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Algorithmic Principles for Building Efficient Overlay Computers

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Critical resource sharing:
State-of-the-art survey and algorithmic solutions

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1 Introduction

The aim of Critical Resource Sharing is to provide the user of a global computer with algorithms and protocols enabling to communicate in a transparent way and according to some quality of service and cost. Therefore, there is a need for using the underlying resources efficiently and in a scalable way.

The technologies deployed in communication networks are numerous, varied, and constantly changing with the result that both the structure and the use of telecommunications networks are evolving. We are mainly faced with three big challenges.

One challenge is how to model the increasingly dynamic nature of the networks and network behaviors.

A second challenge is presented by the heterogeneous nature and behavior of modern networks which can include an optical fiber backbone, many different kinds of switching and routing devices, and wireless access by radio devices. It is important to consider heterogeneous networks in their entirety; indeed a unified approach to developing multi-level solutions can avoid duplication of resources.

A third challenge is to ensure the scalability of solutions in very large networks such as overlay networks, which involve the superposition of many virtual networks. This is the challenge of global (or ubiquitous) computing.

Finally, fault tolerance mechanisms, which guarantee correct behavior of the network, have to be investigated in the context of dynamic, heterogeneous, and scalable networks.

In an overlay computer, the user may have a vision of a structured network of resources, while the underlying infrastructure may be very irregular and heterogeneous. The users do not know and do not want to know what is the effective protocol or physical path used. The work to be done is to provide efficient and scalable algorithms for transparent bandwidth sharing in a heterogeneous large-scale global computer in order to match the quality of service expected by the overlay computer.

There are two distinct approaches to tackle these dynamic aspects. One is to consider an evolving system. This approach lacks combinatorial structures, and is surveyed in deliverable D5.2.1. On the other hand, one can consider such a system as a sequence of static snapshots that have to be handled separately. This document surveys algorithmic and combinatorial researches that has been conducted about critical resource sharing in these settings.

A generic problem consists in satisfying a family of requests (or a traffic matrix) on a virtual (logical) network which is itself embedded in the physical network (in fact there might be many layers). It is the case for example when considering SONET over WDM rings or IP traffic over WDM networks using MPLS technology. In the latter case we have to assign a lightpath to each request in the virtual network and then to route the lightpaths in the WDM network under various constraints such as capacity constraints.

A simple model of two layers networks consists in considering two digraphs (or graphs) sharing the same vertex set. The first one is a logical or virtual multi-digraph I whose arcs represent the virtual connections (virtual channel in ATM, or lightpaths in MPLS). For example, the number of arcs from i to j corresponds to the number of such lightpaths from i to j. A request between two users will be satisfied in this virtual graph ; an example of a measure of quality of service can be the hop count (number of virtual arcs the request has to use). The second digraph is the physical one G; in many cases it is symmetric. The capacity constraints are expressed on this physical graphs ; for example in a WDM network the number of wavelengths available on a given optical fiber is limited.

Routing problems are found both in the virtual graph and in the physical one and we quickly survey this topic in Chapter 2; the tools used rely on flows in networks.

All these lines of research were considering the transmission bandwidth as the critical resource and the aim was to optimize it by minimizing for example the number of wavelengths used in the network. In the mean time, the bandwidth of each wavelength ($>$ 10 Gbit/s), the number of wavelengths per fiber ($>$ 100) and the number of fibers per cable ($>$ 100) have exploded, thus reporting the operational cost of a wavelength into the terminal equipment cost: filters, optical cross-connect, add/drop multiplexer (ADM). For example, in a node of an optical network we place an ADM only for those wavelengths carrying a request which has to be added or dropped in this node. So nowadays the objective is to minimize the total number of ADMs in the network, which is a challenging issue we will consider in chapter 3 as grooming problems.

Finally, in the last chapter, we survey some issues on fault tolerance.

2 Topology Design

2.1 Routing and Multicommodity flow

Routing problems are found both in the virtual graph and in the physical one. Indeed, a request is satisfied by assigning to it a dipath (directed path) in the virtual network. A virtual connection is satisfied by assigning a dipath in the physical graph. The family of virtual connections is satisfied, if we can route them in such a way that the capacity constraints of the physical network are satisfied. This is known as the routing problem. Let us define the load of an arc as the number of routes (dipaths) containing it. Typically one wants either to insure that the load does not exceed the capacity of the arc or to minimize the load for a given family of virtual connection.

2.1.1 Multicommodity flows

The problem is then usually modeled as a *multicommodity flow* problem or some variation of it which can be solved the same way (see for example, [134] of [6] for a variation modeling the routing in WDM network).

A *flow network* is a digraph $G = (V, E)$ with a capacity function c on the arcs. The arcs would support the flow, and the vertices would be intermediary points, flow sources, or destinations. We are given a multiset of *commodities* $C = \{(s_i, t_i),\ s_i, t_i \in V,\ i = 1, \ldots, k\}$ corresponding to the request. A *flow* f_i from s_i to t_i is a function on the arcs fitting *flow conservation constraints* [87] which correspond to Kirchoff law at each vertex but the source and the target. The flow *intensity* is the amount of flow leaving the source s_i, which equals to the amount arriving at t_i.

A *multicommodity flow* of C is an union of flows for each commodity, such that the sum fits the capacity of G : $\forall e \in G$, $\sum_i f_i(e) \leq c(e)$. Let Z be the set of requests.

Such a problem may be formulated as a *Linear Program*:

$$\begin{array}{cc} \forall e \in E, & \sum_{z\in Z} x_{e,z} \leq c(e) \\ \forall v \in V, \forall z \in Z, & \sum_{e- \in A^-(v), e^+ \in A^+(v)} x_{e^-,z} - x_{e^+,z} = out(v,z) - in(v,z) \\ \forall e \in E, \forall z \in Z, & x_{e,z} \geq 0 \\ \text{Minimize} & \sum_{z\in Z, e\in E} x_{e,z} \end{array}$$

with $x_{e,z}$ the flow variable for the arc e and request z, $in(v, z)$ (resp. $out(v, z)$) the flow going in (resp. out) at vertex v and $A^-(v)$ and $A^+(v)$ the sets of arcs entering (resp. leaving) vertex v.

This formulation has a polynomial number of variables ($O(|E||Z|)$) and constraints ($O(|V||Z| + |E||Z| + |E|)$). Therefore the (fractional version of the) problem can be solved in polynomial time (for example by the *ellipsoid method* [153], chap I.6). However, very often, we need integral solutions: for every $e \in E$ and $z \in Z$, the numbers $x_{e,z}$ must be an integer. Then the problem becomes NP-complete [89] (Annex A2, page 216) and we need to find approximation algorithms.

2.1.2 Unsplittable Flow Problem

In many networking settings, each request has to be served by a unique connection in the network. Such integrality constraints are conveniently modeled by the *Unsplittable Flow Problem.* This problem has been introduced in 1996 by Kleinberg [126] and has then fostered numerous studies [78, 171, 130, 3, 58, 13, 131, 98, 129, 4, 2].

The unsplittable flow problem is stated as follows. Take a digraph $G = (V, E)$, with arc capacity $c_e \geq 0, \forall e \in E$, k commodities (s_i, t_i) with demand $d_i \geq 0$. The goal is to find a unique path p_i from s_i to t_i with capacity d_i for each commodity (s_i, t_i, d_i), such that the flow on each arc fits in the capacity. Several objective to optimize have been considered.

- **Minimum Congestion** Minimize the value $\alpha \geq 1$ such that the unsplittable flow violate the arc capacity by a factor at most α.
- **Minimum Partition** Find a partition of the commodities in minimum number of subsets such that an unsplittable flow exists for each subset.
- **Maximum routable demand** Find an unsplittable flow for a subset of the commodities of maximum sum of demand.

Some studies ([78, 171, 130]) considered arc costs, trying to minimize the congestion of the arcs while keeping the solution below a given budget.

2.1.3 Approximating the integral multicommodity flow

Randomized rounding The *randomized rounding* [158] of the multicommodity flow has been proved to achieve a good theoretical approximation ratio despite the simplicity and obvious sub-optimality of the process [150]. This algorithm [157, 62] first solves the linear program described above to obtain fractional flows. A fractional flow of n units from s to t can be decompound into many paths with positive fractional weights summing up to n. The randomized rounding essentially consists in selecting at random one of these paths with probability its weight divided by n. A simple analyze shows that the integral capacity obtained after randomly rounding a whole multicommodity flow is a sum of Bernoulli trials with expectancy the fractional capacity. Therefore the gap between the rounded solution and the fractional one is low with high probability.

The main computational drawback of this process is that the number of paths can be exponential. Hopefully one can prove with a martingale argument that these paths are not explicitly required. The fractional unit of flow describes in the network a weighted *directed acyclic graph* (DAG) which requires linear time computation to be generated from the flow variables. A random walk inside this DAG gives a path which could be selected by the randomized rounding. If the probability to go through an edge is proportional to its weight the path is selected with the same probability as the randomized rounding.

Approximating the fractional multicommodity flow The previously described algorithms compute a better approximation of the integer multicommodity flow, but at the cost of solving a fractional multicommodity flow for each commodity in an iterative process. Solving the fractional multicommodity flow efficiently is therefore a crucial issue.

But, since the fractional multicommodity flow is used to compute an approximated integral solution, there is no real need for the use of optimal fractional flow. Indeed, the approximation yielded by the randomized rounding process is an additive gap of order the square root of the fractional capacities [157, 62]. If these fractional capacities are $(1+\epsilon)$-approximations of the optimal capacities, the magnitude of the final gap will not change dramatically. It is therefore natural to exploit this freedom in order to consequently speed up the integer multicommodity flow approximation algorithm. Two distinct approaches have been investigated, both following a common general idea of manipulating a metric on the edges that is an exponential measure of the flow supported by each edge introduced in [169]. Their common objective is to avoid the linear program solvers, much more costly to run than combinatorial algorithms.

The first approach [139] applies to general fractional packing and covering problems [156, 125] and is inspired by Lagrangian relaxation. It consists in an iterative re-routing of a non admissible flow until capacities are fit up to a $(1+\varepsilon)$ factor.

The second approach has been introduced in more general settings [201] and later applied to multicommodity flow [90]. The technique relies on a primal/dual algorithm that builds a $(1+\epsilon)$-approximated maximum flow that fit the capacity constraints. This algorithm has been improved by Fleischer [86], decreasing the complexity from $O(\epsilon^{-2}km^2n^2)$ to $O(\epsilon^{-2}m^2\log n)$. At the opposite of the previous approach, the algorithms of this family start from an empty solution and push small quantities of flow along shortest paths. Further improvements were given in [38] using dynamic shortest paths and then in [63] with an incremental algorithm.

2.1.4 Extracting paths

The computation of the integral multicommodity flow does not give directly the set of routes. Hence the flow obtained for each request needs to be decomposed into paths. This decomposition is not unique and could made following different criteria. Practically because the grooming (see Section 3) is a key issue in an overlay computer, we would like to minimize the number of such paths. Unfortunately, as proved in [134] and [43], this minimization problem is NP-complete. However, a non-optimal but efficient greedy algorithm has been shown in [134] to decompose a flow into paths.

To avoid this extracting problem, another approach of the multicommodity flow has been proposed in [134]. It is based on a different formulation of this problem as a linear program which computes the flow via the sets $\mathcal{P}_z$ of all possible paths for a request z.

$$\begin{array}{rc} \forall z \in Z, & \sum_{P \in \mathcal{P}_z} q(P,z) = size(z) \\ \forall e \in E, & \sum_{z \in Z, P \in \mathcal{P}_z, e \in P} q(P,z) \leq c(e) \\ \forall z \in Z, \forall P \in \mathcal{P}_z, & q(P,z) \geq 0 \\ \text{Minimize} & \sum_{z \in Z, P \in \mathcal{P}_z, e \in P} q(P,z) \end{array}$$

with $q(P, z)$ the quantity of flow of the request z using the path P.

The disadvantage of this formulation is that we need to know all the paths of $\mathcal{P}_z$ which size grows exponentially with the size of the graph. Hence it would not be efficient to obtain an optimal fractional solution of the multicommodity flow. However, it is of interest to approximate the integral multicommodity flow using heuristics generating subsets of $\mathcal{P}_z$. The advantage in this case, is that the routes are then directly given by the solution.

2.2 RWA and VPL problems

2.2.1 Routing and Wavelength Assignment

Many backbone networks are now WDM optical ones. Indeed Wavelength Division Multiplexing (WDM) enables to use the bandwidth of an optical fiber by dividing it in multiple non overlapping frequencies or wavelength channels (see [151, 162]). Satisfying a virtual connection in a WDM optical network consists not only in assigning to it a route (dipath), but also a wavelength, which shall stay unchanged if no conversion is allowed. Therefore, two requests, having the same wavelength,must be routed by two arc disjoint dipaths or, equivalently, two requests, whose associated dipaths share an arc, have to be assigned different wavelengths. Hence the scare resource is the number of available wavelengths. This problem is known in the literature as the RWA (Routing and Wavelength Assignment) problem ([73, 71, 81]).

Minimizing the load or/and the number of wavelengths are difficult problems and in general an NP-hard problem. These problems have been extensively studied in the literature for various topologies or special families of requests like multicast or all to all (see for example the survey [9] or [127, 161]). Many particular cases where the minimum number of wavelengths is equal to the minimum load have been given. For example, in [10] it is shown that for any digraph and for a multicast instance (all the requests have the same origin), there is equality and both problems can be solved in polynomial time. For some topologies the load might be easily computed, but the minimum number of wavelengths is NP-hard to compute as it is related to coloring problems. This is the case for symmetric trees (see the survey [42]). However, for symmetric trees it has been proved that there is equality for the all to all instance ([GHP01]) and approximation algorithms have been given ([42, 79]). Fractional coloring ([40, 41]) appears to be a useful tool.

As the RWA problem is very difficult to solve, it is often split into two separate problems: the first one solves the routing problem by determining dipaths which minimize the load or are easy to compute like shortest paths. Then, the routing being given, one solves the wavelength assignment problem. In that case, the input of the problem is not a family of requests but a family of dipaths $\mathscr{P}$. We will denote by $\pi(G, \mathscr{P})$ the maximum of the load of all the arcs of the digraph. Determining the minimum number $w(G, \mathscr{P})$ of wavelengths (colors) needed to color a family of dipaths $\mathscr{P}$ in such a way that two dipaths with the same wavelength are arc-disjoint is still NP-hard in that case. Indeed it corresponds to finding a vertex coloring of the conflict graph : graph whose vertices represent the dipaths; two vertices being joined if the corresponding dipaths intersect. There are examples of topologies where there are at most 2 dipaths using an arc ($\pi(G, \mathscr{P}) = 2$), but where we need as many wavelengths as we want and so for these digraphs there is no ratio between $w(G, \mathscr{P})$ and $\pi(G, \mathscr{P})$ [1].

