Joint Online Routing, Wavelength Assignment and Regenerator Allocation in Translucent Optical Networks

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***Abstract*—In translucent (or managed reach) WDM optical networks, regenerators are employed at specific nodes. Some of the connections in such networks are routed transparently, while others have to go through a sequence of 3R regenerators that serve as "refueling stations" to restore their quality of transmission (QoT). We extend an online multicost algorithm for transparent networks presented in our previous study [1], to obtain an IA-RWA algorithm that works in translucent networks and makes use, when required, of the regenerators present at certain locations of the network. To characterize a path, the algorithm uses a multicost formulation with several cost parameters, including the set of available wavelengths, the length of the path, the number of regenerators used, and noise variance parameters that account for the physical layer impairments. Given a new connection request and the current utilization state of the network, the algorithm calculates a set of non dominated candidate paths, meaning that any path in this set is not inferior with respect to all cost parameters than any other path. This set consists of all the cost-effective (in terms of the domination relation) and feasible (in terms of QoT) lightpaths for the given source-destination pair, including all the possible combinations for the utilization of available regenerators of the network. An optimization function or policy is then applied to this set in order to select the optimal lightpath. Different optimization policies correspond to different IA-RWA algorithms. We propose and evaluate several optimization policies, such as the most used wavelength, the best quality of transmission, the least regeneration usage, or a combination of these rules. Our results indicate that in a translucent network the employed IA-RWA algorithm has to consider all problem parameters, namely, the QoT of the lightpaths, the utilization of wavelengths and the availability of regenerators, to efficiently serve the online traffic.**

***Index Terms*—Impairment-aware routing and wavelength assignment (IA-RWA) algorithms, multicost algorithms, physical layer impairments, translucent networks, quality of transmission, wavelength routed WDM networks, 3R regenerators.**

I. Introduction

In Wavelength Division Multiplexing (WDM) optical networks, data are transmitted in the form of optical pulses. The optical pulses are transported over (semi-) permanent circuits, called *lightpaths*. A lightpath is realized by determining a path (that may span multiple fiber links) between the source and the destination nodes and allocating a free wavelength on all the links of the path. The selection of the path and the wavelength to be used by a lightpath is an important optimization problem, known as the *Routing and Wavelength Assignment* (abbreviated RWA) problem. The quality of the RWA solutions determine the number of customers (connections) that are accommodated or rejected (in case of congestion) for a given network topology and a given number of available wavelengths, and, thus, it is important to propose efficient RWA algorithms.

In *opaque* (point-to-point) optical networks the signal is regenerated at every intermediate node via optical-electronic-optical (OEO) conversion. As the size of opaque networks increases, network designers and architects have to consider more electronic terminating and switching equipments, which both contribute to cost (CAPEX), heat dissipation, energy consumption, difficult upgradability, physical space requirements, and operation and maintenance costs (OPEX). The current trend clearly shows an evolution towards low-cost and high capacity all-optical networks that do not utilize OEO conversion, taking advantage of the significant changes that optical networking has undergone in recent years. Initially, the cost of an opaque network can be reduced by moving towards a network where OEO is only performed at some nodes. The corresponding network is usually referred to as a *translucent* (or *managed reach*) network. If the network does not employ OEO conversion (and therefore no regeneration is performed at any step), it is referred to as a *transparent* network.

In a transparent or a translucent WDM network, where the signal of the lightpaths remains in the optical domain for more than one link, signal transmission is significantly affected by physical limitations of fibers and optical components. For the remainder of this paper we will refer to such phenomena as *physical layer impairments* (PLI). Some of the more significant PLIs include linear effects such as amplified spontaneous emission noise (ASE), chromatic dispersion (CD), polarization mode dispersion (PMD), filter concatenation (FC) and nonlinear effects such as self- and cross-phase modulation (SPM, XPM), and four-wave-mixing (FWM), etc. All these PLIs may degrade the received signal quality to the extent that the bit-error rate (BER) at the receiver may be so high that signal detection may be infeasible for some lightpaths. For the remainder of this paper we will refer to such a phenomenon as *physical-layer blocking*, as opposed to the *network-layer blocking*, which is due to the rejection of new connection when there are no available wave-

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lengths to serve it. The existence of PLIs necessitates the introduction of the quality of transmission (QoT) as an additional parameter during the RWA process. The RWA problem, when considering the PLIs, is usually denoted in the literature as Impairment-Aware (IA-) RWA problem [2].

Note that although physical- and network-layer blockings are generated by different phenomena, in reality they are strongly related. Typically, in order to confront physical impairments the IA-RWA algorithm spreads the lightpaths in the available wavelength space so that the interference among lightpaths is reduced. However, this may result in an increase in the network-layer blocking, due to bad usage of the available wavelengths. Clearly there is a tradeoff between physical- and network-layer blocking, and the IA-RWA problem can be viewed as a cross-layer optimization problem between the network and the physical layers.

Intelligent IA-RWA algorithms cannot always mitigate the effects of physical impairments, especially in large networks involving long geographical distances. In these networks the only satisfactory method to overcome the physical impairments is re-amplifying, re-shaping and re-timing of optical pulses (referred to as 3R regeneration). Note that 3R regeneration is usually performed through opto-electo-optical OEO conversion using a free pair of transceiver-receiver (add-drop ports) connected back-to-back. Moving from opaque networks towards transparent or translucent networks would mean that the ability to perform regeneration is not going to be available at every node. In a translucent network, where regenerators are available at some but not all locations, a long end-to-end lightpath that needs regeneration at some intermediate node(s) can be set up in a multi-segment manner, so that the connection is split into two or more consecutive transparent lightpath-segments, referred to as sub-paths. The regenerator at the end of each lightpath-segment serves as a "refueling station" that restores signal quality. This makes translucent optical networks [3] to be a more appropriate and realistic solution at present and in the near future. Thus, in translucent networks, the IA-RWA algorithm, apart from deciding the paths and the wavelengths for serving the connection requests, it also decides which connections should be served using regenerators and the exact sequence of regenerators such connections are going to use.

Our previous study in translucent WDM networks was presented in [4], where we considered the IA-RWA problem as well as the regenerator placement and allocation problems for *static* (offline) traffic demands. The algorithm of [4] applies to the design (planning) phase of the translucent network, where it is given as input the network topology and a traffic matrix. The algorithm selects the 3R regeneration sites and the number of regenerators that need to be deployed on these sites, so that the RWA solution, also returned by the algorithm, consists of lightpaths with acceptable quality of transmission (QoT) performance. To address the joint IA-RWA and regenerator assignment problem we decomposed it into two parts. We formulated the problem of regenerator placement and regenerator assignment, as a virtual topology design problem, and addressed it using various algorithms, ranging from a series of integer linear programming (ILP) formulations to simple greedy heuristic algorithms. Once the sequence of regenerators to be used by the non-transparent connections has been determined, we transformed the initial traffic matrix by replacing non-transparent connections with a sequence of transparent connections that terminate and start at the specified regeneration intermediate nodes. Using the transformed matrix we then applied an offline IA-RWA algorithm designed for transparent networks.

In this paper we focus on the operational phase of a translucent network and present a dynamic (online) IA-RWA. In the online traffic case, there is no traffic matrix that has to be served, but connection requests arrive dynamically, over an infinite time horizon, and have to be served on demand, one by one. Moreover, we assume a given placement of regenerators in the network, performed by an appropriate algorithm similar e.g., to that of [4]. We present an online multicost IA-RWA algorithm for translucent WDM networks as an extension of our study for transparent networks [1]. The online IA-RWA problem for translucent networks is considerably more difficult than the corresponding problem for transparent networks, since it also includes the problem of selecting the regenerators that may have to be used for serving a connection.

