Design of WDM Networks Exploiting OTDM and Light-Splitters

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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-LightTree, which uses a simple bit level Time Division Multiplexing that can be directly implemented in the optical domain, to split the wavelength bandwidth over a tree 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-LightTree RWA problem computationally intractable, we propose two heuristics for which we show that the number of wavelengths required to overlay a given logical topology on a given physical topology is reduced by more that 70% using Super-LightTrees.

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 [1], based upon 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) switched 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 vertexes 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 recent years, a large effort has been devoted by the research community to solve the problem of identifying the best logical topology that minimizes a given cost function, while accommodating the traffic pattern given as input to the problem. 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).

Once the LTD problem 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 to 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 to in the literature as Routing and Wavelength Assignment (RWA) problem [2], [3], [4], [5], [6], [7], [8]. Wavelength converters can be instrumental to simplify the RWA problem.

This work was supported by the Italian Ministry for University and Scientific Research under the IPPO (IP Over Optics) project.

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 be reassembled, processed, forwarded and then possibly converted again to the optical domain if the current node is not the final destination of the data (hence is implementing a multi-hop routing strategy for the considered traffic flow). While the current optical technology allows to transmit data at very high speed, the electronic conversion and processing 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 should be a major goal in the future optical 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) uses more electronic resources in the network, possibly increasing the network bandwidth requirements.

There is a trade off 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.

We proposed in [9] the joint use of WDM and Optical Time Division Multiplexing (OTDM) technologies [10], which offers an interesting opportunity of splitting the bandwidth of a lightpath into a fixed number of sub-channels, using a Time Division Multiplexing (TDM) scheme directly in the optical domain.

Given 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 called 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. Note that, to avoid synchronization problems, only the transceiver of the node where the Super-Lightpath is rooted transmits in the optical pipe.

A Super-Lightpath can travel through many nodes, and a node can receive one (or many) sub-channel(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.

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, which, instead of being a-point-to-point link between 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 affects 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. In the first case, a transmitter of capacity c is needed for each lightpath, while in the secon case, being D traffic relations multiplexed in the time domain, the resulting Super-Lightpaths have capacity Dc.

The optimal RWA 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. In [9] we solved the RWA problem with Super-Lightpaths with the constraints that each Super-Lightpath, at each node traversed in the physical topology, is either terminated or routed to the next destination node, so that a "linear" route is followed from the source nodes to all the destination node in the same Super-Lightpath. However, the availability of *Light-Splitters* [1] allows us to remove

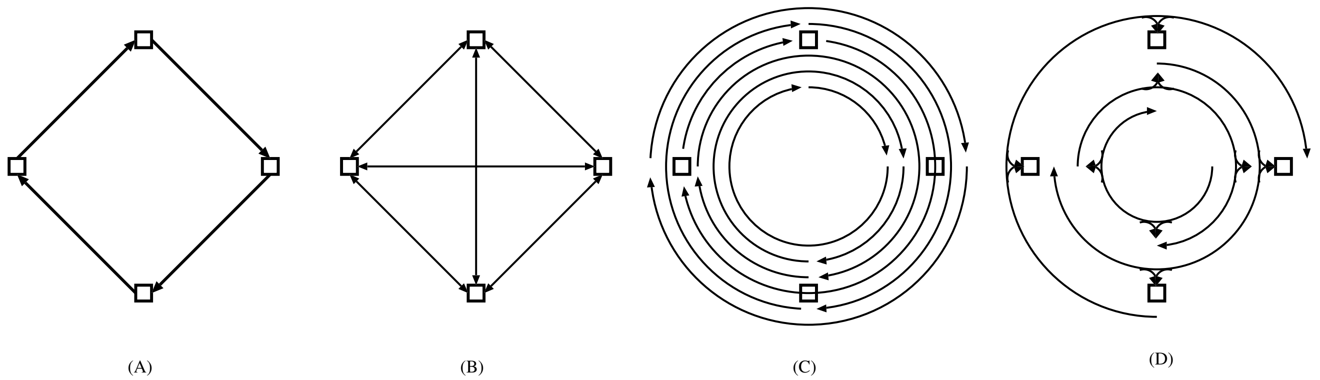

Fig. 1. Example: (A) - Physical Topology; (B) Logical Topology; (C) Classic RWA; (D) Novel Super-Lightpath RWA

this constraints. Several designd of optical cross connects are based upon broadcast-and-select structures (see e.g. [11]), which naturally offer the light splitting function studied in this paper.

