Resource Allocation in Survivable WDM Networks Under a Sliding Scheduled Traffic Model

Ying Chen
University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation
https://scholar.uwindsor.ca/etd/7862

This online database contains the full-text of PhD dissertations and Masters’ theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email (scholarship@uwindsor.ca) or by telephone at 519-253-3000ext. 3208.
RESOURCE ALLOCATION IN SURVIVABLE WDM NETWORKS UNDER A SLIDING SCHEDULED TRAFFIC MODEL

BY

YING CHEN

FACULTY OF GRADUATE STUDIES
UNIVERSITY OF WINDSOR
2009
Resource Allocation in Survivable WDM Networks Under a Sliding Scheduled Traffic Model

By

Ying Chen

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

Windsor, Ontario, Canada

2009

© 2009 Ying Chen
Resource Allocation in Survivable WDM Networks Under a Scheduling Traffic Model

LEDL
THES
Thesis
2009
.0467
Resource Allocation in Survivable WDM Networks Under a Sliding Scheduled Traffic Model

by

Ying Chen

APPROVED BY:

Dr. Kevin W. Li, External Examiner,
Odette School of Business

Dr. Dan Wu, Internal Examiner,
School of Computer Science

Dr. Arunita Jaekel, Supervisor,
School of Computer Science

Dr. Alioune Ngom, Chair of Defense,
School of Computer Science

May 8, 2009
Declaration of Co-Authorship / Previous Publication

I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is a result of joint research undertaken in collaboration with my supervisor, Dr. Arunita Jaekel. The collaboration is covered in Chapters 3-5 of the thesis.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

II. Declaration of Previous Publication

This thesis includes one original paper that has been previously published/submitted for publication in peer reviewed journals, as follows:

<table>
<thead>
<tr>
<th>Thesis Chapter</th>
<th>Publication title/full citation</th>
<th>Publication status</th>
</tr>
</thead>
</table>

I certify that I have obtained a written permission from the copyright owner(s) to include the above published material(s) in my thesis. I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone’s copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University of Institution.
Abstract

In recent years there has been an increasing number of applications that require periodic use of lightpaths at predefined time intervals, such as database backup and on-line classes. A new traffic model, referred to as the scheduled traffic model, has been proposed to handle such scheduled lightpath demands. In this thesis we present two new integer linear program (ILP) formulations for the more general sliding scheduled traffic model, where the setup and teardown times may vary within a specified range. We consider both wavelength convertible networks and networks without wavelength conversion capability. Our ILP formulations jointly optimize the problem of scheduling the demands (in time) and allocating resources for the scheduled lightpaths. Simulation results show that our formulations are able to generate optimal solutions for practical sized networks. For larger networks, we have proposed a fast two-step heuristic to solve the demand scheduling problem and the RWA problem separately.
Dedication

To my parents, Wenzheng and GuiQin, my husband, Ziyi, and my daughter, Christina.

I would like to express my deep appreciation to my supervisor, Dr. Arunita Joekel. This work could not have been achieved without her guidance, generous support and continuing encouragement.

I would like to thank Dr. Kevin W. Li, Dr. Dan Wu and Dr. Alboune Ngom for their valuable time and constructive comments.

My special thanks to my husband and my daughter for their endless love, care and understanding. They are always the source of support and encouragement.
Acknowledgements

I would like to express my deep appreciation to my supervisor, Dr. Arunita Jaekel. This work could not have been achieved without her guidance, generous support and continuing encouragement.

I would like to thank Dr. Kevin W. Li, Dr. Dan Wu and Dr. Alioune Ngom for their valuable time and constructive comments.

My special thanks to my husband and my daughter for their endless love, care and understanding. They are always the source of support and encouragement.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declaration of Co-Authorship / Previous Publication</td>
<td>iii</td>
</tr>
<tr>
<td>Abstract</td>
<td>iv</td>
</tr>
<tr>
<td>Dedication</td>
<td>v</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>vi</td>
</tr>
<tr>
<td>List of Tables</td>
<td>x</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xi</td>
</tr>
<tr>
<td><strong>1. INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1. Problem statement</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Motivations</td>
<td>2</td>
</tr>
<tr>
<td>1.3. Solution Outline and Contributions</td>
<td>3</td>
</tr>
<tr>
<td>1.4. Thesis Organization</td>
<td>5</td>
</tr>
<tr>
<td><strong>2. BACKGROUND INFORMATION</strong></td>
<td>6</td>
</tr>
<tr>
<td>2.1. Physical Topology and Logical Topology</td>
<td>6</td>
</tr>
<tr>
<td>2.2. Computation Complexity of the RWA problem</td>
<td>8</td>
</tr>
<tr>
<td>2.4. Fault-tolerance in Optical Networks</td>
<td>13</td>
</tr>
<tr>
<td><strong>3. RESOURCE ALLOCATION UNDER THE SLIDING</strong></td>
<td></td>
</tr>
<tr>
<td>3.1. Network Model</td>
<td></td>
</tr>
<tr>
<td>3.2. The Dedicated Protection with Wavelength Conversion</td>
<td></td>
</tr>
<tr>
<td>3.3. The Dedicated Protection without Wavelength Conversion</td>
<td></td>
</tr>
<tr>
<td>3.5. Handle Fault-free Networks</td>
<td>32</td>
</tr>
<tr>
<td><strong>4. TWO-STEP DESIGN HEURISTIC</strong></td>
<td>34</td>
</tr>
<tr>
<td>vesi</td>
<td></td>
</tr>
</tbody>
</table>
2.1. Physical Topology and Logical Topology

2.2. Computation Complexity of the RWA problem

2.3. Traffic Models

2.4. Fault-tolerance in Optical Networks

3. RESOURCE ALLOCATION UNDER THE SLIDING SCHEDULED TRAFFIC MODEL

3.1. ILP Formulations

3.1.1. Network Model

3.1.2. ILP Variables

3.1.3. Conditions of Demands Overlapping

3.2. ILP for Dedicated Protection with Wavelength Conversion (ILP-D1)

3.3. ILP for Shared Protection with Wavelength Conversion (ILP-S1)

3.4. Dedicated and Shared Protection without Wavelength Conversion (ILP-D2 and ILP-S2)

3.5. Handle Fault-free Networks

4. TWO-STEP DESIGN HEURISTIC
4.1. Demand Scheduling 34

4.2. RWA of Scheduled Demands Without Wavelength Conversion 35

4.3. RWA of Scheduled Demands With Wavelength Conversion 38

5. EXPERIMENTS AND RESULTS 40

5.1. Simulation Parameters 40

5.2. Comparison of the Number of Integer Variables 44

5.3. Results of ILP Formulations 47

5.4. Results of Heuristic Approach 50

6. CONCLUSION AND FUTURE WORK 54

6.1. Future Work 55

6.1.1. Resource Allocation under the Non-continuous Model 55

6.1.2. Resource Allocation using light-trails 56

Bibliography 58

Vita Auctoris 62
List of Tables

Table 1  Number of Integer Variables for ILP Formulations for wavelength convertible networks

Table 2  Increase of integer variables with problem size
List of Figures

Figure 1    Some lightpaths on the physical topology 7
Figure 2    Logical topology $G_L$ corresponding to the lightpath shown in Figure 1 7
Figure 3    An example of routing under the fixed window scheduled traffic model and the sliding traffic model 12
Figure 4    A categorization of fault management schemes 14
Figure 5    Shared path protection 15
Figure 6    Dedicated path protection 16
Figure 7    Path protection scheme vs. link protection scheme 17
Figure 8    Non-overlapping windows vs. Overlapping windows 24
Figure 9    Overview of RWA heuristic for scheduled demands without wavelength conversion 37
Figure 10   Overview of RWA heuristic for scheduled demands with wavelength conversion 39
Figure 11   A simple example with four demands 41
Figure 12   Topology of 10-node network 43
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Topology of NSFNET</td>
</tr>
<tr>
<td>14</td>
<td>Increase of integer variables with problem size</td>
</tr>
<tr>
<td>15</td>
<td>Comparison of resource requirements for 14-node wavelength convertible network</td>
</tr>
<tr>
<td>16</td>
<td>Comparison of resource requirements for 10-node network without path protection</td>
</tr>
<tr>
<td>17</td>
<td>Comparison of resource requirements for 10-node network with dedicated protection</td>
</tr>
<tr>
<td>18</td>
<td>Comparison of resource requirements for 10-node network with shared protection</td>
</tr>
<tr>
<td>19</td>
<td>Variation of resource requirements with window size for networks without wavelength conversion</td>
</tr>
<tr>
<td>20</td>
<td>Variation of resource requirements with window size for networks with wavelength conversion</td>
</tr>
<tr>
<td>21</td>
<td>Variation of resource requirements with demand size for 20-node network</td>
</tr>
</tbody>
</table>
### Chapter 1

**INTRODUCTION**

#### 1.1 Problem statement

Wavelength division multiplexing (WDM) optical networks [1] divide the large bandwidth on an optical fiber into different wavelengths. They are an ideal choice for high throughput backbone networks due to some important advantages, such as high speed, high reliability, and low cost. The resource allocation optimization problem in WDM optical networks under static and dynamic traffic models has been widely investigated. However, in recent years there has been an increasing number of applications that require periodic use of lightpaths (e.g. once per day, or once per week) at predefined time intervals. For example, an online "class" with one two-hour lecture per week during a specified time frame on a specified day, or a bank transferring its data to a central location every night between 2am and 4am. The start time and the duration of such traffic requirements are known in advance. This new type of traffic demand is classified as scheduled lightpath demand. A new traffic model, the so-called scheduled traffic model [2], was introduced to handle such scheduled lightpath demands in 2003. In
this model, Routing and Wavelength Assignment (RWA) [3] algorithms take into account the information of the demand setup time and holding time, so the resource allocation problem can be optimized in both space and time dimension, leading to a more efficient utilization of available network capacity. In this thesis we address the resource allocation optimization problem in survivable WDM networks for the more general and flexible sliding scheduled traffic model, where the setup and teardown times may vary within a specified range.

