EXPLOITING OTDM GROOMING IN DYNAMIC WAVELENGTH ROUTED NETWORKS *

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Abstract We consider dynamically reconfigurable wavelength routed networks in which lightpaths carrying IP traffc are established on demand. In wavelength routed networks usually each lightpath is established by reserving a wavelength on each fiber belonging to one of the physical paths that connect the end-point routers.

In this paper we exploit the joint use of WDM and Optical Time Division Multiplexing technologies; the latter offers an interesting opportunity of partitioning the bandwidth of each lightpath into a fixed number of sub-channels, using a bit-level Time Division Multiplexing scheme directly in the Optical domain (OTDM). A single transmitter feeds each wavelength, so that no synchronization is required among network nodes. We propose simple and novel algorithms to allocate user connection requests in a dynamic traffic scenario, and show that the adoption of a joint WDM-OTDM multiplexing technique can lead either to a reduction of the network cost, or to a significantly improvement of the network performance.

1. Introduction

Wavelength Routed (WR) networks 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, but do not require complex processing functionalities in the optical domain.

In WR networks, remote high-capacity (electronic) routers are connected through IP-tunnels. IP tunnels are implemented by optical pipes called *lightpaths* that may extend over several physical links. Lightpaths are routed in the optical layer through the physical topology using a wavelength (we do not

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assume to exploit wavelength conversion); at intermediate nodes, incoming wavelengths belonging to in-transit lightpaths are switched to outgoing fibers through an optical cross-connect that does not process in-transit information. At the IP layer, lightpaths are seen as data-link channels through which packets are moved from a router to another router toward their destinations following the classic IP forwarding procedure. Therefore, in a WR network, an *IP layer topology* (also called logical topology), whose vertexes are IP routers and whose edges are lightpaths, is overlayed to the *physical topology*, made of optical fibers and optical cross-connects (OXC). If the OXC node implementation requires opto/electronic conversions, the technology is usually called “opaque”. Otherwise, if switching of lightpaths is fully performed in the optical domain, the term “transparent” is used. In this second case, the cost of switching a lightpath is almost independent on the transmission data-rate [1]. In this paper we consider the latter technology, which is also the most promising one.

The switching cost in transparent WR networks can be considered to be essentially insensitive to the transmission data-rate. On the other hand, the complexity and cost of optical switches exhibit a strong dependency on the number of lightpaths to be switched in the nodes, i.e., on the number of input/output ports (or connectivity degree) of a node. As a consequence, at the optical layer it is more convenient to increase the lightpaths data-rate thereby reducing the connectivity degree of the logical IP topology. A lower connectivity degree of the IP topology, however, would entail longer paths on the logical topology, thus resulting in an increase of the bandwidth to be switched at the IP layer. In addition, increasing the lightpath data-rate increases the granularity of the lightpath capacity, thus resulting in possible bandwidth waste.

Therefore, it is strongly desirable to decouple the data-rate of lightpaths at the optical layer from the data-rate of tunnels at the IP layer, by grooming several lower speed IP-tunnels onto the same higher capacity optical pipe.

Lightpaths can either be semi-permanent [2], or be allocated in on-demand fashion [3]. In the first case a static topology is seen at the IP layer, while in the second case more adaptivity can be gained at the cost of additional complexity both at the optical layer and the IP layer.

In [7–8], we considered static WR networks (with semi-permanent lightpaths), and we proposed the joint use of WDM and Optical Time Division Multiplexing (OTDM) technologies, which offers the 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. According to our proposal, a *fixed bit level 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 (single) transmitter multiplexes sub-channels into the frame, and transmits the resulting stream into one *Super-*

Lightpath, using the same wavelength. An intermediate node receives in the electronic domain a de-multiplexed stream of bits, while it switches in the optical domain the entire wavelength toward the next destination node. While this approach might not produce optimal results with respect to the bandwidth utilization, it avoids all the technological issues related to bit level synchronization.

