Add/Drop Contention-Aware RWA with directionless ROADMs: the Offline Lightpath Restoration case

Pablo Pavon-Marino, Maria-Victoria Bueno-Delgado

***Abstract*—Directionless Reconfigurable Add/Drop Multiplexers (ROADMs) permit to change the direction of an added/dropped lightpath without manual intervention. If the ROADM is also colorless, its wavelength can be automatically reconfigured. In broadcast-and-select (B&S) directionless ROADM architectures the number of lightpaths that can be added/dropped using the same wavelength is limited by the so-called add/drop contention factor *C*. This is a source of lightpath blocking that reduces the network capacity. A previous work investigated this aspect for the case of unprotected and 1+1 protected lightpaths. In this paper, we address the case in which lightpath restoration is the fault recovery technique in the network. We hypothesize that using an appropriate network planning, the add/drop contention effects can be mitigated. For this, we propose and investigate the Add/Drop Contention Aware Routing and Wavelength Assignment with Lightpath Restoration (ADCA-RWA-LR) offline planning problem, considering colored ROADMs. To solve the problem, an effective heuristic is presented. Extensive results are reported for four reference topologies. In our tests, the reduction in the network capacity caused by add/drop contention is eliminated in practice for factors *C*=2, or even *C*=1 in some topologies. These results contribute to the dimensioning of directionless ROADMs.**

***Index Terms*—ROADM, Directionless, Colorless, Contentionless, Routing and Wavelength Assignment, Network Planning.**

I. Introduction

Transparent optical networks based on wavelength division multiplexing (WDM) are in the core of current high-speed backbone networks [1][2]. In such networks, traffic is carried over a set of all-optical connections, called lightpaths. A lightpath originates at an E/O transmitter in the ingress node, where it is said to be *added*. It is allocated a wavelength channel in each traversed physical link, and terminates at an O/E receiver in the egress node, where it is said to be *dropped*. The lightpaths are optically switched (transparently) at the intermediate nodes, and with respect to those nodes, are commonly referred as *express* lightpaths.

Pablo Pavon-Marino and Maria-Victoria Bueno-Delgado are with the Universidad Politécnica de Cartagena, Pza. Hospital 1, 30202, Cartagena, Spain (e-mail: {pablo.pavon, mvictoria.bueno}@upct.es).

Optical Add/Drop Multiplexers (OADMs) are the specialized equipment in charge of implementing the add, drop and optical bypass of the lightpaths. The Reconfigurable-OADMs (ROADMs) are more agile versions of OADMs. In ROADMs, part of the optical switching functionality is implemented by means of active optical devices, governed by a coupled control and management plane. As a result, a subset of the lightpath reconfigurations can be software-driven, and completed without an on-site manual intervention. This opens the door to reducing operational costs, and permitting a fast lightpath provisioning.

Fig. 1 shows a diagram of a ROADM of degree three, that relies on the broadcast-and-select (B&S) scheme to implement the switching functionality. Degree three means that the node is connected to other three nodes, or using a common terminology, that the node has three directions (named East, West and North in Fig. 1). The optical signal from a specific direction is broadcasted to the other directions' modules and to the drop module. The drop module consists of a passive demultiplexer which separates the WDM optical channels into different output ports, where the transceivers are placed. In the output side of each direction, a Wavelength Selective Switch (WSS) combines the channels coming from other directions and from the add module. The WSS is a reconfigurable device which is able to switch any wavelength channel at any of its input ports, to any of its output ports, and vice-versa. In the add module, the transceivers are connected to the adequate ports of a multiplexer (according to their wavelength), which injects the multiplexed signal into an input port of the WSS.

ROADMs like Fig. 1 have limited versatility, in the sense that they still require a manual intervention to: (i) change the outgoing direction of an added lightpath, (ii) change the incoming direction of a dropped lightpath and (iii) change the transmission wavelength of the lightpath. The reason for (i) and (ii) is that separated transceiver banks exist for different directions, so that changing a lightpath direction requires physically changing its bank. Similarly, (iii) is caused by the use of passive optical mux/demux components which have a fixed association between ports and wavelengths. Therefore, changing the wavelength of a (tunable) transceiver requires also manual intervention to physically change its port in the mux/demux.

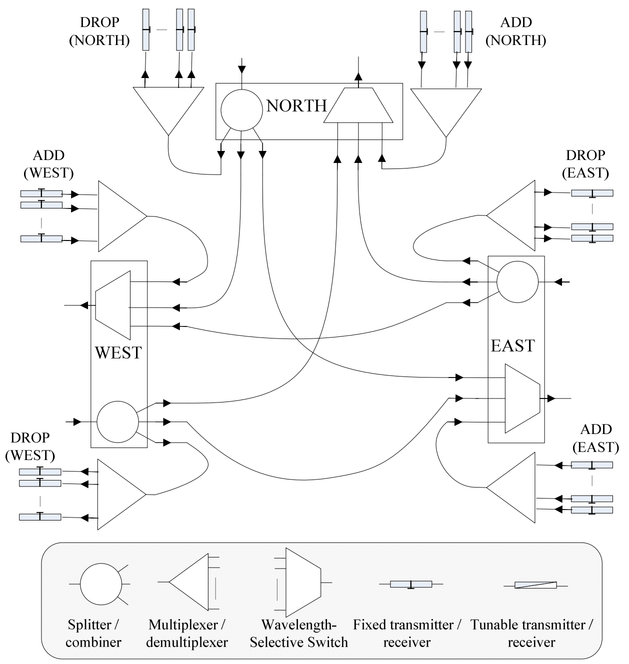


Fig. 1. B&S ROADM architecture

In summary, ROADMs like in Fig. 1 eliminate the need of on-site technician visits to reconfigure the intermediate nodes of a lightpath, but still do not eliminate the technicians' visit to the lightpath end nodes sites. As a collateral effect, the paradigm of automatic lightpath restoration [3][4][5], as a process for surviving to network failures by dynamically reconfiguring the optical layer, cannot be implemented. For example, under a link failure, the lightpaths added and dropped at the failing link end nodes need a fast change of its direction, which is not possible when this requires on-site manual procedures.

A. Directionless, contentionless, colorless

Next generation of ROADMs are addressing the lack of flexibility described above. New terms have been coined describing new reconfiguration capabilities, aiming at (i) directionless and (ii) colorless ROADM architectures. *Directionless* architectures permit to reconfigure the direction of an added or dropped lightpath without manual intervention. Similarly, *colorless* ROADMs can change the wavelength of an added/dropped lightpath without manual intervention. As mentioned before, directionless (colorless or colored) ROADMs are an unavoidable requirement for implementing lightpath restoration paradigms in the network, since they enable a fast rerouting of the lightpaths added/dropped at the failing link end nodes.

