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A Comparative Study of Node Architectures with Add/Drop Constraints in WDM Networks

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1. Introduction

The advent of WDM technology has resulted in transmission capacities that have increased manifold in recent years. 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 (Ramaswami & Sivarajan, 1995). In the absence of wavelength conversion, a lightpath must be assigned a common wavelength on each link it traverses; this restriction is referred to as the wavelength continuity constraint. However, two lightpaths may occupy the same wavelength, as long as they use disjoint sets of links; this property is known as wavelength reuse. The RWA problem is usually considered under two alternative traffic models. Static Lightpath Establishment (SLE) addresses the case where the set of connections is known in advance and Dynamic Lightpath Establishment (DLE) considers the case where connection requests arrive randomly, over an infinite time horizon, and are served one-by-one.

The key elements that make WDM technology feasible are optical line terminals, optical add/drop multiplexers, and optical cross-connectors (Ramaswami & Sivarajan, 2001). 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. Wavelength selective switch (WSS) technology has recently enabled the introduction of multi-degree ROADM and the deployment of cost-effective dynamic wavelength switched networks (Kaman et al., 2006).

In order to handle more complex topologies and utilize a large number of wavelengths optical cross-connects (OXC) are 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 non-directionless (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 order for such a port to switch to another wavelength or to another fiber respectively, manual intervention is required. In any case, the number and the type of transponders (TSPs) at each node are also important, since they determine not only the number of wavelengths that can be added or dropped but also the flexibility of the node.

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/non-directionless, ii) colored/directionless, iii) colorless/non-directionless, 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 (since the operators seldom refuse a connection, but undertake the necessary, manual work to serve it), and the cost of the node architecture used. In the process of comparing 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 provision strategies and determine their effect on the network performance achieved. The term TSP assignment policy is referred to the correlation between a transponder and a network port. For example, the choice of a port in a directed architecture means that we have to decide in which fiber we want the TSP to be able to send/receive. Our simulation results show that the color constraint affects more negatively the network performance than the direction constraint. In addition, the performance of the architectures is highly affected by the transponder assignment policy used and the provision strategies.

The remainder of the paper is organized as follows. In Section 2 we report on previous work. In Section 3 we describe the network and node models used. In Section 4 we propose an RWA algorithm that accounts for the node limitations and also present various TSP assignment policies. Simulation results are presented in Section 5. Our conclusions are given in Section 6.

2. Previous work

ROADMs enable carriers to offer a flexible service and provide significant savings in Operational Expenditure (OpEx) and Capital Expenditure (CapEx) (Mezghoudi et al., 2006). (Mezghoudi et al., 2006) compare alternative ROADM network architectures and show that optimally deployed higher-degree ROADMs with optical bypass and grooming can

significantly reduce the cost. In (Keyworth, 2005) the author describes the available technology options, and corresponding subsystem features, while highlighting the key advantages and implementation challenges associated with each of them. ROADM subsystems can be implemented using a variety of architectures and technologies, each with their own trade-offs in performance and functionality. (Roorda & Collings 2008) and (Homa & Bala, 2008), present different WSS-based ROADM architectures.

Currently, most of the RWA algorithms proposed either assuming a network with ideal physical layer (Zang et al., 2000) or a network with physical layer impairments (Saradhi & Subramaniam, 2009), assume that node architectures are fully flexible. Very few studies consider RWA algorithms assuming nodes that have architectural constraints. Authors in (Shen et al., 2003) 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 (Zhu & Mukherjee, 2005) 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 (Turkcu & Subramaniam, 2009) 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 the 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). The authors in (Staessens et al., 2010) assess the impact of node directionality on restoration in transparent networks.

3. Node models

In our study we consider the following types of add/drop ports and optical cross-connects (OXCs). We present four node architectures for the optical cross-connects (OXCs); their characteristics affect the final cost of the design strategy applied for serving a set of connection requests. All node architectures offer the same functionality for the transit traffic, namely, full remote re-configurability. They primarily differ in the way the traffic local to the node is treated. Therefore, categorizing OXCs mainly refers to the features/flexibility of add/drop ports.

3.1 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.

3.2 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. 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. All the OXC architectures can remotely configure all transit traffic with a broadcast and select architecture. The incoming channels (for example from box A in Fig.1-4) are broadcasted (with a splitter) to all other network interfaces (for example boxes B and C in Fig. 1-4). A WSS is connected to the outgoing fiber and can select which wavelength from which other network interface or add/drop terminal it wants to add. Each network interface (NI) consists of a WSS and a splitter.

3.2.1 Colored/Directed node architecture

As previous mentioned, OXC architectures are primarily differ in the way the add/drop terminals are implemented. In colored/directed architecture (Fig. 1) each add/drop

