Designing Survivable Wavelength Division Multiplexing (WDM) Mesh Networks

by

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Abstract

This thesis focuses on the survivable routing problem in WDM mesh networks where the objective is to minimize the total number of wavelengths used for establishing working and protection paths in the WDM networks. The past studies for survivable routing suffers from the scalability problem when the number of nodes/links or connection requests grow in the network. In this thesis, a novel path based shared protection framework namely Inter-Group Shared protection (I-GSP) is proposed where the traffic matrix can be divided into multiple protection groups (PGs) based on specific grouping policy. Optimization is performed on these PGs such that sharing of protection wavelengths is considered not only inside a PG, but between the PGs. Simulation results show that I-GSP based integer linear programming model, namely, ILP-II solves the networks in a reasonable amount of time for which a regular integer linear programming formulation, namely, ILP-I becomes computationally intractable. For most of the cases the gap between the optimal solution and the ILP-II ranges between (2-16)%. The proposed ILP-II model yields a scalable solution for the capacity planning in the survivable optical networks based on the proposed I-GSP protection architecture.

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Dedication

To my Grandparents

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Chapter 1

Introduction

The rapid growth and advances in the photonic communication technology have opened the door for Wavelength Division Multiplexing (WDM) based optical networks which carry data traffic in a rate of Tera-bit per second. Any unexpected disruption to such an ultra-high speed network may result in a huge loss to its end-users and the carrier itself. Thus survivability has been well-recognized as one of the most important objectives in the design of WDM mesh networks such that any unexpected interruption upon the working traffic can be restored in a short time to guarantee service continuity and data integrity. For this purpose, the effort of pre-planning spare capacity (i.e., protection paths) for the corresponding working capacity (i.e., working paths) has been well recognized as one of the most effective approaches. With pre-planned spare capacity, the working paths affected by the failure can be switched over to the protection paths for maintaining service continuity. This task is known as survivable routing where the traffic demand is known in advance.

1.1 Objectives

This thesis focuses on the survivable routing problems where the objective is to minimize the total number of wavelengths used for establishing working and protection paths in the networks. In this study, the survivable routing problem is formulated as follows: given a set of traffic demand and a WDM network, the objective is to establish the lightpaths (both working and protection) in the network for the given demand while minimizing the number of wavelength channels.

1.2 Contributions

To develop an effective scheme that can be both capacity-efficient and computation-efficient has long been a challenge. The past studies for survivable routing took approaches of optimization for allocating the working and protection paths. A limitation of such approaches is that as the number of nodes/links or connection requests grow, the problem quickly becomes computationally intractable even in moderate-sized networks. To overcome the scalability problem, one of the most commonly adopted ideas is to divide the traffic demands into different protection groups (PGs).

In this thesis, a path based shared protection framework is proposed namely Inter-Group Shared Protection (I-GSP) that divides the total traffic demand (i.e., traffic matrix) into multiple PGs and optimization is conducted on each of the PG where sharing of protection resources between the PGs is considered. Based on the I-GSP framework, this thesis introduces an Integer Linear Programming (ILP) model, namely ILP-II which optimizes the task of resource allocation in each PG where sharing of protection resources between the PGs is allowed. The working paths in each PG are mutually link-disjointedly routed. To compare the capacity efficiency of ILP-II, ILP-I is introduced which also formulates path based shared protection but optimization is conducted on the total traffic matrix. It is clear that ILP-I will produce the optimal solution since the optimization is performed on the total traffic matrix, but will become computationally intractable when the network size and traffic demand grow [4,6,7,16,17,38]. Results from ILP-I will be compared with ILP-II to evaluate the gap between the optimal and ILP-II solution. A dedicated protection scheme is also implemented, namely, ILP-III which is similar to the ILP-I except that no sharing of spare resources is allowed. Results from ILP-III will be used to compare the capacity efficiency between “sharing” and “no-sharing” scenarios. The performance and the computation complexity of each model will be investigated.

1.3 Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 formulates the problem. In chapter 3, a whole picture of survivable design for the mesh WDM networks is presented as well as a number of representative reported schemes are discussed. Chapter 4 introduces the proposed I-GSP survivable routing scheme. Simulation results are reported in chapter 5. Finally, a summary of the thesis and some future research directions are presented in Chapter 6.

Chapter 2

Problem Formulation

Let the network be denoted as *G*(*V,E*), where *V* and *E* are the set of nodes and directional links in the network, respectively. Suppose a traffic pattern defined in a traffic matrix *T* is given in advance. The design objective is to minimize the total number of wavelength channels used for establishing the working and their corresponding protection paths for traffic matrix *T* for achieving 100% restorability, where the shared protection is adopted in each matrix and the single failure scenario is assumed.

Let $x_{i,j}^{k^{\lambda}}$ be a binary variable that takes on a value of 1 if working path *k* goes through link *(i,j)* using wavelength λ, and 0 otherwise. Let $y_{i,j}^{k^{\lambda}}$ indicates whether wavelength λ is used by protection path *k* on link (*i,j*). This binary variable takes on a value of 1, if wavelength is used, 0 otherwise. Objective function for this problem can be formulated as follows:

Minimize

$$\sum_{i,j}\sum_{k}\sum_{\lambda} x_{i,j}^{k^{\lambda}} + \sum_{i,j}\sum_{k}\sum_{\lambda} y_{i,j}^{k^{\lambda}}$$

The above target function aims to establish the working-protection path pairs for all the connection requests in given traffic matrix *T* over the network *G*, such that the total number of wavelength channels used is minimized. Following assumptions are made:

- The number of wavelength channels available along each link is limited
- The wavelength conversion capability is not present in the network

- Sharing of wavelengths among the protection paths within a group and between the groups is allowed
- A particular wavelength λ on link *(i.j)* can only be used either by a working path *k* or by a protection path *k* or can be shared by protection paths
- A working path and its corresponding protection path are always link-disjointedly routed
- If a wavelength λ is shared by two or more protection paths, their corresponding working paths are link-disjointedly routed

Chapter 3

Background

Important concepts that are necessary for a complete understanding of the materials discussed in this thesis are introduced as well as the state-of-the-art progress in the survivable routing scheme in WDM mesh networks is presented in this chapter.

3.1 Concepts, Terminologies, and Related Work

3.1.1 Wavelength Division Multiplexing (WDM)

A WDM system uses a multiplexer at the source to multiplex several wavelength channels on to a single fiber and demultiplexes the composite signal at the receiving end with the help of a demultiplexer [1].