Other proposals (see [4–6] for example) already considered joint use of WDM and TDM technologies, in which a traditional TDM framing is superposed to the WDM capability to build a circuit switched network. Each switching node has the capability of switching circuits in both at wavelength and time domains, therefore requiring a very tight synchronization among nodes in the network (or buffering capabilities to break the synchronization requirements). On the contrary, our solution does not require any synchronization among network nodes, because only the source node transmits data into a Super-Lightpath, which is then transparently routed inside the network only in the wavelength domain.

In this paper we consider dynamically reconfigurable WR networks in which lightpaths are on demand established. We rely again on the joint use if WDM and OTDM technologies to allow the partition of the lightpath bandwidth into several lower speed IP-tunnels. We show that the adoption of a joint WDM-OTDM multiplexing technique can lead either to a reduction of the network cost (considering a given performance), or to a significantly improvement of the network performance (considering a given cost).

In the remaining of the paper, Section 2 provides a more detailed description of the Dynamic OTDM Lightpath approach, presenting the allocation problem together with some heuristic solutions. Section 3 presents simulation results which compare the proposed approach with the traditional one. Finally, Section 4 concludes the paper.

2. Dynamic Super-Lightpath

In classic WR networks that support the dynamic allocation of lightpaths according to user requests, the Routing and Wavelength Assignment (RWA) problem must be faced. Indeed, for each connection request, a route across the physical topology must be found, and a wavelength must be selected with the constrains that i) two (or more) lightpaths sharing the same fiber must be identified by two (or more) different wavelengths (also called "wavelength integrity constraint") and ii) a lightpath must be identified by the same wavelength on all the physical fibers along the path (also called "wavelength continuity constraint"). If such a path/wavelength exists, a point-to-point lightpath is established for the duration of the connection. On the contrary, the connection may be blocked given the limited number of wavelengths supported by fibers and

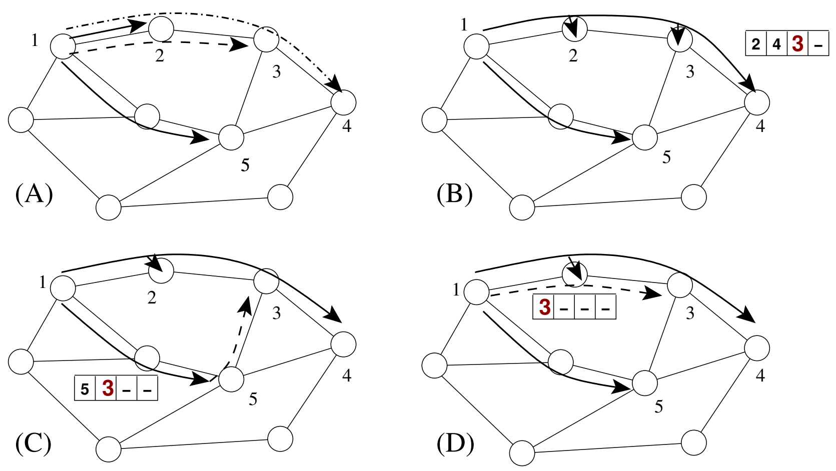

Figure 1. Allocation of a new connection in WR networks: (A) classic point-to-point lightpath approach; (B) time allocation only in an already present point-to-multipoint Super-Lightpath; (C) time allocation and Super-Lightpath extension; (D) time allocation and new Super-Lightpath creation.

OXCs. The goal of the RWA is therefore to minimize the connection blocking probability, and several algorithms have been proposed to address this problem [9].

In this paper we introduce a new dimension to the problem, overlaying a TDM multiplexing scheme to the WDM channels already offered by the optical layer. In particular, we propose the use of OTDM technologies [10–11], which have been originally proposed to enable high-speed channels directly in the optical domain. A bit level TDM scheme is created, and D receivers/transmitters can be de/multiplexed to form a D times faster point-to-point optical channel. The multiplexing of D tributaries can be obtained by optical, electronic or mixed technologies [12]. As in [7–8], we propose to extend the OTDM bit-stream carried by a single wavelength to several destinations nodes, obtaining point-to-multipoint channels (or tree)[1], that we call "*Super-Lightpath*". Note that a single transmitter feeds each Super-Lightpath, so that technological complexities due to adding information to in-transit synchronous frames are avoided. An intermediate node receives in the electronic domain a de-multiplexed stream of bits, while forwarding in the optical domain the entire wavelength toward the next destination. The time de-multiplexing can be obtained directly in the optical domain, so that the receiver complexity is only marginal increased.

