-FF, and AQoS.

Adaptive algorithms fall into two categories: traditional and physically-aware. Traditional adaptive algorithms do not consider signal quality, however, physically-aware adaptive algorithms do.

2.5.1 Traditional Adaptive RWA

The Lexicographical Routing Algorithm (LORA) algorithm was proposed in [5]. The main idea behind LORA is to route connection requests away from congested areas of the network, increasing the probability that connection requests will be accepted. This is accomplished by setting the cost of each link to be

$$cost(l) = \beta^{usage(l)} \tag{2.12}$$

where β is parameter that can be dynamically adjusted according to the traffic load and $usage(l)$ is the number of wavelengths in use on link l. A standard shortest path algorithm can then be used to find the path. This requires each optical switch to broadcast recent usage information periodically. Note that LORA does not consider any physical impairments.

When β is equal to one, the LORA algorithm is identical to the SP algorithm. Increasing the value of β will increase the bias towards less used routes. The optimal value of can be calculated using the well-known hill climbing algorithm. In [5], the optimal values of β were between 1.1 and 1.2.

Algorithm 2 Lexicographical Routing Algorithm (LORA)

1. Determine the appropriate value of β according to the current network traffic load
2. Set the cost of each link L using $cost(L) = \beta^{U_l}$
3. Return the minimal costs paths using a shortest path(s) algorithm

2.5.2 Physically Aware Adaptive RWA

The Physically Aware Backward Reservation Algorithm (PABR) is an extension of LORA. [5] PABR is able to improve performance in two ways: considering physical impairments and improved wavelength selection. As PABR is searching for an optical path, paths with an unacceptable signal quality due to linear impairments are pruned. In other words, PABR can be formalized as

$$\textbf{Minimize}: \sum_{l \in pathP} \beta^{usage(l)} \tag{2.13}$$

subject to

$$\sum_{l \in pathP} ASEnoise(l) < threshold \tag{2.14}$$

Note that PABR only considers ASE noise. The algorithm's basic idea, however, could be extended to include all linear impairments, such as Polarization Mode Dispersion. The nonlinear impairments, on the other hand, would not be possible to estimate in a distributed environment due to their requirement of global traffic knowledge.

PABR also considers signal quality when making the wavelength selection. It accomplishes this by removing from consideration all wavelengths with an unacceptable signal quality level. The approach is called Quality First Fit and it is discussed in the following section.

It should also be noted that both LORA and PABR can be implemented with either single-probing or multi-probing. The maximum number of probes p is denoted as LORA-p or PABR-p. With single-probing, only one path is selected by the route selection. With multi-probing, multiple paths are attempted in parallel, increasing the probability of connection success.

The Impairment Aware Best Fit (IA-BF) algorithm was proposed in [19]. This algorithm is a distributed approach that is dependent upon a large amount of communication to use global information to always pick the shortest available path and wavelength. This is accomplished through the use of serial multi-probing. The shortest available path and wavelength are attempted first, and upon failure, the second shortest available path and wavelength are attempted. This process continues until a successful path and wavelength have been found or all wavelengths have been attempted.

The multi-probing approach will allow IA-BF to outperform both PABR-1 and LORA-1. However, as the number of probes increases to 4, the performance of the algorithms is similar. With more than 8 probes, PABR and

Algorithm 3 Physically Aware Backward Reservation Algorithm (PABR)

```
while H is not empty do
    P = FirstElement(H)
    if P==D then
        if number of paths in the result buffer < required number then
            put the path from S to D in the result buffer
        else
            return result buffer
        end if
    else
        for each adjacent node a_i of P do
            if a_i ∉ S → P && ASE(S → a_i) < threshold then
                a_i.parent = P
                a_i.cost = P.cost + β^{usage(P->a_i)}
                insert a_i into H
            end if
        end for
    end if
end while
```

LORA both outperform IA-BF. Some simulation results are presented in the following Chapter.

Algorithm 4 Impairment Aware Best Fit (IA-BF)

```
 1. for each wavelength w do
 2.     cost(w) = shortest path in w
 3. end for
 4. m = index with minimum value in cost
 5. send probe message using wavelength m to destination to estimate
    signal quality
 6. if response is acceptable then
 7.     reserve network resources and establish connection
 8. else
 9.     if additional wave available then
10.         Goto Step 4
11.     else
12.         Connection Request Fails
13.     end if
14. end if
```

Impairment Aware First Fit (IA-FF) is a simple extension of IA-BF. [19] Instead of picking the wavelengths in terms of the minimum cost, the wavelengths are selected in order according to their index. IA-BF tends to outperform IA-FF under most scenarios.