3.1.2 Lightpath and Wavelength Continuity Constraint

In WDM networks, a connection request is satisfied by establishing a lightpath from the source node of the connection to the destination node. A lightpath is an all-optical channel which may span multiple fiber links, to provide a circuit-switched interconnection between two nodes.

In the absence of wavelength converters, a lightpath would occupy the same wavelength on all fiber links that it traverses. This is called the wavelength-continuity constraint. Two lightpaths on a fiber link must also be on different wavelength channels to prevent the interference of the optical signals [2].

3.1.3 Shared Risk Link Group (SRLG)

SRLG is defined as a group of network elements (i.e., links, nodes, physical devices, software/protocol identities, or a combination thereof) subject to the same risk of single failure [4]. In practical cases, an SRLG may contain multiple seemingly unrelated and arbitrarily selected links/nodes. The fact that two paths do not take any common SRLG is referred to as the SRLG-disjointedness, which is the major effort of achieving 100% restorability under a single failure scenario if one of the paths is taken as the working path and the other is taken as the protection path. A working path is considered involved in a SRLG only if it traverses through any network element that belongs to the SRLGs. A path may be involved in multiple SRLGs. This study focuses on the case that each arc in the network topology is an SRLG, where an arc is composed of two links in opposite directions terminated by two adjacent nodes in the network topology. Thus, a working path traversing through H hops will be involved in H different SRLGs. To achieve 100% restorability, it is sufficient and necessary for every link traversed by the working path to be protected by at least one link-disjoint protection path. In the event where a failure interrupts a working path, the switching fabric in each node along the corresponding protection path is configured by prioritized signaling mechanisms; then traffic-switchover is performed to recover the original service supported by the working path. Therefore, the protection path of different working paths can share spare capacity if their working paths are not involved in any common SRLG. In other words, whether two protection paths can share spare capacity depends on the physical location of their working paths. The dependency is the reason for the existence of the SRLG constraint. A simple example [4] is shown in Fig. 1 where W_1 and P_1 form a working and protection path-pair. The backup path of W_2 (another working path) should exclude the possibility of using any of the spare capacity (or wavelength channels) taken by P_1 because W_2 traverses link A-B, which shares the same risk of a single failure with W_1.

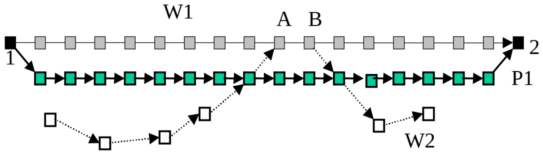


Fig. 1: An example to illustrate the SRLG constraint

With survivable routing, two types of protection schemes are defined – dedicated and shared protection, according to whether or not resource sharing (i.e., wavelength sharing) is allowed between different protection lightpaths. The SRLG disjointedness between the working and the corresponding protection path must be guaranteed for both dedicated and shared protection.

3.1.4 Dedicated Protection

Dedicated protection (i.e., 1+1 or 1:1) provides a very fast restoration service at the expense of the fact that the ratio of redundancy (i.e., the ratio of capacity taken by protection and working paths in the network) usually reaches 100%. To implement dedicated protection in mesh WDM networks, the physical routes for the working and protection paths must be determined. With 1+1 dedicated protection, each working and protection path-pair is pre-configured, and is launched with the same copy of data transmitted between a source-destination pair during the normal operation. The two paths are SRLG-disjoint such that no any single failure will affect both paths at the same moment. The 1:1 dedicated protection, on the other hand, only has the working path to be launched with data traffic while the capacity reserved by the protection path is not in use.

3.1.5 Shared Protection

The concept of SRLG serves as the key role in the development of shared protection schemes. It has been observed that the resource sharing between different protection paths can substantially reduce the ratio of redundancy required to achieve 100% restorability [5]. For shared protection, the spare capacity (i.e., wavelength) taken by protection paths can possibly be shared by some other protection paths. The SRLG disjointedness must exist not only between the working-protection path-pair, but also among the working paths for which the corresponding protection paths share the same wavelength. It is clear that the implementation of shared protection imposes one more disjointedness requirement than that for dedicated protection. This leads to a fact that the development of shared protection schemes is generally more complicated.

From the implementation point of view, the survivable routing schemes can be divided into two categories: the link-oriented and path-oriented. The former restores the working capacity once subject to any unexpected interruption by switching to and merging back from the corresponding spare capacity at the two ends of the link. On the other hand, the latter case addresses spare capacity for each working path and investigates the link-disjointedness constraint in the networks.

3.1.6 Link-oriented Shared Protection

In a mesh network, link-oriented schemes have been well recognized as feasible approaches with high restoration speed but low capacity efficiency [18,19]. The fast restoration from a failure is due to the fact that the deployment of spare capacity along each link is dedicated to the working capacity along a specific physical span, which may yield a smaller length of protection cycles.

In terms of WDM networks with multi-service environments, the link-oriented approach nonetheless falls short of means in service differentiation and manipulation of distribution for the spare capacity. Note that each lightpath in the optical domain is taken as a discrete bandwidth unit with a specific service level agreement. In the event that the wavelength continuity constraint (e.g., the case without wavelength conversion or with partial/sparse wavelength conversion) is considered, most of the reported link-oriented approaches can hardly be applied except being provided with some extent of modifications. However, these modifications may largely increase the computation complexity by jointly considering the working capacity on multiple wavelength planes and the lightpaths with different class of services along each link [4]. Some of the major link-oriented protection schemes include Minimum Node-Cover [19,21], Ring-Cover [22, 23, 24], and P-cycle [25,26,27].

3.1.7 Path-oriented Shared Protection

With the path-oriented approach, spare capacity for a working path is allocated along a protection path that is link-disjointedly routed with the working path. The path-oriented approach can create a better platform of achieving service differentiation and traffic engineering for both working and protection paths. In a mesh network, path protections are more feasible than link protections with available technologies. Link protection schemes depend on fault localization, while no fault localization is necessary for path protection. Path rerouting performed at the edge of the network may allow some or all of the recovery functions to be moved into the end-system. Thus, it simplifies network design, and allows applications to make use of application specific information such as tolerance for latency in making rerouting decisions [3]. Path based survivable routing has been considered in this study.