Building directionless ROADMs based on the B&S approach, means that the add/drop transceiver pools should be no longer coupled to a specific direction, but shared by all the directions in the node [6]. Fig. 2(a) shows a directionless version of the switch in Fig. 1 according to [6]. The add side of the shared add/drop module requires a multiplexer which combines the signal from the transceivers, and a splitter which broadcast them to the output directions. In the drop side, the individual channels to be dropped are extracted by a WSS from the optical signals coming from the different directions. The architecture in Fig. 2(a) is colored, since changing the wavelength of a lightpath requires moving the transceiver to the port in the mux/demux associated with that wavelength. Fig. 2(b) shows the colorless version of Fig. 2(a). The constraint coupling the transceiver wavelength and the WSS port is removed by replacing the multiplexer and demultiplexer devices in the add/drop module by WSSs.

Directionless ROADMs like the ones in Figs. 2(a) and 2(b) are affected by the so-called *add/drop contention*. Because of the existence of a single bank of transceivers, it is not possible to add (drop) two lightpaths in the same wavelength, even if they are routed through different directions. The add/drop contention in the nodes is a source of lightpath blocking, which degrades the capacity of the network. This problem can be addressed by augmenting the number of transceiver banks (still all of them shared by all the directions). Fig. 2(c) illustrates this, showing a colored, directionless ROADM with two transceiver banks. The number of transceiver banks defines the so-called add/drop contention factor C of the ROADM: the maximum number of lightpaths that can be added/dropped using the same wavelength. In the limit, *contentionless* nodes are those directionless ROADMs in which the contention limitation is totally eliminated. This can be guaranteed using a factor C equal to the number of directions of the node.

B. Paper contributions

In this paper, we consider an optical transport plane with directionless colored ROADMs (e.g. like the one in Figs. 2(a) or 2(c)). We assume that the network operator has chosen lightpath restoration as the fault recovery technique at the optical layer. We focus on the static (offline) planning of the network, so that the reactions (lightpath reroutings) to a set of predefined failure states are planned in advance. Note that since ROADMs are colored, the wavelength of the lightpaths cannot change during the restoration process. In other words, only the route of the lightpaths can change to adapt to a network failure. Then, we are interested in studying how the lightpath blocking performance is affected by the add/drop contention factor C of the nodes. In this scenario, *lightpath blocking* refers to the reduction in the amount of traffic the network can carry because of the add/drop contention, with respect to the case in which all the nodes are equipped with contentionless ROADMs.

Path restoration is considered in this paper, in opposition to sub-path restoration or link restoration (using the terminology in [4]). Path restoration means that under a link failure, the affected lightpaths are torn down, and then setup again, so that the new lightpath route can share links with the old lightpath route or not. The only constraint in the routing is not using the failed links. On the contrary, in subpath restoration, when a fiber fails, the affected lightpaths are rerouted by the failing link upstream end nodes. Then, the portion of the lightpath route upstream with respect to the failing link, is the same before and after the failure. Finally, in link restoration, the route of the lightpath upstream and downstream the failing link, is not changed.

We consider two types of path restoration strategies, which are denoted as B&R and no-B&R. In the former, it is assumed that under a link failure, any lightpath in the network can be rerouted using a bridge-and-roll (B&R) procedure. This means that lightpaths not affected by the failure may be anyway rerouted to release resources which can then be used by failing lightpaths. In the no-B&R case, only the lightpaths which traverse a failing link change their routes in the restoration process, while the non-affected lightpaths cannot be rerouted. Therefore, the B&R restoration strategy gives more flexibility to the planner, at a cost of a potentially higher signaling complexity. The decision of which strategy to adopt is at the carrier level.

Our hypothesis is that if the network is appropriately planned, it is possible to mitigate or even eliminate the lightpath blocking caused by add/drop contention. To investigate this, we study the Add-Drop Contention Aware Routing and Wavelength Assignment with Lightpath Restoration problem (ADCA-RWA-LR) for this scenario, and model it as an ILP (Integer Linear Program). Given a traffic demand and a set of failure states, the ADCA-RWA-LR problem finds the RWA for each lightpath under any predefined failure state, minimizing the lightpath blocking, and considering the add/drop contention in the nodes.

An effective heuristic is provided to solve the ADCA-RWA-LR problem. Extensive tests using four reference topologies and traffic matrices are conducted. By doing so, we are able to explore in different situations the dependence of the network capacity on the contention factor *C*. In addition, the designed tests permit to compare the network performance with the optimum performance achievable by a so-called *totally agile* network. This is a network of colorless-contentionless nodes, equipped with wavelength converters in the nodes and a B&R restoration process. Then, we are able to observe the maximum possible benefits if the network hardware was upgraded towards a totally agile network infrastructure. Interestingly, results show that little or no incentives in terms of performance (extra traffic that can be carried) exist, to upgrade the ROADMs with add/drop contention factors higher than two.

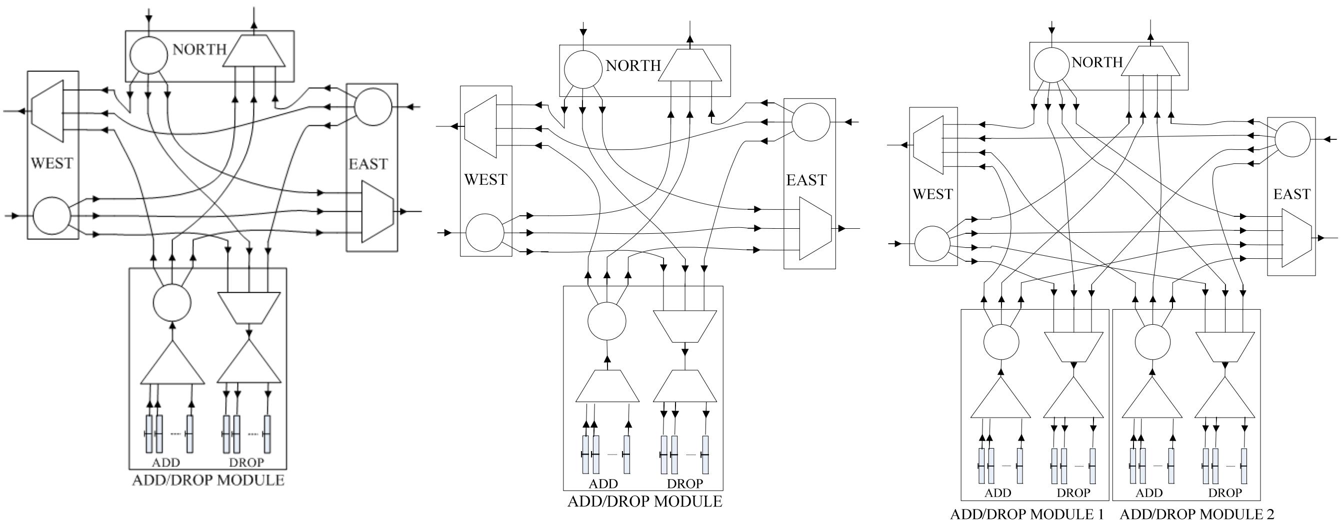
The rest of the paper is organized as follows. Section II collects related work in the topic. Section III presents the ILP formulation of the ADCA-RWA-LR problem variant addressed, and the heuristic algorithm proposed. Then, Section IV reports the results obtained. Finally, Section V concludes the paper.