2.2.2 Virtual path layout

The embedding of the virtual network in the physical one has also gives rise to a wide literature on the problem called *Virtual Path Layout (VPL)*. In its most general formulation, the Virtual Path Layout (VPL) problem is an optimization problem in which, given a certain communication demand between pairs of nodes and constraints on the maximum load and hop count, it is first required to design a system of virtual paths satisfying the constraints and then minimizing some given function of the load and hop count. More precisely one problem can be restated as follows :

Given a capacity on each physical arc, minimize the diameter of an admissible virtual digraph that does not load an arc more than its capacity.

The problem has been considered in the undirected case, for example, in [106, 105, 176, 99, 132, 74]. The problem of minimizing the maximum load over all VPL with bounded hop-count is studied in [82, 11], and minimizing also the average load is considered in [105]. The one-to-many problem is handled in [82, 105], where the focus is on minimizing the eccentricity of the virtual graph from a special point called the root (this problem is the *rooted virtual path layout problem*) rather than minimizing the diameter of the virtual graph. A duality in the path network between the problem of minimizing the hop-count knowing the maximum load, and the one of minimizing the load, knowing the maximum hop-count, is established in [82]. The reader can find an excellent survey of the results in the undirected model in [204] or in [29] and we will not comment it more here.

3 Traffic Grooming

Traffic grooming refers to techniques used to combine low speed traffic streams onto high speed wavelengths in order to minimize the network-wide cost in terms of line terminating equipment and/or electronic switching.Many current network infrastructures are based on the synchronous optical network (SONET). A SONET ring typically consists of a set of nodes connected by an optical fiber in a unidirectional ring topology. Nodes of the network insert and/or extract the data streams on a wavelength by means of an add drop multiplexer (ADM). A WDM (*wavelength-division multiplexed*) or DWDM (*dense WDM*) optical network can handle many wavelengths, each with large bandwidth available. On the other hand a single user seldom needs such large bandwidth. Therefore, by using multiplexed access such as TDMA (time-division multiple access) or CDMA (code-division multiple access), different users can share the same wavelength, thereby optimizing the bandwidth usage of the network. Traffic grooming is the generic term for packing low rate signals into higher speed streams (see the surveys [71, 149, 174]). By using traffic grooming, not only is the bandwidth usage optimized, but also the cost of the network can be reduced by lessening the total number of ADMs.

Such techniques become increasingly important for emerging network technologies, including SONET/WDM rings and MPLS/MPλS backbones [182], for which traffic grooming is essential.

The general traffic grooming problem being NP-complete [45], recent works focus on specific issues. Most of the algorithms aim at grooming traffic in such a way that all the traffic between any given pair of nodes is carried on a minimum number of wavelengths (efficient use of the fiber, see section. However, a large part of the cost depends on the size of the multiplexing equipment required at each node. Hence, in order to minimize the overall network cost, algorithms have to take into account a tradeoff between the number of wavelengths used and the number of required (optical) Add-Drop Multiplexers (ADMs).

Indeed minimizing the number of ADMs is different from minimizing the number of wavelengths. Indeed, the number of wavelengths and the number of ADMs cannot always be simultaneously minimized (see [45, 100] for uniform traffic) although in many cases both parameters can be minimized simultaneously. Both minimization problems have been considered by many authors. See surveys [9, 73] for minimization of the number of wavelengths and [20, 22, 25, 71, 83, 100, 103, 108, 119, 190, 207] for minimization of ADMs. Numerical results, heuristics and tables have also been given (see for example [192, 149, 173]).

The first part of this chapter is organized as follows: In Section 3.1.1 we described the grooming problem on unidirectional cycles with all-to-all unitary traffic and summarize the results obtained. New results have been obtained using a modeling of the problem as a graph partition problem and using tools of design theory. Then in Section 3.1.2 we propose a general model in terms of graph partitioning and give as example its application to the grooming problem on a simple path. In Section 3.1.3 we give the results for more general settings.

In the second part, we consider a model of network in which the topology is arbitrary (mesh network) and the data is transmitted into a set of hierarchical optical containers. We consider a node as an N-layer switch, in which a given layer k is an aggregated set of elements of layer $k-1$.

Typical examples of layers are wavelengths, wavebands and fibers. A waveband is made of a set of lightpaths and is routed across the nodes as a single channel, using a single port of a waveband optical crossconnect (B-OXC). The cost of a given node depends on the number of input and output ports of each layer. Assuming this model and a traffic matrix - with unity elements in layer 0 - minimizing the cost of the network will consist in grooming traffic in such a way that as much traffic as possible will be switched in the higher possible layer (fibers in our example). When some traffic is switched along a path in the network within the same layer, it is represented with a pipe. Each pipe has an associated linear cost depending on the current layer and the number of nodes crossed in that pipe. For example wavelengths (W) are included in wavebands (B) that are included in fibers (F). Each level in the hierarchy is called a *layer* and is mapped to a specific switching cost.

3.1 Traffic Grooming: Minimizing the number of ADMs

3.1.1 Unidirectional cycle

In this section we consider the particular case of unidirectional rings, so that the routing is unique. There is static uniform symmetric all-to-all traffic, i.e. there is exactly one request of a given size from i to j for each pair (i, j), and no wavelength conversion. With a pair of nodes, $\{i, j\}$, is associated a circle, $C_{\{i,j\}}$, containing both the request from i to j and from j to i. We assume that both requests use the same wavelength. For uniform symmetric traffic in an unidirectional ring, this assumption is not an important restriction and it allows us to focus on the grooming phase independent of the routing. A circle is then a reservation of a fraction of the bandwidth in the whole ring network corresponding to a communication between two nodes. (It is also possible to consider more general classes other than circles containing two symmetric requests packed into the same wavelength. These components are known as circles [45, 207, 24], circuits [192] or primitive rings [53, 56].) If each circle requires only $\frac{1}{C}$ of the bandwidth of a wavelength, we can "groom" C circles on the same wavelength. C is the *grooming ratio* (or grooming factor). For example, if the request from i to j (and from j to i) is packed in an OC-12 and a wavelength can carry up to an OC-48, the grooming factor is 4. Given the grooming ratio C and the size N of the ring, the objective is to minimize the total number of (SONET) ADMs used, denoted $A(C, N)$. This lowers the network cost by eliminating as many ADMs as possible compared to the "no grooming" case.

For example, let $N = 4$; we have 6 circles corresponding to the 6 pairs $\{0, 1\}$, $\{0, 2\}$, $\{0, 3\}$, $\{1, 2\}$, $\{1, 3\}$, $\{2, 3\}$. If we don't use grooming, that is if we assign one wavelength per circle, we need 2 ADMs per circle, and thus a total of 12. Suppose now that $C = 4$, that is we can groom 4 circles on one wavelength. One can groom on wavelength 1 the circles associated with $\{0, 1\}, \{1, 2\}, \{2, 3\}, \{3, 0\}$ requiring 4 ADMs and on wavelength 2 the circles associated with $\{0, 2\}$ and $\{1, 3\}$ requiring 4 ADMs and so a total of 8. A better way is to groom the circles associated with $\{0, 1\}, \{0, 2\}, \{0, 3\}$ using 4 ADMs and those associated with $\{1, 2\}, \{1, 3\}, \{2, 3\}$ using 3 ADMs for a total of 7 ADMs.

Another interesting example is with $N = 9$. We have $R = 36$ circles. Without grooming, we need $A(1, 9) = 72$ ADM's and for grooming factors $C = 3, 12, 36$ we need respectively, $A(3, 9) = 36$, $A(12, 9) = 18$, and $A(36, 9) = 9$ ADM's. For $C = 36$, we groom all the circles on one wavelength.

For $C = 12$, let the vertex set be $A_1 \cup A_2 \cup A_3$ with $|A_i| = 3$. $A_i = \{a_i^j,\ j = 1, 2, 3\}$. We can groom on wavelength i, $i = 1, 2, 3$, the 3 circles $\{a_i^j, a_i^{j+1}\}$ and the 6 circles $\{a_i^j, a_{i+1}^k\}$ where all the indices are taken modulo 3. So wavelength i use only 6 ADMs. For $C = 3$, we groom the circles in 12 wavelengths each containing 3 circles of type $\{i, j\}$, $\{j, k\}$ and $\{i, k\}$. Thus, by increasing the grooming factor, we significantly reduce the total amount of ADM's in the network.

The problem of minimizing the number of ADMs in a unidirectional ring with uniform traffic can be modeled by graphs as shown in [23]. Given a unidirectional SONET ring with N nodes, $\overrightarrow{C}_N$, and grooming ratio C, consider the complete graph K_N, i.e. the graph with N vertices in which there is an edge (i, j) for every pair of vertices i and j. The number of edges of K_N equals the number of circles $R = \frac{N(N-1)}{2}$. Moreover there is a one–to–one mapping between the circles of $\overrightarrow{C}_N$, $C_{\{i,j\}}$, and the edges of K_N, (i, j). Let $\mathcal{S}$ be an assignment of wavelengths and time slots for all requirements among all possible pairs of nodes requiring A ADMs. Let B_ℓ be a subgraph of K_N representing the usage of a given wavelength ℓ in the assignment $\mathcal{S}$. To be precise, let the edges in $E(B_\ell)$ correspond to the circles $C_{\{i,j\}}$ groomed onto the wavelength ℓ, and let the vertices in $V(B_\ell)$ correspond to the nodes of $\overrightarrow{C}_N$ using wavelength ℓ. The number of vertices of B_ℓ, $|V(B_\ell)|$ is the number of nodes using wavelength ℓ or, alternatively, the number of ADMs required for wavelength ℓ. Evidently the total number of edges of B_ℓ, $E(B_\ell)$ is at most the grooming ratio C. With these correspondences the original problem of finding the minimum number of ADMs, $A(C, N)$, required in a ring $\overrightarrow{C}_N$ with grooming ratio C, is equivalent to the following problem in graphs:

Problem 1 *Given a number of nodes N and a grooming ratio C find a partition of the edges of K_N into subgraphs B_ℓ, $\ell = 1, \ldots, W$ with $|E(B_\ell)| \leq C$ such that $\sum_{1 \leq \ell \leq W} |V(B_\ell)|$ is minimum.*

Remark: As we said in the introduction, most interest has focused on a different objective function which was to minimize the number W of subgraphs (wavelengths) of the partition. This is in this context an easy problem as $W_{\min} = \lceil \frac{R}{C} \rceil = \left\lceil \frac{N(N-1)}{2C} \right\rceil$.

Optimal constructions for given grooming ratio C have been obtained using tools of graph and design theory [51]. In particular, results are available for grooming ratio $C = 3$ [18], $C = 4$ [119] with a shortest proof in [24], $C = 5$ [19], $C = 6$ [20], partly for $C = 12$ and $C \geq N(N-1)/6$ [24]. The problem is also solved for large values of C ([24]). Table 1 gives the values of $A(C, N)$ for $N \leq 16$ and some values of C as the table in [192].

Theorem 2 ([18]) $A(\vec{C}_n, K_n^*, 3) = n(n-1)/2 + \varepsilon_3(n)$, *where* $\varepsilon_3(n) = 0$ *when* $n \equiv 1, 3 \pmod 6$, $\varepsilon_3(n) = 2$ *when* $n \equiv 5 \pmod 6$, $\varepsilon_3(n) = \lceil n/4 \rceil + 1$ *when* $n \equiv 8 \pmod{12}$, *and* $\varepsilon_3(n) = \lceil n/4 \rceil$ *otherwise.*

Theorem 3 ([119, 24]) $A(\vec{C}_n, K_n^*, 4) = n(n-1)/2$.

Theorem 4 ([19]) $A(\vec{C}_n, K_n^*, 5) = 4 \lfloor n(n-1)/10 \rfloor + \varepsilon_5(n)$, *where* $\varepsilon_5(n) = 0$ *when* $n \equiv 0, 1 \pmod 5$, $n \neq 5$, $\varepsilon_5(5) = 1$, $\varepsilon_5(n) = 2$ *when* $n \equiv 2, 4 \pmod 5$, $n \neq 7$, $\varepsilon_5(7) = 3$, $\varepsilon_5(n) = 3$ *when* $n \equiv 3 \pmod 5$, $n \neq 8$, *and* $\varepsilon_5(8) = 4$.

Theorem 5 ([20]) *When* $n \equiv 0 \pmod 3$*, then* $A(\vec{C}_n, K_n^*, 6) = \lceil n(3n-1)/9 \rceil + \varepsilon_6(n)$*, where* $\varepsilon_6(n) = 1$ *when* $n \equiv 18, 27 \pmod{36}$*, and* $\varepsilon_6(n) = 0$ *otherwise, except for* $n \in \{9, 12\}$ *and some possible exceptions when* $n \leq 2580$*.*

When $n \equiv 1 \pmod 3$*,* $A(\vec{C}_n, K_n^*, 6) = \lceil n(n-1)/3 \rceil + \varepsilon_6(n)$*, where* $\varepsilon_6(n) = 2$ *when* $n \equiv 7, 10 \pmod{12}$*, and 0 otherwise, except for* $A(\vec{C}_7, K_7^*, 6) = 17$*,* $A(\vec{C}_{10}, K_{10}^*, 6) = 34$*, and* $A(\vec{C}_{19}, K_{19}^*, 6) = 119$*.*

When $n \equiv 2 \pmod 3$*, then* $A(\vec{C}_n, K_n^*, 6) = (n^2+2)/3$*, except possibly for* $n = 17$*.*

$C \setminus N$	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3	3	7	12	17	21	31	36	48	57	69	78	95	105	124
4	3	7	10	15	21	28	36	45	55	66	78	91	105	120
12	3	4	5	9	12	16	18	24	30	35	39	47	55-56	60
16	3	4	5	6	11	14	18	20	26	32	36	41	45	53-54
48	3	4	5	6	7	8	9	10	16	19	22	24	30	32
64	3	4	5	6	7	8	9	10	11	15	19	22	25	28

Table 1: $A(C, N)$ for $N \leq 16$ and $C = 3, 4, 12, 16, 48, 64$

3.1.2 General model and traffic grooming on a path

In the same spirit as above we can formalize the grooming problem for the virtual graph of connections using the notion of load.

