APPENDIX 1

Linear Programming in a Nutshell

Mathematical programming is a widely used family of techniques for making decisions under the restriction of limited resources. The first step in approaching a decision problem is to identify its two important components [377]:

1. *Objective*,
2. *Variables*.

The specification of a problem to be solved using mathematical programming is called the *formulation* of the problem. The objective is the desired end result, typically expressed as the maximization or minimization of some mathematical function. Such functions are often called *objective functions*. The variables are those parameters that are under the control of the designer and hence may be allowed to change (or vary) in order to reach the objective. The most popular type of problem formulation is called *linear program* where the objective function as well as the restrictions (often called *constraints*) are linear functions of the variables.

The standard revised simplex algorithm for processing a Linear Program (LP) to minimize an objective function subject to a number of linear constraints is given below. In this description of a linear program *FORM* 11, only the simplest form of the constraints has been considered. This is a concise description and more details, with proof of correctness, are available in standard textbooks such as [93, 377].

Notation used in *FORM* 11

$\boldsymbol{\widehat{n}_c}$: the number of constraints in *FORM* 11.

$\boldsymbol{\widehat{n}_v}$: the number of variables in *FORM* 11.

$\boldsymbol{A}$: a matrix of size $\widehat{n}_c \times \widehat{n}_v$ where each element in the matrix is a constant, used to specify the constraints of *FORM* 11.

$\boldsymbol{[A|I]}$: a matrix of size $\widehat{n}_c \times (\widehat{n}_v + \widehat{n}_c)$ such that the first $\widehat{n}_v$ columns of $[A|I]$ are taken from A and the remaining $\widehat{n}_c$ columns of $[A|I]$ are taken from identity matrix I.

$\overrightarrow{\boldsymbol{A^j}}$: the j^{th} column of $[A|I]$.

$\boldsymbol{a_{ij}}$: the element in row i, column j of A — a constant.

$\overrightarrow{\boldsymbol{b}}$: a column vector of $\widehat{n}_c$ nonnegative constants.

$\boldsymbol{b^k}$: the k^{th} element of vector $\overrightarrow{b}$.

$\overrightarrow{\boldsymbol{c}}$: a row vector of $\widehat{n}_v$ constants.

$\overrightarrow{\boldsymbol{c_B}}$: a row vector of $\widehat{n}_c$ constants.

$\overrightarrow{\boldsymbol{x}}$: a column vector of $\widehat{n}_v$ variables.

$\overrightarrow{\boldsymbol{y}}$: a row vector of $\widehat{n}_c$ variables.

$\overrightarrow{\boldsymbol{d}}$: a column vector of $\widehat{n}_c$ variables.

$\boldsymbol{x^i}$: the i^{th} element of vector $\overrightarrow{x}$.

$\overrightarrow{\boldsymbol{x_B}}$: a column vector of $\widehat{n}_c$ variables, called basic variables.

$\boldsymbol{x^i_B}$: the i^{th} element of $\overrightarrow{x_B}$.

$\boldsymbol{B}$: a nonsingular matrix of size $\widehat{n}_c \times \widehat{n}_c$.

$\boldsymbol{I}$: identity matrix of size $\widehat{n}_c \times \widehat{n}_c$.

$\overrightarrow{\boldsymbol{x_s}}$: a column vector of $\widehat{n}_c$ variables.

$\boldsymbol{x^i_s}$: the i^{th} element of x_s, also called the i^{th} *slack variable*.

$\overrightarrow{\boldsymbol{[x|x_s]}}$: a column vector of $(\widehat{n}_v + \widehat{n}_c)$ elements, such that the first $\widehat{n}_v$ elements of $\overrightarrow{[x|x_s]}$ are taken from $\overrightarrow{x}$ and the remaining $\widehat{n}_c$ elements of $\overrightarrow{[x|x_s]}$ are taken from $\overrightarrow{x_s}$.

$\overrightarrow{\boldsymbol{0}}$: a vector of all 0s.

The formulation for *FORM* 11

The input to the LP is a set of $\widehat{n}_c$ linear constraints and an objective function.

The i^{th} constraint is in the form $\displaystyle\sum_{j=0}^{\widehat{n}_v} a_{ij}x^j \le b^i$, for all $i, 1 \le i \le \widehat{n}_c$. The cost function is in the form $\displaystyle\sum_{j=0}^{\widehat{n}_v} c_j x^j$.

Using matrix notation, the LP may be conveniently specified as follows:

Objective function:

$$\text{minimize} \quad \overrightarrow{c} \cdot \overrightarrow{x} \tag{A1.1}$$

subject to

$$A\overrightarrow{x} \leq b \tag{A1.2}$$

$$x^i \geq 0 \qquad \forall i, 1 \leq i \leq \widehat{n}_v \tag{A1.3}$$

The constraints in (A1.2) are called *linear constraints* because the left-hand side of each constraint (i.e., each row of $A\overrightarrow{x}$) is a linear function of the variables in $\overrightarrow{x}$. The first step is to add *slack* variable x_s^i in the i^{th} constraint, for all $i, 1 \leq i \leq \widehat{n}_c$, in (A1.2) and replace the $\leq$ symbol by the equality symbol so that the LP now becomes

Objective function:

$$\text{minimize} \quad \overrightarrow{c} \cdot \overrightarrow{x} \tag{A1.4}$$

subject to

$$[A|I]\overrightarrow{[x|x_s]} = \overrightarrow{b} \tag{A1.5}$$

$$x^i \geq 0 \tag{A1.6}$$

$$x_s^i \geq 0 \tag{A1.7}$$

It is well known that it is possible to obtain an $\widehat{n}_c \times \widehat{n}_c$ non-singular sub-matrix B of $[A|I]$ and a nonnegative vector $\overrightarrow{x_B}$ by choosing $\widehat{n}_c$ suitable variables from $\overrightarrow{[x|x_s]}$ for inclusion in $\overrightarrow{x_B}$ and by selecting the corresponding columns of $[A|I]$ for inclusion in B [93], satisfying the following condition:

$$B\overrightarrow{x_B} = \overrightarrow{b} \tag{A1.8}$$

The matrix B is called the *basis*, the variables in $\overrightarrow{x_B}$ are called *basic variables*. (A1.8) can be solved to get a unique solution since B is non-singular. The variables in $\overrightarrow{x}$ or in $\overrightarrow{x_s}$ which are not included in $\overrightarrow{x_B}$ are called *nonbasic variables*. It is convenient to form a row vector $\overrightarrow{c_B}$ of all coefficients in vector $\overrightarrow{c}$ corresponding to the variables in $\overrightarrow{x_B}$. A solution of the LP may be found by setting all the nonbasic variables to 0. The value of the objective function is now $\overrightarrow{c_B} \cdot \overrightarrow{x_B}$. This process of determining the matrix B, the vector of variables $\overrightarrow{x_B}$, and the cost vector $\overrightarrow{c_B}$ before starting the iterations of the revised simplex method is called finding an *initial feasible solution (IFS)*. In the simple form considered here, an IFS is B = I (the identity matrix), $\overrightarrow{x_B} = \overrightarrow{x_s}$ (the vector of slack variables), and $\overrightarrow{c_B} = \overrightarrow{0}$.

Once the initial feasible solution has been obtained, the idea is to improve the value of the objective function, if possible, in successive iterations of the revised simplex method until no further improvement in the value of the objective function is possible. In each iteration, one column of the basis is

replaced by a column from $[A|I]$, currently not appearing in the basis. The column being replaced is called the *leaving column* and the column replacing it is called the *entering column*. The variable in $\overrightarrow{[x|x_s]}$ corresponding to the leaving column is called the *leaving variable* and the variable corresponding to the entering column is called the *entering variable*. The steps in one iteration of the revised simplex method are as follows.
Step 1: Solve the equation $\overrightarrow{y} \cdot B = \overrightarrow{c_B}$.
Step 2: Find, if possible, a column $\overrightarrow{A^j}$ from $[A|I]$ such that the $\overrightarrow{y} \cdot \overrightarrow{A^j} > c_j$. If no such column can be found, stop. Otherwise, $\overrightarrow{A^j}$ is the entering column that has to be included in the basis.
Step 3: Solve the equation $B \cdot \overrightarrow{d} = \overrightarrow{A^j}$.
Step 4: Find the largest t such that $\overrightarrow{x_B} \geq t\,\overrightarrow{d}$. The component of $\overrightarrow{x_B} - t\,\overrightarrow{d}$ which is 0 is the leaving variable and the corresponding column in B is the leaving column.
Step 5: In the basis B, replace the leaving column by the entering column. Recompute $\overrightarrow{x_B}$ using the formula by $\overrightarrow{x_B} = B^{-1}\overrightarrow{b}$. Replace the cost of the leaving column in $\overrightarrow{c_B}$ by the cost of the entering column.

The elements in $\overrightarrow{y} = \overrightarrow{c_B}B^{-1}$, computed in Step 1, are called *simplex multipliers*. The i^{th} simplex multiplier is the i^{th} element in $\overrightarrow{y}, 1 \leq i \leq \widehat{n}_c$.

In many problems, the variables must have integer values only. This situation occurs frequently in optical network design. Such problems are called *Integer Linear Programs* (ILPs). If a formulation contains some continuous variables and some integer variables, such formulations are called Mixed Integer Linear Programs (MILPs).

APPENDIX 2

The de Bruijn Graph

One interconnection architecture that has been widely studied is the de Bruijn graph [199, 240]. A very brief overview of the de Bruijn graph and related terms in graph theory is given below. It is convenient to model an interconnection architecture using a directed graph $G = (V, E)$ where each processor is a vertex in the set of vertices V in the graph G, and E is the set of edges in G. If two processors u and v are connected by a link allowing communication from u to v, there is a directed edge $e = u \rightarrow v$ in G. The edge e is an element in the set of edges E. Given two vertices $s, d \in V$, a *walk* W is a sequence of edges represented as $W = x_0 \rightarrow x_1 \rightarrow x_2 \ldots \rightarrow x_{k-1} \rightarrow x_k$, where $s = x_0$, $d = x_k$, and there is an edge $e = x_i \rightarrow x_{i+1} \in E$, for all $i, 0 \leq i < k$. The length of this walk from s to d is k. A walk may involve a loop, meaning that the same vertex may appear more than once in a walk. A *path* is a walk where no vertex appears more than once. In general, there are many paths from any node s to any node d.

Using standard graph theoretic terminology [42], the *in-degree* (*out-degree*) of a vertex v will denote the number of edges to (from) v. Given two vertices s and d, a *routing algorithm* is used to construct a path from s to d. In most cases, the routing algorithm gives the shortest directed path from s to d. In a multiprocessor system, for example, such an algorithm is very useful to enable any processor to communicate with any other processor as quickly as possible. In characterizing graphs, the *diameter* is an important property and is defined as the largest value of the shortest path between any pair of vertices.

Topologies such as the de Bruijn graph are attractive because they have a low diameter ($O(\log_d N_{DB})$ where N_{DB} is the number of vertices in the graph and d is the in-degree and out-degree of every vertex). The de Bruijn graph is an example of a *regular* graph where the in-degree and out-degree of each vertex is the same. An attractive property of many regular graphs, including the de Bruijn graph, is that the interconnection between the vertices follows some simple rules so that the routing algorithm for communication between vertices is quite straightforward and does not involve the need for complex routing tables.

Interconnection rules and routing in a de Bruijn graph

A *de Bruijn* graph with in-degree and out-degree d and a diameter k, denoted by $B(d,k)$, is a directed graph with d^k vertices, where the vertices are represented by strings of length k, choosing the symbols of the string from the set $Z_d = \{0,1,2,\ldots,d-1\}$. Let vertex u (v) be a vertex in $B(d,k)$, represented by the string of k digits $u_k u_{k-1} \ldots u_1$ ($v_k v_{k-1} \ldots v_1$), where $u_i \in Z_d$ ($v_i \in Z_d$), for all $i, 1 \leq i \leq k$. There will be an edge $u \to v$ in $B(d,k)$ iff $v_i = u_{i-1}, 1 < i \leq k$. Here, the value of v_1 can be any digit i in Z_d. The edge $u_k u_{k-1} \ldots u_1 \to u_{k-1} u_{k-2} \ldots u_1 i$ will be called the i^{th} edge of vertex $u_k u_{k-1} \ldots u_1$.

$B(d,k)$ is regular, since the rule for the existence of edge $u \to v$ is the same for all pairs of vertices (u,v). Each vertex has in-degree and out-degree d. There are d vertices with self-loops.[7] It may be readily verified that if a vertex in $B(d,k)$ is represented by a string $iii \ldots i, 0 \leq i < d$, then the vertex has a self-loop.

It is convenient to associate numbers $0,1,2,\ldots,d^k-1$ with the vertices of $B(d,k)$. If n is the number associated with a vertex u represented by the string $u_k u_{k-1} \ldots u_1$, then $n = \sum_{i=1}^{k} u_i \cdot d^{i-1}$.

Example A2.1. The diagram of a de Bruijn graph $B(d,k)$ with $d=2$ and $k=3$ is shown in Figure A2.1. Each vertex has a vertex number (shown on the first line inside the square representing the vertex) and a string representing the vertex (shown on the second line inside the square representing the vertex). Vertex number 5 has the string representation 101 since $5 = 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$. The vertex with the string representation 010 has directed edges to two vertices with string representations 100 and 101, following the rules of interconnection given above. The vertices with string representations 000 and 111 have one edge to themselves. These are the self-loops. □

A somewhat more complex de Bruijn graph, $B(3,2)$, is shown in Figure A2.2.

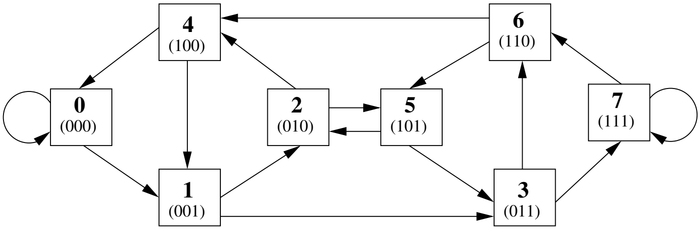

Fig. A2.1. The de Bruijn graph $B(2,3)$ with eight vertices

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[7] A *self-loop* is any edge $u \to u$ for some $u \in V$.

Since the string representation of a vertex in a de Bruijn graph $B(d, k)$ identifies the vertex, it is convenient to refer to the string representation as the *address* to identify a vertex. Let any two vertices u and v have addresses $u_k u_{k-1} \ldots u_1$ and $v_k v_{k-1} \ldots v_1$. Clearly, there is a walk in $B(d, k)$ of length k given by $u_k u_{k-1} \ldots u_1 \rightarrow u_{k-1} u_{k-2} \ldots u_1 v_k \rightarrow u_{k-2} u_{k-3} \ldots u_1 v_k v_{k-1} \rightarrow \ldots \rightarrow v_k v_{k-1} \ldots v_1$.

Example A2.2. In the de Bruijn graph $B(2, 3)$ shown in Figure A2.1, there is a walk 100 → 000 → 000 → 001 from vertex number 4 to vertex number 1. This has a loop 000 → 000.

There is a path 100 → 001 → 011 → 111 from vertex number 4 to vertex number 7. □

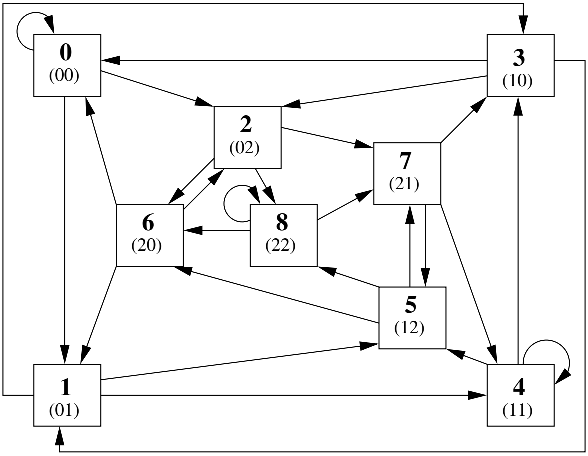

Fig. A2.2. The de Bruijn graph $B(3, 2)$ with nine vertices

Clearly, in a $B(d, k)$, for any two vertices u and v, a walk of length k from u to v is always possible. For $u = 000 \ldots 0$ and $v = 111 \ldots 1$, this walk is a path. This illustrates that the diameter of $B(d, k)$ is k.

Definition A2.1. *The* suffix*(x, p) (*prefix*(x, p)) of a vertex x in a $B(d, k)$ having an address $x_k x_{k-1} \ldots x_1$ and $p < k$, is the string $x_p x_{p-1} \ldots x_1$ ($x_k x_{k-1} \ldots x_{k-p+1}$).*

The shortest path from a vertex u to a vertex v in a $B(d, k)$ is unique and is of length $k - t$ if t is the length of the longest suffix of the string $u_k u_{k-1} \ldots u_1$ that appears as the prefix of $v_k v_{k-1} \ldots v_1$. The shortest path from u to v is $u_k u_{k-1} \ldots u_1 \rightarrow u_{k-1} u_{k-2} \ldots u_1 v_{k-t} \rightarrow u_{k-2} u_{k-3} \ldots u_1 v_{k-t} v_{k-t-1} \rightarrow \ldots \rightarrow u_t u_{t-1} \ldots u_1 v_{k-t} v_{k-t-1} \ldots v_1$.

Since suffix$(u, t) =$ prefix(v, t), $u_t u_{t-1} \ldots u_1 v_{k-t} v_{k-t-1} \ldots v_1 = v_k v_{k-1} \ldots v_1$.

Example A2.3. In the shortest path from $u = 100$ to $v = 011$ in $B(3, 2)$, the longest suffix of u which matches the prefix of v has length $t = 1$, since suffix(100, 1) = prefix(011, 1) = 0, suffix(100, 2) = 10 $\neq$ prefix(011, 2) = 01. Therefore, the shortest path from 100 to 011 is $100 \rightarrow 001 \rightarrow 011$. □

APPENDIX 3

Network Flow Programming

This appendix is a very concise overview of network flow programming. Standard textbooks, such as [4], are available for more information. Network flow programming is used to solve problems where one or more distinct *commodities* have to be shipped over a transportation network (e. g., a roadway system or a set of railway tracks). Each commodity is something (e.g., grains or minerals) that has to be transported from one or more sources for the commodity to one or more destinations. A transportation network is represented by a directed graph $G = (V, E)$. Each vertex in V represents a potential source or destination of a commodity (e.g., a rail station) and each edge $i \rightarrow j$ represents a link on the transportation network (e.g., the rail line between two stations). An edge $i \rightarrow j$ is an element in the form (i, j) in the set of edges E. Each edge $i \rightarrow j$ has a capacity and a cost/unit flow $(u_{ij},\ c_{ij})$ associated with it. Such graphs are called *capacitated networks* because each edge has a capacity associated with it. Figure A3.1 shows a directed network with a pair (capacity, cost) associated with every edge.

