Survivable Traffic Grooming in WDM Mesh Networks under SRLG Constraints

Wang Yao and Byrav Ramamurthy
Department of Computer Science and Engineering,
University of Nebraska-Lincoln, Lincoln NE 68588 USA
Email: {wyao,byrav}@cse.unl.edu

Abstract—**Survivable traffic grooming (STG) is a promising approach to provide reliable and resource-efficient multi-granularity connection services in optical networks. In this paper, we study the static STG problem in WDM mesh networks employing path protection at the lightpath level. To make connections survivable under various failures such as fiber cut and duct cut, we consider the general shared risk link group (SRLG) diverse routing constraints. In addition to providing the results from the integer linear programming (ILP) approach, we propose three efficient heuristics, namely separated grooming algorithm (SGA), integrated grooming algorithm (IGA) and tabu search grooming algorithm (TSGA). While SGA and IGA correspond to an overlay model and a peer model respectively, TSGA further improves SGA and IGA by incorporating the tabu search method. Numerical results show that the heuristics use much shorter running times to generate network throughputs close to those of the ILP formulations.**

Index Terms— **Survivable traffic grooming, WDM, SRLG, path protection, Tabu search, Integer Linear Programming.**

I. INTRODUCTION

Traffic grooming [1][2] is an essential function of a wavelength-routed network (WRN) to address the bandwidth gap between low-rate connections and high-rate wavelength channels (lightpaths). With the improvement of optical technology, the capacity of a single wavelength can reach OC-192 (10Gbps). However, the bandwidth of a connection may be at OC-3 (155Mbps) or even lower. To make efficient use of the bandwidth provided by wavelengths, traffic grooming needs to pack low-rate connections effectively onto high-rate lightpaths, which in turn are established over the wavelength links.

Fault recovery capability is of critical importance for optical networks, because a single failure may affect large volumes of traffic. Survivable traffic grooming (STG) addresses jointly the resource-efficiency and survivability in the provisioning of sub-wavelength connections. It seeks to provide fault recovery capability for connections while minimizing the consumption of spare capacities in the network.

Protection is a fault recovery mechanism aimed at extremely fast recovery. Protection is classified into link protection and path protection. In the two-layered grooming network, path protection can be applied at two different levels, namely protection at lightpath (PAL) and protection at connection (PAC) [3]. PAL is a coarse-granularity protection scheme operating at aggregate (lightpath) level and PAC is a fine-granularity protection scheme operating at per-flow (connection) level. On the other hand, PAL can be viewed as a segment protection scheme, because a lightpath is a concatenation of wavelength links and a connection is a concatenation of lightpaths. In this paper, we focus on path protection at the lightpath level. Interested readers are referred to our work in [4] for the STG problem with protection at the subwavelength connection level.

In path protection, the backup path must not share a common resource with its primary path. This requirement prevents a single failure from affecting both the primary path and backup path. Shared risk link group (SRLG) [5] is a set of links that share a common resource (risk) whose failure affects all the links in the set. In practice, the risk can be an optical cross-connect (OXC) node, a fiber or a duct. For example, if the risk is a duct, then all the fiber links buried into this duct belong to a SRLG corresponding to the duct.

To make the connections survivable after various failure scenarios such as fiber cut and duct cut, it is necessary to consider SRLG diverse routing constraints in the traffic grooming problem. The SRLG diverse routing constraint is more general than link-disjoint or node-disjoint constraints. It stipulates that the primary path and backup path of a connection must be risk-disjoint paths to guarantee survivability. In addition, for the shared path protection scheme, the backup paths can share resources only if their primary paths are risk-disjoint.

The work in [7] focused on the survivable grooming policies as to whether primary connections and backup connections should be groomed on the same lightpath. The work in [3] compared PAL and PAC in the WDM mesh grooming networks. Heuristics were proposed to provision dynamically arriving connections. The work in [8] present an ILP formulation of the STG problem to minimize the total number of wavelength links in WDM optical networks with path protection. In [3][7][8], either node or link disjoint constraints were considered to solve the STG problem.

In this work, we study the static traffic STG problem under the SRLG constraints. The objective is to maximize network throughput (or revenue) given network resources and connection requests. In addition to the exact ILP solution approach, we propose three efficient heuristic grooming algorithms: separated grooming algorithm (SGA), integrated grooming algorithm (IGA) and tabu-search grooming algorithm (TSGA). Both dedicated and shared path protection at the lightpath level are considered. Our work differs from previous work not only in that we consider the general SRLG constraints in the STG, but also in that we construct the grooming heuristics from the network architectural point of view. SGA and IGA are based on an overlay model and a peer model respectively. TSGA further improves the grooming results from SGA and IGA by incorporating the effective tabu search [13] method.