1.2 Motivation

There has been considerable research interest in the area of resource allocation in WDM optical networks. The previous works mainly focus on the RWA problem under the static and dynamic traffic model. A number of integer linear program (ILP) formulations as well as heuristics are available to solve this problem [3]. Recently, the scheduled traffic model has gained more and more research attention. Several approaches for optimal resource allocation under the fixed window model have been presented in the literature [2], [4] – [13]. It has been shown that connection holding time aware approaches consistently outperform traditional RWA algorithms for scheduled lightpath demands [4].

In the fixed window scheduled traffic model, the setup and teardown times of the demands are known in advance. It can be augmented so that the setup and teardown times are no longer fixed, but can slide within a larger window [14], [15]. This is referred to as the sliding scheduled traffic model. The sliding scheduled traffic model provides us more
flexibility, but is also more complex. It deals with jointly scheduling demands in time to minimize demand overlap and allocating resources to lightpaths, and has been typically handled using heuristics in the literature [14], [15], [16].

To design reliable optical networks, fault-tolerance techniques such as the path protection technique [17], are widely used to ensure the network survivability. For the sliding scheduled traffic model, only fault-free networks have been considered in the literature. Even for such fault-free networks, only heuristic solutions have been proposed so far.

In summary, the existing techniques for resource allocation in WDM networks under the sliding scheduled traffic model

i) do not guarantee optimality and

ii) only consider networks without faults.

Unlike the existing techniques, we consider the optimal design of survivable WDM networks, both with and without wavelength conversion capabilities, under the sliding scheduled traffic model.

1.3 Solution Outline and Contributions

In this thesis we present two sets of generalized ILP formulations for designing survivable WDM networks under the sliding scheduled traffic model. The first set is for wavelength convertible networks and the second is for networks without wavelength conversion capabilities. A preliminary version of this approach has been introduced in
We achieve network survivability using both dedicated and shared path protections. As shown in Section 3.5, fault-free networks can be easily handled in our model by simply removing the relevant constraints for backup lightpaths. We also show that the fixed window scheduled traffic model can be treated as a special case of our formulations by resetting the window size, as explained in Section 3.1.3.

The ILPs presented in this thesis are able to provide optimal solutions to the joint scheduling and RWA problem for practical sized networks in a reasonable time. For larger networks, we also propose a simple two-step process, where an efficient ILP formulation is used to first schedule the demands (in time), such that the overlap between demands is minimized. Once this is done, the problem is reduced to the simpler fixed window scheduled traffic model, and the corresponding RWA problem is solved more easily using heuristics. The performance of our proposed heuristic is validated by comparing it with optimal solutions (generated by the ILPs) for smaller networks.

Two main objectives have been considered in the literature for the RWA problem. The first is to minimize the number of wavelength-links. The second is to minimize the congestion of the network (i.e. the number of lightpaths on the most heavily loaded link [2]). Existing ILPs typically minimize the number of wavelength-links required to support a given set of demands. This is important for opaque WDM networks, where a transmitter/receiver is needed for a WDM channel on each fiber link. However, minimizing congestion may be more appropriate in networks that use all-optical lightpaths to support demands, and where the number of wavelengths per fiber is limited. Our formulation provides a generalized scheme, which can be used to minimize either the...
number of wavelength-links or the network congestion, by simply selecting certain parameter values.

The main contributions of this thesis are:

1. Efficient ILP formulations for optimal resource allocation, using dedicated and shared path protection, in WDM networks with full wavelength conversion under the sliding scheduled traffic model.

2. A second set of ILP formulations that address the same problem under the wavelength continuity constraint.

3. Experimental results demonstrating that our approach can generate optimal solutions for practical sized networks such as the 14-NSFNET topology.

4. A two-step heuristic approach, for larger networks, which optimally schedules the demands (in time) and then performs RWA separately.

1.4 Thesis Organization

The remainder of this thesis is organized as follows. Chapter 2 reviews the traffic models for the design of WDM network, as well as the fault-tolerant techniques. Chapters 3 and 4 present our ILP formulations and two-step heuristic. We discuss and analyze our results in Chapter 5 and conclude the thesis with a summary of the original contributions and directions of the future work in Chapter 6.
2.1 Physical Topology and Logical Topology

In wavelength division multiplexing (WDM) optical networks, a set of all-optical lightpaths [19] are set up between pairs of end-nodes. A lightpath is a point-to-point communication path that optically connects a transmitter at a source end-node to a receiver at a destination end-node with no opto-electronic conversion at any intermediate node in the route from the source to the destination of the communication. A logical topology, also called a virtual topology, can be established above the physical topology by setting up a set of lightpaths to meet all the network traffic requirements. A logical (or virtual) edge, $e_i \rightarrow e_j$, is a directed link in the logical topology if there is a lightpath from end-node $e_i$ to end-node $e_j$.

Figures 1 and 2 are taken from [20]. Figure 1 shows the physical topology of a small-size optical network with four end-nodes and four router nodes represented by circles and rectangles, respectively. Router nodes receive signal from a source node or other router nodes and forward them to the destination node or next router node in a route. Here,
directed dash lines represent lightpaths that are set up over the physical topology. For example, lightpath 1 (L1) can be used to send data from end-node E1 to E3. It starts from source node E1, passes through router node R1, R2, R3, and finally reaches the destination node E3. Figure 2 is the logical topology corresponding to the lightpaths shown in figure 1. Logical edge E1 --> E3 represents lightpath L1.

Figure 1: Some lightpaths on the physical topology (Bandyopadhyay, 2008:4)

Figure 2: Logical topology G_L corresponding to the lightpath shown in Figure 1 (Bandyopadhyay, 2008:5)
A lightpath may traverse one or more fibers, and must be assigned a single WDM channel on each fiber link it traverses. The Routing and wavelength assignment (RWA) problem [3] deals with selecting a route over the physical topology and a suitable wavelength for every lightpath established over the network. In wavelength convertible networks, a lightpath can be assigned a different channel on each fibre it traverses. However, full range all-optical wavelength conversion is generally not feasible, due to both cost and technological restrictions. Therefore, most practical networks do not assume wavelength conversion capabilities. In the absence of wavelength converters, a lightpath must be assigned the same channel on all links. This is called the wavelength continuity constraint.

2.2 Computation Complexity of the RWA Problem

The Routing and Wavelength Assignment (RWA) problem has been proven to be NP-complete in [21], and is typically handled using heuristics for large-sized networks. Chlamtac et al [21] show that the static lightpath establishment (SLE) problem is equivalent to the graph coloring problem. $G_L(V_L, E_L)$ is an undirected graph where $V_L$ is the set of lightpaths to be established, and each link in $E_L$ connects a pair of lightpaths, if two lightpaths have at least one common link. They color the graph in such a way that no two adjacent vertices have the same color. This implies that two lightpaths cannot be assigned to the same wavelength if they go through common link(s). The chromatic number of the graph indicates the minimal number of wavelengths required to support a set of traffic demands.
In the sliding scheduled traffic model, the resource allocation optimization problem deals with jointly scheduling demands in time to minimize demand overlap and allocating resources to lightpaths.

### 2.3 Traffic Models

A number of different traffic models have been considered for the RWA problem, such as static traffic, dynamic traffic, incremental traffic, and scheduled traffic models. In a static traffic model, the set of lightpaths to be established is known in advance and exists throughout the lifetime of the network once established. Under a dynamic traffic model, the arrival time and duration of demands are randomly generated based on certain distributions. In dynamic allocation, lightpaths are set up when needed and are taken down when the communication is over. When a new lightpath is introduced to support a new traffic request, a dynamic RWA algorithm has to avoid interrupting all existing lightpaths. A dynamic scheme does not guarantee that the communication is always possible. If sufficient network resources cannot be found to create a new lightpath without disrupting the existing data flows, the new request will be blocked. In an incremental traffic model, demands are added to the network incrementally.

Kuri et al. appear to be the first to propose the scheduled traffic model [2] to handle scheduled lightpath demands. In the fixed window scheduled traffic model, the setup and teardown times of the demands are known in advance. Each demand is represented by a tuple \((s, d, n, t_s, t_e)\), where \(s\) and \(d\) are the source and destination, respectively, \(n\) represents the number of requested lightpaths for the demand, and \(t_s, t_e\) are the setup and teardown times of the demand.
Kuri et al [2] present a branch and bound algorithm and a tabu search based algorithm to solve the routing problem in fault-free networks. Then they use a generalized graph coloring approach to solve the wavelength assignment problem separately. The authors also define the time correlation factor to determine the amount of overlap (in time) for the demand set. They claim that the time complexity of their branch and bound algorithm is \( O(K_{\text{max}}^M) \), where \( K_{\text{max}} \) is the maximum number of physical shortest routes for each demand, and \( M \) is the size of the given demand set.