Definition 6 *Grooming problem: Given a digraph* G *(network), a digraph* I *(set of requests) and a grooming factor* C*, find for each arc* $r \in I$ *a path* $P(r)$ *in* G*, and a partition of the arcs of* I *into subgraphs* I_w*,* $1 \leq w \leq W$*, such that* $\forall e \in E(G)$*,* $\text{load}(I_w, e) = |\{P(r); r \in E(I_w); e \in P(r)\}| \leq C$*. The objective is to minimize* $\sum_{w=1}^{W} |V(I_w)|$*, and this minimum is denoted by* $A(G, I, C)$*.*

Remark: In a unidirectional cycle $\vec{C}_n$, the path from i to j is unique. Wlog we can assign the same wavelength to the two requests (i, j) and (j, i), then the two associated paths contain each arc of $\vec{C}_n$. Therefore the load condition becomes $|E(I_w)| \leq C$ and the grooming problem is that described before.

The traffic grooming problem has also been considered when the network is reduced to a path. In particular, it has been shown in [120] that the grooming problem is NP-Complete when the grooming factor is larger that 2, and a polynomial time algorithm for the special case of grooming factor 1 and general set of requests has been given in [15].

Notice that when the network is a path, the shortest path from node i to node j is unique, and we can split the requests into two classes, those with $i < j$ and those with $i > j$. Therefore the grooming problem for P_n^*, that is a bidirectional path, can be reduced to two distinct problems on $\vec{P}_n$, the direct path. In particular we have $A(P_n^*, K_n^*, C) = 2A(\vec{P}_n, TT_n, C)$, where TT_n is a transitive tournament as define bellow.

Definition 7 *TT_n is a transitive tournament on n vertices, that is the digraph with arcs $\{(i,j) \mid 1 \leq i < j \leq n\}$. We denote $\{a,b,c\}$ the TT_3 with arcs $\{a,b\}$, $\{b,c\}$, and $\{a,c\}$.*

For example, $A(\vec{P}_7, TT_7, 2) = 20$, and the partition consists of 6 subgraphs, the 5 TT_5 {2,4,5}, {3,4,6}, {1,5,6}, {2,6,7}, and {1,4,7}, plus the union of two TT_3 {1,2,3}+{3,5,7}.

Theorem 8 ([15]) *When n is odd, $A(\vec{P}_n, TT_n, 2) = \lceil (11n^2 - 8n - 3)/24 \rceil$; When n is even, $A(\vec{P}_n, K_n, 2) = (11n^2 - 4n)/24 + \varepsilon(n)$, where $\varepsilon(n) = 1/2$ when $n \equiv 2, 6 \pmod{12}$, $\varepsilon(n) = 1/3$ when $n \equiv 4 \pmod{12}$, $\varepsilon(n) = 5/6$ when $n \equiv 10 \pmod{12}$, and $\varepsilon(n) = 0$ when $n \equiv 0, 8 \pmod{12}$.*

Another interesting study on the path has been done in [21] where a polynomial time algorithm for maximizing the number of requests on a given wavelength with given grooming factor is presented. This algorithm is an optimal greedy algorithm on a matroid. This paper also provide explicit formula for the maximum number of requests that can be groomed. Such formulas are required to established tight lower bound for the traffic grooming problem on the path.

3.1.3 Other settings

We have seen above that the traffic grooming problem has been extensively studied in the last years [209, 83, 108, 173] and we have presented the results obtained in particular cases, namely unidirectional rings and paths with all-to-all unitary traffic [22]. Other optimal construction were obtained for bidirectional ring topology [25]. For more general set of requests, approximation algorithms have recently been given.

For the special case $C = 1$ on unidirectional cycle, where the problem is already NP-Hard, an approximation algorithm with proven upper bound of $OPT + 0.6|I|$, where OPT is the cost of an optimal solution and $|I|$ is the number of lightpaths (requests), has been given in [85].

For the traffic grooming problem on the ring topology for general instances and $C \geq 2$, a polynomial time approximation algorithm has been obtained in [83]. Its approximation is shown to be $2 \ln C + o(\ln C)$. This is the best known approximation algorithm for the grooming problem with a general grooming factor g. The results has been extended to trees in [84] with the same approximation factor. Complexity and approximability issues in star networks are also considered in [84].

Finally a first tentative to capture the dynamicity of the networks has been done in [55]. Intuitively,there are two time periods ; the traffic in time periods T and T' is specified by different requirements connections (virtual digraphs I and I') In the first time period, the traffic between node pairs of I has a grooming ratio of C. In the second time period only a subset of nodes are active with the traffic among them therefore able to run at a higher rate (and hence $C' < C$). Here again the authors model the problem in terms of graph decompositions.

3.2 Traffic Grooming in Mesh Networks

In the case of arbitrary mesh networks the design theory proposed above does not applies. A model of network in which data are transmitted into a set of hierarchical optical containers has been introduced in [121]. This model applies for WDM backbones planning processes which consists in computing the paths associated with some traffic requests (lightpaths) and then assigning lightpaths to actual optical containers such as wavelengths, wavebands or fibers. This last stage of the planning process decides the size and kind of equipment required at each node. The paths chosen during the first stage may lead to a different overall cost of the network. The more the number of wavelengths which are groomed into wavebands, the less the size (and the cost) of the wavelength optical crossconnects.

Consequently, routing algorithms influence the performance of the grooming stage and the tube selection. Several policies for selecting tubes have been proposed, aiming at maximizing the grooming of lightpaths, when the routing is given [210, 121, 138]

3.2.1 Multi-Layer WDM Networks

A WDM network is made up of nodes and links with capacities assigned to the links. The capacity is equal to the number of fibers times the number of wavelengths per fiber, which is an integer. Wavelengths are grouped into wavebands of fixed size as shown in the cable detail of Fig. 3.2.1 (one fiber dotted with three wavebands of three wavelengths each). The physical topology is modeled by a directed graph $G = (V, E)$. Consider a traffic instance for the problem where $\mathcal{D}(G)$ denotes the set of static requests to be routed on the graph G. Satisfying a request $r = (s, t, \lambda)$ consists in finding a flow of size λ wavelengths from node s to node t. If no split is allowed - i.e. the request uses one path from s to t, and this is called an *Unsplittable routing* of size λ. Otherwise, several paths are used and a lightpath is associated to each path with a given number of wavelengths such that the total sum of the wavelengths used by the lightpaths are equal to λ, resulting in a *Multi routing*.

An example of a request assignment is shown in Fig. 3.2.1. The subset of nodes in G being source or destination nodes of some traffic is $\mathcal{D}(G)$. Arcs between two nodes in $\mathcal{D}(G)$ represent some traffic requests between them. The bold arrow between nodes s and t corresponds to a request of size 7. The corresponding paths in G are shown with bold arrows and are split into two groups (one group of 5 wavelengths and another group of 2 wavelengths).

The way the lightpaths are switched across the nodes is described in Fig. 3.2.1. At any node in the network, the input fibers are connected to the input ports of a F-OXC and may be switched to output ports according to the routing. When some wavebands included in an input fiber have to be switched onto different output fibers, wavebands are first extracted from the input fiber and then multiplexed onto the chosen outgoing fibers by the means of a B-OXC. When some wavelengths multiplexed onto one input waveband have to use different outgoing paths, the same process applies through W-OXC during the first stage, and then the wavebands are multiplexed during the second stage. This two-stage multiplexing switch is named as a hierarchical crossconnect (HXC) according to [114, 138]. At any node, one could add or drop a wavelength, a waveband or a fiber.

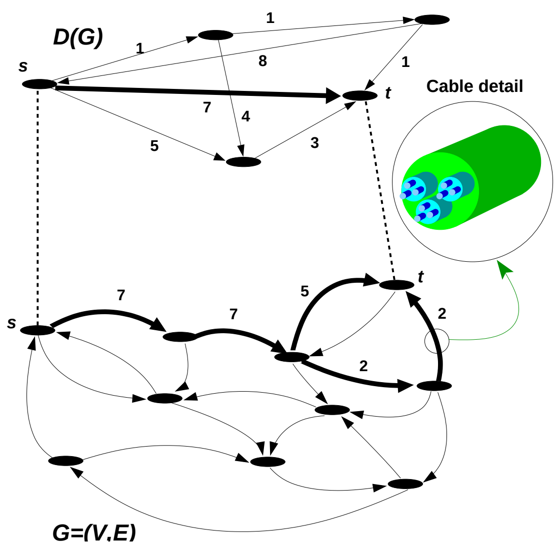


Figure 1: Mapping requests

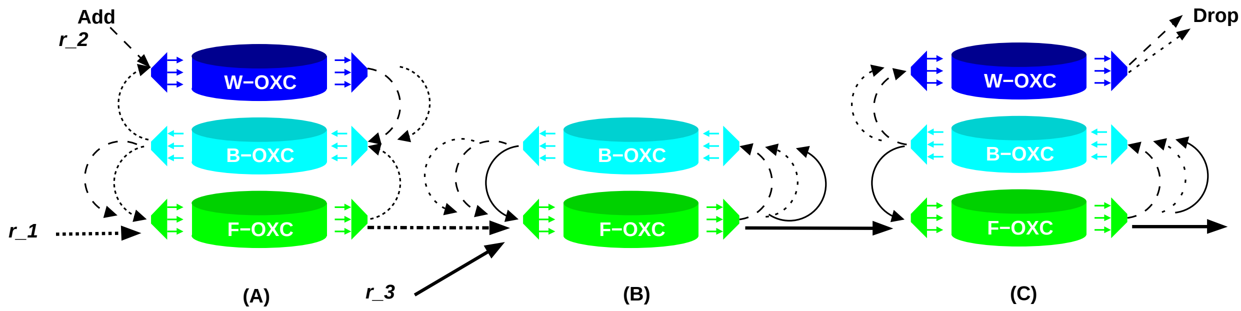


Figure 2: Wavelengths and wavebands multiplexing onto fibers

Grooming Grooming wavelengths into wavebands consists in assigning lightpaths sharing a common subpath in the network to the same sequence of wavebands along this subpath. The group of lightpaths is routed through B-OXCs as a single channel. An example is given in Fig. 3.2.1. The network includes a path A, B, C with one fiber per edge of capacity 4 wavebands. Each waveband has capacity 8 wavelengths. Consider 3 requests of size 4 wavelengths each: r_1 entering the node A from a preceding node (fiber shown dotted in A) with destination node C; r_2 entering the node A in the W-OXC layer with destination node C; and r_3 arriving at node B from a different fiber than AB and as destination node some node following C in the path. At node A the wavelengths of request r_1 and r_2 are multiplexed onto one waveband at the B-OXC layer. At node B, the waveband from requests r_1 and r_2 and the waveband carrying request r_3 are multiplexed together with output in the fiber BC. In this example, one can see that node B does not need to be equipped with a W-OXC, hence saving a lot of ports in the system. Usually one considers that F-OXC's are much less expensive than B-OXC's and that B-OXC's are much less expensive than W-OXC's. Hence the grooming algorithm has a strong influence on the cost of nodes. Note that wavelength-continuity constraints along a pipe have not been introduced in that definition. Nevertheless, a good grooming algorithm usually leads to a simpler wavelength assignment problem. The general wavelength assignment problem was deeply treated in [5].

The objective of the grooming problem is to minimize the complexity of the OXCs. At first, and for the sake of simplicity, the cost function is simplified to the number of wavelengths crossing the W-OXC. Note that this problem belongs to the class of $\mathcal{NP}$-complete problems even with simplified objective functions associated to the global cost of the network. As pointed out earlier, the case for ring networks has been extensively investigated for single stage grooming. In the case of mesh networks, integer linear programming solutions are given in [210, 72, 138] and [121]. The mathematical formulation in [210] is very detailed but the resulting computational complexity is very high and results are presented for small networks only. In [121] the authors assume that the routing paths are already computed and this is a strong assumption for this problem. Indeed, grooming optimization issues should be taken into account during the routing stage as described in the following section.

When some traffic is routed along a path in the network and switched within the same layer on some sub-path, it is represented with a pipe.

The topology of the physical layer, the links capacity, the traffic demand of each node-pair and the routing of demands are fixed as input of the grooming problem. The output is a set of pipes that could transport the traffic under capacity constraints and that minimize the cost of pipes defined below. In example 3 fiber-pipes are layer 3 pipes with capacity 2, bands-pipes are layer 2 pipes with capacity 2 and wavelengths-pipes are layer 1 pipes.

Each demand of size s is considered as s demands of size 1 and has an associated path computed in the routing phase of the optimization process.

Solving this problem on networks with k layers can be approximated by solving the problem recursively on each pair of layer. In the case of the example of figure 3, that means a two steps algorithm: first step is grooming of wavelengths into bands, and second step is grooming of bands into fibers.

Example 1 *in the case of the problem of Fig. 3, one solution is to use the 4 band-pipes* $N_0 \to N_4$, $N_1 \to N_6$, $N_4 \to N_5$, $N_4 \to N_6$. *Another solution would consist in using pipes* $N_0 \to N_2$, $N_1 \to N_2$, $N_2 \to N_6$, $N_4 \to N_5$.

Considering the general k layers problem as a stack of 2 layers sub-problems fits the structure of multi-layered networks: pipes of layer l are considered as traffic demands that must be carried by the layer $l + 1$ that has to be designed.

This model has some advantages: it prevents from modeling a switch (which would increase the complexity of the model, as in [50]); and it gives a more generic approach to the problem: it introduces a pure grooming problem in terms of an intuitive combinatorial problem.

On the other hand, this bottom-up approach leads to sub-optimal solutions, since an optimum cost for layer 1 could turn out to be poorly groomable in layer 2.

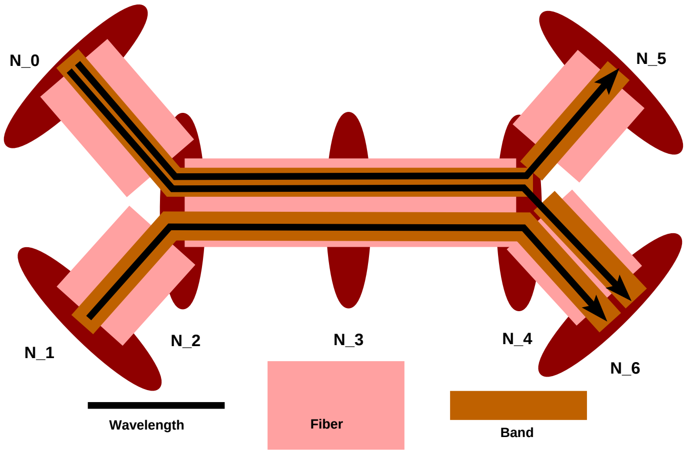


Figure 3: A grooming example

3.2.2 Traffic Grooming Heuristics

In order to face the complexity of the traffic grooming problem and the combinatorial explosion of ILPs, several heuristics have also been proposed in the literature to groom traffic efficiently.

