Performance Evaluation of Node Architectures with Color and Direction Constraints in WDM Networks

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***Abstract*— We consider routing and wavelength assignment (RWA) in a WDM network consisting of optical cross-connect (OXC) nodes that have color and direction constraints. These restricted node architectures have a smaller cost than the more flexible (and best performing) ones usually assumed in the RWA problem. This introduces an interesting tradeoff between the network performance achieved, in terms of network blocking and number of manual interventions required, and the cost of the node architecture used. In the process of comparing the node architectures, we propose an adaptation of an RWA algorithm that accounts for the lack of node flexibility, aiming to achieve using the constrained node architectures, performance similar to that obtained with the fully flexible node architectures. Additionally, we consider different transponder assignment policies and determine their effect on performance.**

***Index Terms*—optical cross-connect, color and direction constraints, routing and wavelength assignment.**

I. INTRODUCTION

Advances on optical devices, communication sub-systems, and network architectures have led to a profound transformation in all aspects of optical network communications. The most common architecture used for establishing communication in WDM optical networks is wavelength routing, where data are transmitted over all-optical WDM channels, called lightpaths, which may span multiple consecutive fibers. A lightpath is realized by determining a path between the source and the destination and allocating a free wavelength on all the links of the path. The selection of the path and the wavelength to be used by a lightpath is an important optimization problem, known as the routing and wavelength assignment (RWA) problem [1].

The key elements that make this technology feasible are optical line terminals, optical add/drop multiplexers, and optical cross-connectors [2]. An optical line terminal (OLT) includes multiplexers/demultiplexers of wavelengths and transponders (TSPs). A TSP is responsible for adapting the signal to a form suitable for transmission over the optical network for originating traffic and for the reverse operation when traffic is terminated. An optical add/drop multiplexer (OADM) takes in signals at multiple wavelengths and selectively drops some of these wavelengths locally, while letting others to pass through. There are two types of OADMs: fixed (FOADM) and reconfigurable (ROADM). FOADMs are capable of adding or dropping fixed wavelengths, while ROADMs select the desired wavelengths to be dropped and added on the fly, a feature that is quite desirable.

OADMS are useful network elements to handle simple network topologies, such as linear or ring topologies and utilize fibers with small number of wavelengths. In order to handle more complex topologies and utilize a large number of wavelengths an optical cross-connect (OXC) is required. An OXC essentially performs functions similar to the ROADMS but at much larger sizes. OXC node architectures can be distinguished based on whether colored or colorless and directed or directionless add/drop ports are utilized. Colored ports, unlike colorless add/drop ports, have a permanently assigned wavelength channel. Also, in a node equipped with directed add/drop ports, a channel on a specific transmission fiber originating from or terminating at the node, can be added/dropped only by a particular multiplexing/ demultiplexing element (port) connected to this transmission fiber. In any case, the number and the type of transponders (TSPs) at each node are also important, since they determine not only the exact number of wavelengths that can be added or dropped but also the flexibility of the node. In architectures with colored or/and directed ports, the only way one can switch a plugged TSP, from one port to another, is manually; for this reason we call such an operation as manual intervention. In what follows, we focus on OXCs; however our study also applies for ROADMs.

In our work we evaluate how a routing and wavelength assignment (RWA) algorithm performs under optical cross-connect (OXC) node architectures with different levels of color- and direction-related flexibility. In particular, we concentrate on four node architectures that use add/drop ports with the following configurations: i) colored/directed, ii) colored/directionless, iii) colorless/ directed, and iv) colorless/directionless. These node architectures come with a different cost; that is, the more flexible ones are also more expensive. As a result, an interesting tradeoff is introduced between the network performance achieved, in terms of network blocking and number of manual interventions, and the cost of the node architecture used. In the process of comparing

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the node architectures of differing degrees of flexibility, we propose an adaptation of an online RWA algorithm that takes into account the lack of node flexibility, and aims at achieving using the more constrained node architectures, performance similar to that obtained with the more flexible and more expensive node architectures. Additionally, we evaluate different transponder (TSP) assignment policies and determine their effect on the network performance achieved. Our simulation results show that the color constraint affects more negatively the network performance than the direction one. In addition, the performance of the architectures is highly affected by the transponder assignment policy used.