The rest of the paper is organized as follows. Section II formally states the STG problem under the SRLG constraints. Section III presents SGA and IGA. Section IV presents TSGA. Section V discusses numerical results.

II. PROBLEM DEFINITION AND ILP FORMULATIONS

The STG problem in WRNs under the SRLG constraints can be formally stated as follows. We assume the protection is provided at the lightpath level, i.e., each lightpath has a primary path and a backup path.

- **Inputs**:

1). Physical topology represented as a unidirectional graph $G_p = (V_p, E_p)$. The number of nodes is $N = |V_p|$.
2). The set of wavelengths supported by each fiber is *W* and the capacity of each wavelength is *C*. We assume that the same set of wavelengths is deployed on every link. The capacity of a wavelength is normalized to an integer *C* based on the smallest grooming granularity in the network. For example, if one wavelength supports an *OC*-48 channel, and the smallest grooming granularity is *OC*-3, then *C* equals 48/3=16.
3). The number of transmitter and receiver pairs at each node is Δ_i for $1 \le i \le N$. In this study, we assume the transceivers are tunable to any wavelength operating on the fiber.
4). Connection requests represented as a set of $N \times N$ traffic matrices $\Lambda^x (x \in X)$, where X is the set of low-speed connection granularities. For example, *X*={*OC*-3, *OC*-12, *OC*-48}. $\Lambda^x_{s,d}$ represents the number of connection requests of *OC-x* granularity from nodes *s* to *d*.
5). SRLG information is represented as a set of SRLGs. Each SRLG is identified by a risk number *r* and comprises of all the links affected by the risk.

- **Constraints**:

1). Resource Constraints: To establish a lightpath over a path, there must have at least one wavelength available on each of the links in the path. Besides, there must have at least one free transmitter and one free receiver at the source node and destination node respectively.
2). Wavelength Continuity Constraint: For a network without wavelength conversion capability, a lightpath must use the same wavelength on all links in its path.
3). Diverse Routing constraints: The primary path and backup path of a lightpath must not share a common risk.
4). Lightpath Capacity Constraint: The total bandwidth of all the connections carried over a lightpath must not be larger than the bandwidth of a lightpath.

- **Objective:**

The objective is to establish a virtual topology over the physical topology and maximize the network throughput by routing the connection requests over the virtual topology.

We formulate the above STG problem as two ILP problems, one for dedicated protection and the other for shared protection. Due to the page limit, the ILP formulations are not presented here. However, we will present the results of the ILP formulations in section V.

III. GREEDY GROOMING HEURISTICS

The routing and wavelength assignment (RWA) problem in optical WDM networks is NP-complete. The traffic grooming problem is also NP-complete, as RWA is a special case of the traffic grooming problem. The work in [6] proved that finding two SRLG-diverse paths between a node pair is NP-complete. Therefore, it is easy to see that the STG problem subject to the SRLG constraints is NP-hard. To efficiently solve a NP-hard problem, heuristics are needed.

Operationally, the two layers involved in traffic grooming can be managed separately (overlay model) or jointly (peer model). Corresponding to the two models, we propose two grooming algorithms, namely separate grooming algorithm (SGA) and integrated grooming algorithm (IGA).

A. Separate Grooming Algorithm (SGA)

With SGA, the STG problem is divided into two subproblems. One is the survivable virtual topology design (SVTD) problem, which is to establish a virtual topology over the physical topology with each (primary) lightpath path protected by a backup lightpath. The other one is the subwavelength connection routing (SWCR) problem, which is to pack the subwavelength connections on the lightpaths in the virtual topology.

1) *Survivable Virtual Topology Design (SVTD)*

Virtual topology design (VTD) problem has been studied extensively in previous studies [9]. To solve the SVTD subproblem, we propose the maximizing single-hop traffic (MSHT-SVTD) heuristic, which tries to establish lightpaths between node pairs having large amounts of traffic. We also propose the two time Dijkstra's risk-disjoint paths (TTD-RDJP) heuristic algorithm to find two risk-disjoint paths. Risk-disjoint path selection algorithms have been studied in [10][11]. The work in [10] provides a three-step algorithm to find two span-disjoint paths. We extend the three-step algorithm into TTD-RDJP to find risk-disjoint paths. Fig. 1. shows the general procedures of the MSHT-SVTD and TTD-RDJP heuristics.