Light-Splitters have been already proposed as a mean to allow multicast transmission in the optical domain. The resulting optical tree is called usually *LightTree* [12]. In this paper, thus, we extend the concept of Super-Lightpath to the one of Super-LightTree.

II. Routing and Wavelength Assignment

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 its 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 classic RWA problem, without using wavelength converters, can be formulated as follows.

GIVEN

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

FIND

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.

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 implies the capability of splitting in the optical layer an incoming lightpath into many outgoing lightpaths.

In this paper we consider this opportunity, combining the OTDM capability in the source/destination nodes, with the ability of wavelength-routers to split an incoming wavelength into many outgoing fiber. The resulting object is called *Super-LightTree*.

Note that the use of Super-LightTrees only affects the RWA solution. We call the RWA problem with Super-LightTrees the SuperTree-Routing and Wavelength Assignment (ST-RWA). We will compare the results obtained using the classic RWA approach with the new ST-RWA solution. We will also explicitly compare the performance improvements obtained by using LightTrees with respect to the solution that only considers “linear” trees, i.e., supposing that a lightpath cannot be split in a node, but either terminated or routed to the next node. We call the RWA problem with linear Super-Lightpaths only the Super-Routing and Wavelength Assignment (S-RWA).

To give the intuition of the different approaches, Figure 2 shows a physical topology in which a node has 4 logical links to 4 different destinations. In (A), a possible classic RWA solution is depicted, which involves 3 wavelengths and 9 optical fibers. In (B), one possible S-RWA solution is presented, which involves only one wavelength and 11 optical fibers. In (C), one possible ST-RWA solution is presented, which requires one wavelength, and 9 optical fibers.

The problem can be generally formulated as follows.

GIVEN

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

FIND

for each source:

1) the set of destinations that, using TDM, are multiplexed in a Super-LightTree;

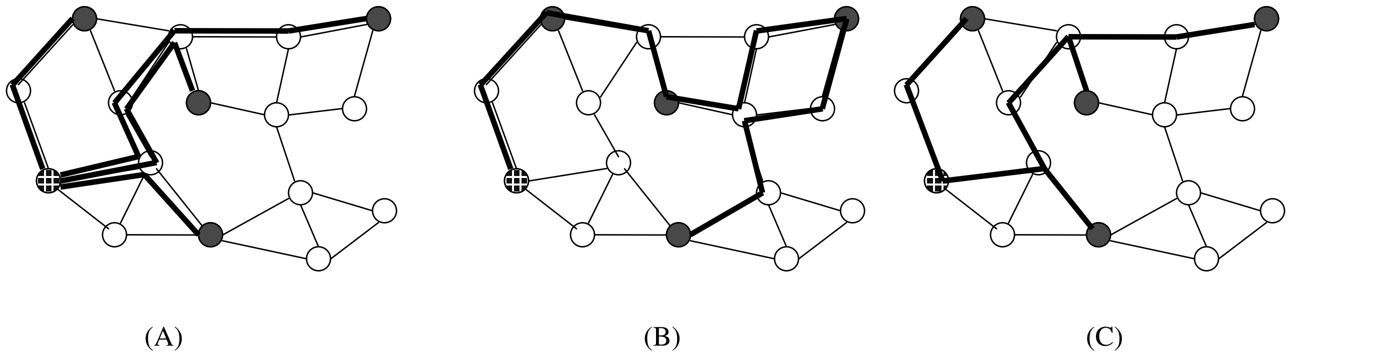

Fig. 2. Example: One source node (dotted), four destination nodes (black). Possible solution using: (A) - RWA; (B) S-RWA; (C) ST-RWA

2) the order in which those destination must be reached by the Super-LightTree;

and for each Super-LightTree:

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

such that the total number of required wavelengths is minimized.

