Optimal Allocation of Limited Optical-Layer Resources in WDM Networks under Static Traffic Demand

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***Abstract* ¾ In this paper, four heuristic algorithms for the optimal allocation of limited optical-layer resources in WDM networks (virtual-topology optimization by routing and wavelength assignment) under static traffic demand are compared. While some previous papers assumed that all connection requests must be necessarily satisfied, in this work algorithms are studied aiming at comparing their ability in minimizing both the usage of optical-layer resources and the number of connection requests that cannot be allocated. Thus, this paper reports the results obtained on a 13-nodes simplified topology of the pan-European optical transport network designed in the COST239 Project. The results of a few hundreds simulations with different traffic matrices have been gathered, by considering separately the cost of resources allocated and the percentage of rejected connections. One algorithm resulted best performing, because in most tests it allocated the lowest cost of optical-layer resources. On the other hand, the four algorithms exhibited comparable performance with respect to the percentage of rejected connections.**

***Index Terms* ¾ Optical Networks, Wavelength Division Multiplexing, Virtual topology, lightpath, heuristics.**

I. Introduction

The huge demand for telecommunications bandwidth, fostered by the exponential growing of Internet users and the new broadband services, is determining an unprecedented increase of network traffic in the high-capacity transport infrastructure. Wavelength Division Multiplexing (WDM) is a good solution to face this tremendous demand. While originally it was considered basically a mean to multiplex several high-capacity transmission channels on a common optical fiber, nowadays the WDM optical layer has evolved to support such network functions as circuit switching, routing and wavelength conversion and assignment [1]—[3].

In WDM networks, a wavelength is assigned to each connection in such a way that all traffic is handled in the optical domain, without any electrical processing on transmission. The established connections are called *lightpaths*: each of them occupies only one wavelength per link. The established lightpaths forms the *virtual topology*, or *logical topology*, opposed to the network *physical topology* made of nodes and fibers. Different lightpaths on the same fiber must use different wavelengths. To avoid conflicts, proper Wavelength Assignment (WA) at switching nodes must be done: each lightpath has to be routed being assigned an appropriate wavelength on each output link.

The complexity of the WA problem depends on the wavelength-conversion capability of network nodes. The combination of the two aspects is usually called Routing and Wavelength Assignment (RWA) problem. If lightpaths are judiciously routed, higher capacity networks can be built. For this reason, the definition of the virtual topology must fit as best as possible the traffic demand. In this paper, we consider static circuit requests. The problem of static optimization can be so summarized: given a static traffic matrix, find the optimum values for a set of network variables that minimizes a given cost function, under a set of constraints.

In many previous papers, the main objective of optimization is the cost of the physical network [4]—[7]. The network topology is given, except for one parameter (e.g., the number of fibers or of wavelengths on each link), which has to be minimized. In our study, instead, the physical topology is completely assigned and we want to exploit as best as possible the resources of the optical layer. Therefore, our objective is the optimal allocation of optical-layer resources (virtual-topology optimization) under static traffic demand.

Actually, other papers somehow addressed this topic [8]—[10] and many different objective functions were proposed. A widely accepted heuristic approach is to decompose the problem as follows: first, determine the virtual topology (i.e., route lightpaths); second, assign a wavelength to each lightpath; third, route the traffic. Our approach, instead, enables solving both routing and wavelength assignment at the same time. Considering simultaneously both aspects should lead to a better final solution.

Moreover, similar previous studies aimed at such virtual topology optimization, but assuming that *all* connection requests must be necessarily satisfied. Results evaluated by different algorithms are thus compared only for instances that satisfy all demands. Nevertheless, given some physical topology, it is difficult to think that heavy traffic demand matrices can be completely allocated: it may be acceptable that some connection requests are rejected. Therefore, in this paper, heuristic algorithms are compared aiming at minimizing both the usage of optical-layer resources and the number of rejected connection requests.

In Sec. II, we present the model of the network that has been employed to solve, at the same time, the routing and wavelength assignment problem. In Sec. III, we formulate our RWA problem by means of Integer Linear Programming (ILP). Unfortunately, this RWA problem is NP-hard: the optimal solution, therefore, cannot be found in practical cases. Thus, in Sec. IV, we propose heuristic methods for the design of quasi-optimal solutions. In Sec. V, finally, we present some

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simulation results. Several tests were carried out on mesh networks, considering different types of traffic requests and different values of the wavelength number on fibers.