II. RELATED WORK

The first mention in the literature to directionless and to colorless ROADM architectures is found in [7] and [8] respectively. After that, the scientific community showed a growing attention in this topic, and a significant amount of works are published exploring the alternatives in the design of more versatile ROADMs [6][9]-[19]. A strong interest from the industry is motivating and driving these investigations, since the directionless and colorless functionalities are key differential features in the new generation of ROADMs.

The majority of the related works up to date [6]-[16] investigate on the practical feasibility and scalability of different ROADM architectures in terms of cost, optical impairments or both. The high cost and limited scalability of WSS devices composing ROADM architectures motivates these studies. As an example, the largest WSS commercially available the authors could found in year 2011 is a 1x23 WSS [20] for the 50 GHz grid (up to 96 channels). The switching function is implemented by liquid crystal-based switching elements. Other technological options like 2D MEMS and 3D MEMS [21] (or 1-axis and 2-axis MEMS) are being successfully applied for building WSSs, and improvements in the WSS sizes are expected in the future.

However, none of the works [6]-[16] mentioned address the planning of the network considering the add/drop contention constraints, and thus, do not study the consequences in terms of network performance brought by different ROADM architectures. To the best of our knowledge, the only works investigating these aspects are [17][18] and [19]. The work in [17] evaluates the lightpath



(a) (b) (c)

Fig. 2. B&S ROADM architectures, (a) directionless *C*=1, (b) directionless-colorless *C*=1, (c) directionless *C*=2

blocking caused by internal contention in a directionless and colorless node, under lightpath demands arriving randomly (online planning scenario). The authors assume that the RWA planning is done with no concern on the possible internal contention in the node. That is, they study the case in which the planning is *not* used as a mechanism to alleviate the effects of add/drop contention. The results obtained show a significant lightpath blocking in most of the cases, but when the node is contentionless. In [18], the same authors study the situation when the online RWA planning is now specifically designed to consider the add/drop contention constraints. The authors propose several ADCA-RWA online planning algorithms, and compare their performance. However, the tests in [18] are dedicated to compare several ROADM schemes, all of them contentionless. Thus, they do not address the dimensioning of the add/drop contention factor of the ROADMs.

The works in [17] and [18] differ from the work in this paper in two key aspects: (i) we assume an offline planning case, when the demands are known in advance, (ii) we investigate on how an appropriate RWA planning can reduce the add/drop contention when the node is not contentionless. Finally, the works in this paper and in [19] address different network scenarios. In [19] we investigate the planning in a network where lightpaths are unprotected, or protected with a 1+1 scheme. In this paper, we investigate the case in which the network carrier chooses the lightpath restoration as the fault-recovery technique in the network.

III. The ADCA-RWA-LR problem

In this section we present an ILP model and an effective heuristic algorithm for solving the Add-Drop Contention Aware RWA with Lightpath Restoration (ADCA-RWA-LR) problem. We assume nodes equipped with colored and directionless ROADMs. The add/drop contention factor C in each node is an input parameter. The wavelength continuity constraint applies, since nodes are not equipped with wavelength converters. Lightpath restoration in the form of *path restoration* is the fault recovery technique in the optical layer. The two types of path restoration strategies considered are denoted as B&R and no-B&R. No-B&R corresponds to the case when, under a link failure, only the lightpaths traversing the failing link can be rerouted. In its turn, this constraint is not present in the B&R restoration type.

A. Problem formulation

Let N be the set of nodes in the network, E the set of unidirectional fiber links, and W the set of wavelengths in each fiber. We assume that all the fibers in the network have the same number of wavelengths. Let C_n and C_n' be the add and drop contention factors respectively, at node $n \in N$. We denote as $a(e)$ and $b(e)$ the initial and ending nodes of fiber $e \in E$. We also denote $\delta^+(n)$ and $\delta^-(n)$ the set of fibers initiated and ending at node $n \in N$ respectively. D denotes the set of lightpath demands, and for each lightpath $d \in D$, $a(d)$ and $b(d)$ denote their initial and end nodes respectively. Finally, the set of possible failure states in which the network can be at a given time, is represented by S. For each failure state $s \in S$, E_s is the set of links in the network that are failing. We represent as s_0 the network state in which all the links are working properly (and then, $E_{s_0} = \emptyset$).

The decision variables of the problem are:

- $x_{dews} = \{0,1\}$, $d \in D$, $e \in E$, $w \in W$, $s \in S$. x_{dews} takes the value 1 if the lightpath d traverses fiber link e in wavelength w, during network failure state s. Otherwise, x_{dews} takes the value 0.
- $y_{dw} = \{0,1\}$, $d \in D$, $w \in W$. y_{dw} takes the value 1 if the lightpath d uses wavelength w. Otherwise, y_{dw} takes the value 0.

