Dimensioning the add/drop contention factor of directionless ROADMs

P. Pavon-Marino, M. V. Bueno-Delgado

Abstract—**Reconfigurable Optical Add/Drop Multiplexers (ROADM) are the optical switching equipment of transparent optical networks. Directionless ROADMs permit the network carriers to change the direction of an added and/or dropped lightpath without the need of a technician on-site intervention in the lightpath end nodes. Colorless ROADMs provide the same versatility for changing the lightpath transmission wavelength. Cost-effective directionless ROADM architectures (colorless or colored) can be built if the maximum number of lightpaths that can be added/dropped using the same wavelength is limited. We name this limit as the node add/drop contention factor, and denote it as *C*. In this paper we investigate the network lightpath blocking performance as a function of this add/drop contention factor of the nodes. The scenarios considered are the static planning of a network (i) with unprotected traffic, (ii) with traffic 1+1 protected for single-link failures, and (iii) with traffic 1+1 protected for single-link or single-node failures. Since for these scenarios, the wavelength of an existing lightpath does not have to be dynamically reconfigured, the work in this paper applies to both colorless and colored nodes. An ILP model and an effective heuristic are presented to solve the so-called Add/Drop Contention Aware RWA (ADCA-RWA) planning of the network. Extensive results are reported. In all the cases, an add/drop factor *C*=2 is sufficient to provide the same performance as contentionless nodes (*C*=∞). Furthermore, in all the tests a factor *C*=1 was also sufficient, or produced a minor lightpath blocking performance degradation (below 0.5% in the unprotected cases, and below 2.5% in the 1+1 protected cases).**

Index Terms—**Reconfigurable Optical Add-Drop Multiplexer, Directionless (ROADM) architectures, directionless and contentionless ROADM architectures, Routing and Wavelength Assignment.**

I. INTRODUCTION

Transparent optical networks based on wavelength division multiplexing (WDM) are an enabling technology for high-speed backbone networks [1][2]. In transparent networks, traffic is carried over 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 occupies a wavelength channel in each traversed link, and terminates at an O/E receiver in the egress node, where it is said to be *dropped*. The lightpaths are optically switched at the intermediate nodes, and with respect to those nodes, are commonly referred as *express* lightpaths.

Add, drop and optical bypass of the lightpaths are implemented by specialized equipment in the network: the Optical Add/Drop Multiplexers (OADMs). Initial versions of OADMs consisted of optical interconnection equipment where the connections were hard-wired, and every change in the add/drop/bypass state of the switch required a manual intervention. The expected growing dynamicity of the traffic, and the promise of a reduction in the network operational costs (OpEx), pushed the carriers to increase the agility of the optical transport equipment. The Reconfigurable-OADMs (ROADMs) are the key technology for this. In ROADMs, part of the optical switching functionality is implemented by means of active optical devices, under the control of a coupled control and management plane. As a result, a subset of the lightpath reconfigurations can be completed in the order of seconds, without an on-site visit of a technician.

ROADMs are often talked about in terms of degrees of switching. The degree is other name for referring to a switching direction, associated to a transmission fiber pair which connects the node with its neighboring nodes. First generation of ROADMs was restricted to nodes of degree two, situated as switching equipment in bidirectional rings. The two directions corresponded to the neighboring nodes, and were commonly named as East and West. Second generation of ROADMs introduced a multi-degree capability, usually to a maximum degree of eight, suitable for constructing mesh physical topologies. However, the issue of first and second generation of ROADMs is their limited flexibility, since ROADMs 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. As a result, existing ROADMs eliminate the need of manual intervention to reconfigure the intermediate nodes of a lightpath, but still do not eliminate the technicians' visit to the lightpath end nodes sites.

Next generation of ROADMs are addressing this lack of flexibility, aiming at the so-called *directionless* and/or

---

The work described in this paper was carried out with the support of the BONE project ("Building the Future Optical Network in Europe"); a Network of Excellence funded by the European Commission through the 7th ICT-Framework Program. This research has been partially supported by the MEC project TEC2010-21405-C02-02/CALM, it is also developed in the framework of the project from Fundación Seneca "Programa de Ayudas a Grupos de Excelencia de la Región de Murcia", F. Séneca (Plan Regional de Ciencia y Tecnología 2007/2010).

P. Pavon-Marino and M.V. Bueno-Delgado are with Technical University of Cartagena (UPCT), Pza. Hospital 1, 30202 Cartagena, Spain (e-mail: {pablo.pavon, mvictoria.bueno}@upct.es).

colorless ROADMs. Directionless architectures permit to automatically reconfigure the direction of an added or dropped lightpath (points (i) and (ii) in previous paragraph). In colorless ROADMs, the transmission wavelength of a lightpath can be modified without manual intervention (point (iii) in previous paragraph). Unfortunately, practical implementations of directionless architectures (both colorless or not) add an internal contention to the ROADMs, not present in previous generation equipment: the maximum number of lightpaths that can be added and dropped in a node, using the same wavelength, can be limited by the ROADM architecture. We name this maximum number as the node add/drop contention factor, and denote it as C. The add/drop contention in the nodes is a source of lightpath blocking, which adds more constraints to the network planning, and degrades the capacity of the network. It is possible to build ROADM architectures with lower blocking by increasing the equipment cost. In the limit, *contentionless* nodes are those directionless ROADMs in which the contention limitation is totally eliminated, or eliminated in the practice.

In this paper, we consider an optical transport plane with directionless ROADMs, which can be colorless or not. We are interested in studying the cost vs performance trade-off that appears in the dimensioning of the add/drop contention factors (C) of the nodes. We focus on the static planning case, in which the traffic demand is given by a lightpath demand matrix, known in advance. Then, we observe the improvements in the maximum traffic volume supported by the network, for different values of the contention factor, in three cases: (i) networks in which no optical protection scheme is planned, (ii) networks with 1+1 protection for single-link failures, and (iii) networks with 1+1 protection for single-link or single-node failures.