1. *Maximizing Single-Hop Traffic (MST)* [210]: This simple heuristic seeks to establish single lightpath hops for the traffic demands as far as possible and the demands are considered in the order of their magnitudes. The lightpaths are routed along the shortest path between source and destination, subject to wavelength availability and node equipment constraints. If no more single hop lightpaths can be established, the remaining demands are routed based on the virtual topology network state created so far.

2. *Maximizing Resource Utilization (MRU)* [210]: This heuristic seeks to maximize the average traffic per wavelength link. The ratio of the traffic demand size and the physical hop distance between the source and the destination is used to determine the priority of the demand for routing. The procedure is the same as for MST except for the manner of assigning priorities to traffic demands.

3. *Grouping lightpaths with the same destination* [138]: This is applied to networks using wavebands. To construct the wavebands, the lightpaths having the same destination are grouped together since then there would be no need to ungroup them before the destination. The lightpaths are first routed. This is followed by grouping lightpaths in the same class (corresponding to one destination) into wavebands.

4. *Pipe filtering* [121]: taking all the subpaths of existing demands as the set of potential pipes is leading to hard integral linear program as this set is too large. The main goal is to discard any long pipe that would in any case be almost empty. In order to eliminate such pathological

pipes one use an evaluation function f that given a pipe, its length l and the maximum amount of traffic t that it can use, assigns a pipe grade $f(l,t)$. All pipes receiving a grade lower than *mingrade* are discarded. Note that by tuning the value *mingrade* the selectivity of this process can be adjusted (as an example we can keep 10 percents of the best pipes).

Another efficient heuristic is to limit the number of split allowed per demand (i.e. the number of different pipes that will carry that demand from source to destination).

The first two heuristics have been compared to the optimal solution (in terms of the ILP formulated) [210]. However one may like to compare the performance of the last to the optimal grooming solution for a given routing. The mathematical formulation in [210] is very detailed but the resulting computational complexity is very high and results are presented for small networks only. In [121] the authors assume that the routing paths are already computed and this is a strong assumption for this problem. Indeed we believe that grooming optimization issues should be taken into account during the routing stage.

The multi-layered ILP gives the optimal solution for a given routing (considering 2 layers at a time) in a hierarchically layered network and this can be used to test the efficiency of grooming the routed lightpaths by common destination.

Since the general grooming is hard, some more tractable subproblems have been studied restricting to special cases of the topology and/or the demands. Most of the research has been focusing on ring networks modeling SONET/SDH rings surveyed in the section 3.1. However some studies [65, 66] on IP/MPLS over optical networks trying to take into account the asymmetric nature of the traffic offered to the IP/MPLS layout.

3.2.3 Conclusion

From a theoretical point of view, the exact difficulty of the grooming problem is still unknown. Indeed, the problem is $\mathcal{NP}$-hard but no one knows if polynomial approximation algorithms exist or not. Moreover, efficiency of fast algorithms (e.g. like greedy selection of best payoff pipes) is unknown. Note that the problem difficulty depends highly on the pipe pricing: with a pipe cost proportional to its length the problem is trivial while with a constant pipe cost the problem is equivalent to minimizing the number of add-drop nodes and the problem becomes much harder.

4 Survivability

Network survivability (i.e. the ability to recover traffic affected by failures) has become a key issue in the design of ultra-high capacity networks. A lot of research has already been done on the design and analysis of survivable network architectures, as well as recovery protocols for the different transport technologies (see e.g. [196] for an excellent survey).

As the protection and restoration techniques today implemented and under analysis are mainly addressing a single technology/network layer, the study of new solutions taking into account the overall system is crucial (see [196, 197]) for overlay networks which have several layers. Indeed when survivability is planned independently for each layer, it often induces a performance drop because of a unorganized protection scheme requiring to much bandwidth. Sometimes it may even happen that the survivability mechanisms are unable to recover the traffic [142, 64, 70].

For example, consider the survivability of the IP/WDM networks which is essential to the foundation and success of the next generation Internet. Considerable research efforts have been dedicated to the study of survivability mechanisms in WDM [101, 102, 140, 144, 159, 160] and IP/GMPLS network respectively [44, 148, 154, 170]. But in order to provide a comprehensive and globally efficient survivable network service, an optimal integration between the survivability mechanisms at these two different layers is required. Indeed, the survivability mechanisms in WDM layer are faster, coarser- grained (per wavelength or fiber) and more scalable than those in IP/GMPLS layer, but they cannot handle faults occurring at IP/GMPLS layer, such as router fault and service degradation in IP layer. On the other hand, the survivability mechanisms at IP/GMPLS layer besides handling errors at this layer they offer finer-grained service to different traffics, but they are usually slower and less scalable than their counterparts in WDM layer. For example a single WDM link failure might result in failure of thousands of IP layer traffic. Also knowledge of WDM layer topology is needed to guarantee WDM layer diversity for backup path in IP layer [193]. Therefore, it is natural to integrate the survivability mechanisms in both IP/GMPLS and WDM layers.

Hence, for few years, the integration and coordination of multiple recovery schemes active in different network layers has been studied [205, 67, 187]. Classical survivability strategies of single layer network are still used in multi-layer networks. However, we need to precise the exact role of each layer, to define the interactions between the recovery mechanisms in the treatment of a failure and to manage the recovery resources available at each level.

Here we first present the single-layer survivability strategies which can be chosen for each layer in a multi-layer network. We then present the strategies for multi-layer survivability.

4.1 Survivability in single layer networks

4.1.1 Classical survivability schemes

There are two classical kinds of mechanism to recover traffic in case of a failure. One called *restoration* is a reactive mechanism. It reroutes dynamically the traffic each time a failure occurs in the network. The other one called *protection* is a proactive mechanism. In this case, each failure is anticipated and the source and destination nodes of each connection statically reserve backup paths during call setup.

Path protection/restoration In *path protection*, the source and destination nodes of each connection statically reserve backup paths on an end-to-end basis during call setup. In path restoration, the source and destination nodes of each connection that traverses a failed link dynamically discover a backup route on an end-to-end basis (such a backup path could be on a different wavelength channel) after the link failure.

Link protection/restoration In *link protection/restoration*, all the connections that traverse the failed link are rerouted around that link. The link switch-over is transparent to the source and destination nodes. In link protection, during call setup, backup paths and wavelength are reserved around each link of the primary path. In link restoration, the end-nodes of the failed link dynamically discover a route around the link, for each wavelength that traverses the link.

Dedicated and shared protection In *dedicated-path protection*, at the time of call setup for each primary path, a link-disjoint backup path and wavelength are reserved, and dedicated to that call. In *shared-path protection*, at the time of call setup for a primary path, a link-disjoint backup path and wavelength are also reserved. However, the backup wavelength reserved on the links of the backup path may be shared with other backup paths, which make this solution more cost effective than dedicated-path protection.

There are two ways to achieve dedicated-path protection. One, called *1+1 protection*, consists in sending twice the same message on two disjoint paths, the primary one and the backup one. At the destination node, the signal is normally received twice guaranteeing that it arrives once in case of a failure. In the other, called *dedicated 1:1 protection*, a backup path is also reserved but only activated in case of failure. Hence the signal always arrive only once at the destination node.

Shared-path protection is also called 1:1 protection. In these case, the backup path may share their resources. More generally, for more flexibility one used he called $M : N$ protection : for each request, M primary paths are protected by N backup paths, which can share resources with other backup paths (for the same request or not) that do not activate for the same failure.

Shared-link protection and dedicated-link protection work similarly as their path counterparts. However, dedicated-link protection is often impossible as it may not be possible to allocate a dedicated backup path around each link of the primary call, and on the same wavelength as the primary path [159].

4.1.2 Comparison of the different classical survivability schemes

In designing survivability options, there are many factors involved. The most important ones are: resource utilization, restoration/switching time, recovery ratio, control complexity. The ideal goal is to achieve maximum survivability with minimum recovery time, while maintaining maximum resource utilization. It is difficult to achieve all these goals at the same time and trade-offs between different solutions are needed. The characteristics of the different survivability schemes have been compared according to some of some of these factors [159, 160, 69, 122]. Some qualitative comparison results are shown in Table 2.

Generally, link-level schemes provide faster recovery while path-level mechanisms provide better resource (such as bandwidth) utilization and higher restoration ratio. The protection schemes offer shorter recovery time while the restoration options offer better resource utilization. Usually, the restoration time is hundreds of milliseconds (200 ms or so), while the protection switching time is less than a hundred milliseconds (50ms or so). Also it is usually less complex to control protection that to control restoration.

Survivability mechanisms	Resource utilization	Protection switching/ Restoration speed	Recovery ratio	Ease of control
Dedicated path protection	⋆⋆	⋆⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆⋆
Shared path protection	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆⋆	⋆⋆
Shared link protection	⋆	⋆⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆
Path restoration	⋆⋆⋆⋆	⋆	⋆⋆⋆	⋆
Link restoration	⋆⋆⋆⋆	⋆⋆	⋆⋆	⋆

Table 2: Comparison of survivability mechanism. (*the more star in a block, the better the corresponding mechanism.*)

In protection schemes (path/link level, dedicated/shared), there are spare resources reserved for each protected part while those resources are not used under normal conditions. So restoration usually has better resource utilization than protection. Shared protection means multiple protected parts share the same spare resource, while dedicated protection means each protected part has dedicated spare resource. So shared protection schemes usually have better resource utilization than dedicated resource utilization.

As for recovery time, protection usually takes shorter time to recover from failure than restoration does. This is because the protection path has been found before failure, while in restoration it is needed to dynamically search for the alternate path. Link restoration tries to find the alternate path locally while path restoration tries to find the alternate path globally, so link restoration usually takes less time to find the alternate path. Path protection usually also takes longer time than link protection does. Indeed, in path protection, once a node detects a failure, it has to send a message through to the end nodes so that they can activate the backup path while for link protection the node detecting the failure activates the backup path.

During network failure, it is possible that not all the affected traffic could be restored. We refer recovery ratio (efficiency) as the ratio of the recovered traffic to the total of affected traffic. In protection scheme, the affected traffic is usually guaranteed to be recovered from failure because there is dedicated spare network resource for it, while in restoration scheme there is no such guarantee. So, protection schemes usually have higher restoration ratio than restoration schemes.

In view of control complexity, it is usually easier to control failure-recovery operation in protection schemes because the protection path has already been fixed beforehand while in restoration schemes, the alternate path is found on the fly, which means more coordination of network and more control.

Since dedicated-path protection uses too much resources, shared-path protection is generally preferred. A variant of the shared-path protection is the *Demand-wise Shared Protection*. The bandwidth required by a connection is divided into several paths so that any failure may affect only a small percentage of the bandwidth [122]. This reduces resource utilization compared to shared-path protection.

Furthermore shared-path protection is generally preferred to shared-link protection since one better use less resource despite a longer switching time [123]. Therefore several variants of path protection have been introduced in order to reduce this time. In *Local to egress protection*[178], in case of a failure the primary path is used until the node preceding the failure and the backup path is computed between this node and the destination. The *protection by segment* [198] divides the primary paths into several sub-paths or segments which are protected independently.

4.1.3 Protection by cycles

A new protection strategy which is both a link protection and a path protection and then combines the advantages of the two has been introduced.

The idea is to cover the communication requests with subnetworks that are protected independently from each other. The subnetworks are chosen to be loops (cycles) in order to minimize the complexity of the routing problem with full survivability. The advantage is that a loop (cycle) is secured by its reverse loop. Given the failure of any single link, we can reroute the traffic going through the failed link via the other part of the cycle. (More precisely one can associate two wavelengths to each cycle of the covering: one for the normal traffic and another as a spare one.) This problem has been considered by several authors [39, 75, 76, 77, 100, 141]. Let the physical graph G be a symmetric digraph and let the request graph be represented by a logical graph I which is symmetric if the requests are symmetric. Furthermore if the routing of symmetric requests is done in a symmetric way (that is the case in backbone networks of phone companies), one can consider undirected graphs instead of symmetric digraphs for both physical and logical graphs. The survivability problem mentioned above consists of finding a cycle partition or covering of the edges of I with an associated routing over G. For the protection reason, or minimizing the damage causing by the failure of the vertices, we have an additional constraint which is defined as follows.

Definition 1.1. A routing is said to satisfy the Disjoint Routing constraint, or *DR constraint*, if the requests involved in a cycle of the covering are routed via vertex disjoint paths (equivalently, their routings form an elementary cycle in the physical graph G).

As an illustration, let G be C_4 and I be K_4 (See Figure 4). A first covering is given by the two C_4's $(1,2,3,4,1)$ and $(1,3,4,2,1)$ (See Figure 4.(c)), but there does not exist an edge disjoint routing for the cycle $(1,3,4,2,1)$. In counterpart, the covering given in Figure 4.(d) by the C_4 $(1,2,3,4,1)$ and the two C_3's $(1,2,4,1)$ and $(1,3,4,1)$, satisfy the edge disjoint routing property.

Note that if a covering of I by triangles C_3 $(= K_3)$ is wanted, the DRC is satisfied as soon as G is Hamiltonian or 3-connected. However 2-connectivity is not enough as shown by the example of Figure 5.(a) where it is impossible to satisfy DRC for the triangle ABC. Furthermore, a covering by C_k satisfies DRC if G is k-connected; indeed in a k-connected graph there is always a cycle containing k given vertices.