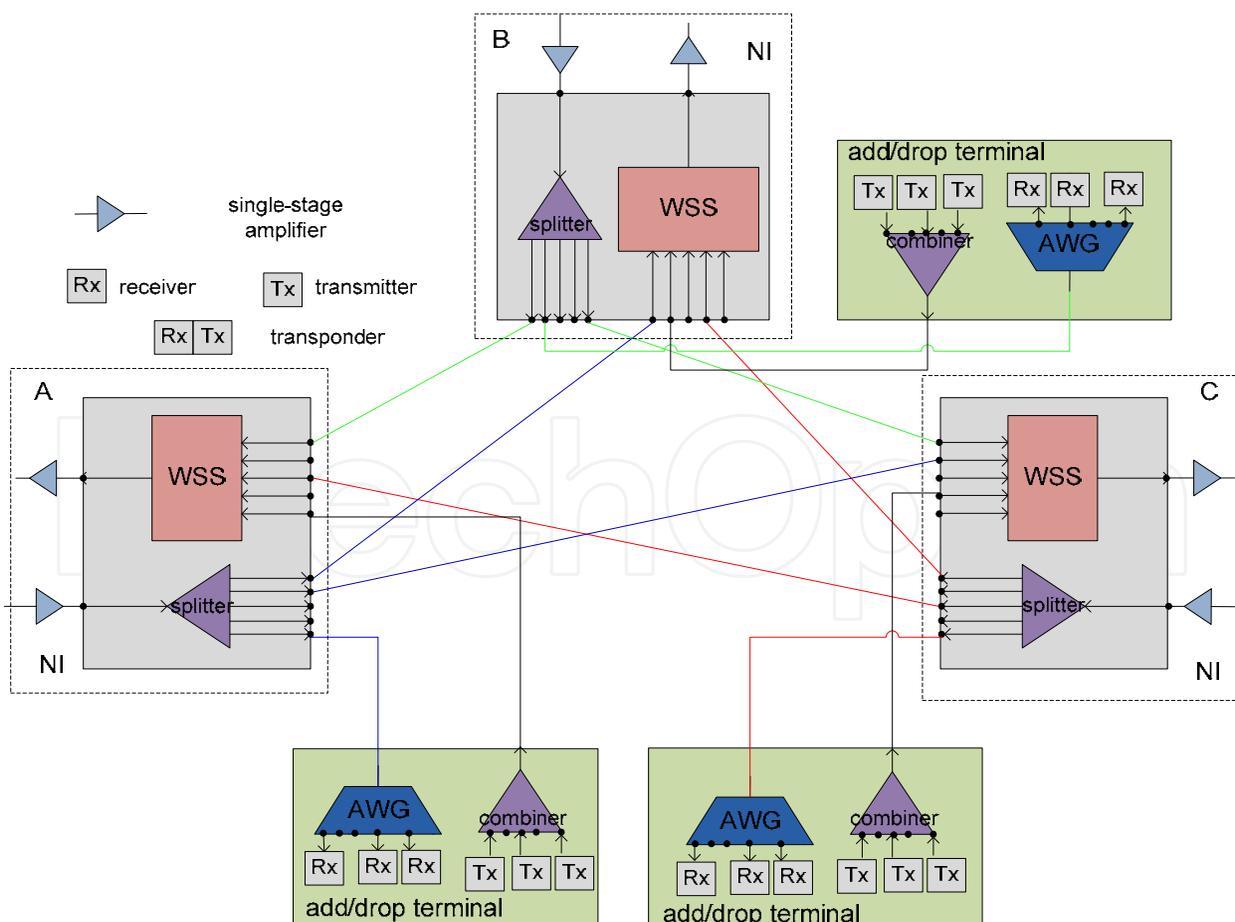


Fig. 1. Colored/directed node architecture

terminal (green box) is connected to a specific network interface and as a consequence to a specific optical fiber (directed feature). Moreover, each transponder located in the add/drop terminal is connected through fixed wavelength demultiplexing element (for example an arrayed waveguide grating (AWG)). The AWG is used to separate the drop channels to the receivers. Using an AWG imposes fixed wavelengths on the drop (colored feature). Also in this add/drop terminal, a combiner is used to collect all the added traffic. The advantage of this architecture is that there is no need for WSS equipment in the add/drop terminals and only an AWG and a combiner are needed to implement each add/drop terminal.

3.2.2 Colored/Directionless node architecture

To avoid having separate add/drop terminals for each network interface and to be able to share the add/drop ports between the network interfaces, one common add/drop terminal (green box) per node is utilized and each port of the add/drop terminal is physically connected to all the fibers of NIs of the node. In this architecture the drop part of the add/drop terminal contains of a WSS and an AWG. The WSS is used to collect the drop traffic from the different directions and the AWG to separate the drop channels to the receivers. Channels

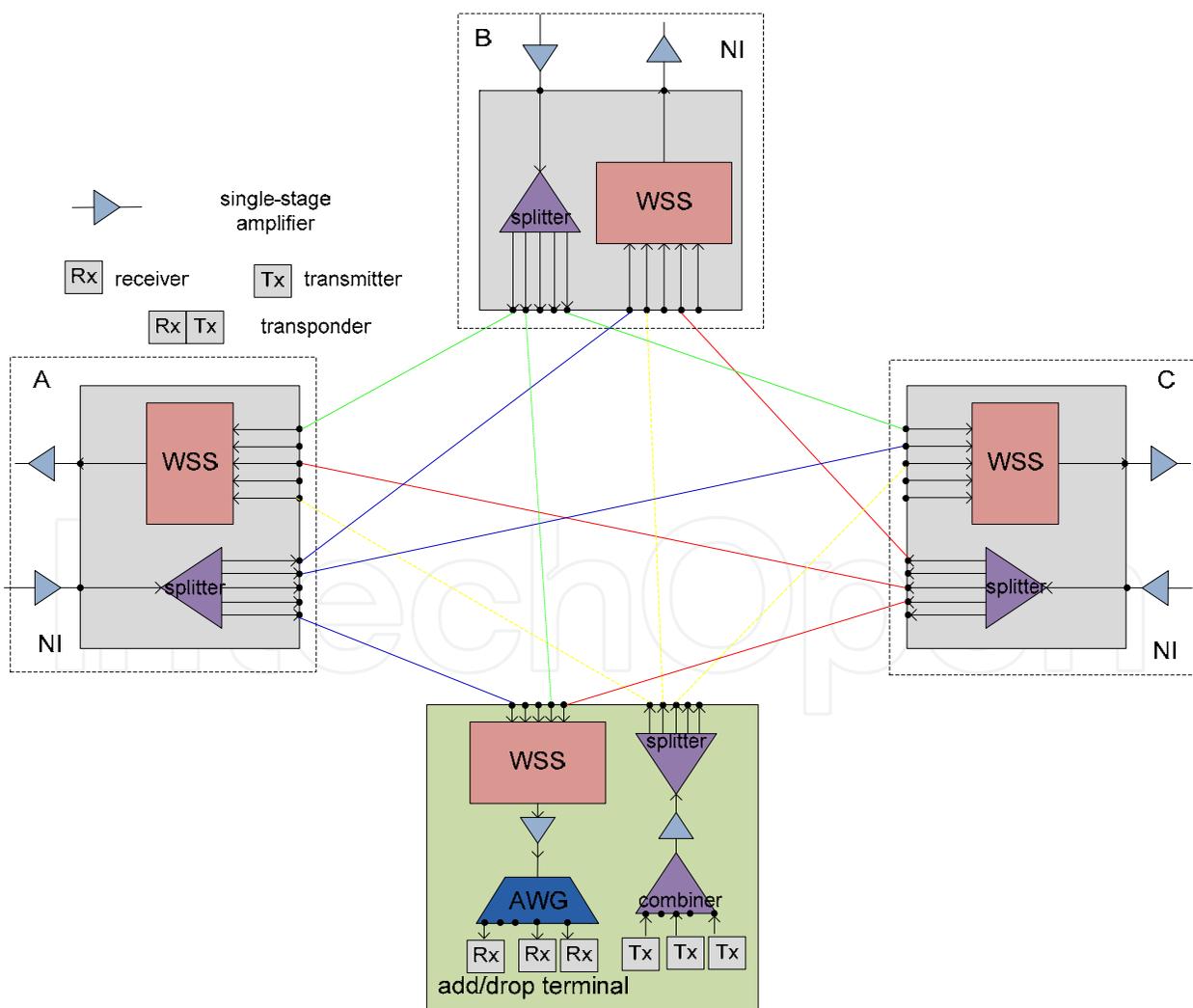


Fig. 2. Colored/directionless node architecture

from a bank of (different) wavelengths can be switched towards any network port connected to the OXC, as shown in Fig. 2. The drawback of this architecture is that only those wavelengths equipped in the channel bank can be used for traffic connections, and every wavelength can only be used to terminate a single network interface, only one wavelength per color can be used.