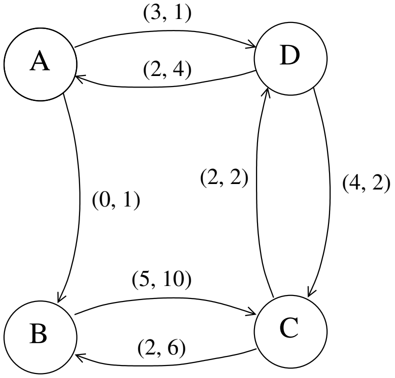

Fig. A3.1. A capacitated network.

A problem involving a network where there is only one commodity flowing from one or more sources to one or more destinations is called a *single commodity network flow problem.* If the network supports the flow of more than one commodity, it is called a *multi-commodity network flow problem.* The following formulations of network flow problems are of interest.

Problem 1

Given a capacitated network G, one source s, and one destination d of a single commodity flowing on network G, find the scheme to transport the maximum amount of the commodity.

This is called the *max-flow* problem and can be handled using linear program formulation *FORM* 12 given below.

Notation used in *FORM* 12

$\boldsymbol{G}$: a directed graph (V, E) with V representing the set of vertices and E representing the set of edges so that if $(i, j) \in E$ there is an edge $i \rightarrow j$ from i to j. Each vertex is assigned a unique number $i, 1 \leq i \leq N$.

$\boldsymbol{s}$ $(\boldsymbol{d})$: the source (destination) of the commodity.

$\boldsymbol{c_{ij}}$: cost/unit flow of using the edge $(i, j) \in E$.

$\boldsymbol{u_{ij}}$: capacity of the edge $(i, j) \in E$.

$\boldsymbol{\widehat{v}}$: amount of commodity transported from s to d.

$\boldsymbol{X_{ij}}$: continuous variable denoting the amount of flow on the edge $(i, j) \in E$.

$\boldsymbol{N}$: number of vertices in V.

The Formulation for *FORM* 12

Objective function:

$$\text{maximize} \quad \widehat{v} \tag{A3.1}$$

subject to

1. Satisfy flow constraints.

$$\sum_{j:(i,j)\in E} X_{ij} - \sum_{j:(j,i)\in E} X_{ji} = \begin{cases} v & \text{if } i = s, \\ -v & \text{if } i = d, \quad \forall i, 1 \leq i \leq N \\ 0 & \text{otherwise.} \end{cases} \tag{A3.2}$$

2. Ensure that the capacities of edges are not exceeded.

$$X_{ij} \leq u_{ij}, \quad \forall i, j, (i, j) \in E \tag{A3.3}$$

3. Flows cannot be negative.

$$X_{ij} \geq 0, \quad \forall i, j, (i, j) \in E \tag{A3.4}$$

Justification of *FORM* 12

The objective function is to maximize the amount $\widehat{v}$ of a commodity transported from s to d.

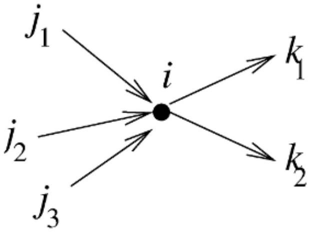

Fig. A3.2. Node i in a network

Figure A3.2 shows a typical node i with three incoming edges ($j_1 \rightarrow i$, $j_2 \rightarrow i$, $j_3 \rightarrow i$) to i and two outgoing edges ($i \rightarrow k_1$, $i \rightarrow k_2$) from i. The total *inflow* (i.e., the sum of flows into node i on all incoming edges $j \rightarrow i$) is the sum of the flows on edges $j_1 \rightarrow i$, $j_2 \rightarrow i$, and $j_3 \rightarrow i$. The total *outflow* (i.e., the sum of flows from node i, on all outgoing edges $i \rightarrow j$ for node i) is the sum of the flows on edges $i \rightarrow k_1$ and $i \rightarrow k_2$.

The commodity flowing from s to d may involve node i. If so, the following cases have to be considered:

Case I) ($i = s$) No flow can use an edge to i but one or more flows will start from i, using one or more of the outgoing edges from i.

Case II) ($i = d$) No flow can start from i but one or more flows will terminate at i, using one or more of the incoming edges to i.

Case III) ($i \neq s$ and $i \neq d$) There will be one or more flows into i, using one or more incoming edges to i, so that the total inflow to i is matched by the total outflow from i, using one or more outgoing edges from i.

Since the objective is to maximize $\widehat{v}$, any solution where the total inflow to (outflow from) node s (d) is nonzero decreases the value of $\widehat{v}$ and hence is not optimal.

The total inflow for node i is $\sum\limits_{j:(j,i)\in E} X_{ji}$. Similarly the total outflow is $\sum\limits_{j:(i,j)\in E} X_{ij}$.

(A3.2) should be interpreted as follows:

Case I) ($i = s$) Since i is the source of the commodity, the total outflow from i is $\widehat{v}$ and the total inflow is 0. Thus the difference between the total outflow and the total inflow must be $\widehat{v}$.

Case II) ($i = d$) Since i is the destination of the commodity, the total inflow to i is $\widehat{v}$ and the total outflow is 0. Thus the difference between the total outflow and the total inflow must be $-v$.

Case III) ($i \neq s$ and $i \neq d$) Since i is neither the source nor the destination of the commodity, the total inflow must be matched by the total outflow so that the difference between the total outflow and the total inflow must be 0.

(A3.2) is called *flow balance equation* (also called *flow conservation equation*). The purpose of (A3.3) is to state that the flow on edge $i \rightarrow j$ cannot exceed the capacity u_{ij} of the edge. All flows must be positive (A3.4).

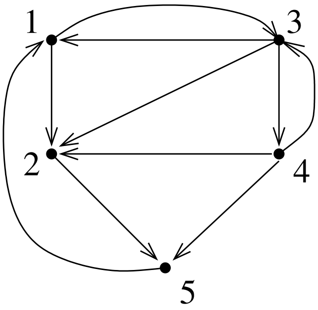

Fig. A3.3. A network

It is very easy to generate constraints corresponding to formulations such as this one. For instance, in the network shown in Figure A3.3, if node 3 is the source and 5 is the destination, the constraints corresponding to (A3.2) for selected nodes are as follows:

$$X_{31} + X_{32} + X_{34} - X_{13} - X_{43} = \widehat{v} \tag{A3.5}$$

$$X_{12} + X_{32} + X_{42} - X_{25} = 0 \tag{A3.6}$$

$$X_{51} - X_{25} - X_{45} = -v \tag{A3.7}$$

(A3.5), (A3.6), and (A3.7) arise from (A3.2) applied to nodes 3, 2, and 5, respectively.

Problem 2

Given a network $G = (V, E)$, one source s, and one destination d, find the minimum cost path from s to d, where each edge $(i, j) \in E$ has a cost c_{ij} associated with it.

This problem may be solved using integer linear program formulation *FORM* 13 given below.

Notation used in *FORM* 13

$\boldsymbol{G}$, $\boldsymbol{s}$, $\boldsymbol{d}$, $\boldsymbol{c_{ij}}$: same as in Problem 1.

$\boldsymbol{x_{ij}}$: a binary variable (i.e., a variable which is either 0 or 1) denoting the amount of flow on the edge $(i, j) \in E$.

The Formulation for *FORM* 13

Objective function:

$$\text{minimize} \sum_{(i,j)\in E} c_{ij} \cdot x_{ij} \tag{A3.8}$$

subject to

1. Satisfy flow constraints.

$$\sum_{j:(i,j)\in E} x_{ij} - \sum_{j:(j,i)\in E} x_{ji} = \begin{cases} 1 & \text{if } i = s, \\ -1 & \text{if } i = d, \quad \forall i, 1 \le i \le N \\ 0 & \text{otherwise.} \end{cases} \tag{A3.9}$$

2. Ensure that the variable x_{ij} is either 0 or 1.

$$x_{ij} \in \{0, 1\} \quad \forall i, j, (i, j) \in E \tag{A3.10}$$

Justification of *FORM* 13

It will be shown below that the above constraints generate a path $\mathbb{P}$ from s to d by ensuring that $x_{ij} = 1$ if and only if the edge $i \to j$ appears in the path $\mathbb{P}$. Figure A3.4 shows a typical path $\mathbb{P} = s \to i \to j \to k \to l \to m \to d$. Since $x_{ij} = 1$ if and only if $i \to j$ is in path $\mathbb{P}$, $\sum_{(i,j)\in E} c_{ij} \cdot x_{ij}$ gives the cost of the path from s to d. The objective function in (A3.8) is to find the minimum value of $\sum_{(i,j)\in E} c_{ij} \cdot x_{ij}$ and hence the minimum cost path.

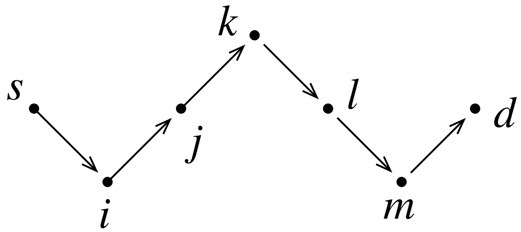

Fig. A3.4. A path from s to d

The purpose of (A3.10) is to ensure that x_{ij} is either 0 or 1. (A3.9) is similar to (A3.2). Here, the traffic is 1 so that the outflow from (inflow to) the source (destination) s (d) is 1. When $i = s$, (A3.9) becomes $\sum_{j:(s,j)\in E} x_{sj} = 1$. Since $x_{ij} \in \{0, 1\}$, this means that the value of $x_{sj} = 1$ for exactly one value of j and there is only one edge from s carrying the outflow from s. The same argument shows that there is exactly one edge to d carrying the inflow to s. For node $i, i \neq s, i \neq d$, (A3.9) states that $\sum_{j:(i,j)\in E} x_{ij} - \sum_{j:(j,i)\in E} x_{ji} = 0$. If there is exactly one edge, say $j_1 \rightarrow i$ carrying an inflow of 1 to node i, (A3.9) becomes $\sum_{j:(i,j)\in E} x_{ij} = x_{j_1 i} = 1$ so that there must be exactly one outgoing edge $i \rightarrow k_1$ to some k_1 such that $x_{ik_1} = 1$. In summary, (A3.9) ensures that the formulation finds a path from s to d.

Problem 3

The idea of the Multi-Commodity Network Flow (MCNF) problem is to optimize some parameter associated with the flow of an arbitrary number of commodities. Two popular problems, for instance, are the maximum multi-commodity network flow problem [152] and the minimum cost network flow problem [4]. The maximum multi-commodity network flow problem is to maximize the sum of flows for all commodities between their respective source/destination pairs. The minimum cost network flow problem is to determine the flow satisfying the demands of all commodities at a minimum cost without violating the capacity constraints of all the edges. An example similar to the single commodity problem (Problem 1) discussed above illustrates the MCNF problem involving a minimum cost network.

On a capacitated network G, q commodities are flowing; each commodity identified by a commodity number $k, 1 \leq k \leq q$. Each commodity has one source, one destination, and a specified amount of required traffic. The flows of different commodities may share edges. In general, an edge $i \rightarrow j$ has a number of commodities flowing on the edge. It must be ensured that the total traffic on edge $i \rightarrow j$, taking into account all the commodities flowing on the edge, does not exceed the capacity of the edge. The problem is to determine flows on each edge such that the specified traffic, for all commodities, is transported at a minimum cost. The problem may be solved using linear program formulation *FORM* 14 given below.

Notation used in *FORM* 14

G, c_{ij}, u_{ij} : same as in Problem 1.

s^k (d^k) : the source (destination) of commodity number k.

q : number of commodities to be transported.

τ^k : amount of commodity number k to be transported from s^k to d^k.

z_{ij}^k : continuous variable denoting the amount of flow of commodity number k on the edge $(i, j) \in E$.

The Formulation for *FORM* 14

Objective function:

$$\text{minimize} \sum_{k=1}^{q} \sum_{(i,j)\in E} z_{ij}^k \times c_{ij} \tag{A3.11}$$

subject to

1. Satisfy flow constraints for each commodity $k, 1 \le k \le q$.

$$\sum_{j:(i,j)\in E} z_{ij}^k - \sum_{j:(j,i)\in E} z_{ji}^k = \begin{cases} \tau^k & \text{if } i = s, \quad \forall k, 1 \le k \le q \\ -\tau^k & \text{if } i = d, \quad \forall i, 1 \le i \le N \\ 0 & \text{otherwise.} \end{cases} \tag{A3.12}$$

2. Ensure that the capacities of edges are not exceeded.

$$\sum_{k=1}^{q} z_{ij}^k \le u_{ij}, \quad \forall i, j, (i, j) \in E \tag{A3.13}$$

3. Flows cannot be negative.

$$z_{ij}^k \ge 0, \quad \forall i, j, (i, j) \in E, \forall k, 1 \le k \le q \tag{A3.14}$$

Justification of *FORM* 14

The flow of commodity k on edge $i \rightarrow j$ is z_{ij}^k (which may very well be 0, meaning that there is no flow of commodity k on edge $i \rightarrow j$). Since the cost per unit flow on edge $i \rightarrow j$ is c_{ij}, the cost of flow z_{ij}^k is $z_{ij}^k \times c_{ij}$. The objective function in (A3.11) is to find the minimum value of $\sum_{k=1}^{q} \sum_{(i,j) \in E} z_{ij}^k \times c_{ij}$, the minimum cost for transporting τ^k quantity from s^k to d^k, for all commodities $k, 1 \leq k \leq q$.

(A3.12) is similar to (A3.3), except that there is one set of equations for each commodity, and should be interpreted as follows:

Case I) ($i = s^k$) Since i is the source of the commodity k, the outflow for commodity k from i is τ^k and the inflow is 0. Thus the difference between the outflow and the inflow must be τ^k.

Case II) ($i = d^k$) Since i is the destination of the commodity k, the inflow to i for commodity k is τ^k and the outflow is 0. Thus the difference between the outflow and the inflow must be $-\tau^k$.

Case III) ($i \neq s^k$ and $i \neq d^k$) Since i is neither the source nor the destination of commodity k, the total inflow for commodity k must be matched by the total outflow for commodity k, so that the difference between the outflow and the inflow must be 0.

(A3.13) is like (A3.2) except that the sum of the flows for all commodities cannot exceed the capacity u_{ij} of the edge.

References

1. A. S. Acampora and S. I. A. Shah. Multihop lightwave networks: a comparison of store-and-forward and hot-potato routing. *IEEE Transactions on Communications*, 40(6):1082–1090, June 1992.
2. A. Aggarwal, A. Bar-Noy, D. Coppersmith, R. Ramaswami, B. Schieber, and M. Sudan. Efficient routing in optical networks. *Journal of the ACM*, 43(6):973–1001, 1996.
3. G. P. Agrawal. *Fiber-Optic Communication Systems*. Wiley, 2002.
4. R. K. Ahuja, T. L. Magnanti, and J. B. Orlin. *Network Flows: Theory, Algorithms, and Applications*. Prentice Hall, 1993.
5. M. Alanyali and E. Ayanoglu. Provisioning algorithms for WDM optical networks. *IEEE/ACM Transactions on Networking*, 7(5):767–778, October 1999.
6. M. Ali and J. Deogun. Power-efficient design of multicast wavelength-routed networks. *IEEE Journal on Selected Areas in Communications*, 18:1852–1862, October 2000.
7. D. Amar, A. Raspaud, and O. Togni. All-to-all wavelength-routing in all-optical compound networks. *Discrete Mathematics*, 235(1-3):353–363, 2001.
8. R. Andersen, F. Chung, A. Sen, and G. Xue. On disjoint path pairs with wavelength continuity constraint in WDM networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, pages 524–535, March 2004.
9. Y. Aneja, A. Jaekel, and S. Bandyopadhyay. An improved ILP formulation for path protection in WDM networks. In *7th IEEE International Conference on High Speed Networks and Multimedia Communications (HSNMC)*, volume 3079, pages 903–911, June/July 2004.
10. Y. Aneja, A. Jaekel, and S. Bandyopadhyay. Approximation algorithms for traffic routing in wavelength routed WDM networks. In *International Conference on Broadband Networks (BroadNets)*, volume 1, pages 23–30, October 2005.
11. Y. P. Aneja, A. Jaekel, and S. Bandyopadhyay. Logical topology design for WDM networks using survivable routing. In *IEEE International Conference on Communications (ICC)*, volume 6, pages 2471–2476, June 2006.
12. A. Arora, S. Subramaniam, and H.-A. Choi. Logical topology design for linear and ring optical networks. *IEEE Journal on Selected Areas in Communications*, 20(1):62–74, January 2002.

13. A. S. Arora and S. Subramaniam. Converter placement in wavelength routing mesh topologies. In *IEEE International Conference on Communications (ICC)*, pages 1282–1288, June 2000.
14. V. Auletta, I. Caragiannis, L. Gargano, C. Kaklamanis, and P. Persiano. Sparse and limited wavelength conversion in all-optical tree networks. *Theoretical Computer Science*, 266(1-2):887–934, 2001.
15. V. Auletta, I. Caragiannis, C. Kaklamanis, and P. Persiano. Bandwidth allocation algorithms on tree-shaped all-optical networks with wavelength converters. In D. Krizanc and P. Widmayer, editors, *International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, pages 24–39. Carleton Scientific, 1997.
16. V. Auletta, I. Caragiannis, C. Kaklamanis, and P. Persiano. Efficient wavelength routing in trees with low–degree converters. In *Multichannel Optical Networks: Theory and Practice, DIMACS Series in Discrete Mathematics and Computer Science, (AMS)*, volume 46, pages 1–14, 1998.
17. V. Auletta, I. Caragiannis, C. Kaklamanis, and P. Persiano. On the complexity of wavelength converters. In L. Brim, J. Gruska, and J. Zlatuska, editors, *International Symposium on Mathematical Foundations(MFCS)*, volume 1450 of *Lecture Notes in Computer Science*, pages 771–779. Springer, 1998.
18. V. Auletta, I. Caragiannis, C. Kaklamanis, and P. Persiano. Randomized path coloring on binary trees. In K. Jansen and S. Khuller, editors, *Workshop on Approximation Algorithms for Combinatorial Optimization Problems (APPROX)*, volume 1913 of *Lecture Notes in Computer Science*, pages 60–71. Springer, 2000.
19. V. Auletta, I. Caragiannis, C. Kaklamanis, and P. Persiano. Randomized path coloring on binary trees. *Theoretical Computer Science*, 289(1):355–399, 2002.
20. B. Awerbuch, Y. Azar, A. Fiat, S. Leonardi, and A. Rosén. On-line competitive algorithms for call admission in optical networks. *Algorithmica*, 31(1):29–43, 2001.
21. S. Balasubramanian, W. He, and A. K. Somani. Light-trail networks: Design and survivability. In *IEEE Conference on Local Computer Networks (LCN)*, pages 174–181, November 2005.
22. I. Baldine and G. N. Rouskas. Traffic adaptive WDM networks: a study of reconfiguration issues. *IEEE/OSA Journal of Lightwave Technology*, 19(4): 433–455, April 2001.
23. S. Bandyopadhyay, A. Jaekel, Y. P. Aneja, and S. Saha. A comparative study of schemes for robust logical topology design in wavelength routed WDM networks. In *IASTED International Conference on Optical Communication Systems and Networks (OCSN)*, pages 230–237, 2006.
24. S. Bandyopadhyay, A. Jaekel, A. Sengupta, and W. Lang. A virtual wavelength translation scheme for routing in all-optical networks. *Photonic Networks Communications*, 4(3-4):391–407, July 2002.
25. D. Banerjee and B. Mukherjee. A practical approach for routing and wavelength assignment in large wavelength-routed optical networks. *IEEE Journal on Selected Areas in Communications*, 14(5):903–908, June 1996.
26. D. Banerjee and B. Mukherjee. Wavelength-routed optical networks: linear formulation, resource budgeting tradeoffs, and a reconfiguration study. *IEEE/ACM Transactions on Networking*, 8(5):598–607, October 2000.