When G is the cycle C_n, where the vertices are labeled with integers modulo n, represented by the set $\{0,1,...,n-1\}$, a C_k satisfies DRC if and only if its vertices can be ordered cyclically modulo n, that is if the vertices can be written $(a_1,a_2,\dots,a_k)$ with $0 \leq a_1 \leq a_2 \leq \cdots \leq a_k \leq n-1$. As an example, in Figure 5.(b), the cycle $(0,2,3,6,0)$ satisfies DRC, but the cycle $(0,4,3,6,0)$ does

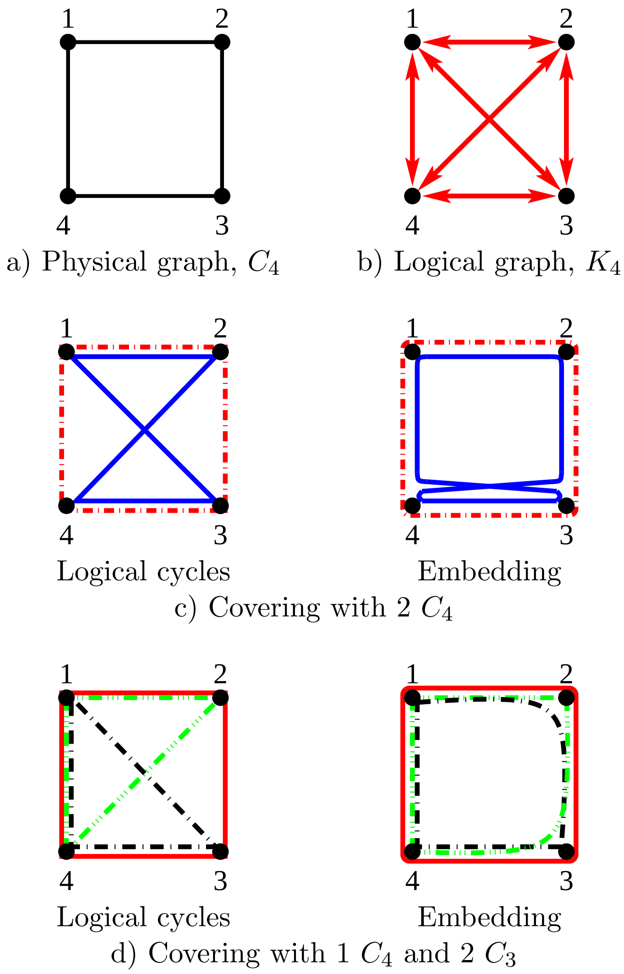
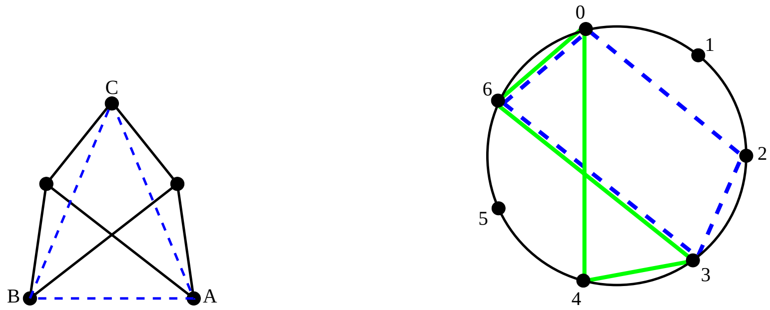


Figure 4: Cycle covering example.

not satisfy it.



a) 2-connectivity is not enough b) vertices must be cyclically ordered

Figure 5: Disjoint Routing Constraint

The aim is to minimize the cost of the network; that is a very complex function depending on the size of the ADMs put in each node, the number of wavelengths (associated to the subnetworks) in transit in each optical node and a cost of regeneration and amplification of the signal. In a first approximation, some authors reduce it to minimize the number of cycles of the covering (which is related to the problem of minimizing the number of wavelengths used and the cost of transmission); other minimize the sum of the number of vertices of the rings ; other insist on using very small cycles in the covering (short cycles are easier to manage and in case of failures, rerouting is easier). One can also want to minimize the total load (using or not shortest paths).

Exact results have been obtained only in some particular cases for example when the logical graph I is K_n, which corresponds to the instance of communication called total exchange or all-to-all, where each vertex wants to communicate with all the others simultaneously, and when the the physical graph G is C_n, a cycle of length n ([16, 26]) or a torus $T(n)$ of size n by n (([31]). In the case of $G = C_n$ case, the DR constraint implies that the paths associated with the routing of a request cycle form the C_n and they give a load 1 to each edge. So all the optimization criteria are reduced to minimizing the number of cycles in the partition denoted by $\rho(n)$.

Theorem 9 *When $n = 2p + 1$, $\rho(n) = \frac{n^2-1}{8} = \frac{p(p+1)}{2}$. Furthermore, a DRC-covering of K_{2p+1} consists of p C_3 and $\frac{p(p-1)}{2}$ C_4.*

Theorem 10 *When $n = 2p$, $p \geq 2$, $\rho(n) = \left\lceil \frac{n^2+4}{8} \right\rceil = \left\lceil \frac{p^2+1}{2} \right\rceil$. Furthermore, when $n = 4q$, $q \geq 2$, a DRC-covering of K_{4q} consists of 4 C_3 and $2q^2 - 3$ C_4, and when $n = 4q+2$, $q \geq 1$, a DRC-covering of K_{4q+2} consists of 2 C_3 and $2q^2 + 2q - 1$ C_4.*

Our problem is related to finding the minimum number of colors (wavelengths), denoted $w(G, I)$, required to color the edges of the logical graph I such that the paths associated to the requests with the same color are edge (arc) disjoint in the physical graph G . In the undirected case for $G = C_n$, the problem is similar as finding a DRC cycle covering of K_n ; indeed, we can associate to each cycle of a DRC-covering a color and conversely, we can build a cycle from the paths with the same color, as in C_n edge disjoint paths are also vertex disjoint. So our results give the values of $w(C_n, K_n)$ (see [27, 194]). But our results are stronger ; indeed the paths of [27, 194] with the same color are not vertex disjoint and furthermore the subnetworks induced by a color are not small cycles.

But for the torus, these two problems are different. Indeed, if we consider the paths associated with the requests having the same color, they are edge-disjoint, not vertex disjoint. Furthermore, the solutions obtained do not consist of the union of vertex disjoint cycles. Therefore, the previous results ([8, 27, 165]) on w can not be used here.

4.1.4 Protection for multiple failures

As suggested by the results of [145], several independent failures may occur at the same time. Therefore some survivability mechanisms for multiple failures have been proposed for optical level[47, 167, 48, 68, 110] or IP level [49].

The strategy of [49] consists in decomposing the network into several connected spanning subnetworks in a particular way. IP routes are computed in these networks so that several failures occurs in the same networks then the routes are given by the other networks.

At optical level, *protection by p-cycles* is often used [109, 166, 147, 128, 68, 110]. The networks is decomposed into cycles so that each link either belongs to a cycle or is a chord of a cycle. When a link fails, the affected wavelengths are switched on the part of the cycle which is still in use.

4.2 Survivability in multi-layer networks

To define a multi-layer recovery approach, the following question is raised: "For each failure, which layer networks are responsible for its recovery?"

4.2.1 Recovery interworking strategies

Recovery at the lowest layer A first recovery approach, denoted as *recovery at the lowest layer*, is to recover the affected network connections in the lowest possible layer. Hereby, the survivability is provided as close as possible to the origin layer of the failure. Because of the coarser switching granularity of lower layers, such an approach is generally simpler in the number of affected connections to be rerouted. In contrast to other recovery approaches, recovery at the lowest layer generally enables to restrict the recovery actions to nodes closer to the failure origin.

If a failure occurs only in one layer (e.g., cable cut), recovery at the lowest layer resolves it using a single recovery scheme. However, when "recoverable failure set" also contains failures affecting several layers at the same time (e.g., complete site breakdown affecting both SDH and ATM equipment), several schemes will have be activated (see [181].

Due to the coexistence of multiple schemes, some interworking functionality needs to be provided to correctly assign and coordinate the recovery responsibilities of each recovery scheme [181]. For instance, the end nodes of disrupted network connections at a client layer can generally not distinguish a client layer failure from a server layer failure. Indeed, in the event of a server layer failure, subsequent alarm messages will be passed through each layer after they are generated (see [186]). These may trigger the client layer recovery scheme. Because the network is planned to resolve server layer failures "at the lowest layer", this may create a situation for client layer resource competition. In order to activate the client recovery mechanism only in case of client layer failures, some interworking functionality needs to be provided (See [67]).

A second consequence is the presence of multiple spare capacity pools in the network. Indeed, every survivable network layer requires its own spare resources for the rerouting of affected connections. Due to the independent operation of different layers, a single-layer recovery scheme can not draw directly upon spare resources in other network layers. The spare capacity pool of a higher layer has to be supported through lower layer paths and thus imposes additional investment costs for all layers below (see [112]). If the network is designed in a negligent way, multi-layer survivability may thus require a serious amount of resources. However, a spare capacity concept, called common pool survivability [112, 183], has been devised that provides the means for an inter-layer spare capacity pool.

Recovery at the highest layer A second multi-layer recovery approach, denoted *recovery at the highest layer*, consists in recovering disrupted traffic in a layer closer to the origin of the traffic. A higher layer recovery scheme is (in principle) able to resolve failures occurring in all layers below. For a certain traffic, this approach ensures service resilience against different failures (at the same layer and in lower layers) with a single survivability scheme, i.e. a scheme residing in the *highest* layer. Providing resilience at the highest possible layer has the following advantages:

- A transport network often carries several service classes, each with a different reliability requirement. It is often easier to provide multiple reliability degrees when the survivability schemes reside in higher layers.

- Since a single recovery scheme then suffices to provide protection against failures occurring in every layer involved in the transport of the traffic, the implementation complexity of interworking between different schemes can be avoided. In this case, interworking merely comprises activating the responsible recovery scheme as fast as possible at the appropriate layer network.

- Because the granularity of the higher layers is finer, relatively less spare capacity can be needed (from a single-layer point of view) compared to lower layer recovery. Nevertheless, this does not imply that also from an overall cost point of view, highest layer recovery is cheaper than lowest layer recovery (see e.g. [113]).

On the other hand, the finer switching granularity of the higher layers may complicate the rerouting in event of lower layer failures, because many entities are then affected at the same time. For instance, a cable cut may involve a very complex failure scenario at a higher layer, since many paths have to be rerouted. This will probably slow down the recovery time. Secondly, when the server layer paths supporting the higher network layer are rather long, the recovery process may involve reconfiguration in network elements far away from the original failure cause. Most probably, special precautions will have to be taken to adapt the survivability scheme of the higher layer (to solve the lower layer failure scenarios). For example, with restoration at the ATM layer it is envisaged to assemble VPs sharing physical routes into VP groups as a way to reduce the recovery "efforts" in case of physical failures. In addition, the network design phase has to ensure that the spare and working resources of the higher layer are physically disjoint. This may lead to a higher capacity requirement, because the routing (and rerouting) constraints of higher layer paths are much more severe than in the lowest layer approach (see [113]).

Recovery at multiple layers A third approach, denoted *recovery at multiple layers*, could be to recover disrupted traffic not within a single layer network but distributed at multiple layer networks. This approach tries to combine the advantages of both previous recovery approaches.

In this case, one needs to use an *interworking strategy* (also called *escalation strategy* [143, 152]) consists of a set of rules describing when to start, stop and how to efficiently coordinate the activities of the different recovery schemes. Two options have been identified concerning the order of activation: starting two or more recovery schemes in parallel or starting them sequentially. The (independent) parallel strategy is fast and requires no communication or coordination between the schemes. However, since the working and spare resources are not disjoint, recovery mismatch between the schemes may occur (e.g., two layers recover the same disrupted traffic) and lead inefficient use of the resources or even worse to unstable routing. Hence a sequential strategy should be preferred. It determines the order of activation of the schemes and provides coordination between the schemes (ensuring that schemes are activated at an appropriate moment). This prevent blocking problems between recovery mechanisms as only one mechanism is active at a time. On the other hand, it may be slower and requires more coordination, and hence messaging, to stop mechanisms and trigger others. This coordination may be implemented in a distributed or centralized (e.g., via TMN [124]) way.

There are two different sequential strategies:

- *bottom-up:* It starts at the layer network which is closest to the failure assuring a very quick activation of the recovery mechanism; when the recovery in a layer fails the upper layer starts its recovery mechanism.

- *top-down:* It starts at the highest layer network; when the recovery in a layer fails, the lower layer starts its recovery mechanism. With this strategy, it is easier to offer a differentiated protection according to the type of traffic. However, since lower layers are not always able to detect if the upper one fails to recover the traffic, an extra interlayer functionality has to be added for this purpose.

A layer decide if to start its mechanism either upon the expiration of a time out or if its receives a message directly from the layer which fails or by intervention of a unique control device, if it exists.

The use of such a device seems very promising [177]. In particular for IP over WDM networks, a mechanism based on a hold-off timer has been considered whereby the client layer recovery mechanism is delayed for a certain period before it is invoked, giving the optical layer sufficient time to complete its recovery [102]. These works do not address algorithmic issues such as route selection and improving sharing efficiency. In [57], static traffic demands with the objective of capacity planning is considered. A multi-layer protection scheme is discussed where optical level protection and IP level protection are provided against link failure and router failure, respectively. In [208], dynamic traffic is studied with the objective to optimize the blocking performance. A multi-layer protection scheme is presented that provides protection either at the optical level or at the IP level to connection requests based on their restoration time requirements.

4.2.2 Shared risk resource group

Modern day networks are multi-layer networks where traffic flows are routed on meshed topologies whose links are indeed end-to-end paths on a high bandwidth infrastructure. IP/WDM, MPLS or MP?S networks, as well as P2P or GRID computing overlay structures are example of such a hierarchy. In these settings, customers expect an uninterrupted service, even in the event of failures such as power outages, equipment failures, natural disasters and cable cuts. Many layer wide protection schemes have been proposed in the literature, as for instance for the WDM optical networks [185]. One method to provide survivability is through path protection schemes, in which a disjoint backup path is pre-computed for every working path. Such protection schemes provide 100% reliability against any single link failure in the network layer that is considered. However, in multi-layer network settings, a single failure event in the underlying layer may result in the failure of several links in the virtual network. For example, in a MPLS/WDM network, several apparently independent label switched paths (LSP) may be routed on the same fiber. Even though these LSPs represent disjoint links of the MPLS virtual topology, the cut of an optical fiber can cause all the LSPs to fail. For example, in Figure 6 the failure of the link FG induces multiple failures on the set of links of the virtual topology. The concept of *Shared Risk Link Group*, generalized to *Shared Risk Resource Group* [46, 155, 168], modeled correlation between resources. A SRRG is a set of resources breaking down simultaneously when a given failure occurs.