3.2.3 Coloreless/Directed node architecture

To avoid having to spend a lot of CapEx upfront to allow a more flexible routing, the architecture according to Fig. 3 can be used. Colorless ports are generally created by replacing a fixed wavelength demultiplexing element (AWG) with a wavelength selective switch (WSS). A WSS can steer each optical channel present on its input port toward one of its output ports. The dropped channels from a network port are distributed to the corresponding wavelength transponders via a 1xN WSS. In the add direction, all wavelengths are combined and sent to the corresponding network interface. This allows the reduction of the number of equipped transponders while still maintaining routing flexibility.

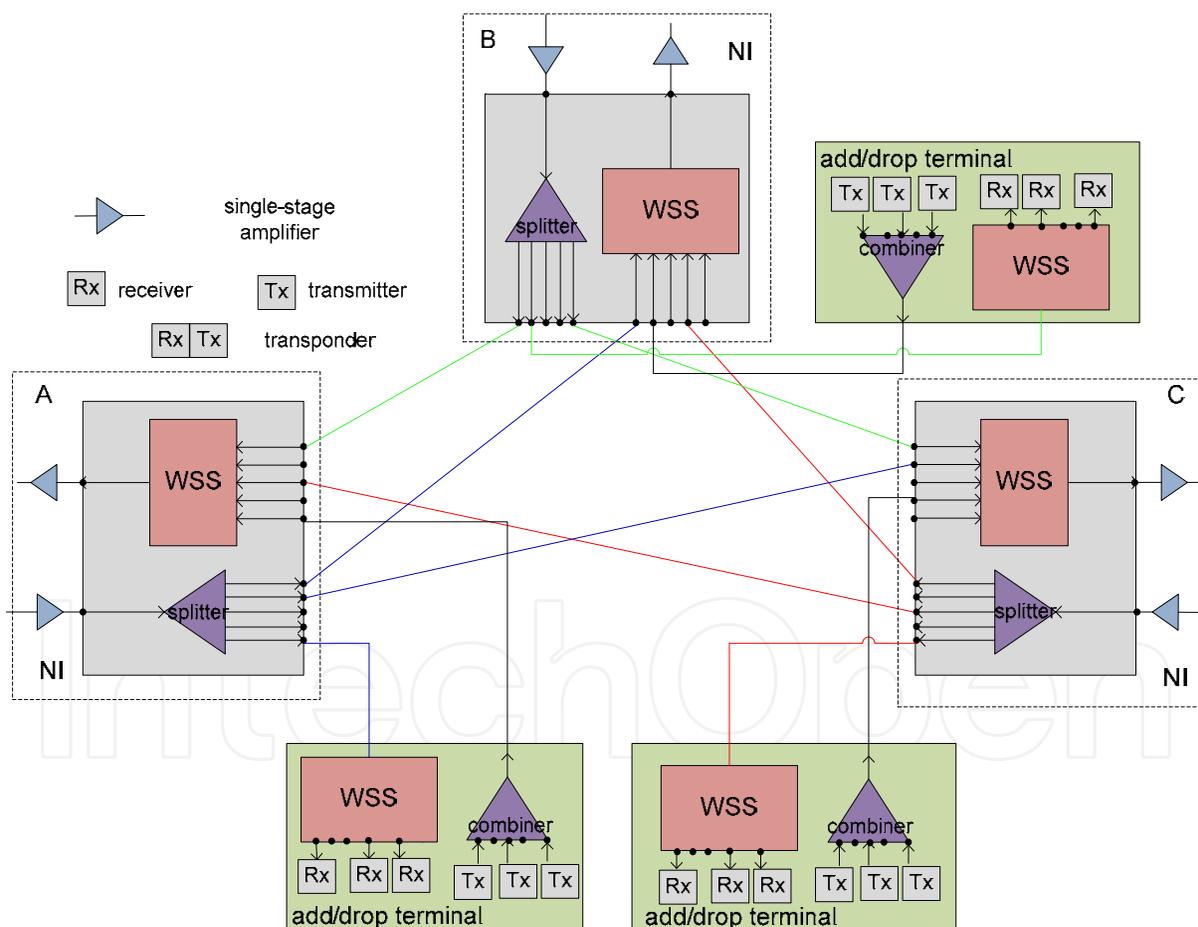


Fig. 3. Coloreless/directed node architecture

3.2.4 Coloreless/Directionless node architecture

To add more flexibility at the add/drop side of the architecture of Fig. 2, it is possible to use an extra network interface instead of an AWG component to select which wavelengths have

to be dropped from the other network interfaces. This extra network interface adds the directionless feature of the node (see Fig. 4), and is the first stage of the add/drop terminal. The colorless feature is implemented by the second stage of the add/drop terminal. In that box a combiner is used to add all the wavelengths and a WSS is used to select which wavelength you want to drop at which port.

If one add/drop terminal is used in this node configuration, only one unique wavelength can be dropped at an add/drop terminal, because a WSS can only drop the same wavelength channel once to its output port (contention feature). If more than one add/drop terminals (Fig. 4) are used then wavelength blocking at the add/drop terminal is prevented.