The remaining of this paper is organized as follows. In Section II we report on previous work regarding the RWA problem in translucent networks. In Section III, we present our quality of transmission model. In Section IV, we present the proposed multicost online IA-RWA algorithm for translucent networks. We carried out simulations reported in Section V to evaluate the performance of the proposed algorithms that use different optimization policies. Section VI concludes our paper.

II. Previous Work

Several studies address the RWA problem for translucent optical networks, proposing algorithms for regenerator placement and RWA with regenerator allocation. The authors in [6] review a range of translucent optical networks issues. In general, several problems need to be addressed when planning and operating translucent networks, such as transparent island division, opaque node placement, 3R regenerator allocation and routing and wavelength assignment. The first three issues are related to translucent network planning and are specific to each type of translucent network, and the fourth issue is common to the operation of all types of translucent networks. An algorithm can address these issues separately or jointly.

In [14], the authors address the problem of designing a translucent network by proposing several regenerator placement algorithms assuming information on the future network traffic patterns is available. In [5] a large-scale network is divided into several islands of transparency or optically transparent domains. Within the same island, a lightpath can transparently reach any other node without intermediate signal regeneration. For communication across islands, regeneration nodes located at the island boundaries are used to perform 3R regeneration on the crossing connections. Given the network topology and the maximum diameter of a transparent island, authors in [7] propose an ILP (Integer Linear Programming) formulation, for partitioning the topology into the smallest number of transparent sub-networks. Also a greedy heuristic partitioning algorithm is proposed.

The authors in [8] first propose a simple heuristic for sparse regenerator placement and then present a two-dimensional Dijkstra RWA algorithm for translucent optical networks, which takes as input the locations of the regenerators and a maximum transparent distance parameter and produces as output the paths and wavelengths that will be used to serve a new connection. A lightpath whose length exceeds the maximum transparent distance bound is considered infeasible in the model assumed in [8]. In [13], the problem of maximizing the number of successfully established connections, under a constraint on the maximum transparent length, is formulated as a mixed-integer linear program (MILP). Since MILP is NP-hard, the authors also propose a heuristic algorithm. However, [13] does not consider impairment effects other than the transparent length. A quality of transmission (QoT) based heuristic algorithm for IA-RWA in translucent optical networks is presented in [15]. In the first phase of this algorithm, a random search heuristic RWA algorithm is used, while in the second phase, regeneration placement is performed after estimating the BER of the lightpaths chosen in the first phase.

Approaches for dynamic resource allocation and routing are considered in [9] and [10], where spare transceivers (transmitter-receiver pairs or add-drop ports connected back-to-back) at the nodes are used to regenerate signals. Every node with a spare transceiver can become a potential regenerator. A Max-spare algorithm for selecting the regeneration nodes to be used by a new connection is proposed in [11] and compared to a Greedy algorithm used in conjunction with a wavelength-weighted and a length-weighted RWA algorithm. In [12], two online RWA algorithms for translucent networks with sparse regenerator placement are presented. IA-RWA algorithms that assume worst-case physical transmission penalties corresponding to a fully loaded system, or that take into account the current network utilization state and the actual number of active channels, are also investigated. In [16] authors propose a suite of dynamical routing schemes. Dynamic allocation, advertisement and discovery of regeneration resources are used to support the sharing of transmitters and receivers between regeneration and access functions.

The novelty of our online IA-RWA algorithm for translucent networks presented in this paper, compared to all the other works previously presented, is that our algorithm calculates all the feasible lightpaths between the given source to the given destination, including all the possible combinations for the utilization of the available regenerators of the network. In order to do so and also have an algorithm that runs in low and acceptable time, during the execution of the algorithm we use an appropriate domination relationship to reduce the path space and also prune sub-paths that have unacceptable QoT performance. Once the algorithm calculates the possible candidate lightpaths for source-destination pair, it can select the one that optimizes any given optimization function or policy. To the best of our knowledge, the algorithm presented in this paper is the only online IA-RWA algorithm for translucent networks that addresses optimality issues, compared to heuristic approaches previously presented in the literature. Note that some heuristic approaches may perform as well as the described algorithm, but can be reproduced by the proposed algorithm by defining appropriate optimization policies. Our focus is not only to find a specific optimization policy that minimizes blocking (this would probably depend on the network, traffic and physical layer parameters), but to propose a general algorithm, a "framework", to evaluate different optimization policies.

III. Quality of Transmission

Among a number of measurable optical transmission quality attributes, such as optical power, OSNR, CD, PMD, the Q-factor appears to be more suitable as a metric to be integrated in an RWA algorithm, due to its monotonic relation to the BER [20]. The Q-factor is sensitive to all forms of BER impacting impairments and is related (assuming Gaussian shaped noise) to the system's BER through the relation:

$$\mathrm{BER}(Q) = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

where $\mathrm{erfc}(\,)$ denotes the complementary error function. The higher the value of the Q-factor, the smaller the BER is and the better the quality of the signal.

The Q-factor of a lightpath (p, w), that is, wavelength w on path p, is given by:

$$Q_p(w) = \frac{I_{`1',p}(w) - I_{`0',p}(w)}{\sigma_{`1',p}(w) + \sigma_{`0',p}(w)} = \frac{I_{`1',p}(w)}{\sigma_{`1',p}(w) + \sigma_{`0',p}(w)} \quad (1)$$

where $I_{`1'}$ and $I_{`0'}$ are the mean values of electrical voltage of signal 1 and of signal 0, respectively, and $\sigma_{`0'}$ and $\sigma_{`1'}$ are their standard deviations, at the input of the decision circuit at the destination (end of path p), assuming a given type of receiver with a known electrical bandwidth.

In the approach that we have adapted in this study for measuring QoT performance $I_{`1',p}(w)$ depends on the transmitter's power, the gains and losses of the amplifiers and links over the path, and the so called "eye impairments", namely, SPM/CD, PMD and FC. The remaining physical impairments are considered as noise or noise-like and must be included in the calculation of the standard deviations $\sigma_{`0',p}(w)$ and $\sigma_{`1',p}(w)$. Thus, for the electrical noise variances of lightpath (p, w) we have:

$$\begin{aligned}\sigma^2_{`1',p}(w) &= \sigma^2_{\mathrm{ASE},`1',p}(w) + \sigma^2_{\mathrm{XT},`1',p}(w) + \sigma^2_{\mathrm{XPM},`1',p}(w) \\ &\quad + \sigma^2_{\mathrm{FWM},`1',p}(w) \\ \sigma^2_{`0',p}(w) &= \sigma^2_{\mathrm{ASE},`0',p}(w) + \sigma^2_{\mathrm{XT},`0',p}(w) + \sigma^2_{\mathrm{FWM},`0',p}(w)\end{aligned}$$

where $\sigma^2_{\mathrm{ASE}}, \sigma^2_{\mathrm{XT}}, \sigma^2_{\mathrm{XPM}}$, and σ^2_{FWM}, are the electrical noise variances due to ASE, XT, XPM, and FWM, respectively. Note that XT, XPM, and FWM depend on the utilization of the other wavelengths. Moreover, XPM and FWM are transmission impairments generated in the fiber, while XT is related to the nonideal switching fabric of the optical cross-connects (OXC). In what follows, by the term "link" we will refer to a link and the OXC switch that is connected at its end.

In the general case, the Q-factor of a lightpath cannot be calculated directly by the Q-factors of the links that comprise it. In order to estimate the Q-factor of a lightpath we perform the following calculations that are based on the noise characteristics of the links that comprise the lightpath and the eye impairments of the end-to-end route.