Adaptive Quality of Service (AQoS) was proposed in [12]. This algorithm is unique in a couple of ways. First, each node maintains two counters: N_{BER} and N_{wave}. The purpose of each counter is to determine which issue is a bigger factor in blocking: Path and wavelength availability or Quality requirements. The algorithm chooses routes differently based upon the larger issue.

Another distinction is that AQoS uses the Q-factor as the link cost. The cost of the i_{th} link is calculated by this formula

$$D_i = \frac{\sum_{j=1}^{N_i} 10 \log[Q_{i,j}^{(s)}/Q_{i,j}^{(d)}]}{N_i} \tag{2.15}$$

where N_i is the number of lightpaths on the i_{th} link, $Q_{i,j}^{(s)}$ and $Q_{i,j}^{(d)}$ are the Q-factor measurements of the j_{th} lightpath at the source and destination nodes of the i_{th} link, respectively. The repeated Q-factor estimations are computationally very expensive.

Algorithm 5 Adaptive Quality of Service (AQoS)

1. Initialize link costs
2. Initialize both N_{BER} and N_{wave} for all nodes
3. For all connection requests, consider N_{BER} and N_{wave}
4. If $N_{BER} \geq N_{wave}$, select the route that gives the least Q-degradation
5. Else if $N_{BER} < N_{wave}$, calculate the k shortest paths and choose the path with the most available wavelengths.
6. If the request is successful, accept it. Update the link weights.
7. If the request is not successful, block it. Update both $N_{BER} \geq N_{wave}$.
8. When the connection is finished, update the link weights.

This algorithm is single probing approach. The multi-probing approach, which the paper names ALT-AQoS (Alternate AQoS) is a simple extension upon the same basic idea.

2.6 Wavelength Assignment

Two of the most common methods for wavelength assignment are First Fit and Random Fit. First Fit chooses the available wavelength with the lowest index. Random Fit determines which wavelengths are available and then chooses randomly amongst them. The complexity of both algorithms is $O(w)$, where w is the number of wavelengths. First Fit outperforms Random Fit.

An extension to First Fit and Random Fit was proposed in [5] to consider signal quality. Quality First Fit and Quality Random Fit eliminate from consideration wavelengths which have an unacceptable signal quality. The complexity of these algorithms is higher though, as up to w calls to estimate the Q-factor are required.

There are several other wavelength assignment algorithms: Least Used, Most Used, Min Product, Least Loaded, Max Sum [21], and Relative Capacity Loss [22]. Most Used outperforms Least Used use significantly, and slightly outperforms First Fit [22]. Min Product, Least Loaded, Max Sum, and Relative Capacity Loss all try to choose a wavelength that minimizes the probability that future requests will be blocked.

A significant disadvantage of these algorithms is that they require a significant communication overhead, making them unpractical to implement unless you have a centralized network structure.

2.7 Joint Routing and Wavelength Assignment

An alternate approach to selecting a route and wavelength separately is to consider them jointly. These approaches tend to more theoretical and not very practical. As this is a NP-complete problem, any exact solution is likely not be possible. The approximation techniques usually aren't very useful either, as they will require centralized control and, usually, predefined traffic demands. Two joint approaches are ILP formulation and Island Hopping.

The ILP formulation listed in Section 2.2 can be solved using a traditional ILP solver. This is typically done by temporarily relaxing the integer constraints, solving the problem optimally, and converting the real solution to a integer solution. Additional constraints can be added and the process repeated indefinitely using a branch and bound approach.

Another approach presented in [23] is called Island Hopping and Path Coloring. This paper does not attempt to solve RWA but gives solutions for two related problems: fiber minimization (MinFib) and hop minimization (MinHop).

It is often the case that multiple fibers exist between two optical nodes, but only a subset of the fibers are actually in use. This is due to economics: the cost of laying each additional fiber after the first is minimal, but the cost deploying the electronics necessary for each fiber is high. The goal of MinFib is thus to minimize the total number of fibers required to meet a traffic demand. MinFib has only limited applicability to RWA.

Optical switches are categorized by a degree which measures their ability to switch optical signals [24]. If the degree of the switch is too low, then an OEO conversion is required for some connections. MinHop is an algorithm that segregates the network into transparent islands. Each transparent island can switch optical signals without an OEO conversion, but each hop between islands would require an OEO conversion. The goal of MinHop is to minimize the number of hops, i.e. OEO conversions.

In [23], several proofs are given to show the complexity of MinHop using a graph theory apporach. While it is trivial to $O(n)$ approximate MinHop, it is difficult to do much better. With the increasing degree of optical switches, this problem is becoming less important. Future networks will have full switching capabilities, so OEO conversions will not be necessary. [24] That being said, it is believed that several of the approaches present to solve MinHop might be extendable to the RWA problem.

Chapter 3

Current Work

This section details the work I have already completed in regards to RWA. I have made progress in developing a software package for RWA simulation with promising results. I have extended some existing algorithms from single-probing to multi-probing.