To plan the network we investigate, for the first time in the literature, the Add/Drop Contention Aware Routing and Wavelength Assignment (ADCA-RWA) planning problem. We present a set of ILP (Integer Linear Programming) models for this problem, and effective heuristics suitable for realistic network instances. The optimization target is minimizing the lightpath blocking (that is, maximizing the carried traffic). A large set of experiments are conducted, ranging four reference topologies with their respective reference traffic matrices. These traffic matrices are normalized according to the maximum traffic that can be carried by a network (i) equipped with contentionless nodes and (ii) for which the wavelength continuity constraint is relaxed. Thanks to this normalization process, we are able to estimate the maximum performance degradation that non-contentionless ROADMs bring to the network. In our results, a contention factor C=2 in the nodes suffices in all the cases to provide the same network capacity as contentionless nodes. Moreover, the maximum lightpath blocking observed when nodes have a factor C=1 was quite low: 0.5% in the unprotected cases, and 2.5% in the 1+1 protected cases. These results are of direct application to the design of directionless ROADM architectures.

The rest of the paper is organized as follows. Section II provides a more detailed background and related work to this topic. In Section III we explore the ADCA-RWA planning. Section IV reports the results obtained, and Section V concludes.

II. BACKGROUND

A. ROADM architectures

Fig. 1 helps us to illustrate the role of an ideal ROADM, for a node with N input and output fibers, W wavelengths per fiber, and L and L' add and drop ports respectively. The switching functionality would be ideally implemented by a fully reconfigurable non-blocking (NW+L)×(NW+L') optical switch. However, such an optical structure is currently far from being feasible from the technical point of view, nor even profitable. Thus, as in other switching technologies, the history of ROADM architecture design is the history of how to build sufficiently large and versatile reconfigurable architectures, making use of the components available.

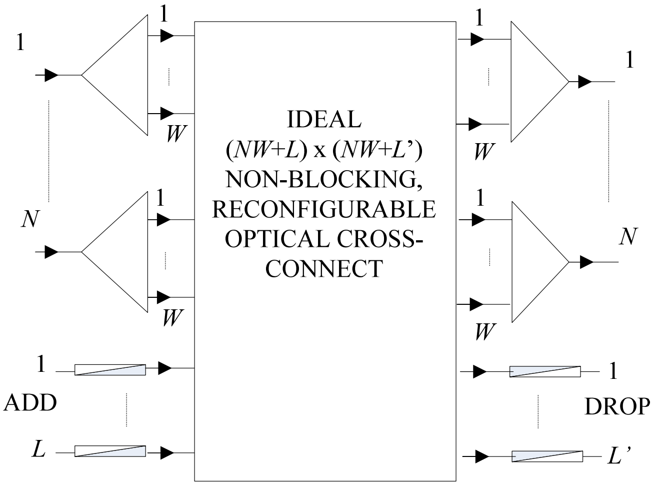

Fig. 1. Ideal ROADM

The diagrams of the basic optical components used as building blocks in the construction of ROADM switching architectures are shown in Fig. 2. The optical splitter and combiner and the optical multiplexers and demultiplexers are passive devices. Fixed and tunable transceivers, wavelength-selective switches (WSS) and photonic cross-connects (PXC) are active devices. 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 year 2010, the largest WSS commercially available is a 1x23 WSS [3] 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 [4] (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. The PXC has, in general, a larger amount of input and output ports. In contrast to WSSs, PXCs cannot separately switch to different output ports the WDM channels in an input port. PXCs of size 320x320 are commercially available [5], based on 3D MEMS technology.

The majority of the ROADM architectures are based on the broadcast-and-select (B&S) approach to implement the switching functionality. Fig. 3(a) shows a diagram of a second generation (directed) B&S ROADM of degree two, with the two directions named as East and West. The optical signal from a specific direction is split by an optical splitter. A part of the signal is sent to each output direction modules, and a part to the drop module. In each output direction, a WSS combines the channels coming from other directions and from the add module. The drop module consists of a passive demultiplexer which physically separates the WDM optical channels into different output ports, where the transceivers are placed. In its turn, the transceivers in the add module 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.

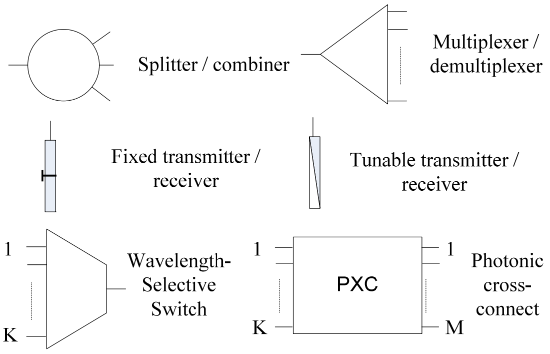

Fig. 2. Optical components

While the architecture in Fig. 3(a) implements a non-blocking switching operation, it offers a poor versatility in the sense that many reconfigurations require manual intervention to be completed. This is because, the place in which the transceiver of an added or dropped lightpath is installed, is determined by (i) the direction of the lightpath, and (ii) the wavelength of the lightpath. The former limitation comes from the fact that separated transceiver banks exist for different directions. The latter comes from the use of passive optical mux/demux components which have a fixed association between ports and wavelengths.

Fig. 3(b) shows a directionless version of the switch in Fig. 3(a). To implement the directionless functionality, add and drop modules are installed in a common transceiver bank, shared by all the directions. The add side of the shared add/drop module requires a multiplexer which combines the signal from the transponders, and a splitter which distributes them to the possible directions. In the drop side, the individual channels to be dropped are extracted by a WSS device from the optical signals coming from the different directions. Still,