The remainder of the paper is organized as follows. In Section II we report on previous work. In Section III we describe the network and node models used. In Section IV we propose an RWA algorithm that accounts for the node limitations and also present various TSPs assignment policies. Simulation results are presented in Section V. Our conclusions are given in Section VI.

II. PREVIOUS WORK

ROADMs enable carriers to offer a flexible service and provide significant savings in Operational Expenditure (OpEx) and Capital Expenditure (CapEx) [3]. Authors in [3] compare alternative ROADM network architectures and show that optimally deployed higher-degree ROADMs with optical bypass and grooming can significantly reduce the cost. ROADM subsystems can be implemented using a variety of architectures and technologies, each with their own trade-offs in performance and functionality [8]. In [4] authors describe the available technology options, and corresponding subsystem features, while highlighting the key advantages and implementation challenges associated with each of them.

Currently, most of the RWA algorithms proposed [1], assume that node architectures are fully flexible. Very few studies consider RWA algorithms assuming nodes that have architectural constraints. Authors in [5] study the performance of WDM networks with limited number of add/drop ports in OXCs. They consider the impact of the number of add/drop ports and conclude that only a limited number of add/drop ports are required at each node to achieve performance very close to that of a network where each node is equipped with the full number of widely tunable add/drop ports. The authors in [6] compare the design of metro optical WDM network architectures using two different ROADM architectures, namely, a switching-based architecture and a tuning-based architecture, and demonstrate that tuning-based architectures are more cost-effective for the metro networks under the current technologies. The same authors consider the tuning process of ROADMs with the constraint that it does not interfere with working wavelengths and provide heuristics to avoid such interference. Authors in [7] investigate the blocking performance of all-optical reconfigurable networks with constraints on reconfigurable optical add/drop multiplexers (ROADMs) and transponders (TSP) that can be tuned to transmit and receive to a certain set of wavelengths (limited tunable). They, also, develop an analytical model to calculate call blocking probability in a network of arbitrary topology for two different models of transponder sharing within a node: the share-per-link (SPL) and the share-per-node (SPN).

III. NETWORK AND NODE MODELS

In this section we describe the network and node models that we use in our work.

A. Network Model

A network topology is represented by a connected graph $G=(V,E)$. V denotes the set of OXCs-nodes. E denotes the set of (point-to-point) single-fiber links. Each fiber is able to support a common set $C=\{1,2,\dots,W\}$ of W distinct wavelengths. Each link l is characterized by the delay of the link d_l (or its length) and the availability of the wavelengths in the form of a boolean vector $\overline{W_l}=(w_l(1), w_l(2),\dots,w_l(W))$. We set $w_l(i)$ equal to 0 when the wavelength λ_i is occupied, and equal to 1 when λ_i is free (available). This vector is called the link's wavelength availability vector.

In our work, we assume that nodes are equipped with TSPs that can be tuned to transmit and receive at any wavelength (widely tunable TSPs). In particular, the number of TSPs T_n each node n is equipped with, depends on its degree D_n. The number of TSPs of node n, which are assigned to each link l is assumed to be constant and equal to T and as a result node n has a total of $T_n = D_n \cdot T$ TSPs.

B. Node Model

In our study we consider the following types of add/drop ports and optical cross-connects (OXCs).

1) Add/Drop ports

Colorless add/drop ports do not have a permanently assigned wavelength channel but rather are provisioned as to which wavelength channel will be added/dropped. In contrast, colored add/drop ports have a permanently assigned wavelength channel.

In directed add/drop ports, a channel on a specific transmission fiber originating from or terminating at the node can be added/dropped only by a multiplexing/demultiplexing element connected to this transmission fiber. In OXCs with directionless add/drop ports, traffic can be added/dropped to/from arbitrary transmission fibers.