We assign to each link parameters that correspond to the electrical noise variances of all noise or noise-like impairments. These link-related parameters can be added over a path, after accounting for the gains and losses of the amplifiers and the fiber segments over this path. More specifically, for a path p consisting of links $l = 1, 2, \ldots, k$ with known electrical noise variances $\sigma^2_{\mathrm{ASE},`1',l}(w)$, $\sigma^2_{\mathrm{ASE},`0',l}(w)$, $\sigma^2_{\mathrm{XT},`1',l}(w)$, $\sigma^2_{\mathrm{XT},`0',l}(w)$, $\sigma^2_{\mathrm{XPM},l}(w)$, $\sigma^2_{\mathrm{FWM},`1',l}(w)$ and $\sigma^2_{\mathrm{FWM},`0',l}(w)$ per wavelength w, and known gains or losses $G_l(w)$ (G_l is typically expressed in dB and accounts for the losses of the fiber segments and the components of the link l and the ending OXC, and the gains of the inline amplifiers of the link l and the ending OXC), we have

$$\sigma^2_{`1',p}(w)=\sum_{l=1}^{k}\left(\sigma^2_{`1',l}(w)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right)= \sum_{l=1}^{k}\left(\left(\sigma^2_{\mathrm{ASE},`1',l}(w)+\sigma^2_{\mathrm{XT},`1',l}(w)+\sigma^2_{\mathrm{XPM},`1',l}(w)+\sigma^2_{\mathrm{FWM},`1',l}(w)\right)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right),$$

$$\sigma^2_{`0',p}(w)=\sum_{l=1}^{k}\left(\sigma^2_{`0',l}(w)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right)= \sum_{l=1}^{k}\left(\left(\sigma^2_{\mathrm{ASE},`0',l}(w)+\sigma^2_{\mathrm{XT},`0',l}(w)+\sigma^2_{\mathrm{FWM},`0',l}(w)\right)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right).$$

Note that the electrical noise variances from each link grow with the square of the remaining gain/loss up to the receiver.

The eye penalty impairments do not change appreciably with the utilization of the other wavelengths, but depend mainly on the selected path. More specifically, the PMD penalty depends on the path length and is independent of the utilization of the other wavelengths. The FC penalty depends on the number of filters of the path. Typically, in a transparent WDM network, an OXC switch is designed to have two filters, and, thus, to calculate the FC effect we only have to count the number of OXCs (or hops) on the path. Finally, the effect of SPM/CD is the most complicated eye impairment to calculate, and it usually has to be estimated for an end-to-end path. However, a transparent optical network is typically designed so that the effect of SPM/CD is greatly reduced at the end of each link using pre-compensation techniques.

Since the eye impairments and the transmitters' power and amplifiers/links gains/losses do not change vastly when a new connection is established or released, we can pre-calculate the aforementioned effects so as to obtain $I_{`1',p}(w)$ for all candidate lightpaths and store them in a database. Even though the temperature and other parameters may affect these values, we assume that a periodic process keeps this database up to date. Another approach is to use quick and efficient models to calculate $I_{`1',p}(w)$ as the algorithm is executed.

IV. Multicost Algorithms for Translucent Networks

In this section we extend the Sigma-Cost algorithm presented in [1] for transparent networks so as to operate in translucent networks and make use of the 3R regenerators available in such networks.

We consider a WDM network represented by a connected graph G $= (N, L)$. N denotes the set of nodes (switches), while L denotes the set of (point-to-point) single-fiber links. Each link $l \in L$ supports m wavelengths, $\lambda_1, \lambda_2, \ldots, \lambda_m$. We assume that 3R regenerators are sparsely placed in the network, forming pools of regenerators at some nodes. We let $R \subseteq N$ be the set of nodes that are equipped with at least one 3R regenerator and $n(r)$ be the number of available regenerators at node $r \in R$. We assume that all nodes have access to a central database, which holds physical layer related parameters, such as $I_{`1',p}(w)$ and $\sigma^2_{\mathrm{ASE},`1',l}(w)$, $\sigma^2_{\mathrm{ASE},`0',l}(w)$, $\sigma^2_{\mathrm{XT},`1',l}(w)$, $\sigma^2_{\mathrm{XT},`0',l}(w)$, $\sigma^2_{\mathrm{XPM},l}(w)$, $\sigma^2_{\mathrm{FWM},`1',l}(w)$ and $\sigma^2_{\mathrm{FWM},`0',l}(w)$, etc, or can calculate them in a timely efficient manner (please refer to Section III). The cost of updating this database, or the cost of distributing this information is outside the scope of the current work.

In the online (dynamic) version of the IA-RWA problem we assume that connection requests arrive at random time instants and are served one by one by the algorithm. So, along with the network G the inputs to the algorithm are: (i) the source node $s \in N$ of the connection, (ii) the destination $d \in N$, (iii) the utilization state of the network at the time of the request, including the wavelength and regeneration allocation.

To serve a connection request, the algorithm finds either a transparent lightpath from the source to the destination node, or uses a sequence of transparent lightpaths (sub-paths) between the source and a regenerator, between regenerators and, finally, between a regenerator and the destination node. In both cases the selected lightpath(s) must have acceptable quality of transmission (QoT) performance, as measured in terms of their Q-factors [(1)]. The objective of the proposed algorithm is to jointly maximize the number of established connections and to minimize the number of required regenerators, while taking into account linear and non-linear physical constraints.

We assume that a 3R equipped node is capable of restoring the signal quality of a lightpath but also performs wavelength conversion if desired. Fig. 1 shows an example of a pan-European translucent optical network, where some nodes (noted by the R symbol) are equipped with 3R regenerators. A connection request between the source-destination pair (s, d) can be served using a path consisting of five transparent sub-paths: $s - r_3, r_3 - r_{18}, r_{18} - r_{12}, r_{12} - r_{10}$, and $r_{10} - d$. Each of these five sub-paths can utilize a different wavelength (depicted with different colors in the figure). This is because a regenerator can be used to restore the signal quality and reduce physical-layer blocking, but also can be used as a wavelength converter in order to reduce the network-layer blocking.

