Exploiting OTDM technology in WDM networks

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***Abstract*—**

Wavelength routed optical networks allow to design a logical topology, comprising lightpaths and routers, which is overlayed on the physical topology, comprising optical fibers and optical cross-connects, by solving a Routing and Wavelength Assignment (RWA) problem.

In this paper we extend the concept of lightpath to the one of Super-Lightpath, which uses a simple bit level Time Division Multiplexing that can be directly implemented in the optical domain, to split the wavelength bandwidth among more than one traffic flow. This allows to design logical topologies with an increased number of logical links, thus reducing the average distance among nodes, i.e., the number of electro-optic and opto-electronic conversions, and the traffic congestion on logical links. At the same time, this reduces the number of wavelengths required to solve the RWA problem. Being the Super-Lightpath RWA problem computationally intractable, we propose two heuristics which show that the number of wavelengths required to overlay the same logical topology on the same physical topology is reduced by more that 65% using Super-Lightpaths.

I. INTRODUCTION

Internet is facing a constant increase in bandwidth demand, due to the growth of both the services available on-line, and the number of connected users. The fact that new users are increasingly attracted by new services, causes a positive feedback, whose consequence is the need for continuous upgrades of the network infrastructure. Wavelength-Routed (WR) optical networks, which employ Wavelength Division Multiplexing (WDM), are considered the best candidate for the short-term implementation of a high-capacity IP infrastructure, since they permit the exploitation of the huge fiber bandwidth, and do not require complex processing functionalities in the optical domain.

In WR networks, high-capacity (electronic) routers are connected through semi-permanent optical pipes called *lightpaths* that may extend over several physical links. Lightpaths can be seen as chains of physical channels through which packets are moved from a router to another toward their destinations. At intermediate nodes, incoming channels belonging to in-transit lightpaths are (transparently) coupled to outgoing channels through an optical cross-connect that does not process in-transit information. Instead, incoming channels belonging to terminating lightpaths are converted to the electronic domain, so that packets can be extracted and processed, and possibly retransmitted on outgoing lightpaths after electronic IP routing.

In a WR network, a *logical topology*, whose vertices are the IP routers and whose edges are the lightpaths, is therefore overlayed to the *physical topology*, made of optical fibers and optical cross-connects. In principle, the *logical topology* configuration is independent from the physical topology; however, a number of constraints exist: i) the number of lightpaths departing and terminating at each node is limited by the number of transmitters/receivers and by the processing capability of electronics; ii) the establishment of each lightpath requires the reservation of physical resources (i.e., a WDM channel on the optical fibers along the path); since the number of wavelengths per optical fiber is limited, only a subset of logical topology configurations is feasible; iii) the maximum allowable length of lightpaths (in terms of both physical span and number of crossed devices) may be limited by the degradation of optical transmission parameters along lightpaths.

In recent years, a large effort has been devoted to solve the problem of identifying the best logical topology that minimizes a given cost function, while accommodating the traffic pattern given as input. Traffic that cannot be directly transfered from the source node to the destination node (because no direct link is present in the logical topology) will be using a multi-hop routing approach. This problem is generally called in the literature Logical Topology Design (LTD). It has been shown that the identification of the optimal logical topology is computationally intractable for large size networks [1], [2], and several heuristic approaches were proposed for the identification of suboptimal solutions [2], [3], [4], [5], [6], [8], [7], [9], [10], [11], [12], [13], [14].

Once the LTD problems has been solved, the resulting logical topology must be overlayed over the physical topology. This procedure must i) identify the set of physical optical fibers over which each lightpath will be routed from the source node toward the destination node, (i.e., a suitable physical path must be identified), ii) choose the correct wavelength that will be used for each lightpath, such that two lightpaths that are routed over the same optical fiber use two different wavelengths. This problem is usually referred in the literature as Routing and Wavelength Assignment (RWA) problem [15], [16], [17], [18], [19], [20], [21]. Wavelength converters can be instrumental to simplify the RWA problem.

Once the LTD and RWA problems are solved, and the logical network is set up, IP routers are able to transfer data among them, using the classic IP approach.

A possible bottleneck in a WDM system is the need of electronic conversion whenever a lightpath is terminated in a node. Data must be converted to the electronic domain, packets must

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be reassembled, processed, forwarded and then eventually converted again to the optical domain if the current node is not the final destination of the data (hence is implementing a multihop routing strategy for the considered traffic flow). While the current optical technology allows to transmit data at very high speed, the electronic conversion and elaboration is more speed limited and very costly at high speeds. Electronic processing is however still required at lightpaths endpoint, due to the lack of optical memory and processing power, but the minimization of the number of electronic conversions is one major goal in the future high speed networks. Moreover, a traffic flow that is accommodated on a multihop electronic path (because there is not a direct optical link between the source and the destination) consumes more electronic resources in the network, possibly increasing the network bandwidth requirements.

There is a tradeoff between the number of links in the logical topology and the RWA problem: it is quite intuitive that the larger the number of lightpaths, the smaller is the number of required electronic conversions. However, this increases the number of wavelengths that are necessary to solve the RWA problem, and the number of transmitters/receivers that each node must have, resulting in a more costly solution both for optical cross-connects and for node interface.

For example, the best logical topology one can build is the fully connected topology in which a logical link exists between each source and destination. This will indeed minimize the number of electronic conversions. However, the fully connected solution maximizes i) the number of lightpaths in the network, ii) the number of wavelengths required to accommodate all the lightpaths, and iii) the number of transmitters and receivers in each node.

We propose in this paper the joint use of WDM and Optical Time Division Multiplexing (OTDM) technologies (see Sec. V), which offers an interesting opportunity of splitting the bandwidth of a lightpath into a fixed number of subchannels, using a Time Division Multiplexing (TDM) scheme directly in the optical domain. We assume that the bandwidth available on a wavelength channel is very large with respect to the bandwidth required by individual information flows. A bit level, fixed framing is determined, such that each bit in a given position in the frame, called bit slot, identifies a particular sub-channel. Using a bit interleaver, the transmitter multiplexes sub-channels into the frame, and transmits the resulting stream into one lightpath, using the same wavelength. We call this TDM lightpath a *"Super-Lightpath"*. Each receiver can then synchronize a tunable receiver to a particular bit slot, and receive only data on that particular sub-channel, directly in the optical domain thanks to OTDM capabilities.