27. S. Baroni and P. Bayvel. Wavelength requirements in arbitrarily connected wavelength-routed optical networks. *IEEE/OSA Journal of Lightwave Technology*, 15(2):242–251, February 1997.
28. S. Baroni, R. J. Gibbens, and P. Bayvel. On the number of wavelengths in arbitrarily-connected wavelength-routed optical networks. In *Optical Networks and Their Applications (ONA)*, January 1998.
29. J. R. Barry and E. A. Lee. Performance of coherent optical receivers. In *Proceedings of the IEEE*, volume 78, pages 1369–1394, August 1990.
30. R. A. Barry. Will optical networks see the light of day? *IEEE Network*, 10(6):6–6, November 1996.
31. R. A. Barry and P. A. Humblet. On the number of wavelengths and switches in all-optical networks. *IEEE Transactions on Communications*, 42(2/3/4): 583–591, 1994.
32. R. A. Barry and P. A. Humblet. Models of blocking probability in all-optical networks with and without wavelength changers. *IEEE Journal on Selected Areas in Communications*, 14(5):858–867, June 1996.
33. Y. Bartal, A. Fiat, and S. Leonardi. Lower bounds for on-line graph problems with application to on-line circuit and optical routing. In *ACM Symp. on Theory of Computing (STOC)*, pages 531–540, May 1996.
34. Y. Bartal and S. Leonardi. On-line routing in all-optical networks. *Theoretical Computer Science*, 221(1-2):19–39, 1999.
35. M. S. Bazaraa, J. J. Jarvis, and H. D. Sherali. *Linear Programming and Network Flows.* Wiley, 1990.
36. B. Beauquier. Broadcasting in WDM optical rings and tori. In *DIMACS Workshop:Multichannel Optical Networks:Theory and Practice*, volume 46, pages 63–73, March 1998.
37. B. Beauquier. All-to-all communication for some wavelength-routed all-optical networks. *Networks*, 33(3):179–187, May 1999.
38. B. Beauquier, J.-C. Bermond, L. Gargano, P. Hell, S. Pérennes, and U. Vaccaro. Graph problems arising from wavelength-routing in all-optical networks. In *Workshop on Optics and Computer Science (WOCS)*, April 1997.
39. B. Beauquier, P. Hell, and S. Perennes. Optimal wavelength-routed multicasting. *Discrete Applied Mathematics*, 84(1-3):15–20, 1998.
40. B. Beauquier, S. Prennes, and M. Syska. Efficient access to optical bandwidth, routing and grooming in WDM networks: State-of-the-art survey. Technical report, Projet MASCOTTE (CNRS/INRIA/UNSA), Sophia Antipolis, July 2002.
41. V. E. Benes. *Mathematical Theory of Connecting Networks and Telephone Traffic.* Academic Press, 1965.
42. C. Berge. *Graphs and Hypergraphs.* American Elsevier Pub. Co, 1973.
43. J.-C. Bermond, L. Braud, and D. Coudert. Traffic grooming on the path. In *12th International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, pages 34–48, Le Mont Saint-Michel, France, May 24-26 2005. LNCS 3499.
44. J.-C. Bermond, L. Braud, and D. Coudert. Traffic grooming on the path. *Theoretical Computer Science*, 2007, to appear.
45. J.-C. Bermond and S. Ceroi. Minimizing SONET ADMs in unidirectional WDM rings with grooming ratio 3. *Networks*, 41(2):83–86, 2003.

46. J.-C. Bermond, C. Colbourn, D. Coudert, G. Ge, A. Ling, and X. Muñoz. Traffic grooming in unidirectional WDM rings with grooming ratio C=6. *SIAM Journal on Discrete Mathematics*, 19(2):523–542, 2005.
47. J.-C. Bermond, M. Cosnard, D. Coudert, and S. Perennes. Optimal solution of the maximum all request path grooming problem. In *Advanced International Conference on Telecommunications (AICT)*. IEEE, 2006.
48. J.-C. Bermond and D. Coudert. Traffic grooming in unidirectional WDM ring networks using design theory. In *IEEE International Conference on Communications (ICC)*, volume 2, pages 1402–1406, Anchorage, Alaska, May 2003.
49. J.-C. Bermond and D. Coudert. *The CRC Handbook of Combinatorial Designs (2nd edition)*, volume 42 of *Discrete Mathematics and Its Applications*, chapter VI.27, Grooming, pages 493–496. CRC Press, C.J. Colbourn and J.H. Dinitz edition, Nov. 2006.
50. J.-C. Bermond, D. Coudert, and X. Muñoz. Traffic grooming in unidirectional WDM ring networks: The all-to-all unitary case. In *7th IFIP Working Conference on Optical Network Design & Modelling (ONDM)*, pages 1135–1153, Budapest, Hungary, 2003.
51. J.-C. Bermond, D. Coudert, X. Muñoz, and I. Sau Valls. Traffic grooming in bidirectional WDM ring networks. In *IEEE-LEOS International Conference on Transparent Optical Networks (ICTON/COST 293 GRAAL)*, volume 3, pages 19–22, June 2006.
52. J.-C. Bermond, L. Gargano, S. Perennes, A. A. Rescigno, and U. Vaccaro. Efficient collective communication in optical networks. In *International Colloquium on Automata, Languages and Programming (ICALP), year = 1996, pages = 574-585, crossref = DBLP:conf/icalp/1996, bibsource = DBLP, http://dblp.uni-trier.de.*
53. J.-C. Bermond, L. Gargano, S. Perennes, A. A. Rescigno, and U. Vaccaro. Efficient collective communication in optical networks. *Theoretical Computer Science*, 233(1-2):165–189, 2000.
54. R. Berry and E. Modiano. Reducing electronic multiplexing costs in SONET/WDM rings with dynamically changing traffic. *IEEE Journal on Selected Areas in Communications*, 18(10):1961–1971, October 2000.
55. G. Bhati and G. Saraph. ADM reduction in SONET-WDM rings for stochastically varying traffic. In *International Conference on Broadband Networks (BroadNets)*, pages 333–335. IEEE, 2005.
56. L. Bhuyan and D. P. Agarwal. Generalized hypercube and hyperbus structure for a computer network. *IEEE Transactions on Computers*, C-33:323–333, April 1984.
57. Z. Bian, Q.-P. Gu, and X. Zhou. Wavelength assignment on bounded degree trees of rings. In *International Conference on Parallel and Distributed Systems (ICPADS)*, pages 73–80. IEEE Computer Society, 2004.
58. Z. Bian, Q.-P. Gu, and X. Zhou. Tight bounds for wavelength assignment on trees of rings. In *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*. IEEE Computer Society, 2005.
59. V. Bilò, M. Flammini, and L. Moscardelli. On Nash equilibria in non-cooperative all-optical networks. In V. Diekert and B. Durand, editors, *International Symposium on Theoretical Aspects of Computer Science (STACS)*, volume 3404 of *Lecture Notes in Computer Science*, pages 448–459. Springer, 2005.

60. A. Birman. Computing approximate blocking probabilities for a class of all-optical networks. *IEEE Journal on Selected Areas in Communications*, 14(5):852–857, June 1996.
61. E. Bouillet, J.-F. Labourdette, G. Ellinas, R. Ramamurthy, and S. Chaudhuri. Stochastic approaches to compute shared mesh restored lightpaths in optical network architectures. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 801–807, June 2002.
62. M. Bouklit, D. Coudert, J.-F. Lalande, C. Paul, and H. Rivano. Approximate multicommodity flow for WDM networks design. In J. Sibeyn, editor, *International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, number 17, in Proceedings in Informatics, pages 43–56, Umeå, Sweden, 2003. Carleton Scientific.
63. D. Buchfuhrer, T. Carnes, B. Tagiku, E. Celis, and R. Libeskind-Hadas. Traffic grooming for single-source multicast communication in WDM rings. In *IEEE International Conference on Communications (ICC)*, volume 3, pages 1613–1619, 2005.
64. B. V. Caenegem, W. V. Parys, F. D. Turck, and P. M. Demeester. Dimensioning of survivable WDM networks. *IEEE Journal on Selected Areas in Communications*, 16(7):1146–1157, September 1998.
65. G. Călinescu and P.-J. Wan. Traffic partition in WDM/SONET rings to minimize SONET ADMs. In *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, page 201. IEEE Computer Society, 2001.
66. G. Călinescu and P.-J. Wan. Splittable traffic partition in WDM/SONET rings to minimize SONET ADMs. *Theoretical Computer Science*, 276(1-2):33–50, 2002.
67. G. Călinescu and P.-J. Wan. Traffic partition in WDM/SONET rings to minimize SONET ADMs. *Journal of Combinatorial Optimization*, 6(4):425–453, 2002.
68. I. Caragiannis. Wavelength management in WDM rings to maximize the number of connections. In W. Thomas and P. Weil, editors, *International Symposium on Theoretical Aspects of Computer Science (STACS)*, volume 4393 of *Lecture Notes in Computer Science*, pages 61–72. Springer, 2007.
69. I. Caragiannis, A. Ferreira, C. Kaklamanis, S. Perennes, P. Persiano, and H. Rivano. Approximate constrained bipartite edge coloring. *Discrete Applied Mathematics*, 143(1-3):54–61, 2004.
70. I. Caragiannis, A. Ferreira, C. Kaklamanis, S. Perennes, and H. Rivano. Fractional path coloring with applications to WDM networks. In F. Orejas, P. G. Spirakis, and J. van Leeuwen, editors, *International Colloquium on Automata, Languages and Programming (ICALP)*, volume 2076 of *Lecture Notes in Computer Science*, pages 732–743. Springer, 2001.
71. I. Caragiannis and C. Kaklamanis. Approximate path coloring with applications to wavelength assignment in WDM optical networks. In V. Diekert and M. Habib, editors, *International Symposium on Theoretical Aspects of Computer Science (STACS)*, volume 2996 of *Lecture Notes in Computer Science*, pages 258–269. Springer, 2004.
72. I. Caragiannis, C. Kaklamanis, and P. Persiano. Bounds on optical bandwidth allocation on directed fiber tree topologies. In *International Parallel Processing Symposium, 2nd Workshop on Optics and Computer Science (WOCS'97)*, Geneva, Switzerland, April 1997. IEEE Press.

73. I. Caragiannis, C. Kaklamanis, and P. Persiano. Wavelength routing of symmetric communication requests in directed fiber trees. In L. Gargano and D. Peleg, editors, *International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, pages 10–19. Carleton Scientific, 1998.
74. I. Caragiannis, C. Kaklamanis, and P. Persiano. Edge coloring of bipartite graphs with constraints. In M. Kutylowski, L. Pacholski, and T. Wierzbicki, editors, *International Symposium on Mathematical Foundations(MFCS)*, volume 1672 of *Lecture Notes in Computer Science*, pages 376–386. Springer, 1999.
75. I. Caragiannis, C. Kaklamanis, and P. Persiano. Symmetric communication in all-optical tree networks. *Parallel Processing Letters*, 10(4):305–314, 2000.
76. I. Caragiannis, C. Kaklamanis, and P. Persiano. Wavelength routing in all-optical tree networks: A survey. *Computing and Informatics (formerly Computers and Artificial Intelligence)*, 20(2):95–120, 2001.
77. I. Caragiannis, C. Kaklamanis, and P. Persiano. Edge coloring of bipartite graphs with constraints. *Theoretical Computer Science*, 270(1-2):361–399, 2002.
78. I. Caragiannis, C. Kaklamanis, and P. Persiano. Approximation algorithms for path coloring in trees. In *Efficient Approximation and Online Algorithms*, LNCS 3484, pages 74–96. Springer, 2006.
79. I. Caragiannis, C. Kaklamanis, P. Persiano, and A. Sidiropoulos. Fractional and integral coloring of locally-symmetric sets of paths on binary trees. In K. Jansen and R. Solis-Oba, editors, *Workshop on Approximation and Online Algorithms (WAOA)*, volume 2909 of *Lecture Notes in Computer Science*, pages 81–94. Springer, 2003.
80. G.-K. Chang, G. Ellinas, J. K. Gamelin, M. Z. Iqbal, and C. A. Brackett. Multi-wavelength reconfigurable WDM/ATM/SONET network testbed. *IEEE/OSA Journal of Lightwave Technology*, 14(6):1320–1340, June 1996.
81. M. W. Chbat, E. Grard, L. Berthelon, A. Jourdan, P. A. Perrier, A. Leclert, B. Landousies, A. Ramdane, N. Parnis, E. V. Jones, E. Limal, H. N. Poulsen, R. J. S. Pedersen, N. Flaarønning, D. Vercauteren, M. Puleo, E. Ciaramella, G. Marone, R. Hess, H. Melchior, W. V. Parys, P. M. Demeester, P. J. Gødsvang, T. Olsen, and D. R. Hjelme. Toward wide-scale all-optical transparent networking: the ACTS Optical Pan-European Network (OPEN) project. *IEEE Journal on Selected Areas in Communications*, 16(7):1226–1244, September 1998.
82. B. Chen, G. N. Rouskas, and R. Dutta. Traffic grooming in WDM ring networks with the min-max objective. In *LNCS NETWORKING*, volume 3042, pages 174–185, May 2004.
83. B. Chen and J. Wang. Efficient routing and wavelength assignment for multicast in WDM networks. *IEEE Journal on Selected Areas in Communications*, 20(1):97–109, January 2002.
84. L. Chen and E. Modiano. Efficient routing and wavelength assignment for reconfigurable WDM ring networks with wavelength converters. *IEEE/ACM Transactions on Networking*, 13(1):173–186, February 2005.
85. Y. Chen, C. Qaio, and X. Yu. Optical burst switching: a new area in optical networking research. *IEEE Network*, 18(3):16–23, May-June 2004.
86. A. L. Chiu and E. H. Modiano. Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks. *IEEE/OSA Journal of Lightwave Technology*, 18(1):2–12, January 2000.

87. I. Chlamtac, A. Farago, and T. Zang. Lightpath (wavelength) routing in large WDM networks. *IEEE Journal on Selected Areas in Communications*, 14(5):909–913, June 1996.
88. I. Chlamtac, A. Ganz, and G. Karmi. Lightpath communications: an approach to high bandwidth optical WAN's. *IEEE Transactions on Communications*, 40(7):1171–1182, July 1992.
89. I. Chlamtac, A. Ganz, and G. Karmi. Lightnets: topologies for high-speed optical networks. *IEEE/OSA Journal of Lightwave Technology*, 11(5):951–961, May-June 1993.
90. H. Choi, S. Subramaniam, and H. Choi. Loopback recovery from double-link failures in optical mesh networks. *IEEE/ACM Transactions on Networking*, 12(6):1119–1130, December 2004.
91. T. Y. Chow, F. Chudak, and A. M. Ffrench. Fast optical layer mesh protection using pre-cross-connected trails. *IEEE/ACM Transactions on Networking*, 12(3):539–548, June 2004.
92. X. Chu and B. Li. Dynamic routing and wavelength assignment in the presence of wavelength conversion for all-optical networks. *IEEE/ACM Transactions on Networking*, 13(3):704–715, June 2005.
93. V. Chvatal. *Linear Programming.* W. H. Freeman, 1983.
94. C. Clos. A study of nonblocking switching networks. *Bell System Technical Journal*, 32:406–424, March 1953.
95. C. J. Colbourn and A. C. H. Ling. Graph decompositions with application to wavelength add-drop multiplexing for minimizing SONET ADMs. *Discrete Mathematics*, 261(1-3):141–156, 2003.
96. D. Coudert, P. Datta, S. Perennes, H. Rivano, and M.-E. Voge. Shared risk resource group: Complexity and approximability issues. *Parallel Processing Letters*, 2007, to appear.
97. D. Coudert and X. Muñoz. *Recent Research Developments in Optics, 3*, chapter 37, Graph Theory and Traffic Grooming in WDM Rings, pages 759–778. Research Signpost. Kerala, India, 2003. ISBN: 81-271-0028-5.
98. D. Coudert, S. Perennes, H. Rivano, and M.-E. Voge. Shared risk resource groups and survivability in multilayer networks. In *IEEE-LEOS International Conference on Transparent Optical Networks (ICTON/COST 293 GRAAL)*, volume 3, pages 235–238, 2006. Invited Paper.
99. D. Coudert and H. Rivano. Lightpath assignment for multifibers WDM optical networks with wavelength translators. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 3, pages 2686–2690, Taiwan, Nov. 2002. OPNT-01-5.
100. O. Crochat, J.-Y. L. Boudec, and O. Gerstel. Protection interoperability for WDM optical networks. *IEEE/ACM Transactions on Networking*, 8(3): 384–395, June 2000.
101. G. Dantzig and R. V. Slyke. Generalized upper bounding technique. *Journal of Computer and System Sciences*, 1(3):213–226, 1967.
102. D. Das, M. De, and B. Sinha. A new network topology with multiple meshes. *IEEE Transactions on Computers*, 48(5):536–551, May 1999.
103. S. Datta, S. Sengupta, S. Biswas, and S. Datta. Efficient channel reservation for backup paths in optical mesh networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 4, pages 2104–2108, November 2001.