The constraints to the problem are given by (1a)-(1g):

$$\sum_{e \in \delta^+(n)} x_{dews} - \sum_{e \in \delta^-(n)} x_{dews} = \begin{cases} y_{dw} \text{ if } n = a(d) \\ -y_{dw} \text{ if } n = b(d) \\ 0 \text{ otherwise} \end{cases} \quad (1a)$$
$$d \in D, w \in W, n \in N, s \in S$$

$$x_{dews} = 0, \quad d \in D, e \in E_s, w \in W, s \in S \quad (1b)$$

$$\sum_{d \in D} x_{dews} \le 1, \quad w \in W, e \in E, s \in S \quad (1c)$$

$$\sum_{w \in W} y_{dw} \le 1, \quad d \in D \quad (1d)$$

$$\sum_{d \in D | a(d) = n} y_{dw} \le C_n, \quad n \in N, w \in W, s \in S \quad (1e)$$

$$\sum_{d \in D | b(d) = n} y_{dw} \le C_n', \quad n \in N, w \in W, s \in S \quad (1f)$$

$$-\sum_{e' \in E_s} x_{de'ws_0} \le x_{dews_0} - x_{dews} \le \sum_{e' \in E_s} x_{de'ws_0} \quad (1g)$$
$$d \in D, e \in E, w \in W, s \in S - \{s_0\}, \text{(only no-B\&R case)}$$

Constraints (1a) are the routing conservation constraints: if a lightpath d is carried in wavelength w (y_{dw}=1), there should be a route between $a(d)$ and $b(d)$ in every failure state. Constraints (1b) forbid using the failing links, and (1c) are the wavelength clashing constraints. The colored add/drop constraints are included in (1d): lightpaths are allowed to be assigned at most one wavelength (or no wavelength if the lightpath is blocked). Constraints (1e) and (1f) reflect the add and drop contention constraints respectively. Finally, constraints (1g) represent the limitations to the plan that the no-B&R restoration procedure implies. In this sense, these constraints are not present in the B&R restoration model. For a given failure state $s \neq s_0$, the left hand side and right hand side summations in (1g) equal to 0, when none of the links traversed by the lightpath in state s_0 fail during state s. In this case, the lightpath traversed links in the state s_0 and the state s are forced to be the same.

The objective function (1h) is the maximization of the carried traffic (or equivalently, the minimization of the blocking traffic). Note that a lightpath is carried only if it has a valid route in all the network failure states.

$$\text{Max} \sum_{d \in D, w \in W} y_{dw} \quad (1h)$$

B. Heuristic algorithm

This section presents a heuristic algorithm for solving instances of realistic sizes of the previous ILP formulation. Fig. 3 shows a flow diagram of the algorithm. The main loop is executed $|W|$ times, one per wavelength. During the step associated with wavelength w, the algorithm tries to maximize the traffic carried in that wavelength. This is implemented by a nested loop composed of two consecutive procedures, $P1$ and $P2$.

Procedure $P1$ selects a set L of a maximum size of L_{max} lightpaths, among the lightpaths in the set D-L_{ne}. Set D contains the lightpaths pending to be carried. Set L_{ne} contains those lightpaths that will be no longer eligible to be part of set L in further calls to $P2$ in the same wavelength. These are those lightpaths for which we know that they cannot be carried in this wavelength, since the required resources are already occupied. If those lightpaths were included in L, they would only prevent other true candidate lightpaths in D to be carried in this iteration. The criteria for selecting the lightpaths in set L among the lightpaths in set D-L_{ne}, is a variation of the well known HLDA (Heuristic Logical Design Algorithm) strategy [22]. For each input output node pair (i,j), we compute the number of eligible lightpaths in D-L_{ne} which have i and j as their initial and ending nodes. Then, one lightpath is selected among the eligible lightpaths associated with node pair (i',j'), being (i',j') the node pair with the largest amount of eligible lightpaths. The selected lightpath is added to L and to L_{ne}. The process is repeated until (i) the set D-L_{ne} is empty, or (ii) $|L|=L_{max}$. The factor L_{max} is an input parameter of the heuristic algorithm, used to appropriately limit the complexity of the procedure $P2$.

Procedure $P2$ intends to carry as many lightpaths in L as possible, in the residual network for wavelength w. The residual network is defined as the network in which the resources occupied by the already carried lightpaths (wavelengths in the links and add/drop ports) are not available. After procedure $P2$ finishes, L_c contains the lightpaths in L that $P2$ was able to carry, and L_{nc} the ones that $P2$ was not able to carry. Then, the set D of pending demands is updated by removing the set L_c. In addition, the set L_{ne} of non-eligible lightpaths for wavelength w is updated by adding two sets of lightpaths: (i) the set $L_{nc}\subset L$ of lightpaths that were not carried: since they could not be carried by $P2$, we know that there are no available resources in this wavelength for them. (ii) The lightpaths in D that are initiated (ended) in any node which have all its add (drop) ports for this wavelength already occupied. We denote this set as $L^0_{A/D}$. Since there are no add/drop ports available in this wavelength, these lightpaths would anyhow not be carried in next call to $P2$.

Procedure $P2$ uses formulation (2) to carry the lightpaths in L in the residual network for wavelength w. The decision variables of the formulation are a simplified version of (1), removing the w index, and limiting the demand set to L:

- x_{des} = {0,1}, $d\in L$, $e\in E$, $s\in S$. x_{des} takes the value 1 if the lightpath d traverses link e, during network failure state s. Otherwise, x_{des} takes the value 0.
- y_d = {0,1}, $d\in L$. y_d takes the value 1 if the lightpath d is carried. Otherwise, y_d takes the value 0.

The constraints to the problem are given by (2a)-(2f):

$$\sum_{e\in\delta^+(n)} x_{des} - \sum_{e\in\delta^-(n)} x_{des} = \begin{cases} y_d \text{ if } n=a(d) \\ -y_d \text{ if } n=b(d) \\ 0 \text{ otherwise} \end{cases} \quad d\in L, n\in N, s\in S \tag{2a}$$

$$x_{des}=0, \quad d\in L, e\in E_s, s\in S \tag{2b}$$

$$\sum_{d\in L} x_{des} + R_{es} \le 1, \quad w\in W, e\in E, s\in S \tag{2c}$$

$$\sum_{d\in L|a(d)=n} y_{dw} \le CR_n, \quad n\in N, w\in W, s\in S \tag{2d}$$

$$\sum_{d\in L|b(d)=n} y_{dw} \le CR_n', \quad n\in N, w\in W, s\in S \tag{2e}$$

$$-\sum_{e'\in E_s} x_{de's_0} \le x_{des_0} - x_{des} \le \sum_{e'\in E_s} x_{de's_0} \quad d\in L, e\in E, w\in W, s\in S-\{s_0\}, \text{(only } \textit{no-B\&R} \text{ case)} \tag{2f}$$

Constraint (2a), (2b) and (2f) are trivial adaptations versions of the constraints (1a), (1b) and (1g) constraints respectively, to the problem with one wavelength and the reduced demand set L. Constraints (2c), (2d) and (2e) are also adaptations of the wavelength clashing constraints and add/drop contention constraints in problem (1). However, two relevant variations have to be introduced to reflect that the lightpaths have to be carried in the *residual* network. That means, to forbid that the resources allocated to lightpaths carried in previous iterations of the loop, are allocated again. In constraints (2c), the values R_{es} are introduced in the wavelength clashing constraints, with this purpose. R_{es} is an input parameter to the problem (2), which has the value 1 if a lightpath already allocated traverses link e during failure state s, and 0 otherwise. Constraints (2d) and (2e) differ from the add/drop contention constraints (1e) and (1f) in the right hand side of the inequalities. The CR_n and CR_n' values are the number of add and drop ports available in the residual network for that wavelength: the values C_n and C_n', minus the add/drop ports occupied by the lightpaths already allocated.