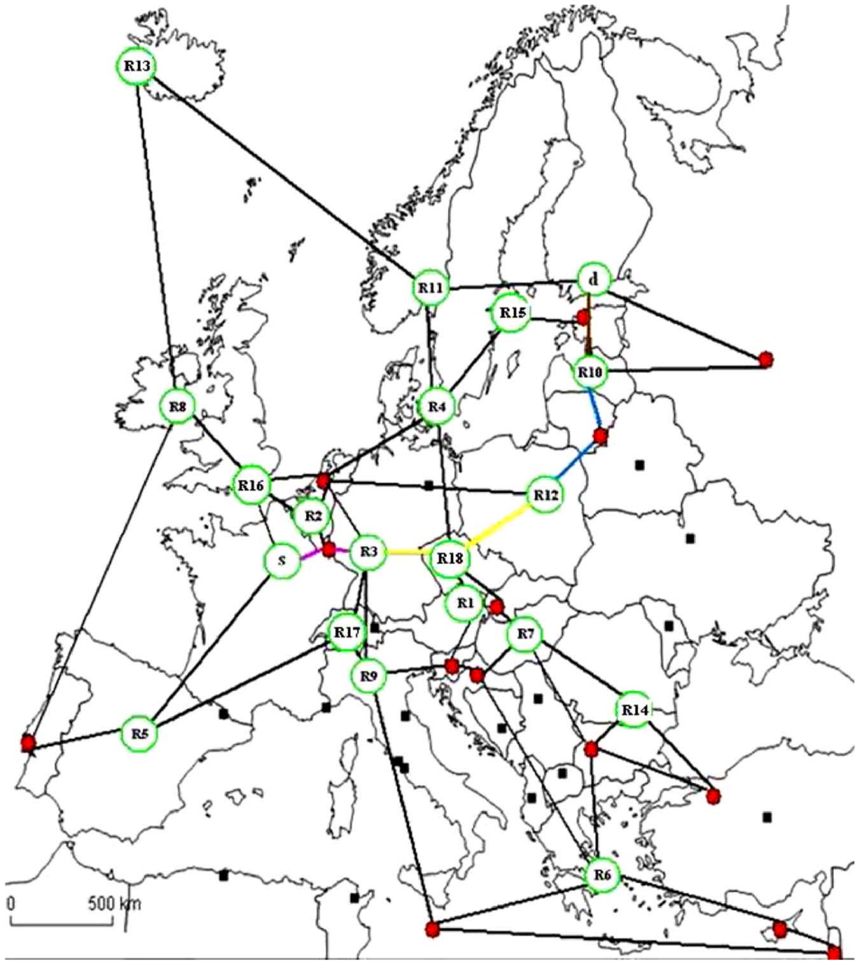

Fig. 1. Geant-2 network topology with 18 regeneration sites. The established path between the source-destination pair (s, d) is broken into four transparent sub-paths: $s - r_3, r_3 - r_{18}, R_{18} - r_{12}, r_{12} - r_{10}$ and $r_{10} - d$. Each of these five sub-paths can use a different wavelength.

A. Link and Path Vectors

1) Cost Vector of a Link: The algorithm we propose for translucent networks takes into account the current utilization of the network, which changes dynamically as new connections are established or released, in order to calculate the noise variances due to impairments of all the links of the network. In particular, each link is assigned a cost vector that contains (at least) $1 + 4 \cdot m$ cost parameters:

(i) the delay of the link d_l—or its length (scalar parameter),
(ii) a vector $\overline{G_l} = (G_l(1), G_l(2), \ldots, G_l(m))$ that records (in dB) the gain/loss for each of the wavelengths of link l,
(iii) a vector $\overline{\sigma^2_{1',l}} = (\sigma^2_{1',l}(1), \sigma^2_{1',l}(2), \ldots, \sigma^2_{1',l}(m))$ that records the noise variances of signal 1 for each of the wavelengths of link l,
(iv) a vector $\overline{\sigma^2_{0',l}} = (\sigma^2_{0',l}(1), \sigma^2_{0',l}(2), \ldots, \sigma^2_{0',l}(m))$ that records the noise variances of signal 0 for each of the wavelengths of link l, and
(v) the utilization of wavelengths in the form of a Boolean vector $\overline{W_l} = (w_l(1), w_l(2), \ldots, w_l(m))$. We set $w_l(i)$ equal to 0 (false) when the wavelength λ_i is occupied, and equal to 1 (true) when λ_i is free (available).

Note that the vectors $\overline{\sigma^2_{1',l}}, \overline{\sigma^2_{0',l}}$ and $\overline{W_l}$ have all size equal to m. The cost vector characterizing a link l is then given by

$$V_l = \left(d_l, \overline{G_l}, \overline{\sigma^2_{1',l}}, \overline{\sigma^2_{0',l}}, \overline{W_l}\right).$$

In following subsections we describe how the cost vector of a path is obtained from the cost vectors of the links that comprise it. In order to do so, it is sufficient to describe how a path with a known cost vector is extended by adding a new link at its end.

The most general case is when the end node of the path that is extended contains an available 3R regenerator. This regenerator may or may not be used to restore signal quality. Therefore, when extending such a path, two paths (options) are created, both of which have to be considered for the remaining of the algorithm. One of them makes use of the regenerator, while the other does not. The impairment parameters of the two paths will naturally be different, since the path that uses the regenerator eliminates the effects of all impairments up to that point (up to the regenerator), while the path that does not make use of the regenerator does not restore its signal quality. The notation and procedures required to consider these two cases are described in the following two subsections.

2) Cost Vector of a Path Without Regeneration: Similarly to a link, a path is characterized by a cost vector with $1+4\cdot m$ parameters, in addition to the list $*p$ of links that comprise the path and the list $*r$ of the regenerators *used* by the path. We denote the cost vector of path p as

$$V_p = \left(d_p, \overline{G_p}, \overline{\sigma^2_{1',p}}, \overline{\sigma^2_{0',p}}, \overline{W_p}, *p, *r\right).$$

Since no regenerators are used by this path, the list $*r$ is empty. The cost vector of path p can be calculated by the cost vectors of the links $l, l=1,2,\ldots k$, comprising it as follows:

$$V_p = \left(\sum_{l=1}^{k} d_l, \sum_{l=1}^{k} \overline{G_l}, \sum_{l=1}^{k}\left(\overline{\sigma^2_{1,l}}\cdot \prod_{i=l+1}^{k} 10^{2\cdot\overline{G_i}/10}\right),\right.$$
$$\sum_{l=1}^{k}\left(\overline{\sigma^2_{0,l}}\cdot \prod_{i=l+1}^{k} 10^{2\cdot\overline{G_i}/10}\right),$$
$$\left.\mathop{\&}_{l=1}^{k} \overline{W_l}, *p=(1,2,\ldots,k), *r=\oslash\right),$$

where the operator & denotes the bitwise AND operation. Note that all operations between vectors have to be interpreted component-wise (that is, separately for each wavelength).

3) Cost Vector of a Path With Regeneration at Intermediate Nodes: For a path p that contains and uses regenerator(s) located at some intermediate nodes, the cost vector of that path is transformed into a matrix. Assuming that the path p up to node n uses z regenerators, we denote by $*r=(r_1,r_2,\ldots,r_z)$ the list of regenerator identifiers used by the path. Then, each row of the path's cost matrix V_p corresponds to the cost vector of a sub-path between the source and the first regenerator (s,r_1), or two regenerator nodes (r_i,r_j), or the last regenerator and the last node $n(r_z,n)$. In particular, the first row of the cost matrix corresponds to the last transparent sub-path, the second row of the matrix corresponds to the second to last transparent sub-path, and so on, up to the last row of the matrix that corresponds to the sub-path between the source node and the first regenerator.

To be more specific, assuming path p ending at node n we denote the cost matrix of p that utilizes one or more regenerator nodes as

$$V_p = \left[\overline{d_p}, \overline{\overline{G_p}}, \overline{\overline{\sigma^2_{1',p}}}, \overline{\overline{\sigma^2_{0',p}}}, \overline{\overline{W_p}}, *p, *r\right], \text{ where}$$

(i) $\overline{d_p} = d_p(i) = (d_{p(r_z-n)};\ldots;d_{p(r_1-r_2)};d_{p(s-r_1)})$ is a $z\times 1$ vector that records the delays (or, equivalently, the lengths) of the transparent sub-paths that comprise path p. Notation ';' denotes the introduction of a new row in the vector,

(ii) $\overline{\overline{G_p}}=\overline{G_p}(i)=(\overline{G_{p(r_z-n)}};\ldots;\overline{G_{p(r_1-r_2)}};\overline{G_{p(s-r_1)}})$ is a $z\times m$ matrix that records the gains of the sub-paths that comprise path p, where each row records the gain of each transparent sub-path,

(iii) $\overline{\overline{\sigma^2_{1',p}}}=\overline{\sigma^2_{1',p}}(i)=(\overline{\sigma^2_{1',p(r_z-n)}};\ldots;\overline{\sigma^2_{1',p(r_1-r_2)}};\overline{\sigma^2_{1',p(s-r_1)}})$ is a $z\times m$ matrix that contains the noise variances of signal 1 for each of the wavelengths, where each row corresponds to a transparent sub-path,