A Super-Lightpath can travel through many nodes, and a node can receive one (or many) subchannel(s) from it, instead of converting the whole bit stream to the electronic domain, while transparently routing the entire Super-Lightpath toward another node. It is thus possible to split a lightpath into many sub-channels, each having a bandwidth that is fraction of the lightpath bandwidth.

Figure 1 shows a simple scenario: in (A) the physical topology is plotted, comprising four nodes, connected in a monodirectional ring by means of optical fibers. The logical topology is reported in (B), where each node is connected with all other nodes, thus forming a fully connected logical topology. Figure (C) shows a possible solution of the RWA problem, where each node is source of three lightpaths that are terminated at each destination node; six wavelengths are used on each optical fiber. The solution using the Super-Lightpath approach is shown in (D), where each node is equipped with only one transmitter, and each Super-Lightpath is (partly) converted to the electronic domain in each destination node. Each Super-Lightpath multiplexes, using a fixed TDM frame, the three logical links exiting from the same source node. Note that using Super-Lightpaths the number of wavelengths required is 4, and no more that 3 wavelengths are present on the same optical fiber. Moreover, each node is equipped with only one (tunable) transmitter, that has a line speed that is 3 times larger than those used in (C), while the number of receivers in each node is the same.

From a networking point of view, a logical link is completely identified by the wavelength of the Super-Lightpath and the bit slot of the TDM frame. From an optical point of view, instead, the union of the bit slots of the TDM frame forms a Super-Lightpath, that, instead of being a-point-to-point link among two nodes (as a classic lightpath), is a point-to-multipoint link, which originates from the source node, and sequentially reaches all the destination nodes in the TDM frame using the same wavelength.

Note that the use of the Super-Lightpath will affect only the RWA problem, because the same logical topology can be overlayed by using point-to-point lightpaths carrying one logical link, or using point-to-multipoint Super-Lightpaths, each one carrying more than one logical link, multiplexed by TDM.

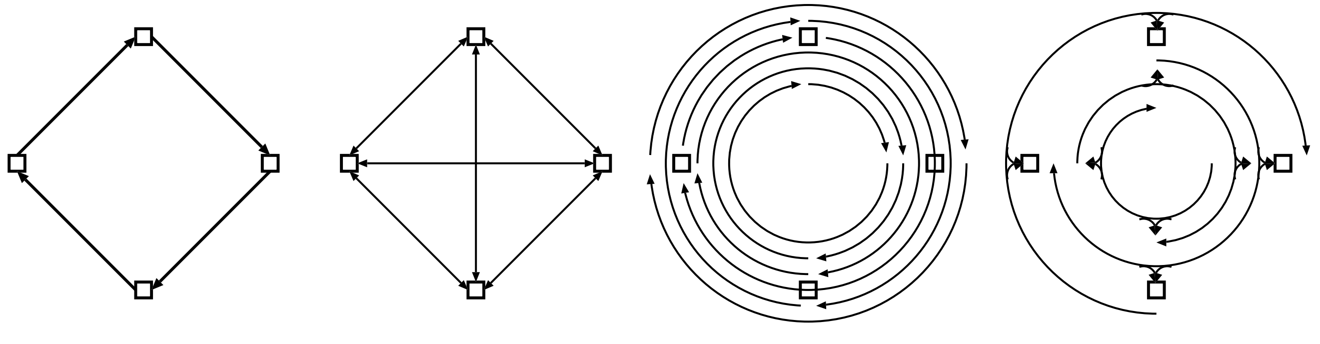
There are a number of advantages using the Super-Lightpath approach:

- reduction in the number of transmitters per node: each transmitter will be used to send data to more than one receivers, thanks to the TDM approach;
- increment of the number of point-to-point logical links, leading to the opportunity of building a more connected logical topology;
- more flexibility in the bandwidth allocation, because the lightpath bandwidth can be split among many receivers;
- reduction in the number of the wavelengths required to solve the RWA problem.

The remaining of the paper is organized as follows. In Section II we focus on the LTD problem and the impact of the connectivity degree on performance indices such as average distance and congestion in the logical topology. In Section III we formulate the RWA problem, using a mixed integer linear formulation of the problem, and prove that it is NP-complete. Two heuristics are presented in Section III-B and the performance results are presented in Section IV. The technological issues related to the OTDM technology are briefly presented and discussed in Section V. Finally, Section VI summarizes the paper.

II. IMPACT OF CONNECTIVITY DEGREE ON THE LOGICAL TOPOLOGY DESIGN

One of the advantages offered by the WDM technology is the flexibility in designing logical topologies that can be superposed on the existing physical infrastructure. In this section we



(A) (B) (C) (D)

Fig. 1. Example: (A) - Physical Topology; (B) Logical Topology; (C) Classic RWA; (D) Novel Super-Lightpath RWA

evaluate the impact of the connectivity degree, i.e., the number of transmitters/receivers each node is equipped with, on the logical topology design. In particular we show that increasing the connectivity degree reduces network diameter, thus reducing the number of electronic conversions and processing a packet will suffer toward its destination. This results in a better exploitation of the network capacity, leading to a reduced traffic congestion. However, the number of required lightpath increases, as well as the number of wavelengths used by the RWA solution. The problem of the optimal Logical Topology Design (LTD) can be generally stated as follows.

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1) a network of M nodes, where each node i is equipped by $\delta_O^{(i)}$ output ports and $\delta_I^{(i)}$ input ports;
2) a routing strategy to be adopted on the logical topology;
3) a description of the traffic exchanged by sources and sets of destinations;

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the logical topology that minimizes a target function (or cost).

This problem was proven to be NP-hard [13] and thus computationally intractable, even for networks with a moderate number of nodes.

A. Diameter and Average Distance

Different cost functions can be chosen as optimization target. In this section we ignore the traffic pattern description and only concentrate on the impact of the connectivity degree (i.e., the number of logical links exiting from, and entering to a node) on the number of electronic conversions that a traffic flow must face before reaching the destination node, i.e., the number of nodes that a traffic flow has to cross on the logical topology before reaching the destination node. In this case, it is straightforward to observe that the multihop routing algorithm that minimizes the distance between the source and the destination is a shortest path algorithm with link weight equal to 1 for all links.