The problem solved in ILP $P2$ is clearly still of NP-hard complexity. However, by an appropriate selection of the L_{max} parameter, it is possible to effectively control the computational complexity of the algorithm, as will be shown in the next section.

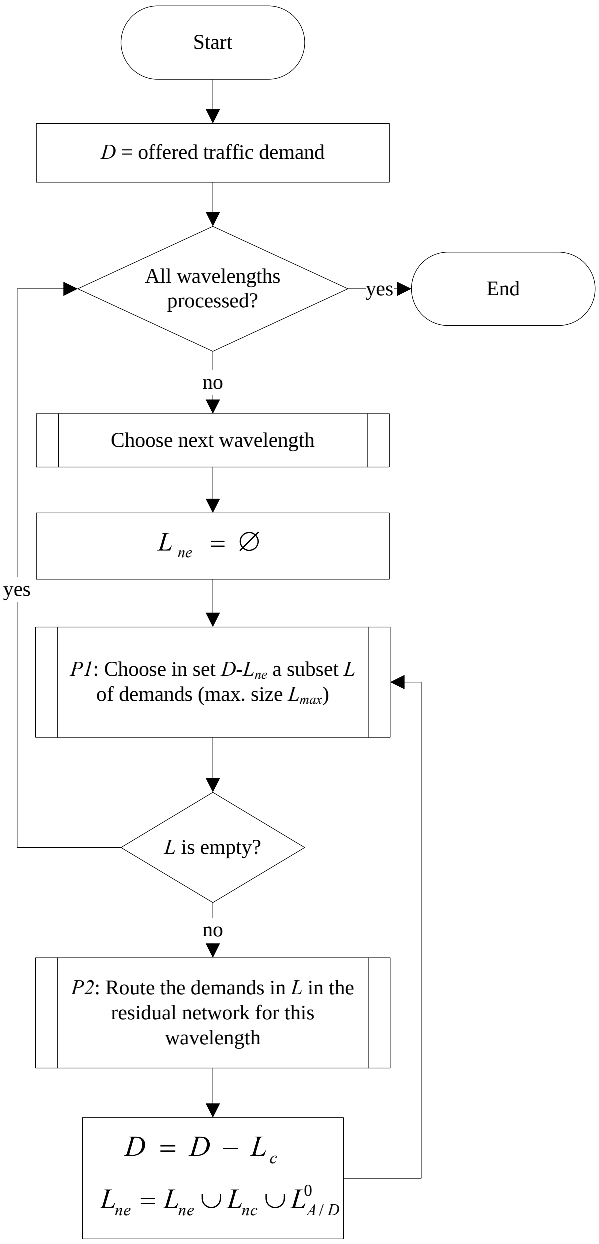


Fig. 3. Heuristic algorithm scheme

IV. Results

This section collects and analyzes extensive results obtained for exploring the capacity of transparent networks with lightpath restoration, when network nodes are equipped with colored ROADMs subject to add/drop contention constraints. The ADCA-RWA-LR network planning is obtained running the algorithm described in Section III.B. The algorithm has been implemented and tested in the MatPlanWDM tool [23], which interfaces with the TOMLAB/CPLEX solver [24].

A. Testing scenario

Four reference network topologies, together with their corresponding reference traffic matrices, are used in our study: Internet2 [25], NSFNET [26], and the topologies tagged as *Atlanta* [27] and *France* [28] in the SNDLIB [29] repository. The number of wavelengths per fiber tested is $|W| \in \{40, 80\}$ Table I summarizes some major data from these topologies.

TABLE I
INFORMATION ON THE TOPOLOGIES TESTED

	Internet2	NSFNET	Atlanta	France
Reference	[25]	[26]	[27]	[28]
Nodes ($\|N\|$)	9	14	15	25
Links ($\|E\|$)	26	42	44	90
Av. in degree	2.9	3	2.9	3.6

Optical switching nodes are built using directionless colored ROADMs. The add/drop contention factor C ranges $C \in \{1,2,3,\infty\}$. The case $C=\infty$ represents the pure contentionless case. The restoration is designed considering single-link failures. A link failure is supposed to affect the two directions of the link simultaneously. We repeat the tests for the two reconfiguration strategies B&R and no-B&R.

We assume that the network operator does not carry a lightpath if the network plan cannot guarantee that it can be restored for any single-link failure state. In this situation, we say that the lightpath is blocked. Then, we are interested in assessing the lightpath blocking performance for the different configurations described, and different traffic load conditions.

B. Traffic normalization

We devise a traffic normalization process for computing the lightpath demand in our tests. It is based on the computation of the maximum lightpath demand matrix that could be carried by the network if it was equipped with (i) colorless and contentionless ROADMs, (ii) wavelength converters in the nodes, so that the wavelength continuity constraint does not apply and (iii) with a path restoration process making use of the B&R functionality. For the sake of clarity, in the sequel we refer to a network with these properties as a network with *total agility*. Then, we assign the load factor $\rho=1$ to the maximum demand matrix that a totally agile network can carry, and compute the traffic demands for lower load factors $\rho<1$ by weighting the traffic accordingly. We do that, since the maximum traffic matrices computed for totally agile networks ($\rho=1$) are *upper bounds* to the maximum traffic matrix that our network of interest can carry. Note that this means that if a network configuration in our tests (e.g. colored, not contentionless, without wavelength converters, and applying or not B&R restoration) supports the traffic matrix associated to $\rho=1$, we can safely say that a totally agile upgraded version of the network would not be able to carry more traffic.