A. Problem formulation of the ST-RWA problem

In this section we provide a problem formulation of the ST-RWA problem, in which a Super-LightTree is identified by the couple sc, being c the ordinal number of the Super-LightTree rooted in node s.

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 M be the total number of nodes.

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_{max} 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^{sdc} be binary variables that take the value 1 if the source s is using the Super-LightTree c to reach destination d.

Let z^{sdc} be binary variables that take the value 1 if the source s is using Super-LightTree c to reach destination d, and d is a leaf of the Super-LightTree, i.e., d is the last destination served by Super-LightTree c.

Let p^{sc}_{mnw} be binary variables used to describe the route of Super-LightTree c from s. p^{sc}_{mnw} is equal to 1 if the wavelength w is used by Super-LightTree c from s on the optical fiber from node m to node n.

Finally, let k^{sdc}_{jw} be a binary variable that assumes the value of 1 if, in node d, the wavelength w of the tree c rooted in source s is split on j or more outgoing fibers. For example, consider the c tree rooted in s that has been assigned wavelength w. In node d, the incoming wavelength can be split to two outgoing fibers. Then k^{sdc}_{1w} will assume the value of 1, while $k^{sdc}_{jw} = 0 \;\; \forall j > 1$. If instead three branches are generated, will have $k^{sdc}_{1w} = 1$, $k^{sdc}_{2w} = 1, k^{sdc}_{jw} = 0 \, \forall j > 2$.

The following ILP formulation describes the ST-RWA problem

$$\min \; W_{max} \tag{1}$$

Subject to:

$$\sum_{w} \beta_w = W_{max} \tag{2}$$

$$\beta_w \leq \beta_{w-1} \qquad 0 \leq w \leq W_{max} \tag{3}$$

Equation (3) 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.

$$\sum_{c=1}^{\gamma_O^{(s)}} a^{sdc} = \mathbf{T}^{sd} \quad \forall s, d = 1, \ldots, M \tag{4}$$

$$\sum_{d=1}^{M} a^{sdc} \leq D \quad \forall s = 1, \ldots, M, \;\; c = 1, \ldots, \gamma_O^{(s)} \tag{5}$$

Equation (4) 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-LightTree; $\gamma_O^{(s)}$ is the maximum number of Super-LightTrees that can depart from source s, i.e., the connectivity degree.

Equation (5) limits the number of the destinations that can be reached by one Super-LightTree; D is the *multiplexing factor* that represents the bandwidth of the Super-LightTree in terms of destinations, i.e., the degree of multiplexing that can be used on a Super-LightTree using the TDM approach. Thus the connectivity degree for node s in the logical topology is $\delta_O^{(s)} = \gamma_O^{(s)} D$.

$$z^{sdc} \leq a^{sdc} \quad \forall s, c, d \tag{6}$$

The previous inequalities state that a node d can be the last node in a Super-LightTree only if it is also reached by the same Super-LightTree.

$$p_{mnw}^{sc} \leq \mathbf{F}_{mn} \quad \forall s, c, w \tag{7}$$

$$p_{mnw}^{sc} \leq \beta_w \quad \forall m, n, s, c, w \tag{8}$$

$$\sum_{s=1}^{M} \sum_{c=1}^{\gamma_O^{(s)}} p_{mnw}^{sc} \leq 1 \quad \forall m, n, w \tag{9}$$

$$\sum_{w=1}^{W} p_{mnw}^{sc} \leq 1 \quad \forall m, n, s, c \tag{10}$$

$$\sum_{w=1}^{W} \sum_{m=1}^{M} p_{mdw}^{sc} \leq a^{sdc} \quad \forall s, c, d \tag{11}$$

The inequalities in this set state that a Super-LightTree must be routed over an existing physical link (Eq. (7)), that a wavelength used on such a link must be turned on (Eq. (8)), that no more than a Super-LightTree can use the same wavelength on the same link (Eq. (9)), and that at most one wavelength can be used by each Super-Lightpath on each optical fiber (Eq. (10)). Finally, (Eq. (11)) states that a destination of a Super-LightTree must be reached only by one wavelength from all the incoming links (i.e., no merging of LightTree branches is allowed).

