

# Indirect and Direct Multicast Algorithms for Online Impairment-Aware RWA

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**Abstract**—We consider the online impairment-aware routing and wavelength assignment (IA-RWA) problem in transparent WDM networks. To serve a new connection, the online algorithm, in addition to finding a route and a free wavelength (a lightpath), has to guarantee its transmission quality, which is affected by physical-layer impairments. Due to interference effects, the establishment of the new lightpath affects and is affected by the other lightpaths. We present two multicast algorithms that account for the actual current interference among lightpaths, as well as for other physical effects, performing a cross-layer optimization between the network and physical layers. In multicast routing, a vector of cost parameters is assigned to each link, from which the cost vectors of the paths are calculated. The first algorithm utilizes cost vectors consisting of impairment-generating source parameters, so as to be generic and applicable to different physical settings. These parameters are combined into a scalar cost that indirectly evaluates the quality of candidate lightpaths. The second algorithm uses specific physical-layer models to define noise variance-related cost parameters, so as to directly calculate the  $Q$ -factor of candidate lightpaths. The algorithms find a set of so-called nondominated paths to serve the connection in the sense that no path is better in the set with respect to all cost parameters. To select the lightpath, we propose various optimization functions that correspond to different IA-RWA algorithms. The proposed algorithms combine the strength of multicast optimization with low execution times, making them appropriate for serving online connections.

**Index Terms**—Cross-layer optimization, multicast algorithms, online or dynamic traffic, physical-layer impairments (PLIs), quality of transmission (QoT), routing and wavelength assignment (RWA), transparent all-optical networks, wavelength-routed WDM networks.

## I. INTRODUCTION

WAVELENGTH division multiplexing (WDM) is the most common multiplexing technique used for establishing communication in optical transport networks [1]. In wavelength-routed WDM, data is transmitted over *lightpaths*, that is, all-optical WDM channels that may span multiple consecutive fibers. From the network perspective, establishing a lightpath for a new connection requires the selection of a route (path) and a free wavelength on the links that comprise the path. The wavelength must be consistent for the entire path,

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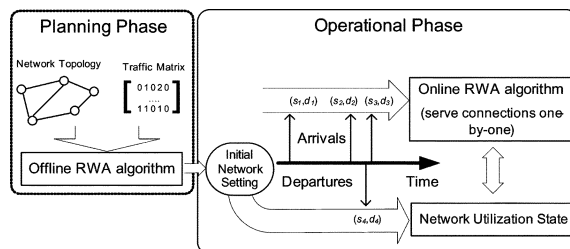


Fig. 1. Planning and operational phases of a wavelength-routed WDM network. In the planning phase, we use offline (static) RWA algorithms to find lightpaths for a given, usually large, initial set of connection requests (given, e.g., in the form of a traffic matrix). In the operation phase, we use online (dynamic) RWA algorithms to serve new connections dynamically as they arrive.

assuming that wavelength converters are not available. This is known as the *routing and wavelength assignment (RWA)* problem.

Fig. 1 presents a conceptual view of the two phases a wavelength-routed WDM network undergoes, namely: 1) the *planning*, and 2) the *operational* phases. In the planning phase, the network is configured based on the traffic it is predicted to handle, given in the form of a static set of connection requests. This is a “one-time” problem. The joint optimization of the lightpaths in order to optimize some efficiency criterion, which in the majority of cases is the network cost, is usually referred to as *offline* or *static* RWA [4]–[6].

In the operational phase, new lightpath requests arrive dynamically, at random times, and they have to be established upon their arrival, one by one, taking into account the current utilization state of the network, that is, the previously established lightpaths. Connections may also terminate at random time instances, releasing the used resources for future use. The problem is usually referred to as *online* or *dynamic* RWA [4]. The objective here is to minimize the blocking probability of the arriving connections over the time horizon. The traffic between sites usually grows in a smooth way, and given the coarse, wavelength-level granularity of WDM systems, relatively large periods of time pass until an additional wavelength needs to be established. Note that offline RWA algorithms can be periodically reexecuted, when traffic has changed substantially, so as to optimally reconfigure the network, but this may affect existing connections and is in most cases undesirable. It is expected that future applications will require wavelength-on-demand services, a scenario where online RWA algorithms will play a key role.

The optical technology most often used in the core is *opaque* point-to-point networks, where the signal is regenerated at every intermediate node via optical–electronic–optical (OEO) conversion. As the network traffic increases, more electronic terminating and switching equipment are required, contributing

to cost (CAPEX), energy consumption, heat dissipation, physical space requirements, and operation and maintenance costs (OPEX). The current trend clearly shows an evolution toward more transparent networks that use fewer OEO transponders. The vision of the DICONET project [23] is to increase the transparency of the network. For example, a network that would be designed using regenerators due to inefficient selection of lightpaths would have a lower cost if it were designed with the same type of transponders and without or with fewer regenerators by using a sophisticated IA-RWA algorithm to set up the lightpaths.