II. NETWORK MODEL: THE WAVELENGTH GRAPH

Instead of routing lightpaths on the physical topology and then assigning wavelengths, we want to solve both problems at the same time (RWA problem). This can be done by using a tool usually called *wavelength graph* (WG) [4][8][11][12]. The WG is a graph that shows directly how lightpaths must be routed through the network to avoid wavelength collisions. It is a representation of the available wavelengths in the fibers and of the operations carried out by different nodes.

A network consists of nodes and links connecting nodes. This can be modeled by a graph: a node is a vertex and a link is an edge. Having multiple wavelengths, each edge represents only one of them. Each node type is modeled by a sub-graph, with weighted edges representing (with cost associated) fiber conversion and wavelength conversion. Different types of nodes have been considered: namely, Optical Add-Drop Multiplexer (OADM), Electro-Optical Cross-Connect (EXC) and Optical Cross-Connect (OXC) with full or limited wavelength conversion capability. Node models have been adapted from [8], with some changes mainly consisting in the fact that we deal with circuit requests.

Choosing a path through the WG model, therefore, means choosing a particular fiber and wavelength on each link and configuring the intermediate nodes. When a lightpath is routed through the WG, the corresponding edges are removed: in this way, the WG constantly shows only available resources of the optical layer.

A. *Optical Add-Drop Multiplexer*

OADM nodes have commonly two bi-directional ports (four unidirectional fibers). Their function is either to transmit a wavelength channel or to terminate it. They do not allow wavelength or fiber conversion. The WG model of OADM node is then shown in Fig. 1, for the sample case of four unidirectional fibers with three wavelengths on each. Each port has a number of vertices equal to the number of wavelengths on the fiber. Moreover, two further vertices (*end vertices*) represent lightpaths that begin (right) or end (left) in that particular node. In the WG, only end vertices can terminate lightpaths.

All edges are unidirectional. Two different end vertices have been introduced in the model to avoid algorithms using these edges as a possible route for transiting circuits [8], thus satisfying a connection request with two cascaded lightpaths. Moreover, no weights have been assigned to those edges, because all network lightpaths necessarily have to cross one of them at the start and one at the end. Finally, in our example, edges representing transition have been assigned the weight 25, as done in [8].

B. *Electro-Optical Cross-Connect*

EXC nodes allow all kinds of processing on incoming channels. Each one of them is converted to electronic domain, space-switched and then converted back to optical domain. This makes all operations to exhibit the same cost: in our model, we assigned the double value than for wavelength channel transmission in OADMs, i.e. 50. The WG model of EXC node is then shown in Fig. 2, again for the sample case of four unidirectional fibers with three wavelengths on each. Each pair of input-output vertices should be connected by an edge. However, in order to simplify the model, we used an auxiliary node, connected to all others by edges with half the total weight (in our example, 50/2=25).

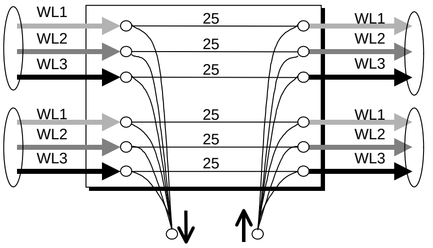

Fig. 1: WG model of OADM node.

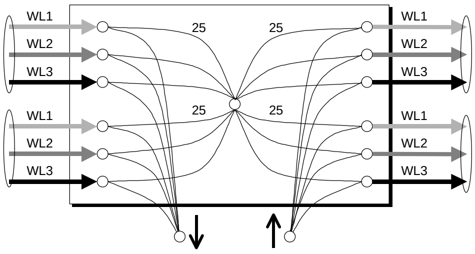

Fig. 2: WG model of EXC node.

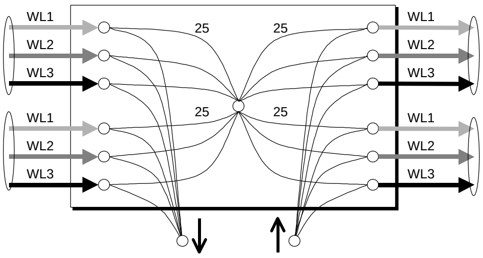

Fig. 3: WG model of OXC simple node without wavelength conversion capability.

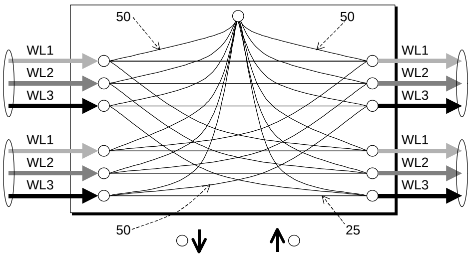

Fig. 4: WG model of OXC node with wavelength conversion capability.