Path-oriented spare capacity allocation can be performed by formulating the problem either into ILP or heuristics. Compared with the link-oriented spare capacity allocation schemes, much less efforts have been put on the path-oriented ones in the past due to its high computation complexity and unsuitability for networks mostly supporting best effort traffic. However, as the connection-oriented traffic with QoS requirements is expected to dominate the network control and management, the path-oriented approach is becoming more important than ever, particularly for the spare capacity allocation in All-Optical WDM networks where each lightpath is nonetheless transparent and subject to several constraints. However, with the much improved computing power nowadays compared with the situation a decade ago when the span-oriented ones were the only choice for network designers, the path-oriented scheme becomes an alternative with much promise for achieving better service differentiation and capacity efficiency particularly for mesh WDM networks. Depending on the size of the problem (i.e., number of nodes, number of links, number of wavelengths, number of traffic demands etc.), the running time for the path oriented survivable routing solution may vary from few minutes to few days. Even with high-end computational facilities, such optimization task often become computationally intractable and even running after few weeks, results may not be obtained. On the other hand, heuristics can be developed that can solve the above problem in polynomial time, but they are far from the optimal. A balance between the time and the level of optimization is desired where a solution can be obtained in a reasonable time frame while minimizing the resource consumption as much as possible. A number of major reported survivable routing schemes are detailed below.

Since the optimization for path oriented survivable routing is usually subject to a very high computation complexity even in a middle-sized network, the scalability and computation-efficiency have long been a major challenge in the design of the algorithms. Most of the previous work on spare capacity allocation of mesh WDM networks modeled the static protection design as an integer linear programming (ILP) problem. Unfortunately, the resulting ILP formulation is NP-hard [6]. To obtain the optimal solution for even a small size network, such as a few tens of nodes, is very time consuming using available mathematical tools [3].

Without considering grouping, the studies on path shared protection have been reported in the past few years [6-11]. [7] examined both path and link protection approaches to survive single-link failures in an optical network where authors formulated ILPs to determine the capacity utilization for different protection schemes for a static traffic demand. The numerical results indicate that shared-path protection provides significant savings in capacity utilization over dedicated-path and shared-link protection schemes. Relaxation methods are also proposed in a number of literatures to approximate the IP solution. In [8], authors examined relaxations to ILP that find survivable routings with reduced complexity. The basic idea behind these relaxations is to enforce only a subset of the cut-set constraints. Lagarangian relaxation, which decomposes the original complex problem into several easier sub problems, was used by Doshi et al [9]. Simulated annealing and Tabu searching based methods were proposed in [6, 10] and [11], respectively. Two-Step-Approach (TSA) based heuristics are also reported in [28-37] where shortest paths between each S-D pair are iteratively inspected one after the other until the least-cost working and protection path-pair is derived.

On the other hand, grouping of network resources has been considered in the studies in [12-16]. The study in [13] elaborates this idea by grouping working paths with a relatively diverse distribution in the network topology and shows simulation results comparing different grouping policies: Most-diverse, Most-overlapped, and Randomly-distributed. An analysis is given to the performance versus computation complexity. ILP-II in this thesis differs from the Most-diverse [13] by the fact that, Most-diverse approach selects the mutually link-disjoint working paths from already established working paths to form a group, whereas ILP-II grouping algorithm forces the working paths to be mutually link-disjointedly routed to form a protection group. In [15], working paths are grouped such that the optimization is interleaved into multiple sub-processes, each of which is calculated sequentially to reduce the total computation complexity. The survivability issue in the design of networks with inter group sharing has never been addressed.

Chapter 4

Inter-Group Shared Protection (I-GSP)

To achieve network survivability, the most commonly seen approach is to allocate spare capacity for the working capacity such that the affected working traffic can be restored by switching over to the protection paths which are Shared Risk Link Group (SRLG) [17–19] disjoint from the corresponding working paths. The design premise for protection is straightforward. However to develop an effective scheme that can be both capacity-efficient and computation-efficient has long been a challenge. The most difficult problem is to make the schemes scalable with the network size and the amount of traffic. Due to the huge computation complexity, the most intuitive approach for allocating working and spare capacity in such networks is to group the working capacity and to conduct optimization upon each group. Each group of connections is called a *Protection Group* (PG) where a specific protection scheme can be arranged.

In this chapter, a novel path shared protection architecture namely Inter-Group Shared Protection (I-GSP) has been proposed. I-GSP is aimed at providing a general framework for static survivable routing schemes in WDM mesh networks. In the I-GSP framework, n protection groups are defined in the networks, each of which supports N working paths protected by M protection wavelengths where protection resources (i.e., wavelengths) are shared among M protection wavelengths in a group and also among n protection groups. The link-disjointedness of the working paths has been taken as the grouping policy for creating the protection groups.

The design of the I-GSP scheme aims at overcoming the scalability issue by sub-grouping working lightpaths in the networks into multiple protection groups and also aims at achieving near-optimal performance in terms of capacity efficiency by sharing the protection wavelengths not only within a PG, but also between the PGs. In addition to the scalability that can be gained due to the sub-grouping of the network traffic in the control plane, I-GSP reduces the number of affected working paths due to a single link failure in the network. I-GSP requires the working paths to be link-disjointedly routed in a single PG, the number of working paths along a link is upper-bounded by the number of PGs in the network. Thus, the number of working paths affected by a single failure is also well bounded.

Based on the I-GSP framework, this thesis introduces a novel ILP model, namely ILP-II, which serves as a solution to the survivable routing problem. ILP-II breaks down the total traffic matrix into multiple small PGs where all the working paths in each PG are mutually link-disjointedly routed, while ILP-I optimizes the task of resource allocation by taking the whole traffic demand as a single PG. The motivation of introducing ILP-II is to overcome the scalability problem that may arise in the ILP-I scheme when the amount of traffic demands is large. Note that ILP-I could be subject to intolerably lengthy computation in solving the ILP formulation in such a situation. A dedicated protection scheme is also formulated into an ILP namely, ILP-III which is very similar to the ILP-I except there is no sharing of protection resources. ILP-II is expected to solve large size traffic matrix even with high nodal degree in much shorter time than ILP-I.

4.1 ILP-I

ILP-I is designed to optimally allocate the working and spare capacity considering the total traffic demand (i.e., traffic matrix) such that the total number of wavelength channels required for the working and protection paths is minimized. With ILP-I, the total traffic matrix *T* is considered as an individual PG in which protection paths may share spare capacity, and the ILP formulation for allocating the working and protection paths for *T* is solved using CPLEX [20].