(iv) $\overline{\overline{\sigma^2_{0',p}}}=\overline{\sigma^2_{0',p}}(i)=(\overline{\sigma^2_{0',p(r_z-n)}};\ldots;\overline{\sigma^2_{0',p(r_1-r_2)}};\overline{\sigma^2_{0',p(s-r_1)}})$ is a $z\times m$ matrix that contains the noise variances of signal 0 for each of the wavelengths, where each row corresponds to a transparent sub-path,

(v) $\overline{\overline{W_p}}=\overline{W_p}(i)=(\overline{W_{p(r_z-n)}};\ldots;\overline{W_{p(r_1-r_2)}};\overline{W_{p(s-r_1)}})$ is a Boolean $z\times m$ matrix, which plays a role similar to the role played by vector $\overline{W_l}$ in the transparent case; here, again each row of the matrix records the wavelength availability of each transparent sub-path of path p,

(vi) $*p=(1,2,\ldots,k)$ is the list of link identifiers that comprise path p and

(vii) $*r=(r_1,r_2,\ldots,r_z)$ is the list of regenerator identifiers used by the path.

Note that symbol i is used as an index to the rows $1,2,\ldots,z$ of the cost matrix, so that row i corresponds to the ith sub-path counting from the end of the path. Thus, element (i,j) of a matrix correspond to the jth wavelength of the ith sub-path.

From the above, we can deduce that the cost vector of a path that does not use the available regenerators (described in Section IV.A.2) is a special case of the cost vector (more appropriately, cost matrix) of a path that uses regeneration (described in this section). In particular, we can view the cost vector of a path that does not use regeneration as the cost matrix of a path that uses regeneration, having only a single row $(z=1)$. Based on this observation, we will use the same notation for both cases when no confusion can arise.

B. Algorithm's Description

The online Sigma-Cost IA-RWA algorithm that we propose for translucent WDM networks, is based on the multicost concept, and consists of two phases. In the first phase we compute a set of non-dominated paths for serving a connection, while in the second phase we use an appropriate optimization function (or selection policy) to choose one of the non-dominated paths. In what follows, the term "path" refers not only to the sequence of nodes followed, but also to the available wavelengths and the sequence of regenerators (if any) used by it. This information is carried as parameters in the cost vector of the path, along with the impairment-related cost parameters.

Phase 1: Computing the Set of Non-Dominated Paths P_{n-d}: For computing the set of candidate non-dominated paths P_{n-d}, our scheme uses the algorithm described in [17] and also used in [1], appropriately modified so as to account for the availability of regenerators at certain nodes. The main extensions that have to be made to the IA-RWA algorithm for transparent networks of [1] are related to the way a path p whose end node r has an available 3R regenerator is extended to obtain a longer path that also includes the outgoing link $l=(r,n)$ from the regeneration node r to next node n. In this case, two new candidate paths are created that consist of the same list of links $*p$, but utilize differently the regenerator located at node r. Fig. 2 illustrates this process. Let V_p be the cost vector of path p from source s up to node regenerator node r. When we add the cost

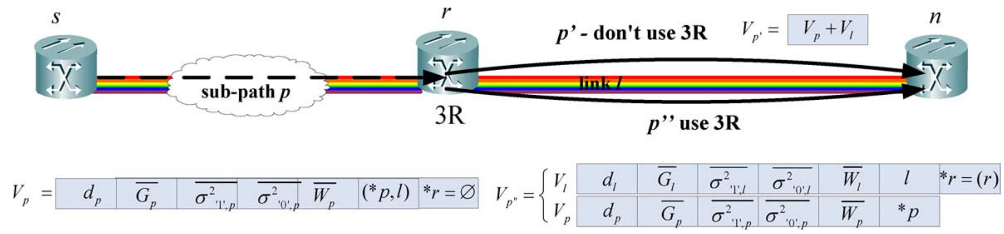

Fig. 2. Path cost vector bifurcation at a node r where a regenerator is available. A path p ending at node r, when extended so as to include link $l=(r,n)$, gives rise to two paths p' and p''. One of them makes use of the regenerator, while the other does not. The impairment parameters of the two paths will differ, since the path that uses the regenerator restores its signal quality, removing all impairments up to that point.

vector of link l, we create two paths. The first path p' is created with the assumption that the regenerator at node r is ignored (not utilized). In this case, we calculate the cost vector $V_{p'}$ by adding to the cost vector of path V_p the cost vector V_l of link l, as presented in Section IV.A.2. The second path p'' is created assuming that the regenerator at node r is utilized. In this case we formulate a cost matrix $V_{p''}$ that keeps both the cost vectors V_p and V_l, as presented in Section IV.A.3, without performing any operation between these two vectors. Note that if an available wavelength of path p has acceptable QoT up to node r, when forming path p'' its quality of transmission will not deteriorate further by adding the next link l. The process of extending further path p'' will continue using the cost vector of link l, as if a new (sub)-path starts from the regeneration node r. This way we formulate the "regeneration" of the signal by the 3R of node r. To sum up, two paths p' and p'' are created from node s to node n, both of which will have to be further considered in the remaining of the algorithm.

During the path's construction and before applying the non-domination relation (to be described in the subsequent paragraph), we check the Q-factor of available wavelengths to see if the paths can be extended further. In particular, for a path p, utilizing or not regenerator(s), we check if the available wavelengths of the last sub-path (marked by 1 in $\overline{W_p}(1)$) have acceptable Q-factor. To examine the Q performance, we use the cost vector/matrix V_p to obtain from its first row the vectors $\overline{\sigma_{`1',p}}(1)$ and $\overline{\sigma_{`0',p}}(1)$, and we also use the list of links $*p$ to obtain the power $I_{`1',p}$ through a database lookup or quick calculation. Then, by using (1) we calculate the Q-factor of each wavelength on the last sub-path, that is the vector/matrix $\overline{Q_p}(1)=(Q_p(1,1),Q_p(1,2),\ldots,Q_p(1,m))$. We finally check if the Q-factor of the available wavelengths is higher than a given threshold (recall that the higher the Q-factor, the better the signal quality is). For those wavelengths that do not exceed the given threshold we set the corresponding index of the utilization vector/matrix $\overline{W_p}$ equal to zero, making these wavelengths unavailable due to poor performance. In the end, we check if path p has at least one available wavelength for the last sub-path. If $\overline{W_p}(1)=\mathbf{O}$ (the all zero row/vector), path p is rejected.

When we extend a path and reach node n we apply the following domination relationship between the new path and the other paths already calculated by the algorithm that end at node n. The paths that are dominated are pruned so as to reduce the set of candidate paths and consequently the algorithm's execution time. In particular, in our multicost scheme for translucent networks, we will say that a path p_1 dominates a path p_2, with or without the presence of 3R's (notation: $p_1 > p_2$) **iff**

$$\sum_i d_{p_1}(i) \le \sum_i d_{p_2}(i) \text{ and } \overline{W_{p_1}}(1) \ge \overline{W_{p_2}}(1) \text{ and } \overline{Q_{p_1}}(1) \ge \overline{Q_{p_2}}(1) \text{ and } |{*r_{p_1}}| \le |{*r_{p_2}}|, \quad (2)$$

where $\overline{W_p}(1)$ and $\overline{Q_p}(1)$ is the wavelength utilization and Q vectors for all the wavelengths m of the latest sub-path of path p (corresponds to the first row of the cost matrix, if the path uses regeneration, or the single line of a cost vector, if the path does not use regeneration]. The "$\ge$" relationship for vectors $\overline{W_p}(1)$ and $\overline{Q_p}(1)$ should be interpreted component-wise, that is, separately for each wavelength. The domination operation also examines the number of regenerators $|{*r}|$ a path crosses and the relationship $|{*r_{p_1}}| \le |{*r_{p_2}}|$ means that p_2 uses more regenerators than p_1. Note that the domination between these paths is checked over the last transparent sub-path for the two paths. A different domination approach would be to check all the cost vectors of the sub-paths belonging to the two paths. In this case, if all sub-paths of path p_1 dominate all sub-paths of path p_2, then p_1 dominates p_2. This approach is expected to slightly improve the algorithm's performance (in terms of the QoT of the chosen paths) but would also increase the algorithm's complexity and its execution time.