TTD-RDJP (see Fig.1) is an adaptive algorithm in that it updates the link weights according to the current network state and selects the shortest available paths. The link weight function $C_p(m,n)$ is defined as (1).

$$C_p(m,n) = \begin{cases} l_{m,n} & if\ W_a^l(m,n) \ne \varnothing \\ \infty & otherwise \end{cases}, \qquad (1)$$

```
Algorithm MSHT-SVTD
Input: Connection requests $\Lambda^x (x \in X)$, physical topology $G_p$, wavelength and transceivers, and SRLG information.
Output: A virtual topology $G_v$.
1) Sum the traffic matrix set to form a single residual traffic
   matrix $\Lambda^*$, where $\Lambda^*_{s,d} = \sum_{x \in X} (\Lambda^x_{s,d} \times x)$ represents the total
   bandwidth needed from node s to d.
2) while (not all the elements of $\Lambda^*$ are zero)
       Select the node pair (s',d') with the maximum residual
       bandwidth in matrix $\Lambda^*$. Ties are broken arbitrarily.
       if ( TTD-RDJP(s', d', p, b) )
           if ( dedicated protection )
               Establish a lightpath from s' to d' using primary
               path p and backup path b.
           else if ( shared protection )
               Establish a lightpath from s' to d' on primary
               path p and reserve the resource on backup path b.
       $\Lambda^*_{s',d'} \leftarrow \Lambda^*_{s',d'} - C$, where C is the bandwidth capacity
       of a lightpath.
```

```
Algorithm TTD-RDJP(s, d, p, b)
Input: Source node s, destination node d, physical topology $G_p$, usage of wavelengths and transceivers, and SRLG information.
Output: Risk-disjoint primary path p and backup path b, if successful; return NULL, otherwise.
1) Update the link weights of $G_p$ according to the current state of
   the network, and run Dijkstra's algorithm to select the shortest
   path as the primary path p.
2) if ( p )
       Delete any link in $G_p$ that share at least one risk with the
       any link in p.
       if ( shared protection )
           Update the link weights of $G_p$ again according to the
           current state of the network and primary path p.
       Run Dijkstra's algorithm to select the shortest path as
       the backup path b.
       if ( b )
           return (p, b).
3) return NULL.
```

Fig. 1. The MSHT-SVTD and TTD-RDJP heuristics.

where $l_{m,n}$ is the length of the link (m,n), $W_a^l(m,n)$ is the set of wavelengths available on (m,n).

Note that the link weights are updated again before the second running of Dijkstra's algorithm in TTD-RDJP if shared protection is used. To fully exploit backup path sharing, we design a different link weight function $C_b(m,n,p)$ for the backup path search when shared protection is used. In this case, the link weights depend not only on the network state, but also on the primary path *p*.

$$C_b(m,n,p) = \begin{cases} \alpha \times l_{m,n} & \text{if } W_s^l(m,n,p) \neq \varnothing \\ l_{m,n} & \text{if } W_s^l(m,n,p) = \varnothing \text{ and } W_a^l(m,n) \neq \varnothing \\ \infty & \text{otherwise} \end{cases}, \quad (2)$$

where $W_s^l(m,n,p)$ is the set of wavelengths on physical link (m,n) that have been reserved by other backup paths and is sharable to the backup path of p, α, $0 \le \alpha \le 1$, is a parameter to weight sharable links. When we say a wavelength w on link (m,n) is sharable to the backup path of p, it means that p does not share any common risk with any of the primary paths whose backup paths share the wavelength w on (m,n). By making α a small number, we encourage the backup path to share wavelengths with other backup paths. On the other hand, α should not be set too small to avoid using sharable wavelengths unnecessarily.

2) *Subwavelength Connection Routing (SWCR)*

As protection is only provided at the lightpath level, the SWCR subproblem does not need to consider SLRG-diverse routing constraints. Actually, the protection of lightpaths can be regarded as being transparent to connections. In this case, any shortest path routing algorithm can be used to find a path for a connection request in the virtual topology obtained in the SVTD subproblem.

To maximize network throughput, the connection requests are first sorted in non-decreasing traffic amount order, then the connection requests are provisioned one by one on the virtual topology. If no path can be found for a connection request, then it is blocked; otherwise, the connection is established over the path.