Saradhi and Gurusamy [5] present two circular arc graph theory based algorithms, namely Independent Sets Algorithm (ISA) and Time Window Algorithm (TWA) to solve the RWA problem under the fixed window scheduled traffic model in fault-free networks without wavelength conversion. Their algorithms take advantage of wavelength reusing by time-disjoint demands. ISA clusters time-disjoint demands into independent sets so that only one wavelength is needed for each independent set. Whereas, TWA groups the time-overlapping demands into different batch windows in such a way that network resources can only be shared by the demands within a batch. In another word, the demands across the batches cannot be assigned the same wavelength if they use a common link.

Skorin-Kapov [6] improves the Tabu search based routing algorithm proposed in [2]. Instead of relying on randomized neighbourhood search, the author develops a neighbourhood reduction technique to reduce the search space significantly. The author also derives lower bounds for the RWA scheduled lightpath demand problem with/without the group lightpath constraint [6]. For the wavelength assignment problem, the author uses the greedy graph coloring algorithm presented in [2].
In 2005, Wang et al extend the fixed scheduled traffic model to a more general and flexible setting, called the sliding scheduled traffic model [14], to handle the scheduled lightpath demands. In the sliding scheduled traffic model, the demand setup and teardown times \( (t_s \text{ and } t_e) \) are not known beforehand. Each demand is represented by a tuple \( (s, d, n, a, \omega, \tau) \), where \( s \) and \( d \) are the source and destination, respectively, \( n \) represents the number of requested lightpaths for the demand and \( a, \omega \) are the start and end times of the larger window. The corresponding demand is allowed to be scheduled within the range of the specific window, and \( \tau \) \((0 < \tau \leq \omega - a)\) is the demand holding time.

The advantages of the sliding scheduled traffic model are illustrated by the example in Figure 3. We consider a single fiber link and for simplicity, we assume that the link can accommodate only one WDM channel. We also consider two demands \( d_1 \) and \( d_2 \), where \( d_1 \) \((d_2)\) requires the entire WDM channel for 3 hours \((4\text{ hours})\), starting from 2am \((3\text{ am})\). Clearly, under the fixed window scheduled traffic model, it will not be possible to accommodate both of these demands. However, if we allow demands \( d_1 \) and \( d_2 \) to be rescheduled within the window 1 - 6 \((2 - 8)\), as shown in Figure 3b, both demands can be easily handled using the sliding scheduled traffic model, by setting actual start time \( t_{s1} \) \((t_{s2})\) of the demand \( d_1 \) \((d_2)\) to 1am \((4\text{ am})\).
Wang et al [14] provide a heuristic algorithm for scheduling the demands and solving the RWA problem for a fault-free network without wavelength conversion. The objective is to minimize the total network resources in terms of the total number of wavelength-links needed to accommodate all the scheduled lightpath demands. The authors concentrate on two sub-problems:

i) first, a demand time conflict reduction algorithm is used to schedule demands in such a way that the time overlapping among a set of demands is minimized,
ii) Once this is done, the problem is reduced to the fixed window scheduled traffic model. And two algorithms, window based RWA algorithm and traffic matrix based RWA algorithm, are used to solve the RWA problem separately.

Furthermore, the authors consider how to rearrange a blocked demand by setting a new start time with a minimal schedule changing.

Su and Sasaki [15] investigate the relationship between wavelength efficiency and time flexibility of the scheduled demands. They also present and compare a number of heuristics for resource allocation in fault-free networks.

Traffic grooming algorithms under the sliding scheduled traffic model are proposed in [16]. The priority of demands is considered, and the demands with higher priority will be routed and assigned wavelength prior to the lower priority demands. To determine the actual start time of each demand, the authors use a demand time conflict reduction algorithm to find the best position for each demand in its corresponding time window. They also present a time window based traffic grooming algorithm to route and groom demands with the objective of minimizing the total wavelength-links used. If sufficient network resources to serve all the demands are not available, low priority demands will be rearranged.

### 2.4 Fault-tolerance in Optical Networks

Wavelength division multiplexing (WDM) optical networks are widely used for high capacity backbone networks due to their ability to carry large volumes of data with a high degree of reliability and at a relatively low cost [1]. Currently, the data carrying capacity
of each lightpath ranges from 2.5 Gbps to over 10 Gbps depending on the technology [20]. A failure of a network component, like a fibre cut, will lead to a tremendous data loss. Fault-tolerance techniques are essential for designing a reliable optical network. Fault-Management schemes [22] are classified into path/link protection and path/link restoration as shown in figure 4.

A protection scheme is determined at the design phase. In path protection, a primary (or working) lightpath and an edge-disjoint backup (or protection) lightpath are established for each unit of bandwidth demand. In this thesis, we assume one unit of bandwidth demand to be equal to the capacity of a single lightpath. If a link on a primary path fails, the traffic will be automatically redirected to the pre-assigned backup path.

In shared path protection, backup multiplexing allows two or more backup lightpaths to share wavelength channels if their corresponding primary lightpaths are link-disjoint. The backup multiplexing is illustrated in Figure 5. We can see that primary path 1 (P1: 1
primary path 2 (P2: 4 → 2) do not have any common edge(s). Under the single link failure scenario, the data flow carried by P1 and P2 will not be interrupted by a failed link at the same time. So we can assign wavelength 1 (λ1) for both backup path 1 (B1: 1 → 4 → 5 → 6) and backup path 2 (B2: 4 → 5 → 3 → 2) on their common link 4 → 5.

In dedicated path protection, such sharing is not allowed. B1 and B2 have to be assigned to different channels since they both include link 4 → 5 in their route. As shown in Figure 6, wavelength 1 (λ1) is reserved for B1 and wavelength 2 (λ2) is used for B2.

Figure 5: Shared path protection
Clearly, backup resource sharing achieves better network utilization than dedicated path protection. In this thesis, we focus on shared protection, due to its superior performance in terms of resource utilization.

In link protection, a backup path is reserved around the failed link only, instead of the entire path. Figure 7 illustrates how link protection differs from path protection. As shown in figure 7a, the primary path (1→2→3→6) and the link-disjoint backup path (1→4→5→6) are allocated for the connection with source node 1 and destination node 6. In the case that the link 2→3 on the primary path fails, nodes 2 and 3 send link-fail messages to the source and destination nodes. The traffic will be resent along the predetermined backup path. In the same situation of the link failure, the link protection scheme replaces the failed link 2→3 by the backup path 2→4→5→6 without notifying the source and destination nodes.
The backup path for each connection is reserved at the time of connection setup, so that protection schemes can guarantee recovery and the recovery time is very fast.

On the other hand, restoration schemes dynamically search for available network resources to set up backup path after a failure occurs. It may not guarantee recovery and the recovery time is slower than for protection schemes. The advantage of restoration schemes is efficient capacity utilization, since it does not need to reserve backup paths for all possible failure scenarios.

For the scheduled traffic model, previous work on the design of survivable WDM networks has been primarily restricted to the fixed window model [4], [7] – [13]. Wang et al [4], [7] propose optimal ILP formulations for the design of survivable wavelength convertible networks under the fixed window scheduled traffic model. For large-size networks, Wang et al [7] also design a two-step optimization approach to solve the routing and wavelength assignment problem separately. For each demand, Eppstein’s k-shortest
path algorithm is used to pre-compute a set of routes as its working path candidates. For each of the working paths, a set of link-disjoint protection paths are found by the same algorithm. The routing information is the inputs to the wavelength assignment step.

Heuristic solutions for the same problem have been presented in [8], [9], [10]. These heuristic approaches can be used for large problems and demonstrate that connection holding time aware schemes can achieve much better resource utilization when compared to schemes that are holding time unaware.

In [11] ILP formulations for dedicated and shared protection are proposed for the fixed window model without wavelength conversion. Two objective functions are formulated. The first one is to minimize the network cost, and the second one is to maximize the number of demands accommodated by the given limited network resource. It is evident from their simulation results that consideration of connection holding times allows more efficient use of available resources.

In [12], a generalized ILP formulation and heuristic is presented for prioritized demands under the fixed window scheduled traffic model with wavelength conversion. The authors consider multiple service levels, where idle backup resources can be used to carry low-priority traffic under the fault-free conditions. When a fault occurs, the resources allocated for a backup path need to be reclaimed, any low-priority traffic on the affected channels is dropped. The authors conclude that allowing multiple service levels leads to significant improvements in resource utilization.

The work in [13] appears to be the first to address the complete survivable traffic grooming problem under the fixed window scheduled traffic model. The authors present efficient ILP formulations that exploit knowledge of the connection holding times of
traffic demands leading to more efficient resource allocation. They solve the joint problem of the topology design, traffic routing and RWA, using path protection at the lightpath level. The authors point out that although individual demands may be short lived; it is desirable to have a logical topology that is relatively stable and not subject to frequent changes. They are aiming to design a stable logical topology that can accommodate a collection of low-speed traffic demands with specified setup and teardown times. The objective is to minimize the resource requirements. The authors also proposed a simplified version of their ILP formulations that can solve the problem in a way that is computationally more tractable.