For the sake of simplicity, let us consider $\delta_O^{(i)} = \delta_I^{(j)} = \Delta \ \forall i, j$. The *distance* between node i and node j in a given (logical) topology is the minimum number of logical links that must be traversed to reach node j starting from node i, and is denoted by d_{ij}. Obviously, $d_{ii} = 0$. The maximum distance in a given logical topology is denoted by $d_{\max} = \max_{(i,j)} d_{ij}$. This is usually referred as *network diameter*.

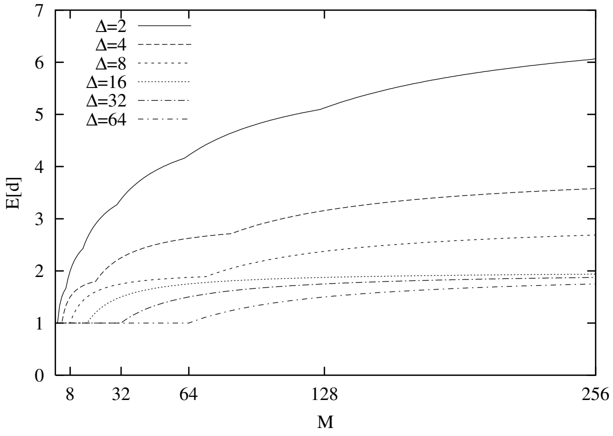

Fig. 2. Lower bound on the average distance in a topology with M nodes and connectivity degree Δ.

The average distance related to node i in a given logical topology is denoted by $E[d_i]$, and can be obtained as

$$E[d_i] = \frac{1}{M-1}\sum_{j=1}^{M} d_{ij} = \frac{1}{M-1}\sum_{d=1}^{d_{\max}} d\, m_i(d) \qquad (1)$$

where $m_i(d)$ denotes the number of nodes at distance d from node i. Note that the situation where a node transmits to itself is ruled out by this definition.

The overall average distance in a given logical topology is denoted by $E[d]$, and it can be obtained as

$$E[d] = \frac{1}{M}\sum_{i=1}^{M} E[d_i] \qquad (2)$$

1) Lower Bound: It is possible to devise a lower bound on $E[d]$ by considering the (infeasible) logical topology obtained by rooting in each source i a tree of degree Δ, similarly to [2]. There will be Δ destinations at one hop distance from i, Δ^2 at two hops, Δ^3 at three hops, etc. Thus, being all the sources roots of a similar tree, we derive:

$$d_{\max}(M, \Delta) \geq \lceil \log_\Delta M \rceil \qquad (3)$$

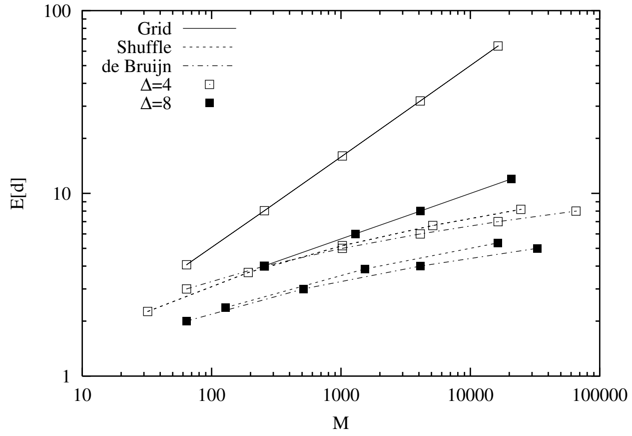

Fig. 3. Average diameter for different regular topologies.

$$E[d](M,\Delta) \geq \frac{1}{M-1}\sum_{i=1}^{d_{\max}(M,\Delta)-1} i\Delta^i + \left(M - \sum_{i=1}^{d_{\max}(M,\Delta)-1}\Delta^i\right)\frac{d_{\max}(M,\Delta)}{M-1} \tag{4}$$

Figure 2 plots the lower bound (4) of the average distance $E[d]$ versus the number of nodes M in a network, for different connectivity degree Δ. As expected, the higher the connectivity degree, the lower the average distance. Moreover, in small size networks, increasing Δ does not always provide a benefit, while in large size networks, the gain in term of average distance becomes significant.

2) Regular Topologies: In order to consider a feasible logical topology, the use of regular topologies can be instrumental to find a solution to the optimization problem that aims to minimize the average distance. This approach has been thoroughly studied in the literature [8], [7], [12], [22], [23], and it has been shown to yield good solutions. While it is not possible to design a regular topology for all values of M and Δ, we can still compare the average distance of networks with the same connectivity degree and different number of nodes.

Figure 3 reports average distance obtained using *grid*, *twin shuffles*, and *de Bruijn* topologies for $\Delta = 4$ and for $\Delta = 8$. The reader interested in the analytical expressions of $d_{\max}$ and $E[d]$ is referred to [23].

These graphs clearly show that increasing the connectivity degree can drastically reduce the average distance. For example, considering the grid topology with $M = 256$, it is possible to halve $E[d]$ using $\Delta = 8$ instead of $\Delta = 4$; considering instead the de Bruijn topology, it is possible to build topologies with average distance equal to 4 that comprise 256 nodes with connectivity degree of 4, or 4096 nodes with connectivity degree of 8.

B. Congestion Level

When considering the whole optimization problem including a traffic pattern description, the cost function that is commonly used is the maximum congestion level $\alpha_{\max}$ in the network, defined as the maximum ratio between the total traffic flow on a given lightpath and its bandwidth. This metric normally drives important network performance indices, such as loss probability and delay [3]. Both the queueing delay and the loss probability, indeed, mainly depend on the congestion experienced on the traversed lightpath with highest-load.