When the risk of failure concerns nodes instead of links the group is said to be a Shared Risk Node Group, and more generally the notion of Shared Risk Resource Group (SRRG) has been defined to encompass any kind of resources sharing a common risk of unavailability. Recently in [203, 59] the SRRG notion has been formalized through colored graphs: Each SRRG is associated to a color and each link of the network is assigned colors according to which SRRG it belongs. Shared Risk Resource Groups are naturally modeled by associating to each group (or risk) a *color*, and to each edge (or resource) the colors representing the risks affecting it [80, 203]. According to the general case of Shared Risk Resource Groups, an edge may belong to several colors, modeling the fact that a resource may face different and independent risks. In [80], a *colored graph* is thus defined as an undirected graph associated to a collection of subsets of edges, the colors, covering the edge set. However, depending on the context, this property may be interpreted in several ways

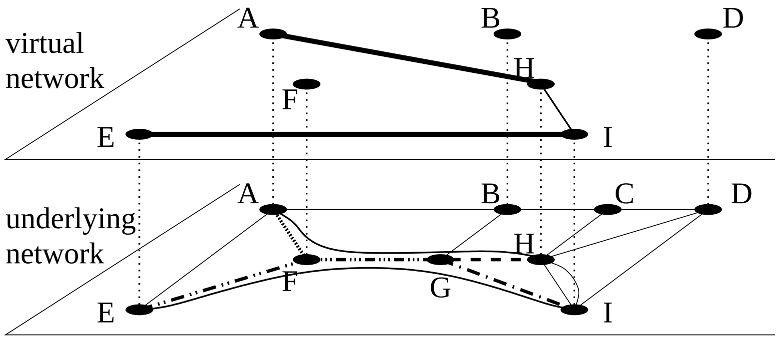


Figure 6: A Shared Risk Link Group in a multi-layer networks : AH and EI links share the same risk of failure, FG.

whether *all the colors associated to an edge* or *only one color among the set of associated colors* is considered to be used when this edge belongs to a path or a cut or any kind of structure. That is why another definition for colored graphs is presented in [203]. In case a single color of an edge is used when this edge is crossed by a path, an edge belonging to X colors can easily be replaced by X monochromatic parallel edges, and in case all the colors are used when the edge is crossed, the edge is replaced by a chain of X monochromatic edges. Therefore, we may assume that edges are monochromatic, in other words colors not only cover the edge set but also partition it. This definition is actually encompassed in the definition of [80], consequently all the complexity and inapproximability results proved with the monochromatic assumption extend to the more general settings of [80].

In this context, optimization problems in colored graphs have been studied to answer survivability challenges in the SRRG context [36, 60, 188, 189, 59]. The *span* of a color, that is the number of connected components of the subgraph induced by a the edges of this color, appears to be a very important parameter as the complexity and approximability properties depends on the maximum span of the graph.

The fundamental problem called the color disjoint paths problem as also been studied. It consists in finding two paths between a pair of nodes in the virtual network such that no single failure in the underlying layer may cause both paths to fail simultaneously. This problem is much more difficult than the traditional disjoint path problem of graph theory [59, 36] and recent studies have proven its NP-completeness [117, 172]. In [59], it was shown that it is NP-hard to approximate the maximum number of disjoint paths in the SRRG settings: that is no polynomial time algorithm can provide solutions which are guaranteed to be lower than the optimal number of paths multiplied by some factor depending on the size of the graph. This fosters the relevance of the different heuristic approaches studied for this problem [203, 117].

One of the common problems that arise in restoration path computation is the existence of a trap topology [199]: if a service path is routed over a trap topology, then there may not exist a diverse restoration path, even though two diverse paths exist in the network. A challenge that

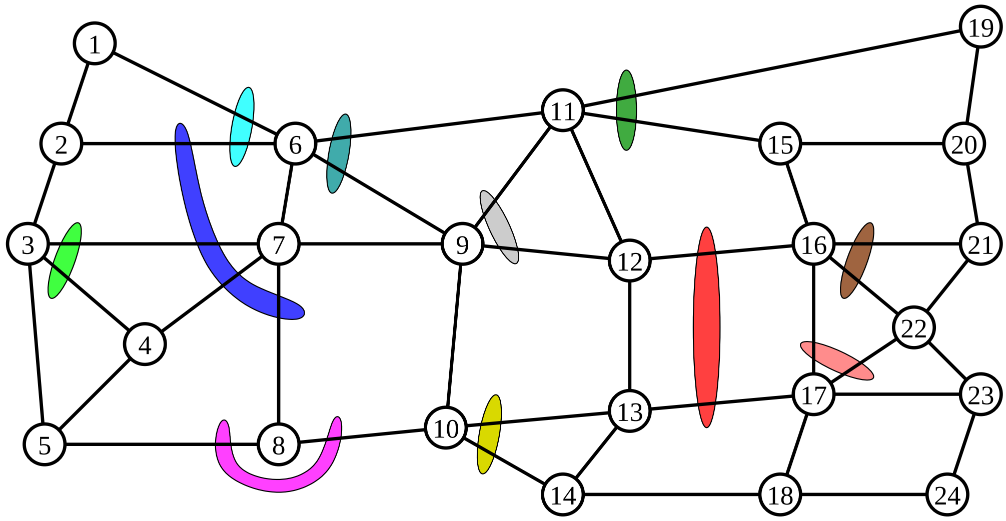


Figure 7: Shen, Yang, Ramamurthy, IEEE/ACM ToN, *to appear*

SRRG protection schemes have to face consists in the impossibility to provide 100% reliability against certain multiple link failure events, depending on the SRRG configuration [203]. In these cases, an objective may be to find one or more paths for each connection, such that the reliability for each connection is maximized: it is the minimum overlapping paths problem. It consists in finding a set of paths sharing a minimum number of SRRG, or colors. This problem as well as the minimum cost SRRG diverse routing problem and the routing problem under both link capacity and path length constraints have also been shown to be NP-complete [117].

The network of Figure 7 has frequently been used to benchmark heuristic algorithms [172, 185]. However, a careful analysis of the inputs (network and SRLGs) allow us to prove that the problem can be solved polynomialy in this case. Therefore, we provide in [61] an efficient MILP formulation for the minimum color path problem that allow us to identify such polynomial cases.

References

[1] A. Aggarwal, A. Bar-Noy, D. Coppersmith, R. Ramaswami, B. Schieber, and M. Sudan. Efficient routing in optical networks. *Journal of the ACM*, 46(6):973-1001, November 1996.

[2] F. Alvelos and J.M. Valério de Carvalho. comparing branch-and-price algorithms for the unsplittable multicommodity flow problem. In Walid Ben-Ameur and Alain Petrowski, editors, *International Network Optimization Conference*, pages 7–12. Institut National des Télécommunications, October 2003.

[3] Y. Asano. Experimental evaluation of approximation algorithms for the minimum cost multiple-source unsplittable flow problem. In *ICALP workshop*, pages 111–121, 2000.

[4] Y. Azar and O. Regev. Strongly polynomial algorithms for the unsplittable flow problem. In *Proceedings of the 8th International IPCO Conference on Integer Programming and Combinatorial Optimization*, pages 15–29. Springer-Verlag, 2001.

[5] 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.

[6] S. Baroni, P. Bayvel and R. J. Gibbens. Analysis and design of resilient multifiber wavelength-routed optical transport networks. *Journal of lightwave technology*, 17(5):743-758, 1999.

[7] P. Batchelor et al. Ultra high capacity optical transmission networks : Final report of action COST 239. Technical Report ISBN 953-184-013-X, Faculty of Electrical Engineering and Computing, HR, Zagreb, 1999.

[8] B. Beauquier, All-to-all communication in some wavelength-routed all optical networks, *Networks* 33 (1999), 179-187.

[9] 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 IEEE Workshop on Optics and Computer Science, Geneva, Switzerland, Apr 1997.

[10] B. Beauquier, P. Hell, and S. Perennes. Optimal wavelength-routed multicasting. *Discrete Applied Mathematics*, 84:15–20, 1998.

[11] L. Becchetti, P. Bertolazzi, C. Gaibisso, and G. Gambosi. On the design of efficient ATM routing schemes. 1997.

[12] F. E. Bennett, Y. Chang, G. Ge, and M. Greig, *Existence of* $(v, \{5, w^*\}, 1)$*-PBDs*, Discrete Math., 279 (2004), pp. 61–105.

[13] C. Bentz, M.-C. Costa, L. Létocart, and F. Roupin. A bibliography on multicut and integer multiflow problems. Technical Report 654, CeDRIC Centre de Recherche en Informatique du Cnam, http://cedric.cnam.fr/AfficheMembre.php?id=30, 2004.

[14] J.-C. Bermond, L. Braud, and D. Coudert. Traffic grooming on the path. In *SIROCCO*, vol. 3499 of LNCS, 2005, pp. 34–48.

[15] J.-C. Bermond, L. Braud, and D. Coudert. Traffic grooming on the path. In *Theretical Computer Science*, To appear.

[16] J-C. Bermond, L. Chacon, D. Coudert, and F. Tillerot, A note on cycle covering, *ACM Symposium on Parallel Algorithms and Architectures – SPAA*, Crete, July 2001, pp. 310-311.

[17] J-C. Bermond, L. Chacon, D. Coudert, and F. Tillerot. Cycle covering. In *International Colloquium on Structural Information and Communication Complexity – SIROCCO*, pages 21–34, 27-29 June 2001.

[18] J.-C. Bermond and S. Ceroi, *Minimizing SONET ADMs in unidirectional WDM ring with grooming ratio 3*, Networks, 41 (2003).

[19] J.-C. Bermond, C. J. Colbourn, A. C. H. Ling, and M.-L. Yu, *Grooming in unidirectional rings : $K_4 - e$ designs*, Discrete Mathematics, 284 (2004), pp. 67–72.

[20] J-C. Bermond, C.J. Colbourn, D. Coudert, G. Ge, A. Ling, and X. Munoz, *Traffic grooming in unidirectional WDM rings with grooming ratio $C = 6$*, SIAM Journal on Discrete Mathematics (to appear)

[21] 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.

[22] J-C. Bermond and D. Coudert. *The CRC Handbook of Combinatorial Designs (2nd edition)*, chapter VI.27, Grooming. CRC Press, c.j. colbourn and j.h. dinitz edition, to appear.

[23] J.-C. Bermond and D. Coudert, *Traffic grooming in unidirectional WDM ring networks using design theory*, in IEEE ICC, Anchorage, Alaska, May 2003.

[24] J.-C. Bermond, D. Coudert, and X. Muñoz, *Traffic grooming in unidirectional WDM ring networks: the all-to-all unitary case*, in The 7th IFIP Working Conference on Optical Network Design & Modelling – ONDM'03, Feb. 2003, pp. 1135–1153.

[25] J-C. Bermond, D. Coudert, X. Muñoz, and I. Sau. Traffic grooming in bidirectional WDM ring networks. In *IEEE/COST 293 annual conference on GRAphs and ALgorithms in communication networks*, volume 3, pages 19–22, June 2006.

[26] J.-C. Bermond, D. Coudert, and M.-L. Yu, On DRC-covering of K_n by cycles, *Journal of Combinatorial Designs* 11 (2003), 100-112.

[27] J-C. Bermond, L. Gargano, S. Perennes, A. Rescigno, and U. Vaccaro. Efficient collective communication in optical networks. *Theoretical Computer Science*, (233):165–189, 2000.

[28] J-C. Bermond, C. Huang, A. Rosa, and D. Sotteau. Decomposition of complete graphs into isomorphic subgraphs with five vertices. *Ars Combinatoria*, pages 211–254, 1980.

[29] J.-C. Bermond, N. Marlin, D. Peleg, and S. Prennes. Directed virtual path layout in ATM networks. *Theoretical Computer Science*, 291:3–28, 2003.

[30] J.C. Bermond and J. Schönheim, G-decomposition of K_n, where G has four vertices or less, *Discrete Math.* 19 (1977), 113-120.

[31] J.-C. Bermond, and M.-L. Yu, Vertex disjoint routings of cycles over tori, *Networks* to appear.

[32] R. Berry and E. H. Modiano. Grooming dynamic traffic in undirectionnal SONET ring networks. in *Proc. OFC*, San-Degio, USA, February 1999.

[33] J.-C. Bermond, O. DeRivoyre, S. Pérennes, and M. Syska. Groupage par tubes. In *Conference ALGOTEL*, May 2003, pp. 169–174.

[34] J.-C. Bermond and D. Sotteau, *Graph decompositions and G-designs*, in 5th British Combinatorial conference, Congressus Numerantium 15 Utilitas Math. Pub., Aberdeen, 1975, pp. 53–72.

[35] T. Beth, D. Jungnickel, and H. Lenz, *Design Theory*, Cambridge University Press, 1993. First published in 1985 by Bibliographisches Institut, Zurich. ISBN 0 521 33334 2.

[36] R. Bhandari. *Survivable Networks: Algorithms for Diverse Routing.* Kluwer Academic, 1999.

[37] R. Bose, S. Shrikhande, and E. Parker, *Further results on the construction of mutually orthogonal Latin squares and the falsity of Eulers conjecture*, Canadian J. Math., 12 (1960), pp. 189–203.

[38] M. Bouklit, D. Coudert, J.-F. Lalande, C. Paul, and H. Rivano. Approximate multicommodity flow for wdm networks design. In *Sirocco 10*, Umea, Sweden, june 2003.

[39] G. Calinescu, O. Frieder, and P-J. Wan. Minimizing electronic line terminals for automatic ring protection in general WDM optical networks. *IEEE Journal on Selected Areas in Communications*, 20(1):183–189, January 2002.

[40] I. Caragianis, A. Ferreira, C. Kaklamanis, S. Pérennes, and H. Rivano. Fractional path coloring on bounded degree trees . In F. Orejas, P. G. Spirakis, and J. van Leeuwen, editors, *Proceedings of the 28th ICALP*, volume 2076 of *Lecture Notes in Computer Science*, pages 732–743, Crete, Greece, July 2001. Springer-Verlag.

[41] I. Caragiannis, A. Ferreira, C. Kaklamanis, S. Pérennes, P. Persiano, and H. Rivano. Approximate constrained bipartite edge coloring. *Discrete Applied Mathematics*, 143(1-3):54–61, September 2004.

[42] I. Caragiannis, C. Kaklamanis, and P. Persiano. Wavelength routing in all-optical tree networks: A survey. *Computers and Artificial Intelligence*, 2001.

[43] F. Chauvet, P. Chrétienne, P. Mahey and B. Vatinlen. Minimisation du nombre de chemins décomposant un flot. In *Algotel'04*, INRIA editor, pages 39–43, Batz-sur-Mer, France, May 2004.

[44] T. M. Chen, T. H. Oh. Reliable services in MPLS. *IEEE Communications Magazine*, December 1999, pp.58-62

[45] A. L. Chiu and E. H. Modiano. Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks. *Journal of Lightwave Technology*, 18(1):2–12, January 2000.

[46] A. L. Chiu, J. Strand and R. Tkach. Issues for routing in the optical layer. it IEEE Communications Magazine, 39(2):81–87, 2001.

[47] H. Choi, S. Subramaniam and H. Choi. On double-link failure recovery in WDM optical networks. In *IEEE Infocom*, pages 806–816, New York, USA, June 2002.

[48] H. Choi, S. Subramaniam and H. Choi. Loopback recovery for double-link failures in optical mesh networks. In *IEEE Infocom*, pages 806–816, New York, USA, June 2002.