C. *Optical Cross-Connect*

In a first, simple model of OXC node, without wavelength conversion ability, a lightpath can transit to any output port, provided that this port supports the particular wavelength required and that such wavelength is not yet used (fiber conversion). The WG model of this OXC simple node is then shown in Fig. 3 (four unidirectional fibers with three wavelengths on each). Weights are set according to the criterion that simple transit (weight=25) is preferred to fiber conversion (weight=50).

In some OXC nodes, however, wavelength conversion is also provided. The WG model of this second type of OXC node is then shown in Fig. 4 (four unidirectional fibers with three wavelengths on each). To represent wavelength conversion we used again an auxiliary vertex, as for the EXC model. Each edge connected to this vertex has weight equal to 50, so that wavelength conversion has been assigned total weight equal to 100.

III. PROBLEM FORMULATION

In this section, we formulate our RWA problem as an ILP problem, applied to the WG model presented in Sec. II. The objective function (total cost that we aim at minimizing) is:

$$\min \sum_{s,d\in \mathrm{L}} \left(c_r r_{s,d} + \sum_{i,j\in V} c_{i,j} x_{i,j}^{s,d} \right) \tag{1}$$

where the unknown variables, whose optimum values are aimed at, are:

$x_{i,j}^{s,d}$	Boolean (0,1) lightpath indicator, which denotes the presence of a lightpath from source node *s* to destination node *d*, on the edge *i-j* ($s,d\in V_E$; $i,j\in V$);
$r_{s,d}$	nonnegative integer number of rejected lightpaths from node *s* to node *d*.

The network physical topology, the type of the nodes (viz. OADM, EXC, OXC with and without wavelength conversion) and the following data are given:

L	static traffic matrix of lightpath requests; the element of the matrix $l_{s,d}$ denotes the number of lightpath requests from node *s* to node *d*; moreover, for the sake of brevity, with $s,d\in \mathrm{L}$ we denote the all couples of source and destination nodes for which $l_{s,d}>0$;
W	maximum number of wavelengths on each fiber (on the WG, $W=1$);
$c_{i,j}$	cost associated to edge *i-j*;
c_r	cost of rejecting one lightpath;
V	set of vertices;
V_E	set of end vertices.

Moreover, the following set of constraints, under which the total cost (1) must be minimized, is given:

$$\sum_{s,d\in \mathrm{L}} \sum_{i\in V} x_{i,r}^{s,d} = \sum_{s,d\in \mathrm{L}} \sum_{j\in V} x_{r,j}^{s,d} \qquad \forall r\in V-V_E \tag{2}$$

$$\sum_{d\in V_E} \sum_{j\in V} x_{s,j}^{s,d} \le \sum_{d\in V_E} l_{s,d} \qquad \forall s\in V_E \tag{3}$$

$$\sum_{s\in V_E} \sum_{i\in V} x_{i,d}^{s,d} \le \sum_{s\in V_E} l_{s,d} \qquad \forall d\in V_E \tag{4}$$

$$r_{s,d} \le l_{s,d} \qquad \forall s,d\in \mathrm{L} \tag{5}$$

$$x_{i,j}^{s,d} \le l_{s,d} \qquad \forall s,d\in \mathrm{L}\ ; \forall i,j\in V \tag{6}$$

$$\sum_{s,d\in \mathrm{L}} x_{i,d}^{s,d} \le W \qquad \forall i,j\in V \tag{7}$$

$$\sum_{j\in V} x_{s,j}^{s,d} = \sum_{i\in V} x_{i,d}^{s,d} \qquad \forall s,d\in \mathrm{L} \tag{8}$$

$$l_{s,d} - \sum_{j\in V} x_{s,j}^{s,d} = r_{s,d} \qquad \forall s,d\in \mathrm{L} \tag{9}$$

Constraint (2) ensures lightpath conservation in non-end vertices, i.e. it imposes that in such vertices the number of input and output lightpaths is the same. Constraints (3)(4) impose that the number of lightpaths between *s* and *d* (end vertices) does not exceed the corresponding requests. Constraint (5) ensures that the number of rejected lightpaths from *s* to *d* do not exceed the number of corresponding requests. With constraint (6), lightpaths are routed only between nodes requesting connection, while constraint (7) expresses that at most *W* optical channels can be built on each edge. Constraint (8) imposes that the number of lightpaths starting from *s* with destination *d* is equal to the number of lightpaths ending in *d* with origin *s* (i.e., that lightpaths end at their destination node and nowhere else). Finally, constraint (9) establishes the relationship between total requests, allocated requests and rejected requests.