$$\sum_{d=1}^{M} \sum_{j=1}^{D-1} k_{jw}^{sdc} \leq D \quad \forall s, c, w \tag{12}$$

$$k_{(j+1)w}^{sdc} \leq k_{jw}^{sdc} \quad \forall s, d, c, w, j \tag{13}$$

Inequality (12) states that no more than D splitting points can be present in a tree . Eq. (13) simply forces that splitting points are chosen in increasing order.

$$1 + \sum_{j=1}^{D-1} \sum_{d=1}^{M} k_{jw}^{sdc} = \sum_{d=1}^{M} z^{sdc} \quad \forall s \neq s, c, w \tag{14}$$

$$\sum_{j=1}^{M} p_{jnw}^{sc} - \sum_{i=1}^{M} p_{niw}^{sc} + \sum_{j=1}^{D-1} k_{jw}^{snc} = z^{snc} \quad \forall s \neq n, c, w, n \tag{15}$$

These equations involves the construction of the tree, enforcing the number of splitting nodes (Eq. (14)), and the classic continuity equality that forces the Super-LightTree to be a continuous tree (Eq. (15)).

The above formulation considers physical links as monodirectional, forces each Super-LightTree to use the same wavelength (thus not assuming the presence of wavelength converters) and allows the logical topology to have at most one logical link between two nodes.

The ST-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 ST-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 ST-RWA formulation reduces to a classic RWA formulation, and the variables a_c^{sd} and z_c^{sd} assume the same meaning (being $c \leq 1$).

Indeed, the problem of finding a minimum-cost tree is also a well-known NP-hard problem (usually referred as "minimum Steiner Tree problem"), but several heuristic are known to find good solutions to this problem. Among all the available solutions, we selected the "*Selective Closest Terminal First*" ($SCTF$) algorithm proposed in [13], that, given the tree source s, the group definition d, and the graph describing the physical topology, finds a Steiner Tree with a good trade-off between performance and computational complexity.

A brief description of the algorithm follows.

$SCTF$ algorithm

Let s be the root of the tree, and $\mathcal{D}$ the set of destinations to be reached. Let $\mathcal{T}$ be a dynamic structure in which the Steiner Tree is gathered:

1) set $S = \{s\}$; $D = \mathcal{D}$; $\mathcal{T}$=NULL;
2) *while* ($D \neq \emptyset$) *do*
3) select the node $d \in D$ closest to nodes in S;
4) select s', the node in S closest to d;
5) extract d from D;
6) select the shortest path route r from s' to d;
7) add the links of r to $\mathcal{T}$;
8) insert all the nodes crossed by r in S;
9) keep the latest z nodes in S;
10) *done*

The algorithm requires at each step the knowledge of all the shortest paths from nodes in S to nodes in $\mathcal{D}$, which can be easily solved by running for example the Dijkstra's shortest path algorithm. To reduce the algorithm complexity, the algorithm considers only the latest z nodes when selecting the closest destination d to S (step 9).

B. ST-RWA heuristic

We present two greedy heuristics to solve the ST-RWA problem. The first one is called *SuperTree-Shortest Path First Fit* (ST-SPFF), and is a very simple algorithm that, starting from the source node, builds a Super-LightTree selecting from the current node the closest one among the destination nodes still not used, until D destinations are reached. The resulting Super-LightTree is then routed building a tree using the $SCTF$ algorithm. The wavelength assignment is done then looking for the first available wavelength on the resulting path.

The second algorithm presented, called *SuperTree-Maximum Fill* (ST-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-LightTrees on such a wavelength.