B. *Integrated Grooming Algorithm (IGA)*

In IGA, the provisioning of the lightpaths and connections are considered jointly. The objective is to accommodate as many connections as possible. New lightpaths are established to carry connections only when necessary. It is possible to establish a connection only using existing lightpaths or using a combination of existing and new lightpaths.

IGA is based on a link bundled auxiliary graph model (LBAG) [12]. The LBAG model is constructed as a two-layered graph including wavelength edges, transceiver edges and lightpath edges. With the LBAG model, IGA can find a minimum-cost path which may include both existing lightpaths and new lightpaths for a sub-wavelength connection request.

The following procedure describes the IGA heuristic (see Fig. 2) based on the LBAG model. The goal of the OTD-RDJP procedure in IGA is to find a risk-disjoint backup lightpath for an already known primary lightpath. It is similar to the TTD-RDJP procedure used in SGA and hence not specified separately. The difference is that OTD-RDJP only runs Dijkstra's algorithm once since the primary lightpath is already known. The link weights of wavelength edges are handled the same way as (1) and (2) in SGA.

IV. TABU SEARCH BASED GROOMING HEURISTIC

Tabu search (TS) [13] is a meta-heuristic that defines general neighborhood search strategies to tackle difficult combinatorial optimization problems. TSGA is a grooming algorithm following the general TS procedure. It starts with an initial solution which can be obtained by either SGA or IGA. Then it proceeds to an iterative optimization phase which keeps

```
Algorithm IGA
Input: Connection requests $\Lambda^x (x \in X)$, physical topology $G_p$, wavelength and transceivers, and $SRLG$ information.
Output: A virtual topology $G_v$ and the connections established over $G_v$.
1) Initialize the LBAG $G_a$ according to the physical topology.
2) Sort all the connection requests in non-increasing traffic amount order in a list $Q$.
3) while ( the list $Q$ is not empty )
      3.1) Get and remove the connection request $\phi(s, d, B)$ from the head of $Q$, where $s$ is source node, $d$ is destination node and $B$ is the required bandwidth.
      3.2) Update the link weights of the edges in $G_a$ according to the current network state.
      3.3) Run Dijkistra's algorithm on $G_a$ to find the shortest path $p$ from virtual node $s$ to virtual node $d$.
      if ( $p$ is found )
         if ( $p$ includes new lightpaths )
            for each new lightpath $l$ in the path $p$ do
               if ( OTD-RDJP($l$, $b$) )
                  if ( dedicated protection )
                     Establish a lightpath using primary path $l$ and backup path $b$.
                  else if ( shared protection )
                     Establish a lightpath on primary path $l$ and reserve the resources on backup path $b$.
               else
                  Release the other newly established lightpaths, block the connection request $\phi$ and goto step 3.1.
         Establish the connection on path $p$.
      else
         Block the connection request $\phi$.
```

Fig. 2. The IGA heuristic.

changing the current solution by executing the selected move. At any time, a solution comprises of a set of satisfied connections and a set of blocked connections.

In TSGA, a move is defined as either an add operation or a drop operation. For an add operation, a previously blocked connection request is satisfied by successfully finding a path for the connection. Because a connection is satisfied, the objective function value (throughput or revenue) increases from the last iteration. For a drop operation, a satisfied connection is disconnected and all the bandwidth it uses along its path is released. The objective function value decreases after the drop operation. Note that we can only perform an add operation on a blocked connection and perform a drop operation on a satisfied connection.

To select the best move, we define the move value of a connection as (3). The move with the largest move value is selected.

$$g(C^x_{s,d}, p) = \begin{cases} \dfrac{V^x_{s,d}}{WPC(p)} - freq(C^x_{s,d}) & \text{if add} \\ \dfrac{-V^x_{s,d}}{WPC(p)} - freq(C^x_{s,d}) & \text{if drop} \end{cases}, \tag{3}$$

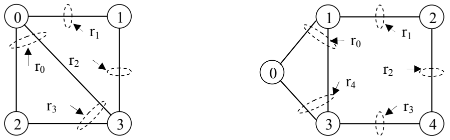
where $g(C^x_{s,d}, p)$ is the move value of an *OC-x* connection from s to d, p is the path assigned to a satisfied connection or the path to be used for a blocked connection, $V^x_{s,d}$ is the revenue (or bandwidth) of the connection $C^x_{s,d}$, $WPC(p)$ is the weighted path cost of path p, $freq(C^x_{s,d})$ is the frequency of the connection $C^x_{s,d}$ being selected in the best move.