104. S. Datta, S. Sengupta, S. Biswas, D. Saha, and H. Kobayashi. Analysis of subwavelength traffic grooming efficiency in optical mesh networks. In *IEEE International Conference on Communications*, volume 3, pages 1811–1815, 2004.
105. P. Degano, R. Gorrieri, and A. Marchetti-Spaccamela, editors. *Automata, Languages and Programming, 24th International Colloquium, ICALP'97, Bologna, Italy, 7-11 July 1997, Proceedings*, volume 1256 of *Lecture Notes in Computer Science*. Springer, 1997.
106. P. Demeester, M. Gryseels, A. Autenrieth, C. Brianza, L. Castagna, G. Signorelli, R. Clemenfe, M. Ravera, A. Jajszczyk, D. Janukowicz, K. V. Doorselaere, and Y. Harada. Resilience in multilayer networks. *IEEE Communications Magazine*, 37(8):70–76, August 1999.
107. P. Demeester, T. H. Wu, and N. Yoshikai. Survivable communication networks. *IEEE Communications Magazine*, 37(8), Aug 1999. Special Issue.
108. E. W. Dijkstra. A note on two problems in connexion with graphs. *Numerische Mathematik*, 1:269–271, 1959.
109. A. Ding and G. S. Poo. A survey of optical multicast over WDM networks. *Computer Communications*, 26(2):193–200, February 2003.
110. B. T. Doshi, S. Dravida, P. Harshavardhana, O. Hauser, and Y. Wang. Optical network design and restoration. *Bell Labs Technical Journal*, 4(1):58–84, January 1999.
111. P. W. Dowd. Wavelength division multiple access channel hypercube processor interconnection. *IEEE Transactions on Computers*, 41(10):1223–1241, October 1992.
112. F. J. Duarte. *Tunable Laser Optics*. Academic Press, 2003.
113. A. K. Dutta, N. K. Dutta, and M. Fujiwara, editors. *WDM Technologies: Optical Networks*. Elsevier, 2004.
114. N. K. Dutta, A. K. Dutta, and M. Fujiwara, editors. *WDM Technologies: Passive Optical Components*. Elsevier, 2003.
115. R. Dutta, S. Huang, and G. N. Rouskas. Traffic grooming in path, star, and tree networks: complexity, bounds, and algorithms. In *2003 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, pages 298–299, New York, NY, USA, 2003. ACM Press.
116. R. Dutta and G. N. Rouskas. A survey of virtual topology design algorithms for wavelength routed optical networks. *SPIE Optical Networks Magazine*, 1(1):73–89, January 2000.
117. R. Dutta and G. N. Rouskas. On optimal traffic grooming in WDM rings. *IEEE Journal on Selected Areas in Communications*, 20(1):110–121, January 2002.
118. R. Dutta and G. N. Rouskas. Traffic grooming in WDM networks: past and future. *IEEE Network*, 16(6):46–56, November 2002.
119. T. Eilam, S. Moran, and S. Zaks. Approximation algorithms for survivable optical networks. In *International Symposium on Distributed Computing (ISDC)*, pages 104–118, 2000.
120. T. Eilam, S. Moran, and S. Zaks. Lightpath arrangement in survivable rings to minimize the switching cost. *IEEE Journal on Selected Areas in Communications*, 20(1):172–182, January 2002.
121. G. Ellinas, K. Bala, and G. K. Chang. Scalability of a novel wavelength assignment algorithm for WDM shared protection rings. In *IEEE/OSA Optical Fiber Communications Conference (OFC)*, February 1998.

122. J. M. H. Elmirghani and H. T. Mouftah. All-optical wavelength conversion: technologies and applications in DWDM networks. *IEEE Communications Magazine*, 38(3):86–92, March 2000.
123. L. Epstein and A. Levin. Better bounds for minimizing SONET ADMs. In G. Persiano and R. Solis-Oba, editors, *Workshop on Approximation and Online Algorithms (WAOA)*, volume 3351 of *Lecture Notes in Computer Science*, pages 281–294. Springer, 2004.
124. L. Epstein and A. Levin. The chord version for SONET ADMs minimization. *Theoretical Computer Science*, 349(3):337–346, 2005.
125. L. Epstein and A. Levin. SONET ADMs minimization with divisible paths. In T. Erlebach and G. Persiano, editors, *Workshop on Approximation and Online Algorithms (WAOA)*, volume 3879 of *Lecture Notes in Computer Science*, pages 119–132. Springer, 2005.
126. T. Erlebach and K. Jansen. Scheduling of virtual connections in fast networks. In *Proc. of 4th Workshop on Parallel Systems and Algorithms (PASA'96)*, pages 13–32. World Scientific Publishing, 1996.
127. T. Erlebach and K. Jansen. Efficient implementation of an optimal greedy algorithm for wavelength allocation in directed tree networks. In K. Mehlhorn, editor, *Algorithm Engineering*, pages 13–24. Max-Planck-Institut für Informatik, 1998.
128. T. Erlebach and K. Jansen. Maximizing the number of connections in optical tree networks. In K.-Y. Chwa and O. H. Ibarra, editors, *International Symposium on Algorithms & Computation (ISAAC)*, volume 1533 of *Lecture Notes in Computer Science*, pages 179–188. Springer, 1998.
129. T. Erlebach and K. Jansen. Efficient implementation of an optimal greedy algorithm for wavelength assignment in directed tree networks. *ACM Journal of Experimental Algorithms*, 4:article 4, 1999.
130. T. Erlebach and K. Jansen. The complexity of path coloring and call scheduling. *Theoretical Computer Science*, 255(1-2):33–50, March 2001.
131. T. Erlebach and K. Jansen. The maximum edge-disjoint paths problem in bidirected trees. *SIAM J. Discrete Math.*, 14(3):326–355, 2001.
132. T. Erlebach, K. Jansen, C. Kaklamanis, M. Mihail, and P. Persiano. Optimal wavelength routing on directed fiber trees. *Theoretical Computer Science*, 221(1-2):119–137, 1999.
133. T. Erlebach, K. Jansen, C. Kaklamanis, and P. Persiano. An optimal greedy algorithm for wavelength allocation in directed tree networks. In *DIMACS Workshop on Network Design: Connectivity and Facilities Location (April 28-30, 1997)*, volume 40 of *DIMACS Series in Discrete Mathematics and Theoretical Computer Science*, pages 117–129, Rutgers University, NJ, 1998. American Mathematical Society.
134. T. Erlebach, K. Jansen, C. Kaklamanis, and P. Persiano. Directed tree networks. In *Encyclopedia of Optimization, Volume I*, pages 444–453. Kluwer Academic Publishers, June 2001.
135. T. Erlebach, A. Pagourtzis, K. Potika, and S. Stefanakos. Resource allocation problems in multifiber WDM tree networks. In H. L. Bodlaender, editor, *Workshop on Graph Theoretical Concepts in Computer Science (WG)*, volume 2880 of *Lecture Notes in Computer Science*, pages 218–229. Springer, 2003.
136. T. Erlebach and S. Stefanakos. On shortest-path all-optical networks without wavelength conversion requirements. In H. Alt and M. Habib, editors, *International Symposium on Theoretical Aspects of Computer Science (STACS)*,

volume 2607 of *Lecture Notes in Computer Science*, pages 133–144. Springer, 2003.

137. T. Erlebach and S. Stefanakos. Wavelength conversion in shortest-path all-optical networks. In T. Ibaraki, N. Katoh, and H. Ono, editors, *International Symposium on Algorithms & Computation (ISAAC)*, volume 2906 of *Lecture Notes in Computer Science*, pages 595–604. Springer, 2003.
138. T. Erlebach and S. Stefanakos. Wavelength conversion in all-optical networks with shortest-path routing. *Algorithmica*, 43(1-2):43–61, 2005.
139. J. Fang, M. Sivakumar, A. K. Somani, and K. M. Sivalingam. On partial protection in groomed optical WDM mesh networks. In *IEEE International Conference on Dependable Systems and Networks (DSN) — Dependable Computing and Communications Symposium (DCCS)*, pages 228–237, June 2005.
140. J. Fang and A. K. Somani. Enabling subwavelength level traffic grooming in survivable WDM optical network design. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 5, pages 2761–2766, December 2003.
141. J. Fang and A. K. Somani. IP traffic grooming over WDM optical networks. In *9th IFIP/IEEE conference on Optical Networks Design and Modeling (ONDM)*, pages 393–402, February 2005.
142. F. Farahmand, X. Huang, and J. Jue. Efficient online traffic grooming algorithms in WDM mesh networks with drop-and-continue node architecture. In *International Conference on Broadband Networks (BroadNets)*, pages 180–189, 2004.
143. A. Ferreira, S. Perennes, H. Rivano, A. W. Richa, and N. E. S. Moses. Models, complexity and algorithms for the design of multi-fiber WDM networks. *Journal of Telecommunication Systems*, 24(2-4):123–138, October 2003.
144. A. Ferreira, S. Prennes, A. W. Richa, H. Rivano, and N. Stier. On the design of multifiber WDM networks. In *10th IEEE International Conference on Telecommunications – ICT 2003*, volume I, pages 12–18, Tahiti, 2003.
145. M. Flammini, G. Monaco, L. Moscardelli, M. Shalom, and S. Zaks. Approximating the traffic grooming problem in tree and star networks. In F. V. Fomin, editor, *Workshop on Graph Theoretical Concepts in Computer Science (WG)*, volume 4271 of *Lecture Notes in Computer Science*, pages 147–158. Springer, 2006.
146. M. Flammini, L. Moscardelli, M. Shalom, and S. Zaks. Approximating the traffic grooming problem. In X. Deng and D.-Z. Du, editors, *International Symposium on Algorithms & Computation (ISAAC)*, volume 3827 of *Lecture Notes in Computer Science*, pages 915–924. Springer, 2005.
147. M. Flammini, A. Navarra, and A. Proskurowski. On routing of wavebands for gossiping in all-optical paths and cycles. In J. F. Sibeyn, editor, *International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, volume 17 of *Proceedings in Informatics*, pages 133–145. Carleton Scientific, 2003.
148. M. Flammini, A. Navarra, and A. Proskurowski. On routing of wavebands for all-to-all communications in all-optical paths and cycles. *Theoretical Computer Science*, 333(3):401–413, March 2005.
149. M. Flammini and C. Scheideler. Simple, efficient routing schemes for all-optical networks. *Theory of Computing Systems*, 32(3):387–420, June 1999.
150. M. Flammini, M. Shalom, and S. Zaks. On minimizing the number of ADMs — tight bounds for an algorithm without preprocessing. In T. Erlebach, editor,

CAAN, volume 4235 of *Lecture Notes in Computer Science*, pages 72–85. Springer, 2006.

151. M. Flammini, M. Shalom, and S. Zaks. On minimizing the number of ADMs in a general topology optical network. In S. Dolev, editor, *International Symposium on Distributed Computing (DISC)*, volume 4167 of *Lecture Notes in Computer Science*, pages 459–473. Springer, 2006.
152. L. Ford and D. Fulkerson. A suggested computation for maximal multicommodity network flows. *Management Science*, 5(1):97–101, November 1958.
153. A. Frank. Edge-disjoint paths in planar graphs. *Journal of Combinatorial Theory, Series B*, 39(2):164–178, 1985.
154. A. Frank, T. Nishizeki, N. Saito, and H. Suzuki. Algorithms for routing around a rectangle. *Discrete Applied Mathematics*, 40(3):363–378, 1992.
155. A. Fumagalli, I. Cerutti, M. Tacca, F. Masetti, R. Jagannathan, and S. Alagar. Survivable networks based on optimal routing and WDM self-healing rings. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 726–733, March 1999.
156. A. Fumagalli and L. Valcarenghi. IP restoration vs. WDM protection: is there an optimal choice? *IEEE Network*, 14(6):34–41, November/December 2000.
157. A. Ganz and X. Wang. Efficient algorithm for virtual topology design in multihop lightwave networks. *IEEE/ACM Transactions on Networking*, 2(3): 217–225, June 1994.
158. M. R. Garey, D. S. Johnson, G. L. Miller, and C. H. Papadimitriou. The complexity of coloring circular arcs and chords. *SIAM J. Algebraic Discrete Methods*, 1:216–227, 1980.
159. L. Gargano. Limited wavelength conversion in all-optical tree networks. In K. G. Larsen, S. Skyum, and G. Winskel, editors, *International Colloquium on Automata, Languages and Programming (ICALP)*, volume 1443 of *Lecture Notes in Computer Science*, pages 544–555. Springer, 1998.
160. L. Gargano. Multicasting in optical networks. In R. Freivalds, editor, *Fundamentals of Computation Theory (FCT)*, volume 2138 of *Lecture Notes in Computer Science*, pages 459–460. Springer, 2001.
161. L. Gargano, P. Hell, and S. Perennes. Colouring paths in directed symmetric trees with applications to WDM routing. In Degano et al. [105], pages 505–515.
162. L. Gargano, P. Hell, and S. Pérennes. Coloring all directed paths in a symmetric tree, with an application to optical networks. *Journal of Graph Theory*, 38(4):183–196, 2001.
163. L. Gargano and A. Rescigno. Coloring circular arcs with applications to WDM routing. In *Workshop on Approximation and Randomization Algorithms in Communication Networks (ARACNE'00)*, pages 155–166, July 2000.
164. L. Gargano, A. Rescigno, and U. Vaccaro. Multicasting to groups in optical networks and related combinatorial optimization problems. In *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, page 223a. IEEE Computer Society, 2003.
165. L. Gargano and V. Vaccaro. *Numbers, Information and Complexity, I. Althofer et al. (Eds.)*, chapter Routing in All-Optical Networks: Algorithmic and Graph-Theoretic Problems, Tutorial, pages 555–578. Kluwer Academic Publisher, February 2000.
166. O. Gerstel and S. Kutten. Dynamic wavelength allocation in all-optical ring networks. In *IEEE International Conference on Communications (ICC)*, volume 1, pages 432–436, June 1997.

167. O. Gerstel and R. Ramaswami. Optical layer survivability – an implementation perspective. *IEEE Journal on Selected Areas in Communications*, 18(10): 1885–1899, October 2000.
168. O. Gerstel and R. Ramaswami. Optical layer survivability: a services perspective. *IEEE Communications Magazine*, 38(3):104–113, March 2000.
169. O. Gerstel, R. Ramaswami, and G. Sasaki. Benefits of limited wavelength conversion in WDM ring networks. In *IEEE/OSA Optical Fiber Communications Conference (OFC)*, pages 119–120, 16-21 February 1997.
170. O. Gerstel, R. Ramaswami, and G. Sasaki. Cost-effective traffic grooming in WDM rings. *IEEE/ACM Transactions on Networking*, 8(5):618–630, October 2000.
171. A. Ghatak and K. Thyagarajan. *An Introduction to Fiber Optics.* Cambridge University Press, 1998.
172. A. M. Glass, D. J. DiGiovanni, T. A. Strasser, A. J. Stentz, R. E. Slusher, A. E. White, A. R. Kortan, and B. J. Eggleton. Advances in fiber optics. *Bell Labs Technical Journal*, 5(1):168–187, 2000.
173. D. R. Goff. *Fiber Optic Reference Guide.* Elsevier Science, 2002.
174. J.-P. Goure and I. Verrier. *Optical Fibre Devices.* CRC Press, 2002.
175. P. Green. Progress in optical networking. *IEEE Communications Magazine*, 39(1):54–61, January 2001.
176. P. E. Green. *Fiber Optic Networks.* Prentice Hall, 1992.
177. A. Grosso, E. Leonardi, M. Mellia, and A. Nucci. Logical topologies design over WDM wavelength routed networks robust to traffic uncertainties. *IEEE Communications Letters*, 5(4):172–174, April 2001.
178. J. Gruber and R. Ramaswami. Moving toward all-optical networks. *Lightwave*, pages 60–68, December 2000.
179. Q.-P. Gu. On-line permutation routing on WDM all-optical networks. In *IEEE International Conference on Parallel Processing (ICPP)*, pages 419–428. IEEE Computer Society, August 2002.
180. Q.-P. Gu and S. Peng. Efficient protocols for permutation routing on all-optical multistage interconnection networks. In *IEEE International Conference on Parallel Processing (ICPP)*, pages 513–520, 2000.
181. Q.-P. Gu and S. Peng. Wavelengths requirement for permutation routing in all-optical multistage interconnection networks. In *IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, pages 761–768. IEEE Computer Society, 2000.
182. Q.-P. Gu and S. Peng. Multihop all-to-all broadcast on WDM optical networks. *IEEE Transactions on Parallel and Distributed Systems*, 14(5):477–486, May 2003.
183. A. Gumaste and I. Chlamtac. Light-trails: an optical solution for IP transport. *Journal of Optical Networking*, 3(5):261–281, May 2004.
184. K. P. Gummadi, M. J. Pradeep, and C. S. R. Murthy. An efficient primary-segmented backup scheme for dependable real-time communication in multihop networks. *IEEE/ACM Transactions on Networking*, 11(1), 2003.
185. A. M. Hamad and A. E. Kamal. A survey of multicasting protocols for broadcast-and-select single-hop networks. *IEEE Network*, 16(4):36–48, July/August 2002.
186. H. Harai, M. Murata, and H. Miyahara. Performance of alternate routing methods in all-optical switching networks. In *IEEE International Conference*

on Computer Communications (INFOCOM), volume 2, pages 516–525, April 1997.

187. H. Harai, M. Murata, and H. Miyahara. Heuristic algorithms of allocation of wavelength convertible nodes and routing coordination in all-optical networks. *Journal of Lightwave Technology*, 17(4):535–545, April 1999.
188. J. R. K. Hartline, R. Libeskind-Hadas, K. M. Dresner, E. W. Drucker, and K. J. Ray. Optimal virtual topologies for one-to-many communication in WDM paths and rings. *IEEE/ACM Transactions on Networking*, 12(2):375–383, April 2004.
189. O. Hauser, M. Kodialam, and T. V. Lakshman. Capacity design of fast path restorable optical networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 817–826, 2002.
190. J. Hecht. *City of Light: The Story of Fiber Optics*. Oxford University Press, New York, US, 1999.
191. J. Hecht. *Understanding Fiber Optics*. Prentice Hall, 2005.
192. P. Hell and F. S. Roberts. Analogues of Shannon capacity of a graph. *Annals of Discrete Mathematics*, pages 155–168, 1982.
193. M.-C. Heydemann, J.-C. Meyer, and D. Sotteau. On forwarding indices of networks. *Discrete Applied Mathematics*, 23:103–123, 1989.
194. M. G. Hluchyj and M. J. Karol. Shuffle net: an application of generalized perfect shuffles to multihop lightwave networks. *Journal of Lightwave Technology*, 9(10):1386–1397, October 1991.
195. P. Ho and H. Mouftah. Routing and wavelength assignment with multi-granularity traffic in optical networks. *Journal of Lightwave Technology*, 20: 1292–1303, August 2002.
196. P.-H. Ho and H. Mouftah. A framework for service-guaranteed shared protection in WDM mesh networks. *IEEE Communications Magazine*, 40(2):97–103, February 2002.
197. P.-H. Ho and H. T. Mouftah. Allocation of protection domains in dynamic WDM mesh networks. In *International Conference on Network Protocols (ICNP)*, pages 188–189, November 2002.
198. M. E. Houmaidi, M. Bassiouni, and G. Li. Optimal traffic grooming in WDM mesh networks under dynamic traffic. In *IEEE/OSA Optical Fiber Communications Conference (OFC)*, volume 2, pages 23–27, February 2004.
199. J. Hromkovič, R. Klasing, A. Pelc, P. Ružička, and W. Unger. *Dissemination of Information in Communication Networks: Part I. Broadcasting, Gossiping, Leader Election, and Fault-Tolerance*. Springer-Verlag, 2005.
200. J. Hu. Traffic grooming in wavelength-division-multiplexing ring networks: a linear programming solution. *Journal of Optical Networking*, 1(11):397–408, November 2002.
201. J. Q. Hu and B. Leida. Traffic grooming, routing, and wavelength assignment in optical WDM mesh networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 495–501, March 2004.
202. J.-Q. Hu and E. Modiano. *Optical WDM Networks: Principles and Practice*, volume II, chapter Traffic Grooming in WDM Networks. Kluwer Academic Publishers, 2004.
203. S. Huang and R. Dutta. Research problems in dynamic traffic grooming in optical networks. In *International Conference on Broadband Networks (BroadNets)*, October 2004.