As pointed out earlier, for the sliding scheduled traffic model, only fault-free networks have been considered in the literature. Even for such fault-free networks, only heuristic solutions have been proposed so far. In this thesis, we present generalized ILP formulations for designing survivable WDM networks under the *sliding* scheduled traffic model, both with and without wavelength conversion capabilities. For larger networks, we also develop a fast two-step process, which optimally schedules the demands and solves the RWA problem separately.
Chapter 3

RESOURCE ALLOCATION UNDER THE SLIDING SCHEDULED TRAFFIC MODEL

In this chapter, we describe our ILP formulations for resource allocation under the sliding scheduled traffic model, using dedicated and shared path protections. We first consider wavelength convertible networks and then extend our model to networks without wavelength conversion. The objective here is to minimize the network cost to accommodate the demand set. Our ILP formulations jointly optimize the problem of scheduling the demands in time and allocating resources for the scheduled lightpaths. The fixed window model and fault-free networks can be treated as special cases of our formulations.

3.1 ILP Formulations
3.1.1 Network Model

The following network parameters are given as inputs.

- A physical fiber network \( G[V, E] \), where \( V \) is the set of nodes, and \( E \) is the set of links.
- A set of channels \( K \) that each fiber can accommodate.
- A set of lightpath demands \( L = \{(s_1, d_1, n_1, \alpha_t, \omega_t, \tau_t)\} \) for the sliding scheduled traffic model defined in Section 2.3.
- A set of \( R \) edge-disjoint paths, over the physical topology, between each source-destination pair.
- \( f_{e}^{sd,r} = 1 \) if and only if the \( r^{th} \) route between source \( s \) and destination \( d \) uses fiber link \( e \).

3.1.2 ILP Variables

The variables required for the ILP are defined in this section. We note that only the following three types of variables are defined as binary (0,1) variables

i) route assignment variables \((p_{r,l} \text{ and } b_{r,l})\)

ii) channel assignment variables \((w_{k,e,l}, z_{k,e,l} \text{ for wavelength convertible networks})\) and \((w_{k,e,l}, z_{k,l} \text{ for wavelength continuous networks})\)

iii) scheduling variables \((S_{l,s,l} )\)

All the other variables are defined as continuous variables, even though, through the careful formulation of constraints, they may be restricted to take on integer values only.
The motivation for this approach is that integer variables increase the computational complexity exponentially, and should be used sparingly.

- \( p_{r,l} (b_{r,l}) = 1 \), if and only if demand \( l \) uses the \( r \)th route to establish the primary (backup) lightpath, from its source \( s_l \) to destination \( d_l \).

- \( w_{k,e,l} (z_{k,e,l}) = 1 \), if and only if the primary (backup) lightpath for demand \( l \) is assigned channel \( k \) on link \( e \).

- \( w_{k,l} (z_{k,l}) = 1 \), if and only if a primary (backup) lightpath for demand \( l \) is assigned channel \( k \). These are required only for ILP-D2 and ILP-S2.

- \( S_{t_p,t_q} = 1 \), if and only if demand \( l_p \) ends after demand \( l_q \) is scheduled to start, i.e. \( st_p + t_p - st_q > 0 \).

- \( x_{l,e} (y_{l,e}) = 1 \), if and only if demand \( l \) uses link \( e \) on its primary (backup) route.

- \( c_{k,e} = 1 \), if and only if, channel \( k \) is used on link \( e \) by one or more lightpaths.

- \( \lambda_e \) = the number of WDM channels that have been assigned to at least one lightpath, on link \( e \).

- \( \lambda_{\text{max}} = \max\{ \lambda_e, e \in E \} \), the congestion of the network.

- \( st_l \) = the actual start time of demand \( l \), within its specified window.

- \( T_{l_p,t,q} = 1 \), if and only if demands \( l_p \) and \( l_q \) overlap in time, \( \forall l_p, l_q \in L, p < q \).

3.1.3 Conditions of Demands Overlapping
In the *sliding* scheduled traffic model, $\alpha_l$ and $\omega_l$ specify the larger window within which demand $l$ is to be scheduled. The actual start time ($st_l$) of a demand $l$ must be calculated by the ILP.

In order to determine if two scheduled demands can share resources, it is necessary to know whether or not they are time-disjoint. In the *fixed window* model, this is trivial and can be determined by the start and end times of the demands, which are specified as inputs. In the sliding scheduled traffic model, it becomes more difficult.

Clearly, if the windows corresponding to demands $l_p$ and $l_q$, are time disjoint, then the actual demands will necessarily be time disjoint (Figure 8a). However, the converse may not always be true. This means that, even if two windows $(\alpha_p, \omega_p)$ and $(\alpha_q, \omega_q)$ overlap in time, the corresponding demands may still be time disjoint, as shown in Figure 8b. Two scheduled demands $l_p$ and $l_q$, will overlap in time (i.e. $T_{l_p,l_q} = 1$) if and only if both of the following conditions are satisfied.

- $st_l + \tau_l - st_l > 0$ and
- $st_l + \tau_l - st_l > 0$

This situation is illustrated in Figure 8c. We make use of this observation in our ILP formulations, which optimally position each demand inside its specified window to minimize the amount of resources required.
ILP formulations for the fixed window model can be treated a special case of our formulations, where $r_i = o_i - a_i$ and $s_t = a_i, \forall t \in L$. Since the start and end times are known beforehand, it is possible to determine $T_{l_{p,t}}$ ahead of time. So, $T_{l_{p,t}}$ is no longer a variable and can be considered as an input. Hence, for the fixed window model, constraints (2a)–(4c) can be removed from our formulations, and everything else remains unchanged.

3.2 ILP for Dedicated Protection with Wavelength Conversion (ILP-D1)

Minimize $b_1 \sum_{e \in E} \sum_{k \in K} c_{k,e} + b_2 \cdot \lambda_{\max}$ (1)
The objective function in (1) can be selected to either minimize the total number of wavelength-links required to accommodate the demand set, or minimize the congestion of the network, by appropriately setting the values of the constants $b_1$ and $b_2$. If $b_1 = 1$ and $b_2 = 0$, the ILP minimizes the number of wavelength-links. Alternatively, if $b_1 = 0$ and $b_2 = 1$, the ILP minimizes congestion. If $b_1$ and $b_2$ both have non-zero values, we get a composite objective function, where the relative importance of each component can be varied by changing the values of $b_1$ and $b_2$.

Subject to:

\[ st_l \geq \alpha_l, \forall l \in L \quad (2a) \]

\[ st_l + \tau_l \leq \omega_l, \forall l \in L \quad (2b) \]

\[ st_{l_p} + \tau_{l_p} - st_{l_q} \leq M \cdot S_{l_p,l_q}, \forall l_p,l_q \in L, l_p \neq l_q \quad (3) \]

Constraints (2a) and (2b) ensure that each demand is always scheduled within its specified window. Constraint (3) forces the binary variable $S_{l_p,l_q}$ to be 1, if demand $l_p$ ends after demand $l_q$ starts. Here $M$ is a constant that represents the entire time interval from the start of the earliest window to the end of the final (latest) window. For example, if we are considering a 24-hour period and start and end times of all the demand windows are between 0 and 24 hours, then we set $M = 24$.

\[ S_{l_p,l_q} + S_{l_q,l_p} - T_{l_p,l_q} \leq 1, \forall l_p,l_q \in L, p < q \quad (4a) \]

\[ S_{l_p,l_q} - T_{l_p,l_q} \geq 0, \forall l_p,l_q \in L, p < q \quad (4b) \]
We note that $S_{l_p,l_q}$ and $S_{l_q,l_p}$ are not symmetrical. So it is possible that $S_{l_p,l_q} = 1$, $S_{l_q,l_p} = 0$, and vice versa. As explained in Figure 8c, two demands will overlap in time if and only if both $S_{l_p,l_q} = 1$, and $S_{l_q,l_p} = 1$. Constraints (4a) – (4c) force $T_{l_p,l_q} = 1$, if and only if both $S_{l_p,l_q}$ and $S_{l_q,l_p}$ are 1.

\[
\sum_r p_{r,l} = 1, \forall l \in L \quad (5a)
\]

\[
\sum_r b_{r,l} = 1, \forall l \in L \quad (5b)
\]

Constraint (5a) ensures that when a demand $l$ requires multiple units of bandwidth (i.e. $n_l > 1$), all primary lightpaths for this demand are allocated to one common route over the physical topology. Similarly, (5b) ensures that all backup lightpaths for a given demand $l$ use the same route, which should be edge-disjoint with the primary route.

\[
x_{l,e} = \sum_r p_{r,l} \cdot f_e^{s_l,d_l,r}, \forall l \in L, \forall e \in E \quad (6a)
\]

\[
y_{l,e} = \sum_r b_{r,l} \cdot f_e^{s_l,d_l,r}, \forall l \in L, \forall e \in E \quad (6b)
\]

Constraints (6a) and (6b) are used to define variables $x_{l,e}$ and $y_{l,e}$. The variable $x_{l,e}$ ($y_{l,e}$) will have a value of 1 if the primary (backup) lightpath, from source $s_l$ to destination $d_l$, uses the $r^{th}$ route, i.e. $p_{r,l} = 1$ ($b_{r,l} = 1$), and edge $e$ is on the $r^{th}$ route i.e. $f_e^{s_l,d_l,r} = 1$. In other
words, \( x_{l,e} = 1 \) (\( y_{l,e} = 1 \)) if and only if the primary (backup) lightpaths for demand \( l \) use edge \( e \).

\[
p_{r,l} + b_{r,l} \leq 1, \quad \forall l \in L, r = 0,1,\ldots,R - 1 \quad (7)
\]

Constraint (7) guarantees that the primary and backup lightpaths for the new connection are never assigned the same route. This ensures that primary and backup paths are always link-disjoint since the \( R \) routes for a given source-destination pair are already pre-selected to be link-disjoint.