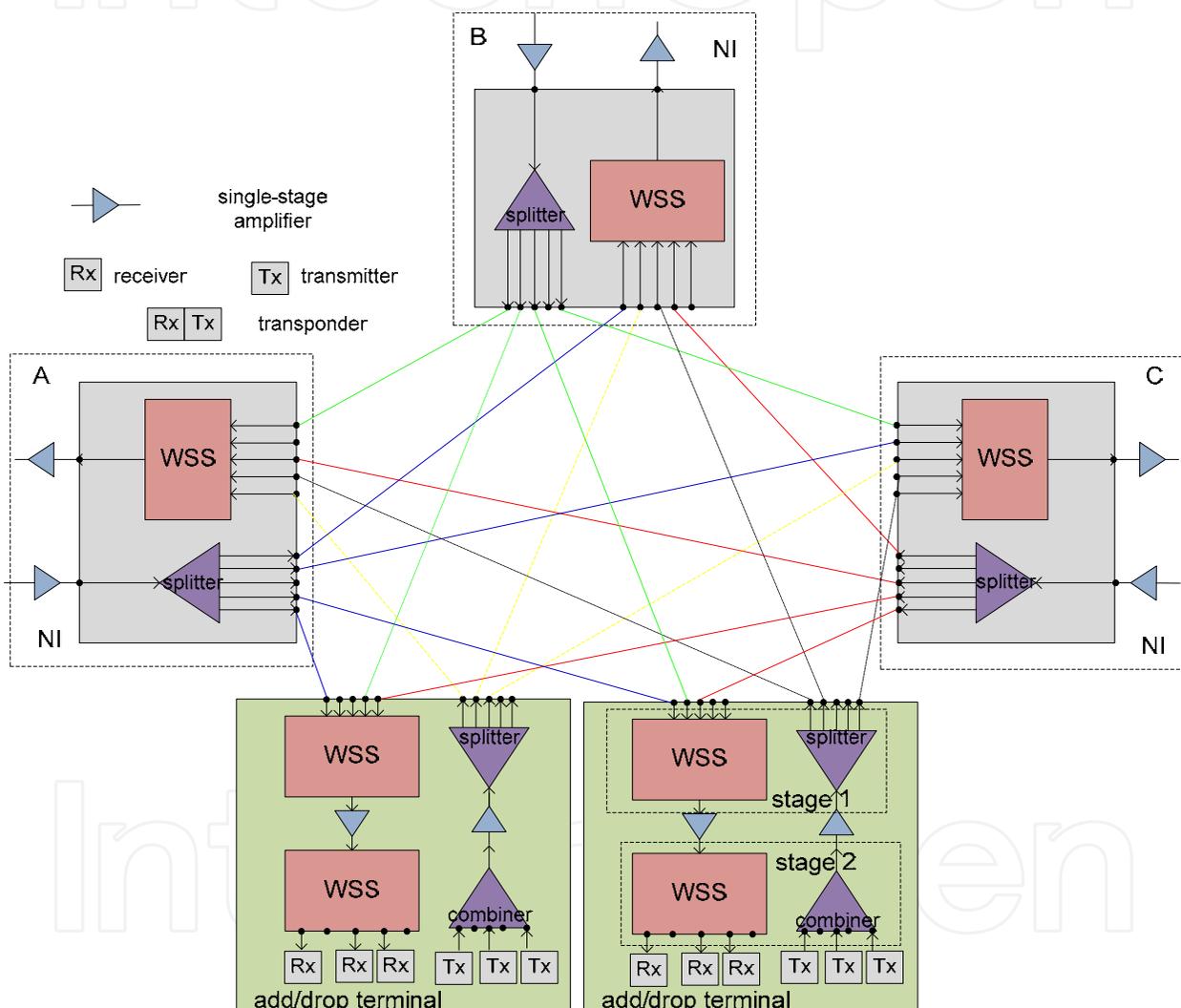


Fig. 4. Coloreless/directionless node architecture

4. 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.

4.1 RWA algorithm with full flexibility

The proposed multi-cost RWA algorithm consists of two phases. In contrast to traditional single-cost approach, where each link is characterized by a scalar, in the multi-cost approach a vector of cost parameters is assigned to each link, from which the parameter vectors of candidate lightpaths are calculated. 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 each node n is equipped with, depends on its degree D_n . The number of TSPs of node n , that 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.

4.1.1 Computing the cost vector of a path

We consider a WDM network with N nodes and L fiber-links, each of which carries m wavelengths. Each fiber is able to support a common set $C = \{\lambda_1, \lambda_2, \dots, \lambda_m\}$ of W distinct wavelengths. The WDM network employs no wavelength conversion. We also assume that the node where the algorithm is executed (in a decentralized or centralized architecture) has a picture of the wavelengths' utilization of all links. Although the algorithm may run in a decentralized way, and thus due to propagation delays utilization information might be outdated, we will not focus on such problems. We assume that all nodes are fully flexible (colorless/directionless nodes) without add/drop constraints.

Cost vector of a link

Each link l is assigned a cost vector that contains $m+1$ cost parameters:

- i. the length L_l of the link (scalar);
- ii. the availability of wavelengths in the form of a Boolean vector $\overline{W}_l = (w_{l1}, w_{l2}, \dots, w_{lm})$, whose i^{th} element w_{lm} is equal to 0 (false) if wavelength λ_i is used and equal to 1 (true) when λ_i is free.

Thus, the cost vector characterizing a link l is given by

$$V_l = (L_l, \overline{W}_l)$$

Cost vector of a path

Similarly to a link, a path has a cost vector with $m+1$ parameters, in addition to the list of labels of the links that comprise the path. Assume a path p with cost vector

$$V_p = (L_p, \overline{W}_p, *p),$$

where L_p , and \overline{W}_p are as previously described, and $*p$ is the list of identifiers of the links that comprise path p . The cost vector of p can be calculated by the cost vectors of the links $l=1,2,\dots,k$, that comprise it as:

$$V_p = \left(\sum_{l=1}^k L_l, \& \overline{W}_l, (1, 2, \dots, k) \right),$$

where the operator $\&$ denotes the bitwise AND operation. Note that all operations between vectors have to be interpreted component-wise.

Checking if the path is further extendable

We check if path p has at least one available wavelength.

If $\overline{W}_p = 0$ (all zero vector), then path p is rejected.

Domination relationship

We also define a *domination* relationship between two paths that can be used to reduce the number of paths considered by the RWA algorithm. In particular, we will say that

$$p_1 \text{ dominates } p_2 \text{ (notation: } p_1 > p_2) \text{ iff } L_{p_1} \leq L_{p_2} \text{ and } \overline{W}_{p_1} \geq \overline{W}_{p_2}$$

The " \geq " relationship for vectors \overline{W} , should be interpreted component-wise. A path that is dominated by another path has larger length and worse wavelength availability than the other path and there is no reason to consider it or extend it further.

4.1.2 Multi-cost RWA algorithm

The proposed multi-cost RWA algorithm consists of two phases:

Phase 1: Computing the set of non-dominated paths P_{n-d}

The algorithm that computes the non-dominated paths from a given source to all network nodes (including the destination) can be viewed as a generalization of Dijkstra's algorithm that only considers scalar link costs. The basic difference is that instead of a single path, a set of non-dominated paths between the origin and each node is obtained. Thus a node for which one path has already been found is not finalized (as in the Dijkstra case), since we can find more "non-dominated" paths to that node later. An algorithm for obtaining the set P_{n-d} of non-dominated paths from a given source to all nodes is given in (Varvarigos et al., 2008). By definition, for the given source and destination, the non-dominated paths that the algorithm returns have at least one available wavelength.

Phase 2: Choosing the optimal lightpath from P_{n-d}

In the second phase of the proposed algorithm we apply an optimization function or policy $g(V_p)$ to the cost vector, V_p , of each path $p \in P_{n-d}$. The function g yields a scalar cost per path and wavelength (per lightpath) in order to select the optimal one. Given the connections already established, we order the wavelengths in decreasing utilization order and choose the lightpath whose wavelength is most used. This approach is the well known "most used wavelength" algorithm (Zang et al., 2000), proven to exhibit good network-layer blocking assuming ideal physical layer. 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.

4.2 RWA algorithm with limited flexibility

A network topology is represented by a connected graph $G=(V,E)$. V denotes the set of OXCs-nodes.