2) Optical cross-Connects

Node architectures (OXCs) are categorized based on the type of add/drop ports, which are used to implement them. We evaluate four different node architectures: *colored/directed*, *colored/directionless*, *colorless/directed* and *colorless/ directionless*; Figure 1 shows these architectures. For example, Figure 1a illustrates four add/drop ports connected statically to Fibers 1 and 2 and wavelengths 1 and 2 respectively, while

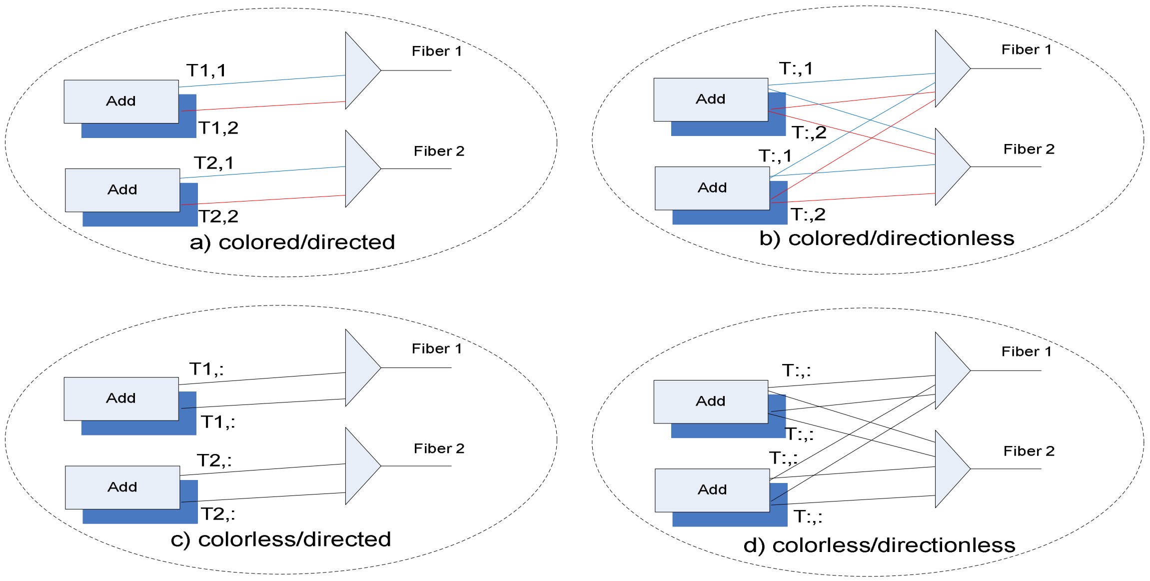

Fig. 1. Different node architectures: a) colored/directed, b) colored/directionless, c) colorless/directed, d) colorless/directionless. Tx,y express the ability of add/drop port: x is the fiber and y is the wavelength that the transponder (TSP) is plugged in. The symbol ':' denotes that there is no limitation.

Figure 1d presents four add/drop ports that can switch on the fly to any of the two fibers, serving any wavelength. In general, architectures using add/drop ports without color and direction limitations are more flexible, while adding more constraints on the add/drop ports makes the architectures less flexible.

IV. RWA PROBLEM

The Routing and Wavelength Assignment (RWA) problem is usually considered under two alternative traffic models. *Offline* (or *static*) lightpath establishment addresses the case where the set of connections is known in advance, usually given in the form of a traffic matrix that describes the number of lightpaths that have to be established between each pair of nodes. *Dynamic* (or *online*) lightpath establishment considers the case where connection requests arrive at random time instants, over a prolonged period of time, and are served upon their arrival, on a one-by-one basis. We focus our study on the online RWA problem.

A. RWA Algorithm with full flexibility

The RWA algorithm we consider in case nodes have full flexibility (colorless/directionless nodes) is similar to the one proposed in [9], but without the physical impairment considerations present in that algorithm. Considering physical impairments would only complicate our study, without adding any insight on it. This RWA algorithm consists of two phases: In the first phase, the algorithm computes a set of paths from a given source to the destination as a generalization of Dijkstra's algorithm. This set of paths is passed to the next phase. Each path is associated with a wavelength availability vector. The wavelength availability vector $\overline{W}$ of a path is computed by applying the logical AND operator in the wavelength availability vectors (component-wise) of its constituent links $\overline{W_l}$. In the second phase, the algorithm from the set of candidate paths selects the one with the most used wavelength. In the end, the algorithm establishes the decided lightpath if there are available transponders (TSPs) in the source/destination nodes of the connection, assuming colorless/directionless node architectures.