To illustrate the differences, Fig. 1.A reports a simple example, in which classic point-to-point lightpaths are used to route 4 channels in a WR network. Being a same fiber shared by 3 connections, 3 wavelengths must be used. In (B), the Super-Lightpath approach is presented, in which connections (1→2),(1→3) and (1→4) are routed using three different time slots on the same Super-Lightpath. Only *one* wavelength is required in this case.

The introduction of the time dimension modifies the RWA problem, transforming it in a Routing, Time and Wavelength Assignment (RTWA) problem[2]. Indeed, a new connection can be allocated either:

- assigning a free time slot in an already established Super-Lightpath rooted at the source node and crossing the destination node;
- extending an already present Super-Lightpath rooted at the source node, but not reaching the destination node and then assigning a free time slot
- creating a new Super-Lightpath, rooted at the source node and terminating in the destination node, and then assigning a free time slot (which necessarily exists).

Fig. 1 sketches the three previous cases in (B), (C) and (D) respectively. It considers a new connection request generated at node 1 and going to node 3.

Finally, notice that if $D = 1$ then the RTWA problem degenerates in the RWA problem. Being the RWA a well-know NP-complete problem, also the RTWA belongs to the same class of problems.

2.1 Allocation Problem and Algorithms

Given the similarities between the classic RWA and the novel RTWA problems, most of the algorithms that have been already proposed in the literature can be extended to include the time allocation problem, or novel ad-hoc algorithms may be devised.

The scheme we followed to devise heuristics to solve the RTWA problem was derived from the observation that the accommodation of connections using only the time dimension does not consume precious resources as wavelength are. Therefore, we will try to allocate the new connection:

1 performing a time slot allocation on a Super-Lightpath which already connects the source and the destination node; Super-Lightpaths will be tested following a predefined order or looking for a optimal candidate, and the algorithm will use the first available time slot;

2 otherwise, extending an already present Super-Lightpath rooted in the source node, and performing a time allocation; also in this case the algorithm will select a Super-Lightpath (eventually according to some optimality criterion) that can be successfully extended to accommodate the request;

3 otherwise creating a new Super-Lightpath, as done by the classic RWA problem, and then performing a time slot allocation.

Considering a dynamic scenario in which connections have finite durations, we have to define a policy to release resources when a connection is terminated. In particular, when a connection is tore down, the corresponding bit slot becomes free. When all bit slot on a part of a Super-Lightpath are free, the corresponding wavelength will be freed up, resulting in a "shorter" Super-Lightpath, eventually releasing all wavelength if no time slot are used on any link of the Super-Lightpath.

Extension of classic heuristics. To solve the RWA problem, we selected two algorithms that were shown to give good performance: the *First-Fit Alternate* (FF-alt) and *First-Fit Least-Congested* (FF-LC) [9]. In more details, when searching for available wavelengths on a given path, a lower numbered wavelength is considered before higher numbered wavelengths, and the first available wavelength is then selected (First Fit Strategy) by both algorithms. As regards the path selection, the FF-alt algorithm considers a pre-ordered list of available paths from source to destination nodes. In case no wavelength is available on the first path, than the second alternate path is tested, followed by the third one, etc. (alternate routing scheme). Paths are sorted according to their hop count, in a static way.

The FF-LC algorithm, instead, dynamically sorts the path list, so that always the least congested is tested first. The "congestion" metric counts the number of wavelengths already used on a fiber, so that the path with the largest number of unused wavelengths is chosen.

Novel heuristics. We propose a novel algorithms to solve the RTWA problem, which try to exploit the larger number of possibilities that can be used to accommodate a connection when using Super-Lightpaths. In particular, among all possible allocation solutions, we select the one which steals the fewest resources as possible to future connection requests.