\[
\sum_{k \in K} w_{k,e,l} = x_{l,e} \cdot n_1, \quad \forall l \in L, \forall e \in E \quad (8a)
\]

\[
\sum_{k \in K} z_{k,e,l} = y_{l,e} \cdot n_1, \quad \forall l \in L, \forall e \in E \quad (8b)
\]

Constraints (8a) and (8b) ensure that a sufficient number of channels are allocated along primary and backup routes for each demand. For each link \( e \) on the primary route of demand \( l \) (i.e. \( x_{l,e} = 1 \)), (8a) reserves exactly \( n_1 \) number of channels for the demand. If a particular link \( e \) is not on the primary route (i.e. \( x_{l,e} = 0 \)), then no channels are assigned to primary lightpaths for demand \( l \) on that link. Similarly (8b) reserves \( n_1 \) channels on each link of the backup route for demand \( l \).

\[
c_{k,e} \geq w_{k,e,l} + z_{k,e,l}, \quad \forall k \in K, \forall e \in E, \forall l \in L \quad (9a)
\]

\[
c_{k,e} \leq \sum_{l \in L} w_{k,e,l} + z_{k,e,l}, \quad \forall k \in K, \forall e \in E \quad (9b)
\]
$c_{k,e} \leq 1, \forall k \in K, \forall e \in E$ \hspace{1cm} (9c)

Constraints (9a) – (9c) are used to define the variables $c_{k,e}$. Constraint (9a) states that $c_{k,e} \geq 1$ if channel $k$ on link $e$ has been allocated to a primary or backup lightpath for at least one demand $l \in L$. Constraint (9b) forces $c_{k,e}$ to be 0, if channel $k$ on link $e$ has not been assigned to any lightpath, and (9c) ensures that $c_{k,e}$ does not exceed 1, even if channel $k$ on link $e$ has been assigned to more than one lightpath (e.g. for shared protection).

\[
\lambda_e = \sum_{k \in K} c_{k,e}, \forall e \in E \hspace{1cm} (10)
\]

Constraint (10) defines $\lambda_e$ for each link in the network and (11) ensures that for each $e \in E$, $\lambda_e$ does not exceed the congestion of the network.

3.3 ILP for Shared Protection with Wavelength Conversion (ILP-S1)

The following three constraints are responsible for performing a feasible routing and wavelength assignment. They ensure that the lightpaths (either primary or backup), corresponding to demands $l_p$ and $l_q$, do not share the same channel $k$ on a common link $e$, unless they are time disjoint. These constraints hold for $\forall k \in K, \forall e \in E, \forall l_p, l_q \in L, l_p \neq l_q$.

\[
w_{k,e,l_p} + w_{k,e,l_q} + T_{l_p,l_q} \leq 2, \hspace{1cm} (12)
\]

\[
w_{k,e,l_p} + z_{k,e,l_q} + T_{l_q,l_p} \leq 2, \hspace{1cm} (13)
\]
Constraint (12) states that primary lightpaths for demands $l_p$ and $l_q$ cannot be assigned the same channel $k$ on a common link $e$ if they overlap in time (i.e. $T_{l_p,l_q} = 1$). Similarly, (13) states that primary lightpaths for demand $l_p$ must be edge-channel disjoint with all backup lightpaths for demand $l_q$ if they overlap in time. Finally, (14) states that backup lightpaths for demands $l_p$ and $l_q$ cannot be assigned the same channel $k$ on a common link $e$ if they overlap in time.

### 3.3 ILP for Shared Protection with Wavelength Conversion (ILP-S1)

In shared protection, the constraints for assigning routes over the physical topology, determining time overlap of scheduled demands and allocating channels for primary lightpaths are the same as for dedicated protection. The only difference is in allocating resources for backup lightpaths, which can share resources if certain conditions are met. So, we use the same objective function given in (1), which can minimize the number of wavelength-links, or the congestion of the network. We also use constraints (2) – (13) as given in the ILP for dedicated protection. Constraint (14) is replaced by constraints (15a) – (17), which enforce the conditions for backup multiplexing. In addition to the variables in ILP-D1, we also introduce the following variables. Both of these new variables are defined as continuous variables, but constraints are used to ensure they only take on values of 0 or 1.

- $\beta_{l_p,l_q}^e = 1$ if and only if demands $l_p$ and $l_q$ both use link $e$ for their primary routes.
\( \delta_{l_p,l_q} = 1 \) if an only if demands \( l_p \) and \( l_q \) have at least one common link on their primary routes.

Constraints (15a) – (15c) are used to define the variable \( \beta_{l_p,l_q}^e \). If either \( x_{l_p,e} = 0 \) or \( x_{l_q,e} = 0 \), then (15b) and (15c) set \( \beta_{l_p,l_q}^e = 0 \). These constraints also ensure that \( \beta_{l_p,l_q}^e \leq 1 \).

Constraint (15a) sets \( \beta_{l_p,l_q}^e = 1 \) if and only if both \( x_{l_p,e} = 1 \) and \( x_{l_q,e} = 1 \).

\[
\begin{align*}
    x_{l_p,e} + x_{l_q,e} - \beta_{l_p,l_q}^e & \leq 1, \forall e \in E, \forall l_p, l_q \in L, l_p \neq l_q \\
    x_{l_p,e} - \beta_{l_p,l_q}^e & \geq 0, \forall e \in E, \forall l_p, l_q \in L, l_p \neq l_q \\
    x_{l_q,e} - \beta_{l_p,l_q}^e & \geq 0, \forall e \in E, \forall l_p, l_q \in L, l_p \neq l_q
\end{align*}
\]  

(15a) \hspace{1cm} (15b) \hspace{1cm} (15c)

Constraints (16a) – (16c) are used to set \( \delta_{l_p,l_q} = 1 \) if and only if demands \( l_p \) and \( l_q \) share at least one fiber on their primary routes, and 0 otherwise.

\[
\begin{align*}
    \delta_{l_p,l_q} & \geq \beta_{l_p,l_q}^e, \forall e \in E, \forall l_p, l_q \in L, l_p \neq l_q \\
    \delta_{l_p,l_q} & \leq \sum_{e \in E} \beta_{l_p,l_q}^e, \forall l_p, l_q \in L, l_p \neq l_q \\
    \delta_{l_p,l_q} & \leq 1, \forall l_p, l_q \in L, l_p \neq l_q
\end{align*}
\]  

(16a) \hspace{1cm} (16b) \hspace{1cm} (16c)
Constraint (17) is used to enforce the conditions for backup multiplexing. It states that if two demands \( l_p \) and \( l_q \) overlap in time (i.e. \( T_{l_p,l_q} = 1 \)), and share a common link on their primary routes (i.e. \( \delta_{l_p,l_q} = 1 \)), then the corresponding backup lightpaths cannot share the same channel \( k \) on a common link \( e \) (i.e. \( z_{k,e,l_p} + z_{k,e,l_q} \leq 1 \)).

\[
z_{k,e,l_p} + z_{k,e,l_q} + \delta_{l_p,l_q} + T_{l_p,l_q} \leq 3 \tag{17}
\]

### 3.4 Dedicated and Shared Protection without Wavelength Conversion (ILP-D2 and ILP-S2)

The ILP formulations developed for wavelength convertible networks can be easily adapted to handle networks without wavelength conversion capabilities. In this case, each lightpath is allotted the same channel on each fiber that it traverses. The formulations for dedicated protection (ILP-D2) and shared protection (ILP-S2) in networks with no wavelength conversion are obtained by making the changes outlined in this section to ILP-D1 and ILP-S1 respectively. In order to enforce the *wavelength continuity constraint*, we replace constraints (8a) and (8b) with the following two constraints:

\[
\sum_{k \in K} w_{k,l} = n_l, \forall l \in L \tag{18}
\]

\[
\sum_{k \in K} z_{k,l} = n_l, \forall l \in L \tag{19}
\]
According to these constraints there are exactly \( n_l \) wavelengths allocated for the \( n_l \) lightpaths in demand \( l \), along both the primary and backup routes. This means that each lightpath can be allocated exactly one channel along its entire route (both primary and backup).