Given a network topology T, we denote as $M^R(T)$ the reference traffic matrix for this topology (in Erlangs or any arbitrary units), brought from literature. Given a real number α, we define the matrix M^α as (3).

$$M^\alpha = round\left(\alpha \cdot M^R(T)\right) \tag{3}$$

The *round* operation rounds each coordinate of a matrix to its closest integer value. Rounding is needed since the number of lightpaths between two nodes must be an integer. The idea behind the normalization process is finding the largest matrix of the form (3) which can be carried in a totally agile network in any failure state $s \in S$. The formulation (4) checks if a totally agile network defined by link set E can carry the traffic demand M^{α} under a given network failure s.

$$\text{Find } x_{ije} \geq 0, \text{integer}, i, j \in N, e \in E - E_s, \text{subject to:} \quad (4a)$$

$$\sum_{e \in \delta^+(n)} x_{ije} - \sum_{e \in \delta^-(n)} x_{ije} = \begin{cases} -M_{ij}^{\alpha} \text{ if } n = j \\ M_{ij}^{\alpha} \text{ if } n = i \qquad i, j, n \in N \\ 0 \text{ otherwise} \end{cases} \quad (4b)$$

$$\sum_{i,j \in N} x_{ije} \leq W, \quad e \in E \quad (4c)$$

Note that formulation (4) corresponds to a standard multicommodity flow problem with integer flows, for a network with link set E-E_s (so that the failing links are removed), and link capacity W. Constraints (4b) are the flow conservation constraints, while (4c) are the capacity constraints. The key concept is that any feasible solution obtained by (4), could be realized by a so-called totally agile network.

Although the problem in (4) is known to be NP-hard, we are able to solve it for the network sizes of interest in relatively fast executions (e.g. in the order of few seconds). We take benefit of this, to devise an iterative process to compute the upper bound matrices $M^{MAX}(T,W)$: starting with a high value of α, each iteration tries decreasing values of α, until the formulation (4) has a feasible solution for all failure states $s \in S$. The upper bound matrix we are searching is thus given by (5).

$$M^{MAX}(T,W) = round\left(\alpha_{MAX}(T,W) \cdot M^R(T)\right) \quad (5a)$$

$$\alpha_{MAX}(T,W) = \text{Max}\begin{Bmatrix} \alpha : \text{feasible solution of (4)} \\ \text{exists for } M^{\alpha},\ \forall s \in S \end{Bmatrix} \quad (5b)$$

We call $M^{MAX}(T,W)$ the maximum lightpath demand matrix for the network T, with W wavelengths per fiber. The lightpath demand matrix $M(T,W,\rho)$ associated to a load ρ<1 is calculated as the matrix of the form (3) which has a number of lightpaths equal to the ρ fraction of the number of lightpaths in $M^{MAX}(T,W)$ matrix (or its closest integer value).

C. Tests

The tests completed cover every combination of the following parameters:

- Network topologies T={Internet2, NSFNET, Atlanta, France}.
- Wavelengths per fiber $|W|$={40, 80}.
- Traffic load factors ρ={1, 0.8}.
- Add/drop contention factors C={1, 2, 3, ∞}.
- Restoration type: B&R={Yes, No}.

The L_{max} parameter of the algorithm is set to L_{max}=15 for the Internet2 tests, L_{max}=10 for NSFNET and Atlanta topologies, and L_{max}=2 for France topology.

D. Lower bound to the lightpath blocking

In order to assess the quality of the planning algorithms, we devise a lower bound to the lightpath blocking in the network. Let M be the lightpath demand matrix, C the add/drop contention factor in the nodes, and $|W|$ the number of wavelengths per fiber. The lower bound B_{LB} to the lightpath blocking is the minimum number of lightpaths that will be blocked because of add/drop contention. It is based on the fact that the maximum number of lightpaths a node can add or drop is limited to $C \cdot |W|$. B_{LB} is computed in (6a) as the worst case between the unavoidable blocking caused by the add contention (B_{LB}^{ADD}) and the same for the drop contention (B_{LB}^{DROP}). B_{LB}^{ADD} is obtained in (6b) by summing for each node i, the difference between the number of lightpaths to be added ($\sum_j M_{ij}$), and the maximum number of lightpaths that can be added because of add contention constraint ($C \cdot |W|$). B_{LB}^{DROP} is calculated analogously in (6c).

$$B_{LB} = \max\{B_{LB}^{ADD}, B_{LB}^{DROP}\} \quad (6a)$$

$$B_{LB}^{ADD} = \sum_i \left(\max(0, \sum_j M_{ij} - C\,|W|) \right) \quad (6b)$$

$$B_{LB}^{DROP} = \sum_j \left(\max(0, \sum_i M_{ij} - C\,|W|) \right) \quad (6c)$$

E. Results

First, we investigate the dependence of the maximum lightpath blocking on the node add/drop contention factor. We define the maximum lightpath blocking as the fraction of traffic that the network cannot carry when the offered traffic is exactly the maximum lightpath demand matrix (computed for ρ=1). Recall that the maximum lightpath demand matrix is the largest matrix of the form (3) that can be fully carried by a totally agile network. As a result, the maximum lightpath blocking is also the maximum benefits in terms of extra carried traffic that could be obtained if the network equipment was upgraded towards what a totally agile network is.

TABLE II
LIGHTPATH BLOCKING (%). LOAD FACTOR P =1

Internet2					
$\|W\|$	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	2 (0)	0	0	0
	Yes	1 (0)	0	0	0
80	No	1 (0)	0	0	0
	Yes	1 (0)	0	0	0
NSFNET					
$\|W\|$	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	18 (1)	15	15	15
	Yes	8 (1)	7	7	7

80	No	18 (0)	15	14	14
	Yes	8 (0)	6	6	6
Atlanta					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	25 (14)	1	1	1
	Yes	25 (14)	0	0	0
80	No	23 (13)	3	3	3
	Yes	23 (13)	1	1	1
France					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	13 (4)	6	6	5
	Yes	7 (4)	0	0	0
80	No	8 (2)	2	2	2
	Yes	3 (2)	0	0	0

Table II collects the results obtained, measured in percentage of lightpaths blocked with respect to the offered traffic. In the column corresponding to C=1, we report the values (also in %) of the lower bound B_{LB} computed as in (6). For the rest of the cases C={2, 3, ∞}, the B_{LB} bound was always equal to zero.

Table II allows us to observe relevant and interesting effects. First, in *all* the cases, the maximum lightpath blocking of networks equipped with ROADMs C=2 was equal to the one for the contentionless case C=∞. The only exception is an improvement of 1% in a France topology test, {W=40, B&R=No}. This suggests that in our case, ROADMs with contention factor C=2, can behave in the practice as contentionless.