The frequency function is incorporated into the move value function as in (3), thus making the less frequently selected moves more favorable than the more frequently selected moves. This is a diversification technique to force the search to go into unexplored search spaces and prevent the search from being trapped in a small portion of the search space.

V. NUMERICAL RESULTS AND DISCUSSION

In this section, we present results to illustrate the performance of the ILP formulations and heuristics. We first apply the ILP formulations and heuristics to two small networks shown in Fig. 3. Then we apply the heuristics to a 24 node network and examine its results. In the following figures, we assume that the fiber links covered by a dashed circle belong to the same SRLG. We assume that the networks have adequate grooming capability (enough number of transceivers) at every node. The traffic matrices are randomly generated.

A. *ILP vs Heuristics*



(a) (b)

Fig. 3. (a) Network 1: a 4-node network. (b) Network 2: a 5-node network.

We use CPLEX [14] to solve the ILPs. Table I shows the results of the ILPs and heuristics. For network 1, we assume that the capacity of a lightpath is 2 units and every connection requests 1 unit of bandwidth. The total amount of traffic requested by the connections is 12 units. For network 2, we assume that the capacity of a lightpath is 4 units and the connections requests are of either 1 or 2 units in bandwidth. The total amount of traffic is 39 units.

TABLE I

RESULTS FROM ILP, SGA, IGA AND TSGA. THE TOTAL AMOUNT OF TRAFFIC REQUESTED IS 12 FOR NETWORK 1 AND IS 39 FOR NETWORK 2. (NET: NETWORK, W: NUMBER OF WAVELENGTHS)

NET	W	Dedicated Protection				Shared Protection			
		ILP	SGA	IGA	TSGA	ILP	SGA	IGA	TSGA
1	1	4	4	4	4	6	4	4	6
1	2	8	8	5	8	10	9	8	10
1	3	9*	10	9	11	11*	11	11	12
1	4	*	11	10	12	*	12	12	12
2	1	8	8	8	8	16	8	8	8
2	2	16	15	15	15	27	23	21	26
2	3	15*	20	15	20	19*	26	28	31
2	4	*	26	21	30	38*	35	34	38
2	5	*	32	24	33	*	37	38	39

For the ILP results, a number without asterisk represents an optimal solution, a number with asterisk represents the best solution obtained by CPLEX within 10 hours, and a single asterisk means that no feasible solution is found within 10 hours. As can be seen from Table I, ILP solutions are the best whenever the CPLEX program gives optimal solutions. However, even for small networks with three or four wavelengths and a few connection requests, the computational complexity of ILP approach is formidable and CPLEX fails to generate optimal solutions. Among the three heuristics, TSGA gives optimal or close-to-optimal solutions in most cases and outperforms SGA and IGA.

B. *Heuristics Comparison*

To compare the three heuristics, we apply them to a 24 node network, as shown in Fig. 4. In this scenario, we assume that the capacity of a lightpath is 16 units and there are two different connection granularities, 1 unit and 4 units. The total traffic amount requested is 2208 units.

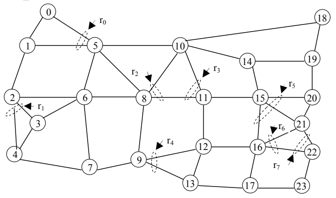


Fig. 4. A 24-node network. The links covered by a dashed circle belong to the same SRLG. Any link not covered in any dashed circle is a SRLG by itself.

Fig. 5 shows the performance of SGA, IGA and TSGA with dedicated protection in terms of total accommodated traffic. As can be seen, IGA accommodates more traffic than SGA when the number of wavelengths (W) is relatively small and SGA outperforms IGA when W is larger than 22. This difference is because that SGA tries to satisfy as many connections as possible with a single new lightpath for each one, and then routes the rest of the connections using the residual bandwidth on the established lightpaths. On the other hand, IGA tries to balance the use of new lightpaths and existing lightpaths from the beginning. It finds the path with the minimum cost and only establishes a lightpath when it is included in the minimum cost path. While the IGA strategy is effective when the resources are relatively scarce, SGA performs better when there are enough resources to establish direct lightpaths for a majority of the connections. Fig. 5 also shows that TSGA has about 10% improvement over SGA when W is 20 or less. However, as W increases, the improvement margin reduces rapidly to zero. This is in part because of the reduced improvement space as the throughput increases close to the total requested bandwidth.