3.1 RAPTOR

RAPTOR (Routing Assignment Program for Transparent Optical Routes) is a software package that I developed for simulating optical networks. The program is highly flexible and can be extended to run most RWA algorithms with minimal work. Early results show that RAPTOR is also very fast, which should allow it to run larger and more complex scenarios.

Originally, the plan was to use Opnet [27] for our optical simulations. Opnet was very inflexible and proved too be very CPU and memory intensive. These issues effectively prevented us from using Opnet for optical simulations for large optical networks. Setting up and modifying the simulation was also very tedious with Opnet. The decision was thus made to develop our own simulator: RAPTOR.

RAPTOR is a custom built application using mostly ANSI C++. There are approximately 6,550 lines of source code, of which 2,800 lines are header files. The program has been compiled and tested using Microsoft Visual Studio .NET 2003 on Windows XP and g++ version 4.1.2 on Red Hat 4.1.2, although it is believed that RAPTOR will run on any platform with a C++ compiler and the appropriate libraries. There are only 3 external dependencies required to run: Boost, Matlab, and PThreads.

Boost is a freely available, peer reviewed library written in C++. Boost provides a large array of functionality, such as a sophisticated graph library and a matrix library, however, RAPTOR only uses the random number generation. Boost is available on almost any modern operating system. We used version 1.34 in our simulation, however, I believe that any recent version of Boost is sufficient. [25]

Matlab is a commercially available mathematical computing environment and programming language maintained by MathWorks, Inc. Several of the Q-factor calculations are written in Matlab, so their compiler is required to create a library used by RAPTOR. Once the library is compiled, the freely available Matlab Component Runtime library is sufficient to run the application. We used versions R2007a (7.4.0) and R2007b (7.5.0) in our simulation, however I believe that any recent version of Matlab is sufficient. [26]

POSIX Threads, or PThreads, is a library used to create and manipulate threads. PThreads are most commonly used in Linux, however versions are available for Windows as well. RAPTOR utilizes PThreads to run on multi-core machines and to mutex lock certain critical sections of the program.

KShortestPath is a library used to calculate the k-shortest-paths using Yen's Ranking Loopless Paths Algorithm. [20] This library is written completely in ANSI C++ and can be distributed freely with RAPTOR. The worse case running time is $O(kn(m + n \log n))$.

Efficiency was a large concern when designing RAPTOR. In our previous network simulations, we used Opnet. [27] Opnet simulations were slow and memory intensive, making large and complex simulations impossible. On the 24 node mesh network presented in [19] the SP algorithm with First Fit wavelength assignment (SP-FF) runs in 143 minutes using Opnet and just 8 minutes using RAPTOR. This represents a 94.4% reduction in run time.

The memory requirements have also been dramatically reduced. The SP-FF algorithm required over 715 MB of RAM, while RAPTOR required only 25 MB. This is a 96.5% reduction in memory usage. This efficiency, both in run time and memory usage, will permit us to run larger and more complex scenarios in the future.

RAPTOR has achieved even further performance gains using multi-threading. RAPTOR creates t threads, where t is a user configurable number. Each thread is tasked with a single data point (an algorithm and traffic load) until all traffic loads for all algorithms are completed. To test the multi-threading efficiency, I ran several tests on a 8 core machine within the department. Table 3.1 is included detailing the results.

The first column lists that number of threads. The next column gives the total run time in seconds for SP-FF, SP-Random, LORA-FF, LORA-

Threads	Total Run Time (sec)	Average Run Time (sec)	Speedup
1	2290.7	381.78	1.000
2	1187.7	197.94	1.929
3	827.3	137.89	2.769
4	667.0	111.17	3.434
5	553.0	92.17	4.142
6	494.0	82.33	4.637
7	443.0	73.83	5.171
8	398.0	66.33	5.756

Table 3.1: Multi-threading Performance

Random, PABR-FF, and PABR-Random. The following column is the average run time in seconds per algorithm. Finally, the last column gives the speed up factor.

There are several reasons why the speed up with multi-threading is less than optimal. The first reason is that threading results in some overhead. There are also some portions of the code that can not be multi-threaded. Also, in most cases, it is not possible to distribute the data points perfectly evenly, so some threads end up being tasked with more work than others.

RAPTOR is capable of providing accurate estimates of the Q-factor, based upon the framework presented in [28]. This is accomplished through estimations of ASE noise, Cross Phase Modulation, and Four Wave Mixing. Our analytical models have been shown to be very accurate.

Other nonlinear effects, such as Self Phase Modulation and Polarization Mode Dispersion are not considered. This is due to the complexity of their calculation. If more efficient modules were developed for these effects, they would easily fit within our framework.