B. RWA Algorithm with limited flexibility

1) Colored vs. Colorless architecture

Colored add/drop ports in network nodes limit the flexibility of the RWA algorithm, mainly regarding which channels/wavelengths it can use for serving a connection request. This is because the node ports are permanently assigned to specific wavelengths. In this case, the links' wavelength availability vectors $\overline{W_l}$, used by the RWA algorithm, are updated according to these wavelengths. If the algorithm cannot find a lightpath for serving a connection request, then manual intervention can be performed. In particular, manual intervention corresponds to the assignment of an available TSP to a different port than the one already provisioned. If no TSPs are available, then the demand is finally blocked.

Figure 2a shows how the definition of the wavelength availability vector $\overline{W_l}$ of link l has to be modified to account for the color related constraints. If node d is the destination of a connection request, then the availability vectors of the node's incoming links are modified according to its available receivers - drop ports (that are tuned to specific wavelengths). For example in Figure 2a, the original vector of link l is $\overline{W_l} = [0\ 1\ 1\ 1\ 1]$, implying that the available wavelengths of link l are the w_2, w_3, w_4, w_5 (the example assumes five wavelengths per fiber). In case the RWA algorithm attempts to find a lightpath that terminates at node *d*, then all the availability vectors of the links incoming to *d* are modified based on the way node's *d* drop ports are colored. In our example, node *d* can only receive on wavelengths w_1, w_3 because only receivers / drop ports R_1 and R_3 are available and therefore, the original availability vector is updated to $\overline{W_{l,\mathrm{T}}} = [0\ 0\ 1\ 0\ 0]$. This means that only wavelength w_3 of link *l* is actually available for use by the RWA algorithm in order to end the lightpath in node *d*.

If the RWA algorithm cannot find a lightpath, either due to the unavailability of a path and/or wavelength from source to destination or due to the color constraint, manual intervention is necessary. In this case the RWA algorithm is re-executed for deciding the lightpath that will serve the request, assuming that there are not color constraints. Next, based on the RWA algorithm's decisions manual intervention is performed so as to plug a TSP at the decided (input or output) port. As mentioned, the RWA algorithm (that does not consider color constraints) is executed only if there are free TSPs at the source and destination nodes of the connection request; otherwise the connection is blocked.

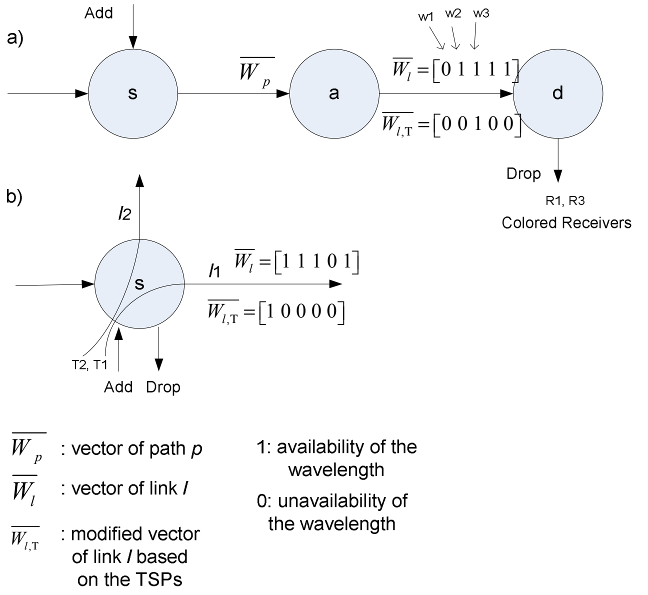

Fig. 2. a) Availability vectors of the RWA algorithm when considering colored ports. Receivers / drop ports R_1, R_3 can only receive wavelengths w_1, w_3, respectively. b) Availability vectors of the RWA algorithm when considering directed ports, where transmitter / input port T_1 can only send traffic to link l_1 and transmitter / input port T_2 can only send traffic to link l_2.