When extending a path that crosses a regeneration node, the paths p' and p'' created (see Fig. 2) are non-dominated due to the way these paths are constructed. In particular, the noise variance of signal 1, $\overline{\sigma^2_{`1',p}}+\overline{\sigma^2_{`1',l}}$, for path p' is clearly larger than noise variances of signal 1, $\overline{\sigma^2_{`1',l}}$, for path p'', which means that $\overline{Q_{p'}} < \overline{Q_{p''}}$. On the other hand, the number of regenerators used by path p' is smaller than the number of regenerators used by path p'', therefore $|{*r_{p'}}| < |{*r_{p''}}|$ (please refer to Fig. 3). As a result, according to (2), the paths p' and p'' do not dominate each other, and thus both have to be further considered by the algorithm.

By definition, for the given source and destination pair, the non-dominated paths returned by the algorithm have at least one available wavelength. Moreover, the paths and available wavelengths have acceptable Q-factor performance, since lightpaths with unacceptable Q-factor were made unavailable during the process of the algorithm.

Phase 2: Choosing the Optimal Lightpath From the Set P_{n-d} of Non-Dominated Lightpaths: In the second phase of the algorithm we apply an optimization function or policy $f(V_p)$ to the cost vector V_p of each path $p \in P_{n-d}$. The function f yields a scalar cost that is used to select the optimal path and wavelength. When a path p uses regenerators, function f may penalize severely their use. The function f can be different for different connections, depending on their quality of service (QoS) requirements and on other (e.g., pricing) considerations. Note that the optimization function f applied to a cost vector has to be monotonic in each of the cost components. For example, it is natural to assume that it is increasing with respect to delay, noise variance, number of regenerators used, etc.

In its first phase, the algorithm has calculated the set of non-dominated paths P_{n-d}, which by definition includes all the paths from the given source to the given destination that have at least one available wavelength and acceptable QoT, including all the possible combinations with respect to the utilization of available regenerators of the network. The set of non-dominated paths P_{n-d} includes all the paths with a distinct cost that can affect the objective function f. Thus, under the monotonicity assumption on the optimization function, the optimum solution is bound to be in the set of paths P_{n-d} calculated by the algorithm. Note that using different optimization policies we obtain a series of different IA-RWA algorithms, and for each policy we can obtain the optimum as if we have used an algorithm specifically designed for this optimization objective.

In the context of this study, we have evaluated the following policies for selecting the optimal path from the set of non-dominated paths:

i) *Most Used Wavelength (MUW) policy*
Given the already established connections, we order the wavelengths in decreasing utilization order and choose the lightpath whose wavelength is most used. This approach is the well known "most used wavelength" algorithm [19] that has been found to exhibit good network performance, when the physical layer is error free. In order to compute the most used wavelength in a path that uses regenerators and consists of several transparent sub-paths, we compute the most used wavelength of each sub-path and then find the minimum of these most used wavelengths for all sub-paths. In this way every path is characterized by a single metric irrespectively of whether it is transparent or non-transparent. In the end if a path with more than one sub-paths is selected, then every sub-path may use a different wavelength (the most used one), based on the availability of the wavelengths in each sub-path. We should note that this approach does not differentiate between the Q-factors of the solutions, though all the candidate paths P_{n-d} and available wavelengths (lightpaths) have acceptable Q-factor. As a result, it is possible that the chosen lightpath has a Q value close to the threshold and may become infeasible when new connections are admitted; resulting in connection blocking or rerouting.

ii) *Best Q performance (bQ) policy*
From the available non-dominated paths we select the one that has the highest Q value. In case a path uses regenerators and consists of several transparent sub-paths, we calculate the minimum of the maximum Q-factor of these sub-paths. This approach does not consider the wavelength utilization in the network, making it more difficult for future connections to be served due to network-layer blocking.

iii) *Better Q and wavelength utilization (bQ-MUW)*
This approach is a combination of approaches (i) and (ii). We start by finding the highest Q value as in (ii). Then, from the set P_{n-d} of non-dominated paths we find the paths that have Q-factors close to this value (e.g., keeping the paths with Q-factor no less than 0.5 dB from the highest Q). From this set we finally select the path whose wavelength is used most in the network, similarly to (i).

iv) *Least Regenerators Usage and Most Used Wavelengths (LRU-MUW)*
We choose the non-dominated path(s) that use the fewest regenerators, and then apply the most used wavelength policy (i). This approach does not differentiate between the Q-factors of the solutions. As a result, it is possible that the chosen lightpath has a Q value close to the threshold, and may become infeasible when new connections are established.

v) *Fewer Regenerators Usage and Most Used Wavelengths (FRU-MUW)*
In this approach we start by finding the paths that use the fewest regenerators as in (iv). Then from the set P_{n-d} we find the paths that the number of regenerators they use, is equal to the lowest value plus a margin of some additional regenerators (e.g., keeping the paths with one or two additional regenerators). From this set we finally select the path whose wavelength is used most in the network, similarly to (i).

vi) *Least Regenerators Usage and best Q (LRU-bQ)*
We choose the non-dominated path(s) that use the smallest number of regenerators and then apply the best Q policy (ii).

vii) *Fewer Regenerators Usage and best Q (FRU-bQ)*
In this approach we start by finding the paths that use the fewest regenerators as in (iv). Then from the set P_{n-d} we find the paths that use a number of regenerators equal to the lowest value plus some margin of regenerators (e.g., keeping the lightpaths with two additional regenerators). From this set we finally select the lightpath that has the best Q performance, as in policy (ii).

viii) *Least Regenerators Usage and better Q and Most Used Wavelengths (LRU-bQ-MUW)*
This approach is a combination of policies (iii) and (iv). For each non-dominated path we choose the path that uses the fewest regenerators. As a second step, we find the highest Q value as in (ii). Then from the set P_{n-d} we find the paths that have Q-factors close to this value (e.g., keeping the paths with Q-factor no less than 0.5 dB from the highest Q). From this set we finally select the path whose wavelength is most used in the network, similarly to policy (i).

ix) *Fewer Regenerators Usage better Q and Most Used Wavelengths (FRU-bQ-MUW)*

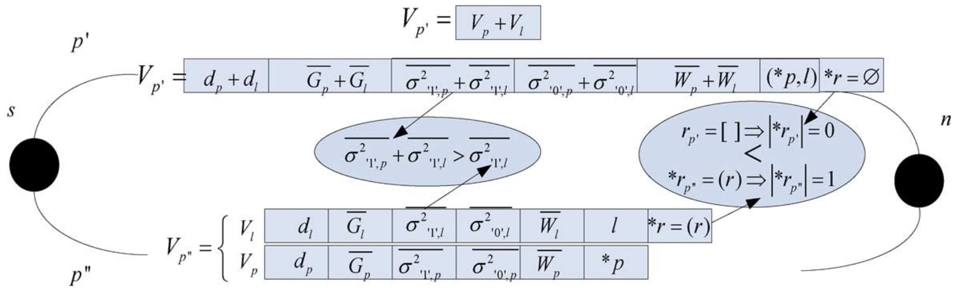

Fig. 3. Two non-dominated paths p' and p'' created due to the available 3R regenerator at node r.