The SP, LORA, PABR, and IA algorithms have all been implemented in RAPTOR. SP and LORA were implemented with the First Fit and Random wavelength assignment algorithms. PABR was implemented with the Quality First Fit and Quality Random Fit wavelength assignment algorithms. IA was implemented using both the Best Fit and First Fit wavelength assignment algorithms.

The First Fit wavelength assignment algorithm outperformed the Random fit for SP, LORA, and PABR. It should be noted that all the results presented for SP, LORA, and PABR include only the First Fit results; the Random results are omitted.

There are 3 causes of connection blocking: collisions, bad quality, and no

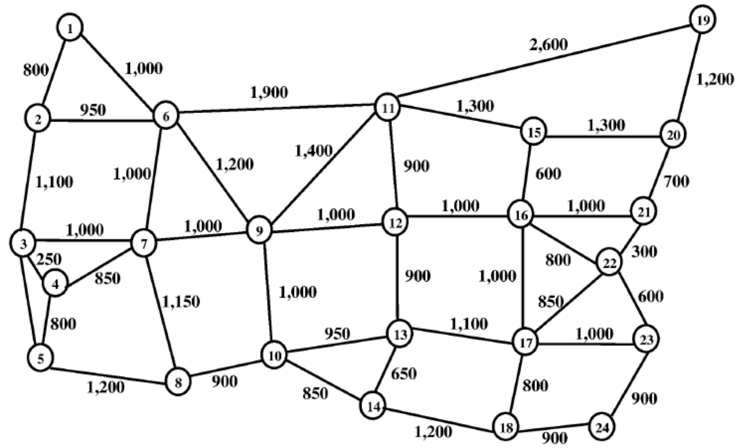


Figure 3.1: Mesh network

resources. Collision blocking occurs when two connection requests attempt to reserve the same resource simultaneously. No Resource blocking occurs when there is no valid path and/or wavelength available. Bad Quality blocking occurs when there is a valid path and wavelength, however, the signal quality is insufficient.

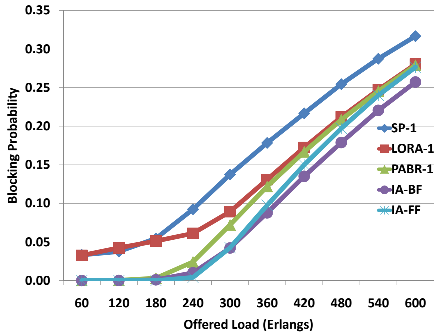
All of the results discussed in this paper use a mesh-type network that was taken from [19] and shown in Figure 3.1. This is a 24 node, 43 edge network and is roughly the size of the United States. EDFAs were required every 80 km. All edges were assumed to be bi-directional. In other words, an edge between a and b implies there is also an edge between b and a.

Workstations are distributed randomly and uniformly across the network. Each workstation adds one Erlang of traffic using a Poisson process. Each workstation generates a request every 150 seconds, on average. Each connection request has a duration of 150 seconds, on average.

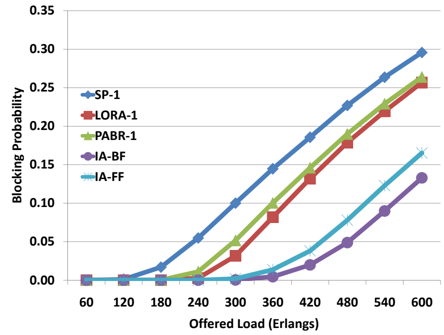
The IA algorithms outperformed SP, LORA, and PABR. This is caused primarily by IA's ability to search multiple paths through the use of serial multi-probing. Due to the serial nature of the multi-probing, both IA algorithms have the highest average connection delay time. For applications where delay is more important than the bandwidth, this could become problematic.

The Non Resource blocking is clearly the dominant factor in overall blocking. The IA algorithms have a much lower Non Resource blocking, but a higher Bad Quality blocking for large traffic loads. The IA algorithms are better at finding a path, however, this leads to a greater percentage of the paths having a Bad Quality.

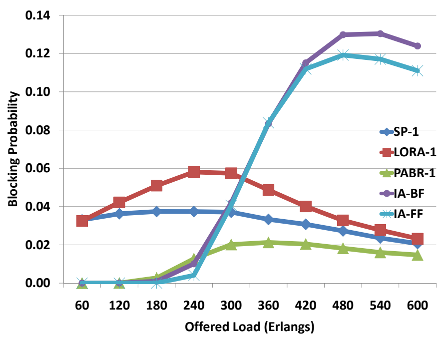
The collision blocking is rather insignificant. The IA algorithms are capable of reducing the collision errors through the use of multi-probing.