IV. HEURISTIC ALGORITHMS

In this section, we propose four different heuristic methods for approaching a solution of the problem formulated in Sec. III: finding a sub-optimal allocation of optical-layer resources, given a network physical topology and a static traffic demand, while minimizing both the usage of resources and the number of rejected connection requests.

These algorithms are all based on the same principle: connection requests $s\rightarrow d$ are sorted according to some criterion and allocated in sequence, one lightpath at a time, routed via the minimum-cost path. Such algorithms are often referred to as *Sequential Shortest Path* (SSP) algorithms.

After every lightpath allocation, a new permutation of the sequence of requests to submit is done and the first request is then served. In some previous works [8], the permutation is generated only once, at initialization; nevertheless, re-sort requests after each lightpath allocation improves the method accuracy. The four methods differ from each other in the criterion used to sort requests. Analogous criteria (but in different contexts) have been used in [5][8][13]—[15]. Thus, the algorithm steps are as follows.

1. Create a permutation of the connection requests $s \rightarrow d$ that have not been served yet, according to the sorting criterion selected. If the traffic request matrix L is empty, then END.
2. Find the shortest path between the two end nodes s, d of the first request in the permutation. If no such path is found, discard all lightpath requests pending between this pair of nodes, else allocate one lightpath and decrement the corresponding matrix element $l_{s,d}$ by one unit.
3. Update the available links of the network model and the number of rejected requests accordingly.
4. Goto 1.

We selected the following basic criteria to sort connection requests in a new permutation.

- *Random Sequential Shortest Path* (RSSP): the permutation is generated randomly, with uniform probability;
- *Minimum Hop* (mH, SSP-1.0): requests are sorted by the number of fibers (hop distance) needed to connect the end nodes. Shorter demands are presumably cheaper, and thus more room for the others to come is left.
- *Maximum Request* (MR, SSP-0.0): requests are sorted by the number of lightpaths requested, with precedence to largest demands. These are the requests that are more difficult to satisfy and thus they are served first.
- *Maximum Request and Minimum Hop* (SSP-x): a weighted mix of previous criteria is adopted. Requests are sorted according to the following function to minimize:

$$f(x) = x\frac{h_{s,d}}{\sum_{s',d'\in \mathrm{L}} h_{s',d'}} - (1-x)\frac{N_{s,d}}{\sum_{s',d'\in \mathrm{L}} N_{s',d'}} \qquad (10)$$

where h_d denotes the hop distance between the end nodes of the request s, d and N_d is the number of circuits that are requested between them. The parameter x ($0<x<1$) sets the relative importance of the two criterions. Note that x=0 corresponds to MR sorting, while x=1 to mH sorting: this explains the algorithm names above. In our simulations, we settled x=0.5.

V. COMPARISON OF ALGORITHM PERFORMANCE

The four heuristic algorithms proposed were tested on mesh networks, for different traffic matrices and different values of the number of wavelengths W, aiming at comparing their ability in minimizing both the usage of optical-layer resources and the number of rejected connection requests.

In this section, we report tests carried out on a 13-nodes simplified topology of the pan-European optical transport network designed in the COST239 Project [16][7][8], shown in Fig. 5. The nodes where more than two physical links converge (e.g., Paris) are OXCs, while the others are simple OADMs. The number of wavelengths on each fiber was set to W=2, 4, 8 and 16.

Since we aim at comparing algorithm performance, traffic requests have been generated randomly, offering heavy traffic demand to yield unrealistic high reject probability. Moreover, we considered three different traffic patterns: 1) few nodes pairs, each one requesting many circuits; 2) many node pairs, each one requesting few circuits; 3) an intermediate case between previous two. No substantial difference was experienced in algorithm performance depending on the traffic pattern.

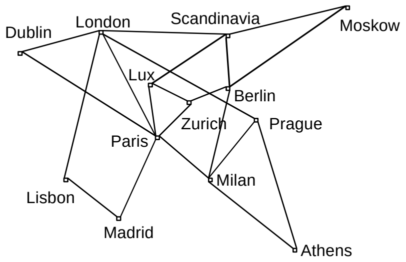

Figure 5: Simplified topology of the Pan-European optical network [16].