Fig. 6 shows the performance of SGA, IGA and TSGA with shared protection. Comparing Fig. 6 with Fig. 5, it is clear that shared protection is much more resource-efficient than dedicated protection, as shared protection uses about 16 wavelengths to accept all the connection requests while dedicated protection uses about 28 wavelengths to achieve the same objective. Fig. 6 also shows that IGA outperforms SGA for shared protection scheme, accepting an average of about 20% more traffic when W is between 10 and 14. This indicates that the integrated approach is more effective to exploit resource sharing than the overlay approach. Still, TSGA provides an average of about 4% improvement over SGA in terms of the amount of the accepted traffic when W is between 10 and 15.

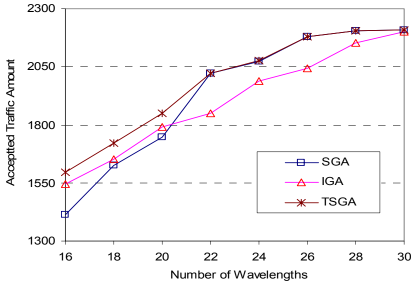


Fig. 5. Heuristics with dedicated protection. (Total traffic is 2208 units).

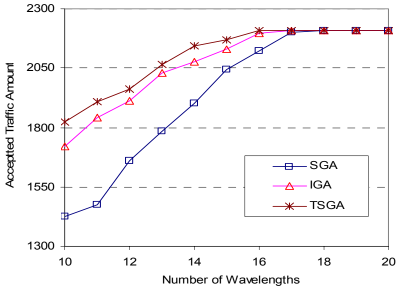


Fig. 6. Heuristics with shared protection. (Total traffic is 2208 units).

REFERENCES

[1] K. Zhu, B. Mukherjee, "Traffic Grooming in an Optical WDM Mesh Network," *IEEE Journal on Selected Areas in Communications*, vol.20, no.1, Jan. 2002.

[2] A. Lardies, R. Gupta, R. A. Patterson, "Traffic Grooming in a Multi-layer Network," Optical Network Magazine, May/Jun. 2001.

[3] C. Ou, K. Zhu, B. Mukherjee, "Survivable Traffic Grooming in WDM Mesh Networks," *OFC 2003*, vol. 2, pp. 624-625, 2003.

[4] Wang Yao and Byrav Ramamurthy, "Survivable Traffic Grooming with Path Protection at the Connection Level in WDM Mesh Networks", *in Proc. of the BroadNets'2004*, San Jose, CA, USA, Oct. 2004.

[5] P. Sebos, J. Yates, G. Hjalmtysson, A. GreenBerg, "Auto-discovery of Shared Risk Link Groups," in *Proc. OFC 2001*, Mar. 2001.

[6] J. Hu, "Diverse Routing in Optical Mesh Networks," *IEEE Trans. on Communications*, vol. 51, no. 3, pp. 489-494, Mar. 2003.

[7] S. Thiagarajan, A. Somani, "Traffic Grooming for Survivable WDM Mesh Networks," *Optical Network Magazine*, May/Jun. 2002.

[8] J. Fang, A. K. Somani, "Enabling Subwavelength Level Traffic Grooming in Survivable WDM Optical Network Design," *IEEE Globecom* Dec. 2003.

[9] R. Dutta, G. N. Rouskas, "A Survey of Virtual Topology Design Algorithms for Wavelength Routed Optical Networks," *Optical Networks Magazine*, Jan. 2000.

[10] G. Li, B. Doverspike, C. Kalmanek, "Fiber Span Failure Protection in Mesh Optical Networks," in *Proc. of SPIE OptiComm 2001*, Denver, CO, Aug. 2001.

[11] P. H. Ho, J. Tapolcai, H. T. Mouftah, "Diverse Routing for Shared Protection in Survivable Optical Networks," *IEEE Globecom*, Dec. 2003.

[12] W. Yao, B. Ramamurthy, "Constrained Dynamic Traffic Grooming in Optical WDM Mesh Networks with Link Bundled Auxiliary Graph Model," *in Proc. of IEEE HPSR 2004*, Phoenix, AZ, Apr. 2004.

[13] F. Glover, M. Laguna, "Tabu Search," Kluwer Academic Publishers, ISBN 0-7923-9965-X, Jul. 1997.

[14] ILOG CPLEX, ILOG Inc., Montain View, California, [Online]. Available: http://www.ilog.com/products/cplex/.