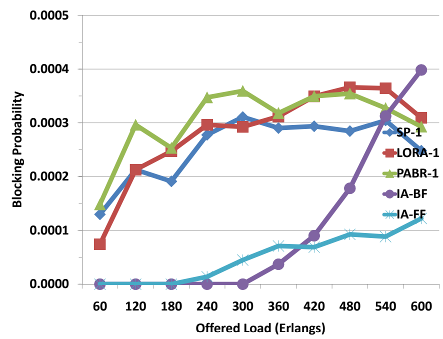
(a) Overall Blocking



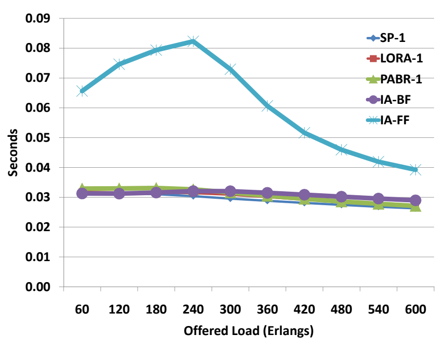
(b) Non Resource Blocking



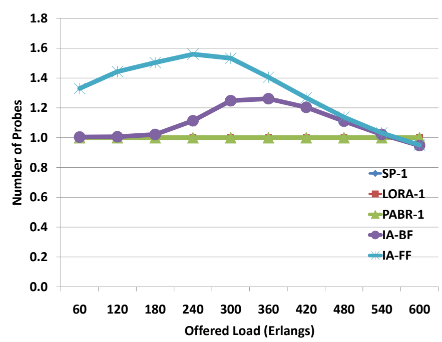
(c) Bad Quality Blocking



(d) Collision Blocking



(e) Average Delay Time



(f) Average Probe Count

Figure 3.2: Single Probing Results

The average number of probes per connection request shows that the SP, LORA, and PABR algorithms are indeed single probing. The IA algorithms send more than one probe per request on average. At higher traffic loads, the IA algorithms may send slightly less than 1 probe per request on average. This is due to cases where there is no such path to test, the connection request fails without any probes being sent.

The results presented from RAPTOR were compared against the results from Opnet to guarantee the correctness of our implementation. In each case, the overall blocking probabilities from RAPTOR were within one standard deviation of the Opnet results.

3.2 Multi-probing

The results presented in the previous section show that the IA-BF and IA-FF algorithms outperformed the SP-1, LORA-1, and PABR-1 algorithms. One of the reasons for this is that the IA algorithms are multi-probing. This means that for each connection request, multiple probes will be sent out serially until either one succeeds or the probe limit has been reached. The SP-1, LORA-1, and PABR-1 algorithms are single probing, so if the first probe fails, the connection request will fail.

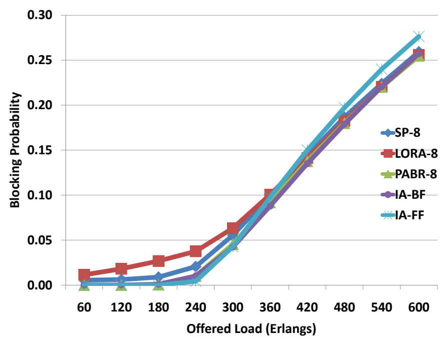
I implemented a parallel multi-probing capability with SP-p, LORA-p, and PABR-p. For each connection request, there will be up to p probes messages sent in parallel, where p is a configurable parameter. Parallel multi-probing will reduce the overall connection delay time, however, parallel multi-probing will send more probes in total than serial multi-probing.

With multi-probing, both LORA-8 and PABR-8 outperform the IA algorithms. Even SP-8 is close to beating the IA algorithms. There really is very little distinction between the various algorithm's performance at this level of multi-probing. Note that the parallel multi-probing used by SP, LORA, and PABR do not adversely effect the average connection delay time. The IA algorithms, especially IA-FF, have a much higher delay.

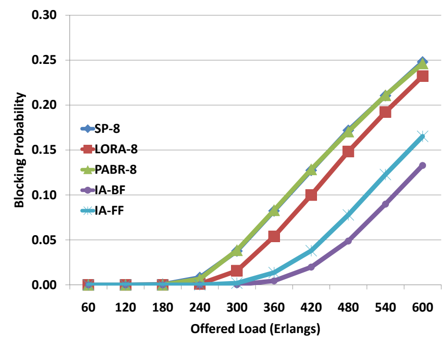
The multi-probing reduces blocking probability primarily by reducing the Non Resource blocking. The Bad Quality blocking is also reduced, but not significantly.

The multi-probing also nearly eliminates the collisions for SP, LORA, and PABR. The IA algorithms still have a small amount of collisions, but they are a very minor contribution to the total blocking probability.