In all the topologies but NSFNET, a stronger statement can be made. In all these cases, a network with factor C=2 had maximum lightpath blocking from 6% to 0%. That means that the benefits from upgrading the network with colorless and contentionless nodes (towards total agility) are very limited. In its turn, the NSFNET case exhibits higher lightpath blockings up to 15%, which do not decrease in contentionless nodes. Using B&R capabilities in the restoration can reduce the maximum lightpath blocking to a 7%-6%.

By observing the maximum lightpath blocking for the case C=1, we see that in a significant amount of cases, the blocking incurred is very limited. For example, in all the Internet2 tests, or the cases making use of the B&R capabilities in the NSFNET and France topologies. Interestingly, in all these cases, a network equipped with the simplest colored nodes, contention factor C=1, was able to carry practically the same traffic as the maximum traffic a totally agile network supports. The case of Atlanta topology exhibits higher lightpath blocking, in the order of 25%. By comparing the lightpath blocking and its lower bound for these cases, we observe that a significant part of this blocking is directly caused by the add/drop contention in the nodes. In other words, the degradation in the lightpath blocking observed in these cases is not caused by the planning algorithm, but is an unavoidable blocking that the ADCA-RWA-LR planning cannot mitigate.

Table III complements the results in Table II. While Table II focused on the maximum blocking observed if the network was operated at its maximum load (ρ=1), Table III studies the network in a more relaxed situation (ρ=0.8). We intend to observe the lightpath blocking when the traffic carried is still the 80% of the traffic that the network infrastructure could ideally support (if it was totally agile). Since network carriers commonly expand its network capacity (e.g. by activating more fibers) before a 100% occupation is achieved, this seems also a realistic situation to observe. Would a network carrier operating the network in this manner, perceive a significant lightpath blocking difference caused by add/drop contention?

TABLE III
LIGHTPATH BLOCKING (%). LOAD FACTOR P =0.8

Internet2					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	0 (0)	0	0	0
	Yes	0 (0)	0	0	0
80	No	0 (0)	0	0	0
	Yes	0 (0)	0	0	0
NSFNET					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	6 (0)	4	4	4
	Yes	0 (0)	0	0	0
80	No	3 (0)	1	1	1
	Yes	0 (0)	0	0	0
Atlanta					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	19 (11)	0	0	0
	Yes	19 (11)	0	0	0
80	No	15 (9)	0	0	0
	Yes	15 (9)	0	0	0
France					
|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
40	No	2 (0)	0	0	0
	Yes	0 (0)	0	0	0
80	No	0 (0)	0	0	0
	Yes	0 (0)	0	0	0

Interestingly, we see that in all the cases but Atlanta topology, equipping the network with colored nodes, C=1, produces no significant differences in terms of blocking with respect to a totally agile infrastructure. In the Atlanta case, the lightpath blocking observed was below 19%-15%, and zero if C=2 ROADMs were used. Then, it seems clear that network carriers which do not operate their network in the limit of its capacity (in terms of WDM channels occupied in the fibers), have no clear incentive in terms of lightpath blocking to move in the direction of totally agile networks. Naturally, these observations hold as long as an appropriate ADCA-RWA-LR planning is applied in the network.

F. Algorithm complexity

This section is devoted to give some insight on the time complexity of the planning algorithm presented. Table IV collects the execution time in number of minutes of each of the tests. The L_{max} parameter of the algorithm executions are L_{max}=15 for the Internet2 tests, L_{max}=10 for NSFNET and Atlanta topologies, and L_{max}=2 for France topology. These values have been chosen to limit the complexity of the formulations in terms of number of variables and constraints. Some tests with slightly higher vaules of L_{max}

parameter were tried, producing similar results with an increase in the execution time.

TABLE IV
HEURISTIC ALGORITHM EXECUTION TIME (MINUTES)

|*W*|	*B&R*	*C*=1	*C*=2	*C*=3	*C*=∞
Internet2 [L_{max}=15]					
40	No	<1	<1	<1	<1
	Yes	<1	<1	<1	<1
80	No	1.1	1.6	1.7	1.7
	Yes	<1	1.6	1.7	1.7
NSFNET [L_{max}=10]					
40	No	6.1	12.1	6.7	6.3
	Yes	<1	1.1	1.2	1.1
80	No	5.7	15.1	16.2	19.1
	Yes	1.5	2.4	2.8	2.5
Atlanta [L_{max}=10]					
40	No	5.6	2.5	3.2	2.8
	Yes	<1	<1	<1	<1
80	No	9.9	7.1	8.3	7.6
	Yes	1.0	1.8	2.2	2.2
France [L_{max}=2]					
40	No	12.7	23.2	29.1	28.5
	Yes	1.6	4.9	5.8	6.0
80	No	26.6	59.4	68.6	69.4
	Yes	3.9	12.1	14.5	14.5

First observation is that in the majority of the cases, the execution times are in the order of 10 minutes or below, with a maximum of aprox. 1 hour. These are satisfactory execution times for offline network planning. The execution time was higher (in general, from 3 to 10 times higher) in the planning of networks no-B&R-capable. This is because of the extra constraints in the problem, which couple the solutions at different values *s* of the decision variables $x_{des.}$ The time complexity also tends to increase with higher values of factor *C*. However, this evolution is more random, and has exceptions. This is common in algorithms containing modules based on ILP formulations, since the actual execution time of the solver (CPLEX v.12 in our case) depends on uncontrollable decisions taken during the internal branch-and-bound steps. Finally, the effect of the |*W*| factor is approximately linear, as is also the effect of the load factor (ρ) not shown in this paper. This is because (i) both |*W*| and ρ factors are linearly related with the size of the traffic demand, and (ii) the manner in which the algorithm partitions the demand into sets of L_{max} lightpaths, is effective in creating an approximately linear complexity growth with respect to the size of the lightpath demand.

V. CONCLUSIONS

In this paper, we investigate for the first time the dimensioning of the add/drop contention factor *C* (or number of transponder banks) of the ROADMs, in a network where lightpath restoration is the technique selected for network survivability. For this, we present and study the Add/Drop Contention Aware RWA with Lightpath Restoration offline planning problem (ADCA-RWA-LR).

