Dimensioning of Survivable WDM Networks

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***Abstract*—In this paper routing, planning of working capacity, rerouting, and planning of spare capacity in wavelength division multiplexing (WDM) networks are investigated. Integer linear programming (ILP) and simulated annealing (SA) are used as solution techniques. A complex cost model is presented. The spare capacity assignment is optimized with respect to three restoration strategies. The benefit of wavelength conversion, the choice of the fiber line system, and the influence of cost parameter values are discussed, with respect to the different restoration strategies and solution techniques. Wavelength conversion is found to be of limited importance, whereas tunability at the end points of the connections has substantial benefits.**

***Index Terms*—Dimensioning, integer linear programming, optimization techniques, planning, restoration strategies, simulated annealing, wavelength division multiplexing (WDM) networks.**

I. INTRODUCTION

WAVELENGTH division multiplexing (WDM) is evolving from a research topic to a real alternative for network operators in upgrading their transport network infrastructure. The first step is upgrading point-to-point links by using multiple channels in one fiber in order to share the amplifier costs among more channels, thus lowering the cost per information unit. The next step is the switching of the channels in the optical layer by using all optical crossconnects, thus avoiding the cost of high-speed electronic processing equipment for transit traffic in the nodes. An essential part of the design of WDM networks is the choice of the fiber line system or, in other words, the definition of the channel plan, i.e., the number of wavelengths per fiber to be used (4, 8, 16, 32), the channel spacing, and the absolute wavelengths. Compatibility between different channel plans is possible if the channels partly coincide or if transponders are used. Throughout the rest of the paper, however, we assume that one specific fiber line system is adopted for the entire network. Hence, only homogeneous networks are considered. This can be relaxed, however, when a transponder interface is used in between the fiber line system and the crossconnect. A transponder converts any input signal to a signal compliant with the entering system. In this way, for example, the output of two fiber ports in the same direction could be grouped onto one fiber or bidirectional transmission on a single fiber could be used. This is particularly interesting in the case of fiber-exhausted links.

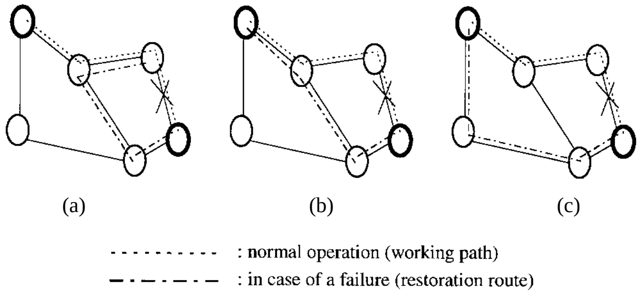

Fig. 1. Restoration strategies. (a) Link restoration (LR). (b) Path restoration (PR). (c) Path restoration with link-disjunct route (PRd).

Once the number of wavelengths per fiber is defined, the planning consists of defining the paths on which the demand is routed and dimensioning the links (i.e., defining the number of fibers and channels for each link). In some studies the purpose is to minimize the number of wavelengths [1], [2]. Others focus on minimizing the number of fibers [3], [4]. The purpose of this paper is the design of a fiber topology and optical path layer for future WDM networks, with a fixed channel plan, minimizing the total cost for a given static traffic demand.

Optical fiber, with its large bandwidth, and WDM paved the way for transmitting more data through a single fiber [5]. This makes the network vulnerable, however, in the event of cable breaks. A huge amount of data may be affected, which makes efficient and fast restoration necessary. To survive a cable break, spare capacity on the remaining links is required, together with a well-chosen restoration strategy. Some kind of automatic protection is attractive, since it can react quickly on a failure and yields a simple implementation. Protection strategies are, in the first instance, considered for point to point links and in ring structures. Protection requires many spare resources, which can be seen as a disadvantage. In meshed networks, rerouting strategies can be applied more efficiently; spare capacity is not really dedicated to protect working entities, but the spare resources are shared among several working entities. The planning of these spare resources is, however, more complex. In this paper three rerouting strategies are considered for single link failures (Fig. 1).

1) Link restoration (LR) reroutes the broken traffic between the end nodes of the failed link. This allows a quick rerouting, as only a limited part of the network around the failure must be reconfigured.
2) Path restoration (PR) reroutes the broken traffic between the end nodes of the affected paths. In this way, spare

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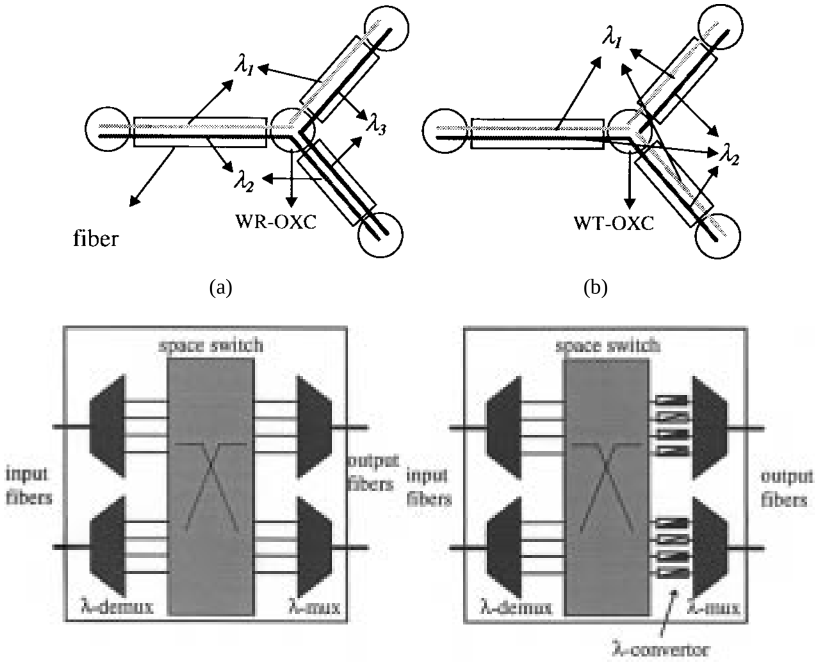

(a) (b) (c) (d)

Fig. 2. (a) WP network. (b) VWP network. (c), (d) Crossconnect architectures.

capacity all over the network is used and a lower spare capacity requirement is expected than in LR. In this case, many more nodes are involved in the restoration phase, since every broken path needs to be restored separately.

3) Path restoration with link-disjunct route (PRd) reroutes the demand of each affected path through a designated preassigned link-disjunct route (a route that has no link in common with the working path). This link-disjunct route belongs to a specific path and is useful as restoration route in case of any link failure affecting the specific path. This scheme has the advantage of starting the restoration process immediately upon discover of a path-defect, without knowing the exact location of the link failure.

For the path restoration schemes, capacity that was used by the working paths can be released and reused for restoration purposes. In this way, however, more reconfiguration is required to restore the original network status.

The spare capacity assignment problem has been tackled before, in [6]–[9], for general meshed networks. In [10] and [11] this is applied on WDM networks, as is the case in this paper.