204. X. Huang, F. Farahmand, and J. P. Jue. An algorithm for traffic grooming in WDM mesh networks with dynamically changing light-trees. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 3, pages 1813–1817, November 2004.
205. K. Hwang and F. A. Briggs. *Computer Architecture and Parallel Processing.* McGraw-Hill Companies, 1984.
206. ILOG CPLEX 9.1. Documentation available at *http://www.iitb.ac.in/ ieor/resources/cplex91/refcallablelibrary/index.html.*
207. J. Iness, S. Banerjee, and B. Mukherjee. Gemnet: A generalized shuffle-exchange-based regular, scalable and modular multihop network based on WDM lightwave network. *IEEE/ACM Transactions on Networking*, August 1995.
208. R. R. Iraschko and W. D. Grover. A highly efficient path-restoration protocol for management of optical network transport integrity. *IEEE Journal on Selected Areas in Communications*, 18(5):779–794, May 2000.
209. A. Jaekel, S. Bandyopadhyay, S. Roychoudhury, and A. Sengupta. A scalable logical topology for optical networks. *Journal of High Speed Networks*, 11(2):79–87, 2002.
210. S. Janardhanan, A. Mahanti, and D. Saha. A heuristic search based optimal wavelength assignment algorithm to minimize the number of SONET ADMs in WDM rings. In M. Y. Sanadidi, editor, *Communications and Computer Networks*, pages 152–157. IASTED/ACTA Press, 2005.
211. S. Janardhanan, A. Mahanti, D. Saha, and S. K. Sadhukhan. A routing and wavelength assignment (RWA) technique to minimize the number of SONET ADMs in WDM rings. In *Hawaii International Conference on System Sciences (HICSS).* IEEE Computer Society, 2006.
212. K. Jansen. Approximation results for wavelength routing in directed trees. In *International Parallel Processing Symposium, 2nd Workshop on Optics and Computer Science (WOCS'97)*, Geneva, Switzerland, 1997. IEEE Press.
213. K. Jansen. Approximate strong separation with application in fractional graph coloring and preemptive scheduling. *Theoretical Computer Science*, 1-3(302):239–256, 2003.
214. X.-H. Jia, D. Du, X. Hu, M. Lee, and J. Gu. Optimization of wavelength assignment for QoS multicast in WDM networks. *IEEE Transactions on Communications*, 49(2):341–350, February 2001.
215. A. Jukan and G. Franzl. Path selection methods with multiple constraints in service-guaranteed WDM networks. *IEEE/ACM Transactions on Networking*, 12(1):59–72, February 2004.
216. J.Wang, L. Sahasrabuddhe, and B. Mukherjee. Path vs. subpath vs. link restoration for fault management in IP-over-WDM networks: Performance comparisons using GMPLS control signaling. *IEEE Communication Magazine*, 40(11):80–87, November 2002.
217. C. Kaklamanis and G. Persiano. Efficient wavelength routing on directed fiber trees. In J. Díaz and M. J. Serna, editors, *European Symposium on Algorithms (ESA)*, volume 1136 of *Lecture Notes in Computer Science*, pages 460–470. Springer, 1996.
218. C. Kaklamanis, P. Persiano, T. Erlebach, and K. Jansen. Constrained bipartite edge coloring with applications to wavelength routing. In Degano et al. [105], pages 493–504.

219. I. A. Karapetyan. On coloring of arc graphs. *Doklady Akad. Nauk Armianskoi CCP*, 70(5):306–311, 1980. In Russian.
220. E. Karasan and E. Ayanoglu. Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks. *IEEE/ACM Transactions on Networking*, 6(2):186–196, April 1998.
221. G. Keiser. *Optical Communications Essentials*. McGraw-Hill, 2003.
222. F. W. Kerfoot and W. C. Marra. Undersea fiber optic networks: past, present, and future. *IEEE Journal on Selected Areas in Communications*, 16(7): 1220–1225, September 1998.
223. D. Kettler, H. Kafka, and D. Spears. Driving fiber to the home. *IEEE Communications Magazine*, 38(11):106–110, November 2000.
224. S. Kim and S. S. Lumetta. Capacity-efficient protection with fast recovery in optically transparent mesh networks. In *International Conference on Broadband Networks (BroadNets)*, pages 290–299, 2004.
225. T. Kitani, M. Yonedu, N. Funabiki, T. Nakanishi, K. Okayama, and T. Higashino. A two-stage hierarchical algorithm for wavelength assignment in WDM-based bidirectional Manhattan Street networks. In *IEEE International Conference on Networks*, pages 419–424, Sept-Oct 2003.
226. R. Klasing. Methods and problems of wavelength-routing in all-optical networks. In *International Symposium on Mathematical Foundations(MFCS) Workshop on Communication*, August 1998.
227. M. Kodialam and T. V. Lakshman. Integrated dynamic IP and wavelength routing in IP over WDM networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 258–366, April 2001.
228. M. Kodialam and T. V. Lakshman. Dynamic routing of restorable bandwidth-guaranteed tunnels using aggregated network resource usage information. *IEEE/ACM Transactions on Networking*, 11(3):399–410, June 2003.
229. V. R. Konda and T. Y. Chow. Algorithm for traffic grooming in optical networks to minimize the number of transceivers. In *IEEE Workshop on High Performance Switching and Routing (HPSR)*, pages 218–221, May 2001.
230. M. Kovacevic and A. Acampora. Benefits of wavelength translation in all-optical clear-channel networks. *IEEE Journal on Selected Areas in Communications*, 14(5):868–880, June 1996.
231. R. M. Krishnaswamy and K. N. Sivarajan. Algorithms for routing and wavelength assignment based on solutions of the LP-relaxations. *IEEE Communications Letters*, 5(10):435–437, October 2001.
232. R. M. Krishnaswamy and K. N. Sivarajan. Design of logical topologies: A linear formulation for wavelength-routed optical networks with no wavelength changers. *IEEE/ACM Transactions on Networking*, 9(2):186–198, April 2001.
233. V. Kumar and E. J. Schwabe. Improved access to optimal bandwidth in trees. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 437–444, 1997.
234. J. Kuri, N. Puech, M. Gagnaire, and E. Dotaro. Routing foreseeable lightpath demands using a tabu search meta-heuristic. In *IEEE Global Telecommunications Conference (GLOBECOM)*, pages 2803–2807, November 2002.
235. J. Labourdette, E. Bouillet, R. Ramamurthy, and A. A. Akyama. Fast approximate dimensioning and performance analysis of mesh optical networks. *IEEE/ACM Transactions on Networking*, 13(4):906–917, August 2005.

236. J.-F. P. Labourdette and A. S. Acampora. Logically rearrangeable multihop lightwave networks. *IEEE Transactions on Communications*, 39(8):1223–1230, August 1991.
237. C.-C. Lam, C.-H. Huang, and P. Sadayappan. Optimal algorithms for all-to-all personalized communication on rings and two dimensional tori. *Journal of Parallel and Distributed Computing*, 43(1):3–13, 1997.
238. J. P. Lang, V. Sharma, and E. A. Varvarigos. An analysis of oblivious and adaptive routing in optical networks with wavelength translation. *IEEE/ACM Transactions on Networking*, 9(4):503–517, August 2001.
239. K.-C. Lee and V. O. K. Li. A wavelength-convertible optical network. *Journal of Lightwaveve Technology*, 11(5):962–970, May/June 1993.
240. F. Leighton. *Introduction to Parallel Algorithms and Architectures: Array, Trees, Hypercubes*. Morgan Kaufmann Publishers, September 1992.
241. E. Leonardi, M. Mellia, and M. A. Marsan. Algorithms for the logical topology design in WDM all-optical networks. *Optical Network Magazine*, 1(1):35–46, January 2000.
242. S. Leonardi. On-line network routing. In A. Fiat and G. J. Woeginger, editors, *Online Algorithms*, volume 1442 of *Lecture Notes in Computer Science*, pages 242–267. Springer, 1996.
243. S. Leonardi, A. Marchetti-Spaccamela, A. Presciutti, and A. Rosén. On-line randomized call control revisited . *SIAM Journal on Computing*, 31(1):86–112, 2001.
244. S. Leonardi and A. Vitaletti. Randomized lower bounds for online path coloring. In M. Luby, J. D. P. Rolim, and M. J. Serna, editors, *Randomization and Approximation Techniques in Computer Science(RANDOM)*, volume 1518 of *Lecture Notes in Computer Science*, pages 232–247. Springer, 1998.
245. B. Li, X. Chu, and K. Sohraby. Routing and wavelength assignment vs. wavelength converter placement in all-optical networks. *IEEE Communications Magazine*, 41(8):S22–S28, August 2003.
246. D. Li, Z. Sun, X. Jia, and K. Makki. Traffic grooming on general topology WDM networks. *IEE Proceedings Communications*, 150:197–201, 2003.
247. G. Li and R. Simha. On the wavelength assignment problem in multifiber WDM star and ring networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 3, pages 1771–1780, March 2000.
248. G. Li, D. Wang, C. Kalmanek, and R. Doverspike. Efficient distributed path selection for shared restoration connections. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 140–149, June 2002.
249. L. Li and A. K. Somani. Dynamic wavelength routing using congestion and neighborhood information. *IEEE/ACM Transactions on Networking*, 7(5):779–786, October 1999.
250. L. Li and A. K. Somani. A new analytical model for multifiber WDM networks. *IEEE Journal on Selected Areas in Communications*, 18(10):2138–2145, October 2000.
251. R. Libeskind-Hadas and R. Melhem. Multicast routing and wavelength assignment in multihop optical networks. *IEEE/ACM Transactions on Networking*, 10(5):621–629, October 2002.
252. E. Limal, S. L. Danielsen, and K. E. Stubkjaer. Capacity utilization in resilient wavelength-routed optical networks using link restoration. In *IEEE/OSA*

Optical Fiber Communications Conference (OFC), volume 2, pages 297–298, February 1998.

253. C. F. Lin. *Optical Components for Communications: Principles and Applications.* Springer, 2004.
254. H. C. Lin and C. H. Wang. A hybrid multicast scheduling algorithm for single-hop WDM networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 169–178, April 2001.
255. K. Liu and J. Ryan. All the animals in the zoo: the expanding menagerie of optical components. *IEEE Communication Magazine*, 39(7):110–115, July 2001.
256. L. Liu, X.-Y. Li, P.-J. Wan, and O. Frieder. Wavelength assignment in WDM rings to minimize SONET ADMs. In *IEEE International Conference on Computer Communications (INFOCOM)*, pages 1020–1025, 2000.
257. X. Liu and Q.-P. Gu. Multicasts on WDM all-optical multistage interconnection networks. In *International Conference on Parallel and Distributed Systems (ICPADS)*, pages 601–608, 2001.
258. X. Liu and Q.-P. Gu. Multicasts on WDM all-optical butterfly networks. *Journal of Information Science and Engineering*, 18(6):1049–1058, November 2002.
259. Y. Liu, D. Tipper, and P. Siripongwutikorn. Approximating optimal spare capacity allocation by successive survivable routing. *IEEE/ACM Transactions on Networking*, 13(1):198–211, February 2005.
260. C. Looi, W. Liao, and D. Yang. Service differentiation in optical burst switched networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 3, pages 2313–2317, November 2002.
261. K. Lu, G. Xiao, and I. Chlamtac. Behavior of distributed wavelength provisioning in wavelength-routed networks with partial wavelength conversion. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 3, pages 1816–1825, April 2003.
262. S. S. Lumetta and M. Médard. Towards a deeper understanding of link restoration algorithms for mesh networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 367–375, April 2001.
263. S. S. Lumetta, M. Médard, and Y.-C. Tseng. Capacity versus robustness: a tradeoff for link restoration in mesh networks. *Journal of Lightwave Technology*, 18(12):1765–1775, December 2000.
264. M. W. Maeda. Management and control of transparent optical networks. *IEEE Journal on Selected Areas in Communications*, 16(7):1008–1023, September 1998.
265. R. Mahalati and R. Dutta. Reconfiguration of traffic grooming optical networks. In *International Conference on Broadband Networks (BroadNets)*, pages 170–179, 2004.
266. J. Manchester, P. Bonenfant, and C. Newton. The evolution of transport network survivability. *IEEE Communications Magazine*, 37(8):44–51, August 1999.
267. Y. Manoussakis and Z. Tuza. The forwarding index of directed networks. *Discrete Applied Mathematics*, 68(3):279–291, July 1996.
268. M. A. Marsan, A. Bianco, E. Leonardi, and F. Neri. Topologies for wavelength-routing all-optical networks. *IEEE/ACM Transactions on Networking*, 1(5):534–546, October 1993.

269. C. Mas and P. Thiran. An efficient algorithm for locating soft and hard failures in WDM networks. *IEEE Journal on Selected Areas in Communications*, 18(10):1900–1911, October 2000.
270. M. F. Maxemchuk. Routing in Manhattan Street networks. *IEEE Transactions on Communications*, COM-35(5):503–512, May 1987.
271. M. Médard, R. A. Barry, S. G. Finn, W. He, and S. Lumetta. Generalized loop-back recovery in optical mesh networks. *IEEE/ACM Transactions on Networking*, 10(1):153–164, February 2002.
272. M. Médard, S. G. Finn, and R. A. Barry. WDM loop-back recovery in mesh networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 752–759, March 1999.
273. E. Medova. Network flow algorithms for routing in networks with wavelength division multiplexing. *IEE Proceedings Communications*, 142(4): 238–242, August 1995.
274. Y. Mei and C. Qiao. Efficient distributed control protocols for WDM all-optical networks. In *International Conference on Computer Communications and Networks (ICCCN)*, pages 150–153, September 1997.
275. M. Mihail, C. Kaklamanis, and S. Rao. Efficient access to optical bandwidth — wavelength routing on directed fiber trees, rings, and trees of rings. In *Symposium on Foundations of Computer Science (FOCS)*, pages 548–557, October 1995.
276. K. Miliotis, G. I. Papadimitriou, and A. S. Pomportsis. Adaptive weight functions for wavelength-continuous WDM multi-fiber networks. In *IEEE International Conference on Networks*, pages 413–418, Sept-Oct 2003.
277. D. Mitra and J. B. Seery. Comparative evaluations of randomized and dynamic routing strategies for circuit-switched networks. *IEEE Transactions on Communications*, 39(1):102–116, January 1991.
278. E. Modiano. Random algorithms for scheduling multicast traffic in WDM broadcast-and-select networks. *IEEE/ACM Transactions on Networking*, 7(3):425–434, June 1999.
279. E. Modiano and P. J. Lin. Traffic grooming in WDM networks. *IEEE Communications Magazine*, 39(7):124–129, July 2001.
280. E. Modiano and A. Narula-Tam. Survivable lightpath routing: A new approach to the design of WDM-based networks. *IEEE Journal on Selected Areas in Communications*, 20(4):800–809, May 2002.
281. G. Mohan and C. S. R. Murthy. Lightpath restoration in WDM optical networks. *IEEE Network Magazine*, 14(6):24–32, November 2000.
282. G. Mohan, C. S. R. Murthy, and A. K. Somani. Efficient algorithms for routing dependable connections in WDM optical networks. *IEEE/ACM Transactions on Networking*, 9(5):553–566, October 2001.
283. A. Mokhtar and M. Azizoglu. Adaptive wavelength routing in all-optical networks. *IEEE/ACM Transactions on Networking*, 6(2):197–206, April 1998.
284. K. Mosharaf, J. Talim, L. Lambadaris, and L. Marmorkos. Service differentiation and fairness control in WDM grooming networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 3, pages 1968–1973, November 2004.
285. H. T. Mouftah and J. Zheng. *Optical WDM Networks: Concepts and Design Principles.* John Wiley & Sons, 2004.
286. B. Mukherjee. *Optical Communication Networks.* McGraw-Hill, 1997.

287. B. Mukherjee. WDM optical communication networks: progress and challenges. *IEEE Journal on Selected Areas in Communications*, 18(10):1810–1824, October 2000.
288. B. Mukherjee. *Optical WDM Networks.* Springer, 2006.
289. B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee. Some principles for designing a wide-area WDM optical network. *IEEE/ACM Transactions on Networking*, 4(5):684–696, October 1996.
290. M. Murata, H. Harai, and H. Miyahara. Performance analysis of wavelength assignment policies in all optical networks with limited-range wavelength conversion. *IEEE Journal on Selected Areas in Communications*, 16(7):1051–1060, September 1998.
291. L. Narayanan, J. Opatrny, and D. Sotteau. All-to-all optical routing in chordal rings of degree 4. *Algorithmica*, 31(2):155–178, 2001.
292. A. Narula-Tam, P. J. Lin, and E. Modiano. Efficient routing and wavelength assignment for reconfigurable WDM networks. *IEEE Journal on Selected Areas in Communication*, 20(1):75–88, January 2002.
293. T. K. Nayak and K. N. Sivarajan. A new approach to dimensioning optical networks. *IEEE Journal on Selected Areas in Communications*, 20(1):134–148, January 2002.
294. G. L. Nemhauser and L. A. Wolsey. *Integer and Combinatorial Optimization.* John Wiley and Sons, 1988.
295. C. Ou, H. Zang, N. K. Singhal, K. Zhu, L. H. Sahasrabuddhe, R. A. MacDonald, and B. Mukherjee. Subpath protection for scalability and fast recovery in optical WDM mesh networks. *IEEE Journal on Selected Areas in Communications*, 22(9):1859–1875, November 2004.
296. C. Ou, J. Zhang, H. Zang, L. H. Sahasrabuddhe, and B. Mukherjee. New and improved approaches for shared-path protection in WDM mesh networks. *Journal of Lightwave Technology*, 22(5):1223–1234, May 2004.
297. C. Ou, K. Zhu, H. Zang, L. H. Sahasrabuddhe, and B. Mukherjee. Traffic grooming for survivable WDM networks — shared protection. *IEEE Journal on Selected Areas in Communications*, 21(9):1367–1383, November 2003.
298. A. Ozdaglar and D. P. Bertsekas. Routing and wavelength assignment in optical networks. *IEEE/ACM Transactions on Networking*, 11(2):259–272, April 2003.
299. J. C. Palais. *Fiber Optic Communications.* Prentice Hall, 1992.
300. G. Panchapakesan and A. Sengupta. On a lightwave network topology using Kautz digraphs. *IEEE Transactions on Computers*, 48(10):1131–1137, October 1999.
301. P. K. Pankaj. Wavelength requirements for multicasting in all-optical networks. *IEEE/ACM Transactions on Networking*, 7(3):414–424, June 1999.
302. R. K. Pankaj and R. G. Gallager. Wavelength requirements of all-optical networks. *IEEE/ACM Transactions on Networking*, 3(3):269–280, June 1995.
303. G. I. Papadimitriou, C. Papazoglou, and A. S. Pomportsis. Optical switching: switch fabrics, techniques, and architectures. *IEEE/OSA Journal of Lightwave Technology*, 21(2):384–405, February 2003.
304. M. Paterson, H. Schröder, O. Sýkora, and I. Vrto. Permutation communication in all-optical rings. *Parallel Processing Letters*, 12(1):23–29, 2002.
305. D. K. Pradhan and S. M. Reddy. A fault tolerant communication architecture for distributed systems. *IEEE Transactions on Computers*, C-31(9):863–870, Sepember 1982.