We define a metric to estimate the impact of a possible accommodation solution, and then evaluate all of them, selecting the one which exhibits the minimum cost. Indeed, in general the cost of allocating a new connection request comprises two terms: the first one that takes into account the cost of consuming a time slot on an already present Super-Lightpath; and the second one which takes into account the allocation of wavelengths along new (part of) Super-Lightpaths.

Let $P = \{p\}$ be the set of pre-calculated[3], loop-free paths p and let $P(l) \subseteq P$ be the subset of paths which includes fiber l; let $T(s, \lambda)$ be the tree used to route a Super-Lightpath from node s using wavelength λ. Let $\Psi(p, \lambda)$ be equal

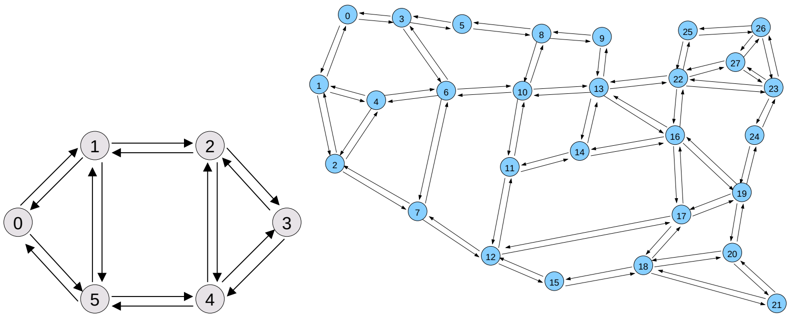

Figure 2. Simple Six-node topology (on the left) and US Network topology (on the right).

to 1 if the wavelength λ is free on all the fibers belonging to the path p. $\Psi(p, \lambda)$ equal 0 otherwise.

Given p' the path that should be added to $T(s, \lambda)$ to reach destination node d, then the cost $C(s, d)$ to allocate a request from s to d is defined as:

$$C(s, d) = |T(s, \lambda)| + \sum_{l \in p'} \sum_{p \in (P(l) \backslash p')} D\Psi(p, \lambda) \tag{1}$$

where the term $|T(s, \lambda)|$ takes into account the fact that a timeslot must be allocated on all links on the selected tree, while the second term considers all the possible (future) connection requests that might be routed using wavelength λ on all fibers of the new path p'. Indeed, allocating λ to the current connection request "steals" D time slots to other possible connections on each link of p'.

For example, if a connection is accommodated by simply allocating a time slot on an already present Super-Lightpath, then $C(s, d) = |T(s, \lambda)|$. On the contrary, $C(s, d) = \sum_{l \in p'} \sum_{p \in (P(l) \backslash p')} D\Psi(p, \lambda)$ when a completely new Super-Lightpath is created.

The algorithm, which is referred as *Maximize Capacity* (MaxCap) in the remaining of the paper, evaluate the cost of *all* possible solution to the connection allocation problem, and select the one that as the minimum cost, if it exists. Otherwise, the connection request will be blocked.

Given the complexity of the algorithm, a *Simplified MaxCap* (MaxCap(S)) version is also proposed, which tries first to allocate the connection using only a free time slot on a minimum cost Super-Lightpath which has been already set-up. Only if such a time slot is not available, then all possible solutions to the allocation problem will be considered before blocking the request.

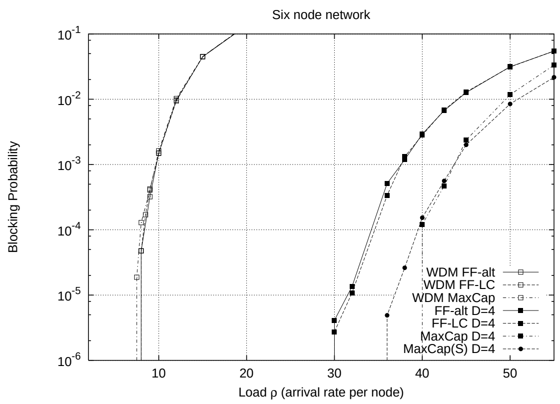

Figure 3. Blocking probability: six node network.