Two different types of WDM networks are considered. Networks that do not use wavelength conversion in the crossconnects are denoted as wavelength path (WP) networks. In a WP network, an established path in the network is characterized by its wavelength. Networks with wavelength conversion in the crossconnects are denoted as virtual wavelength path (VWP) networks. In this case, a path can have different wavelengths on subsequent links (Fig. 2). In WP networks, two cases depending on the tunability of the laser sources can be further distinguished We assume, when planning the working paths, that for each demand pair the wavelength can be chosen. In the case of path restoration, however, two cases can be distinguished wherein the transmitters and receivers are tunable, and a restoration route on another wavelength can be used (WPa), or the transmitter wavelength is fixed and the restoration route must be found on the same wavelength (WPb).

The benefit of using wavelength conversion in WDM networks is still an open issue and has been questioned by many researchers. At present, the optical wavelength conversion technology is still not mature. Wavelength conversion via the electrical domain, however, is possible. In any case, wavelength conversion requires additional components, thus the debate over its necessity continues. For static routing, the benefit has been found to be small [3]. As the subject of this paper is the planning of working and spare capacity for a static traffic demand, the same conclusion is expected. Because most studies (including this one) focus only on a particular network aspect, the conclusions concerning wavelength conversion are not representative of the entire picture of deployed WDM networks and, therefore, may not be understood as the prevailing conclusions.

The planning approach described in this paper has as its starting point the location of the optical crossconnects, a set of candidate links between these crossconnects, and the demand between each pair of nodes, expressed in the number of wavelength channels. Optimization of routing in the network and allocation of working and spare fiber resources is then performed, minimizing the total network cost. Section II of this paper describes the cost model. In Section III, the used optimization techniques are explained. The planning is done in two steps: first, routing and working capacity assignment are optimized and second, the spare capacity is assigned. The outcome is a dimensioned network with an optimized number

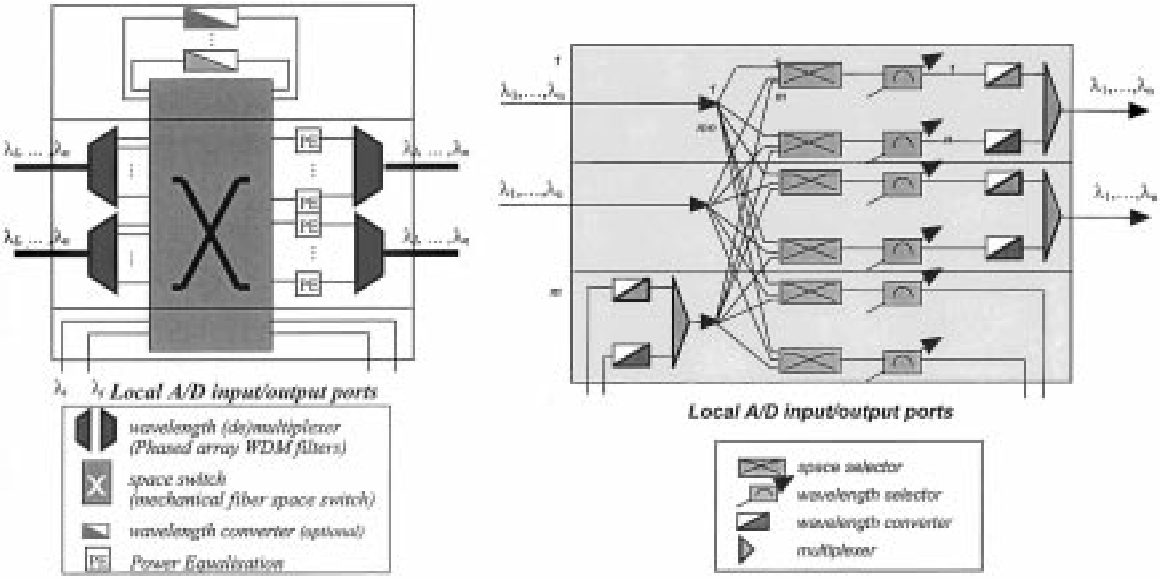

Fig. 3. Cross connect architectures PHOTON and OPEN.

of working and spare fibers (or channels) on each link and the most appropriate working paths on which to route the demand and restoration routes on which to recover from a single link failure. The results are presented in Section IV. The performance of the optimization techniques, the benefit of wavelength conversion, the choice of the fiber line system, and the influence of the cost parameter values are discussed. In Section V conclusions are drawn.

II. COST MODEL OF A WDM NETWORK

This section gives a cost model for a WDM network. Most of the cost sources are mapped to three parameters: the cost related to the cable (α cost), to the fiber (β cost), and to the channel (γ cost). The total link cost is the sum of three contributions: the α cost; the β cost, multiplied by the number of used fibers; and the γ cost, multiplied by the number of used channels. The α cost stands for the required investment in a link before any capacity on this link can be used, e.g., digging costs, leasing costs, or cable/duct maintenance costs. With the β cost, the cost of the line system is typically: the multiplexer, demultiplexer, optical amplifiers, and dispersion compensation management components [e.g., dispersion compensating fiber (DCF)]. For each channel that is used in this line system or fiber, a γ cost is counted, representing the cost for a channel used, e.g., for per-channel management and regeneration and for the wavelength converter in the VWP case. If all the channels of a fiber are fully equipped at once, the cost must be included in the β cost. One may subequip the fibers, however, according to the number of channels that will be used (e.g., with modular wavelength cards). The cost is then included in the γ cost. Each parameter can be dependent on the link. The fiber cost β, for instance, can be subdivided into three components:

- *fixed amount* (β_{oi}): representing the fiber terminating equipment (e.g., (de)multiplexer);
- *amount scaling with the length* (β_{li}): representing, for example, the fiber;
- *amount scaling with the number of amplifiers* (β_{ai}): representing, for example, the amplifier cost.

The total β cost on a link is then: $\beta_i = \beta_{oi}+\beta_{li}\cdot l_i+\beta_{ai}\cdot\#a_i$. ($i$ refers to link i, l to the length, and $\#a$ to the number of amplifiers along the fiber.)

The mapping of the actual cost sources to the cost parameters strongly depends on the architecture and technology used. In [12], two node architectures are described, which are used in the projects OPEN and PHOTON (see Fig. 3). They are principally different and, due to the variety of optical components, many other variants can be thought of. Many components in the crossconnect can be taken into account in the above-noted cost parameters. In the PHOTON crossconnect arrayed waveguide grating (AWG), filters are used as demultiplexers and multiplexers. These filters are typically included in the β cost. The OPEN crossconnect is based on a broadcast and select principle. The incoming signal is split by a passive splitter. and the channels are afterwards selected by individual tunable filters and eventually converted to another wavelength. The splitter can be counted in the β cost, whereas the tunable filters and wavelength converters are only necessary when the channel is used and can, therefore, be counted as a γ cost. As a result, the β and γ cost ratio differs for both crossconnect architectures.

The total link cost ($\alpha_j + \beta_j \cdot \#\ \text{fibers}_j + \gamma_j \cdot \#\ \text{channels}_j$) is not linear in the numbers of channels, and also not in the number of fibers, but the constituents are. Some cost sources, such as node parts that count for all the incident links and do not scale with any of the parameters above, cannot be taken into account via α, β, or γ. Different discrete node sizes, however, can be taken into account, such as a 4×4, 8×8, and 16×16 OXC with a specific cost that is not linear with the incident fibers or channels.

The network cost is, then, the sum of all the link and node costs.