4.2.1 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 5a 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 5a, the original vector of link l is $\overline{W}_l = [0\ 1\ 1\ 1\ 1]$, implying that the available

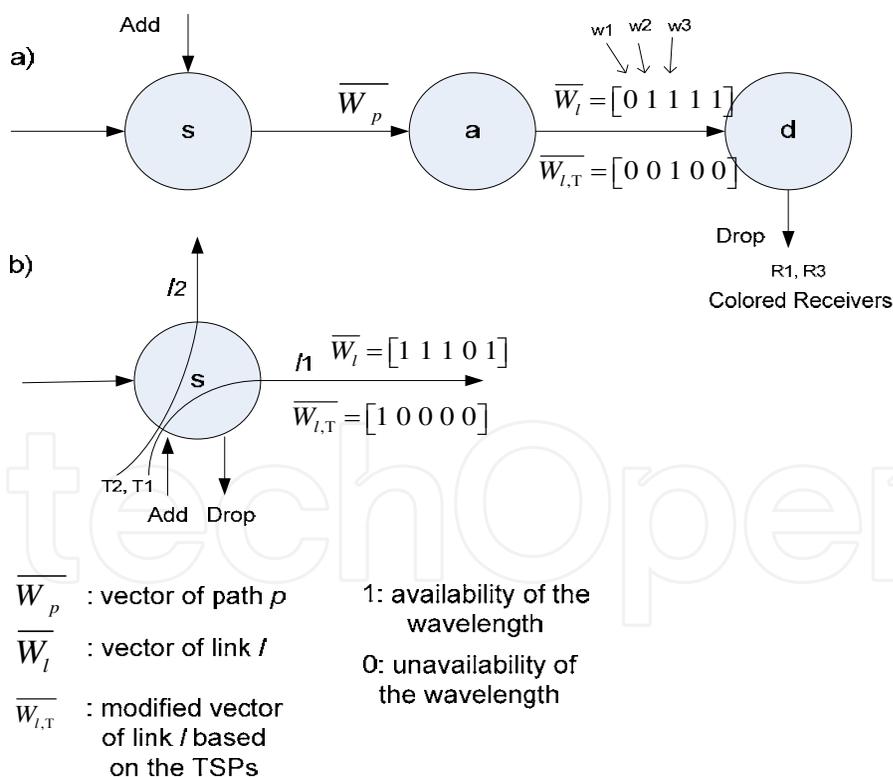


Fig. 5. a) Availability vectors of the RWA algorithm when considering colored ports.

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 .

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 $W_{l,T} = [0\ 0\ 1\ 0\ 0]$. 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.

4.2.2 Directed vs. directionless architecture

Colored Non-Directionless 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 5b, 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.

5. 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.

In Figure 6, we illustrate an abstraction of node architectures based on the configuration of add/drop ports. Also in this figure we depict the way the TSPs are connected to the optical fibers (in which wavelength and direction). For example, Fig. 6a presents four add/drop ports connected statically to Fibers 1 and 2 and wavelengths 1 and 2 respectively, while Fig. 6d presents four add/drop ports that can switch on the fly to any of the two fibers, serving any wavelength.

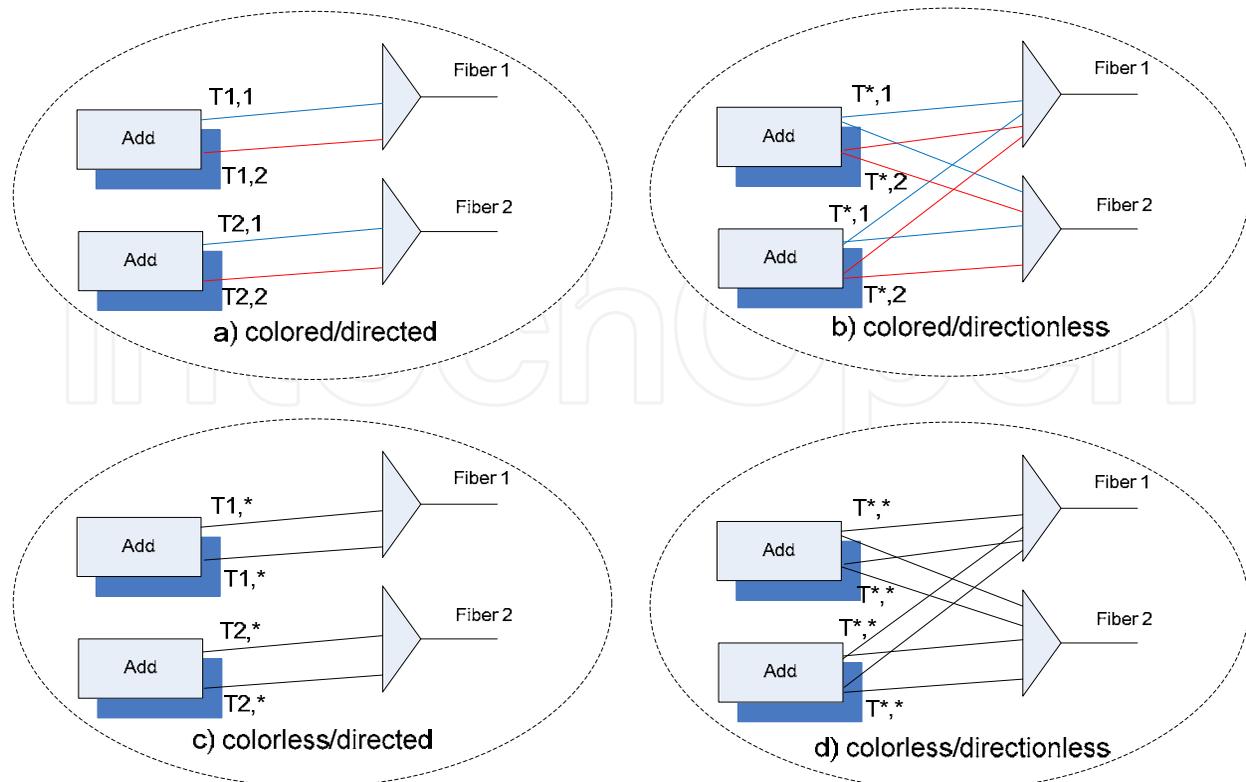


Fig. 6. a) Different node architectures: a) colored/non-directionless, b) colored/non-directionless, c) colored/directionless, d) colorless/directionless. $T_{x,y}$ express the ability of add/drop port: x is the fiber and y is the wavelength that the transponder (TSP) is plugged in. The symbol '*' denotes that there is no limitation.

5.1 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 6a and 6b). This is the simplest TSP assignment policy that can be used in colored architectures.

5.2 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 $2T$, and the provisioning procedure continues similarly to the remaining links, until all the TSPs are provisioned (Figure 7a). The sense behind this policy is that the available TSPs of a node have to be provisioned in as many wavelengths as possible, so as each connection originating/terminating from/to that node to be able to use all the available wavelengths.

5.3 Colored/directionless architecture - policy 2: Full wavelength cover

Under this policy (Figure 7b), all the available TSPs of a node are provisioned to wavelengths 1 to $T_n = D_n \cdot T$, assuming $T_n \leq W$. 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 $T_n \bmod W$. This policy has the same logic as the previous and also taking into advantage the directionless feature of the node.