This approach is the same as policy (viii), with the difference that in the first step, policy (v) is applied.

Note that all the described policies take into account the sub-paths of the paths in order to compute the metrics of the most used wavelength and of the best Q performance.

Optional Operation: Rerouting Connections: As discussed in previous sections, XT, XPM, and FWM impairments depend on the utilization of the other lightpaths. As a result, when a new lightpath is established, the QoT of some existing lightpaths may become unacceptable. To address this issue, in the proposed multicost algorithm for translucent networks, each time we take the decision of establishing a new connection we always evaluate how many of the existing connections will obtain unacceptable Q-factor and reroute the sub-paths that fall beneath the given threshold. Rerouting is a process that we want to avoid, since it involves tearing down the previous connection, re-executing the algorithm and establishing a new lightpath, which would interrupt the service of the connection. If rerouting is prohibited, we can either continue using the existing lightpaths (actually, to be more precise, sequences of lightpaths, if the connection also uses regenerators) with an inferior QoT, or we can block the establishment of a new connection that would lead to at least one rerouting. In case a particular sub-path does not meet the QoT requirement, then only this sub-path is rerouted and not the entire path.

V. Simulation Results

In order to evaluate the performance of the proposed IA-RWA algorithm for translucent networks, we carried out a number of simulation experiments. To examine the feasibility of the lightpaths we used a Q-factor estimator (Q-Tool [18]) that relies on analytical models to account for the most important impairments. The acceptable Q-factor limit was taken equal to $Q_{\min} = 15.5$ dB. We performed our simulations using the Geant-2 network (Fig. 1) that consists of 34 nodes and 54 bidirectional links. All single-hop connections of Geant-2 can be served transparently, but some lengthy, multi-hop connections cannot, making the use of regenerators necessary.

In our simulations, we assume that not all the OXCs of the network have available regenerators. In particular, due to restrictions in capital expenditure (CAPEX) and operational costs (OPEX) the total number of regenerator sites should be kept small, and for this reason regenerators are placed at a limited number of nodes only (sparse regenerator placement). The number of OEO regenerators at each node is fixed but this number may vary from one node to another. Nodes that do not have any regenerators, allow only add and drop of wavelengths. We assume that the regeneration sites location is *a-priori* known, driven by [4]. In Fig. 1 we indicate the nodes where the regenerators were placed for these simulations. In particular, we assume (unless otherwise stated) that there are 18 regeneration sites, equipped with a limited total number of regenerators, and in particular equal to 100.

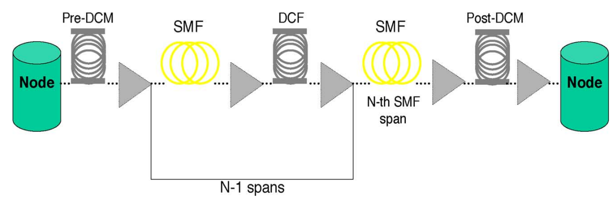

Fig. 4. Link model assumed in the simulatins.

The link model of the reference network is presented in Fig. 4. The physical layer characteristics used in our simulations, were based on [22]. In particular, we assumed 10 Gbps transmission rates and channel spacing of 50 GHz. The span length in each link was set to 80 km. Each link was assumed to consist exclusively of SSMF fibers with dispersion parameter $D = 17$ ps/nm/km and attenuation parameter $a = 0.25$ dB/km. For the DCF we assumed parameters $a = 0.5$ dB/km and $D = -80$ ps/nm/km. PMD coefficient was assumed equal to $D_{\rm PMD} = 0.15$ ps/km$^{1/2}$. The launch power was set to 3 dBm/ch for every SMF span and -4 dBm/ch for the DCF modules. The EDFAs' noise figure was set to approximately 6 dB with small variations (0.5 dB) and each EDFA exactly compensates for the losses of the preceding fiber span. Optimum spectral gain flatness was assumed for all EDFA amplifiers. We assumed a switch architecture similar to [2] and a switch-crosstalk ratio $X_{\rm sw} = 32$ dBs with small variations per node (± 1 dB). Regarding the dispersion management scheme, a pre-compensation module was used in order to achieve better transmission reach: initially the dispersion was set to -400 ps/nm every span was under-compensated by a value of 30 ps/nm to alleviate non-linear effects, and the accumulated dispersion at the input of each switch was fully compensated to zero with the use of an appropriate post-compensation module at the end of the link. Note that these assumptions do not constrain the applicability of the proposed algorithm, which is general and can be used for any network topology, or when the physical layer parameters are different and a different dispersion compensation strategy is employed.

Connection requests, each requiring bandwidth equal to 10 Gbps, are assumed to be generated according to a Poisson process with rate λ requests/time unit. The source and destination of a connection are chosen based on a population related model among the nodes of the network as defined in [18], [21]. The duration of a connection is given by an exponential random variable with average $1/\mu$ time units. Thus, λ/μ gives the total network load in Erlangs. In each experiment 2000 connection requests are generated.

To assess the performance of the proposed policies, we used as performance metrics the blocking probability, the average number of reroutings, and the average execution time per accepted connection. A rerouting is performed when the establishment of a new lightpath turns an already established connection infeasible due to unacceptable QoT. The rerouting operation may cause cascade effects, since the tear down of an existing connection and its re-establishment, may affect the QoT of other existing connections, leading to more reroutings. Thus, it is important to measure the number/level of reroutings caused by a single connection request, since this increases the algorithm's execution time. Note that the average number of re-routings recorded in the results does not refer to reroutings per connection but to sub-path re-routings. Values of this metric larger than one, correspond to the case where on average more than one sub-paths of a connection are rerouted, one or more times. The computation/execution time of a connection request is the time required by our algorithm in order to find a feasible lightpath for serving this request, and it is measured in seconds. We average the execution times for all the successfully served connection requests, that is, the computation time of connection requests that could not be served, are not included in this averaging.

It is worth mentioning that the performance of the proposed policies depends on the network, traffic and physical layer parameters. For different parameters the optimization policies examined will produce different results than the ones that follow. This remark, however, strengthens the importance of the proposed multicost approach. Our focus is not only to find the best optimization function that minimizes blocking, but to propose a general algorithm that can use different optimization policies tailored according to specific requirements.

In Fig. 5(a) we graph the blocking probability of the proposed multicost algorithms for different optimization policies, as a function of the number of available wavelengths, for network load equal to 700 Erlangs. We observe that the Least Regeneration Usage (LRU-) based algorithms produce the worst blocking performance. These algorithms attempt to use the minimum number of regenerators so that the remaining regenerators are available for future connections. However, this strategy results in the selection of lightpaths with poor QoT, that, in many cases, becomes unacceptable due to the establishment of new connections. This results in an increased number of blockings [Fig. 5(a)] and reroutings [Fig. 5(b)]. Also LRU- algorithms have larger execution times [Fig. 5(c)] due to the increased number of re-routings.