[49] T. Cicic, A. F. Hansen, S. Gjessing and O. Lysne. Applicability of resilient routing layers for k-fault tolerant network recovery. In *Proceedings of International Conference on Networking*, pages 173–183, Reunion, France, April 2005.

[50] T. Cinker, D. Marx, C. P. Larsen, and D. Fogaras. Heuristic algorithms for joint configuration of the optical and electrical layer in multi-hop wavelength routing networks. In *IEEE INFOCOM 2000*, volume 2, pages 1000–1009, Tel Aviv, Israel, March 2000.

[51] C. J. Colbourn and J. H. Dinitz, eds., *The CRC Handbook of Combinatorial Designs*, CRC Press, 1996.

[52] C.J. Colbourn and A.C.H. Ling, Graph decompositions with application to wavelength add-drop multiplexing for minimizing SONET ADMs, *Discrete Math.* 261 (2003), 141-156.

[53] C. J. Colbourn and A. C. H. Ling, *Wavelength add-drop multiplexing and minimizing SONET ADMs*, Discrete Mathematics, 261 (2003), pp. 141–156.

[54] C.J. Colbourn, A.C.H. Ling, and G. Quattrocchi, Minimum embedding of P_3-designs into $(K_4 - e)$-designs, *J. Combinatorial Designs*, to appear.

[55] C.J. Colbourn, G. Quattrocchi, and V. R. Syrotiuk, Grooming for Two-Period Optical Networks, to appear.

[56] C. J. Colbourn and P.-J. Wan, *Minimizing drop cost for SONET/WDM networks with $\frac{1}{8}$ wavelength requirements*, Networks, 37 (2001), pp. 107–116.

[57] D. Colle et al. Data-centric optical networks and their survivability. *IEEE Journal on Selected Areas in Communications* 20(1):6–20, 2002.

[58] M.-C. Costa, L. Létocart, and F. Roupin. Minimal multicut and maximal integer multiflow : a survey. *EJOR Eur. J. on Oper. Res. To appear*, 2003.

[59] D. Coudert, P. Datta, S. Pérennes, H. Rivano, and M-E. Voge. Complexity and approximability issues of Shared Risk Resource Group. *Parallel Processing Letter*, to appear.

[60] D. Coudert, P. Datta, H. Rivano, and M-E. Voge. Minimum color problems and shared risk resource group in multilayer networks. Technical report, I3S Research Report I3S/RR-2005-37-FR, 2005.

[61] D. Coudert, S. Perennes, H. Rivano, and M-E. Voge. Shared risk resource groups and survivability in multilayer networks. In *IEEE-LEOS ICTON / COST 293 GRAAL*, volume 3, pages 235–238, June 2006.

[62] D. Coudert and H. Rivano. Lightpath assignment for multifibers WDM optical networks with wavelength translators. In *IEEE Globecom'02*, Taiwan, November 2002. OPNT-01-5.

[63] D. Coudert, H. Rivano, and X. Roche. A combinatorial approximation algorithm for the multicommodity flow problem. In *K. Jansen and R. Solis-Oba, editors, WAOA 03*, number 2909 of *Lecture Notes in Computer Science*, Budapest, Hungary, pages 256–259, September 2003. Springer-Verlag.

[64] O. Crochat and J.-Y. Le Boudec, Protection interoperability for WDM optical networks. *IEEE/ACM Transactions on Networking*, 8(3): 384–395, 2000.

[65] S. De Maesschalck et al. How the asymetric nature of IP traffic influences the cost of the underlying optical layer. *Fiber and Integrated Optics* 22, February 2003.

[66] S. De Maesschalck et al. Multi-layer traffic grooming in networks with an IP/MPLS layer on top of a meshed Optical Layer. *Globecom*, 2006

[67] P. Demeester et al. Resilience in multilayer networks. *IEEE Communications Magazine*, 37:70–76, August 99.

[68] J. Doucette, P. Giese, W. D. Grover. Physical-layer p-cycles adapted for router-level node protection: a multilayer design and operation strategy. *IEEE Journal on Selected Areas in Communications*, in review, April 2006.

[69] R. Doverspike and B. Wilson. Comparison of capacity efficiency of DCS network restoration routing techniques. *J. of Network and System Management*, 2(2):95–123, 1994.

[70] R. Doverspike and J. Yates. Challenges for MPLS in optical network restoration. *IEEE Communications Magazine*, 39 (2):89–96, February 2001.

[71] R. Dutta and G. N. Rouskas. , *On optimal traffic grooming in WDM rings*, IEEE Journal of Selected Areas in Communications, 20 (2002), pp. 1–12.

[72] R. Dutta and G. N. Rouskas. Traffic grooming in WDM networks: Past and future. *IEEE Network*, 16(6):46–56, November/December 2002.

[73] R. Dutta and N. Rouskas. A survey of virtual topology design algorithms for wavelength routed optical networks. *Optical Networks Magazine*, 1(1):73–89, January 2000.

[74] T. Eilam, M. Flammini, and S. Zaks. A complete characterization of the path layout construction problem for ATM networks with given hop count and load. In *24th International Colloquium on Automata, Languages and Programming (ICALP)*, volume 1256 of *Lecture Notes in Computer Science*, pages 527–537. Springer-Verlag, 1997.

[75] T. Eilam, S. Moran, and S. Zaks. Approximation algorithms for survivable optical networks. In *The 14th international Symposium on Distributed Computing (DISC)*, pages 104–118, 2000.

[76] 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.

[77] G. Ellinas, A. Hailemariam, and T. Stern. Protection cycles in mesh WDM networks. *IEEE Journal on Selected Areas in Communications*, 18(10):1924–1937, 2000.

[78] T. Erlebach and A. Hall. Np-hardness of broadcast scheduling and inapproximability of single-source unsplittable min-cost flow. In *SODA '02: Proceedings of the thirteenth annual ACM-SIAM symposium on Discrete algorithms*, pages 194–202, Philadelphia, PA, USA, 2002. Society for Industrial and Applied Mathematics.

[79] 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.

[80] A. Faragó. A graph theoretic model for complex network failure scenarios. In *INFORMS*, 2006.

[81] A. Ferreira, S. Pérennes, A. W. Richa, H. Rivano, and N. Stier. Models, Complexity and Algorithms for the Design of Multi-fiber WDM Networks. *Telecommunication Systems*, 24(2):123–138, Oct 2003.

[82] M. Feighlstein and S. Zaks. Duality in chain ATM virtual path layouts. In *4th International Colloquium on Structural Information and Communication Complexity (SIROCCO)*, Monte Verita, Ascona, Switzerland, July 1997.

[83] M. Flammini, L. Moscardelli, M. Shalom, and S. Zaks. Approximating the traffic grooming problem. In *ISAAC*, vol. 3827 of LNCS, 2005, pp. 915–924.

[84] M. Flammini, G. Monaco, L. Moscardelli, M. Shalom, and S. Zaks. Approximating the traffic grooming problem in tree and star networks. In *32nd International Workshop on Graph-Theoretic Concepts in Computer Science (WG), Bergen, Norway*, June 2006.

[85] M. Flammini, M. Shalom, and S. Zaks. On minimizing the number of adms - tight bounds for an algorithm without preprocessing. In *3rd Workshop on Combinatorial and Algorithmic Aspects of Networking (CAAN), Chester, United Kingdom*, July 2006.

[86] L. Fleischer. Approximating fractional multicommodity flows independent of the number of commodities. *SIAM J. Discrete Math.*, 13(4):505–520, 2000.

[87] L. Ford and D. Fulkerson *Flows in Networks.* Princeton University Press, 1962.

[88] J. Galtier, A. Laugier and P. Pons. Algorithms to evaluate the reliability of a network, In *The 5th International Workshop on Design of Reliable Communication Networks*, pages 93–100, 2005.

[89] M. R. Garey and D. S. Johnson. *Computers and Intractability: a Guide to the Theory of Np-Completeness.* W.H. Freeman, 1979.

[90] N. Garg and J. Konemann. Faster and simpler algorithms for multicommodity flow and other fractional packing problems. In *IEEE Symposium on Foundations of Computer Science*, pages 300–309, 1998.

[GHP01] L. Gargano, P. Hell, and S. Perennes. Colouring all directed paths in a symmetric tree with an application to optical networks. *Journal of Graph Theory*, 38(4):183–196, 2001.

[91] G. Ge and A. C. H. Ling, *Group divisible designs with block size four and group type $g^u m^1$ for small g*, Discrete Mathematics, 285 (2004), pp. 97–120.

[92] ——, *A survey on resolvable group divisible designs with block size four*, Discrete Math., 279 (2004), pp. 225–245.

[93] ——, *Asymptotic results on the existence of 4-RGDDs and uniform 5-GDDs*, Journal of Combinatorial Designs, (to appear).

[94] G. Ge and R. S. Rees, *On group-divisible designs with block size four and group-type $g^u m^1$*, Designs, Codes Cryptogr., 27 (2002), pp. 5–24.

[95] ——, *On group-divisible designs with block size four and group-type $6^u m^1$*, Discrete Math., 279 (2004), pp. 247–265.

[96] G. Ge, R. S. Rees, and L. Zhu, *Group-divisible designs with block size four and group-type $g^u m^1$ with m as large or as small as possible*, J. Comb. Theory Ser. A, 98 (2002), pp. 357–376.

[97] G. Ge and R. Wei, *HGDDs with block size four*, Discrete Math., 279 (2004), pp. 267–276.

[98] J. Geffard. A solving method for singly routed traffic in telecommunication networks. *Annales des Télécommunications*, 56(3-4):140–149, 2001.

[99] O. Gerstel, I. Cidon, and S. Zaks. The layout of virtual paths in ATM networks. *IEEE/ACM Transactions on Networking*, 4(6):873–884, 1996.

[100] O. Gerstel, P. Lin, and G. Sasaki, *Wavelength assignment in a WDM ring to minimize cost of embedded SONET rings*, in IEEE Infocom, San Francisco, California, 1998, pp. 94–101.

[101] O. Gerstel and R. Ramaswami. Optical layer survivability a service perspective. *IEEE Communications agazine*, March 2000, pp.104–113.

[102] O. Gerstel and R. Ramaswami. Optical layer survivability an implementation perspective. *IEEE Journal of Selected Areas in Communications*, 18, (10):1885–1889, October 2000.

[103] O. Gerstel, R. Ramaswami, and G.H. Sasaki. Cost-effective traffic grooming in WDM rings. *IEEE/ACM Transactions on Networking*, 8(5):618–630, October 2000.

[104] O. Gerstel, R. Ramaswami, and W. Wang. Making use of a two-stage multiplexing scheme in a WDM network. In *OFC*, 2000.

[105] O. Gerstel, A. Wool, and S. Zaks. Optimal layouts on a chain ATM network. *Lecture Notes in Computer Science*, 979:508–??, 1995.

[106] O. Gerstel and S. Zaks. The virtual path layout problem in fast networks. In *Symposium on Principles of Distributed Computing (PODC '94)*, pages 235–243, New York, USA, August 1994. ACM Press.

[107] M. Gionfriddo, C.C. Lindner, and C.A. Rodger, 2-colouring $K_4 - e$ designs, *Australas. J. Combin.* 3 (1991), 211-229.

[108] O. Goldschmidt, D. Hochbaum, A. Levin, and E. Olinick, *The SONET edge-partition problem*, Networks, 41 (2003), pp. 13–23.

[109] W. Grover and D. Stamatelakis. Cycle-oriented distributed preconfiguration : ring-like speed with mesh-like capacity for self-planning network restoration. In *IEEE ICC*, volume 1, pages 537–543, 1998.

[110] W. D. Grover et al. *Handbook of Optimization in Telecommunications*, chapter Design of survivable networks based on p-cycles. Springer, 2006.

[111] J. Gruber and R. Ramaswami. Moving toward all-optical networks. *Lightwave*, December 2000.

[112] M. Gryseels et al. Common pool survivability in ATM on SDH ring networks, In *DRCN98 Workshop*, Brugge, Belgium, 1998.

[113] M. Gryseels et al. A cost evaluation of service protection strategies in ATM on SDH transport networks. In *DRCN98 Workshop*, Brugge, Belgium, 1998.

[114] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki. Hierarchical optical path cross-connect systems for large scale WDM networks. In *OFC*, pages 356–358, 1999.

[115] D. S. Hochbaum, editor. *Approximation algorithms for NP-hard problems.* PWS Publishing Company, 1997.

[116] D.G. Hoffman, C.C. Lindner, M.J. Sharry, and A.P. Street, Maximum packings of K_n with copies of $K_4 - e$, *Aequationes Math.* 52 (1996), 284-301.

[117] J.Q. Hu. Diverse routing in mesh optical networks. *IEEE/ACM Transaction on Communications*, 51(3):489-494, 2003.

[118] J.Q. Hu., *Traffic grooming in WDM ring networks: A linear programming solution*, OSA Journal of Optical Networks, 1 (2002), pp. 397–408.

[119] J.Q. Hu. Optimal traffic grooming for wavelength-division-multiplexing rings with all-to-all uniform traffic. *OSA Journal of Optical Networks*, 1(1):32–42, 2002.

[120] Shu Huang, Rudra Dutta, George N. Rouskas Traffic Grooming in Path, Star, and Tree Networks: Complexity, Bounds, and Algorithms *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 4, pp. 66-82, April 2006

[121] G. Huiban, S. Pérennes, and M. Syska. Traffic grooming in WDM networks with multi-layer switches. In *IEEE ICC*, New-York, April 2002.

[122] R. Hülsermann et al. Availability and cost based evaluation of demand-wise shared protection. In *7th ITG-Workshop on Photonic Networks*, pages 161–168, Leipzig, Germany, 2006.

[123] R. R. Iraschko, M. H. MacGregor and W. D. Grover. Optimal capacity placement for path restorationin STM or ATM mesh-survivable networks. *IEEE/ACM Transactions on Networking*, 6(3):325–326, June 1998.

[124] A. Jajszczyk, C. Brianza and D. Janukowicz. TMN-based management of multi-layer communication networks. In *DRCN98 Workshop*, Brugge, Belgium,

[125] K. Jansen and H. Zhang. Approximation algorithms for general packing problems with modified logarithmic potential function. In *TCS'02*, pages 255–266, 2002.

[126] J. M. Kleinberg. Single-source unsplittable flow. *Proceedings of the 37th Annual IEEE Symposium on Foundations of Computer Science*, pages 68–77, 1996.

[127] J. Kleinberg and A. Kumar. Wavelength conversion in optical networks. In *Proceedings of SODA'99*, Baltimore,MD, USA, January 1999.