Let each node in the network be equipped with Δ transmitters and Δ receivers, whose bit rate is B bit/s; thus the bandwidth of each node is $C = \Delta B$. Let $\mathcal{T}$ be a traffic matrix, whose element t_{ij} is the average traffic going from node i to node j. Let f_l be the total traffic that results from the sum of all portions of the traffic flows t_{ij} that are routed on the logical link l. Then[1]

$$\alpha_{\max} = \max_l \left\{\frac{f_l}{B}\right\} \tag{5}$$

We investigate how the connectivity degree impacts on $\alpha_{\max} = \alpha_{\max}(\Delta)$, while keeping constant the total bandwidth of each node and the offered traffic pattern. For example, it is possible to compare a logical topology whose nodes have 4 transmitters/receivers of 10 Gbit/s each, with a network with nodes equipped with 16 transmitters/receivers each of 2.5 Gbit/s bandwidth.

To obtain numerical examples, we implemented an optimization algorithm, derived from [24], [25], that relies on the application of the Tabu Search (TS) methodology [26]. Given a network topology with $M = 50$ nodes, and given a traffic matrix, we imposed a connectivity degree of $\Delta = 2, 4, 8, 16$, while keeping constant the bandwidth of each node, i.e., selecting the logical link bandwidth to be $B = 20, 10, 5, 2.5$ Gbit/s respectively; thus the total bandwidth of the network is equal to $2 \times 20 \times 50 = 2000$ Gbit/s.

We ran the logical topology optimization algorithm and evaluated the maximum congestion on the lightpaths of the resulting optimized topology.

We report results for a traffic pattern matrix $\mathcal{T}$ that is randomly generated, using a uniform distribution with average 150 Mbit/s for each traffic relation, i.e., $t_{ij} = U[1, 299]$ Mbit/s. Compared to the total bandwidth of the network, the total average offered traffic is equal to $150 \times 50 \times 49 = 367.5$ Gbit/s. In order to get different traffic scenarios, five different traffic matrices were generated using different random seeds.

Table I reports, for different values of Δ, the maximum congestion level observed after the optimization of each topology, and the percentage congestion gain $\eta_\alpha(\Delta)$ obtained increasing the bandwidth, with respect to the scenario with $\Delta = 2$, i.e.

$$\eta_\alpha(\Delta) = 100\frac{\alpha_{\max}(2) - \alpha_{\max}(\Delta)}{\alpha_{\max}(2)} \tag{6}$$

Results are reported for the five different traffic matrices, and their average is reported in the last row.

In the case $\Delta = 2$, the maximum congestion level is close to one, meaning that the average utilization of network links is relatively high and probably critical in case of traffic increments or variations. Increasing the connectivity degree to 4, produces a maximum utilization of about 0.8, which corresponds to an

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[1] $\alpha_{\max} < 1$ holds, since otherwise the bandwidth of the network is not large enough to carry the offered traffic $\mathcal{T}$.

TABLE I
NUMERICAL RESULTS IN TERMS OF CONGESTION.

	maximum congestion				congestion gain %		
Δ	2	4	8	16	4	8	16
$\mathcal{T}_1$	0.95	0.77	0.70	0.69	18.5	25.8	27.3
$\mathcal{T}_2$	0.97	0.83	0.77	0.77	12.4	19.3	19.3
$\mathcal{T}_3$	0.95	0.80	0.71	0.70	15.8	25.2	25.9
$\mathcal{T}_4$	0.95	0.79	0.73	0.71	16.2	23.4	24.9
$\mathcal{T}_5$	0.97	0.77	0.67	0.67	18.6	28.8	29.4
E	0.96	0.79	0.71	0.70	16.5	25.3	26.3

average gain of 16.5 %. This means that the total network bandwidth is better fragmented among the logical links, thus allowing a better utilization and performance., i.e., 16.5% more of traffic can be carried, or 16.5% less bandwidth can be installed to obtain performance similar to $\Delta = 2$.

Having a connectivity degree of 8 further improves the congestion gain, leading to a maximum congestion level of about 0.7, which corresponds to a 25% gain when compared to the case $\Delta = 2$. Increasing further the connectivity degree to $\Delta = 16$ brings little additional improvement, as the congestion gain becomes only one percent point higher when compared to the case of $\Delta = 8$. This is not surprising, because the number of nodes in the network is such that with $\Delta = 8$ the length of all source destination paths can be smaller than or equal to 2. For example, a de Bruijn graph of 64 nodes and connectivity degree of 8 has a maximum distance of 2 (see Figure 3). Thus doubling the connectivity degree does not give additional benefits.

These simple scenarios show that a benefit is obtained by increasing the connectivity degree of the logical topology: it results in a finer bandwidth granularity which in general better matches the offered traffic pattern, and in a better utilization of the total network bandwidth.

III. ROUTING AND WAVELENGTH ASSIGNMENT

Once the logical topology has been designed, it must be overlayed on the top of the physical topology. We evaluate here the impact of the TDM scheme The classic RWA problem, which does not use wavelength converters, can be formulated as follows.

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1) a physical topology, comprising nodes connected by optical fibers;
2) a logical topology, comprising nodes connected by logical links;

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for each logical link:

1) a route from the source node to the destination node on the physical topology;
2) wavelength colors such that two logical links using the same optical fiber have two different colors;

such that the required total number of wavelengths is minimized.

Thus, in order to solve the RWA problem, we must identify a physical path and a color for each logical link. The source node then tunes a tunable transmitter to that wavelength, while each node along the path configures the optical cross-connect, and the destination node tunes a tunable receiver. Data can thus travel from the source node to the destination node using the resulting lightpath.

The key idea proposed in this paper is to split the large bandwidth offered by the optical components by means of a TDM scheme, and to reuse the same wavelength to transport information from the same source to more than one node: a number of logical links are multiplexed using a fixed TDM scheme, and then transmitted from the source node using the same wavelength that is optically routed toward all destination nodes in the TDM frame. Each node can thus convert to the electronic domain only a subset of the multiplexed logical links, while transparently coupling the whole lightpath toward the next destination. We call this point-to-multipoint lightpath a Super-Lightpath. Note that the optimal routing solution of a Super-Lightpath assumes to find a minimum cost tree rooted in the source node, that reaches every destination in the same Super-Lightpath. This indeed implies the capability of splitting in the optical layer an incoming lightpath into many outgoing lightpaths. In this paper, however, we do not consider this opportunity, and suppose that a lightpath cannot be split in a node, but either terminated or routed to the next node.