Let $x_{i,j}^{k^{\lambda}}$ be a binary variable that takes on a value of 1 if working path *k* goes through link *(i,j)* using wavelength *λ*, and 0 otherwise. Let $y_{i,j}^{k^{\lambda}}$ indicates whether wavelength *λ* is used by protection path *k* on link (*i*,*j*). This binary variable takes on a value of 1, if wavelength is used, 0 otherwise. Let $z_{i,j}^{\lambda}$ indicates whether wavelength *λ* is used by any protection path on link (*i*,*j*), which takes on a value of 1 if the wavelength channel is used, and 0 otherwise. "src" and "dst" in the following formulation represent the source and the destination node of a connection request in *T*, respectively.

ILP-I is formulated as follows:

Minimize

$$\sum_{i,j}\sum_{k}\sum_{\lambda} x_{i,j}^{k^{\lambda}} + \sum_{i,j}\sum_{\lambda} z_{i,j}^{\lambda} \qquad (1)$$

Subject to

$$\sum_{j}\sum_{\lambda} x_{i,j}^{k^{\lambda}} - \sum_{j}\sum_{\lambda} x_{j,i}^{k^{\lambda}} = \begin{cases} 1, & if \quad i = src \\ -1, & if \quad i = dst \\ 0, & \text{otherwise} \end{cases} \qquad (2)$$

$$\sum_{j}\sum_{\lambda} y_{i,j}^{k\lambda} - \sum_{j}\sum_{\lambda} y_{j,i}^{k\lambda} = \begin{cases} 1, & if \quad i = src \\ -1, & if \quad i = dst \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$\sum_{i} x_{i,j}^{k\lambda} - \sum_{i} x_{j,i}^{k\lambda} = 0; \quad j \neq src, j \neq dst \tag{4}$$

$$\sum_{i} y_{i,j}^{k\lambda} - \sum_{i} y_{j,i}^{k\lambda} = 0; \quad j \neq src, j \neq dst \tag{5}$$

$$\sum_{k} x_{i,j}^{k\lambda} + y_{i,j}^{k\lambda} \leq 1 \tag{6}$$

$$\sum_{\lambda} x_{i,j}^{k\lambda} + \sum_{\lambda} y_{i,j}^{k\lambda} + \sum_{\lambda} y_{j,i}^{k\lambda} \leq 1 \tag{7}$$

$$\sum_{k}\sum_{\lambda} x_{i,j}^{k\lambda} + \sum_{k}\sum_{\lambda} y_{i,j}^{k\lambda} \leq \lambda^{MAX} \tag{8}$$

$$y_{i,j}^{k\lambda} \leq z_{i,j}^{\lambda} \tag{9}$$

$$\sum_{k}\sum_{\lambda'} ((y_{i,j}^{k\lambda} + x_{i',j'}^{k\lambda'} - 1) + (y_{i,j}^{k\lambda} + x_{j',i'}^{k\lambda'} - 1)) \leq 1 \tag{10}$$

Eq. (1) is the target function aiming to establish working-protection path pairs such that the total number of wavelength channels used is minimized by the maximum sharing of protection resource.

Eq. (2) and Eq. (3) address the flow conservation constraint (i.e., satisfying traffic demands in the network) for the working and protection paths to ensure the end-to-end connectivity.

Eq. (4) and (5) ensure the wavelength continuity constraint for working and protection path, respectively.

Eq. (6) ensures that a particular wavelength λ on link *(i.j)* can only be used either by a working path *k* or by a protection path *k* or can be shared by protection paths.

Eq. (7) ensures that a working path and its corresponding protection path are always link-disjointedly routed.

Eq. (8) limits the number of wavelength channels available on link *(i,j)* where λ^{MAX} is a constant.

Eq. (9) ensures the maximum sharing of spare capacity among protection paths. Eq. (10) ensures that if a wavelength λ is shared by two or more protection paths, their corresponding working paths are link-disjointedly routed.

4.2 ILP-II

It is clear that the computation time taken by ILP-I is increased rapidly as the network size or the number of connections defined in *T* is getting larger [4,6,7,16,17,38]. This section proposes a novel integer linear programming formulation, namely ILP-II for the purpose of achieving better scalability without losing much capacity-efficiency. The proposed ILP-II framework is based on the *I-GSP* framework, where each of the PGs has a number of link-disjoint working paths protected by their corresponding protection paths. With this grouping policy, the followings are observed: (a) the number of working paths in each of the *PGs* is well constrained due to the link-disjointedness of the working paths; (b) it is expected that the number of affected working paths due to a link failure in a PG, will be less than the case where the working paths in a PG are shortest path routed. Fig. 2.a and 2.b illustrate this scenario.

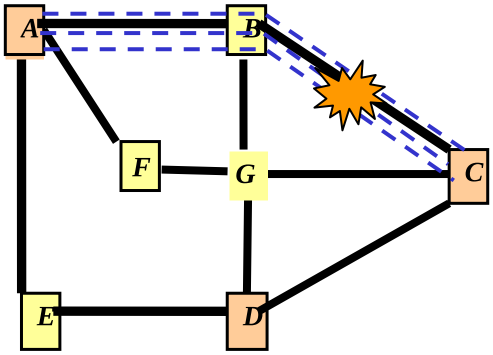


Fig.2.a Working paths are “Shortest-path” routed

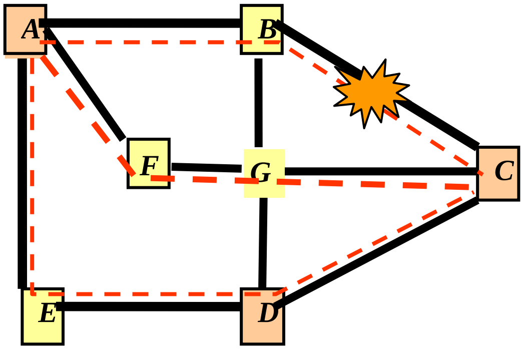


Fig.2.b Working paths are mutually link-disjoint routed

Let’s assume Fig.2.a represents a PG where the working paths are shortest-part routed. In this example, three working paths between A and C are shortest-path routed A-B-C. Now let’s assume Fig. 2.b represents a PG which follows I-GSP framework. In this example, all the three working paths between A-C are mutually link-disjointedly routed through three different paths which are, A-B-C; A-F-G-C; and A-E-D-C, respectively. Note that in case of a failure either on A-B or B-C, I-GSP based PG is less affected than PG in Fig.2.a.