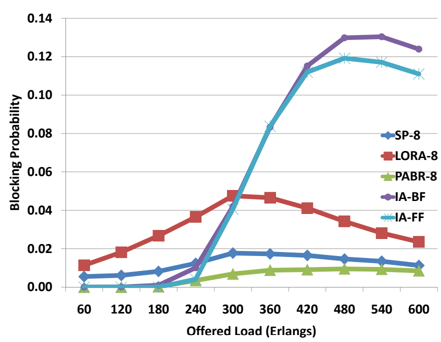
The average number of probes per connection request shows that PABR, LORA, and SP all have a much higher probing overhead than IA. PABR-8



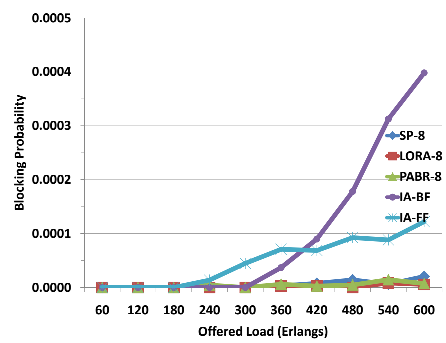
(a) Overall Blocking



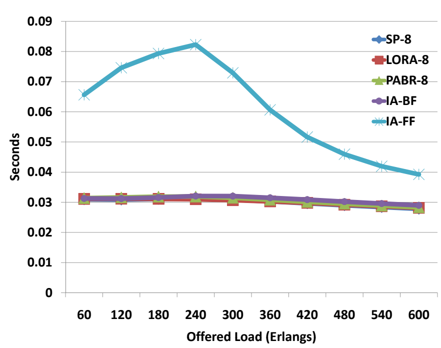
(b) Non Resource Blocking



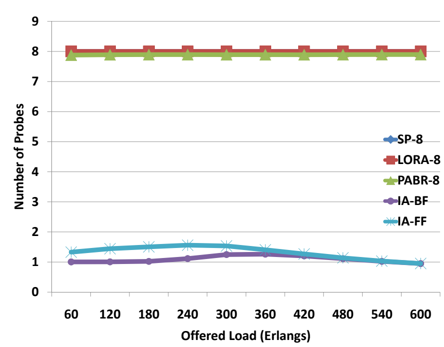
(c) Bad Quality Blocking



(d) Collision Blocking



(e) Average Delay Time



(f) Average Probe Count

Figure 3.3: Multi Probing Results

sends a little less than 8 probes per connection request on average, as some of the longer connections have less than 8 paths with an acceptable ASE noise level.

The multi-probing results from RAPTOR were not validated against other results (as I did with the single-probing results) since there was no source to compare them against. Great care was taken to ensure that the implementation is correct, and I am confident that the results presented here are accurate.

Chapter 4

Future Work

This chapter begins with a clear definition of the goals of this research project: improved physically aware RWA algorithms and a new software package. The remainder of this chapter details approaches to meet these goals. To the best of my knowledge, the ideas presented below have not been used previously in optical networking. While this document details my plan of attack as of now, it is very likely that as I am working on this problem new ideas will likely be developed.

4.1 Research Goals

The goal of this research is to improve the state of the art in all-optical network communications by improving Routing and Wavelength Assignment (RWA) algorithms to consider a wide range of physical impairments in real-life networks. Most existing algorithms do not consider any physical impairments, which can have a tremendous impact upon the Quality of Service (QoS).

The performance of the existing algorithms seems insufficient. As detailed in the previous section, with multi-probing SP, LORA, PABR, and IA all perform similarly. I believe that a more sophisticated algorithm will be able to outperform these simpler approaches.

A secondary goal of this research is the development of a software testbed that can be used to test RWA algorithms and their effectiveness. The testbed should be highly flexible and include modules to provide a reasonable estimate of signal quality. The testbed should also be available on multiple platforms. Along with some documentation, the software package should be available for free distribution to others interested in optical networking.

4.2 Multi-probing Path Diversity

While multi-probing has been shown to be effective at reducing the blocking probability of SP, LORA, and PABR, there are some drawbacks. The current implementation simply sends probes along the p shortest paths, where p is a tunable parameter set to the maximum probes per connection request. It is likely that each of the probes takes a similar path. If one probe fails, then other probes are more likely to fail as well given their similarity.

It was stated in [16] that each of the p paths should be edge-disjoint. I do not believe this to be an appropriate solution, as this approach will eliminate too many candidate light paths.

An improvement might be to calculate more than p paths, say $2p$ paths and then prune half of the paths. This pruning should be done in a manner to maximize the diversity of paths, which should thus increase the likelihood of finding a successful path.

Another idea might be to calculate the shortest path, then remove the most congested edge in the graph, and then calculate the shortest path. This process can be repeated until the p paths have been selected.