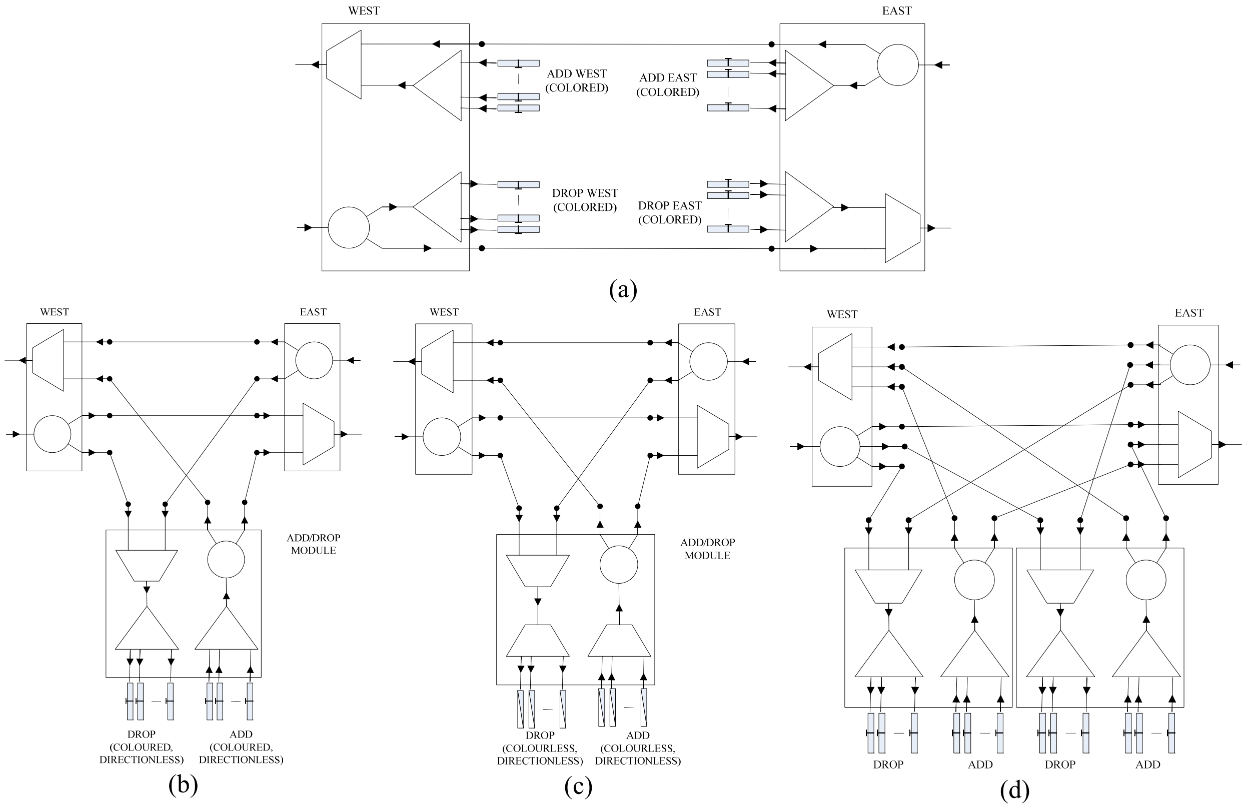

Fig. 3. ROADM architectures. (a) Directed, colored, (b) Directionless (*C*=1), colored, (c) Directionless (*C*=1), colorless, (d) Directionless (*C*=2), colored

the architecture in Fig. 3(b) is colored, in the sense that changing the wavelength of a lightpath requires moving physically the transceiver (assuming tunable transceivers) to a different port of the mux/demux. Fig. 3(c) shows the architecture of a directionless and colorless node, where the multiplexer and demultiplexer in the add and drop modules are replaced by WSSs. Then, retuning a transceiver does not require physically moving it to other slot in the bank.

Figs. 3(b) and 3(c) help us to understand the new internal contention in the ROADMs that can be brought by directionless architectures: because of the existence of a single bank of transponders, it is not possible to add (drop) two lightpaths in the same wavelength, even if they are routed through different directions. How this problem can be solved? An ideal directionless-colorless-contentionless solution would require (i) replacing the add module in Fig. 3(c) by a non-blocking LxN WSS, and (ii) replacing the drop module in Fig. 3(c) by a NxL' WSS. Building a single WSS of this type for the sizes of interest (e.g. N=4, L, L'>100) is far from reality. Naturally, a standard approach could be followed, constructing these large WSSs by the interconnection of WSSs of smaller size. Although practical in theory, this approach would still be a challenging and expensive option.

In this paper, we are interested in investigating the effects in the network capacity, of the add/drop contention factor C in the nodes. This is relevant for ROADM design, since it may be possible to build ROADMs which are contentionless *in practice*. That means, ROADMs which do not enjoy of the hardware to be contentionless, but which have a contention factor high enough for not producing a significant loss of performance in the network. Dimensioning the contention factor is of direct application for architectures like the ones proposed in [6]-[7], in which a contention factor C in the node is obtained by equipping the node with C replicated add/drop modules. Fig. 3(d) shows an example of this approach, in which the directionless colored ROADM in Fig. 3(b) is upgraded to a contention factor C=2. The same approach can be followed for colorless architectures. A pure contentionless (colored or not) node could be obtained only if the number of add/drop modules equals the number of directions in the node. However, increasing the number of transceiver banks implies (i) multiplying the cost of the add/drop hardware and (ii) increasing the number of ports in the combiners and WSSs at the modules of each direction. The work in this paper permits to explore the performance side of the cost vs performance trade-off appearing in this and other similar ROADM architectures.

A final remark should be made regarding the colored vs colorless operation. The results in this paper are of application to both approaches. This is because colorless architectures make a difference only when a dynamic change of the wavelength of a lightpath is needed. In our case of study, the network does not have this requirement. Recall that we are interested in static network planning, where a fast provisioning of new demands arriving dynamically, is not considered. In addition, we focus on the unprotected case and the 1+1 protection schemes. For these scenarios, there is no need to modify the wavelength of a lightpath to react to a network failure, since both the nominal and protection lightpaths are already established. Therefore, the same automatic reconfiguration actions in this type of networks could be implemented by both colored and colorless equipment.

B. Related work

This subection is devoted to review the related work in the design of versatile ROADM architectures. The first mention in the literature to directionless and to colorless architectures is found in [8] and [9] respectively. After that, the scientific community showed a growing interest in this topic, and numerous works have been and are being published exploring the multiple alternatives in the design of more versatile ROADMs [6]-[19]. A strong interest from the industry is driving the research in this topic, since the directionless and colorless functionalities are the differential features in the new generation of ROADMs.