Additionally, the variables \( w_{k,e,l} \) and \( z_{k,e,l} \) no longer need to be defined as integer variables. They can be defined as continuous variables, by adding constraints (20a) – (20c) and (21a) – (21c), which ensure that they are still restricted to take on values of 0 or 1. Thus the number of integer variables is reduced, resulting in a lower complexity for the formulations ILP-D2 and ILP-S2.

\[
\begin{align*}
\text{(20a)} & \quad w_{k,l} + x_{l,e} - w_{k,e,l} & \leq & 1, \forall k \in K, \forall e \in E, \forall l \in L \\
\text{(20b)} & \quad w_{k,l} & \geq & w_{k,e,l}, \forall k \in K, \forall e \in E, \forall l \in L \\
\text{(20c)} & \quad x_{l,e} & \geq & w_{k,e,l}, \forall k \in K, \forall e \in E, \forall l \in L \\
\text{(21a)} & \quad z_{k,l} + y_{l,e} - z_{k,e,l} & \leq & 1, \forall k \in K, \forall e \in E, \forall l \in L \\
\text{(21b)} & \quad z_{k,l} & \geq & z_{k,e,l}, \forall k \in K, \forall e \in E, \forall l \in L \\
\text{(21c)} & \quad y_{l,e} & \geq & z_{k,e,l}, \forall k \in K, \forall e \in E, \forall l \in L 
\end{align*}
\]

### 3.5 Handle Fault-free Networks
Fault-free networks with wavelength conversion can be handled using our model by removing constraints (5b), (6b), (7), (8b), (13) and (14) from ILP-D1 and replacing constraints (9a) – (9c) by (22a) – (22c) given below.

\[ c_{k,e} \geq w_{k,e,l}, \forall k \in K, \forall e \in E, \forall l \in L \]  
\[ (22a) \]

\[ c_{k,e} \leq \sum_{l \in L} w_{k,e,l}, \forall k \in K, \forall e \in E \]  
\[ (22b) \]

\[ c_{k,e} \leq 1, \forall k \in K, \forall e \in E \]  
\[ (22c) \]

Similarly, fault-free networks without wavelength conversion are modeled by removing constraints (5b), (6b), (7), (13), (14) and (19) from ILP-D2 and replacing constraints (9a) – (9c) by (22a) – (22c).
Chapter 4

TWO-STEP DESIGN HEURISTIC

In this chapter, we will outline our two-step approach that can be used for larger networks with many requested demands. In the first step, we optimally schedule each demand within its specified window \((\alpha_k, \omega_k)\). Once the actual start time for each demand is determined, a connection holding time aware heuristic can be used to perform routing and wavelength assignment for the scheduled demands.

4.1 Demand Scheduling

In this section we will outline a simple ILP formulation (ILP-T) for the first step, i.e. scheduling of demands in time. ILP-T is not concerned with RWA at all. The objective is to schedule the demands in \(L\) in such a way that the amount of overlap is minimized, and each demand is within its specified window. We use variables \(s_{l}\), \(S_{l_p, l_q}\), and \(T_{l_p, l_q}\) as defined in the previous section.

ILP-T can now be formulated as,
Minimize \[ \sum_{l_p, l_q \in L, p < q} (n_{l_p} \times n_{l_q}) \cdot T_{l_p, l_q} \] (23)

subject to constraints (2) – (4c).

The weight given to the overlap of a pair of demands \( l_p \) and \( l_q \) is proportional to the product of the number of lightpaths. This formulation is quite fast and can generate optimal solutions very quickly, even for large demand sets.

The objective function (23) minimizes the total weighted overlap between demands. Once the demands have been suitably scheduled, the problem is reduced to the fixed window model. This can be solved more easily either with existing ILPs or by using heuristics such as the ones outlined in this section.

### 4.2 RWA of Scheduled Demands Without Wavelength Conversion

The heuristics described here can be used for RWA of scheduled demands whose setup/teardown times are known in advance. For the sliding scheduled traffic model, ILP-T can be applied first, to determine the actual start time for each demand. The input to the heuristic algorithm is the set of demands \( L \) as well as the physical topology \( G[V, E] \) and the set of channels \( K \) on each fiber. A set of \( R \) edge-disjoint routes \( (p_{sd}) \) between each source destination pair \( \forall s, d \in V, \ 0 \leq r < R \) are also pre-computed using Dijkstra’s shortest path algorithm. The heuristic computes the following information, when attempting to allocate resources for a demand \( l \), with start time \( st_l \).
• $\alpha_{e,t}$, the set of channels (wavelengths) on each link $e \in E$ that have been allocated to a currently active primary lightpath at time $t$. If $\lambda \in \alpha_{e,t}$, it means that wavelength $\lambda$ on link $e$, has been assigned to a primary lightpath for demand $l_p$, and $st_{l_p} \leq t < et_{l_p}$.

• $\beta_{e,t}$, the set of channels (wavelengths) on each link $e \in E$ that have been allocated to a currently active backup lightpath at time $t$. If $\lambda \in \beta_{e,t}$, it means that wavelength $\lambda$ on link $e$ has been assigned to a backup lightpath for demand $l_p$, and $st_{l_p} \leq t < et_{l_p}$.

• $\chi_{e,t,l}$, the set of channels on link $e \in E$ that have been allocated to a currently active backup lightpath at time $t$, such that their corresponding primary paths are edge-disjoint with the selected primary route $(r_p)$ for demand $l$. In other words, $\chi_{e,t,l}$ contains the set of channels on the edge $e$ that satisfy the requirements for backup multiplexing with the backup lightpaths of demand $l$. Clearly, $\chi_{e,t,l} \subseteq \beta_{e,t}$.

• $S_{e,t}$, the set of free channels (not allocated to any primary or backup lightpath) on link $e$ at time $t$.

Figure 9 gives an overview of our heuristic. The set of demands is first sorted in ascending order of start times $st_l$. We then use a greedy heuristic that takes each demand request from the sorted list $L_{sort}$ in turn, and attempts to allocate resources for its primary and backup lightpaths. The goal is to allocate a physical route $r_p$ ($r_b$), and a set of $n_l$ channels on each edge of the selected route, for the primary (backup) lightpaths. This
continues until all demands have been successfully handled. If, at any time, a suitable route cannot be found for a demand \( l \), the algorithm stops and reports failure.

1. \( L_{\text{sort}} = \) sorted list of demands in ascending order of start times (\( st_l \)).
2. For each \( l \in L_{\text{sort}} \) do steps 3-8
3. For each route \( r (0 \leq r < R) \) for demand \( l \)
   a. \( \Lambda_{r,l} = \bigcap_{e \in \rho_{l,d}^r} S_{e,l} \)
   b. \( C_{r,l} = \max\{|\alpha_{e,l}| + |\beta_{e,l}| + n_l | e \in \rho_{l,d}^r\} \)
4. If \( C_{r,l} > |K|, 0 \leq r < R \) STOP and report failure.
   Else select primary route \( r_p \) for demand \( l \) such that
   a. \( C_{r_p,l} \leq |K| \)
   b. Length of primary route (\( l_{r_p} \)) is minimized
5. Select \( n_1 \) wavelengths from \( \Lambda_{r_p,l} \)
6. For each route \( r (0 \leq r < R) \) for demand \( l \)
   a. \( \Lambda_{r,l} = \bigcap_{e \in \rho_{l,d}^r} S_{e,l} \)
   b. \( X_{r,l} = \bigcap_{e \in \rho_{l,d}^r} \chi_{e,l} \)
   c. \( m = \min\{|X_{r,l}|, n_l\} \)
   d. \( C_{r,l} = \max\{|\alpha_{e,l}| + |\beta_{e,l}| + n_l - m | e \in \rho_{l,d}^r\} \)
7. If \( C_{r,l} > |K|, 0 \leq r < R, r \neq r_p \) STOP and report failure.
   Else select backup route \( r_b \) for demand \( l \) such that
   a. \( C_{r_b,l} \leq |K| \)
   b. Length of backup route (\( l_{r_b} \)) is minimized
8. Allocate channels for backup path
   a. Select \( m \) wavelengths from \( X_{r,l} \)
   b. Select \( (n_1 - m) \) wavelengths from \( \Lambda_{r_b,l} \)

Figure 9: Overview of RWA heuristic for scheduled demands without wavelength conversion

We consider each route \( r \) for demand \( l \), and check the corresponding value of congestion \( C_{r,l} \) for the route, if demand \( l \) is routed over \( r \). If \( C_{r,l} \) exceeds the number of available channels per fiber (\( |K| \)) for all of the routes, then the demand cannot be
accommodated and the heuristic fails. Otherwise, we select the shortest route $r_p$ that can accommodate the demand ($C_{r_p,l} \leq |K|$), and select $n_f$ available channels from $\Lambda_{r_p,l}$. The process of selecting a backup route (steps 6 - 8) is only performed if path protection is required. It is similar to selecting the primary route, except that

i) the selected backup route $r_b$ cannot be the same as the primary route $r_p$,

ii) We determine the set of channels $X_{r,f}$ available for backup multiplexing, in addition to the set of free channels $\Lambda_{r,f}$ for each potential route $r$, and

iii) After a suitable route $r_b$ has been found, we first allocate channels from the set $X_{r,f}$, and then the remaining channels from $\Lambda_{r_b,f}$, if necessary.

The above algorithm implements shared path protection. In dedicated protection, backup multiplexing is not allowed. This restriction can be enforced by simply setting $X_{e,d} = \phi, \forall e, \forall r, \forall t$, which means that there are no channels available for backup multiplexing.

### 4.3 RWA of Scheduled Demands With Wavelength Conversion

The algorithm in Figure 9 can be modified slightly to accommodate wavelength conversion capabilities at the network nodes. In this case, step 3a is no longer needed when selecting the route for the primary lightpaths. Also, step 5 is changed so that wavelengths along the primary route can be allocated independently on each link $e$. Similarly, for backup route selection, steps 6c and 6d are modified so that available channels are calculated for each link separately, rather than for the route as a whole.
Finally, in step 8, channels for backup lightpaths are allocated independently for each link. As before, dedicated protection is implemented by setting $X_{e,t,l} = \emptyset \forall e, \forall t, \forall l$. The outline of the heuristic for wavelength convertible networks is given in Figure 10.