4.3 Multi-probing DSR-style

Another approach to increase the efficiency of multi-probing would be to implement a DSR-style route discovery. DSR is a well-known ad hoc wireless mesh network route discovery protocol first described in [29]. This approach would greatly simplify the routing decision (as there would no longer need to be any calls to a shortest path algorithm), while increasing the probing overhead.

Optical networks are relatively small, so the increased probing overhead should be manageable. While pruning is an inherent part of DSR, a more intelligent probe pruning could be used to reduce this overhead further. For example, probes whose path is so long that the ASE noise itself is to high could be pruned. Probes whose paths have no available wavelengths could be pruned.

4.4 First Fit with Ordering Wavelength Assignment

First Fit with Ordering (FFwO) wavelength assignment was first proposed in [30]. The wavelengths are ordered such that the frequency separation by spectrum distance is maximal. It has been shown that this approach increases the probability that the first wavelength considered will have acceptable quality and will reduce the total number of wavelengths considered.

I would like to implement the FFwO wavelength assignment algorithm to test its impact upon SP, LORA, and PABR.

4.5 Least Quality Wavelength Assignment

Most-used (MU) is a well known wavelength assignment algorithm that tends to perform well [31]. In the wavelength assignment, preference is given to the wavelengths that have been assigned to the most links. The general idea is that this approach will result in a tighter wavelength assignment, leaving more resources available for future network connection requests. This does require more information than FF which unfortunately makes it implementation in a dynamic network more difficult.

I would like to propose a Least-Quality (LQ) wavelength assignment algorithm. Using LQ, preference would be given to the wavelength with the lowest, but still acceptable, signal quality. The idea is that this would also lead to a tighter wavelength assignment, similar to the MU approach. This would not require any additional information, so it would be a realistic approach in a dynamic optical network.

4.6 Distributed Island Hopping

Island hopping is proposed in [23]. This approach appears to be a very effective algorithm, however, it has some drawbacks which make it impractical for dynamic optical networks. The algorithm is a centralized approach where the traffic demands are known *a priori*. Island hopping also does not consider signal quality.

I would like to implement the original Island hopping technique to determine its performance against other algorithms. If the algorithm performs well, I believe it would be very worthwhile to investigate the possibilities of a more distributed implementation of the algorithm which considers signal quality.

4.7 Adaptive QoS

Adaptive QoS is an interesting algorithm proposed in [12]. I did not have time to implement this algorithm before preparing this proposal, however I would like to do so in the future. I would like to compare the performance of this algorithm against the others. Implementation may also provide insight on how to improve this algorithm.

4.8 Temporal Behavior

Most studies of RWA algorithms make unrealistic traffic assumptions, such as a uniform traffic load. In real optical networks, specific areas of the network will be more used than others. I believe that some algorithms will perform significantly better than others in these unbalanced traffic scenarios.

The Q-factor also varies over time. The RWA algorithms that are quality aware typically only consider the Q-factor at the beginning of the connection. As future connections are dropped and added, the Q-factor will surely fluctuate. I would like to study the temporal aspects of Q-factor and determine the performance distinction between the various RWA algorithms.

4.9 Research Plan

Below is the estimated plan for my research. This plan will almost certainly change. Along the way, I also plan on submitting papers to conferences/journals with my results. The goal is at least 2-3 papers in submission by the end of the year.

- April 2009: Implement AQoS algorithm and Pass Comprehensive Examination
- May 2009: Multi-probing ideas (both diversity and DSR)
- June 2009: Wavelength assignment ideas (both ordered-first-fit and least quality)
- July 2009: Distributed Island Hopping ideas plus new ideas
- August & September 2009: Complete work on new ideas and begin to work on paper(s) for a journal or conference
- October 2009: Temporal behavior, begin Ph.D. dissertation
- November 2009: Complete Ph.D. dissertation
- December 2009: Defend Ph.D. dissertation

Bibliography

[1] J. Berthold, A. Saleh, L. Blair, and Jane Simmons, "Optical Networking: Past, Present, and Future," *Journal of Lightwave Technology*, Vol 26, No 9, pp. 1104-1117, May 2008.

[2] Wikipeda, the Free Encyclopedia, http://www.wikipedia.org/

[3] A. Kaheel, T. Khattab, A. Mohamed, and H. Alnuweiri, "Quality-of-service mechanisms in IP-over-WDM networks," *IEEE Communications Magazine*, Vol 44, No 12, pp 38 - 43, December 2002.

[4] B. Ramamurthy, D. Datta, H. Feng, J. Heritage, B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routered optical networks," *Journal of Lightwave Technology*, Vol 17, pp 1713 - 1723, October 1999.

[5] W. Lin, "Physically Aware Agile Optical Networks," Ph.D. Dissertation, Montana State University, Bozeman, July 2008.

[6] G. Agrawal, "Nonlinear Fiber Optics," New York, NY: Academic Press, 2007.