The majority of the related works investigate on the practical feasibility and scalability of different ROADM architectures in terms of cost, optical impairments or both [6]-[17]. Among them, the only work in the literature considering the effect in the node cost of increasing the add/drop contention factor (the authors used the expression “grouping constraint”) can be found in [7]. Still, none of the works [6]-[17] addressed in any form the performance side of the question: how the possible internal blocking brought by the ROADM architectural choice may reduce the traffic that the network can carry? The only works in the literature, to the best of the authors’ knowledge, that investigates a somewhat related topic under a performance-wise light, are the ones in [18] and [19]. In [18], the authors focus on a network with colorless and contentionless ROADMs, and study the loss of performance induced if the tunable transceivers (required for the colorless functionality) have a limited tunability. The testing scenario is a network with dynamic (random) arrivals of lightpath demands. The work in [19] evaluates the lightpath blocking caused by internal contention in a directionless and colorless node, also under dynamic lightpath demands arriving randomly. The authors assume that the RWA planning is done with no concern on the possible add/drop contention in the nodes. That is, they study the case in which a sort of ADCA-RWA 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. The work in [19] differs from this work 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 effects. Interestingly, our results contradict the ones in [19], in the sense that factors C=1 and C=2 suffice to make the nodes behave as contentionless ROADMs. Therefore, results motivate the interest in the ADCA-RWA planning as a successful mechanism for eliminating in the practice the add/drop contention effects, without over-equipping the ROADMs.

III. ADD/DROP CONTENTION AWARE RWA (ADCA-RWA) PLANNING

In this section we present a set of ILP models and effective heuristic algorithms for solving the Routing and Wavelength Assignment (RWA) planning of the network, considering add/drop contention constraints in the nodes. We name this planning problem as Add/Drop Contention Aware Routing and Wavelength Assignment (ADCA-RWA). The planning target is the minimization of the lightpath blocking. Nodes are not equipped with wavelength converters. The three problem variants studied correspond to (case I) the unprotected case, (case II) 1+1 protection for single-link failure, and (case III) 1+1 protection for single-link failure or single-node failure. In the first case, a lightpath demand is said to be satisfied if a route is found between its ending nodes, using a common wavelength in all the hops. In the 1+1 protected cases, two link-disjoint routes should be found for each lightpath: one for its nominal path and one for its protection path. Both of them are simultaneously active in the network, so that if a failure affects the nominal path, the protection path is already set. The wavelength of the nominal and the protection lightpaths can be different. In case III, the nominal and protected paths must be link-disjoint and also node-disjoint (excepting for the two ending nodes of the lightpath). In these cases, all the lightpaths of the network could also survive a node failure, but those initiated or originated at the failing node.

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 link. We assume that all fibers in the network have the same wavelength grid defined by W. Let C_n and C_n' be the add and drop contention factor respectively, at node $n \in N$: the maximum number of lightpaths that can be added and dropped respectively, using the same wavelength. 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.

The decision variables of the problem are:

- $x_{dew} = \{0,1\}$, $d \in D$, $e \in E$, $w \in W$, x_{dew} takes the value 1 if the lightpath d traverses link e in wavelength w, and 0 otherwise. In the protected case, x_{dew} values account for both the nominal and protected routes of the lightpath.
- $y_{dw} = \{0,1,2\}$, $d \in D$, $w \in W$. In the unprotected case, y_{dw} takes the value 1 if the lightpath d uses wavelength w, and 0 otherwise. In the protected case, y_{dw} can also take the value 2, if both the nominal and the protected paths of the lightpath use wavelength w.
- $y_d = \{0,1\}$, $d \in D$. y_d takes the value 1 if the lightpath d is carried, and 0 otherwise.

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

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

$$\sum_{d \in D} x_{dew} \le 1, w \in W, e \in E \tag{1b}$$

$$\sum_{d \in D | a(d)=n} y_{dw} \le C_n, n \in N, w \in W \tag{1c}$$

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

Unprotected case: $$\sum_{w \in W} y_{dw} = y_d, d \in D \tag{1e}$$

Protected case: $$\sum_{w \in W} y_{dw} = 2y_d, d \in D \tag{1f}$$

Protected (link failure): $$\sum_{w \in W} x_{dew} \le 1, d \in D, e \in E \tag{1g}$$

Protected (node failure): $$\sum_{e \in \delta^+(n), w \in W} x_{dew} \le 1, d \in D, n \in N - a(d) \tag{1h}$$

Protected (node failure): $$\sum_{e \in \delta^-(n), w \in W} x_{dew} \le 1, d \in D, n \in N - b(d) \tag{1i}$$

Constraints (1a) are a variant of the classical routing conservation constraints: for each lightpath d, the number of routes between its end nodes $a(d)$ and $b(d)$ using wavelength w is equal to y_{dw} (0 or 1 in the unprotected case; 0,1 or 2 in the protected case). Constraints (1b) are the wavelength clashing constraints. Constraints (1c) and (1d) reflect add and drop contention constraints of each node respectively. Constraint (1e) is applied only in the unprotected case, and makes y_d take the value of 1 when one route is found for the lightpath. In its turn, (1f) constraint is applied only in the protected case. It states that for a lightpath to be satisfied (y_d=1), two paths between its end nodes are needed. The rest of constraints are only set in the protected case. Constraints (1g) establish that the nominal and protected paths of a lightpath must be link-disjoint. Finally, constraints (1h) and (1i) are only used in the 1+1 link and node disjoint protected case (case III). (1h) states that at most one path of a lightpath d can leave a node, but in the initial node of the lightpath $a(d)$ (where both the nominal and the protected paths start). Constraint (1i) establishes the analogous constraint, focusing on the routes entering into a node.

The objective function (1j) is the maximization of the carried traffic (or equivalently, the minimization of the blocking traffic). Note that in the protected case, a lightpath is carried if it has both a valid nominal path and protected path.

$$\text{Max} \sum_{d \in D} y_d \tag{1j}$$

B. Heuristic algorithms

The ILP formulations described in the previous section correspond to variants of the RWA planning, a known NP-hard problem [20]. This section presents a set of heuristic algorithms for solving the three problem variants (case I, II, III) in problem instances of realistic sizes. A similar scheme, shown in Fig. 4, is used in the three cases.