306. C. Qiao and D. Xu. Distributed partial information management (DPIM) schemes for survivable networks. Part I. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 302–311, June 2002.
307. C. Qiao and M. Yoo. Optical burst switching (OBS) – a new paradigm for an optical internet. *Journal of High Speed Networks*, 8(1):69–84, 1999.
308. X. Qin and Y. Yang. Multicast connection capacity of WDM switching networks with limited wavelength conversion. *IEEE/ACM Transactions on Networking*, 12(3):526–538, June 2004.
309. P. Raghavan and E. Upfal. Efficient routing in all-optical networks. In *ACM Symp. on Theory of Computing (STOC)*, pages 134–143, 1994.
310. B. Ramamurthy and B. Mukherjee. Wavelength conversion in WDM networking. *IEEE Journal on Selected Areas in Communications*, 16(7):1061–1073, September 1998.
311. B. Ramamurthy and A. Ramakrishnan. Virtual topology reconfiguration of wavelength routed optical networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 2, pages 1269–1275, November 2000.
312. R. Ramamurthy, A. Akyamac, J.-F. Labourdette, and S. Chaudhuri. Preemptive reprovisioning in mesh optical networks. In *IEEE/OSA Optical Fiber Communications Conference (OFC)*, volume 2, pages 785–787, March 2003.
313. R. Ramamurthy, Z. Bogdanowicz, S. Samieian, D. Saha, B. Rajagopalan, S. Sengupta, S. Chaudhuri, and K. Bala. Capacity performance of dynamic provisioning in optical networks. *IEEE/OSA Journal of Lightwave Technology*, 19(1):40–48, January 2001.
314. R. Ramamurthy and B. Mukherjee. Fixed-alternate routing and wavelength conversion in wavelength-routed optical networks. *IEEE/ACM Transactions on Networking*, 10(3):351–367, June 2002.
315. R. Ramamurthy, S. Sengupta, and S. Chaudhuri. Comparison of centralized and distributed provisioning of lightpaths in optical networks. In *IEEE/OSA Optical Fiber Communications Conference (OFC)*, volume 1, pages MH4–1–MH4–3, 2001.
316. S. Ramamurthy and B. Mukherjee. Survivable WDM mesh networks. Part I-Protection. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 744–751, March 1999.
317. S. Ramamurthy and B. Mukherjee. Survivable WDM mesh networks. Part II-Restoration. In *IEEE International Conference on Communications (ICC)*, volume 3, pages 2023–2030, June 1999.
318. S. Ramamurthy, L. Sahasrabuddhe, and B. Mukherjee. Survivable WDM mesh networks. *IEEE/OSA Journal of Lightwave Technology*, 21(4):870–883, April 2003.
319. R. Ramaswami and G. Sasaki. Multiwavelength optical networks with limited wavelength conversion. *IEEE/ACM Transactions on Networking*, 6(6):744–754, December 1998.
320. R. Ramaswami and A. Segall. Distributed network control for wavelength routed optical networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 138–147, March 1996.
321. R. Ramaswami and A. Segall. Distributed network control for optical networks. *IEEE/ACM Transactions on Networking*, 5(6):936–943, December 1997.

322. R. Ramaswami and K. N. Sivarajan. Routing and wavelength assignment in all-optical networks. *IEEE/ACM Transactions on Networking*, 3(5):489–500, October 1995.
323. R. Ramaswami and K. N. Sivarajan. Design of logical topologies for wavelength-routed optical networks. *IEEE Journal on Selected Areas in Communications*, 14(5):840–851, June 1996.
324. R. Ramaswami and K. N. Sivarajan. *Optical Networks:A Practical Perspective.* Morgan Kaufmann Publishers, 2002.
325. S. Ramesh, G. N. Rouskas, and H. G. Perros. Computing blocking probabilities in multiclass wavelength-routing networks with multicast calls. *IEEE Journal on Selected Areas in Communications*, 20(1):89–96, January 2002.
326. A. J. Rogers. *Understanding Optical Fiber Communications.* Artech House, 2001.
327. G. N. Rouskas and M. H. Ammar. Multidestination communication over tunable-receiver single-hop WDM networks. *IEEE Journal on Selected Areas in Communications*, 15(3):501–511, 1997.
328. G. N. Rouskas and V. Sivaraman. Packet scheduling in broadcast WDM networks with arbitrary transceiver tuning latencies. *IEEE/ACM Transactions on Networking*, 5(3):359–370, June 1997.
329. I. Rubin and J. Ling. Failure protection methods for optical meshed-ring communications networks. *IEEE Journal on Selected Areas in Communications*, 18(10):1950–1960, October 2000.
330. P. Saengudomlert, E. Modiano, and R. G. Gallager. Dynamic wavelength assignment for WDM all-optical tree networks. *IEEE/ACM Transactions on Networking*, 13(4):895–905, August 2005.
331. P. Saengudomlert, E. Modiano, and R. G. Gallager. On-line routing and wavelength assignment for dynamic traffic in WDM ring and torus networks. *IEEE/ACM Transactions on Networking*, 14(2):330–340, April 2006.
332. L. Sahasrabuddhe, S. Ramamurthy, and B. Mukherjee. Fault management in IP-over-WDM networks: WDM protection versus IP restoration. *IEEE Journal on Selected Areas in Communications*, 20(1):21–33, January 2002.
333. L. H. Sahasrabuddhe and B. Mukherjee. Light trees: Optical multicasting for improved performance in wavelength-routed networks. *IEEE Communication Magazine*, 37(2):67–73, February 1999.
334. L. H. Sahasrabuddhe and B. Mukherjee. Multicast routing algorithms and protocols: a tutorial. *IEEE Network*, 14(1):90–102, Jan/Feb 2000.
335. G. Sahin and M. Azizoglu. Optical layer survivability for single and multiple service classes. *Journal on High Speed Networks*, 10(2):91–108, 2001.
336. H. Schröder, O. Sýkora, and I. Vrto. Optical all-to-all communication for some product graphs. In *Annual Conference on Current Trends in Theory and Practice of Informatics (SOFSEM)*, pages 555–562, 1997.
337. A. Sen, S. Bandyopadhyay, and B. P. Sinha. A new architecture and a new metric for lightwave networks. *IEEE/OSA Journal of Lightwave Technology*, 19(7):913–925, July 2001.
338. A. Sen, B. Hao, and B. H. Shen. Survivable routing in WDM networks. In *Proceedings IEEE International Symposium Computers and Communications*, pages 726–731, July 2002.
339. A. Sen, B. Hao, B. H. Shen, and G. Lin. Survivable routing in WDM networks — logical ring in arbitrary physical topology. In *IEEE International Conference on Communications (ICC)*, pages 2771–2775, April 2002.

340. A. Sen, S. Murthy, and S. Bandyopadyay. gStreams: A new technique for fast recovery with capacity efficient protection in WDM mesh networks. In *IEEE International Conference on Communications (ICC)*, 2007.
341. A. Sen, B. H. Shen, and S. Bandyopadhyay. Survivability of lightwave networks – path lengths in WDM protection scheme. *Journal of High Speed Networks*, 10(4):303–315, 2001.
342. A. Sen, B. H. Shen, B. Hao, H. Jayakumar, and S. Bandyopadhyay. On a preemptive multi-class routing scheme with protection paths for WDM networks. In *IEEE International Conference on Communications (ICC)*, volume 2, pages 1417–1422, May 2003.
343. A. Sengupta, S. Bandyopadhyay, A. Balla, and A. Jaekel. Algorithms for dynamic routing in all-optical networks. *Photonic Networks Communications*, 2(2):163–184, May 2000.
344. A. Sengupta, S. Bandyopadhyay, and A. Jaekel. A distributed fault management scheme for wavelength routed all-optical networks. *Photonic Networks Communications*, 2(4):369–382, November 2000.
345. A. Sengupta, A. Sen, and S. Bandyopadhyay. Fault-tolerant distributed system design. *IEEE Transactions on Circuits and Systems*, 35(2):168–172, February 1988.
346. S. Sengupta and R. Ramamurthy. Capacity efficient distributed routing of mesh-restored lightpaths in optical networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 4, pages 2129–2133, November 2001.
347. M. Shalom and S. Zaks. A $10/7+\varepsilon$ approximation for minimizing the number of ADMs in SONET rings. In *International Conference on Broadband Networks (BroadNets)*, pages 254–262. IEEE Computer Society, 2004.
348. M. Shalom and S. Zaks. Minimizing the number of ADMs in SONET rings with maximum throughput. In A. Pelc and M. Raynal, editors, *International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, volume 3499 of *Lecture Notes in Computer Science*, pages 277–291. Springer, 2005.
349. V. Sharma and E. A. Varvarigos. Limited wavelength translation in all-optical WDM mesh networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 893–901, April 1998.
350. V. Sharma and E. A. Varvarigos. An analysis of limited wavelength translation in regular all-optical WDM networks. *Journal of Lightwave Technology*, 18(12):1606–1619, December 2000.
351. B. H. Shen, B. Hao, and A. Sen. Minimum cost ring survivability in WDM networks. In *IEEE Workshop on High Performance Switching and Routing (HPSR)*, pages 183–188, 2003.
352. G. Shen, S. K. Bose, and T. H. Cheng. Operation of WDM networks with different wavelength conversion capability. *IEEE Communication Letters*, 4(7): 239–241, July 2000.
353. L. Shen, X. Yang, and B. Ramamurthy. Shared risk link group (SRLG) - diverse path provisioning under hybrid service level agreements in wavelength-routed optical mesh networks. *IEEE/ACM Transactions on Networking*, 13(4): 918–931, August 2005.
354. X. Shen, Q. Hu, H. Dai, and X. Wang. Optimal routing of permutations on rings. In *International Symposium on Algorithms & Computation (ISAAC)*, pages 360–368, 1994.

355. W. T. Silfvast. *Laser Fundamentals.* Cambridge University Press, 2003.
356. D. Sima, T. Fountain, and P. Karsuk. *Advanced Computer Architectures.* Addison-Wesley Longman Publishing, 1997.
357. S. Sinha and C. S. R. Murthy. Information theoretic approach to traffic adaptive WDM networks. *IEEE/ACM Transactions on Networking*, 13(4):881–894, August 2005.
358. K. M. Sivalingam and S. Subramaniam. *Optical WDM Networks: Principles and Practice.* Springer, 2000.
359. K. N. Sivarajan and R. Ramaswami. Lightwave networks based on de Bruijn graphs. *IEEE/ACM Transactions on Networking*, 2(1):70–79, February 1994.
360. P. Solé. Expanding and forwarding. *Discrete Applied Mathematics*, 58(1): 67–78, 1995.
361. A. K. Somani. *Survivability and Traffic Grooming in WDM Optical Networks.* Cambridge University Press, February 2006.
362. A. K. Somani, M. Mina, and L. Li. On trading wavelengths with fibers: a cost-performance based study. *IEEE/ACM Transactions on Networking*, 12(5): 944–951, October 2004.
363. R. Spanke. Architectures for guided-wave optical space switching systems. *IEEE Communications Magazine*, 25(5):42–48, May 1987.
364. M. A. Sridhar and C. S. Raghavendra. Fault-tolerant networks based on the de Bruijn graph. *IEEE Transactions on Computers*, 40(10):1167–1174, 1991.
365. M. Sridharan, A. K. Somani, and M. V. Salapaka. Approaches for capacity and revenue optimization in survivable WDM networks. *Journal of High Speed Networks*, 10(2):109–125, 2001.
366. N. Srinath, C. S. R. Murthy, B. H. Gurucharan, and G. Mohan. A two-stage approach for virtual topology reconfiguration of WDM optical networks. *Optical Network Magazine*, 2(3):58–71, May-June 2001.
367. R. Srinivasan and A. K. Somani. Request-specific routing in WDM grooming networks. In *IEEE International Conference on Communications*, volume 5, pages 2876–2880, April 2002.
368. R. Srinivasan and A. K. Somani. Analysis of optical networks with heterogeneous grooming architectures. *IEEE/ACM Transactions on Networking*, 12(5):931–943, October 2004.
369. S. Stefanakos and T. Erlebach. Routing in all-optical ring networks revisited. In *IEEE Symposium on Computers and Communications (ISCC)*, volume 1, pages 288–293. IEEE Computer Society, 2004.
370. T. Stern and K. Bala. *Multiwavelength Optical Networks: A Layered Approach.* Addison-Wesley Longman Publishing, 1999.
371. H. S. Stone and J. Cocke. Computer architecture in the 1990s. *Computer*, 24(9):30–38, September 1991.
372. J. Strand, A. Chiu, and R. Tkach. Issues for routing in the optical layer. *IEEE Communications Magazine*, 39(2):81–87, February 2001.
373. S. Subramaniam, M. Azizoglu, and A. K. Somani. All-optical networks with sparse wavelength conversion. *IEEE/ACM Transactions on Networking*, 4(4):544–557, August 1996.
374. S. Subramaniam, M. Azizoglu, and A. K. Somani. Connectivity and sparse wavelength conversion in wavelength-routing networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 148–155, March 1996.

375. S. Subramaniam, M. Azizoglu, and A. K. Somani. On optimal converter placement in wavelength-routed networks. *IEEE/ACM Transactions on Networking*, 7(5):754–766, October 1999.
376. S. Subramaniam, A. K. Somani, M. Azizoglu, and R. A. Barry. A performance model for wavelength conversion with non-Poisson traffic. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 499–506, April 1997.
377. H. Taha. *Operations Research: An Introduction.* Macmillan, 1982.
378. A. N. Tam and E. Modiano. Dynamic load balancing in WDM based packet networks with and without wavelength constraints. *IEEE Journal on Selected Areas in Communications*, 18(10):1972–1979, October 2000.
379. K. Tang. Cayleynet: A multihop WDM-based lightwave network. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 3, pages 1260–1267, 1994.
380. D. Thaker and G. N. Rouskas. Multi-destination communication in broadcast WDM networks, a survey. *Optical Networks*, 3(1):34–44, January-February 2002.
381. S. Thiagarajan and A. K. Somani. An efficient algorithm for optimal wavelength converter placement on wavelength-routed networks with arbitrary topologies. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 916–923, March 1999.
382. B. J. Thompson and D. Malacara. *Handbook of Optical Engineering.* Marcel Dekker Inc., 2001.
383. O. Togni. Optical all-to-all communication in inflated networks. In *Workshop on Graph Theoretical Concepts in Computer Science (WG)*, pages 78–87, 1998.
384. O. Togni. Optical index of circulant graphs. Manuscript, LABRI, Université Bordeaux I, 1999.
385. J. Tomlin. Minimum-cost multicommodity network flows. *Operations Research*, 14(1):45–51, January-February 1966.
386. M. Tornatore, G. Maier, and A. Pattavina. WDM network optimization by ILP based on source formulation. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 3, pages 1813–1821, 2002.
387. S. Tridandapani and B. Mukherjee. Channel sharing in multi-hop WDM lightwave networks: Realization and performance of multicast traffic. *IEEE Journal on Selected Areas in Communications*, 15(3):488–500, April 1997.
388. T. Tripathi and K. N. Sivarajan. Computing approximate blocking probabilities in wavelength routed all-optical networks with limited-range wavelength conversion. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 1, pages 329–336, March 1999.
389. A. Tucker. Coloring a family of circular arcs. *SIAM Journal of Applied Mathematics*, 29(3):493–502, November 1975.
390. R. Ul-Mustafa and A. E. Kamal. Design and provisioning of WDM networks with multicast traffic grooming. *IEEE Journal on Selected Areas in Communications*, 24(4):37–53, April 2006.
391. E. W. van Stryland (Editor) and S. Chapman. *Fiber Optics Handbook: Fiber, Devices, and Systems for Optical Communications.* Optical Society of America, 2001.
392. N. Vanderhorn, S. Balasubramanian, M. Mina, R. J. Weber, and A. K. Somani. Light-trail testbed for metro optical networks. In *IEEE Testbeds and Research*

Infrastructures for the Development of Networks and Communities (Tridentcom), pages 310–315, 2006.

393. A. Venkateswaran and A. Sengupta. On a scalable topology for lightwave networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 427–434, March 1996.
394. K. R. Venugopal, M. Shivakumar, and P. S. Kumar. A heuristic for placement of limited range wavelength converters in all-optical networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 2, pages 908–915, March 1999.
395. H. Wang, E. Modiano, and M. Médard. Partial path protection for WDM networks: End-to-end recovery using local failure information. In *Proceedings IEEE International Symposium Computers and Communications (ISCC)*, pages 719–725, July 2002.
396. J. Wang, B. Chen, and R. N. Uma. Dynamic wavelength assignment for multicast in all-optical WDM networks to maximize the network capacity. *IEEE Journal on Selected Areas in Communications*, 21(8):1274–1284, October 2003.
397. J. Wang, W. Cho, V. Vemuri, and B. Mukherjee. Improved approaches for cost-effective traffic grooming in WDM ring networks: ILP formulations and single-hop and multihop connections. *IEEE/OSA Journal of Lightwave Technology*, 19(11):1645–1653, November 2001.
398. J. Wang and B. Mukherjee. Interconnected WDM ring networks: Strategies for interconnection and traffic grooming. *Optical Networks Magazine*, 3(5):10–20, Sept/Oct 2002.
399. J. Wang, X. Qi, and B. Chen. Wavelength assignment for multicast in all-optical WDM networks with splitting constraints. *IEEE/ACM Transactions on Networking*, 14(1):169–182, February 2006.
400. Y. Wang and Q.-P. Gu. Efficient algorithms for traffic grooming in SONET/WDM networks. In *IEEE International Conference on Parallel Processing (ICPP)*, pages 355–364. IEEE Computer Society, 2006.
401. A. N. Washington and H. G. Perros. Analysis of a traffic-groomed optical network with alternate routing. In *International Conference on Information Technology:New Generations (ITNG'07)*, pages 854–862, 2007.
402. J. Y. Wei. Advances in the management and control of optical internet. *IEEE Journal on Selected Areas in Communications*, 20(4):768–785, May 2002.
403. J. Y. Wei and R. I. McFarland. Just-in-time signaling for WDM optical burst switching networks. *Journal of lightwave technology*, 18(12):2019–2037, December 2000.
404. Y. Wen and V. W. S. Chan. Ultra-reliable communication over unreliable optical networks via lightpath diversity: system characterization and optimization. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 5, pages 2529–2535, December 2003.
405. G. T. Wilfong. Minimum wavelength in an all-optical ring network. In T. Asano, Y. Igarashi, H. Nagamochi, S. Miyano, and S. Suri, editors, *International Symposium on Algorithms & Computation (ISAAC)*, volume 1178 of *Lecture Notes in Computer Science*, pages 346–355. Springer, 1996.
406. G. T. Wilfong and P. Winkler. Ring routing and wavelength translation. In *ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 333–341, 1998.
407. T. Wu and A. K. Somani. Cross-talk attack monitoring and localization in all-optical networks. *IEEE/ACM Transactions on Networking*, 13(6):1390–1401, December 2005.