3. Performance Evaluation

In this Section we compare the performance of our approach with classical WR routed networks. We considered two different physical topologies, reported in Fig. 2. The first one (left part of Fig. 2) is a very simple topology, which was proposed in [9] as benchmark topology. It comprises 6 nodes and 8 bidirectional links. The second topology (right part of Fig. 2) is derived from a possible U.S. Long-Distance Network [13] comprising 28 nodes and 45 links. 16 wavelengths are supported on each physical link. We remind that that no wavelength conversion is available at OXCs.

New connection requests arrive according to a Poisson process with parameter $\rho_{s,d}$. The connection duration is supposed to be exponentially distributed with parameter 1. Two traffic scenarios have been used to asses the performance of the algorithm:

- *Uniform traffic scenario*, in which traffic is supposed to be uniformly distributed among the nodes, i.e., $\rho_{s,d} = U[0.5, 1.5]\ \forall s, d$; $U[min, max]$ is random variable distributed according to a uniform distribution between min and max.

- *High-Low load traffic scenario*, in which 1/5 of nodes (selected at random) are considered “High” traffic nodes, and the remaining 4/5 of nodes are considered “Low” traffic. Then $\rho_{s,d} = U[9.5, 10.5]$ if both s and d are labeled ad High traffic; $\rho_{s,d} = U[4.5, 5.5]$ if at least s or d are labeled $High$ traffic; $\rho_{s,d} = U[0.5, 1.5]$ if both s and d are labeled as Low traffic nodes.

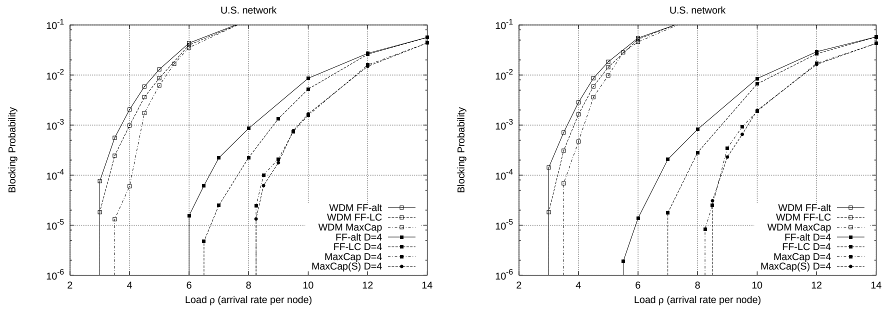

Figure 4. Blocking probability: US Network under Uniform Traffic scenario (on the left) and High-Low traffic scenario (on the right).

For all simulations, the accuracy of the results was assessed using the "batch means" technique with 95% confidence intervals.

Fig. 3 reports the simulation results obtained by considering the six-nodes network under uniform traffic pattern. It reports the blocking probability versus the offered load to the network, which is defined as the number of connection request per time unit per node.

Both classical RWA algorithms and algorithms which jointly exploit WDM and OTDM are considered. As expected, the use of a OTDM multiplexing scheme, superposed to the WDM scheme, leads to a significant reduction of the blocking probability, since it exploits the grooming of several connections onto the same Super-Lightpath. If we identify the maximum amount of traffic that can be transported in the network under the constraint of a maximum blocking probability, we can observe that the capacity of the network is more than four times larger by using a OTDM multiplexing factor $D = 4$, e.g., fixing the blocking probability to 10^{-3}, the offered load carried by a traditional solution is about 10, while adding the OTDM multiplexing scheme the offered load the network can support becomes about 44 using the MaxCap algorithms. This is obtained by multiplying by 4 the capacity of each wavelength, but without increasing the transmission and reception rate at nodes.

Looking at how the different algorithm performs, we observe no differences when the classic RWA problem is faced. On the contrary, the OTDM case makes the problem more difficult, and the increased complexity of the MaxCap and MaxCap(S) algorithms allows to better exploit network resources.