In a first step, the set of demands D is ordered according to the well-known HLDA (Heuristic Logical Design Algorithm) strategy [20], producing the ordered list D_L. This is completed in Procedure $P1$ in Fig. 4. Also, the set D_c of carried demands and the set D_b of blocked demands are initialized to the empty set.

In a second step, the ordered list of demands D_L is partitioned into blocks of L_{max} consecutive demands, but the last block which has a number of demands given by the remainder of $|D_L|/L_{max}$. As an example, if the demand set has 35 demands ($|D|=|D_L|=35$), and $L_{max}=10$, four blocks of demands are created, of sizes 10, 10, 10, and 5. Then, one iteration of the loop is completed for each block. Set L denotes the block of demands processed in current iteration. Procedure $P2$ intends to carry in the residual network as many lightpaths in L as possible. The residual network is defined as the network in which the resources occupied by the already carried lightpaths in previous iterations (wavelengths in the links and add/drop ports) are not available. As will be shown later, Procedure $P2$ is based on ILP (1) which finds an optimal allocation solution restricted to the lightpaths in set L. Then, the complexity of the algorithm can be controlled by the parameter L_{max}, the maximum number of lightpaths in L. At the end of Procedure $P2$, the sets D_c and D_b are updated by adding the new carried and blocked lightpaths in L. Finally, the algorithm ends after all the blocks of demands have been processed, which occur when exactly $|D_L|/L_{max}$ iterations (rounded-up) are completed.

1) *Procedure P1*

The method for ordering the lightpath demands is a variation of the well-known HLDA (Heuristic Logical Design Algorithm) strategy [20]. The method consists of the following steps. First, set D' is initialized as $D'=D$. Then, for each input output node pair (i, j), we compute the number of lightpaths inset D' starting at node i and ending at node j. Let (i',j') be the node pair in D' with a highest number of lightpaths between them (if this holds for more than one node pair, one of them is chosen randomly). One lightpath in D' from node i' to node j' is added at the end of the list D_L, and removed from D'. The process ends when D' is empty, and thus all the original demands have been added to set D_L ($|D|=|D_L|$). Finally, note that the actions in Procedure $P1$ are independent of the network protection scheme.

2) *Procedure P2*

Procedure $P2$ receives the block of lightpaths L, and intends to carry them in the residual network. This means, finding for each lightpath a valid route (unprotected case) or two valid routes (1+1 protected cases). For this, it solves the formulation (1), taking L as the set of demands (and thus, taking the place of set D in (1)).

In order to reflect that the resources occupied by already carried lightpaths (in previous iterations) are not available, the following modifications are made to formulation (1):

- The constraints $x_{dew}=0$, are added for all the lightpaths $d\in L$, and all the link-wavelength pairs (e,w) which are occupied by the lightpaths carried in previous iterations. Then, these resources cannot be allocated for the lightpath in L.
- The values C_n in (1c) and C_n' in (1d), will now contain the number of add/drop ports in the nodes, minus the number of these ports already occupied by the lightpaths carried in previous iterations. In other words, they will contain the number of *available* add/drop ports.

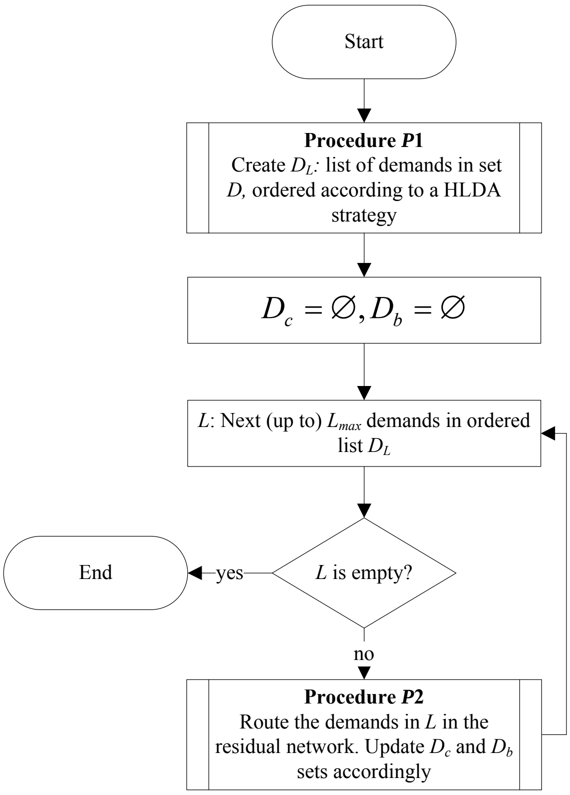

Fig. 4. Scheme of the heuristic algorithm

IV. RESULTS

This section collects and analyzes extensive results to dimension the contention factor C in directionless ROADMs. We consider networks statically planned using the heuristic algorithms described in Section III.B. The algorithms have been implemented in MATLAB code, integrated and tested in the MatPlanWDM tool [21], which interfaces with the TOMLAB/CPLEX solver [22] (TOMLAB v7.4, CPLEX v11). All the tests have been executed in a machine based on an Intel Core i5 2.27 GHz processor, 8 GB of RAM, and 64-bits operating system.

We replicate the tests for three protection types *P*={I, II. III}, respectively corresponding to: (i) unprotected lightpaths, (ii) 1+1 lightpath protection for link failure, and (iii) 1+1 lightpath protection for link or node failure. By doing so, we cover a reasonably wide set of options of interest for network carriers. The main intention of the tests is answering two questions: which is the contention factor the nodes should be equipped, to provide a contentionless behaviour? and, how relevant is the performance degradation if nodes are sub-equipped with respect to this parameter?

A. Testing scenario

Four reference network topologies, together with their corresponding reference traffic matrices, are used in our study: Internet2 [23], NSFNET [24], and the topologies tagged as *cost266* [25] and *atlanta* [26] in the SNDLIB [27] repository. The number |*W*| of wavelengths per fiber tested is |*W*|={20, 40, 80}. Table I summarizes some major data from these topologies.