We propose an ILP model for the ADCA-RWA-LR offline planning problem, and provide an effective heuristic algorithm solving it, together with a lower bound to the lightpath blocking. We run extensive tests for single-link failures using four reference topologies. In our results, a factor *C*=2 (or *C*=1 in some topologies) has shown to be enough to make the network have the same performance as if contentionless nodes where used. The results in [19] (unprotected and 1+1 lightpath protection case), and the results in this paper (lightpath restoration case) suggest that, for the offline planning scenario, if the network is appropriately planned, add/drop contention can be eliminated with limited extra hardware.

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REFERENCES

[1] J. Berthold, A. A. M. Saleh, L. Blair, and J. M. Simmons, "Optical Networking: Past, Present, and Future", *IEEE/OSA Journal of Lightwave Technology*, vol. 26, no. 9, pp.1104-1118, May 2008.

[2] S. Sygletos, I. Tomkos, and J. Leuthold, "Technological challenges on the road toward transparent networking," *Journal of Optical Networking*, vol. 7, no. 4, pp. 321-350, Apr. 2008.

[3] R. Ramamurthy, B. Mukherjee, "Survivable WDM mesh networks, Part II – Restoration", in *Proc. IEEE ICC*, Alaska (US), May 2003, pp. 2023-2030.

[4] J. Wang, L. Sahasrabuddhe, B. Mukherjee, "Path vs. subpath vs. link restoration for fault management in IP-over-WDM networks: Performance comparison using GMPLS control signaling", *IEEE Communications Magazine*, vol. 40, no. 11, pp. 80-87, Nov. 2002.

[5] A. K. Somani, "Survivability and traffic grooming in WDM optical networks", Cambridge University Press 2006.

[6] S. Gringeri, B. Basch, V. Shukla, R. Egorov and T. J. Xia, "Flexible architectures for optical transport nodes and networks", *IEEE Communications Magazine*, vol. 48, no. 7, pp. 40-50, Aug. 2010.

[7] V. Kaman, R. J. Helkey and J. E. Bowers, "Multi-degree ROADM's with agile add-drop access", in *Proc. Photonics in Switching*, San Francisco (US), Aug. 2007, pp. 31-32.

[8] E. B. Basch, R. Egorov, S. Gringeri and S. Elby, "Architectural tradeoffs for reconfigurable dense wavelength-division multiplexing systems", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 12, no. 4, pp. 615-626, July 2006.

[9] V. Kaman, S. Yuan, O. Jerphagnon, R. J. Helkey and J. E. Bowers, "Comparison of wavelength-selective cross-connect architectures for reconfigurable all-optical networks", in *Proc. Photonics in Switching*, Crete, Oct. 2006, pp. 1-3.

[10] R. Shankar, M. Florjanczyk, T. J. Hall, A. Vukovic and H. Hua, "Multi-degree ROADM based on wavelength selective switches: architectures and scalability", *Optics Communications*, vol. 279, no.1, pp. 94-100, Nov. 2007.

[11] S. Thiagarajan, L. Blair and J. Berthold, "Direction-independent add/drop access for multi-degree ROADMs", in *Proc.OFC/NFOEC*, San Diego (US), Feb. 2008, paper OThA7.

[12] P. Roorda and B. Collings, “Evolution to colorless and directionless ROADM architectures”, in *Proc. OFC/NFOEC*, San Diego (US), Feb. 2008, paper NWE2.
[13] P. N. Ji and Y. Aono, “Colorless and directionless multi-degree reconfigurable optical add/drop multiplexers”, in *Proc. WOCC*, Shaghai (China), May 2010, pp. 1-5.
[14] G. Prasanna, S. K. Kishore, G.K. Omprasad, K. S. Raju, R. Gowrishankar, K. Venkataramaniah, R. Johnson and P. Voruganti, “Versatility of a colorless and directionless WSS based ROADM architecture”, in *Proc. Communications Systems and Networks* 2009, Bangalore (India), Jan. 2009, pp. 1-8.
[15] A. Devarajan, K. Sandesha, R. Gowrishankar, B. S. Kishore, G. Prasanna, R. Johnson and P. Voruganti, “Colorless, Directionless and Contentionless multi-degree ROADM architecture for mesh optical networks”, in *Proc. Communications Systems and Networks* 2010, Bangalore (India), Jan. 2010, pp. 1-10.
[16] J. Chen, J. Jacob, C. Santivanez, J. Ho and K. Rauschenbach, “En route to Grouping-Constraint Free, Colorless Directionless ROADMs”, in *Proc. OFC/NFOEC*, 2010, paper NThF1.
[17] M. D. Feuer, S. L. Woodward, P. Palacharla, X. Wang, I. Kim, D. Bihon, “Intra-node contention in dynamic photonic networks”, *IEEE/OSA Journal of Lightwave Technology*, vol. 29, no. 4, pp. 529-535, Feb. 2011.
[18] P. Palacharla, X. Wang, I. Kim, D. Bihon, M. D. Feuer, S. L. Woodward, “Blocking performance in dynamic optical networks based on colorless, non-directional ROADMs”, in *Proc. OFC/NFOEC* 2011, paper JWA8.
[19] P. Pavon-Marino, M. V. Bueno-Delgado, “Dimensioning the add/drop contention factor of directionless ROADMs”, *IEEE/OSA Journal of Lightwave Technology*, vol. 29, no. 21, pp. 3265-3274, Nov. 2011.
[20] CoAdna Photonics.Available: http://www.coadna.com
[21] A. Neukermans and R. Ramaswami, “MEMS technology for optical networking applications”, *IEEE Communications Magazine*, vol. 39, no. 1, pp. 62-69, Jan. 2001.
[22] C. S. R. Murthy and G. Mohan, WDM Optical Networks (Concepts, Design and Algorithms). Prentice Hall PTR, Upper Sadle River, 2002.
[23] MatPlanWDM tool v.0.60. Available: http://www.ait.upct.es/~ppavon/matplanwdm
[24] K. Holmström, A. O. Göran, and M. M.Edvall, “User’s Guide for TOMLAB/CPLEX v11.2”, 2009.
[25] Internet 2 Global Research Network Operations Center, Web Site, [Online]. Available: http://www.abilene.iu.edu
[26] R. Ramaswami, K.N. Sivarajan, “Design of Logical Topologies for Wavelength-routed Optical Networks,” *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 840–851, Jun. 1996.
[27] Atlanta reference network. Available: http://sndlib.zib.de/coredata.download.action?objectName=atlanta&format=native&objectType=network
[28] France reference network. Available: http://sndlib.zib.de/coredata.download.action?objectName=france&format=native&objectType=network
[29] SNDlib (library for Survivable fixed telecommunication Network Design). Available: http://sndlib.zib.de