III. Optimization Techniques and Models

Two optimization techniques have been used: integer linear programming (ILP) and simulated annealing (SA). In order to solve the problem with ILP, it must first be caught in a linear model. The entire problem is solved at once. The integer constraints lead to an extensive branch and bound (B&B) procedure [13]. In contrast to ILP, SA is an heuristic search technique. SA, however, can be superior to other heuristic methods, since it can escape from local optima [14], [15]. It will be shown in this section how these techniques can be applied to our problem.

A. Routing and Capacity Planning

The goal of optimization is to select the best set of routes, with according dimensioning, in order to end up with the cheapest network that can be found within a reasonable time. An initial topology is given, i.e., the nodes and candidate links. Extremely long links, for instance, are not considered, as they are unlikely to occur in the solution. The demand between the node pairs is also given. For routing a demand, k possible routes (the k shortest ones, using the algorithm in [16]) are considered. At this point, long paths can be excluded when these are infeasible due to the physical effects in optical networks. Effects such as dispersion, noise, crosstalk, and fiber nonlinearities degrade the signal quality and may, therefore, impose limitations on the maximum path length or hop count, unless regeneration is used at an intermediate point. The latter, however, may limit the transparency of the optical network and may require an additional step in the planning: the regenerator placement.

The demand is assumed to be symmetrical, and both directions follow the same route on the same wavelength, but in opposite fibers. As a consequence, fibers and channels are planned in pairs (one for each direction). As we consider WDM networks, a demand or flow unit corresponds with a capacity corresponding with a wavelength channel.

1) ILP: The problem is caught in a linear model, where the variables are the flows through the routes and the working channels and fibers on each link. The objective function and constraints are expressed as a linear relationship between the variables.

Consider that the starting topology contains N nodes and L links, the demand contains M connections, and there are I possible sizes of optical crossconnects. The variables and parameters of the ILP problem formulation are then:

$\alpha_j, \beta_j, \gamma_j$	α, β and γ cost of link $j (j{:}\, 1 \cdots L)$;
δ_j	1 if link j is used, 0 otherwise;
UF_j	used fiber pair capacity of link j (= # fiber pairs);
UC_j	used channel pair capacity of link j (VWP) (= # channel pairs);
$UC_{j,\lambda}$	used channel pair capacity on wavelength λ of link j (WP);
C_i	cost of node type i $(i{:}\, 1 \cdots I)$;
K_i	capacity of node type i (e.g., 4 × 4, 8 × 8, 100 × 100);
$\delta_{n,i}$	1 if node n is of node type i, 0 otherwise $n{:}\, 1 \cdots N)$;
mth sd-pair	(s, d): source–destination node pair m; $(m{:}\, 1 \cdots M)$;
k_m	the number of shortest routes that is considered for routing between mth sd-pair;
Λ	the number of wavelengths that is used on a fiber $(\lambda{:}\, 1 \cdots \Lambda)$;
MF	the maximum number of fiber pairs in a cable or link;
d_m	demand of mth sd-pair (symmetrical demand);
$f_{p,m}$	flow through route p serving demand d_m (VWP case) (flow unit = λ channel);
$f_{p,\lambda,m}$	flow through route p on wavelength λ serving demand d_m (WP case);
$\delta_{j,p,m}$	1 if route p of demand d_m uses link j, 0 otherwise;
$\delta_{j,n}$	1 if link j is incident to node n, 0 otherwise.

δ_j, UF_j, UC_j, $UC_{j,\lambda}$, $\delta_{n,i}$, $f_{p,m}$, and $f_{p,\lambda,m}$ are variables to be adapted by the optimization technique, while α_j, β_j, γ_j, C_i, K_i, sd-pair, k_m, Λ, MF, d_m, $\delta_{j,p,m}$, $\delta_{j,n}$ are given or can be derived from the input.

The objective is to minimize the network cost, as described in Section II. The adopted cost model is linear in the variables. Hence, the objective is to minimize the following function:

$$\sum_{j=1}^{L} (\alpha_j \cdot \delta_j + \beta_j \cdot UF_j + \gamma_j \cdot UC_j) + \sum_{n=1}^{N} \sum_{i=1}^{I} (C_i \cdot \delta_{n,i})$$

for the optimization of a VWP network. For a WP network the used channels are summed over λ as follows:

$$\sum_{j=1}^{L} \left(\alpha_j \cdot \delta_j + \beta_j \cdot UF_j + \gamma_j \cdot \sum_{\lambda=1}^{\Lambda} UC_{j,\lambda} \right) + \sum_{n=1}^{N} \sum_{i=1}^{I} (C_i \cdot \delta_{n,i}).$$

The variables are restricted by a number of constraints which define a relationship between these variables and the given input parameters.

A first set of constraints arises from the fact that the flow through the considered routes of each sd pair must be sufficient to route the corresponding demand. In VWP networks

$$\sum_{p=1}^{k_m} f_{p,m} = d_m, \qquad \forall m = 1, 2, \cdots, M.$$

In WP networks, an additional sum over the wavelength dimension is necessary

$$\sum_{p=1}^{k_m} \sum_{\lambda=1}^{\Lambda} f_{p,\lambda,m} = d_m, \qquad \forall m = 1, 2, \cdots, M.$$

A second set of constraints defines that the number of working channels on a link must be sufficient to carry the flow on this link. In VWP networks

$$UC_j \geq \sum_{m=1}^{M} \sum_{p=1}^{k_m} \delta_{j,p,m} \cdot f_{p,m}, \qquad \forall j = 1, 2, \cdots, L.$$

In WP networks, the constraint must hold for each wavelength

$$UC_{j,\lambda} \geq \sum_{m=1}^{M} \sum_{p=1}^{k_m} \delta_{j,p,m} \cdot f_{p,\lambda,m}, \qquad \forall j = 1, 2, \cdots, L, \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

The relationship between the channels and the fibers is expressed in a third set of constraints; the number of working fibers must be sufficient to accommodate the required number of channels. In VWP networks

$$UC_j \leq \Lambda \cdot UF_j, \qquad \forall j = 1, 2, \cdots, L.$$

In WP networks, this becomes

$$UC_{j,\lambda} \leq UF_j, \qquad \forall j = 1, 2, \cdots, L; \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

Whether or not a link is used can be expressed through the following constraints (for VWP as well as for WP networks):

$$UF_j \leq MF \cdot \delta_j, \qquad \forall j = 1, 2, \cdots, L.$$

An additional constraint has been added for survivability reasons. The node degree must be minimal two. That means that to each node, two links must be incident. This assures that recovery from any single link failure is possible, provided that spare capacity is available

$$\sum_{j=1}^{L} \delta_{j,n} \geq 2, \qquad \forall n = 1, 2, \cdots, N.$$

In case node size optimization ($I > 1$) is included in the ILP optimization process, an additional set of constraints is formulated:

$$\sum_{i=1}^{I} \delta_{n,i} = 1, \qquad \forall n = 1, 2, \cdots, N$$

$$\sum_{j=1}^{L} \delta_{j,n} \cdot UF_j \leq \sum_{i=1}^{I} K_i \cdot \delta_{n,i}, \qquad \forall n = 1, 2, \cdots, N.$$

In order to achieve feasible solutions, the capacity of the biggest node type should be large enough: eventually artificially too large and corresponding with an artificially very high cost. In this way, this node type will be avoided due to the very high cost, but in every case a feasible solution is possible. Afterwards, $\delta_{n,I}$ can be checked to see if node n has a reasonable size and, if not, the input settings can be adapted.