In the left plot of Fig 4, the connection blocking probability versus traffic load is reported considering the US network topology under Uniform traffic, while right plot reports results when the High-Low load traffic pattern is simulated. Both classical RWA algorithms and their extension to the OTDM case with a multiplexing factor of $D = 4$ are considered. As expected, also in these

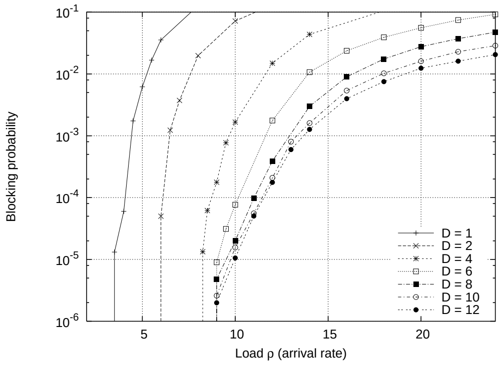

Figure 5. Blocking probability: US network under Uniform Traffic for different values of D.

scenarios there is a large reduction of the blocking probability by exploiting the grooming of several connections onto the same Super-Lightpath.

Note that the FF-LC algorithm slightly outperforms the FF-alt algorithm. This is mainly due to the intrinsic capability of FF-LC to adapt the routes of new lightpaths to the instantaneous congestion state in the network, resulting in a better usage of network wavelengths. The difference is more evident in the RTWA problem, where the point-to-multipoint paths are longer and therefore the impact of a smarter routing choice is more effective. But also in these cases, the MaxCap and MaxCap(S) algorithms outperform the FF-LC algorithm, also when considering the classic RWA problem. Notice that the blocking probability results are very similar when considering the Uniform or the High-Low load scenario. This is due to the fact that the increased variability in the traffic pattern when considering the High-Low load scenario does not influence the blocking probability averaged among all users, but rather the blocking probability of the single traffic relations.

We now give more detailed results considering the US network topology and the Uniform traffic pattern only. The MaxCap(s) algorithm is used to solve the RTWA problem, because it is the algorithm that offered the best performance, while maintaining the computation complexity limited. Fig 5 plots the blocking probability versus the traffic load for different values of multiplexing factor$D$. For small values of D, a significant performance gain is observed by increasing the OTDM multiplexing factor D. For larger values of D (when the factor D becomes comparable with the number of nodes in the topology) the performance gain, instead, becomes less significant. This effect is mainly due to the fact that, for large values of D, the beneficial reduction of the number of Super-Lightpaths required to sustain the traffic that would result from a further increase of D, is compensated by the increased Super-Lightpaths span.

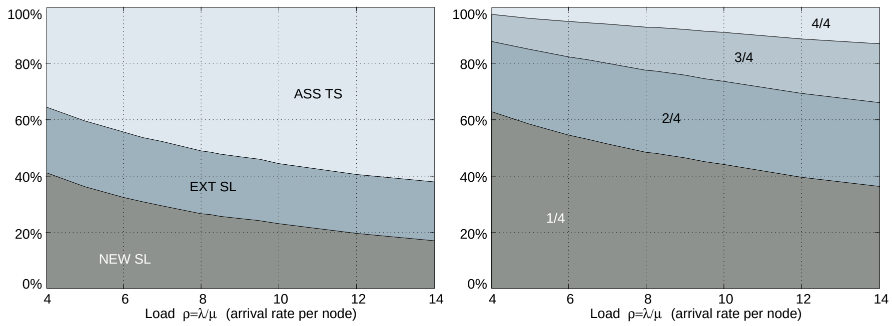

Figure 6. Percentage of time slot assignment, Super-Lightpath extensions, new Super-Lightpath allocation of connections (left graph) and time slot usage on Super-Lightpaths (right graph).

The percentage of connections which are allocated by exploiting only the time dimension (TS ONLY), i.e., by assigning a spare time slot to a new connection on an already established Super-Lightpath, by extending an existing Super-Lightpath (EXT SL), or by establishing a new lightpath (NEW SL), are shown in the left plot of Fig. 6 for the case $D = 4$, and considering the MaxCap(S) algorithm. We notice that the percentage of new connections that are allocated by exploiting only the time dimension increases with the traffic load, thus allocation in the time dimension results dominant at high loads.