We are interested in studying the impact of the joint WDM and OTDM approach compared to the classic WDM approach, as well as in the impact of the splitting capabilities on allocating the Super-LightTree. We are not interested 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 ST-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 vertexes, and $\mathcal{E}$ is the set of arcs
- $\mathcal{D}(s)$ be the set of all the destinations logically connected to s, i.e., $\mathcal{D}(s)=\{d\in\mathcal{V},\ \mathbf{T}_{sd}=1\}$
- $\Pi(\mathcal{F},s,d)$ be a function that returns the shortest path from s to d on graph $\mathcal{F}$.
- $SCTF(\mathcal{F}(\mathcal{V},\mathcal{E}),s,\mathcal{D})$ be a function that returns a tree on graph $\mathcal{F}(\mathcal{V},\mathcal{E})$, rooted in s, and that reaches all the destinations in $\mathcal{D}$
- $\Phi(l,w)$ be a function that takes the value of 1 if wavelength w is already used on physical link l, and 0 otherwise

ST-SPFF:
SuperTree - Shortest Path - First Fit

1) Let $\mathcal{F}(\mathcal{V},\mathcal{E})$ be the physical topology
2) For all $s\in\mathcal{V}$

   Build the destination set
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) if ($c<D$ and $\mathcal{D}(s)\ne\emptyset$) then $c=c+1$; goto 4

   Build the LightTree
7) $\mu(s)=SCTF(\mathcal{F}(\mathcal{V},\mathcal{E}),s,\mathcal{S})$

   Find a wavelength
8) $w=0$
9) for all links $l\in\mu(s)$
10) if ($\Phi(l,w)\ne 0$) then
11) $w=w+1$; goto 9
12) for all links $l\in\mu(s)$ let $\Phi(l,w)=1$
13) route $\mathcal{S}$ on $\mu(s)$ using wavelength w
14) if ($\mathcal{D}(s)\ne\emptyset$) then goto 3
15) end for all $s\in\mathcal{V}$

Items from 3 to 6 build the set $\mathcal{S}$ of destinations to be reached by the Super-LightTree. A Steiner Tree is then built (step 7), and a first-fit coloring algorithm is used (steps 8 to 12) to find a suitable wavelength.

ST-MF:
SuperTree - Maximum Fill

1) $w=0$
2) Let $\mathcal{F}(\mathcal{V},\mathcal{E})$ be the physical topology
3) For all $s\in\mathcal{V}$

   Build the destination set
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} is disconnected in $\mathcal{F}(\mathcal{V},\mathcal{E})$ 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) if ($c<D$ and $\mathcal{D}(s)\ne\emptyset$) then $c=c+1$; goto 5

   Build the tree
9) $\mu(s)=SCTF(\mathcal{F}(\mathcal{V},\mathcal{E}),s,\mathcal{S})$

   Color it and remove edges from $\mathcal{F}(V,E)$
10) for all links $l\in\mu(s)$
11) $\mathcal{E}=\mathcal{E}\setminus\{l\},\ \Phi(l,w)=1$
12) route $\mathcal{S}$ on $\mu(s)$ using wavelength w
13) if ($\mathcal{D}(s)\ne\emptyset$) 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 the algorithm look for a suitable Super-LightTree on the reduced graph, which includes all the arcs in which wavelength w is still free. If such a tree does not exists for all the Super-LightTrees not already routed (step 6), then a new wavelength is tested (step 17).

Given this approach, it is not sufficient to run the Dijkstra algorithm once, because the graph $\mathcal{F}$ is modified every time a Super-LightTree is successfully routed (Line 11). Thus, for each Super-LightTree that is routed, we must run the shortest path algorithm again. The resulting asymptotic complexity is thus increased when compared to the $ST-SPFF$ algorithm, but the resulting wavelength utilization should be higher, as the Super-LightTrees are better packed.

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

III. Experimental Results

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

In particular, we selected two physical topologies: the first one is derived from the U.S. Long-Distance Network [14] comprising 28 nodes and 45 links. The second topology comprises 51 nodes and 166 links, and is derived from a possible evolution of the Japanese WDM network [15].