ILP-II works in two stages. In stage 1, the source-destination pairs in the traffic matrix *T* are grouped into multiple PGs. The purpose of this grouping algorithm is to create the PGs for *T* and provides guarantee of mutual link-disjointedness of the working paths in each PG. The creation of such PGs for a particular *T* guarantees that the constraint (20) in ILP-II is always satisfied and thus preventing the ILP-II from becoming infeasible. It is important to mention that these working and protection paths will be reconfigured in stage 2 of ILP-II according to the optimization procedures. Given a network *G(V,E)* and a traffic matrix *T* to be established, following pseudo code explains the grouping algorithm that takes the traffic entries sequentially from the given traffic matrix and places them into appropriate PGs.

Pseudo Code:

Notations:

src: source of a lightpath

dst: destination of a lightpath

G(V,E): A network *G* with set of *V* nodes and *E* edges

$W^{current\_group\_index}$: Set of working paths routed link-disjointedly with each other in PG *current_group_index*

T : Traffic matrix

PG_n : n^{th} PG

$T_{src,dst}$: Total traffic demand for src-dst

$D_{src,dst}$: a single lightpath demand from a source *src* to a destination *dst*

Input: network ***G(V,E)*;** Traffic matrix ***T***

Output: Set of PGs $PG_1 \dots PG_n$

```
for ( src = 0; src < V; src++)
   for ( dst = 0; dst < V; dst++)

while ($T_{src,dst}$ > 0)
       {
            current_group_index ← 0
            while ( current_group_index <= num_groups)
                        {
                                    if  ($D_{src,dst}$ for src-dst can be routed link
                                         disjointedly with $W^{current\_group\_index}$ in group current_group_index)
                                         {
                                                $T_{src,dst}$ --;
                                                break;
                                         }
                                    else
                                                current_group_index++;
                        } // end while



            if  ($D_{src,dst}$  can not be satisfied in existing groups)
                        {
                        create a new group: num_groups++;
                        route $D_{src,dst}$ for src-dst in newly created group $PG_{num\_groups}$
                        }
          } // end while
```

Flowchart in Fig. 3 explains how ILP-II breaks down traffic matrix *T* into a smaller number of PGs where the working paths are link-disjointedly routed with each other.

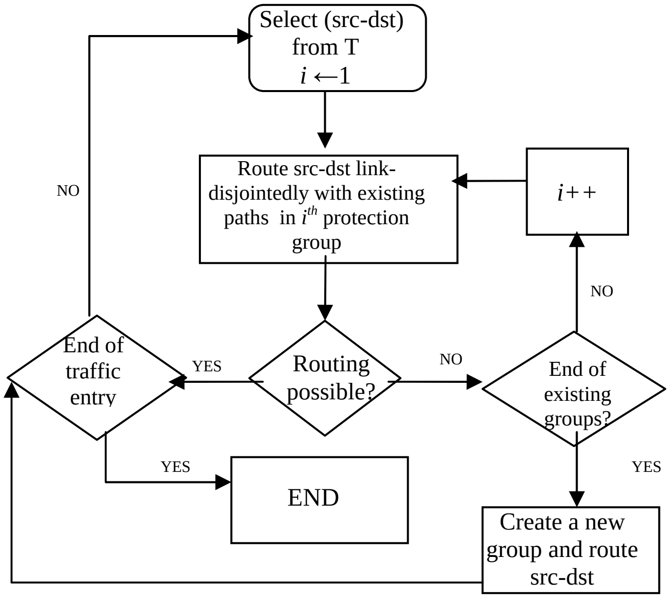
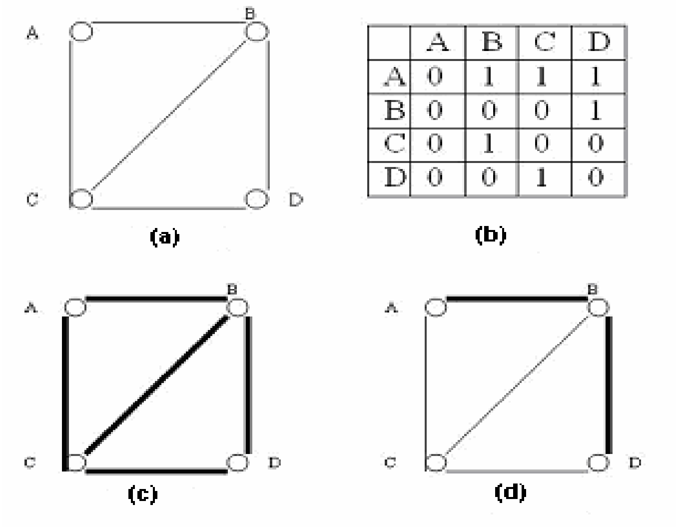


Fig. 3. Dividing *T* into multiple PGs

By using the above grouping algorithm, in Fig. 4, connection request *A-B, A-C, B-D, C-B* and *D-C* can be accommodated in PG_1. Traffic along *A-D* cannot be placed in the PG_1 and hence needs to be placed in a new PG $_2$. Thus *T* can be broken down into small PGs (i.e., set of src-dst pairs) based on their working paths. Once the PGs are created, in stage 2, ILP-II is applied to each of these PGs sequentially to allocate working and protection resources in a single step where sharing of protection wavelengths between PGs is considered (i.e., inter-group sharing). Fig. 4 shows how *T* is broken down into two PG_1 and PG_2.



	A	B	C	D
A	0	1	1	1
B	0	0	0	1
C	0	1	0	0
D	0	0	1	0

Fig. 4. Dividing traffic matrix *T* into multiple PGs
(a) G(V,E) (b) T (c) PG $_1$ (d) PG $_2$

To add the link-disjoint constraint for enforcing the working paths to be link-disjointedly routed with each other in each PG, an extra constraint in Eq. (20) is added in ILP-II formulation. “src” and “dst” in the following formulation represent the source and the destination node of a connection request in *T*, respectively.