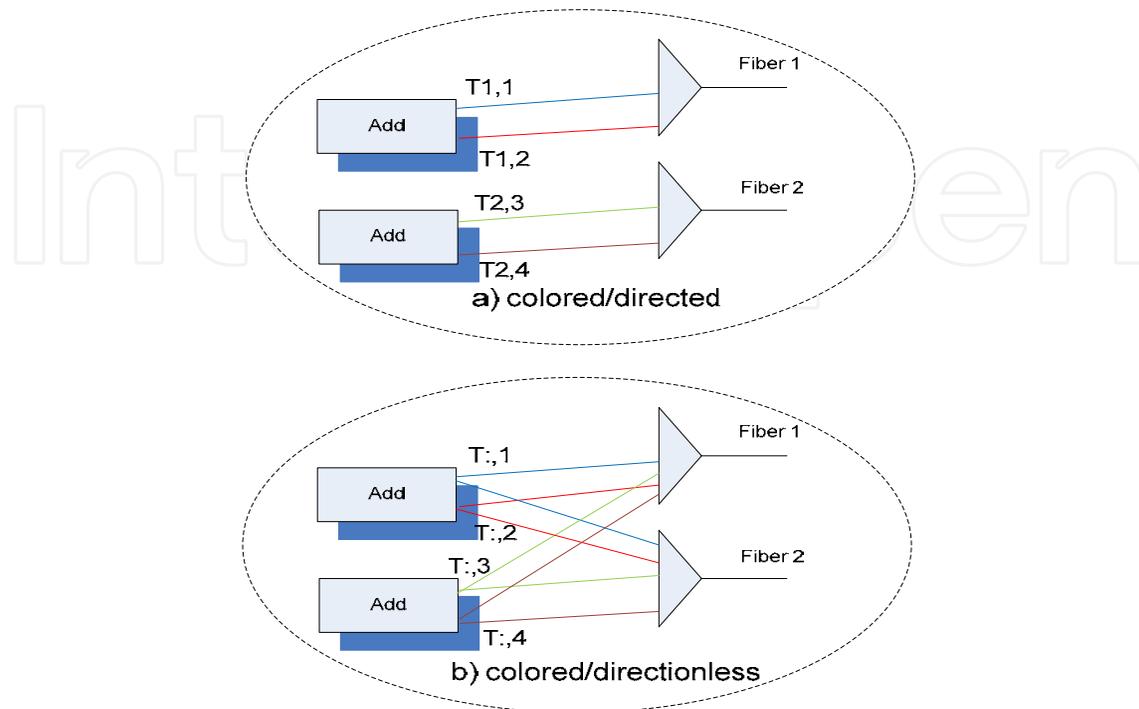


Fig. 7. TSP assignment policy 2 for: (a) the colored/directed architecture, (b) the colored/directionless architecture (as opposed to policy 1 in Fig. 6a and 6b)

6. Simulation results

The network topology used in our simulations was the generic Deutsche Telekom network (DTnet) that has 14 nodes and 23 links (Fig. 8). The capacity of a wavelength was assumed equal to 10Gbps. We performed two different sets of simulations: In the first set, we have limited resources and we report on blocking performance, while in the second set we have enough resources to establish all the requested connections and we report on required manual interventions.

6.1 Impact of node flexibilities in blocking probability

In this set of simulations, 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 this set we also assumed that widely tunable TSPs are plugged into specific ports, while 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.

In Fig. 9 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

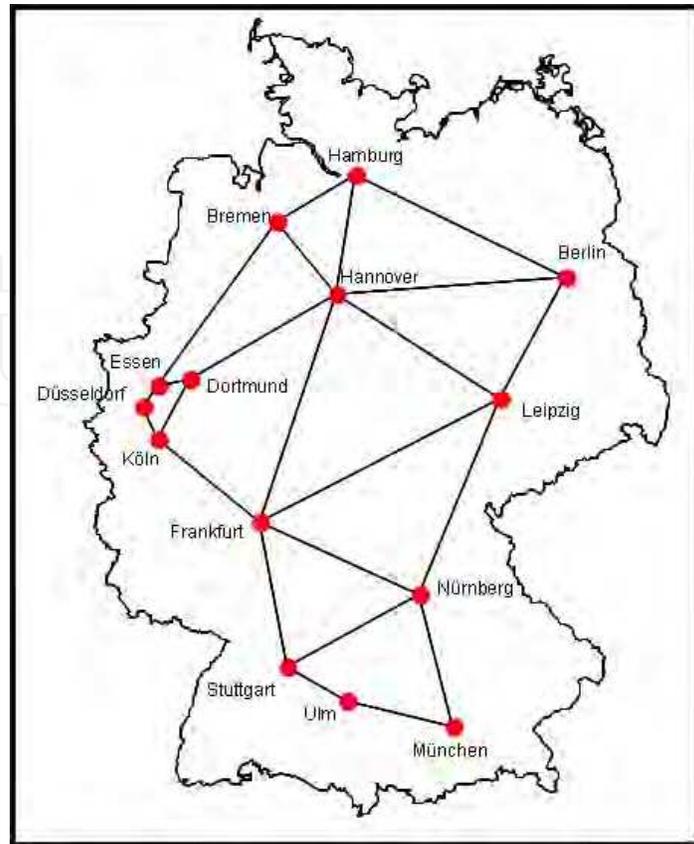


Fig. 8. DT network: 14 nodes, 23 links

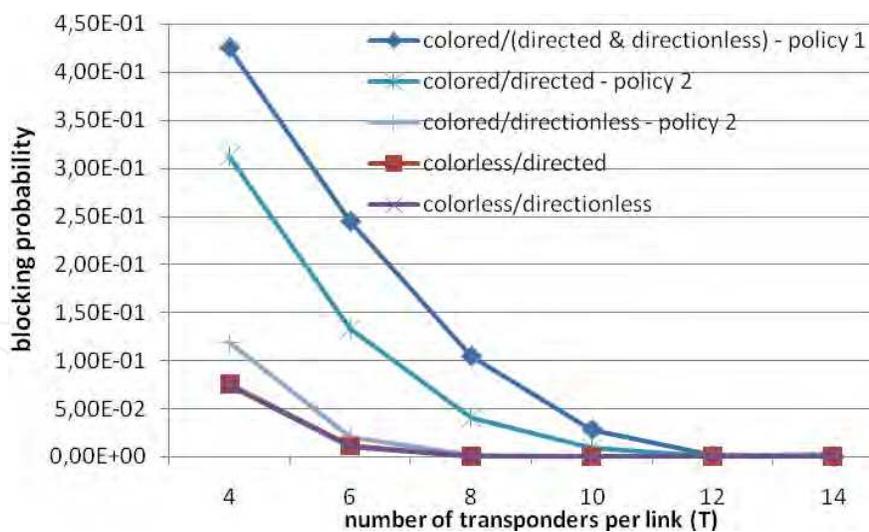


Fig. 9. Blocking probability vs. number of transponders when no manual interventions are allowed, assuming 14 available wavelengths per link and network load equal to 100, for various node architectures and TSP assignment policies

Erlangs and 14 available wavelengths. 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. Colorless/directed architecture exhibits similar performance with the most flexible architecture (colorless/directionless) 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 as restrictive as the color related one.