Last, but not least, the integer constraints must be imposed. For VWP networks:

$$UF_j, UC_j, f_{p,m} \in \mathrm{Z}^+, \quad \begin{array}{l} \forall j = 1, 2, \cdots, L; \\ \forall p = 1, 2, \cdots, k_m; \\ \forall m = 1, 2, \cdots, M \end{array}$$

$$\delta_j, \delta_{n,i} \in \{0, 1\}, \quad \begin{array}{l} \forall j = 1, 2, \cdots, L \\ \forall n = 1, 2, \cdots, N: \forall i = 1, \cdots, I. \end{array}$$

And for WP networks:

$$UF_j, UC_{j,\lambda}, f_{p,\lambda,m} \in \mathrm{Z}^+, \quad \begin{array}{l} \forall j = 1, 2, \cdots, L; \\ \forall \lambda = 1, 2, \cdots, \Lambda \\ \forall p = 1, 2, \cdots, k_m; \\ \forall m = 1, 2, \cdots, M \end{array}$$

$$\delta_j, \delta_{n,i} \in \{0, 1\}, \quad \begin{array}{l} \forall j = 1, 2, \cdots, L \\ \forall n = 1, 2, \cdots, N: \forall i = 1, \cdots, I. \end{array}$$

The studied problem thus requires $\sum_{m=1}^{M} k_m + 3 \cdot L + N \cdot I$ variables and $3 \cdot L + 3 \cdot N + M$ constraints for VWP networks and $\sum_{m=1}^{M} k_m \cdot \Lambda + (2 + \Lambda) \cdot L + N \cdot I$ and $(1 + 2 \cdot \Lambda) \cdot L + 3 \cdot N + M$, for WP networks. The numbers of variables and constraints scale with the numbers of links and nodes in the network. Furthermore, the number of variables also scale with the number of considered shortest routes.

A limitation on these models is that the objective function must be linear because we wish to solve it with linear programming techniques. Therefore, this limitation is due to the optimization technique. The used routes are returned with the solution (i.e., the found values for $f_{p,m}$ and $f_{p,\lambda,m}$) and this set of routes is the most optimal one with respect to the objective function.

The integer constraints are necessary, otherwise it would be most likely to find a solution that is not feasible because of noninteger values for capacities. The noninteger solution obtained from the linear program, however, is a lower bound for the integer solution. The B&B algorithm explores a tree, searching for the optimal integer solution (a B&B routine of the CPLEX callable library is used).[1] This algorithm may take a long time, and therefore it is stopped after finding the first or a predefined number of integer solutions. This procedure no longer guarantees the optimal solution.

2) SA: SA is a nondeterministic search technique [14], [15] and starts with a fully specified network which can be randomly generated; with each demand unit a route is associated and from this the used capacity can be derived. In the case of a WP network, the wavelength of the route is also specified. The cost can then be calculated from the used capacity. In this network, nodes may be connected with only one link, which cannot be made survivable in case of single link failures. The network can be punished since it is not feasible. The objective function includes the real cost which must be minimized and a penalty for infeasibility if nodes are connected to the network with only one link.

From this network a new one is derived by a small and random change (e.g., choosing another route for a demand). This network may be better or worse than the former one, with respect to the objective function. If it is better, then the new proposed solution is accepted unconditionally. Whether or not a worse solution is accepted is controlled by the temperature, which is the characteristic parameter of SA. A frequently used function that gives the probability of acceptance of a worse

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[1] CPLEX Version 5.0 (CPLEX is a division of ILOG).

solution is given by

$$p = \exp - \frac{|F_{obj}(x') - F_{obj}(x)|}{T}.$$

T is the temperature in this equation and $|F_{obj}(x') - F_{obj}(x)|$ the deterioration of the solution compared to the former one. In practice, a random number is generated between zero and one (i.e., this number is uniformly distributed). If this number is less than p, the solution is accepted, otherwise it is rejected. In this way, the acceptance probability is p.

In the beginning of the simulation, the temperature is high enough to accept almost every worse proposed network. During the course of the simulation, the temperature is lowered and the probability of acceptance of worse solutions decreases. Due to this feature, SA has the possibility of escaping from local minima, especially in the beginning of the simulation. The trajectory described in the solution space converges to a local minimum, and if the probability of escape from this minimum is almost zero, the simulation is stopped. The best solution found is returned and describes the resulting network.

B. Rerouting and Spare Capacity Planning

For general meshed networks an ILP formulation for the rerouting and spare capacity problem is presented in [17]. In this paper, the models are extended to WDM networks.

In WP networks, wavelength constraints are imposed on the restoration routes. In the case of link restoration, only the channel in the interrupted link, which is part of the affected route, is rerouted, and therefore the channel must be rerouted on the original wavelength of the path. In the case of path restoration, the transmitter–receiver pairs can be tunable, or spare transmitter–receiver pairs on other wavelengths could be available. In that case, a route on another wavelength is allowed for rerouting (WPa case), otherwise a route on the original wavelength must be found (WPb case). It is clear that the same wavelength must be available along the entire route, as there is no possibility of wavelength conversion in the intermediate nodes.

Consider a network with L links and M paths for which the routes are given. Between the end nodes of the failed link, in the case of link restoration, or between the end nodes of the paths, in the case of path restoration, we consider as eligible restoration routes the k shortest routes [16] in the incomplete network (i.e., the original network excluding the failed link), with the additional requirement of link-disjunctness for PRd.

In the following sections, a solution approach with ILP and with SA is presented.

1) ILP: First we define some additional parameters to be used in the equations for the linear model:

SF_j	spare fiber pair capacity of link j;
SC_j	spare channel pair capacity of link j (VWP);
$SC_{j,\lambda}$	spare channel pair capacity on wavelength λ of link j (WP);
ASC_j	available spare channel pair capacity of link j (VWP);
$ASC_{j,\lambda}$	available spare channel pair capacity on wavelength λ of link j (WP);
$f_{j,p}$	the restoration flow through the pth restoration route of link j upon the failure of link j (for LR) (VWP);
$f_{j,m,p}$	the restoration flow through the pth restoration route of path m upon the failure of link j (for PR and PRd) (VWP);
$f_{j,\lambda,p}$	the restoration flow through the pth restoration route of link j on wavelength λ upon the failure of link j (for LR) (WP);
$f_{j,m,\lambda,p}$	the restoration flow through the pth restoration route of path m on wavelength λ upon the failure of link j (for PR and PRd) (WP);
F_j	the flow through link j (VWP);
$F_{j,\lambda}$	the flow through link j on wavelength λ (WP);
P_j	number of restoration routes for link j;
$\delta_{i,p}$	1 if the pth restoration route uses link i, 0 otherwise;
$\delta_{I,m}$	1 if path m uses link i, 0 otherwise;
d_m	demand of path m (VWP);
$d_{m,\lambda}$	demand of path m on wavelength λ (WP);
P_m	number of restoration routes for path m;
A_j	$= \{m\}$, paths affected upon the failure of link j;
$b_{m,p}$	1 if the pth restoration route is used as backup route of path m, 0 otherwise (for PRd) (VWP);
$b_{m,\lambda,p}$	1 if the pth restoration route on wavelength λ is used as backup route of path m, 0 otherwise (for PRd) (WP);

SF_j, SC_j, $SC_{j,\lambda}$, $f_{j,p}$, $f_{j,\lambda,p}$, $f_{j,m,p}$, $f_{j,m,\lambda,p}$, $b_{m,p}$ and $b_{m,\lambda,p}$ are the variables which must be fixed by ILP. ASC_j, $ASC_{j,\lambda}$, F_j, $F_{j,\lambda}$, P_j, $\delta_{i,p}$, d_m, $d_{m,\lambda}$, P_m, $A_j = \{m\}$, and $\delta_{i,m}$ are known or can be derived from the input. The available spare channels (ASC's) refer to the spare channels in the fibers that are used for routing and, thus, do not require additional spare fibers.