1. $L_{sort} = \text{sorted list of demands in ascending order of start times (st)}$.
2. For each $l \in L_{sort}$ do steps 3-8
3. For each route $r \ (0 \leq r < R)$ for demand $l$
   a. $C_{r,l} = \max \left\{ |\alpha_{e,l}| + |\beta_{e,l}| + n_l \mid e \in \rho_{s_l,d_l}^r \right\}$
4. If $C_{r,l} > |K|, 0 \leq r < R$ STOP and report failure. Else select primary route $r_p$ for demand $l$ such that
   a. $C_{r_p,l} \leq |K|$ 
   b. Length of primary route $(l_{r_p})$ is minimized
5. Allocate channels for each edge $e$ in primary route $r_p$
   a. Select $n_l$ wavelengths from $S_{e,t}$
6. For each route $r \ (0 \leq r < R)$ for demand $l$
   a. $m_e = \min \left\{ X_{e,t,l}, n_l \right\}$
   b. $C_{r,l} = \max \left\{ |\alpha_{e,l}| + |\beta_{e,l}| + n_l - m_e \mid e \in \rho_{s_l,d_l}^r \right\}$
7. If $C_{r,l} > |K|, 0 \leq r < R, r \neq r_p$ STOP and report failure. Else select backup route $r_b$ for demand $l$ such that
   a. $C_{r_b,l} \leq |K|$ 
   b. Length of backup route $(l_{r_b})$ is minimized
8. Allocate channels for each edge $e$ in backup route $r_b$
   a. Select $m_e$ wavelengths from $X_{e,t,l}$
   b. Select $(n_l - m_e)$ wavelengths from $S_{e,t}$

Figure 10: Overview of RWA heuristic for scheduled demands with wavelength conversion
Chapter 5

EXPERIMENTS AND RESULTS

In this chapter we present and analyze our experimental results, obtained using our ILP formulations and heuristics. Our formulations are able to generate optimal solutions for practical sized networks. The performance of the heuristics was validated by comparing with the ILP solutions for smaller networks.

5.1 Simulation Parameters

We have tested our formulations with a number of networks and demand sets, with different demand time correlations $\delta$ (as defined in [2] Section III.C, page: 1234). The value of $\delta(0 \leq \delta \leq 1)$ is used to determine the amount of overlap (in time) for the demand set. A higher value of $\delta$ indicates more overlap. If $\delta = 0$, it means none of the demands overlap in time, and RWA can be trivially solved for each demand separately. If $\delta = 1$, all demands overlap with each other and the design problem reduces to the conventional...
static RWA problem. We used three different values for $\delta$, $\delta = 0.01$ (low overlap), $\delta = 0.5$ (medium overlap) and $\delta = 0.8$ (high overlap).

We elaborate on how to calculate the demand time correlations $\delta$ via a simple example with four demands ($M_1, M_2, M_3, and M_4$) as shown in Figure 11.

First we construct a union set $T$ of demand start time and end time. The basic idea is that the start times and end times of demands are sorted in increasing order, and used to partition the entire time period into disjoint intervals. For each interval $i$, $B_i$ is the set of scheduled lightpath demand indexes $j$ such that the scheduled lightpath demand is active during the interval $i$. $n$ represents the number of requested lightpaths for the demand. Here, we gather the following information for our example.

- $T = \{a_1, a_2, \omega_1, a_3, a_4, \omega_2, \omega_3, \omega_4\}$

- $B_1 = \{M_1\}, B_2 = \{M_1, M_2\}, B_3 = \{M_2\}, B_4 = \{M_2, M_3\}, B_5 = \{M_2, M_3, M_4\}, B_6 = \{M_3, M_4\}, B_7 = \{M_3\}$
The demand time correlation $\delta$ can be computed by the formula [2]

$$\delta = \frac{n_1 (a_1 - a_2) + n_2 (a_1 - a_2) + n_2 (a_4 - a_3) + n_3 (a_4 - a_3) + n_2 (a_2 - a_4) + n_4 (a_2 - a_4) + n_3 (a_4 - a_2) + n_4 (a_4 - a_2))}{(n_1 (a_1 - a_1) + n_2 (a_2 - a_2) + n_3 (a_3 - a_3) + n_4 (a_4 - a_4))}$$

For the sliding window model, the actual start and end times (and hence the actual demand overlap) cannot be known ahead of time, so it is not possible to generate a demand set with a specified $\delta$ for this model. In our experiments we first generated a demand set with a specified $\delta$ for the fixed window model. We then increased the window size by 2h, 4h and 6h, respectively, around these fixed demands. The values of $\delta$ used for the sliding window model (in Figures 15 - 21) indicate the $\delta$ for the initial fixed demand set.

To test the ILP formulations, we considered a 10-node network given in [23] (shown in Figure 12) and a 14-node NSFNET [24] topology (shown in Figure 13). We were able to generate optimal solutions in all cases for the 10-node network and in most cases for the 14-node network. When optimal solutions could not be found, we used the feasible solution obtained after 2 hours. This is reasonable since this type of demand provisioning is expected to be done off-line. We also experimented with larger demand sets on networks of up to 53 nodes (with topologies as given in [23]) using the heuristics outlined in Chapter 4. In our experiments, we consider the network resource requirements under three scenarios

i) no backup (protection) paths,

ii) dedicated path protection and

iii) shared path protection.
For each specified network topology, demand size and protection scenario, the simulation was run 15 times (5 times for each demand correlation). The values reported in the figures 15 – 21, in this section, correspond to the average values (rounded to the nearest integer) over the different simulation runs. The simulations were carried out on a 900MHz SUN platform, with CPLEX 9.0 [25].

Figure 12: Topology of 10-node network: 22-link

Figure 13: Topology of NSFNET: 14-node 21-link
The results reported in Sections 5.2 and 5.3 mainly focus on resource requirement in terms of the number of wavelength-links required to accommodate the demands. We have not included the results for congestion, since there was not much variation in congestion using the different approaches. This is likely because, in most cases, the ILPs were able to maintain a low value of congestion by choosing alternate (possibly longer) routes around congested links.

5.2 Comparison of the Number of Integer Variables

It is well-known that the main factor affecting the complexity of an ILP is the number of integer variables, as the complexity increases exponentially with the number of integer variables. In this section, we compare the complexity of our ILPs, in terms of the number of integer variables, with that presented in [7]. In [7], the authors present an ILP for RWA, under the fixed window scheduled traffic model, using both dedicated protection (ILP-SDP) and shared protection (ILP-SSP). For WDM networks, as the size of network increases, the computational time required to solve the RWA problem increases rapidly.

In our formulations, we have tried to reduce the number of integer variables as much as possible. As mentioned in Section 3.1.2, only three types of variables, route assignment variables, channel assignment variables, and scheduling variables, are defined as binary variables. All the other variables are defined as continuous variables. The constraints are specified to enforce those continuous variables to be assigned integer values only. The use of the continuous variables helps us to reduce the complexity of the formulation by reducing the number of binary variables significantly.
Table 1 shows the number of integer variables required for both dedicated and shared path protections. We assume a wavelength convertible network with $R$ edge-disjoint paths between each source-destination pair, $|K|$ channels per fiber and a set of $|L|$ scheduled lightpath demands.

<table>
<thead>
<tr>
<th>No. of integer variables required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault-free</td>
</tr>
<tr>
<td>$R.</td>
</tr>
<tr>
<td>ILP-D1/ILP-S1</td>
</tr>
<tr>
<td>$2 (R.</td>
</tr>
<tr>
<td>ILP-SDP [7]</td>
</tr>
<tr>
<td>ILP-SSP [7]</td>
</tr>
</tbody>
</table>

Table 1: Number of Integer Variables for ILP Formulations for wavelength convertible networks.

(In[7] $w$: working path, $p$: backup path)

Table 2 shows how the number of integer variables in the formulation varies with the number of demands ($|L|$) and the number of channels per fiber ($|K|$), for the 14-node, 21-link NSFNET topology. Here, ILP-D1 (ILP-S1) is our formulation for dedicated shared path protection under the sliding scheduled traffic model, respectively. The numerical results show that the number of integer variables in our formulation is significantly fewer, compared to the formulation (ILP-SSP) presented in [7] for the simpler fixed scheduled traffic model.

Figure 14 shows the same results as Table 2. Intuitively, we can see that the rate of increase is much slower for our formulations compared to ILP-SSP.
| |K| | |L| = 10 | |L| = 16 | |L| = 32 | |L| = 10 | |L| = 16 | |L| = 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 3540 | 5760 | 12032 | 5018 | 8984 | 23432 |
| 16 | 6900 | 11136 | 22784 | 8546 | 14528 | 34352 |
| 32 | 13620 | 21888 | 44288 | 15602 | 25616 | 56192 |
| 64 | 27060 | 43392 | 87296 | 29714 | 47792 | 99872 |

Table 2: Increase of integer variables with problem size

(14-node NSFNET, 21-link, R = 4, in [7] w = 2, p = 3)

Figure 14: Increase of integer variables with problem size (the number of demands |L| and the number of channels per fiber |K|), for the 14-node, 21-link NSFNET topology.
5.3 Results of ILP Formulations

In this section we first discuss the results for networks with wavelength conversion, obtained using ILP-D1 and ILP-S1. Results for networks without any path protection are obtained by modifying ILP-D1, as indicated in Section 3.5. For each case, we consider three distinct scenarios:

i. holding time unaware demands,

ii. demands with fixed setup and teardown times, and

iii. sliding window model, where the demands must be scheduled within a larger window. We considered window sizes that were 2 hours and 4 hours longer than the actual duration of the demand.