2) Directed vs. Directionless architecture

Directed ports limit the routing choices available to the RWA algorithm, mainly regarding the first and the last link of the path to be used for serving a connection. For example, assume there is only one free input port (with a plugged TSP) connected to a specific fiber in a node *s*. This free input port can only be used by a connection request, which originates from *s* and uses this fiber as its first hop. This constraint must be accounted for by the corresponding RWA algorithm. If a lightpath cannot be found, the connection is either blocked, or manual intervention is performed to connect an available TSP to another fiber. In this case, an RWA algorithm that does not consider direction-related constraints will point out which fiber-link is most efficient to use. In the case where there are no available TSPs then the connection will be blocked.

In Figure 2b, if node *s* is the source of a connection request, then we can only set up a connection from transmitter / input port T_1 to link l_1 and from T_2 to l_2. Also, the wavelength availability vectors of the links are again modified, in a way similar to that used for colored ports. In case we also have color constraints (that is, the ports are not colorless), the RWA algorithm will have to find a solution under both constraints.

C. TSP Assignment Policy

An important factor affecting network efficiency in case colored node architectures are used, is the way the transponders (TSPs) of a link are provisioned to specific wavelengths. Next, we present a number of such TSP assignment policies.

1) Colored Architectures - Policy 1: Lowest wavelength count first

The provision of wavelengths in the TSPs of a link can be performed according to the "lowest available wavelength count first" rule. That is, assuming there are *T* available TSPs per link and no connections are already established, the TSPs can be provisioned to the first *T* wavelengths of the link (Figure 1a and 1c).

2) Colored/directed Architecture - Policy 2: Cyclic wavelength rotation

In this policy, the *T* available TSPs of each link are provisioned based on a cyclic rotation process. That is, the TSPs of the first link of a node are provisioned to wavelengths 1 to *T*, the TSPs of the second link are provisioned to wavelengths *T*+1 to 2*T*, and the provisioning procedure continues similarly to the remaining links, until all the TSPs are provisioned (Figure 3a).

3) Colored/directionless Architecture - Policy 2: Full wavelength cover

Under this policy (Figure 3b), all the available TSPs of a node are provisioned to wavelengths 1 to $T_n = D_n \cdot T$, assuming $T_n \le W$. In case $T_n > W$, then $\lfloor T_n / W \rfloor$ TSPs are provisioned to all the wavelengths and the remaining $T_n \bmod W$ TSPs are provisioned to wavelengths 1 to $T_n \bmod W$.

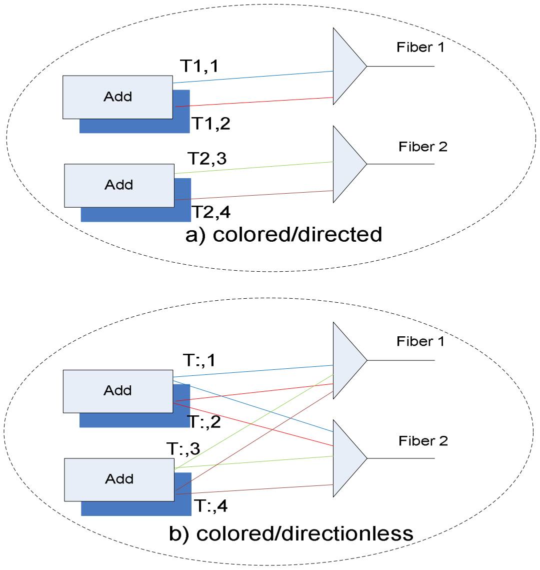

Fig. 3. TSP assignment policy 2 for: (a) the colored/directed architecture, (b) the colored/directionless architecture (as opposed to policy 1 in Figure 1a and 1c).

V. SIMULATION RESULTS

The network topology used in our simulations was the generic Deutsche Telekom network (DTnet) that has 14 nodes and 46 directed links (one fiber-link per direction), as identified by the DICONET project [10]. The capacity of a wavelength was assumed equal to 10Gbps. Connection requests (each requiring bandwidth equal to 10Gbps) are generated according to a Poisson process with rate λ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. The duration of a connection is given by an exponential random variable with average $1/\mu$ (time units). Thus, λ/μ gives the total network load in Erlangs. In our simulations we assume that widely tunable TSPs are plugged into specific ports. In addition, we assume that the number of TSPs is constant during the network operation. That is, we cannot add extra TSPs and if a connection cannot be served due to limited resources then it is blocked. Also, in the cases where we do not have fully flexible architecture and an available TSP has to be assigned to a different port than the one originally assigned, so as to serve a new connection, then a manual intervention (MI) is performed, unless otherwise mentioned.