Note that the use of Super-Lightpaths only affects the RWA solution. We call the RWA problem with Super-Lightpaths the Super-Routing and Wavelength Assignment (S-RWA), because it differs from the classic RWA problem by the fact that, given a source node, it must also identify the set of destinations that will be grouped, and the sequence in which they will appear in a Super-Lightpath. In particular, the problem can be generally formulated as follows.

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1) a physical topology, comprising nodes connected by optical fibers;
2) a logical topology, comprising nodes connected by logical links;

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for each source:

1) the set of destinations that, using TDM, are multiplexed in a Super-Lightpath;
2) the order in which those destination must be reached by the Super-Lightpath;

and for each Super-Lightpath:

1) a route from the source node to all the destination nodes in the Super-Lightpath;
2) a wavelength color such that two Super-Lightpaths using the same optical fiber have two different colors;

such that the total number of required wavelengths is minimized.

A. Problem formulation of the S-RWA problem

In this section we provide a problem formulation of the S-RWA problem.

Let $\mathbf{F} = \{\mathbf{F}_{mn}\}$ be the matrix whose elements are binary variables that take the value 1 if there is a physical optical fiber starting from node m and ending into node n.

Let $\mathbf{T} = \{\mathbf{T}_{sd}\}$ be the matrix whose elements are binary variables that take the value 1 if there is a logical connection starting from node s and ending in node d. Thus, $\mathbf{T}$ is the logical topology that must be superposed to the physical topology $\mathbf{F}$.

Let W be the maximum number of wavelengths that can be used in the optimization. Let β^w be a binary variable that takes the value 1 if the wavelength w is used in the solution.

Let a_c^{sd} be binary variables that take the value 1 if the source s is using the Super-Lightpath c to reach destination d.

Let z_c^{sd} be binary variables that take the value 1 if the source s is using Super-Lightpath c to reach destination d, and d is the endpoint of the Super-Lightpath, i.e., d is the last destination served by Super-Lightpath c.

Let p_{mn}^{scw} be binary variables used to describe the route of Super-Lightpath c from s. p_{mn}^{scw} is equal to 1 if the wavelength w is used by Super-Lightpath c from s on the optical fiber from node m to node n.

With the previous definitions, a Super-Lightpath is identified by the couple sc.

The following ILP formulation describes the S-RWA problem

$$\min\ w \tag{7}$$

Subject to:

$$\beta^w \leq \beta^{w-1} \qquad 0 \leq w \leq W \tag{8}$$

Equation (8) states that the wavelengths used must be turned on "in order". This is not strictly required, but it helps the solver to find a suitable solution.

$$\sum_{c=1}^{\gamma_O^{(s)}} a_c^{sd} = \mathbf{T}_{sd} \quad \forall s, d = 1, \ldots, M \tag{9}$$

$$\sum_{d=1}^{M} a_c^{sd} \leq D \quad \forall s = 1, \ldots, M,\ \ c = 1, \cdots, \gamma_O^{(s)} \tag{10}$$

Equation (9) states that a destination d can be reached from source s only if it is present in the logical topology and that d is reached at most by one Super-Lightpath; $\gamma_O^{(s)}$ is the maximum number of Super-Lightpaths that can depart from source s, i.e., the connectivity degree. Equation (10) limits the number of the destinations that can be reached by one Super-Lightpath; D is the *multiplexing factor* that represents the bandwidth of the Super-Lightpath in terms of destinations, i.e., the degree of multiplexing that can be used on a Super-Lightpath using the TDM approach. Thus the connectivity degree for node s in the logical topology is $\delta_O^{(s)} = \gamma_O^{(s)} D$.

$$z_c^{sd} \leq a_c^{sd} \quad \forall s, c, d \tag{11}$$

$$\sum_{d=1}^{M} z_c^{sd} \leq 1 \quad \forall s, c \tag{12}$$

The previous inequalities state that a node d can be the last node in a Super-Lightpath only if it is also reached by the same Super-Lightpath (Eq. (11)), and that only one termination exists in the Super-Lightpaths (Eq. (12)).

$$p_{mn}^{scw} \leq \mathbf{F}_{mn} \quad \forall s, c, w \tag{13}$$

$$p_{mn}^{scw} \leq \beta^w \quad \forall m, n, s, c, w \tag{14}$$

$$\sum_{s=1}^{M} \sum_{c=1}^{\Gamma} p_{mn}^{scw} \leq 1 \quad \forall m, n, w \tag{15}$$

$$\sum_{w=1}^{W} p_{mn}^{scw} \leq 1 \quad \forall m, n, s, c \tag{16}$$

The equations in this set state that a Super-Lightpath must be routed over an existing physical link (Eq. (13)), that a wavelength used on such a link must be turned on (Eq. (14)), that no more than a Super-Lightpath can use the same wavelength on the same link (Eq. (15)), and finally that an available wavelength must be present (Eq. (16)).

$$\sum_{n} p_{sn}^{scw} = \sum_{d} z_c^{sd} \quad \forall s, c, w \tag{17}$$

$$\sum_{w=1}^{W} \sum_{m=1}^{M} p_{md}^{scw} \geq a_c^{sd} \quad \forall s, c, d \tag{18}$$

$$\sum_{j=1}^{M} p_{jn}^{scw} - \sum_{i=1}^{M} p_{ni}^{scw} = z_c^{sn} \quad \forall s \neq n, c, w, n \tag{19}$$

These equations state that: a Super-Lightpath must depart from its source node (Eq. (17)), it must reach all its destinations (Eq. (18)), and it must be continuous (Eq. (19)).

The S-RWA problem is NP-hard, since it falls in the class of general MILP problems, and thus is numerically intractable, even for networks with a moderate number of nodes. Moreover, the S-RWA problem represents a generalization of the well-known NP-hard RWA problem, in the sense that it includes RWA as a particular instance. More specifically, if $D = 1$, the S-RWA formulation reduces to a classic RWA formulation, and the variables a_c^{sd} and z_c^{sd} assume the same meaning (being $c \leq 1$).

The above formulation considers physical links as monodirectional, forces each Super-Lightpath to use the same wavelength (thus ignoring the presence of wavelength converters) and allows the logical topology to have at most one logical link between two nodes. Moreover, we formulate the routing of the Super-Lightpath problem without considering splitting capabilities in the optical layer, that, if considered, allow to build (light-)trees that can be useful to optimize the routing solution. It could be possible to extend the formulation in order to relax all of the above constraints, but this is out of the scope of this paper.