[7] G. Agrawal, "Lightwave Technology: Telecommunication Systems," Hoboken, NY: Wiley, 2005.

[8] A. Marsden, A. Maruta, and K. Kitayama, "Routing and Wavelength Assignment Encompassing FWM in WDM Lightpath Networks," Proceedings of IFIP ONDM 2008, Vilanova i la Geltr, Spain, Mar. 2008.

[9] T. Jackson, T. Hahn, W. Lin, R. Wolff, and B. Mumey, "EDFA Transient Reduction Using Power Shaping," Proceedings of IASTED WOC 2008. Quebec City, 2008.

[10] R. Wolff, B. Mumey, W. Lin, T. Jackson, T. Hahn, "Bit Error Rate Reduction by Power Shaping in WDM Networks with EDFAs," Optical Fiber Technology. (in submission)

[11] Y. Pointurier, M. Brandt-Pearce, and S. Subramaniam, "Analysis of Blocking Probability in Noise and Crosstalk Impaired All-Optical Networks," Proceedings of IEEE Infocom 2007, pp. 2486-2490, Anchorage, Alaska, May 2007.

[12] T. Deng and S. Subramaniam, "Adaptive QoS Routing in Dynamic Wavelength-Routed Optical Networks," Broadband Networks 2005, pp. 184-193, 2005.

[13] G. Agrawal, "Fiber-optic Communication Systems," 3rd Edition, Wiley-Interscience, pp 164, 2002.

[14] J. He, M. Brandt-Pearce, Y. Pointurier, and S. Subramaniam, "QoT-Aware Routing in Impairment-Constrained Optical Networks," Proceedings of IEEE Globecomm 2007, pp. 2269 - 2274, Washington, DC, 2007.

[15] J. He, M. Brandt-Pearce, and S. Subramaniam, "Connection Provisioning in QoT-Guaranteed Distributed All-Optical Networks," Broadband Communications, Networks and Systems, pp. 820 - 827, September 2007.

[16] H. Zang, J. Jue, and B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength Routed Optical WDM Networks," *Optical Networks Magazine*, January 2000.

[17] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: an approach to high bandwidth optical WAN's," *IEEE Transactions on Communications*, Vol 40, No 7, pp. 1171-1182, July 1992.

[18] S. Evan, A. Itai, and A. Shamir, "On the Complexity of Timetable and Multicommodity Flow Problems," SIAM Journal of Computing, Vol 5, pp 691-703, 1976.

[19] Y. Huang, J. Heritage, and B. Mukherjee, "Connection Provisioning With Transmission Impairment Consideration in Optical WDM Networks With High-Speed Channels," *Journal of Lightwave Technology*, Vol 23, No 3, March 2005.

[20] M. Pascoal and E. Martins. "A new implementation of Yens ranking loopless paths algorithm." 4OR Quarterly Journal of the Belgian, French and Italian Operations Research Societies, 2003.

[21] R. Barry and S. Subramaniam, "The MAX-SUM Wavelength Assignment Algorithm for WDM Ring Networks," Proceedings of Optical Fiber Conference, February 1997.

[22] X. Zhang and C. Qiao, "Wavelength Assignment for Dynamic Traffic in Multi-Fiber WDM Networks," Proceedings of International Conference on Communications, Vol 1, pp 406-410, June 1997.

[23] A. McGregor and B. Shepherd, "Island hopping and path colouring with applications to WDM network design," Proceedings of the ACM-SIAM symposium on Discrete algorithms, pp 864 - 873, New Orleans, LA, 2007.

[24] R. Shankar, M. Florjanczyk, T. Hall, A. Vukovic, and H. Hua, "Multi-degree ROADM based on wavelength selectrive switches: Architectures and scalability," *Optical Communications*, Vol 279, Issue 1, pp. 94-100, 2007.

[25] Boost C++ Libraries, http://www.boost.org/

[26] Matlab, http://www.mathworks.com/products/matlab/

[27] OPNET Technologies - Making Networks and Applications Perform, http://www.opnet.com/

[28] W. Lin, T. Hahn, R. Wolff, and B. Mumey, "A Distributed Impairment Aware QoS Framework for All-Optical Networks," *Optical Switching and Networking*, (currently in submission)

[29] D. Johnson, "Routing in Ad Hoc Networks of Mobile Hosts," Proceedings of the Workshop on Mobile Computing Systems and Applications, pp. 158-163, IEEE Computer Society, Santa Cruz, CA, December 1994.

[30] J. He and M. Brandt-Pearce, "RWA using wavelength ordering for crosstalk limited networks." Proceedings of the IEEE/OSA Optical Fiber Conference, Anaheim, CA March 2006.

[31] J.M. Simmons, *Optical Networking Design and Planning*, Norweel, MA: Springer, 2008.