Fig. 10 illustrates the blocking probability versus the number of TSPs per link for different number of available wavelengths. We assume that each fiber has the same number of wavelengths and TSPs. 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 is performed, for changing the direction and the color of a port. For this reason the results of blocking probability presented in Fig. 10 hold for all the node architectures under consideration. Small variations in blocking probability is possible, 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.

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.

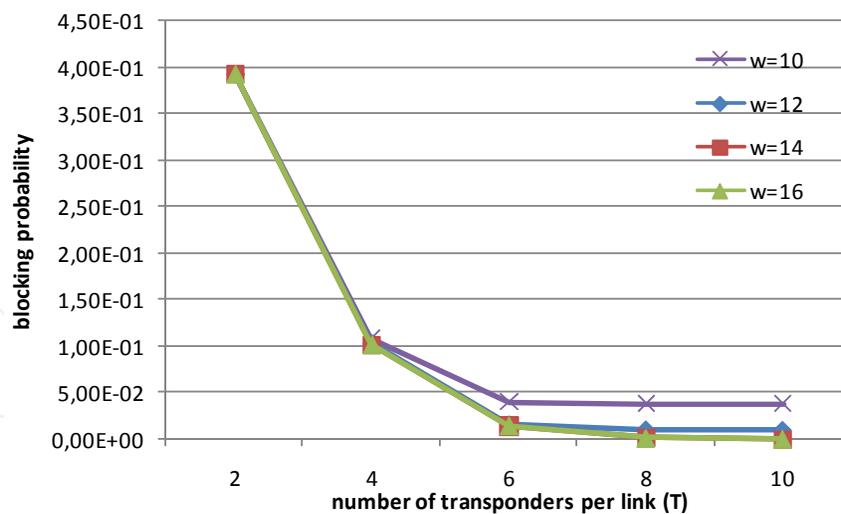


Fig. 10. Blocking probability vs. number of transponders for different number of available wavelengths per link, assuming network load equal to 100. Blocking probability is the same irrespectively of the node architecture used.

6.2 Impact of node flexibilities in operational cost

In this study we evaluate a realistic operational scenario of the DT core network. Initially, we assumed that in year 2008, 270 demands were present. For the year 2008, the network

was provisioned with 460 transponders. We made the assumption that new demands arrive during the next years leading to an increase of 50% in the requested connections per year. In this set of simulations we allow manual interventions in order to change the port of an already installed TSP or to install new TSPs.

We define two different types of manual interventions. The type 1 of manual intervention is the switching of an available transponder from one to another port of the same node. Manual intervention of type 2 is referred to the installation of extra transponders. We consider different pre-provisioning strategies (manual interventions of type 2). All strategies start with 10 TSPs per link, which results in 460 TSPs in total. The first strategy is when there are no more TSPs available at a particular node to establish a connection, and only a new TSP is installed. We call this approach one TSP. In the other approaches a certain amount of TSPs are installed per link (bank of transponders). For example in case of one TSP per link, we will install 3 extra transponders if the node degree is 3. We have also similar approaches with 5, 7 and 9 TSPs per link.

In Fig. 11, we show the sum of the manual interventions of type 1 (MI1) and those of type 2 (MI2) cumulated over three years. The results for different node flexibilities are depicted to point the differences between them. In Fig. 11a) we can observe that provisioning of more transponders has only a little impact on the amount of manual interventions. In Fig. 11b), the architecture with the directionless feature is depicted with TSP assignment policy 2. This results in a lower number of manual interventions as compared to the previous architecture. In Fig. 11c), it is clear that provisioning of more transponders has huge impact on the manual interventions. The difference between three and nine transponders per link is really small. So there is no reason to provision more than 3 transponders per time because the cost will be increased. In Fig. 11d), we consider the colorless/directionless architecture, which has the best performance in terms of MIs because all transponders provisioned in the node can be used for every new demand. There are no constraints in terms of color or fiber anymore. When provisioning only one TSP per link instead of one TSP, the MIs are decreased from 270 to 100.

Based on these remarks we are interested in the operational processes that involve several actions/activities that need to be performed by the operator's staff. The duration of the activity determines, to an important extent, the cost of the action. The costs for transport (going to the location of the node where an intervention is needed) are calculated from the topology characteristics. We assume that technical teams are present on average 2 links away from one another, this is every 340 km. The average distance to the failure location is therefore 85 km. One way and return adds to 170 km, with an average speed of 50 km/h, this means 3.4 hours for transport.

With the number of MI1 and MI2 (Fig. 11) we can calculate the total transport time and the real intervention time that is the time to switch a transponder in case of MI1 and the time to install new transponders in case of MI2. The duration of transport is 3.4 hours and the duration of switching/installing a transponder is 1 hour.

In Fig. 12 we depict the working hours over the years from 2009 to 2011 needed for manual intervention purposes. In this figure we present two blocks for the node architectures, where in the first block we assume that one TSP is installed, while in the second three TSPs per link are installed. We can see that the colored/directed node and the colored/directionless node