TABLE I
INFORMATION ON THE TOPOLOGIES TESTED

	Internet2	**NSFNET**	***cost266***	***atlanta***
Reference	[23]	[24]	[25]	[26]
Name	T1	T2	T3	T4
Nodes (|*N*|)	9	14	37	15
Unidirect. links (|*E*|)	26	42	114	44
Average in degree	2.89	3	3.08	2.93

Optical switching nodes are built using ROADMs as the one shown in Fig. 3(d). All the nodes in the network have the same add/drop contention degree: $C_n = C'_n = C$, $n \in N$. The contention degree *C* ranges $C \in \{1,2,\infty\}$. The case $C=\infty$ corresponds to the pure contentionless case.

We are interested in assessing the lightpath blocking performance for the different *C* factors described, and different traffic load conditions. To formally characterize the load conditions, we first define a traffic normalization process. Given a network topology *T*, the reference traffic matrix for that topology $M^{BASE}(T)$ brought from literature (measured in any arbitrary traffic units), a wavelength grid in the network *W*, and a network protection type *P*={I, II. III} we calculate its associated *maximum lightpath demand matrix* $M^{MAX}(T,W,P)$ given by (2).

$$M^{MAX}(T,W,P) \;= round\left(\alpha^{MAX} \cdot M^{BASE}(T)\right) \qquad (2)$$

The value α^{MAX} is calculated as the maximum value for which the lightpath demand matrix (2) admits a feasible solution of a sort of relaxed version of problem (1). In this sense, $M^{MAX}(T,W,P)$ is an *upper bound* to the maximum traffic of the form (2), that the network defined by the triple (*T*,*W*,*P*) can carry.

We denote as D^{MAX} the demand set composed for the lightpaths in the lightpath demand matrix $M^{MAX}(T,W,P)$. In the unprotected case *P*=I, the upper bound searched is given by the maximum matrix for which (3) allows a feasible solution:

$$\text{Find } x_{de} \geq 0, \text{integer}, d \in D^{MAX}, e \in E, \text{subject to:} \qquad (3a)$$

$$\sum_{e\in\delta^+(n)} x_{de} - \sum_{e\in\delta^-(n)} x_{de} = \begin{cases} 1 \text{ if } n = a(d) \\ -1 \text{ if } n = b(d), d \in D^{MAX}, n \in N \\ 0 \text{ otherwise} \end{cases} \qquad (3b)$$

$$\sum_{d\in D^{MAX}} x_{de} \leq |W|, e \in E \qquad (3c)$$

Constraints (3b) are the standard routing conservation constraints. Constraints (3c) are the link capacity constraints, limiting the maximum number of lightpaths carried in a fiber by the number of wavelengths in the fiber.

In the 1+1 protection case (*P*=II and *P*=III), problem (3) is replaced by problem (4):

$$\text{Find } x_{de} \geq 0, \text{integer}, d \in D^{MAX}, e \in E, \text{subject to:} \qquad (4a)$$

$$\sum_{e\in\delta^+(n)} x_{de} - \sum_{e\in\delta^-(n)} x_{de} = \begin{cases} 2 \text{ if } n = a(d) \\ -2 \text{ if } n = b(d), d \in D^{MAX}, n \in N \\ 0 \text{ otherwise} \end{cases} \qquad (4b)$$

$$\sum_{d\in D^{MAX}} x_{de} \leq W, e \in E \qquad (4c)$$

$$\text{Node failure: } \sum_{e\in\delta^+(n)} x_{de} \leq 1, d \in D^{MAX}, n \in N - a(d) \qquad (4d)$$

$$\text{Node failure: } \sum_{e\in\delta^-(n)} x_{de} \leq 1, d \in D^{MAX}, n \in N - b(d) \qquad (4e)$$

Routing conservation constraints are modified in (4b), so that two link disjoint paths are established per demand. Constraints (4c) are the link capacity constraints. Constraints (4d) and (4e) only appear in the 1+1 protected case when both link and node failures are to be protected (*P*=III).

Formulations (3) and (4) are relaxed versions of the original problem (1), which permit fast executions for the problem sizes of interest. In all the cases tested, these relaxations could be executed in less than 2 seconds. Note that these relaxed versions do not consider the wavelength clashing constraints in the links, nor the add/drop contention constraints in the nodes. In particular, if a solution is found to a relaxed problem for a lightpath demand matrix *M*, this matrix could be carried by a network with contentionless nodes, equipped with transparent wavelength converters in all the nodes. Therefore, matrices $M^{MAX}(T,W,P)$ are upper bounds to the matrices of the type (2) which could be carried without lightpath blocking.

The maximum lightpath demand matrices are used to normalize the load factor in the network. Given a (*T*,*W*,*P*) triple, $M^{MAX}(T,W,P)$ is the traffic demand associated to network load $\rho=1$. Note that there is no guarantee that a feasible solution exists for this case, even in the contentionless case $C=\infty$, since the relaxed version permits wavelength conversion in the lightpaths, while the original problem does not.

Table II shows the total number of lightpaths in $M^{MAX}(T,W,P)$ for all the (*T*,*W*,*P*) triples. Let us denote this maximum traffic volume as $V_{T,W,P}$. Then, the lightpath demand matrices $M(T,W,P,\rho)$ at other network loads $\rho\in[0,1]$, are calculated by finding the factor $\alpha<\alpha^{MAX}$ for which its associated lightpath demand matrix has a volume equal to $\rho V_{T,W,P}$ (or its closest integer value). In this paper, we repeat the tests for network loads $\rho\in\{0.8, 0.85, 0.90, 0.95, 1\}$. Lower network loads produced zero lightpath blocking in all the occasions.

TABLE II. $V_{T,W,P}$: NUMBER OF LIGHTPATHS OF $M_{MAX}(T,W,P)$ MATRICES

|W|	*Protection type*	Internet2	NSFNET	*cost266*	*atlanta*
20	**Unprot.**	144	229	192	61
	1+1 link	72	76	70	17
	1+1 link-node	72	76	70	17
40	**Unprot.**	274	438	562	133
	1+1 link	144	229	192	61
	1+1 link-node	144	229	192	61
80	**Unprot.**	564	868	1180	289
	1+1 link	274	438	562	133
	1+1 link-node	274	438	562	133

B. Results

The tests completed cover every combination of the following parameters:

- Network topologies: $T\in\{T1,T2,T3,T4\}$.
- Wavelengths per fiber: $|W|\in\{20,40,80\}$
- Traffic load factors: $\rho\in\{0.8, 0.85, 0.9, 0.95, 1\}$
- Add/drop contention factors: $C\in\{1,2,\infty\}$
- Protection type: P={I, II. III}. (Case I) unprotected, (Case II) 1+1 single link failure, and (Case III) 1+1 single-link and or single node failures.