In Figure 4a we graph the blocking probability for the four examined node architectures as a function of the network load, assuming there are 16 available wavelengths and 12 TSPs per fiber link. We observe that all node architectures perform similarly in terms of blocking probability. This is explained by the fact that we allow manual interventions (MIs) for changing the direction and the color of a port, and also each fiber has the same number of wavelengths and TSPs. Small variations in blocking probability are because in different architectures the differences in ports flexibilities lead to different wavelength assignment by the RWA algorithm, which assigns the wavelengths based on the already provisioned TSPs. However, as Figure 4b indicates, different node architectures result in differences in the number of manual interventions (MIs). The most flexible architecture with colorless/directionless ports has zero MI because every port can add/drop any wavelength in any direction. The second and the third more flexible architectures are colorless/directed and colored/directionless, respectively. Colorless/directed architecture exhibits very small number of MIs and this can be explained by the characteristics of the DT network. In particular, the average node degree of DT network is small and as result the direction related constraint is not so restrictive as the color related one. As expected the colored/directed architecture needs the largest number of MIs. Also, when the load is large the number of connections blocked due to limited resources (despite the MIs) increases, leading to a small decrease in the number of MIs.

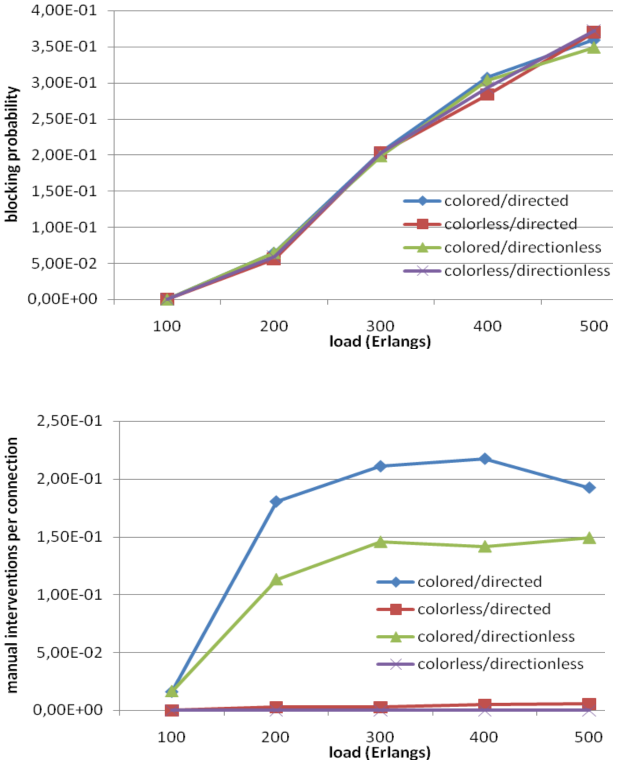

Fig. 4. (a) Blocking probability, (b) average number of manual interventions required per connection vs. network load, assuming 16 wavelengths and 12 transponders per link, for various node architectures.

Figure 5 illustrates the blocking probability versus the number of TSPs per link for different number of available wavelengths. In general, the performance of the RWA algorithm is constrained by the number of transponders; however, as this number increases, then the number of wavelengths becomes the performance bottleneck. In particular, we note that in order to achieve zero blocking probability 8 TSPs and 14 wavelengths per link/fiber are required. When having only 10 available wavelengths per fiber, we cannot achieve zero blocking for load equal to 100 Erlangs, irrespectively of the number of TSPs. These results and observations hold for all the node architectures under consideration.