Minimize

$$\sum_{i,j}\sum_{k}\sum_{\lambda} x_{i,j}^{k^{\lambda}} + \sum_{i,j}\sum_{\lambda} z_{i,j}^{\lambda} \tag{11}$$

Subject to

$$\sum_{j}\sum_{\lambda} x_{i,j}^{k^{\lambda}} - \sum_{j}\sum_{\lambda} x_{j,i}^{k^{\lambda}} = \begin{cases} 1, & if \quad i = src \\ -1, & if \ \ i = dst \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

$$\sum_{j}\sum_{\lambda} y_{i,j}^{k^{\lambda}} - \sum_{j}\sum_{\lambda} y_{j,i}^{k^{\lambda}} = \begin{cases} 1, & if \ \ i = src \\ -1, & if \ \ i = dst \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

$$\sum_{i} x_{i,j}^{k^{\lambda}} - \sum_{i} x_{j,i}^{k^{\lambda}} = 0; \quad j \neq src, j \neq dst \tag{14}$$

$$\sum_i y_{i,j}^{k^\lambda} - \sum_i y_{j,i}^{k^\lambda} = 0;\ \ j \neq src, j \neq dst \tag{15}$$

$$\sum_k \ x_{i,j}^{k^\lambda} + y_{i,j}^{k^\lambda} \le 1 \tag{16}$$

$$\sum_\lambda \ x_{i,j}^{k^\lambda} + \sum_\lambda \ y_{i,j}^{k^\lambda} + \sum_\lambda \ y_{j,i}^{k^\lambda} \le 1 \tag{17}$$

$$\sum_k \sum_\lambda x_{i,j}^{k^\lambda} + \sum_k \sum_\lambda y_{i,j}^{k^\lambda} \le \lambda^{MAX} \tag{18}$$

$$y_{i,j}^{k^\lambda} \le z_{i,j}^{\lambda} \tag{19}$$

$$\sum_\lambda \sum_k x_{i,j}^{k^\lambda} + \sum_\lambda \sum_k x_{j,i}^{k^\lambda} \le 1 \tag{20}$$

Eq. (20) in the above formulation is a constraint ensuring the link-disjointedness of all the working paths in a PG.

The network state information is captured from the output of the ILP-II each time a particular PG is solved. This information is used by the other PGs for inter-group sharing purpose. The wavelength consumption information is stored in a matrix and updated each time a PG is solved by the ILP-II. Fig. 5 illustrates with an example how inter-group sharing is performed in ILP-II.

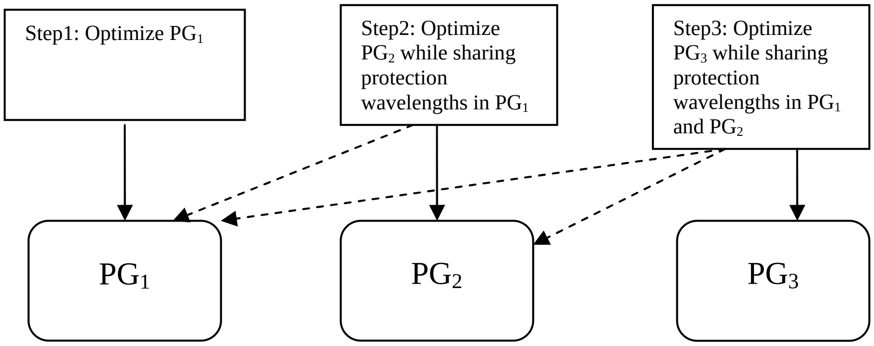


Fig. 5. Inter-group sharing in ILP-II

In the above example, 3 PGs are created from the traffic matrix *T*, namely PG_1, PG_2, and PG_3. ILP-II will be first applied to PG_1 and optimization will be performed only on this group. Upon the optimization of PG_1, the working and protection path information (i.e., network state information) will be collected and will be propagated to the ILP-II formulation for solving PG_2. While solving PG_2, ILP-II will consider sharing the protection resources used in PG_1, if possible. Once PG_2 is solved, the working and protection information will be propagated to PG_3 for formulating ILP-II for PG_3. At this stage, information from PG_1 will also be used by PG_3 formulation. This will allow ILP-II to share protection resources used in PG_1 and PG_2 for solving PG_3. Note that, once the working path and protection paths are configured in a protection group, they will never be reconfigured at a later stage.

4.3 ILP-III

A dedicated protection is implemented namely ILP-III in this section where each working path is protected by a dedicated protection path. ILP-III optimizes the allocation of working-protection path pairs corresponding to the traffic demand defined in a traffic matrix *T*, which is shown as follow:

Minimize:

$$\sum_{i,j}\sum_{k}\sum_{\lambda} x_{i,j}^{k^{\lambda}} + \sum_{i,j}\sum_{k}\sum_{\lambda} y_{i,j}^{k^{\lambda}} \tag{21}$$

Subject to:

$$\sum_{j}\sum_{\lambda} x_{i,j}^{k^{\lambda}} - \sum_{j}\sum_{\lambda} x_{j,i}^{k^{\lambda}} = \begin{cases} 1, & if \quad i = src \\ -1, & if \quad i = dst \\ 0, & \text{otherwise} \end{cases} \tag{22}$$

$$\sum_{j}\sum_{\lambda} y_{i,j}^{k^{\lambda}} - \sum_{j}\sum_{\lambda} y_{j,i}^{k^{\lambda}} = \begin{cases} 1, & if \quad i = src \\ -1, & if \quad i = dst \\ 0, & \text{otherwise} \end{cases} \tag{23}$$

$$\sum_{i} x_{i,j}^{k^{\lambda}} - \sum_{i} x_{j,i}^{k^{\lambda}} = 0; \quad j \neq src, j \neq dst \tag{24}$$

$$\sum_{i} y_{i,j}^{k^{\lambda}} - \sum_{i} y_{j,i}^{k^{\lambda}} = 0; \quad j \neq src, j \neq dst \tag{25}$$

$$\sum_{k} x_{i,j}^{k\lambda} + \sum_{k} y_{i,j}^{k\lambda} \leq 1 \tag{26}$$

$$\sum_{\lambda} x_{i,j}^{k\lambda} + \sum_{\lambda} y_{i,j}^{k\lambda} + \sum_{\lambda} y_{j i}^{k\lambda} \leq 1 \tag{27}$$

$$\sum_{k} \sum_{\lambda} x_{i,j}^{k\lambda} + \sum_{k} \sum_{\lambda} y_{i,j}^{k\lambda} \leq \lambda^{MAX} \tag{28}$$

Eq. (21) is the target function aiming to establish working-protection path pairs such that the total number of wavelength channels used is minimized.

Eq. (22) and Eq. (23) address the flow conservation constraint (i.e., satisfying traffic demands in the network) for the working and protection paths to ensure the end-to-end connectivity. Eq. (24) and (25) ensure the wavelength continuity constraint for working and protection path, respectively.