Four executions are completed for each test, with four different values of the L_{max} parameter $L_{max}=\{15, 30, 60, 90\}$. In general, lower blocking probabilities were obtained for higher values of the L_{max} parameter. This is logical, since more demands are jointly optimized in these cases. However some exceptions occurred, explained by the heuristic nature of the algorithm. Since the running time in all the cases was low (below 1 hour, and usually a few minutes), the results shown in this section for each test, correspond to the best solution found among the four L_{max} factors.

We investigate the dependence of the *maximum network throughput* on the node add/drop contention factor. We define the maximum network throughput, as the maximum network load ρ for which a solution was found with zero lightpath blocking. The network throughput is an indicator on the maximum revenue a carrier can obtain from the network infrastructure.

The first relevant observation from the tests, and indeed the main result of the paper requires no figure to be explained: it is that in *all* the protection types, *all* the network topologies and *all* the number of wavelengths tested, an add/drop contention factor C=2 sufficed to provide a 100% maximum network throughput. In other words, nodes with C=2 were in practice contentionless nodes, and no benefit in terms of performance was obtained by using over-equipped nodes with higher contention factors ($C=\infty$). A secondary observation from these results is that the upper bound matrices calculated using the relaxations (3) and (4) are very accurate: in all the cases the upper bound to the carried traffic computed was also the maximum traffic that could be carried.

After stating that nodes with contention factor C=2 are in the investigated scenarios equivalent to contentionless nodes, we are interested in the performance loss that we can incur if the nodes in the network are built according to a factor C=1. Table III reports the maximum network throughput in this case. For each protection type, number of wavelengths $|W|$, and network topology T, the maximum network throughput (in %) is shown.

TABLE III. MAXIMUM NETWORK THROUGHPUT (%), C=1.

|W|	*Protection type*	Internet2	NSFNET	*cost266*	*atlanta*
20	**Unprot.**	100 %	100 %	100 %	100 %
	1+1 link	100 %	100 %	100 %	100 %
	1+1 link-node	100 %	100 %	100 %	100 %
40	**Unprot.**	95 %	95 %	100 %	100 %
	1+1 link	100 %	100 %	100 %	100 %
	1+1 link-node	100 %	95 %	100 %	100 %
80	**Unprot.**	100 %	95 %	95 %	100 %
	1+1 link	100 %	95 %	95 %	100 %
	1+1 link-node	100 %	95 %	85 %	100 %

Analyzing the network throughput results computed by the algorithm in Table III, some relevant conclusions can be drawn. First observation is that in many cases, a contention factor C=1 suffices to provide the maximum 100% network throughput, and thus be exactly equivalent to the contentionless $C=\infty$ case. As an example, this occurs in all the cases for W=20, and in all the *atlanta* topology tests. In all the tests but one, when a 100% of maximum network throughput is not reached, the performance is just one step below: 95%. The only exception occurs in the *cost266* network, $|W|$=80, P=III, when a zero lightpath blocking could only be achieved at a load factor of 85%.

Finally, it is of interest answering this question: which is the lightpath blocking we are incurring if nodes built according to C=1 are used in the network? Table III pointed out in which cases there was no performance degradation at all, and in which cases some lightpath blocking occurred. Let us now study the case in which some lightpath blocking is accepted by the network carrier. Table IV helps us to study this situation. It shows the percentage of blocked lightpaths for the maximum load case ρ=1. We are interested in this magnitude, since it is the amount of traffic we cannot carry because of the add/drop contention in the nodes with add/drop contention factor C=1.

TABLE IV. LIGHTPATH BLOCKING (%) AT MAXIMUM LOAD. C=1.

$\|W\|$	*Protection type*	Internet2	NSFNET	*cost266*	*atlanta*
20	Unprot.	0 %	0 %	0 %	0 %
	1+1 link	0 %	0 %	0 %	0 %
	1+1 link-node	0 %	0 %	0 %	0 %
40	Unprot.	0.4 %	0.2 %	0 %	0 %
	1+1 link	0 %	0 %	0 %	0 %
	1+1 link-node	0 %	1.3 %	0 %	0 %
80	Unprot.	0 %	0.1 %	0.1 %	0 %
	1+1 link	0 %	1.8 %	0.4 %	0 %
	1+1 link-node	0 %	1.8 %	2.5 %	0 %

Naturally, the lightpath blocking at the maximum load, equals 0% in the cases for which a 100% maximum network throughput was obtained. For the rest of the cases, results show that having a network infrastructure based on ROADMs with contention factor C=1, produced a blocking below 2.5%. Interestingly, the blocking is below 0.5% in all the tests of unprotected networks.

C. *Algorithm time complexity*

This section is devoted to give some insight on the time complexity of the heuristic algorithm presented. As described in Section III.B, the execution time of the heuristics can be controlled by the parameter L_{max}, which limits the number of lightpaths that are jointly optimized within an iteration, by the ILP of Procedure $P2$. Table V reports the execution times of the algorithm (in minutes), for the cases with load factor ρ=1. Blank cells are printed for those tests for which the execution time was below one minute.