The total cost of the spare capacity for full restorability must be minimized. Hence, the objective function to minimize in all models for VWP networks is

$$\sum_{j=1}^{L} (\beta_j \cdot SF_j + \gamma_j \cdot SC_j) + \sum_{n=1}^{N} \sum_{i=1}^{I} (C_i \cdot \delta_{n,i})$$

while for WP networks

$$\sum_{j=1}^{L} \left(\beta_j \cdot SF_j + \gamma_j \cdot \sum_{\lambda=1}^{\Lambda} SC_{j,\lambda} \right) + \sum_{n=1}^{N} \sum_{i=1}^{I} (C_i \cdot \delta_{n,i}).$$

The second double sum is present only if the node size is also optimized.

For the LR models the following constraints must be met.

1) When link j fails, the working flow of this link must be rerouted through the P_j possible restoration routes.

Hence, for VWP networks

$$\sum_{p=1}^{P_j} f_{j,p} \geq F_j, \qquad \forall j = 1, 2, \cdots, L$$

and for WP networks:

$$\sum_{p=1}^{P_j} f_{j,\lambda,p} \geq F_{j,\lambda} \qquad \forall j = 1, 2, \cdots, L; \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

2) If link j fails, the spare capacity on the other links must be sufficient for the flow on the restoration routes. For VWP networks

$$SC_i \geq \sum_{p=1}^{P_j} \delta_{i,p} \cdot f_{j,p}, \quad \forall i, j = 1, 2, \cdots, L \cdot i \neq j$$

and for WP networks:

$$SC_{i,\lambda} \geq \sum_{p=1}^{P_j} \delta_{i,p} \cdot f_{j,\lambda,p}, \quad \forall i, j = 1, 2, \cdots, L \cdot i \neq j, \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

3) The spare capacity channels must be accommodated in the fibers. Therefore, additional spare fibers may be required. Spare channels in fibers used for the working capacity, however, are also available. In VWP networks this constraint yields

$$SC_j - ASC_j \leq \Lambda \cdot SF_j, \qquad \forall j = 1, 2, \cdots, L.$$

In WP networks, this becomes

$$SC_{j,\lambda} - ASC_{j,\lambda} \leq SF_j, \qquad \forall j = 1, 2, \cdots, L; \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

4) The spare capacity and the flows on the restoration routes must be integer and nonnegative values. For VWP networks

$$SF_j, SC_j, f_{j,p} \in \mathrm{Z}^+, \qquad \forall j = 1, 2, \cdots, L \quad \forall p = 1, 2, \cdots, P_j.$$

And for WP networks

$$SF_j, SC_{j,\lambda}, f_{j,\lambda,p} \in \mathrm{Z}^+, \quad \forall j = 1, 2, \cdots, L \quad \forall p = 1, 2, \cdots, P_j; \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

In the PR scheme the constraints are slightly different (the corresponding set of constraints is indicated with the same number as for the LR scheme, but a $'$ is added).

1$'$) When link j fails, every interrupted path m needs to be restored. The restoration routes of the path must carry the demand of the interrupted working path. Hence, for VWP networks

$$\sum_{p=1}^{P_m} f_{j,m,p} = d_m, \quad \forall j = 1, 2, \cdots, L{:}\forall m \in A_j.$$

In the case of a WP network there is a difference between WPa and WPb; for WPa networks

$$\sum_{\lambda=1}^{\Lambda} \sum_{p=1}^{P_m} f_{j,m,\lambda,p} = \sum_{\lambda=1}^{\Lambda} d_{m,\lambda}, \quad \forall j = 1, 2, \cdots, L; \quad \forall m \in A_j.$$

As the transmitters are tunable, it is not important whether a path on wavelength λ is restored on the same wavelength or another wavelength, but in WPb networks the transmitters are not tunable and therefore

$$\sum_{p=1}^{P_m} f_{j,m,\lambda,p} = d_{m,\lambda}, \quad \forall j = 1, 2, \cdots, L; \quad \forall m \in A_j; \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

2$'$) If link j fails, the spare capacity on the other links must be sufficient for the flow on the restoration routes of every interrupted working path m.
For VWP networks

$$SC_i \geq \sum_{m \in A_j} \sum_{p=1}^{P_m} \delta_{i,p} \cdot f_{j,m,p} \quad \forall i, j = 1, 2, \cdots, L \cdot i \neq j.$$

For WP networks

$$SC_{i,\lambda} \geq \sum_{m \in A_j} \sum_{p=1}^{P_m} \delta_{i,p} \cdot f_{j,m,\lambda,p}, \quad \forall i, j = 1, 2, \cdots, L \cdot i \neq j, \quad \forall \lambda = 1, 2, \cdots, \Lambda.$$

3$'$) Constraint set 3) is unchanged applicable for PR.

4$'$) Again, the spare capacity and the flows on the restoration routes must be integer and nonnegative values. For VWP networks

$$SF_j, SC_j, f_{j,m,p} \in \mathrm{Z}^+, \quad \forall j = 1, 2, \cdots, L \quad \forall m \in A_j{:}\forall p = 1, 2, \cdots, P_m.$$

And for WP networks

$$SF_j, SC_{j,\lambda}, f_{j,m,\lambda,p} \in \mathrm{Z}^+, \quad \forall j = 1, 2, \cdots, L; \quad \forall \lambda = 1, 2, \cdots, \Lambda \quad \forall m \in A_j{:}\forall p = 1, 2, \cdots, P_m.$$

For the PRd models, Boolean variables are introduced, indicating whether or not a specific restoration route is used. The entire demand is kept together and rerouted along the backup restoration route. If restoration is allowed along diverse restoration routes, the connections can be split first in connections with demand equal to one. M then becomes $\sum_{m=1}^{M} d_m$

and $d_m = 1$. The constraints to be met become the following (the corresponding set of constraints is indicated with the same number as for the LR scheme, but $''$ is added).

1$''$) Only one restoration route is used for path m, independent on the failing link of path m.
For VWP networks
$$\sum_{p=1}^{P_m} b_{m,p} = 1, \quad \forall m = 1, 2, \cdots, M.$$
For WPa networks
$$\sum_{\lambda=1}^{\Lambda}\sum_{p=1}^{P_m} b_{m,\lambda,p} = 1, \quad \forall m = 1, 2, \cdots, M.$$
For WPb networks
$$\sum_{p=1}^{P_m} b_{m,\lambda,p} = 1, \quad \forall m = 1, 2, \cdots, M$$
(λ being the original wavelength of path m).