For comparing algorithm performance, the results of a few hundreds simulations with different traffic matrices have been gathered, by considering separately the cost of resources allocated and the percentage of rejected connections. Thus, the graph in Fig. 6 compares the average cost of optical resources allocated by the four algorithms, normalized to have the cost achieved by the RSSP algorithm equal to 100, for each value of W. This graph groups results of simulations that yielded any percentage of rejected connections. On the other hand, the graph in Fig. 7 compares the percentage of rejected connections yielded by the four algorithms, for each value of W. This graph groups results of simulations that allocated any cost of optical-layer resources. Obviously, in both graphs, each set of four bars, for a given W, compares results achieved in four sets of simulations with the same traffic matrices. On the contrary, the sets of four bars were obtained with different traffic matrices.

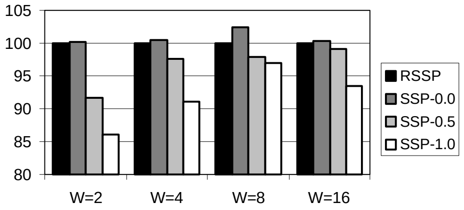

Fig. 6: Average cost of optical resources allocated by the four algorithms (results with any percentage of rejected connections).

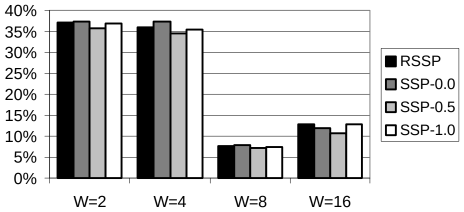

Fig. 7: Percentage of rejected connections yielded by the four algorithms (results with any cost of optical resources).

By inspection of the graph in Fig. 6, we infer that SSP-1.0 (mH) allocated lower costs. Surprisingly enough, SSP-0.0 (MR) gave results similar to RSSP: they yielded the highest costs. By inspection of the graph in Fig. 7, on the other hand, we do not recognize any substantially different behavior of the four algorithms with respect to the percentage of rejected connections. In the same graph, however, we notice that it is not meaningful to compare the different percentages exhibited in simulations for *W*=2, 4, 8 and 16, as achieved with different traffic loads.

Moreover, the graphs shown in Figs. 8 and 9 compare again the normalized average cost of optical resources allocated by the four algorithms, but group only results of simulations with no rejected connections and results of simulations that yielded a percentage of rejected connections in the range 5%÷15%, respectively. By inspection of these graphs, we infer again more or less the same conclusions: SSP-1.0 (mH) allocated lower costs, while SSP-0.0 (MR) often allocated the highest cost.

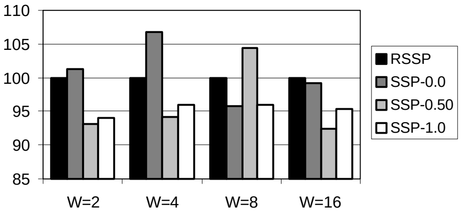

Fig. 8: Average cost of optical resources allocated by the four algorithms (results with no rejected connections).

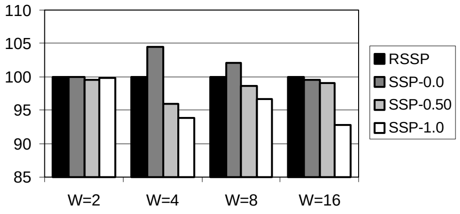

Fig. 9: Average cost of optical resources allocated by the four algorithms (results with percentage of rejected connections in the range 5%÷15%).

VI. CONCLUSIONS

In this paper, four heuristic algorithms for the optimal allocation of limited optical-layer resources in WDM networks (virtual-topology optimization by routing and wavelength assignment) under static traffic demand were compared. While some similar previous papers assumed that all connection requests must be necessarily satisfied, rejecting the entire traffic matrix if not all requests can be accepted, in this work the algorithms proposed were studied aiming at comparing their ability in minimizing both the usage of optical-layer resources and the number of rejected connection requests.

The four heuristic algorithms exhibited no substantial difference in their performance depending on the traffic request pattern (balanced vs. unbalanced). The best performing algorithm resulted that based on minimum-hop sorting of connection requests (SSP-1.0), because in most tests it allocated the lowest cost of optical-layer resources. On the other hand, we did not recognize any substantially different behavior of the four algorithms with respect to the percentage of rejected connections.

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