408. T. H. Wu. *Fiber Network Service Survivability.* Artech House Publishers, 1992.
409. T. H. Wu. Emerging technologies for fiber network survivability. *IEEE Communications Magazine*, 33(2):58–59, 62–74, February 1995.
410. G. Xiao and Y. W. Leung. Algorithms for allocating wavelength converters in all-optical networks. *IEEE/ACM Transactions on Networking*, 7(4):545–557, August 1999.
411. S. Xiao, G. Xiao, and Y.-W. Leung. A network flow approach for static and dynamic traffic grooming in WDM networks. *Computer Networks*, 50(17):3400–3415, 2006.
412. C. Xiaowen, L. Bo, and I. Chlamtac. Wavelength converter placement under different RWA algorithms in wavelength-routed all-optical networks. *IEEE Transactions on Communications*, 51(4):607–617, April 2003.
413. C. Xin, C. Qiao, and S. Dixit. Traffic grooming in mesh WDM optical networks – performance analysis. *IEEE Journal on Selected Areas in Communications*, 22(9):1658–1669, November 2004.
414. C. Xin, Y. Ye, S. Dixit, and C. Qiao. A joint working and protection path selection approach in WDM optical networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 4, pages 2165–2168, 2001.
415. Y. Xiong, D. Xu, and C. Qiao. Achieving fast and bandwidth-efficient shared-path protection. *Journal of Lightwave Technology*, 21(2):365–371, February 2003.
416. D. Xu, Y. Xiong, and C. Qiao. Novel algorithms for shared segment protection. *IEEE Journal on Selected Areas in Communication*, 21(8):1320–1331, October 2003.
417. D. Xu, Y. Xiong, C. Qiao, and G. Li. Trap avoidance and protection schemes in networks with shared risk link groups. *Journal of Lightwave Technology*, 21(11):2683–2693, November 2003.
418. S. Xu, L. Li, and S. Wang. Dynamic routing and assignment of wavelength algorithms in multifiber wavelength division multiplexing networks. *IEEE Journal on Selected Areas in Communications*, 18(10):2130–2137, October 2000.
419. S. Xu, L. Li, S. Wang, and C. Chen. Wavelength assignment for dynamic traffic in WDM networks. In *IEEE International Conference on Networks*, pages 375–379, 2000.
420. X. Yang and B. Ramamurthy. An analytical model for virtual topology reconfiguration in optical networks and a case study. In *International Conference on Computer Communications and Networks (ICCCN)*, pages 302–308, October 2002.
421. W. Yao and B. Ramamurthy. Dynamic traffic grooming using fixed-alternate routing in WDM mesh optical networks. In *First Workshop on Traffic Grooming in WDM Networks, Co-located with BroadNets 2004*, 2004.
422. W. Yao and B. Ramamurthy. Survivable traffic grooming with path protection at the connection level in WDM mesh networks. In *International Conference on Broadband Networks (BroadNets)*, pages 310–319, October 2004.
423. J. Yates, J. Lacey, D. Everitt, and M. Summerfield. Limited-range wavelength translation in all-optical networks. In *IEEE International Conference on Computer Communications (INFOCOM)*, volume 3, pages 954–961, March 1996.
424. Y. Ye, S. Dixit, and M. Ali. On joint protection/restoration in IP-centric DWDM-based optical transport networks. *IEEE Communication Magazine*, 38(6):174–183, June 2000.

425. Y. Ye, H. Woesner, R. Grasso, T. Chen, and I. Chlamtac. Traffic grooming in light trail networks. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 4, pages 1957–1962, November 2005.
426. J. Y. Yoo and S. Banerjee. Design, analysis, and implementation of wavelength-routed all-optical networks: Routing and wavelength assignment approach. *IEEE Communication Survey, Broadband Networks area*, 1997.
427. M. Yoo, C. Qiao, and S. Dixit. QoS performance of optical burst switching in IP-over-WDM networks. *IEEE Journal of Selected Areas in Communications*, 18(10):2062–2071, October 2000.
428. M. Yoo, C. Qiao, and S. Dixit. Optical burst switching for service differentiation in the next-generation optical internet. *IEEE Communications Magazine*, 39(2):98–104, February 2001.
429. S. J. B. Yoo. Wavelength conversion technologies for WDM network applications. *Journal of Lightwave Technology*, 14(6):955–966, June 1996.
430. X. Yuan and A. Fulay. A wavelength assignment heuristic to minimize SONET ADMs in WDM rings. In *IEEE International Conference on Parallel Processing (ICPP) Workshops*, pages 257–262. IEEE Computer Society, 2001.
431. X. Yuan, R. Melhem, R. Gupta, Y. Mei, and C. Qiao. Distributed control protocols for wavelength reservation and their performance evaluation. *Photonic Networks Communications*, 1(3):207–218, November 1999.
432. H. Zang, J. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee. Dynamic lightpath establishment in wavelength-routed WDM networks. *IEEE Communications Magazine*, 39(9):100–108, September 2001.
433. H. Zang, J. P. Jue, and B. Mukherjee. A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks. *SPIE Optical Networks Magazine*, 1(1), January 2000.
434. H. Zang, C. Ou, and B. Mukherjee. Path-protection routing and wavelength assignment (RWA) in WDM mesh networks under duct-layer constraints. *IEEE/ACM Transactions on Networking*, 11(2):248–258, April 2003.
435. J. Zhang and B. Mukherjee. A review of fault management in WDM mesh networks: Basic concepts and research challenges. *IEEE Network*, 18(2):41–48, March/April 2004.
436. J. Zhang, K. Zhu, and B. Mukherjee. A comprehensive study on backup reprovisioning to remedy the effect of multiple-link failures in WDM mesh networks. In *IEEE International Conference on Communications (ICC)*, pages 1654–1658, 2004.
437. S. Zhang and B. Ramamurthy. Dynamic traffic grooming algorithms for reconfigurable SONET over WDM networks. *IEEE Journal on Selected Areas in Communications*, 21(7):1165–1172, September 2003.
438. X. Zhang and C. Qiao. An effective and comprehensive approach for traffic grooming and wavelength assignment in SONET/WDM rings. *IEEE/ACM Transactions on Networking*, 8(5):608–617, October 2000.
439. X. Zhang, J. Y. Wei, and C. Qiao. Constrained multicast routing in WDM networks with sparse light splitting. *Journal of Lightwave Technology*, 18(12):1917–1927, December 2000.
440. Z. Zhang and A. S. Acampora. A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength re-use. *IEEE/ACM Transactions on Networking*, 3(3):281–288, June 1995.
441. F. Zhou, G. Chen, Y. Xu, and J. Gu. Minimizing ADMs on WDM directed fiber trees. *Journal of Computer Science and Technology*, 18(6):725–731, 2003.

442. H. Zhu, H. Zang, K. Zhu, and B. Mukherjee. Dynamic traffic grooming in WDM mesh networks using a novel graph model. In *IEEE Global Telecommunications Conference (GLOBECOM)*, volume 3, pages 2681–2685, November 2002.
443. H. Zhu, H. Zang, K. Zhu, and B. Mukherjee. A novel generic graph model for traffic grooming in heterogeneous WDM mesh networks. *IEEE/ACM Transactions on Networking*, 11(2):285–299, April 2003.
444. K. Zhu and B. Mukherjee. Traffic grooming in an optical WDM mesh network. *IEEE Journal on Selected Areas in Communications*, 20(1):122–133, January 2002.
445. K. Zhu and B. Mukherjee. A review of traffic grooming in WDM optical networks: Architectures and challenges. *Optical Networks Magazine*, 4(2):55–64, March 2003.
446. K. Zhu, H. Zang, and B. Mukherjee. Design of WDM mesh networks with sparse grooming capability. In *IEEE Global Telecommunications Conference (GLOBECOM)*, pages 2696–2700, November 2002.
447. K. Zhu, H. Zang, and B. Mukherjee. A comprehensive study on next-generation optical grooming switches. *IEEE Journal on Selected Areas in Communications*, 21(7):1173–1186, September 2003.
448. K. Zhu, H. Zhu, and B. Mukherjee. Traffic engineering in multigranularity heterogeneous optical WDM mesh networks through dynamic traffic grooming. *IEEE Networks*, 17:8–15, March/April 2003.
449. K. Zhu, H. Zhu, and B. Mukherjee. *Traffic Grooming in Optical WDM Mesh Networks*. Springer, 2005.
450. Y. Zhu, G. N. Rouskas, and H. G. Perros. A comparison of allocation policies in wavelength routing networks. *Photonic Networks Communications*, 2(3): 267–295, August 2000.
451. Y. Zhu, G. N. Rouskas, and H. G. Perros. A path decomposition approach for computing blocking probabilities in wavelength-routing networks. *IEEE/ACM Transactions on Networking*, 8(6):747–762, December 2000.

List of symbols used

$\overrightarrow{\mathbf{1}}$: the unit column vector $[1, 1, \ldots, 1]$ with $|E|$ elements.

$\overrightarrow{\mathbf{0}}$: a vector of all 0s.

$\boldsymbol{x \longrightarrow y}$: denotes a fiber in the network from node x to node y (i.e., an edge in physical topology G).

$\boldsymbol{x \Rightarrow y}$: denotes a lightpath in the network from end node x to end node y (i.e., an edge in the logical topology G_L).

$\boldsymbol{\alpha}$: a string in σ_{sd}^{j}.

$\boldsymbol{\alpha_1}$: a z-conjugate of α.

$\boldsymbol{\alpha_{oc}}$: coupling ratio of an optical coupler.

$\boldsymbol{\alpha_{ke}}$: continuous variable which is only permitted to have a value of either 0 or 1.

$\boldsymbol{A}$: constraints matrix.

$\overrightarrow{\boldsymbol{A^p}}$: column p of constraints matrix A.

$\boldsymbol{a_{ij}}$: the element in row i, column j of constraints matrix A.

$\boldsymbol{\tilde{A}, \tilde{B}, \tilde{T}}$: edge-path incidence matrices where each matrix has one row for every physical edge $i \rightarrow j$ and one column for every logical edge in the network.

$\boldsymbol{A_i^{in}}$, $\boldsymbol{A_i^{out}}$: Access nodes in a network with traffic grooming capabilities.

$\boldsymbol{\hat{A}}$: node, logical-edge incidence matrix of graph G_L.

$\boldsymbol{AC}$: arc-chain incidence matrix of size $m \times \hat{n}$ where m is the number of logical edges and $\hat{n}$ is the total number of chains in the logical network.

$\boldsymbol{AC^k}$: arc-chain incidence sub-matrix of size $m \times \hat{n^k}$ where m is the number of logical edges and $\hat{n^k}$ is the total number of chains in the logical network for commodity k.

$\overrightarrow{\boldsymbol{AC^k_j}}$: the column vector of AC corresponding to the j^{th} chain of commodity K^k.

$\boldsymbol{\tilde{a}^k_{ij}, \tilde{b}^k_{ij}, \tilde{t}^k_{ij}}$: the entry in the row corresponding to the physical edge $i \rightarrow j$ and the column corresponding to the k^{th} logical edge of the network for matrix $\tilde{A}, \tilde{B}$, or $\tilde{T}$ respectively.

$\boldsymbol{ac^k_{ij}}$: the i^{th} element of the j^{th} chain of the k^{th} commodity.

$\boldsymbol{\aleph}$: number of paths in the logical topology from s to d.

$\boldsymbol{B(d,k)}$: de Bruijn graph of degree d and diameter k.

$\overrightarrow{\boldsymbol{b}}$: a column vector of $\widehat{n_c}$ nonnegative constants.

$\boldsymbol{b^k}$: the k^{th} element of vector $\overrightarrow{b}$.

$\boldsymbol{B}$: basis matrix.

$\boldsymbol{\beta}$: a string in σ^j_{sd}.

$\boldsymbol{b_{ij}}$: a binary variable such that

$$b_{ij} = \begin{cases} 1 \text{ if a lightpath exists from end node } E_i \text{ to end node } E_j, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{b_p}$: a binary variable relevant when lightpath ℓ_p is selected.

$\overrightarrow{\boldsymbol{c}}$: a vector of cost coefficients where the p^{th} element c_p represents the cost of the p^{th} column of constraints matrix A.

$\overrightarrow{\boldsymbol{c_B}}$: a vector of cost coefficients, each coefficient corresponding to a variable in the basis.

$\boldsymbol{c_i}$: the i^{th} channel.

$\boldsymbol{c_{ij}}$: cost/unit flow associated with edge $i \rightarrow j$ in a capacitated network.

$\boldsymbol{\mathcal{C}_i}$: set of channels.

$\boldsymbol{C^{in}_{ij}}$: channel node.

$\boldsymbol{C^{out}_{ij}}$: channel node.

$\boldsymbol{\mathcal{C}_{ij}}$: channel bypass edge.

$\boldsymbol{\chi}$: list of channel numbers.

$\boldsymbol{c^k_P}$: the channel assigned to the k^{th} primary path, for all $k, 1 \leq k \leq M$.

$\boldsymbol{c^k_B}$: the channel assigned to the k^{th} backup path, for all $k, 1 \leq k \leq M$.

$\boldsymbol{c_{lightpath}}$: the capacity of a lightpath (varies from 2.5 to 40.0 Gbps now).

$\overrightarrow{\boldsymbol{C}}\boldsymbol{^k_j}$: the j^{th} chain of the k^{th} commodity.

$\boldsymbol{\mathcal{C}_{ikj}}$: channel availability edge.

$\boldsymbol{C_m^d}$: the d-dimensional torus.

$\mathsf{c}(\boldsymbol{G_{\Re}^{\mathcal{I}}})$: congestion (load) of a network G having instance $\mathcal{I}$ and using the routing $\Re$.

$\mathbf{Color}(\boldsymbol{i,j})$: color assigned to the request (i, j).

$\boldsymbol{d}$: degree of the de Bruijn graph $B(d, k)$.

$\mathbf{deg}(\boldsymbol{G})$: maximum degree of graph G.

$\boldsymbol{d_i}$: the destination of the i^{th} logical edge, $1 \leq i \leq q$.

$\boldsymbol{d_i}$: the destination of the i^{th} communication request, $1 \leq i \leq q$.

$\boldsymbol{d^k}$: destination of commodity k.

$\boldsymbol{d_{pr}^e}$: a precomputed binary coefficient for each pair of end nodes (i, j).

$\boldsymbol{\Delta_{in}^i}$: number of receivers at end node i.

$\boldsymbol{\Delta_{in}}$: a constant denoting the number of receivers at every end node.

$\boldsymbol{\Delta_{out}}$: a constant denoting the number of transmitters at every end node.

$\boldsymbol{\Delta_{out}^i}$: number of transmitters at end node i.

$\boldsymbol{\Delta_G}$: maximum degree of graph G.

$\boldsymbol{\delta_k}$: a continuous variable to characterize whether the backup path of the new connection may share an edge and a channel with the k^{th} backup path, $1 \leq k \leq M$.

$\boldsymbol{\delta_e^{kp}}$: continuous variable which is only permitted to have a value of either 0 or 1.

$\boldsymbol{\delta_{ij}^k}$: a binary variable to denote whether the backup path of the new connection may share a channel with the backup path for the k^{th} connection on the physical edge $i \rightarrow j$.

$\mathbf{dest}(\boldsymbol{k})$: the destination of the k^{th} (source, destination) pair, $1 \leq k \leq \hat{q}$, having a nonzero value in T.

$\mathbf{destination}(\boldsymbol{i})$: the destination of logical edge i.

$\boldsymbol{\mathcal{D}_i}$: demux edge.

$\boldsymbol{E}$: the set of all pairs of nodes (i, j) such that $i \rightarrow j$ is a physical link (i.e., a fiber connects nodes i and j) in the network.

$\boldsymbol{E}$: the set of edges in a graph G.

$|\boldsymbol{E}|$: number of edges in a graph G.

$\boldsymbol{E(G)}$: the set of edges of a graph G.

$\boldsymbol{E_i}$: the i^{th} end node in the network.

$\boldsymbol{E_i^{sd}}$: an end node for multi-hop communication from E_s to E_d.

$\overrightarrow{\boldsymbol{e^k}}$: a vector $[1, 1, \ldots, 1]$ of $\hat{n}^k$ 1s.

$\boldsymbol{E_L}$: the set of logical edges.

$\boldsymbol{\epsilon}$: a very small constant.

$\boldsymbol{\eta_e^{kp}}$: a continuous variable which is only permitted to have a value of either 0 or 1.

$\boldsymbol{F = [f_{e,\ell}]}$: the fiber, logical-edge incidence matrix of size $|E| \times |\mathcal{L}|$, where

$$f_{e,\ell} = \begin{cases} 1 \text{ if fiber } e \text{ is used by lightpath } \ell, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{f_p^{sd}}$: a continuous variable denoting the traffic on logical edge ℓ_p from source end node s to destination end node d.

from$\boldsymbol{(r)}$: source of request r.

$\boldsymbol{g}$: the data communication capacity of a single lightpath, using the OC-n notation.

$\boldsymbol{G = (V, E)}$: the (directed) graph model of the physical topology of a network where V is the set of nodes in the network and E is the set of edges.

$\boldsymbol{G_{\Re}^{\mathcal{I}} = (V_{\Re}, E_{\Re})}$: conflict graph (path interference graph).

$\boldsymbol{\mathcal{G}_i}$: grooming edge.

$\boldsymbol{G_L}$: the graph model of the logical topology of a network where V is the set of end nodes in the network and E_L is the set of logical edges.

$\boldsymbol{G_S = (V_s, E_s)}$: the graph model of a scalable topology where V_s is the set of vertices in the network and E_s is the set of edges.

$\boldsymbol{\gamma_e^{kp}}$: continuous variable which is permitted to have a value of either 0 or 1.

$\boldsymbol{\gamma_{ij}}$: a binary variable to denote whether the backup path of the new connection may share a channel with the backup path for any existing connection on the physical edge $i \rightarrow j$.

$\boldsymbol{H}$: number of hops in a route from E_x to E_y.

$\boldsymbol{H_d}$: the d-dimensional hypercube.

$\boldsymbol{I_{SD}}$: collection of source-destination pairs for which route and wavelength assignment needs to be carried out.

$\boldsymbol{I}$: identity matrix.

$\boldsymbol{\mathcal{I}}$: an instance of the RWA problem.

$\boldsymbol{I_{one}}$: one-to-all instance on G with source v.

$\boldsymbol{I_1, I_2}$: inputs to an optical coupler.

$\boldsymbol{(i, i+1, \ldots, j)}$: left-to-right dipath from i to j for a request (i, j) in a bidirectional path.

$\boldsymbol{(i, i-1, \ldots, j)}$: right-to-left dipath from i to j for a request (i, j) in a bidirectional path.

$\boldsymbol{(i, j)}$: communication request from i to j.

$\boldsymbol{(i, j)}$: dipath from i to j.

$\boldsymbol{k}$: diameter of the de Bruijn graph $B(d, k)$.

$\boldsymbol{k_B}$: number of transmitters and receivers in each end node of a broadcast and select network.

$\boldsymbol{K^k}$: commodity corresponding to the traffic from source s_k to destination d_k.