B. S-RWA heuristic

We implemented two greedy heuristics to solve the S-RWA problem: the first one is called *Super-Shortest Path First Fit* (S-SPFF), and is a very simple algorithm that, starting from the source node, builds a Super-Lightpath selecting from the current node the closest one among the destination nodes still not used, until D destinations are reached. The resulting Super-Lightpath is then routed using all the shortest paths from each node to the next one. The wavelength assignment is done then looking for the first available wavelength on the resulting path.

The second algorithm presented, called *Super-Maximum Fill* (S-MF) is more complex, and aims to better pack the wavelengths, as it first selects a wavelength, and then tries to route all the possible Super-Lightpaths on such a wavelength. Obviously, many of the heuristics proposed in the literature to solve the RWA problem can be easily adapted to solve the S-RWA problem. Moreover, we are interested in studying the impact of the coupled WDM and OTDM approach compared to the classic WDM approach. We are not interested in this paper in evaluating and comparing the various known techniques to solve the RWA problem. Thus we will compare solutions obtained with a particular RWA algorithm and its natural extension to the S-RWA problem.

Here we give a more detailed description of the two heuristics. Let $\mathcal{F}(\mathcal{V},\mathcal{E})$ be a graph, where $\mathcal{V}$ is the set of vertices, and $\mathcal{E}$ is the set of arcs. Let $\mathcal{D}(s)$ be the set of all the destinations logically connected to s, i.e., $\mathcal{D}(s) = \{d \in \mathcal{V},\ \mathbf{T}_{sd} = 1\}$. Let $\Pi(\mathcal{F}, s, d)$ be a function that returns the shortest path from s to d on graph $\mathcal{F}$. Let $\Phi(l, w)$ be a function that takes the value of 1 if wavelength w is already used on physical link l, and 0 otherwise.

Shortest Path - First Fit

```
 1) Let $\mathcal{F}(\mathcal{V},\mathcal{E})$ be the physical topology
 2) For all $s \in \mathcal{V}$
 3)     $c = 1,\ d_1 = s,\ \mathcal{S} = \emptyset$
 4)     find $d_{c+1} \in \mathcal{D}(s)$ such that
          $|\Pi(\mathcal{F}, d_c, d_{c+1})| \le |\Pi(\mathcal{F}, d_c, d_i)|,\ \forall d_i \in \mathcal{D}(s)$
 5)     $\mathcal{D}(s) = \mathcal{D}(s) \setminus \{d_{c+1}\}; \mathcal{S} = \mathcal{S} \cup d_{c+1};$
 6)     $\pi(\mathcal{S}) = \pi(\mathcal{S}) \cup \Pi(\mathcal{F}, d_c, d_{c+1})$
 7)     if ($c < D$ and $\mathcal{D}(s) \neq \emptyset$) then $c = c + 1$;
          goto 4
 8)     $w = 0$
 9)     for all links $l \in \pi(\mathcal{S})$
10)       if ($\Phi(l, w) \neq 0$) then
11)           $w = w + 1$; goto 9
12)     for all links $l \in \pi(\mathcal{S})$ let $\Phi(l, w) = 1$
13)     route $\mathcal{S}$ on $\pi(\mathcal{S})$ using wavelength $w$
14)     if ($\mathcal{D}(s) \neq \emptyset$) then goto 3
15) end for all $s \in \mathcal{V}$
```

Items from 3 to 7 build the Super-Lightpath and find a suitable route for it. Then a first-fit coloring algorithm is used (Lines 8 to 12) to find a suitable wavelength.

This algorithm requires the knowledge of all the shortest paths on the physical topology. This can be obtained using the Dijkstra algorithm, which has a computational cost of $O(|\mathcal{V}|^2 \log(|\mathcal{V}|) + |\mathcal{V}||\mathcal{E}|)$, to obtain all shortest paths from all sources. If vectors $\mathcal{D}(s)$ are then sorted according to their distances from s, then the choice of the closest destination to d_c costs $O(1)$. Then for each Super-Lightpath, a simple first-fit algorithm is applied to look for a suitable wavelength on all the physical links of the path: for all $\frac{|\mathcal{V}|\Delta}{D}$ Super-Lightpaths, at most W wavelengths should be checked, for at most $|\mathcal{V}|$ links. Thus we can state that the asymptotic complexity of the SP-FF algorithm is $O(|\mathcal{V}|^2 \log(|\mathcal{V}|) + |\mathcal{V}||\mathcal{E}| + \frac{\Delta}{D} W |\mathcal{V}|^2)$.

Maximum Fill

```
 1) $w = 0$
 2) Let $\mathcal{F}(\mathcal{V},\mathcal{E})$ be the physical topology
 3) For all $s \in \mathcal{V}$
 4)     $c = 1,\ d_1 = s,\ \mathcal{S} = \emptyset$
 5)     find $d_{c+1} \in \mathcal{D}(s)$ such that
          $|\Pi(\mathcal{F}, d_c, d_{c+1})| \le |\Pi(\mathcal{F}, d_c, d_i)|,\ \forall d_i \in \mathcal{D}(s)$
 6)      if ($d_{c+1} = \emptyset$) then $\mathcal{D}(s) = \mathcal{D}(s) \cup \mathcal{S}$;
          goto 14
 7)     $\mathcal{D}(s) = \mathcal{D}(s) \setminus \{d_{c+1}\}; \mathcal{S} = \mathcal{S} \cup d_{c+1};$
 8)     $\pi(\mathcal{S}) = \pi(\mathcal{S}) \cup \Pi(\mathcal{F}, d_c, d_{c+1})$
 9)     if ($c < D$ and $\mathcal{D}(s) \neq \emptyset$) then $c = c + 1$;
          goto 5
10)     for all links $l \in \pi(\mathcal{S})$
11)       $\mathcal{E} = \mathcal{E} \setminus \{l\}, \Phi(l, w) = 1$
12)     route $\mathcal{S}$ on $\pi(\mathcal{S})$ using wavelength $w$
13)     if ($\mathcal{D}(s) \neq \emptyset$) then goto 4
14) end for all $s \in \mathcal{V}$
15) if $\mathcal{D}(s) = \emptyset\ \forall s$ then exit
16) else
17)     $w = w + 1$; goto 2
```

In this case it is not sufficient to run the Dijkstra algorithm only once, because the graph $\mathcal{F}$ is modified every time a Super-Lightpath is successfully routed (Line 11). Thus, for each Super-Lightpath that is routed, we must run the shortest path algorithm again. The resulting asymptotic complexity is thus $O(\frac{\Delta}{D}|\mathcal{V}|(|\mathcal{V}|^2 \log(|\mathcal{V}|) + |\mathcal{V}||\mathcal{E}|))$.