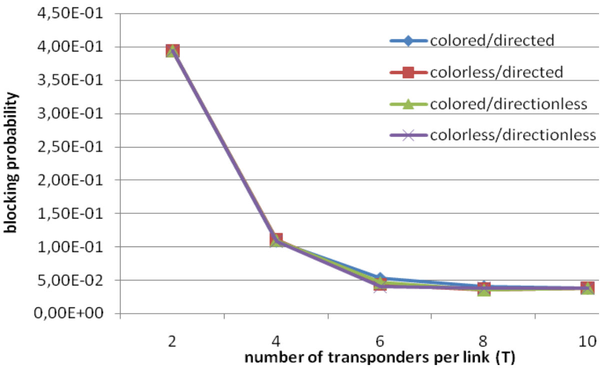

Fig. 5. Blocking probability vs. number of transponders for different number of available wavelengths per link, assuming network load equal to 100. Blocking probability is the same irrespective of the node architecture used.

Figure 6 presents the number of manual interventions (MIs) required per connection versus the number of available TSPs per link assuming 10 wavelengths per link and load equal to 100 Erlangs. The performance results are similar to those described in Figure 4. As the number of transponders per link increases, the number of MIs per connection decreases.

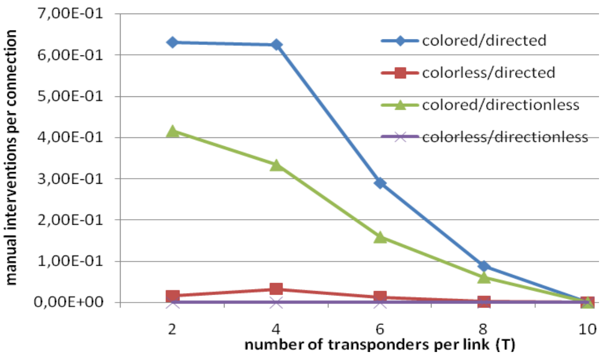

Fig. 6. Manual interventions vs. number of transponders, assuming 10 available wavelengths per link and network load equal to 100, for various node architectures.

In Figure 7 we examine the performance of the various TSP assignment policies proposed in conjunction with the node's architectures considered, assuming network load equal to 100 Erlangs and 14 available wavelengths. In this set of simulations, we assumed that no MIs are allowed and as a result if the wavelength of the transmitter (source) does not fit with the wavelength at the receiver (destination), then the connection is blocked. We observe that the colored/directed and colored/directionless architectures exhibit the same, bad performance when the TSP assignment policy 1 is used. This is due to the fact that under this policy not all the available wavelengths are actually utilized. On the other hand the performance of these architectures, and especially that of the colored/directionless architecture, is improved when TSP assignment policy 2 is used.

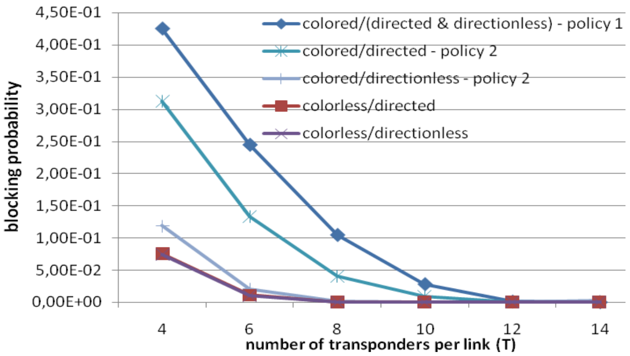

Fig. 7. Blocking probability vs. number of transponders when no manual interventions are allowed, assuming 14 available wavelengths per link and network load equal to 100, for various node architectures and TSP assignment policies.

VI. CONCLUSION

We evaluated and compared the performance of several node architectures with color and direction related constraints used in a WDM network. In comparing the node architectures, we also proposed an adaptation of an RWA algorithm that accounts for the lack of node flexibility, and aims at achieving performance similar to that obtained with fully flexible node architectures. Our results demonstrated that in topologies where the node degree is small, the colored constraint is a more dominant performance limiting factor than the direction related one. In addition, we observed that even if a sufficient number of transponders exist in each node, a small number of wavelengths can also be a bottleneck of the network's performance. Finally, we illustrated that the way transponders are assigned to wavelengths is important and policies utilizing all the available wavelengths should be used.

ACKNOWLEDGMENT

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