[128] A. Kodian, A Sack and W. D. Grover. p-cycle network design with hop limits and circumference limits. In *First International COnference on Broadband Networks (BROADNETS'04)*, pages 244-253, 2004.

[129] S. G. Kolliopoulos and C. Stein. Approximating disjoint-path problems using greedy algorithms and packing integer programs. In *Proceedings of the 6th International IPCO Conference on Integer Programming and Combinatorial Optimization*, pages 153–168. Springer-Verlag, 1998.

[130] S. G. Kolliopoulos and C. Stein. Approximation algorithms for single-source unsplittable flow. *SIAM Journal on Computing*, 31(3):919–946, 2002.

[131] P. Kolman and C. Scheideler. Improved bounds for the unsplittable flow problem. In *Proceedings of the thirteenth annual ACM-SIAM symposium on Discrete algorithms*, pages 184–193. Society for Industrial and Applied Mathematics, 2002.

[132] Kranakis, Krizanc, and Pelc. Hop-congestion trade-offs for high-speed networks. *IJFCS: International Journal of Foundations of Computer Science*, 8, 1997.

[133] D. L. Kreher and D. R. Stinson, *Small group divisible designs with block size 4*, Journal of Statistical Planning and Inference, 58 (1997), pp. 111–118.

[134] J.-F. Lalande. Conception de réseaux de télécommunications : optimisation et expérimentations. Thèse de l'Université de Nice-Sophia Antipolis, Décembre 2004.

[135] E. R. Lamken and R. M. Wilson, *Decompositions of edge-colored complete graphs*, J. Combin. Theory Ser. A, 89 (2000), pp. 149–200.

[136] A. Lardiés and G. Ester. Optimal network design of ultra-long-haul transmission networks. Alcatel Telecommunications Review, 2^{nd} Quarter 2001.

[137] A. Lardies, R. Gupta and R. Patterson. Traffic grooming in a multi-layer network. *Opt. Netw. Mag.*, 2:91-99, May/June 2001.

[138] M. Lee, J. Yu, Y. Kim, C-H. Kang, and J. Park. Design of hierarchical crossconnect WDM networks employing a two-stage multiplexing scheme of waveband and wavelength. *IEEE Journal on Selected Areas in Communications*, 20(1):166–171, January 2002.

[139] T. Leighton, F. Makedon, S. Plotkin, C. Stein, E. Tardos, and S. Tragoudas. Fast approximation algorithms for multicommodity flow problems. *J. Comput. Syst. Sci.*, 50(2):228–243, 1995.

[140] C.-S. Li and R. Ramaswami. Automatic fault detection, isolation, and recovery in transparent all-optical networks. *Journal of Lightwave Technology*, 15(10):1784–1793, October 1997.

[141] E. Limal, B. Mikkelsen, and K. E. Stubkjr. Building WDM wide area resilient network from 4-node semi-mesh and mesh sub-networks. In *IEEE ICC*, volume 36.4, Montreal, June 1997.

[142] Y. Liu and D. Tipper. Multilayer network survivability models and their application on fault tolerant VPN design. In *INFORMS*, 2002.

[143] J. Manchester and P. Bonenfant. Fiber optic network survivability: SONET/Optical protection layer interworking. In *Proc. of NFOEC'96*, Denver, CO, 1996.

[144] J. Manchester, P. Bonenfant and C. Newton. The evolution of transport network survivability. *IEEE Communications Magazine*, August 1999.

[145] A. Markopoulou et al. Characterization of failures in an IP backbone. In *IEEE Infocom*, Hong-Kong, China, March 2004.

[146] J.L. Marzo, F. Solano, J.C. de Oliveira, L.F. Caro, and R. Fabregat. Optimal traffic grooming in wdm using lighttours. In *IEEE/COST 293 annual conference on GRAphs and ALgorithms in communication networks*, volume 3, June 2006. Invited Paper.

[147] C. Mauz. p-cycle protection in wavelength routed networks. In *Proceedings of the Seventh Working Conference on Optical Network Design and Modelling (ONDM'03)*, February 2003.

[148] Li Mo. General considerations for bandwidth reservation in protection. IETF draft, draft-mo-mpls-protection-00.txt, work in progress, July 2000

[149] E. Modiano and P. Lin, *Traffic grooming in WDM networks*, IEEE Communications Magazine, 39 (2001), pp. 124–129.

[150] R. Motwani and P. Raghavan. *Randomized Algoritms*, Press Syndicate of the University of Cambridge, 1995.

[151] B. Mukherjee. *Optical communication networks.* McGraw-Hill,New York, 1997.

[152] L. Nederlof et al. End-to-end survivable broadband Networks. *IEEE Communications Magazine*, 33(9):63–70, 1995.

[153] G. L. Nemhauser and L. A. Wosley. *Integer and Combinatorial Optimization.* John Wiley & Sons, 1988.

[154] K. Owens, S. Makam, V. Sharma and B. Mack-Crane. A path protection /restoration mechanism for MPLS networks. IETF draft, draft- chang-mpls-path-protection-02.txt, July 2000.

[155] D. Papadimitriou, et al. Inference of Shared Risk Link Groups. *IETF Draft*, OIF 2001-066, 2001.

[156] Serge A. Plotkin, David B. Shmoys, and Eva Tardos. Fast approximation algorithms for fractional packing and covering problems. *Mathematics of Operations Research*, 2:257–301, 1995.

[157] P. Raghavan. Probabilistic construction of deterministic algorithm: Approximating packing integer programs. *Journal of Computer and Systems Sciences*, 38:683–707, 1994.

[158] P. Raghavan and C.D. Thompson. Randomized rounding: a technique for provably good algorithms and algorithmic proofs. *Combinatorica*, 7(4):365–374, 1987.

[159] S. Ramamurthy and B. Mukherjee. Survivable WDM mesh networks, part I protection. In *Proc. IEEE Infocom*, vol. 2, pages 774–751, New York, March 1999.

[160] S. Ramamurthy and B. Mukherjee. Survivable WDM mesh networks, part II restoration. In *Proc. IEEE CC*, vol. 3, pages 2023–2030, Vancouver, Canada June 1999.

[161] R Ramaswami and K.N. Sivajaran. Routing and wavelength assignment in all-optical networks. *IEEE Transactions on NetworkingNetwork*, 3(5):489–500, 1995.

[162] R Ramaswami and K.N. Sivajaran. *Optical networks : a practical perspective.* Morgan kaufmann, San Francisco, 1998.

[163] R. S. Rees, *Group-divisible designs with block size k having $k + 1$ groups for $k = 4, 5$*, J. Combin. Designs, 8 (2000), pp. 363–386.

[164] A. A. M. Saleh and J. M. Simmons. Architectural principles of optical regional and metropolitan access networks. *Journal of Lightwave Technology*, 17(12):2431–2448, December 1999.

[165] H. Schroder, O. Sykora, and I. Vrt'o, Optical all-to-all communication for some product graphs, *Proc. (SOFSEM)'97: Theory and Practice of Informatics, Lecture Notes in Computer Science 1338, Springer*, Berlin, 1997, pp. 552-562.

[166] D. A. Schupke, C. Gruber and A. Autenrieth. Optimal configuration of p-cycles in WDM networks. In *IEEE ICC*, volume 5, pages 2761–2765, 2002.

[167] D. A. Schupke and R. G. Prinz. Capacity efficiency and restorability of path protection and rerouting in WDM networks subject to dual failures. *Photonic Network Communications*, September 2003

[168] P. Sebos, J. Yates, G. Hjálmtýsson and A. Greenberg, Auto-discovery of shared risk link group, In *IEEE/OSA OFC*, WDD3-1 – WDD3-3, 2001.

[169] F. Shahrokhi and D. Matula. The maximum concurrent flow problem. *Journal of the ACM*, 37:318 – 334, 1990.

[170] V. Sharma, B. Mack Crane, S. Makam, et al. Framework for MPLS-based recovery. IETF draft, draft-ietf-mpls-recovery-frmwrk-01.txt, November 2000

[171] M. Skutella. Approximating the single source unsplittable min-cost flow problem. *Mathematical Programming*, Ser.B(91):493–514, 2002.

[172] 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 Transaction on Networking*, to appear.

[173] A.K. Somani. *Survivability and Traffic Grooming in WDM Optical Networks.* Cambridge University Press, 2006.

[174] A. Somani, *Survivable traffic grooming in WDM networks*, in Broad band optical fiber communications technology – BBOFCT, D. K. Gautam, ed., Jalgaon, India, December 2001, Nirtali Prakashan, pp. 17–45. Invited paper.

[175] D. Sotteau. Decompositions of $k_{m,n}$ ($k^*_{m,n}$) into cycles (circuits) of length $2k$. *Journal of Combinatorial Theory B*, 30:75–81, 1981.

[176] L. Stacho and I. Vrt'o. Virtual path layouts for some bounded degree networks. In *Structure, Information and Communication Complexity, 3rd Colloquium, SIROCCO*, pages 269–278, june 1996.

[177] D. Staessens et al. Multilayer recovery mechanisms in backbone networks. In *INFORMS Telecommunications Conference*, Dallas, Texas, March 2006.

[178] T. Stidsen and S. Ruepp. Shortcut span protection. In *INFORMS Telecommunications Conference*, Dallas, Texas, March 2006

[179] D.R. Stinson, Hill–climbing algorithms for the construction of combinatorial designs, *Ann. Discrete Math.* 26 (1985), 321–334.

[180] D. R. Stinson, *Determination of a packing number*, Ars Combinatoria, 3 (1977), pp. 89–114.

[181] K. Struyve et al. Design and evaluation of multi-layer survivability for SDH-based ATM networks. In *Proc. of IEEE Globecom '97*, Phoenix, 1997.

[182] D. H. Su and D. W. Griffith. Standards activities for MPLS over WDM networks. *Optical Networks Magazine*, 1(3), July 2000.

[183] F. Touvet and D. Harle. Network resilience in multilayer networks : A critical review and open issues. In *ICN'01 : Proc. of the First International Conference on Networking*, pages 829–838, London, UK, 2001.

[184] F. Tillerot, E. Didelet, A. Daviaud, and G. Claveau, Efficient network upgrade based on a WDM optical layer with automatic protection switching, *OSA Optical Fiber Communications Conference (OFC)*, San Jose, CA, USA, 1998, pp. 296-297.

[185] A. Todimala and B. Ramamurthy. Survivable Virtual Topology Routing under Shared Risk Link Groups in WDM Networks. *In Proc. BroadNets*, pages 103- 139, 2004.

[186] K. Van Doorselaere et al. Fault propagation in WDM-based SDH/ATM networks, Brugge, Belgium, 1998.

[187] K. Vinodkrishnan, N. Chandhok, A. Durresi, R. Jain, R. Jagannathan and S. Seetharaman. Survivability in IP over WDM networks. *Journal of High Speed Networks, Special issue on Survivable Optical Networks*, 2001.

[188] M.-E. Voge. Graphes colorés - arbre couvrant coloré. In *Huitièmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications (AlgoTel'06)*, pages 41–44, Trégastel, May 2006.

[189] M.-E. Voge. How to transform a multilayer network into a colored graph. In *IEEE ICTON/GRAAL*, Nottingham, June 2006. To appear.

[190] P-J. Wan, G. Calinescu, L. Liu, and O. Frieder. Grooming of arbitrary traffic in sonet/wdm BLSRs. *Journal of Selected Areas in Communications*, 18(10):1995–2003, October 2000.

[191] P.-J. Wan, *Multichannel Optical Networks: Network Theory and Applications*, Kluwer Academic Press, 1999.

[192] J. Wang, W. Cho, V. Vemuri, and B. Mukherjee. Improved approches 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.

[193] J. Y. Wei, C.-D. Liu, S.-Y. Park, et al. Network control and management for the next generation Internet. *IEICE Trans. on Communications*, Vol. E83-B, No.10, October 2000, pp. 2191-2209.

[194] G. Wilfong. Minimizing wavelengths in all-optical ring network. In *the 7th International Symposium on Algorithms and Computation (ISAAC'96)*, volume 1178 of *Lecture Notes in Computer Science*, pages 346–355. Springer-Verlag, 1996.

[195] R.M. Wilson. Decomposition of complete graphs into subgraphs isomorphic to a given graph. *Congressus numerantium*, 15:647–659, November 1976.

[196] T.-H. Wu. Emerging technologies for fiber network survivability. *IEEE Communications Magazine*, 33(2):58–74, November 1995.

[197] T.-H. Wu and N. Yoshikai, *ATM Transport and Network Integrity*, Academic Press, 1997.

[198] D. Xu, Y. Xiong and C. Qiao: Novel algorithms for shared segment protection. *IEEE Journal on Selected Areas in Communications*, 21(8):1320-1331, October 2003.

[199] D. Xu, Y. Xiong and C. Qiao: Protection with multi-segments (PROMISE) in Networks with Shared Risk Link Groups (SRLG). *IEEE/ACM Transaction on Networking*, 11(2):248-258, 2003.

[200] Y. Xu, S-C. Xu, and B-X. Wu. Traffic groming in unidirectional WDM ring networks using genetic algorithms. *Computer Communications*, (25):1185–1194, 2002.

[201] N. Young. Randomized rounding without solving the linear program. In *ACM/SIAM SODA'95*, 1995.

[202] X. Yuan and A. Fulay, *Wavelength assignment to minimize the number of SONET ADMs in WDM rings*, in IEEE ICC, New York, Apr. 2002.

[203] S. Yuan, S. Varma, and J.P. Jue. Minimum-Color Path Problems for Reliability in Mesh Networks. In *Proc. IEEE InfoCom*, 2005.

[204] S. Zaks. Path layout in ATM networks - a survey. In *The DIMACS Workshop on Networks in Distributed Computing, DIMACS Center, Rutgers University*, Oct. 1997. manuscript.

[205] H. Zhang and A. Durresi, Differentiated multi-Layer survivability in IP/WDM Networks. In *IEEE/IFIP Network Operations and Management Symposium 02*, 8:681–694, April 2002.

[206] X. Zhang and C. Qiao. On optimal all-to-all personalized connections and cost-effective designs in WDM rings. *IEEE/ACM Transactions on Networking*, 7(3):435–445, 1996.

[207] 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.

[208] Q. Zheng, G. Mohan. Multi-layer protection in IP-over-WDM networks with and with no backup lightpath sharing. *Computer Networks*, 50(3): 301-316 (2006)

[209] K. Zhu and B. Mukherjee. A review of traffic grooming in WDM optical networks: Architectures and challenges. *Optical Networks Magazine*, 4 (2003), pp. 55–64.

[210] 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.