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 ST-RWA problem, with either $D = 1$, i.e., classic approach, or $D = 4$, i.e., using Super-LightTrees that multiplex 4 logical links each. The solution of the Super-LightTree problem has been solved considering both the tree solution (ST-RWA), and considering the Super-Lightpath solution (S-RWA), which has been obtained by imposing $z = 1$ in the $SCTF$ algorithm. 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 as

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

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

Table I 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 RWA problem. Moreover, it shows that the SPFF algorithm is outperformed by the MF. Comparing the results obtained using the classic approach with the Super-LightTree 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-LightTree. Looking at the impact of the splitting capability in the optical domain instead, we observe a little improvement when comparing the ST-RWA solution (which exploits the splitting capabilities) to the S-RWA solution (which considers only "linear" trees). Moreover, the impact of the tree generation capability is larger when considering the SPFF algorithms, while can be almost neglected when the MF family of algorithms are considered.

TABLE I

Average number of wavelengths required to solve the ST-RWA, S-RWA and RWA problem over the US network

	$D=1$	$D=4$		$\eta_w(4)$	
Δ	SPFF	S-SPFF	ST-SPFF	S-SPFF	ST-SPFF
8	24.1	17.0	15.2	29.5	37.0
12	34.5	21.0	18.1	39.1	47.6
16	44.9	24.6	21.3	45.2	52.6
	$D=1$	$D=4$		$\eta_w(4)$	
Δ	MF	S-MF	ST-MF	S-MF	ST-MF
8	18.2	11.2	10.4	38.5	42.9
12	26.8	14.1	13.5	47.4	43.3
16	35.4	16.9	15.9	52.3	55.1

Table II reports result for the Japanese physical topology with 51 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 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-LightTree approach, the number of wavelengths required is reduced to about 40, corresponding to a gain of more than 70%. 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 31 wavelengths when using $D = 4$ instead of 92 wavelengths required with the classic LightTree approach. Also in this case, the impact of the splitting capabilities are little, as a very marginal gain (in the order of 3%) can be obtained when compared to the simpler S-RWA problem.

To give more insight to the reader, Figure 3 plots the number of wavelengths used to solve the S-RWA problem on the Japanese 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-LightTree solution is homogeneous, and moreover,

TABLE II

AVERAGE NUMBER OF WAVELENGTHS REQUIRED TO SOLVE THE ST-RWA, S-RWA AND RWA PROBLEM OVER THE JAPANESE NETWORK

	$D = 1$	$D = 4$		$\eta_w(4)$	
Δ	SPFF	S-SPFF	ST-SPFF	S-SPFF	ST-SPFF
8	68.8	30.3	27.2	55.7	60.5
12	102.4	38.2	35.6	62.7	65.3
16	135.7	45.6	40.2	66.3	70.4

	$D = 1$	$D = 4$		$\eta_w(4)$	
Δ	MF	S-MF	ST-MF	S-MF	ST-MF
8	46.2	20.7	19.3	55.2	58.3
12	69.3	26.9	25.6	61.2	63.1
16	91.8	33.3	30.8	63.7	66.5

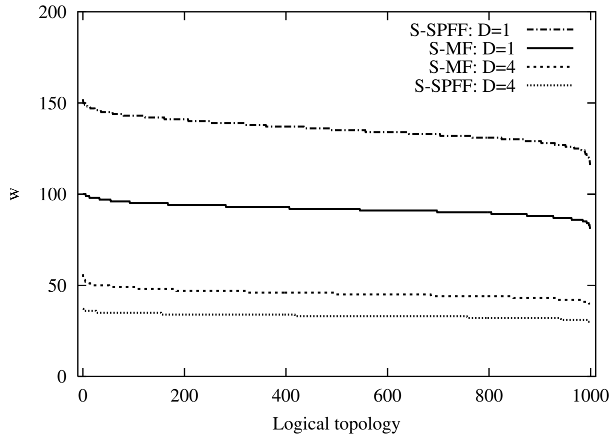

Fig. 3. Distribution of the number of wavelengths required to solve a ST-RWA problem on the Japan network

the variance of the number of wavelengths required is less dependent on the logical topology instance.

Looking at the number of wavelengths required on each optical fibers of a given topology, Figure 4 plots, for each fiber f of the physical topology, the number of wavelengths used on that fiber, usually referred as "load", $W(f)$. A single RWA problem is considered, and the ST-MF algorithm has been used to solve the problem. To better appreciate the plots, the results are sorted in decreasing order, and compared to the average number of wavelengths used on all links, and the maximum number required to solve the complete RWA problem W_{max}, i.e., after the solution of the coloring problem.