2$''$) If link j fails, the spare capacity on the other links must be sufficient for the flow on the restoration routes. In (2$'$) $f_{j,m,p}$ and $f_{j,m,\lambda,p}$ should be replaced by $b_{m,p} \cdot d_m$ and $b_{m,\lambda,p} \cdot d_{m,\lambda}$, respectively.

3$''$) Constraint set 3) is unchanged applicable for PRd.

4$''$) The spare capacity on each link must be integer and nonnegative. The b variables are Boolean. For VWP networks
$$\begin{aligned} &SF_j,\, SC_j \in \mathrm{Z}^+,\, b_{m,p} \in \{0, 1\}, \\ &\quad \forall j = 1, 2, \cdots, L \\ &\quad \forall m = 1, 2, \cdots, M: \\ &\quad \forall p = 1, \cdots, P_m \end{aligned}$$
and for WP networks:
$$\begin{aligned} &SF_j,\, SC_{j,\lambda} \in \mathrm{Z}^+,\, b_{m,\lambda,p} \in \{0, 1\}, \\ &\quad \forall j = 1, 2, \cdots, L; \\ &\quad \forall \lambda = 1, 2, \cdots, \Lambda \\ &\quad \forall m = 1, 2, \cdots, M: \\ &\quad \forall p = 1, \cdots, P_m. \end{aligned}$$

In the case of path restoration (both PR and PRd), the capacity of interrupted paths can be released. When link j fails, some capacity, in addition to the spare capacity of link i, can be used for restoration. Hence, the constraints 2$'$) and 2$''$) become:

2$'$)
$$\begin{aligned} SC_{i(,\lambda)} &+ \sum_{m\in Aj} \delta_{i,m} \cdot d_{m(,\lambda)} \\ &\geq \sum_{m\in A_j}\sum_{p=1}^{P_m} \delta_{i,p} \cdot f_{j,m,p(,\lambda)}, \\ &\qquad \forall i, j = 1, 2, \cdots, L \cdot i \neq j \end{aligned}$$

2$''$)
$$\begin{aligned} SC_{i(,\lambda)} &+ \sum_{m\in Aj} \delta_{i,m} \cdot d_{m(,\lambda)} \\ &\geq \sum_{m\in A_j}\sum_{p=1}^{P_m} \delta_{i,p} \cdot b_{m,p(,\lambda)} \cdot d_{m(,\lambda)}, \\ &\qquad \forall i, j = 1, 2, \cdots, L \cdot i \neq j. \end{aligned}$$

If the node size is also optimized analogously, as in Section III-A1, an additional set of constraints can be formulated (note that at this point UF_j is known as the output from the first optimization step)
$$\sum_{i=1}^{I} \delta_{n,i} = 1, \qquad \forall n = 1, 2, \cdots, N$$
$$\sum_{j=1}^{L} \delta_{j,n} \cdot (UF_j + SF_j) \leq \sum_{i=1}^{I} K_i \cdot \delta_{n,i}, \quad \forall n = 1, 2, \cdots, N.$$

The remarks made in Section III-A about ILP apply here as well. From the nature of this technique, no real rerouting strategy is imposed (e.g., rerouting by trying the routes in order of length). The used routes for rerouting are returned with the solution (i.e., the found values for $f_{j,p}$, $f_{j,\lambda,p}$, $f_{j,m,p}$, $f_{j,m,\lambda,p}$, $b_{m,p}$, and $b_{m,\lambda,p}$). This set of routes is the most optimal one with respect to the objective function, unless the exploration of the B&B tree is prematurely interrupted for calculation time savings.

2) SA: SA can be applied analogously, as explained in Section III-A2. The starting point is a fully specified network with the restoration routes established according to any link failure. Small random changes can be made by choosing another restoration route for both a particular link failure and a particular interrupted demand, which are selected randomly.

This mode of optimization is suited for preplanned restoration. No real rerouting strategy is simulated. When considering a rerouting strategy, in the sense that a list of restoration routes is sequentially explored (e.g., in case of dynamic restoration), another implementation might yield better results. For instance, during the SA optimization, the spare capacity on the links can be randomly changed by a small amount. The restoration degree can be calculated by simulating the restoration process. If the proposed network is not fully restorable, a penalty can be added to the objective function. This penalty can be increased during the simulation (e.g., negatively with the temperature) to avoid the situation in which the resulting network does not meet the restorability requirements.

IV. RESULTS AND DISCUSSION

A. Capacity Planning and Routing

As a case study, the working capacity was allocated in the COST239 network which consists of 18 nodes [18]. The simulations were done for a European load, which was estimated and proposed in the COST239 project [19]. The load has 73 source–destination (sd) pairs, and 254 units of requested demand between these sd-pairs (a demand unit requires one wavelength channel on the followed route). Thirty-nine possible links were considered, resulting in the network represented in Fig. 4.

Simulations were performed for WP and VWP networks, for several values of α (0, 40, 400, 4000), in combination with different values for β (50, 100, 200, 400), while γ is kept equal to 1, for 1, 2, 4, 8, and 16 wavelengths per fiber and several

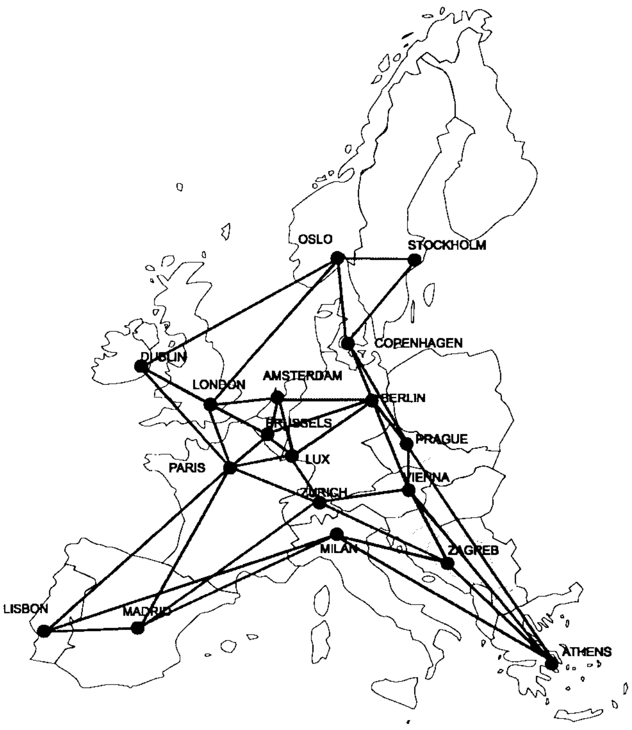


Fig. 4. Initial topology containing 39 links.