Eq. (26) ensures that a particular wavelength λ on link *(i.j)* can only be used either by working path *k* or protection path *k*.

Eq. (27) ensures that a working path and its corresponding protection path are always link-disjointedly routed.

Eq. (28) limits the number of wavelength channels available on link *(i,j)* where λ^{MAX} is a constant.

Chapter 5

Results and Discussion

CPLEX linear optimizer [20] is used to solve ILP-I, ILP-II, and ILP-III running on a dedicated Intel Pentium 4, 2.8 GHz dual processor PC with 1GB of physical memory. The performance metrics taken in this study are the total number of wavelengths taken by working and protection paths, the computation time, and number of affected working paths due to a link failure.

5.1 Network Topology and Simulation Parameters

The simulation is conducted on six different topologies (Fig. 6 - Fig. 11), which are chosen as representatives of typical optical mesh topologies [6]. The following assumptions are made in the simulation: (a) every connection request is a single lightpath that occupies a wavelength channel as traversing through the corresponding links; (b) no wavelength conversion facility is present in the network; (c) each node can serve as an ingress or egress node of the network; and (d) each physical link is equipped with dual fiber in which 8 wavelengths are available in each direction. Dijkstra's shortest path algorithm (in terms of hop counts) is adopted as a routing scheme in implementing the grouping algorithm.

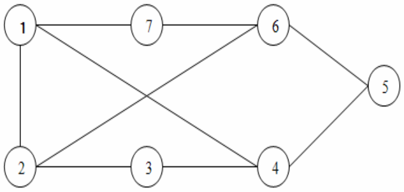


Fig. 6. 7 node test topology

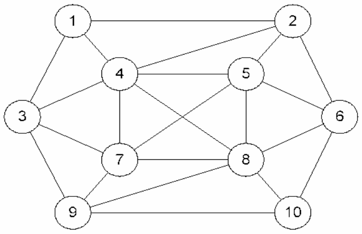


Fig. 7. 10 node test topology

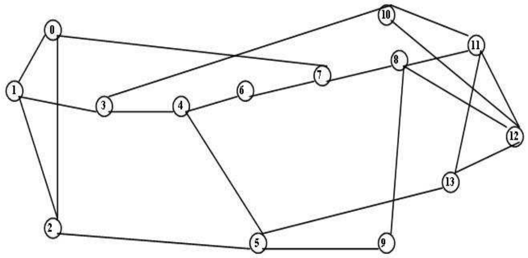


Fig. 8. 14 node NSFNET [7]

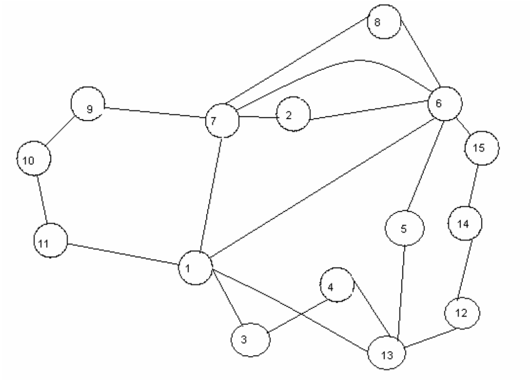


Fig. 9. 15 node test topology

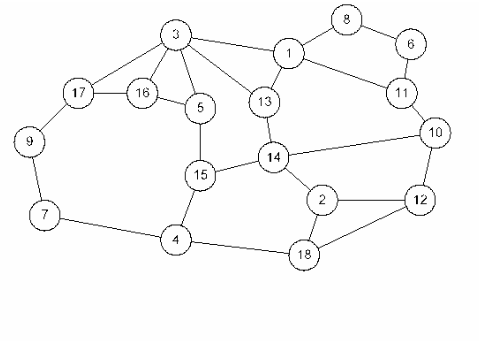


Fig. 10. 18 node test topology

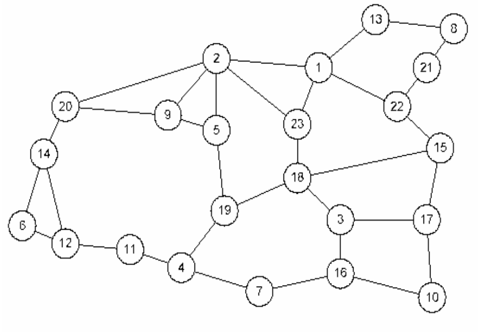


Fig. 11. 23 node test topology

We classify whether the traffic matrix *T* (i.e., number of connection requests) is small, medium or large based on the number of connections it requires. Table 1 defines the Traffic matrix types (small (S), medium (M), and large (L)) and their corresponding number of connections for the experiments.

TABLE I
SMALL, MEDIUM AND LARGE TRAFFIC MATRIX

T Type	**Number of Connections**
SMALL **(S)**	10
MEDIUM **(M)**	20
LARGE **(L)**	30

5.2 Capacity Efficiency

Table II shows the number of wavelength channels used in ILP-I, ILP-II and ILP-III.

TABLE II
NUMBER OF WAVELENGHTS USED BY ILP-I, ILP-II, AND ILP-III SCHEMES

|V|	T	ILP-I (number of wavelengths)			ILP-II (number of wavelengths)			ILP-III (number of wavelengths)		
		S	**M**	**L**	**S**	**M**	**L**	**S**	**M**	**L**
7	T^1	27	47	66	31	53	73	47	97	**Inf
	T^2	25	43	59	28	49	65	46	91	Inf
	T^3	28	47	61	32	51	63	45	87	Inf
10	T^1	24	*Int	Int	25	43	68	38	74	112
	T^2	27	Int	Int	32	52	69	43	78	116
	T^3	25	Int	Int	25	47	63	39	78	112
14	T^1	34	63	Int	36	64	92	56	119	179
	T^2	34	58	Int	41	69	105	55	115	Inf
	T^3	37	Int	Int	43	70	94	58	122	182
15	T^1	39	Int	Int	42	80	110	60	127	194
	T^2	42	Int	Int	45	75	106	66	127	187
	T^3	37	Int	Int	44	82	114	50	126	198
18	T^1	Int	Int	Int	46	88	115	60	133	197
	T^2	Int	Int	Int	36	79	95	59	123	182
	T^3	Int	Int	Int	56	96	138	70	146	210
23	T^1	Int	Int	Int	54	103	156	78	168	Inf
	T^2	Int	Int	Int	49	101	158	73	173	Inf
	T^3	Int	Int	Int	49	105	152	66	151	Inf

* Int: Intractable
** Inf: Infeasible

It is interesting to see that although ILP-I outperforms ILP-II in terms of capacity efficiency as expected, but the capacity efficiency difference (i.e., optimization gap) between them is quite small. Results show that ILP-I requires (2-16)% less wavelengths than ILP-II, for most of the cases. Also, the results show that a significant amount of protection resources can be saved by using a shared protection than dedicated one (i.e., ILP-III).