As it can be observed the ST-MF heuristic finds solutions in which the distance among the most loaded optical fiber (the one with index $f = 0$) and W_{max} is quite small. This shows that the coloring constraints imposed by the RWA have little impact on the solution. Indeed, W_{max} can be larger than or equal to the number of wavelengths

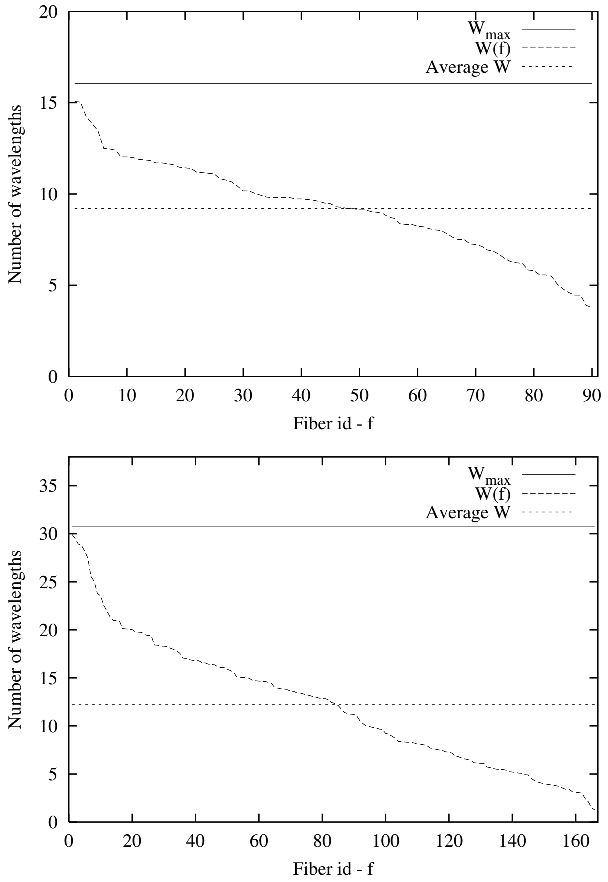

Fig. 4. ST-MF: wavelengths required on the optical link for the USA topology (top) and Japan topology (bottom)

on all the optical fibers. On the contrary, the distribution of $W(f)$ shows that there are few fibers that are crossed by many Super-LightTrees, while a large number of fibers are lightly used. This suggests that there are few "bottleneck" fibers on the physical topology, which must be used to connect most source/destination traffic relations. Therefore, using the same wavelength to carry more than one traffic relation is of great help in reducing the total number of wavelengths required to solve the RWA problem. This offers an intuition on the reason why the S-RWA or ST-RWA solutions reduce the number of wavelengths required by more than 70%.

IV. CONCLUSIONS

In this paper we extended the Lightpath concept to the Super-LightTree. 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. A LightTree is then used to build an optical tree rooted in the source node, that reaches all the destinations, by using Light-Splitters in each WR node.

The Super-LightTree approach modifies only the Routing and Wavelength Assignment problem. Numerical results show a gain of more that 70% in the number of wavelengths required to solve the RWA problem when using Super-LightTrees, making the RWA solution viable with today WDM technology. Thus, the use of Super-LightTrees 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 which traffic flow must face. This also reduces the traffic congestion on logical links. In more details, as we shown in [9], it is possible to solve the RWA problem for the same LTD solution, by using optical transmitters that multiplex D channels on the same wavelength, and have data rate D time higher. In this case the number of wavelengths required is reduced. If instead we consider fixed the number of wavelength, then it is possible to design logical topologies with an increased number of channels, which produces a more connected logical topology, reducing the multihop traffic, the traffic congestion on links, and finally the number of electro/optical conversions.

We have compared the results obtained by allowing wavelength splitting in the optical domain to the solution in which no splitting is allowed, thus forcing the tree to degenerate into a linear path. The results presented shows that a small penalty is paid by removing the traffic splitting capability, which allows to use today optical technology which may lacks this splitting capability.

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