TABLE I
NETWORK COST COMPARISON FOR ROUTING AND DIMENSIONING USING THE THREE TECHNIQUES AND FOR WP AND VWP MODE

			VWP			WP	
nr	α cost	β cost	SHR	iILP	SA	iILP	SA
1	0	50	5452	3996	4650	4800	5542
2	0	100	10452	7686	8550	9304	10332
3	0	200	20452	15300	16156	18298	20142
4	0	400	40452	30100	33364	32088	40550
5	40	50	6972	5610	5962	5528	6930
6	40	100	11972	8560	10032	9680	12198
7	40	200	21972	16234	18038	16270	21656
8	40	400	41972	28276	33996	30522	40374
9	400	50	20652	15998	17022	17648	17834
10	400	100	25652	21502	23612	21384	23334
11	400	200	35652	32868	30132	28078	33324
12	400	400	55652	48064	44940	42474	54140
13	4000	50	157452	125122	128882	136164	130188
14	4000	100	162452	125532	132542	140080	135750
15	4000	200	172452	146098	143736	147472	140946
16	4000	400	192452	148526	162938	161682	174996

values of the parameter k (from "k shortest routes"). Each combination of the parameters leads to a particular problem instance. The problem was solved in the following three ways.

- The shortest route was chosen for each demand and the links were dimensioned accordingly (without optimization). This was done only for VWP networks. In WP networks, a wavelength assignment strategy should be further specified.
- With ILP, as described above, [in fact interrupted ILP (iILP)].
- With SA, as described above.

This resulted in many simulations that allowed us to compare the network costs, number of used links of the initial topology, and the number of used fibers. In the following, comparisons are made and discussed.

Table I shows the results of 16 problems with the assumption of eight wavelengths multiplexed per fiber. The first three columns show the problem number and the α and β cost used uniformly over the whole network. The first column with results shows the network cost obtained from a shortest path routing and dimensioning, by rounding off the number of fibers upwards to the first integer number (100 fibers were required in 38 links) (SHR). The second and third column show the network cost from iILP and SA optimization, respectively, for the network in VWP mode. The last two columns show the network cost for both optimization techniques, with the network in WP mode. For each demand pair, five shortest routes were considered for the optimization ($k = 5$). Because the same cost parameters are used for WP and VWP networks, the cost of the wavelength converters is not accounted for.

SA runs according to a cooling scheme in which parameters can be tuned. Some experience with the technique is required in order to estimate a starting temperature and an adequate cooling scheme. The cooling scheme has been chosen to have runs of about 10-min duration. Longer runs can be obtained by decreasing the cooling speed. The CPLEX library, used for ILP, allows the interruption of the searching process of the B&B tree, after finding the ith integer solution or after a specified time. We fixed the duration at 10 min, unless otherwise stated. This allows us to compare the techniques fairly, as they consumed about the same computation time (on a PC Pentium 200).

When we compare the network cost in the iILP and SA columns with the values in the SHR column, we can estimate the benefit from optimization. On average we obtain a gain of 15% and in some cases up to 30%. iILP outperforms SA by 6%, on average, for VWP problems, and by 11%, on average, for WP problems.

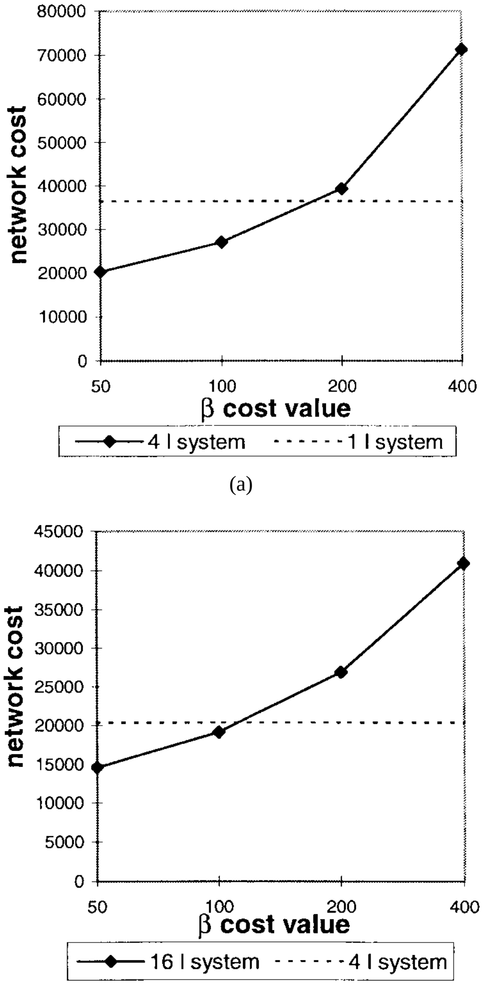
Long runs were made (to 12 h) to verify the gain in further exploring the B&B tree. At times, an up to 20% improvement was obtained on the first found integer solution within 2 h, whereas the additional improvement after searching several hours more, was very small. For the SA technique, a long run was performed by selecting a lower cooling speed. A more extensive search in the solution space can be done in this way. A longer simulation (a couple of hours) found only a 4% better solution than that found by a 10 min simulation.

When comparing iILP with SA for the studied implementation, we note that iILP requires more memory and becomes infeasible for big problems. On the other hand, it allows the optimal solution to a problem (within the memory constraints) and, given the same computation time, it yields better solutions than SA. For iILP, a more complex and larger problem does not mean that a relatively worse solution will be found or that it will take longer to find a solution. For SA, the relationship between problem complexity, computation effort, and solution quality is clearer. In general, for SA, a more complex problem will require more time in order to find a good solution, and a longer simulation will find a better solution.

When comparing the WP and VWP solutions, we can estimate the cost savings of wavelength conversion, while omitting the cost of the wavelength converters themselves. Theoretically, the cost of the VWP solutions should be a lower bound than for that of the WP solutions. In some cases, however, a better WP solution was found within the same cost parameters (e.g., the iILP solutions on rows 11 and 12 in Table I). This is due to the suboptimality of the heuristics. When omitting these odd cases, we obtained a 9% gain, on average, from wavelength conversion with the iILP optimization technique, while a 12% gain was achieved with the SA technique. The cost of the wavelength converters must be considered, relative to the cost of the other network equipment. Furthermore, in a comparison of WP and VWP networks, other aspects of wavelength conversion must be taken into account (e.g., management, interworking, and future proof). It is clear that the choice as to whether or not to use wavelength conversion depends on the network and the network strategy.

The cost of using a link (the α cost) differs for every network operator. Many operators already have dark fiber in the ground and can use it without major investment ($\alpha \approx 0$). Others need to install new fiber, excavate, or lease fiber from other operators. Depending on these considerations, the α cost will vary relative to the other cost values. Increasing the α cost results in a reduction of the number of links that are used in the resulting topology, as it becomes more expensive to use a link. This tendency is stronger when the initial topology is more meshed, which means that more candidate links can be omitted from the resulting topology. It was noted that more possible routes have to be considered (i.e., a higher k value in order to have more routes to choose from) in order to leave more links unused. The unused links can then be omitted from the final topology. An increased number of routes under consideration, however, results in a larger problem to solve, as each possible route corresponds with a variable in the problem.