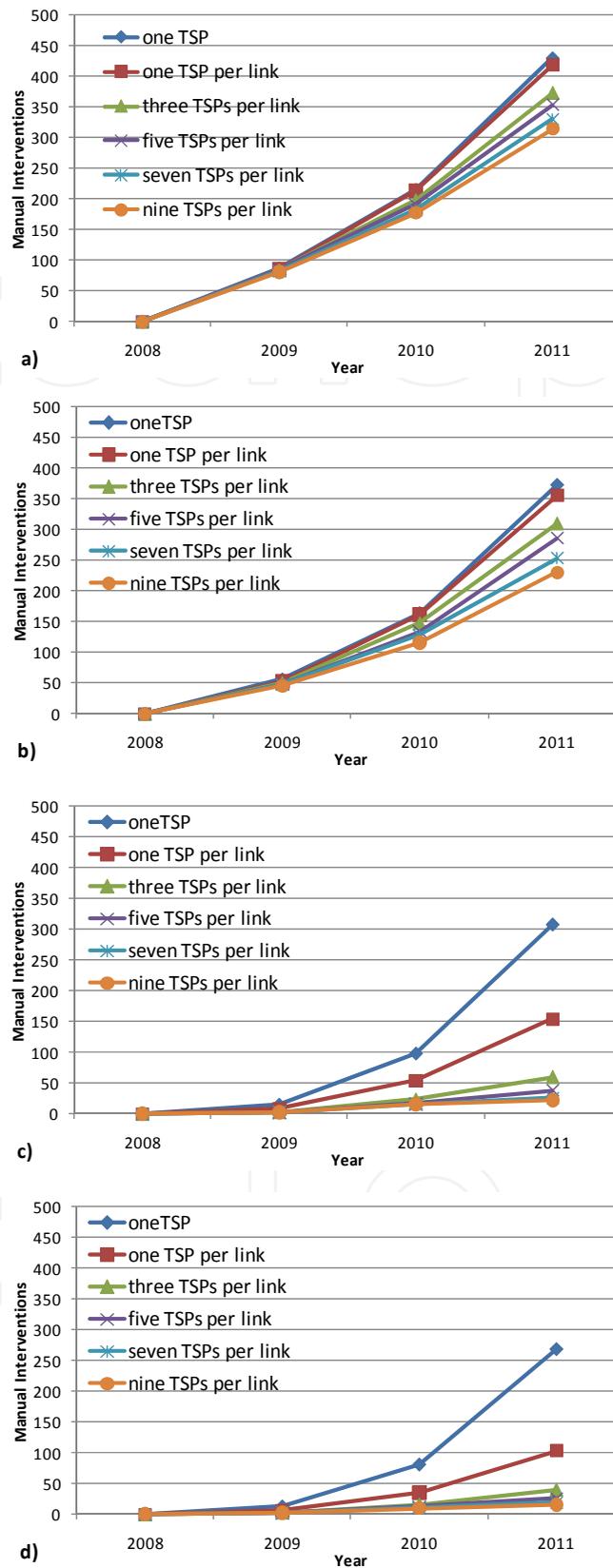


Fig. 11. Cumulative sum of number of manual interventions for a) colored/directed (TSP policy 2), b) colored/directionless (TSP policy 2), c) colorless/directed and d) colorless/directionless.

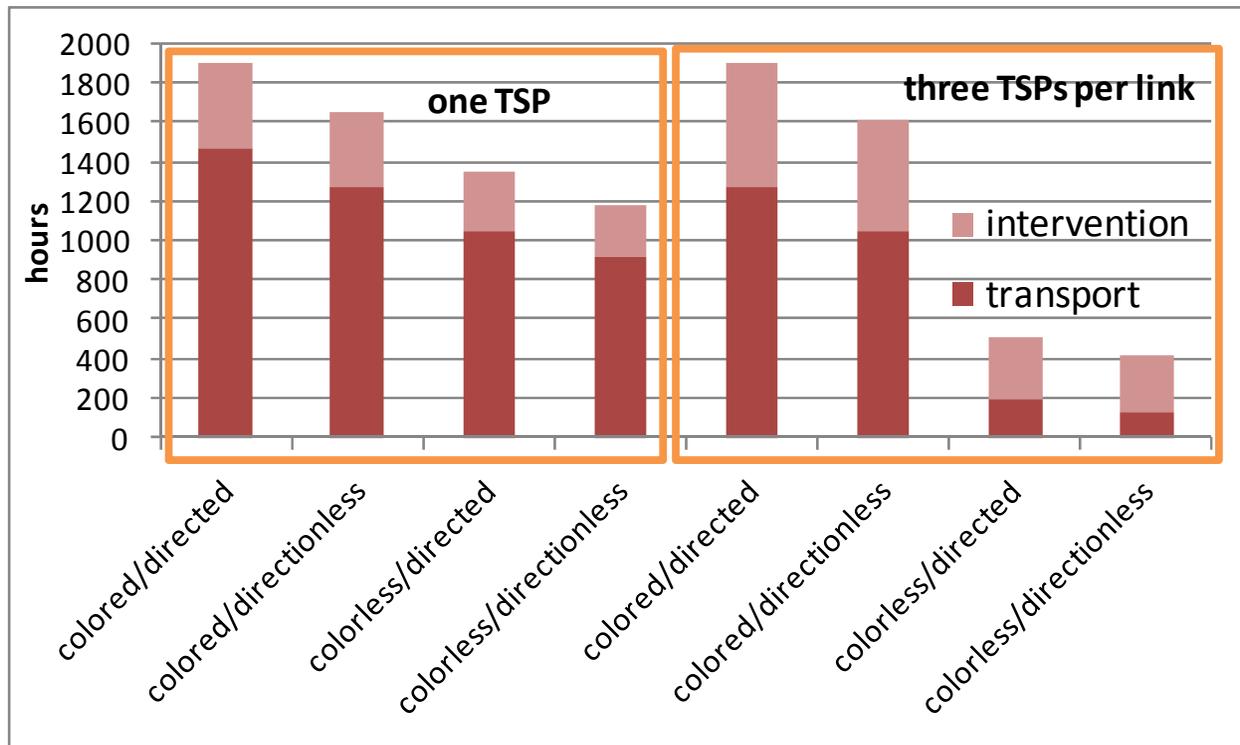


Fig. 12. Working hours of manual interventions

have little improvement in transport times but the intervention times are worst. This happens because when installing more TSPs at once maybe additional MIs of type 1 will be necessary to switch a TSP in different port. The improvement of working hours in case of colorless/directed and colorless/directionless is obvious when installing three TSPs per link instead of one TSP at once, and this happens because of the saving in transport time.

The colorless/directed architecture has almost the same performance as the colorless directionless with the provisioning of 3 TSPs per fiber. The benefits of the directionless architectures are almost negligible due to higher cost and because similar performance can be achieved with directed architectures when appropriate provision strategies and TSP assignment policies are used.

7. 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 and the number of transponders are assigned to wavelengths are important and assignment policies utilizing all the available wavelengths should be used.

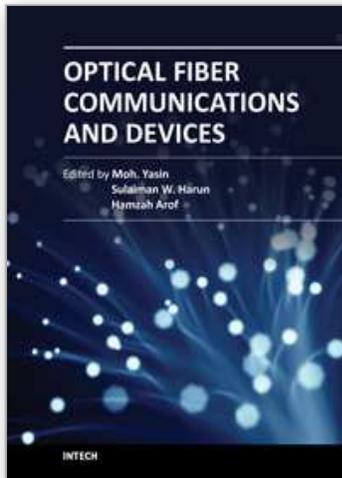
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This book is a collection of works dealing with the important technologies and mathematical concepts behind today's optical fiber communications and devices. It features 17 selected topics such as architecture and topologies of optical networks, secure optical communication, PONs, LANs, and WANs and thus provides an overall view of current research trends and technology on these topics. The book compiles worldwide contributions from many prominent universities and research centers, bringing together leading academics and scientists in the field of photonics and optical communications. This compendium is an invaluable reference edited by three scientists with a wide knowledge of the field and the community. Researchers and practitioners working in photonics and optical communications will find this book a valuable resource.

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