Figure 15 shows the results for a 14-node wavelength convertible network, with 16 demands ($|L| = 16$) and 32 channels per fiber ($|K| = 32$) and $\delta = 0.8$, using dedicated and shared protections. Results for $\delta = 0.01$ and $\delta = 0.5$ follow a similar pattern. We see that the fixed window model yields improvements of about 30% over the holding time unaware case for dedicated protection, 25% for shared protection, and 20% for no protection. Additional improvements (over the fixed window model) of about 2%, 12% and 5%, depending on the window size, can be obtained by using the sliding window model for the cases with no protection, dedicated protection and shared protection, respectively. Figure 15 also shows that, as expected, shared protection requires slightly fewer resources compared to dedicated protection. We note that the benefits of both the holding time aware RWA and the sliding window model are most prominent for dedicated protection. This is because dedicated protection typically requires the most resources and
therefore benefits to a greater degree from proper scheduling of the demands. The solutions for the *holding-time-unaware* case were obtained by setting $T_{l_{p,l_q}} = 1$, $\forall l_{p,l_q} \in L, p \neq q$ in the relevant ILPs.

![Figure 15: Comparison of resource requirements for 14-node wavelength convertible network](image)

We next consider results for networks without wavelength conversion (using ILP-D2 and ILP-S2). Figures 16, 17 and 18 show the corresponding results for the fault-free case, dedicated protection and shared protection, respectively, for the 10-node network with 16 demands ($|L| = 16$) and 32 channels per fiber ($|K| = 32$). We did not include results for the case where the sliding window is increased by 4 hours or 6 hours, since there was little additional improvement over the 2 hour case. Results for the 14-node network followed a similar pattern. As noted in Figure 15, the improvement with the sliding window is the greatest for dedicated protection.
Figure 16: Comparison of resource requirements for 10-node network without path protection

Figure 17: Comparison of resource requirements for 10-node network with dedicated protection

5.4 Results of Heuristic Approach

In this section, we present the results of our experiments on larger networks of up to 53 nodes (with topologies as given in [23]), using the heuristics given in Chapter 4. We varied the window size for each network and investigated how sliding flexibility in the demand setup/teardown times affected resource requirements. We found that, typically, improvements of at least 10% (15%) are realized for networks with (without) wavelength...
We see that, in all cases, the holding time unaware approach requires the most resources, since it is not able to reuse WDM channels for time-disjoint demands. The ILP formulations performed the best and required significantly fewer resources. Furthermore, it is interesting to note that the heuristic also performed quite well. The performance of the heuristic was validated by comparing with the ILP solutions for smaller networks, and we found out that the results were always within 10% - 15% of the optimal solution.

5.4 Results of Heuristic Approach

In this section, we present the results of our experiments on larger networks of up to 53 nodes (with topologies as given in [23]), using the heuristics given in Chapter 4. We varied the window size for each demand and investigated how adding flexibility to the demand setup/teardown times affected resource requirements. We found that, typically, improvements of at least 10% (15%) are realized for networks with (without) wavelength
conversion, even when compared to holding time aware solutions for the fixed window model. Much greater savings are possible over holding time unaware algorithms. Figure 19 shows the reduction in resource requirements with increasing window sizes for survivable wavelength convertible networks, using shared protection with a demand correlation $\delta = 0.8$. We used 32 demands $(|L| = 32)$ and 64 channels per fiber $(|K| = 64)$ for these experiments. The amount of savings increased with the amount of flexibility. For example, increasing the window size by 2 hours, 4 hours and 6 hours resulted in average savings of 11%, 14% and 15%, respectively, over the holding time aware fixed window model.

![Graph showing resource requirements with window size](image)

Figure 19: Variation of resource requirements with window size for networks with wavelength conversion ($\delta = 0.8$)

Figure 20 shows the corresponding values for networks without wavelength conversion. As expected, the resource requirements for such networks are slightly higher. The average improvements obtained by increasing the window size by 2 hours, 4 hours and 6 hours are 17%, 19.5% and 21%, respectively, in this case.
Finally, we also conducted experiments using larger demand sizes, up to $|L| = 80$. Since each demand typically consists of multiple lightpaths, the total number of lightpaths corresponding to these demand sets varied from 60 - 200. Figure 21 shows the average resource requirements for the 20-node network using shared protection and having demand correlation $\delta = 0.8$, both with and without wavelength conversion. Results for the other networks followed a similar pattern. We observe that resource requirements increase steadily with the number of demands and the sliding window model consistently leads to significant reductions over the fixed window model.
Figure 21: Variation of resource requirements with demand size for 20-node network ($\delta = 0.8$)

In the above simulations, we examined the optimisation of survivable WDM networks, both with and without wavelength conversion capabilities, under the sliding scheduled traffic model. We have considered both dedicated and shared path protection and shown that fully-dedicated networks can be treated as a special case of our formulations. We have also demonstrated that the fixed window model, where setup and tear-down times of the demands are specified ahead of time, can be easily handled with our approach by simply setting the window size equal to the demand holding time.

We have presented a number of ILP formulations that jointly optimize the scheduling and RWA of a set of demands for the sliding scheduled traffic model. We have shown that the complexity of our formulation (in terms of the number of integer variables) is lower, even compared to existing approaches, which only consider the RWA problem under the simpler fixed window model. Our formulations are able to generate optimal solutions for practical sized networks in a reasonable time.

We have also proposed a two-step heuristic approach, which can be used for large networks and validated its performance by comparing with optimal solutions for smaller networks.
Chapter 6

CONCLUSION AND FUTURE WORK

In this thesis, we focus on the optimal design of survivable WDM networks, both with and without wavelength conversion capabilities, under the sliding scheduled traffic model. We have considered both dedicated and shared path protection and shown that fault-free networks can be treated as a special case of our formulations. We have also demonstrated that the fixed window model, where setup and teardown times of the demands are specified ahead of time, can be easily handled with our approach by simply setting the window size equal to the demand holding time.

We have presented a number of ILP formulations that jointly optimize the scheduling and RWA of a set of demands for the sliding scheduled traffic model. We have shown that the complexity of our formulation (in terms of the number of integer variables) is lower, even compared to existing approaches, which only consider the RWA problem under the simpler fixed window model. Our formulations are able to generate optimal solutions for practical sized networks in a reasonable time.

We have also proposed a two-step heuristic approach, which can be used for large networks and validated its performance by comparing with optimal solutions for smaller networks.
We have shown that the sliding scheduled traffic model can lead to additional savings, even over connection holding time aware approaches for the fixed window model, by reducing demand overlap and increasing reuse of resources by time-disjoint demands.

6.1 Future Work

6.1.1 Resource Allocation under the Non-continuous Model

In both fixed and sliding window models, once the transmission of a demand is started, it continues until the entire data has been transmitted. However, there are many applications where such continuous data transmission is not strictly required. For example, a bank has to transfer its data nightly to a central location. The actual data transfer requires 1 hour and must be completed some time between 1am and 4am. In this case it is not necessary to send the data continuously; instead the data may be divided into several smaller components and each component is sent separately, as long as the entire data are transferred within the specified time window between 1am and 4am. We will refer to this type of data transmission model as the non-continuous sliding scheduled traffic model, where a demand is decomposed into two or more components and each component can be sent separately.

The non-continuous scheduled traffic model adds another degree of flexibility to the existing sliding window model, which can be exploited to generate more resource efficient solutions to the network design problem, or to accommodate more traffic for a given set of resource constraints.
In addition to the usual routing and wavelength assignment issues involved in scheduling lightpath demands, design strategies under the non-continuous model also need to take into consideration a number of other important factors such as:

- which demands (if any) should be divided into segments,
- the number and sizes of the segments for each demand, and
- how to schedule the individual segments to optimize resource utilization.

Therefore, resource allocation under the non-continuous model can be viewed as a complex optimization problem. We are currently investigating ILP formulation, as well as a heuristic for solving this problem.

6.1.2 **Resource Allocation using light-trails**

In a point-to-point lightpath based WDM network, the wavelength capacity may not be fully utilized due to the bandwidth mismatch of low-speed data streams and the high capacity of the lightpath. In recent years a concept of *light-trails* with sub-wavelength sharing, has been introduced to wavelength division multiplexing (WDM) optical mesh networks to improve utilization of the available network capacity. As indicated by Chlamtac and Gumaste [26], the light-trail technology is comprised of an architecture and a protocol that make dynamic opening possible for an optical path between any selected source and destination nodes, often referred to as a “trail” of length $t$, which allow optical communication (access) to any nodes between the source and destination without reconfiguring optical switches at individual nodes. It supports not only unicasting but also optical multicasting function.
Comparing with the use of traditional lightpath, the advantage of light-trail technique is that it gives the access right to the intermediate nodes on a light-trail, so that any intermediate nodes can use it to send or receive data. To add traffic load to a light-trail, the following constraints have to be satisfied:

i) it has to follow the same traffic direction of the light-trail, and

ii) the total traffic load supported by a light-trail does not exceed the capacity of the light-trail.

Clearly, the flexibility of using light-trail techniques leads to more efficient network utilization, but also increases the complexity of optimal design of survivable WDM networks. Next, we will focus on solving the joint problem of the topology design, route and wavelength assignment, and traffic routing in light-trail based WDM networks. We will also investigate the tradeoffs between the cost of increasing network components and high utilization of network capacity.
Bibliography


VITA AUCTORIS

Chen, Ying obtained her Bachelor of Computer Science Honors Co-op degree from the University of Windsor in 2007. She is currently pursuing her M.Sc. in Computer Science at the University of Windsor and hopes to graduate in Winter 2009.