TABLE V. EXECUTION TIME (MINUTES) OF THE HEURISTIC ALGORITHMS

			Internet2				NSFNET				*cost266*				*atlanta*			
L_{max}			15	30	60	90	15	30	60	90	15	30	60	90	15	30	60	90
$\|W\|$	P	C																
20	I	1								2								
		2												2				
	II	1			2	2							2	2				
		2			2	2							2	2				
	III	1			2	2							2	2				
		2			2	2							2	2				
40	I	1										2	2	4				
		2								2	2	2	4	4				
	II	1			2	37			5	60			2	6				
		2			2	3			2	7			2	2				
	III	1				25			8	40			2	7				
		2				2			2	8			2	7				
80	I	1					2	2	2	2	5	6	8	11				
		2					2	2	2	3	6	9	12	21				
	II	1								9	3	3	5	8				2
		2								5	3	4	6	7				2
	III	1								10	3	7	6	8				2
		2								4	4	8	15	8				2

As can be seen, the running times are moderate in all the cases (usually less than a few minutes), and always below 1 hour. These are satisfactory times for offline network planning algorithms. Execution times increase with higher values of L_{max}, higher number of wavelengths $|W|$, and for the NSFNET and cost266 topologies. The dependence with parameters L_{max} and $|W|$ is logical, since both strongly increase the number of decision variables and constraints in the ILP of procedure $P2$, which dominates the total execution time. The dependence of the algorithm time complexity with the contention factor and protection type is not significant. Some outliers appeared in the case C=1, with tests for which the execution time exceeded the average. These effects are common in ILP solvers, and are caused by the heuristic decisions taken by the solver (CPLEX) governing the branch-and-bound iterations for solving the ILP in procedure $P2$. Same effect explains the higher values observed in NSFNET topology executions, which despite having less than half the number of nodes and links than *cost266* topology, produced the highest execution times.

Finally, although not shown in Table V, the execution time varied in an approximately linear fashion with the network load. This is logical, since the number of iterations in the algorithm completed is given by rounding up the number of lightpaths in the demand, which linearly grows with load factor, divided by the L_{max} parameter.

V. CONCLUSIONS

In this paper, we study the performance of transparent optical networks equipped with directionless ROADMs, with respect to the add/drop contention factor C of the nodes. This factor is defined as the maximum number of lightpaths that can be added or dropped in a node using the same wavelength. We investigate the static planning of the network, considering the unprotected and 1+1 protected cases. Results are of application for both colored and colorless nodes. An ILP model and a heuristic algorithm have been presented to solve the offline ADCA-RWA (Add/Drop Contention Aware RWA) planning problem, investigated for the first time in this paper. Extensive tests are completed. In all the cases studied, a contention factor C=2 sufficed to provide the same blocking performance as contentionless ($C=\infty$) nodes. A factor C=1 was also sufficient in many scenarios. In the rest of the C=1 problem instances, the lightpath blocking observed was marginal: below 0.5% in the unprotected networks, and below 2.5% in the 1+1 protected networks. In summary, in the tests conducted, nodes with a contention factor C=1 produced in the worst case a minor performance degradation with respect to contentionless nodes. These results are of direct application to the design of directionless ROADM architectures.

REFERENCES

[1] J. Berthold, A. A. M. Saleh, L. Blair, and J. M. Simmons, "Optical Networking: Past, Present, and Future", *IEEE 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] CoAdna Photonics.Available: http://www.coadna.com/.

[4] A. Neukermans and R. Ramaswami, "MEMS technology for optical networking applications", *IEEE Communications Magazine*, vol. 39, no. 1, pp. 62-69, Jan. 2001.

[5] CALIENT Technologies. Available: http://www.calient.net.

[6] P. Roorda and B. Collings, "Evolution to colorless and directionless ROADM architectures", in *Proc. of Optical Fiber Communication/National Fiber Optic Engineers Conference 2008*, San Diego (US), Feb. 2008.

[7] J. Chen, J. Jacob, C. Santivanez, J. Ho and K. Rauschenbach, "En route to groupin-constraint free, colorless directionless ROADMs", in *Proc. of Optical Fiber Communication/National Fiber Optic Engineers Conference 2010*, San Diego (US), Mar. 2010.

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

[9] 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, Jul. 2006.

[10] 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. of Photonics in Switching*, Crete, Oct. 2006.

[11] S. Thiagarajan, L. Blair and J. Berthold, "Direction-independent add/drop access for multi-degree ROADMs", in *Proc. of Optical Fiber Communication/National Fiber Optic Engineers Conference 2008*, San Diego (US), Feb. 2008.

[12] P. N. Ji and Y. Aono, "Colorless and directionless multi-degree reconfigurable optical add/drop multiplexers", in *Proc. of 19th Wireless and Optical Communications Conference* (WOCC 2010), Shaghai (China), May 2010.

[13] P. Roorda and B. Collings, "Evolution to colorless and directionless ROADM architectures", in *Proc. of Optical Fiber Communication/National Fiber Optic Engineers Conference 2008*, San Diego (US), Feb. 2008.

[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. of Communications Systems and Networks 2009*, Bangalore (India), Jan. 2009.

[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. of Communications Systems and Networks 2010*, Bangalore (India), Jan. 2010.

[16] 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.

[17] 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.

[18] O. Turkcu and S. Subramaniam, "Performance of optical networks with limited reconfigurability", *IEEE/ACM Transactions on Networking*, vol. 17, no. 6, pp. 2002-2013, Dec. 2009.

[19] M. D. Feuer, S. L. Woodward, P. Palacharla, X. Wang, I. Kim, D. Bihon, "Intra-node contention in dynamic photonic networks", *IEEE Journal of Lightwave Technology*, vol. 29, no. 4, pp.529-535, February 2011.

[20] C. S. R. Murthy and G. Mohan, *WDM Optical Networks (Concepts, Design and Algorithms)*. Prentice Hall PTR, Upper Sadle River, 2002.

[21] MatPlanWDM tool v.0.60. Available: http://www.ait.upct.es/~ppavon&matplanwdm.

[22] K. Holmström, A. O. Göran, and M. M.Edvall, "User's Guide for TOMLAB/CPLEX v11.2", 2009.

[23] Internet 2 Global Research Network Operations Center, Web Site, [Online], Available: http://www.abilene.iu.edu/.

[24] R. Ramaswami, K.N. Sivarajan, "Design of Logical Topologies for Wavelength-routed Optical Networks," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 840–851, Jun. 1996.

[25] COST266 reference network. Available: http://sndlib.zib.de/coredata.download.action?objectName=cost266&format=native&objectType=network

[26] Atlanta reference network. Available: http://sndlib.zib.de/coredata.download.action?objectName=atlanta&format=native&objectType=network

[27] SNDlib (library for Survivable fixed telecommunication Network Design). Available: http://sndlib.zib.de/