Today, in most transport networks, single optical channel systems are used. An important question is when to upgrade to WDM and how many wavelengths should be used. When upgrading from single wavelength channel to multiwavelength channel transmission, fiber termination equipment such as multiplexers and demultiplexers must be installed. Perhaps, more complex gain flattened wide-band optical amplifiers will have to be used as well. Fiber termination components and amplifiers affect the β cost. Fig. 5 compares different line systems in the function of the β cost factor. In Fig. 5(a) the network cost is presented for a single channel system with a β cost value equal to 50. For a 4λ system, simulations have been carried out with β values varying from 50 to 400. The crossing point of both curves indicates how high the β value for the 4λ system may be in order to be less expensive than the single wavelength system. In Fig. 5(b) a 4λ system (with $\beta = 50$) is compared with a 16λ system. Upgrading from a 1λ system to a 4λ system is only advantageous if the β cost of the 4λ system is less than nearly four times higher than the corresponding β cost for the 1λ system, whereas for an upgrade to a 16λ system, β may be, at most, two times higher than the β for the 4λ system. The reason for this result is that in the first case, almost four times fewer fibers are required in the network, whereas in the latter case only half as many fibers are required. Indeed, when more wavelengths per fiber are considered, it is more difficult to fill all of the fibers as efficiently. There is, of course, a strong dependence on the considered network and traffic load. For a higher traffic demand, results show that a high number of wavelengths per fiber is justified. How the β cost value scales with the number of wavelengths of the line system depends on the technology and architecture of the crossconnect and the amplifier.



(a)

(b)

Fig. 5. (a) and (b) network cost comparison of routing and dimensioning for different line systems.

In conclusion, when the α and β cost are higher as compared to the γ cost, optimization will try to aggregate more traffic in a fewer number of fibers and a fewer number of cable links. In these cases, optimization can certainly improve the dimensioning. The variations in the results are, however, quite large, so that quantitative conclusions are difficult to make.

It is clear that by considering more routes and a more meshed initial network (i.e., more candidate links), greater improvement can be expected from optimization. This implies, however, that the solution space for the optimization techniques will get larger with a correspondingly greater computation effort.

TABLE II
RATIO SPARE FIBERS/WORKING FIBERS AFTER SPARE CAPACITY ALLOCATION FOR DIFFERENT RESTORATION STRATEGIES APPLIED FOR WPa, WPb, AND VWP MODE

restoration strategy	WPb	WPa	VWP
LR	79.06977	79.06977	65.11628
PR	69.76744	58.13953	51.16279
PRd	69.76744	53.48837	41.86047
PR+r	69.76744	48.83721	44.18605
PRd+r	69.76744	41.86047	39.53488

B. Spare Capacity Planning and Rerouting

A 31-link network covering Europe was considered for spare capacity planning and rerouting. The fiber capacity and the routes were optimized according to the ILP model described in Section III-B. The network was planned for eight wavelengths per fiber in WP mode. After omitting the wavelength specification for the routes, the same capacity and routes were used for the VWP case. For each restoration strategy (LR, PR, and PRd) the spare capacity was planned on top of the working capacity.

The results are summarized in Table II and expressed as the ratio of spare fibers to working fibers. In terms of spare capacity requirement, LR is most expensive. PR and PRd are cheaper. For the path restoration strategies, the released capacity of interrupted paths on intact links allows capacity reuse on these links and therefore an additional savings in capacity (PR+r and PRd+r). These results are in line with what was discussed in [17]. These conclusions hold for the three optical network modes WPa, WPb, and VWP.

When more candidate restoration routes (higher k value: 5 rather than 2) are considered, 5 to 10% cheaper solutions can be found. More computation effort, however, is required.

From Table II, we can compare the optical network modes. The cost of the spare capacity in the VWP case is less than in the WPa case, although not significantly. A remarkable difference can be noticed in comparing WPa and WPb for the path restoration strategies. It can be seen that wavelength tunable transmitters allow better usage of spare capacity and therefore require a lower spare capacity.

The benefit of wavelength conversion for static routing has already been found to be low [2, Sec. IV-A]. The results here show that for spare capacity assignment and rerouting the benefit is also low, however, tunability of the wavelength end to end gives a substantial benefit.

In the network under study, the working capacity has been optimized for 4, 8, and 16 wavelengths per fiber, with a model derived from the one presented in Section III-A. Fig. 6 shows the ratio of the fibers needed for spare capacity (SF) and the working capacity fibers (WF) for the PRd restoration strategy. One can conclude that the additional number of spare fibers compared with the number of working fibers decreases with the number of wavelengths used per fiber for the optical network modes WPa and VWP. This does not seem to be true for WPb. This can be understood intuitively. as follows. As was noted in Section IV-A, the filling in the case of 16 wavelengths per fiber cannot be done as efficiently as in the case of a lower number of wavelengths, therefore leaving many spare channels. WPa and VWP allow the more flexible use of these channels than is the case in the WPb mode.

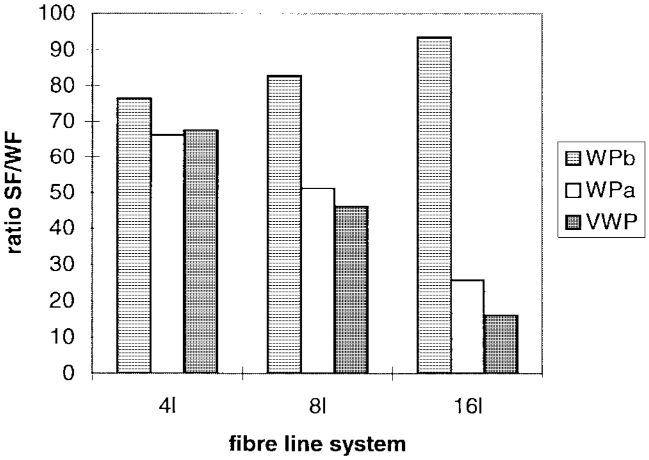


Fig. 6. Spare capacity requirement for different fiber line systems (different number of wavelengths per fiber: 4, 8, and 16).

We have also noticed a dependence on the meshing degree of the input network. In more meshed networks, a lower spare capacity requirement is seen. This is due to the fact that there is more residual spare capacity in these networks, and the meshed structure can be better exploited to do rerouting and to reuse spare capacity. Residual spare capacity refers to the available spare channels in the fibers used to accommodate the working capacity.

In some cases, one-step planning of working and spare capacity could be considered, e.g., in the case of the WPb mode and a path restoration strategy: the fact that the path must be rerouted on the same wavelength is too stringent for the spare capacity allocation when it is done in two steps. The wavelength could be better assigned in a one-step optimization, taking both working and spare capacity into account.

V. CONCLUSIONS

In this paper routing and planning of working capacity and rerouting and planning of spare capacity in WDM networks were investigated. The general optimization techniques ILP and SA have been used. The application of these techniques was explained and results were discussed.

The choice of the number of wavelengths to be used per fiber was discussed. A detailed study of the influence of the cost function on the planning was performed. As can be seen, when planning working capacity and routing, if the use of a link results in higher costs, a more meshed network, containing more candidate links and a larger set of possible routes for a demand pair, has to be considered in order to find a good solution. This implies a larger solution space to be explored during the optimization process.

As far as restoration is concerned, three restoration strategies have been compared and the influence of the network topology was investigated.

In general, from a planning aspect, no significant benefit in resource savings was noted from the use of wavelength conversion. Tunability of the laser sources, when not using wavelength conversion, however, has been found to be of substantial benefit.

In more detail, the benefit of wavelength conversion grows with the number of wavelengths considered per fiber. Therefore, if WDM is introduced with a small number of wavelengths per fiber, wavelength conversion is not strictly needed. It might be preferred, however, when upgrading to more wavelengths per fiber.

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