Comparing the—MUW and $-\mathrm{bQ}$ algorithms we observe that the performance of the $-\mathrm{bQ}$ algorithms is slightly better when the number of wavelengths increases. MUW algorithms do not account for the Q-factor of the selected lightpaths and tend

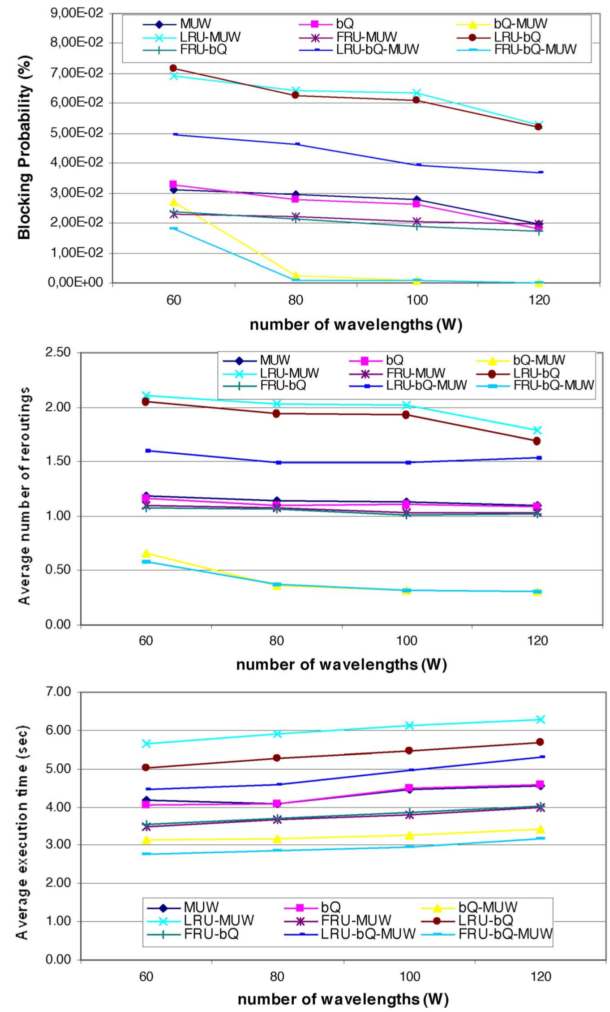

Fig. 5. (a) Blocking probability. (b) Average number of reroutings per connection. (c) Average execution time per accepted connection. All the results are presented as a function of the number of available wavelengths, for fixed network load (equal to 700 Erlangs).

to "pack" the lightpaths so as to use the same wavelengths, avoiding network layer blocking. On the other hand, $-\mathrm{bQ}$ algorithms waste a lot of wavelengths trying to establish a connection (the one with the highest Q value) that is not affected by future connections, resulting in increased network blocking when the number of wavelengths is small.

The mixed bQ-MUV algorithms combine the good network layer performance of the MUV algorithm and the good physical layer performance of bQ algorithm, and as a consequence have smaller blocking probability.

The two algorithms that exhibit the smallest blocking probability among the algorithms considered, are the bQ-MUW and the Fewer Regenerator Usage (FRU) -bQ-MUW algorithms. The FRU- algorithms use a small number of regenerators, but not necessarily the minimum as the LRU- algorithms do. Also, the FRU-bQ-MUW algorithms yield a smaller blocking probability than the bQ-MUW, since they make better use of the available regenerators. Both algorithms reach zero blocking probability when more than 80 wavelengths are available. Given a certain placement and a certain number of regenerators, using inefficiently these resources, reduces the possibility of serving

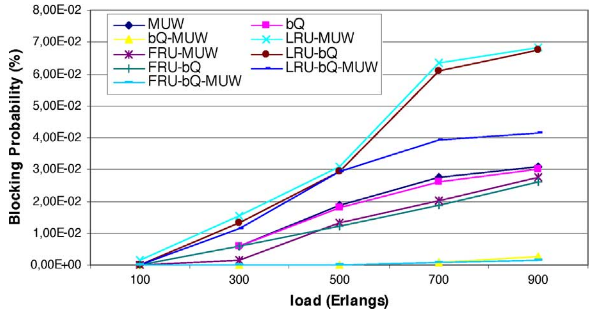

Fig. 6. Blocking probability as a function of network load. Number of wavelengths is equal to 100.

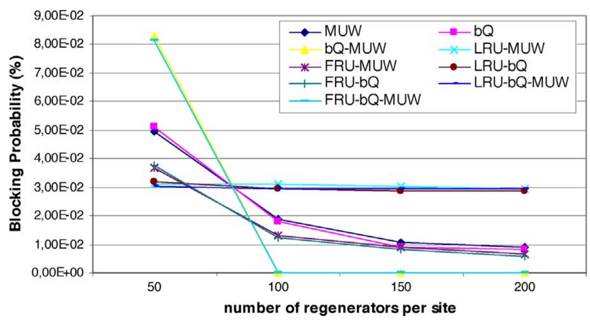

Fig. 7. Blocking probability as a function of the number of regenerators available at each site. Number of wavelengths is equal to 100 and load is equal to 500 Erlangs.

future connection requests. Note that over-provisioning of the resources would not be acceptable by the telecom operators. Thus, it stands to reason that the algorithms that take into account the availability of the regenerators and the wavelengths will perform better in a resource constrained environment.

The average execution time per connection increases as the number of available wavelengths increases [Fig. 5(c)]. This is because when the number of available wavelengths is large, there are more candidate lightpaths that the algorithm has to examine/process, both with respect to the domination operation and the QoT criterion. In any case, the average execution time is kept low and within acceptable values.

In Fig. 6, we examine the performance of the examined policies as a function of the network load, assuming there are 100 available wavelengths. As the network load increases the blocking probability also increases. The blocking performance of the proposed policies is quite similar to that of Fig. 5.

Next, we examine the performance of the proposed algorithms as a function of the number of regenerators available at each site (Fig. 7). We assume that the regenerators are placed in 18 sites, as depicted in Fig. 1. The number of regenerators per site varies from 50 to 200 in each execution, but we assume that all regenerator sites have the same number of regenerators. In Fig. 7 we observe that the performance of all the algorithms in terms of the blocking probability is improved significantly as the number of available regenerators increses, as expected. Also, we observe that when the regenerators per site are limited to 50, the LRU-based algorithms, that take vastly into account the utilization of regenerators, exhibit the best blocking performance. However, the performance of the LRU-based algorithms change slightly with the number of regenerators per site, since these algorithms minimize the number of regenerators used by the established lightpaths, and after a point they do not exploit the extra regenerators available.

Concluding, our results highlight the importance of policies that consider all the parameter involved, and in particular the number of available regenerators, the physical and network layer characteristics. The multicost "framework" we propose in this work provides this possibility through the application of different optimization policies.

VI. Conclusion

In this paper we extended our previous work to obtain an online IA-RWA algorithm for the case of translucent optical networks. The extension was highly non-trivial since the presence of regenerators significantly increases the options that are available for routing a connection with acceptable QoT. A connection that is served by a lengthy path may need to utilize some of the available regenerators. In this way, the established lightpath consists of several transparent lightpaths (referred to as sub-paths) between the used regenerators, which restore signal quality. The cost vectors' of the constituent transparent sub-paths of a path are recorded in a matrix. We described the data structures required by the multicost IA-RWA algorithm, and the mechanisms required to compute them. To serve a connection request the proposed IA-RWA algorithm calculates all the cost-effective and feasible lightpaths for the given source-destination, including all the possible combinations for the utilization of available regenerators of the network. Then, an optimization policy is applied to the candidate paths in order to select the optimal one. If a candidate path contains regenerators, then the worst sub-path characterizes the whole path, and this is used in the optimization policy is applied.

We performed a number of simulation experiments using various optimization policies to select a lightpath, which correspond to a series of different IA-RWA algorithms. We evaluated the performance of these algorithms as a function of the number of available wavelengths per link, the network load, and the number of regenerators per site. In our simulation results, algorithms that make better use of the available resources (regenerators and wavelengths) and select lightpaths with good QoT, produce the best results, in terms of the blocking probability.

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