Note that the above algorithms can be used to solve a classic RWA problem imposing $D = 1$.

IV. EXPERIMENTAL RESULTS

In order to assess the performance of the proposed algorithms and to compare the Super-Lightpath approach to the classic lightpath solution, we present results obtained considering a given physical topology and solving the S-RWA and RWA problems respectively for the same logical topology.

In particular, we selected three physical topologies: the first one is derived from the U.S. Long-Distance Network [33] comprising 28 nodes and 45 links. The second topology comprises 50 nodes and 166 links, and is derived from a possible evolution of the Japanese WDM network [34]. The latter one is randomly generated, and comprises 100 nodes, with an average connectivity degree of 3.5 links per node.

For each physical scenario, and for a selected connectivity degree Δ, we randomly generated 1000 logical topologies. Then, for each logical topology, we evaluated the number of wavelengths required to solve the S-RWA problem, with either $D = 1$, i.e., classic approach, or $D = 4$, i.e., using Super-Lightpaths that multiplex 4 logical links each. The reported results are averaged over the 1000 logical topologies with the same connectivity degree. We also report results in term of percentage gain, defined similarly to the congestion gain (6) as

$$\eta_w(D) = 100 \frac{w(1) - w(D)}{w(1)} \tag{20}$$

TABLE II

AVERAGE NUMBER OF WAVELENGTH REQUIRED TO SOLVE THE S-RWA PROBLEM OVER THE US NETWORK.

	D=1		D=4		$\eta_w(4)$	
Δ	SPFF	MF	S-SPFF	S-MF	S-SPFF	S-MF
8	24.1	18.2	17.0	11.2	29.5	38.5
12	34.5	26.8	21.0	14.1	39.1	47.4
16	44.9	35.4	24.6	16.9	45.2	52.3

TABLE III

AVERAGE NUMBER OF WAVELENGTH REQUIRED TO SOLVE THE S-RWA PROBLEM OVER THE JAPANESE NETWORK.

	D=1		D=4		gain	
Δ	SPFF	MF	S-SPFF	S-MF	S-SPFF	S-MF
8	68.8	46.2	30.3	20.7	55.7	55.2
12	102.4	69.3	38.2	26.9	62.7	61.2
16	135.7	91.8	45.6	33.3	66.3	63.7

where $w(D)$ is the average number of wavelengths required to solve the S-RWA problem using Super-Lightpaths with a multiplexing factor of D.

Table II reports results for the US physical topology. As it can be seen, increasing the connectivity degree also increases the number of wavelengths required to solve the S-RWA problem. Moreover, it shows that the S-SPFF algorithm is outperformed by the S-MF. Comparing the results obtained using the classic approach with the Super-Lightpath one, we see that using a multiplexing factor of 4 greatly reduces the number of wavelengths required by both algorithms. In particular, the higher the connectivity degree, the larger is the gain observed multiplexing more logical channels in the same Super-Lightpath.

Table III reports result for the Japanese physical topology with 50 nodes. The same considerations as above apply. In particular, when a connectivity degree of 16 is considered, we can see that the average number of wavelengths required to solve the classic RWA problem when using the S-SPFF algorithm can be too large, as it requires to have optical transmission equipments that can handle more than 128 wavelengths on the same physical link. Using instead the Super-Lightpath approach, the number of wavelengths required is reduced to about 46, corresponding to a gain of more than 66%. A reduction of approximately the same order is also observed using the more efficient S-MF algorithm: the same logical topology can be overlayed on the same physical topology with only 33 wavelengths when using $D = 4$ instead of 92 wavelengths required with the classic lightpath approach.

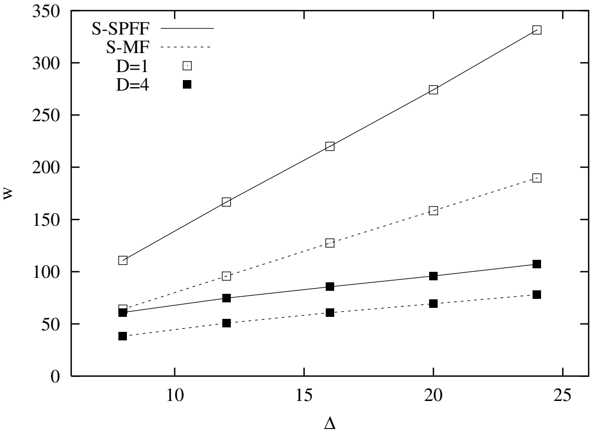


Fig. 4. Average number of wavelengths required to solve the S-RWA problem on the 100 nodes network