5.3 Computation Time

Table III provides the computation time (in seconds) taken by ILP-I, ILP-II, and ILP-III for solving the cases with small, medium, and large *T* on different topologies.

TABLE III
COMPUTATION TIME FOR ILP-I, ILP-II, AND ILP-III SCHEMES

|V|	T	ILP-I (seconds)			ILP-II (seconds)			ILP-III (seconds)		
		S	**M**	**L**	**S**	**M**	**L**	**S**	**M**	**L**
7	T^1	~1	142	592	3	13	25	<1	<1	Inf
	T^2	~1	155	191	3	11	29	<1	<1	Inf
	T^3	~1	29	1094	3	13	20	<1	<1	Inf
10	T^1	11	Int	Int	66	74	72	<1	<1	<1
	T^2	379	Int	Int	73	265	154	<1	<1	<1
	T^3	25	Int	Int	163	313	206	<1	<1	<1
14	T^1	204	758	Int	31	389	154	<1	<1	5
	T^2	110	21322	Int	67	66	165	<1	<1	Inf
	T^3	1345	Int	Int	44	83	146	<1	<1	6
15	T^1	9	Int	Int	25	33	33	<1	<1	8
	T^2	9	Int	Int	58	345	98	<1	<1	9
	T^3	8	Int	Int	110	170	159	<1	<1	9
18	T^1	Int	Int	Int	65	125	966	<1	<1	9
	T^2	Int	Int	Int	39	124	251	<1	<1	8
	T^3	Int	Int	Int	229	144	191	<1	2	10
23	T^1	Int	Int	Int	115	227	387	<1	5	Inf
	T^2	Int	Int	Int	152	428	618	<1	4	Inf
	T^3	Int	Int	Int	101	1797	2043	<1	3	Inf

From Table III, it is clear that ILP-I only produced results for 7-node network and some partial results for 10-node, 14-node, and 15-node networks when *T* is either small or medium. It failed to produce any results for 23-node topology and even failed to produce results for 10-node topology for medium and large *T*. This is due to a very large number of variables and constraints tackled in the ILP solver. On the other hand, ILP-II produces results for all the cases in a reasonable amount of time (i.e., within few seconds to few minutes). ILP-III produces results in a very short time (less than a second). For a number of cases, ILP-

III becomes infeasible, this is due to the high wavelength consumption nature of the dedicated protection – there were not enough wavelengths available to establish the requested number of connections.

5.4 Number of Affected Working Paths

Table IV provides the maximum number of working paths going through a link in different topologies. For most of the cases, the maximum number of working paths going through a link is always higher in ILP-I than in ILP-II. This results show that the proposed grouping policy successfully reduces the number of affected working paths in case of a link failure.

TABLE IV
NUMBER OF Affected Working Paths in ILP-I and ILP-II

|V|	T	ILP-I (max number of working paths going through a link)			ILP-II (max number of working paths going through a link)		
		S	**M**	**L**	**S**	**M**	**L**
7	T^1	5	8	9	3	6	8
	T^2	4	6	10	3	5	8
	T^3	4	7	9	4	6	7
10	T^1	3	Int	Int	2	3	4
	T^2	3	Int	Int	2	3	4
	T^3	2	Int	Int	2	2	4
14	T^1	3	6	Int	2	4	6
	T^2	4	6	Int	2	4	7
	T^3	4	Int	Int	2	4	6
15	T^1	3	Int	Int	3	4	6
	T^2	4	Int	Int	3	4	5
	T^3	3	Int	Int	3	3	5
18	T^1	Int	Int	Int	3	4	6
	T^2	Int	Int	Int	2	4	5
	T^3	Int	Int	Int	3	5	6
23	T^1	Int	Int	Int	2	5	7
	T^2	Int	Int	Int	2	5	7
	T^3	Int	Int	Int	3	4	6

Chapter 6

Summary and Future Research

6.1 Summary

In this thesis, a novel approach in resource allocation for static connection demands in survivable WDM nesh networks is introduced. Based on the proposed I-GSP architecture, the off-line survivability design problem is formulated into an Integer Linear Program (ILP) model, namely ILP-II. Two other integer linear programming models namely ILP-I and ILP-III are formulated for comparing proposed ILP-II solution. The objective for I-GSP design is to initiate a graceful compromise between capacity-efficiency and computation complexity. ILP-I considers the traffic matrix T as a PG and performs resource allocation. With ILP-II, on the other hand, traffic matrix T is broken down into small PGs where all the working lightpaths in a PG are mutually link-disjointedly routed. With ILP-III, like ILP-I, T is considered as a PG performing resource allocation according to the corresponding traffic matrix independently without taking any sharing of resources into account. Simulation is conducted to examine the ILP-II scheme on six different mesh topologies. The scalability issue is verified by addressing the issue of time complexity for ILP-II and found that the ILP-II sucessfuly solves all the traffic matrix in a short time whereas ILP-I fails to produce any results in most of the cases due to its intractable computation complexity.

6.2 Future Research

Following sub-sections summarize possible extensions of the research presented in this thesis:

6.2.1 Optimized Grouping Policy

In I-GSP, the traffic entries from the traffic matrix *T* are sequentially selected for creating the protection groups and within each group the working paths are mutually link-disjointedly routed. What will be the optimal way to create such groups is an open question. In the proposed ILP-II, optimization is performed sequentially on the protection groups which leave room for more optimization. In which order the optimization should be performed is also an open question and requires further investigation.

6.2.2 Lagrangian Relaxation for Comparing I-GSP Scheme

Lagrangian relaxation is a well known technique that is used to obtain sub-optimal solution in the cases where ILP becomes computationally intractable. To further analyze the capacity efficiency of the proposed I-GSP scheme (i.e., ILP-II) Lagrangian relaxation of the survivable routing problem in WDM networks need to be formulated so that the results from this sub-optimization process can be compared to the proposed ILP-II to see the performance gap between these approaches.

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