$\boldsymbol{k_{OC}}$: number of inputs to an OXC.

$\boldsymbol{\ell_{sd}}$: the length of the longest suffix of the string $s = s_k \ldots s_2 s_1$ that is also a prefix of $d = d_k \ldots d_2 d_1$.

$\boldsymbol{\ell(s, d)}$: length of the shortest path from s to d.

$\boldsymbol{\lambda_i}$: wavelength of optical carrier.

$\boldsymbol{\lambda_{pq}}$: wavelength to communicate from end node E_p to end node E_q.

$\boldsymbol{\Lambda_{max}}$: the $\mathfrak{L}$ congestion of a logical topology.

$\boldsymbol{\overrightarrow{\Lambda}}$: a column vector $[\Lambda_{max}, \Lambda_{max}, \ldots, \Lambda_{max}]$ with m occurrences of the variable Λ_{max}.

$\boldsymbol{\lambda^r_{i,j}}$: 1 if the r^{th} request uses the lightpath from i to j as an intermediate logical edge.

$\boldsymbol{\lambda_{sd}}$: wavelength to communicate from s to d.

$\boldsymbol{\mathcal{L}}$: set of all potential logical edges in a network.

$\boldsymbol{\ell_p}$: the p^{th} element of $\mathcal{L}$.

$\boldsymbol{L_i}$: the lightpath corresponding to the i^{th} logical edge.

$\boldsymbol{L_{ij}}$: the number of lightpaths from i to j.

$\boldsymbol{\mathcal{L}_{ij}}$: lightpath edge.

$\boldsymbol{L}$: the set of all pairs of end nodes (i, j) such that $i \Rightarrow j$ is a logical edge (i.e., a lightpath exists from end node i end node j).

$\boldsymbol{L^c_{ij}}$: the number of lightpaths from i to j using channel c.

$\boldsymbol{L^{new}_i}$: a lightpath to replace lightpath L_i if L_i becomes inoperative.

$\boldsymbol{L^P_i}$: the primary lightpath corresponding to the i^{th} logical edge.

$\boldsymbol{L_i^B}$: the backup lightpath corresponding to the i^{th} logical edge.

$\boldsymbol{L_i^{in}, L_i^{out}}$: lightpath nodes.

$\boldsymbol{m}$: number of logical edges.

$\boldsymbol{m_{DM}}$: number of optical carriers carried by the input to a demultiplexer.

$\boldsymbol{M}$: number of connections already established in the network.

$\boldsymbol{\mathcal{M}_i}$: mux edge.

$\boldsymbol{M_{r,s}}$: the $r \times s$ mesh.

$\boldsymbol{\mu_i}$: refractive index of an optical medium.

$\boldsymbol{\hat{M}}$: the number characterizing the set $S_{\hat{M}}$ containing the largest address in a graph G_S.

$\boldsymbol{\aleph}$: the number of routes from s_i to d_i in G.

$\boldsymbol{n}$: a number uniquely identifying an end node in a de Bruijn graph.

$\boldsymbol{n_{oc}}$: number of inputs to (outputs from) an optical coupler.

$\boldsymbol{N}$: number of nodes in a capacitated network.

$\boldsymbol{\mathcal{N}}$: number of nodes (router nodes and end nodes) in a WDM network.

$\boldsymbol{\mathcal{N}_E}$: number of end nodes in the network.

$\boldsymbol{\mathcal{N}_R}$: number of router nodes in the network.

$\boldsymbol{N_S}$: number of vertices in a scalable graph G_S.

$\boldsymbol{N_i}$: node i (either a router node or an end node) in a network.

$\boldsymbol{N_{max}^{TR}}$: the maximum value of the number of transmitters or receivers at any end node in the network.

$\boldsymbol{n_{ch}}$: maximum number of channels that each edge/fiber in this network can accommodate.

$\boldsymbol{n_c}$: number of input/output port of a switch.

$\boldsymbol{n_{DB}}$: number of nodes in a de Bruijn graph.

$\boldsymbol{\widehat{n_c}}$: number of constraints.

$\boldsymbol{\widehat{n_v}}$: number of variables.

$\boldsymbol{\hat{n}}$: total number of chains considering all the commodities.

$\boldsymbol{\hat{n}^k}$: number of chains for the k^{th} commodity.

$\boldsymbol{n_{ij}^{light}}$: number of lightpaths from end node E_i to E_j.

$\boldsymbol{O_1, O_2}$: outputs from an optical coupler.

$\boldsymbol{\Omega_{max}}$: the maximum number of lightpaths that share the same fiber.

$\boldsymbol{\mathfrak{p}}$: probability that a channel is used on a fiber.

$\boldsymbol{\widehat{p}}$: number of extra edges added to a path in G_S.

$\boldsymbol{P_n}$: the bidirectional path of n nodes.

$\boldsymbol{P}$: set of left-to-right (or right-to-left) dipaths on a bidirectional path.

$\boldsymbol{P'}$: set of transformed dipaths on a bidirectional path/ring.

$\mathbb{P}, \mathbb{P}_{\boldsymbol{1}}, \mathbb{P}_{\boldsymbol{2}}, \mathbb{P}_{\boldsymbol{3}}$: a path in G_S.

$\boldsymbol{\zeta}$: number of MNH routes from s_i to d_i.

$\boldsymbol{\wp(s, d)}$: the shortest path from s to d.

$\boldsymbol{\widehat{p}}$: a subpath in the physical topology.

$\boldsymbol{\widetilde{p}}$: number of extra edges required for a path in G_S.

$\boldsymbol{\wp}$: number of logical paths from a specified source to a specified destination.

$\boldsymbol{P_b}$: blocking probability when trying to establish a lightpath.

$\boldsymbol{\mathcal{P}_1, \mathcal{P}_2}$: power levels of signals to an optical coupler.

$\boldsymbol{P}$: number of binary variables in a MILP.

$\boldsymbol{\mathfrak{P}}$: shortest path from a source to a destination in the auxiliary graph for traffic grooming.

$\boldsymbol{P^1}$: list of primary paths already established, $[\rho_1^P, \rho_2^P, \ldots, \rho_M^P]$.

$\boldsymbol{P^2}$: list of backup paths already established, $[\rho_1^B, \rho_2^B, \ldots, \rho_M^B]$.

$\boldsymbol{P_1, P_2}$: lightpaths.

$\boldsymbol{P_1^{payload}, P_2^{payload}}$: payload of P_1, P_2.

$\boldsymbol{P_{mn}^{ij,c}}$: number of lightpaths from i to j, routed through fiber $m \rightarrow n$ on channel c.

$\boldsymbol{p_{mn}}$: the number of fibers from node m to node n.

$\boldsymbol{q}$: number of entries in a traffic matrix T with nonzero values.

$\boldsymbol{q}$: number of source/destination pairs in an instance for the RWA problem.

$\boldsymbol{\mathfrak{q}}$: probability that a channel is used on a fiber.

$\boldsymbol{Q_b}$: blocking probability when trying to establish a lightpath.

$\boldsymbol{R_i}$: i^{th} router node in the network.

$\boldsymbol{r_i}$: receiver tuned to the carrier wavelength corresponding to channel i.

$\boldsymbol{r}$: number of hops in a broadcast and select network.

$\boldsymbol{R}$: the set of traffic requests.

$\boldsymbol{R_n}$: the bidirectional ring of n nodes.

$\boldsymbol{\mathfrak{R}}$: list of MNH routes.

$\boldsymbol{\mathfrak{R} = [r_m]}$: matrix of traffic requests.

$\boldsymbol{r_u^k}$: number of receivers at end node u tuned to the wavelength corresponding to channel k.

$\boldsymbol{\rho_i}$: the route through the physical topology of the lightpath corresponding to the i^{th} logical edge, $1 \leq i \leq q$.

$\boldsymbol{\rho_i}$: the route selected for the pair (s_i, d_i) in G, $1 \leq i \leq q$.

$\boldsymbol{\rho_i^1, \rho_i^2, \ldots, \rho_i^{\aleph}}$: the set of routes from s_i to d_i in G.

$\boldsymbol{\rho_i^P}$: the route of L_i^P through the physical topology.

$\boldsymbol{\mathcal{R}}$: number of edge-disjoint routes over the physical topology, between every pair of end nodes.

$\boldsymbol{R}$: number of edge-disjoint routes over the physical topology, between every pair of end nodes.

$\boldsymbol{\mathfrak{R} = \{\rho_1, \rho_2, \ldots, \rho_q\}}$: routing, i.e., set of selected routes, one for each element in $\mathcal{I}$.

$\boldsymbol{\rho_{xy}^i}$: the i^{th} precomputed route from E_x to E_y.

$\boldsymbol{\rho_{xy}}$: a route from E_x to E_y.

$\boldsymbol{\rho_j^i}$: the i^{th} precomputed route from source(j) to destination(j) where j denotes the lightpath number.

$\boldsymbol{\rho_j}$: the selected route from source(j) to destination(j) where j denotes the lightpath number.

$\boldsymbol{\rho_i^B}$: the route of L_i^B through the physical topology.

$\boldsymbol{RR_i}$: the number of receivers at end node i.

$\boldsymbol{\mathcal{R}_{ij}}$: receiver edge.

$\boldsymbol{s^k}$: source of commodity k.

$\boldsymbol{\mathfrak{s}_r}$: the size of request $r \in R$, using the Optical Carrier level OC-n notation, used in the non-bifurcated traffic model.

$\boldsymbol{s_i}$: the source of the i^{th} logical edge, $1 \leq i \leq q$.

$\boldsymbol{s_i}$: the source of the i^{th} communication request, $1 \leq i \leq q$.

$\boldsymbol{S_n}$: the star of $n+1$ nodes.

$\boldsymbol{\sigma_{sd}}$: the string of length $2k - l_{sd}$ given by $s_k \ldots s_2 s_1 d_{k-l_{SD}} \ldots d_2 d_1$.

$\boldsymbol{\sigma_{sd}^{i}}$: the substring of length k of σ_{sd} starting from the digit i.

$\mathbf{src}(\boldsymbol{k})$: the source of the k^{th} (source, destination) pair, $1 \leq k \leq \hat{q}$, having a nonzero value in T.

$\mathbf{source}(\boldsymbol{i})$: the source of the logical edge i.

$(\boldsymbol{S}, \boldsymbol{D})$: the pair of nodes for which there is a request for a connection.

$\boldsymbol{s}(\boldsymbol{d})$: vertex in a de Bruijn graph having address $s_k s_{k-1} \ldots s_2 s_1$ $(d_k d_{k-1} \ldots d_2 d_1)$.

$\boldsymbol{S_i}$: the set of all strings of k digits, $x_k x_{k-1} \ldots x_2 x_1$, taking each digit from Z_{d+1} such that the i^{th} digit is d.

$\boldsymbol{s_j^i}$: i^{th} input to an OXC using channel j.

$\boldsymbol{T} = [\boldsymbol{t}(\boldsymbol{i}, \boldsymbol{j})]$: a $N_E \times N_E$ matrix, called the traffic matrix. The entry in row i and column j of T gives the traffic from end node i to end node j.

$\boldsymbol{t_i}$: transmitter tuned to the carrier wavelength corresponding to channel i.

$\boldsymbol{\tau_{sd}}$: maximum traffic that can be sent from s to d.

$\boldsymbol{\theta_{e_1 e_2}^{kp}}$: continuous variable which is only permitted to have a value of either 0 or 1.

$\boldsymbol{t_u^k}$: number of transmitters at end node u tuned to the wavelength corresponding to channel k.

$\boldsymbol{TR_i}$: the number of transmitters at end node i.

$\boldsymbol{\mathcal{T}_{ij}}$: transmitter edge.

$\mathbf{to}(\boldsymbol{r})$: destination of request r.

$\boldsymbol{u}$: a variable denoting end node.

$\boldsymbol{u_{ij}}$: capacity of edge $i \rightarrow j$ in a capacitated network.

$\overrightarrow{\boldsymbol{u_r}} = [\boldsymbol{u_{v,r}}]_{\boldsymbol{v} \in \boldsymbol{V}}$: the source-destination column vector for $r \in R$, where

$$u_{v,r} = \begin{cases} 1 & \text{if } v \text{ is the starting end node for request } r, \\ -1 & \text{if } v \text{ is the terminating end node for request } r, \\ 0 & \text{otherwise.} \end{cases}$$

$\boldsymbol{u_k u_{k-1} \ldots u_2 u_1}$: the address of an end node.

$\boldsymbol{\Upsilon^k}$: the traffic $t(src(k), dest(k))$ for the k^{th} commodity, $1 \leq k \leq q$.

$\widehat{\boldsymbol{v}}$: amount of commodity to be shipped.

$\boldsymbol{v}$: a variable denoting end node.

$\boldsymbol{V_E}$: set of end nodes.

$\boldsymbol{V_S}$: set of vertices in a scalable topology.

$\boldsymbol{V}$: set of nodes (end nodes or router nodes).

$\boldsymbol{V}$: set of vertices in a graph G.

$|\boldsymbol{V}|$: number of vertices in a graph G.

$\boldsymbol{V(G)}$: the set of vertices of a graph G.

$\boldsymbol{v_k v_{k-1} \ldots v_2 v_1}$: the address of an end node.

$\boldsymbol{w}$: node in a scalable topology.

$\boldsymbol{W}$: a walk in a graph.

$\boldsymbol{w^1, w^2}$: node in a scalable topology with edge to u.

$\boldsymbol{\mathcal{V}_E}$: $\{v : 1 \le v \le \mathcal{N}_E\}$, the set of all numbers identifying the end nodes in the network.

$\boldsymbol{\mathfrak{w}}$: new vertex to be added to a scalable topology.

$\boldsymbol{\mathfrak{w}_i}$: i^{th} digit of $\mathfrak{w}$.

$\boldsymbol{w_{kp}}$: a binary variable relevant when lightpath ℓ_p is selected.

$\boldsymbol{w_k}$: a binary variable, for all k, $1 \le k \le n_{ch}$, denoting whether channel number k has been used for the primary lightpath.

$\boldsymbol{\wp^i_{sd}}$: the i^{th} path from s to d in the logical topology.

$\boldsymbol{\wp_{sd}}$: a shortest path from s to d in the logical topology.

$\mathtt{w}(\boldsymbol{G^{\mathcal{I}}_{\Re}})$: chromatic number of graph $G^{\mathcal{I}}_{\Re}$.

$\mathtt{w}(\boldsymbol{G^{\mathcal{I}}_{\Re_{min}}})$: minimum value of $\mathtt{w}(G^{\mathcal{I}}_{\Re})$ considering all possible routings $\Re$.

$\boldsymbol{x^i}$: the i^{th} element of vector $\overrightarrow{x}$.

$\boldsymbol{x}$: a vertex in G_S.

$\boldsymbol{x_i}$: a digit in Z_{d+1}.

$\boldsymbol{x^s_i}$: the i^{th} slack variable.

$\overrightarrow{\boldsymbol{x^s}}$: a column vector of m slack variables so that the elements of $\overrightarrow{x^s}$ are x^s_1, x^s_2, …, x^s_m.

$\overrightarrow{\boldsymbol{x_B}}$: the vector corresponding to the variables in the basis.

$\boldsymbol{x^i_B}$: the i^{th} element of $\overrightarrow{x_B}$.

$\boldsymbol{x^{sd}_{ij}}$: a continuous variable to denote the portion of traffic $t(s,d) : t(s,d) > 0$, that is routed through the logical edge $E_i \Rightarrow E_j$.

$\overrightarrow{\boldsymbol{x_r}} = [\boldsymbol{x_{\ell,r}}]_{\boldsymbol{\ell \in \mathcal{L}}}$: the column vector containing lightpath routing variables for $r \in R$, where

$$x_{\ell,r} = \begin{cases} 1 \text{ if request } r \text{ is allotted to lightpath } \ell, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{x^k_j}$: a binary variable denoting the flow in the j^{th} chain of the k^{th} commodity.

$\boldsymbol{\widehat{x}_{pr}}$: a binary variable for the primary path, used if lightpath ℓ_p is selected

$\boldsymbol{\overrightarrow{x^k}}$: the vector $[x_1^k, x_2^k, \ldots x_{\hat{n}^k}^k]$ of variables.

$\boldsymbol{x_{ij}}$: a binary variable for finding the (primary) path.

$\boldsymbol{x_{ij}^k}$: a binary variable for finding the primary path for the k^{th} commodity.

$\boldsymbol{\widehat{x}_{ij}^k}$: a continuous variable denoting the amount of traffic for commodity k flowing on the logical edge $E_i \Rightarrow E_j$.

$\boldsymbol{X_r}$: 1 if the r^{th} request has been successfully allocated to a lightpath, 0 otherwise.

$\boldsymbol{X_{ij}}$: amount of flow on edge (i, j),

$\boldsymbol{\mathcal{X}_{ijk}}$: converter edge.

$\boldsymbol{X_{ij}^k}$: an integer variable having a value of 0 or 1 where

$$X_{ij}^k = \begin{cases} 1 \text{ if the } k^{\text{th}} \text{ lightpath is routed through the edge } i \rightarrow j,\ (i,j) \in E \\ \quad \text{in the physical topology,} \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{X_{ij}^{wk}}$: an integer variable having a value of 0 or 1 where

$$X_{ij}^{wk} = \begin{cases} 1 \text{ if the } k^{\text{th}} \text{ lightpath is routed through the edge } i \rightarrow j, \\ \quad (i,j) \in E \text{ in the physical topology and is assigned channel } c_w, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{\overrightarrow{y}}$: a vector of simplex multipliers.

$\boldsymbol{y}$: a vertex in G_S.

$\boldsymbol{\widehat{y}_{pr}}$: a binary variable for the backup path, used if ℓ_p is selected

$\boldsymbol{Y_j^k}$: an integer variable having a value of 0 or 1 where

$$Y_j^k = \begin{cases} 1 \text{ if the } k^{\text{th}} \text{ lightpath is assigned channel } c_j, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{\overrightarrow{y}_c = [y_{\ell,c}]_{\ell \in \mathcal{L}}}$: the column vector containing channel assignment variables for channel $c, 1 \leq c \leq n_{ch}$, where

$$y_{\ell,c} = \begin{cases} 1 \text{ if channel } c \text{ is assigned to lightpath } \ell, \\ 0 \text{ otherwise.} \end{cases}$$

$\boldsymbol{y_{ij}}$: a binary variable for finding the backup path, used for dynamic wavelength allocation with wavelength continuity constraint.

$\boldsymbol{y_{ij}^k}$: a binary variable for finding the backup path, used for 1:1 path protection in wavelength-convertible networks using static allocation.

$\boldsymbol{z_k}$: a binary variable, for all k, $1 \leq k \leq n_{ch}$, denoting whether channel number k has been used for the backup lightpath.

$\boldsymbol{z_{kp}}$: a binary variable relevant when ℓ_p is selected.

$\boldsymbol{z_{ij}^k}$: continuous variable denoting the amount of flow of commodity number k on the edge $(i, j) \in E$.

$\boldsymbol{Z_d}$: set of digits $\{0, 1, \ldots d - 1\}$.

$\boldsymbol{Z_d^k}$: the set of all k-digit strings from Z_d.

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