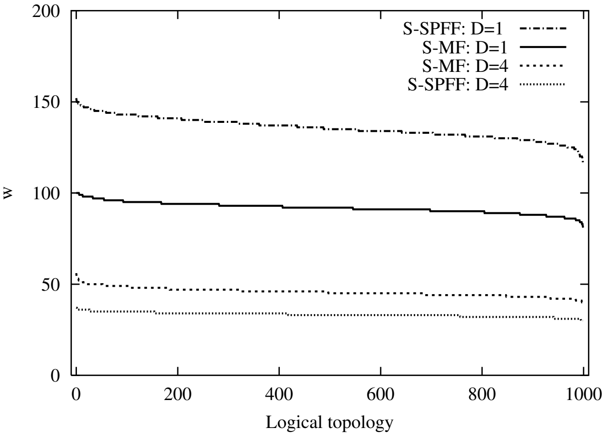


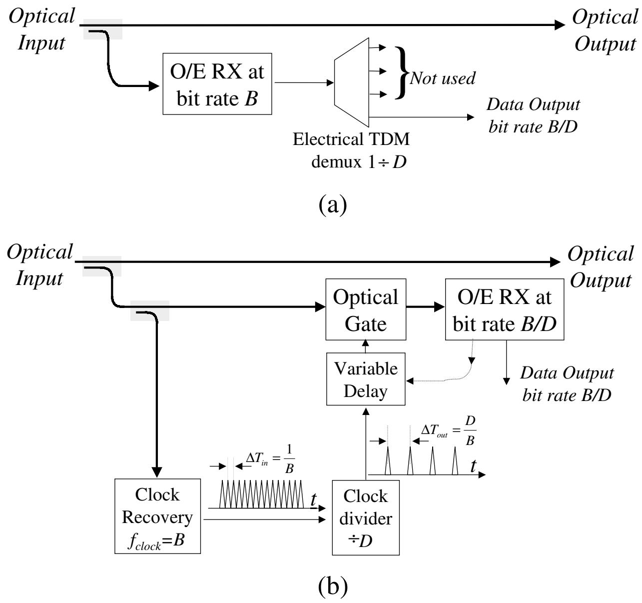
Fig. 5. Distribution of the number of wavelength required to solve a RWA problem on the Japan network

Figure 4 plots the average number of wavelengths required in case of the physical topology comprising 100 nodes. In this case, we solved the S-RWA problem for connectivity degrees up to 24. The plot clearly shows that the number of wavelengths required to solve the S-RWA problem has a linear dependence on the connectivity degree. But, while in the classic RWA problem the number of wavelengths grows quickly and becomes critical for $\Delta \geq 16$, the use of Super-Lightpaths permits to solve the S-RWA problem for larger networks with a largely reduced number of wavelengths.

To give more insight to the reader, Figure 5 plots the number of wavelengths used to solve the S-RWA problem on the 50 nodes physical network, for all the 1000 logical topologies generated with $\Delta = 16$, sorted in decreasing order of w. As it can be seen, the advantages of using the Super-Lightpath solution is homogeneous, and moreover, the variance of the number of wavelengths required is less dependent on the logical topology instance.

V. OTDM TECHNOLOGY

The Super-Lightpath architecture requires components and a system technology suitable to efficiently implement time division demultiplexing on a high bit rate optical signal. The most straightforward solution, shown in Fig.6(a), is totally electrical. Whenever a lightpath is to be received, the input optical signal is split by an optical coupler that taps a fraction of the passing-through optical signal, which is sent to an optoelectronic receiver working at bit rate B, equal to the Super-Lightpath aggregate bit rate. The receiver is followed by an electrical $1 \times D$ TDM demultiplexer that selects one bit every D, generating on the output ports a bit-rate B/D. One of the output ports carries



(a)

(b)

Fig. 6. Super-Lightpath receivers: electronic (a) and all-optical (b) architectures.

the useful traffic destined to the node, while the others remain unused.

An alternative and more advanced solution is shown in Fig.6(b), where time division demultiplexing is implemented using (mostly) optical devices. Optical time division multiplexing has been studied for years now, at the component and system level, and many OTDM setups have been demonstrated [27], [28]. Though optical TDM has not found commercial applications yet, it is recognized to be the only available solution when systems at bit rates above 40 Gbit/s will come of age. The key element for an optical TDM setup, as shown in Fig.6(b), are:

- an optical gate implementing the function of an on-off switch on the tapped passing-through optical signal. The most promising solution proposed so far for this component are electro-absorption modulators (EAM [29]), semiconductor optical amplifiers (SOA, [30]) and non-linear optical loop mirrors (NOLM [31]). Though solutions based on EAMs seems to be the most practical and reliable today for bit rates up to 40 Gbit/s [29], NOLM-based setups have already been demonstrated for rates up to 1.28 Tbit/s [28];
- a clock recovery circuit, followed by a clock divider by D and by a variable delay, generating a properly aligned control signal for the optical gate. This functionality has usually been implemented in the electronic domain in most OTDM demonstrators, but recently several all-optical solutions have been proposed [27].

The pros and cons of the electrical and optical TDM solutions depend largely on the input bit rate B. Given the current state of the art in component technology, the following can be stated:

- for bit rates $B \leq 10$ Gbit/s, the electronic solution is straightforward, being already available in commercial systems at the standard OC-192 SONET rate and below.

  An optical solution based on EAMs can be easily implemented, but at higher costs. It may be interesting only if the cost of EAMs or SOAs will significantly drop in next years, and reliability will increase.
- for bit rates $B = 40$ Gbit/s, both solutions are available in laboratory experiments, but none has yet reached a commercial maturity. Anyway, there is a generic consensus on the fact that the electronics at 40 Gbit/s is going to be the winning solution in the near future, with some major vendors announcing their products on the market by the end of 2001. Still, these receivers are foreseen to be extremely costly, and there may be space for optical solutions if they will be less expensive.
- for bit rates $B > 40$ Gbit/s, the only available solution seems to be all-optical.

Mixed optical and electrical solutions are also been successfully demonstrated. As an example, in [32] a 160 Gbit/s optical data stream was optically demultiplexed to 40 Gbit/s, and then electrically demultiplexed down to 10 Gbit/s.

VI. CONCLUSIONS

In this paper we extended the lightpath concept to the one of Super-Lightpath. Using a simple bit-level Time Division Multiplexing which can be implemented directly in the optical domain, the bandwidth of a wavelength is partitioned among several traffic flows. The Super-Lightpath approach modifies only the Routing and Wavelength Assignment problem. Numerical results show a gain of more that 65% in the number of wavelengths required to solve the RWA problem when using Super-Lightpaths, making the RWA solution viable with today WDM technology. Thus, the use of Super-Lightpaths allows to design networks with a larger connectivity degree, that is useful to reduce the average distance among nodes, and thus the number of electro-optic and opto-electronic conversions that a traffic flow must face. This also reduces the traffic congestion on logical links.

Although we showed in this paper its many advantages, the feasibility of the Super-Lightpath approach depends obviously on the relative cost of optical transmitters and receivers at different rates, and of high-speed, bit-level multiplexers and demultiplexers. These costs are today rapidly changing due to the rapid evolution of electrical and optical technology.

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