Conversely, the percentage of connections which are allocated by creating a new lightpath decreases with the traffic load. This is due to the difficulty in finding suitable paths/wavelengths for new Super-Lightpaths when the traffic load is higher, as most of the 16 available wavelengths are already used. In the right part of Fig. 6, instead, we report the distribution of the number of simultaneous connections supported by network Super-Lightpaths (for the case $D = 4$ and FF-LC algorithm), i.e., the average percentage time slot occupancy on Super-Lightpaths. Results show that the average number of simultaneous connections supported by Super-Lightpaths increases with the traffic load. These results confirm the intuition that is more convenient to allocate a connection in the time domain rather than trying to consume precious wavelength resources. This also explain the marginal differences between the performance of the MaxCap and the MaxCap(S) algorithms.

Finally we study the amount of OXC switching required with our approach. The frequency at which network reconfigurations (i.e., addition, extension and removal of lightpaths) occur in conventional WR networks and in networks exploiting the time dimension are compared in Fig. 7. Since during the optical layer reconfiguration phases complex transient phenomena take place in the optical devices, which may negatively affect the quality of optical channel [14], the reduction of the reconfiguration frequency in the optical layer can

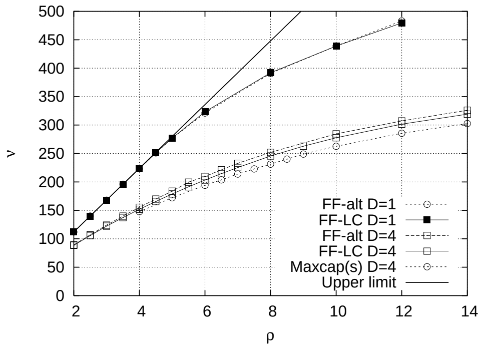

Figure 7. Frequency of physical reconfigurations using OTDM.

have significant beneficial effects on the transmission performance. Indeed, in classical WR networks, a new lightpath must be established for each new connection request successfully allocated and then removed at the connection tear-down. Thus a physical layer network reconfiguration corresponds to each new connection allocation and de-allocation. The Upper Limit curve in Fig.7 is obtained evaluating the average number of connection set-ups and tear-downs as function of the offered load. In WR networks exploiting the OTDM multiplexing scheme, on the contrary, a significant percentage of connections is allocated on already existing Super-Lightpaths by exploiting only the temporal dimension, and, thus, they do not require any physical layer network reconfiguration. As a result, the frequency at which physical layer network configurations occur in networks exploiting both WDM and OTDM is almost halved with respect to pure WDM networks.

4. Conclusions

In this paper we have proposed the adoption of an Optical Time Division Multiplexing scheme together with the classic WDM multiplexing scheme to support IP tunnels in dynamically reconfigurable wavelength routed networks. By grooming at the source node several IP-tunnels on the same wavelength, a Super-Lightpath is formed, in which a single source sends data toward several destination nodes, thereby reducing synchronization problems. An intermediate node receives in the electronic domain a de-multiplexed stream of bits, while it switches in the optical domain the entire wavelength toward the next destination node.

By extending classic RWA algorithms and by proposing novel algorithms, we have shown by simulation that the adoption of a joint WDM-OTDM multiplexing technique can lead either to a reduction of the network costs or to a significantly improvement of the network performance. This is obtained with an increase of the aggregate network capacity, which however comes at limited costs in the optical domain, and additional multiplexing/demultiplexing at network nodes, where complexity is minimal due to our choice of having one source in each Super-Lightpath. The novel algorithms that have been proposed can be used also to solve the classic RWA problem, reducing the network blocking probability.

Notes

1. In[7–8] we considered only Super-Lightpaths following linear paths. Tree shaped lightpath become possible if OXCs have wavelength splitting capabilities, which is usually the case.
2. We do not use the traditional Routing, Wavelength and Time Assignment - RWTA- acronym to stress the differences of our approach with previous proposals [4–6]. Indeed, the Time allocation is fixed in our approach, and no time switching can be applied in a Super-Lightpath.
3. To limit the complexity of the algorithm, P can include only a limited number paths between all source-destination pairs. In the simulation, we limited this number to at most 30 paths for each s-d pair, selecting the shortest paths in term of hop number.

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