In transparent or translucent WDM networks, without or with partial use of regeneration, lightpaths remain in the optical domain for more than one link. *Physical-layer impairments* (PLIs) affect the quality of transmission (QoT) of the lightpaths, and after a point, the signal quality may degrade to the extent that its detection at the receiver is infeasible [1], [2], leading to physical-layer blocking. The interdependence between the physical and the network layers makes the RWA problem in the presence of PLIs a cross-layer optimization problem. To address this, a number of approaches are emerging, usually referred to as *impairment-aware (IA)-RWA* algorithms [8]–[17]. Moreover, due to certain PLIs, namely those related to interlightpath interference, routing decisions made for one lightpath affect and are affected by the routing decisions made for the other lightpaths.

Interference among lightpaths is particularly difficult to formulate in the planning (offline) problem, where the utilizations of lightpaths are the variables of the problem [7]. On the other hand, in the online problem, where connections are established one by one, this interdependence among lightpaths is easier to handle since the employed algorithm can calculate (through appropriate models) or measure (through monitors) the effect of the already established lightpaths on the new lightpath. However, the establishment of a new or a few new lightpaths may turn some of the already established connections unacceptable.

To address this issue, there are two approaches. The first selects only lightpaths that are feasible under a *worst-case interference assumption*, that is, assuming that all wavelengths on all links are fully utilized or taking a constant penalty for nonlinear effects [15], [17]. A lightpath chosen in this way is bound to have acceptable QoT during its entire duration, even if future interfering connections are established. However, such an approach reduces the candidate path space and increases blocking for a given number of available wavelengths. In contrast, cross-layer IA-RWA algorithms that use the current network utilization to account for the *actual interference* among lightpaths can explore a significantly larger path space. The drawback of this latter approach is that the problem becomes more complicated since interlightpath interference has to be modeled and incorporated in the algorithm and additional checks have to be performed on the degradation a new lightpath causes to the existing ones. In this paper, we follow the latter cross-layer optimization approach, while the majority of the works found in the literature are based on the worst-case assumption.

More specifically, we propose and evaluate two online algorithms by applying the multicost framework to the IA-RWA problem. The first *indirect* or *Multi-Parametric* (MP) IA-RWA algorithm [8] includes in its cost vector network-layer parameters that correspond to the most important impairment-generating sources. Such parameters are the length, the hop count,

the number of adjacent and second-adjacent interfering channels, the number of intrachannel-generating sources, the number of four-wave mixing sources, and possibly other parameters. The MP algorithm uses a cost function to combine these parameters, and a corresponding threshold in order to evaluate the feasibility of a lightpath. A lightpath with a small number of impairment-generating sources is *indirectly* expected to exhibit good QoT. The indirect MP algorithm is generic and easily applicable to different conditions (modulation formats and bit rates). The second multicost IA-RWA algorithm [9], called *direct* or *Sigma-Cost* (SC) algorithm, uses specific physical-layer models to define noise variance-related cost parameters. These noise parameters are combined in order to calculate the  $Q$ -factor of a candidate lightpath, so as to *directly* evaluate its QoT feasibility. The direct SC algorithm is bound to give much better solutions than the indirect MP approach for the specific modulation and bit rate settings it has been designed.

The proposed algorithms consist of three main phases, with the addition of one optional fourth phase. In the first phase, the algorithm finds the set of so-called *nondominated paths* from the given source to all network nodes, including the given destination. For this paper, we will say that a path dominates another path if they both have the same source and destination, and the first path has all its cost parameters better than the corresponding cost parameters of the second path. Thus, the set of nondominated paths consists of all the cost-effective paths in terms of the used cost vector since any path of the set is not inferior with respect to all cost parameters than any other path. In the second phase, an optimization function (or policy) is applied to the cost vectors of the nondominated paths to select the optimum lightpath. Various objective functions, corresponding to different IA-RWA algorithms, are proposed and evaluated through simulations. In the third phase, the algorithm determines whether the establishment of the chosen lightpath will make some existing lightpaths infeasible. We consider three options when this situation arises. We either: 1) reject the new lightpath; 2) select another candidate lightpath; or 3) reroute the old connections made infeasible by the admission of the new one. In the fourth optional phase, we can use more detailed (but slower) analytical models to verify the feasibility of the established lightpaths.

We assess the performance of the proposed IA-RWA algorithms through simulations. We use a  $Q$ -factor estimation module (Q-Tool), developed within the DICONET project [23], to judge the physical-layer feasibility of the lightpaths. We assume that Q-Tool captures the full magnitude of the PLIs. Since the Q-tool is quite detailed, its running time is high, and our algorithms are designed so as to avoid using it as much as possible. Our results indicate that the indirect Multi-Parametric algorithm, after undergoing a tuning procedure, provides a practical solution to the IA-RWA problem without using specific analytical models for the physical layer. When analytical models and the corresponding parameter values are available, the direct Sigma-Cost algorithm is able to provide even better solutions. Our results show that the proposed algorithms exhibit low execution times, in the order of a few hundreds of milliseconds for the realistic transparent network used in our simulations up to a few seconds for medium to large networks, which are comparable and in fact better than those reported in the corresponding literature.

The rest of this paper is organized as follows. In Section II, we present previous works on the online IA-RWA problem. Physical-layer impairments and the  $Q$ -factor are introduced in Section III. Then, in Section IV, we present our proposed IA-RWA algorithms, followed by performance evaluation results in Section V. Our conclusions are given in Section VI.

## II. PREVIOUS WORK

The RWA problem has been extensively examined in the literature [4]. Regarding offline RWA, which is known to be an NP-hard optimization problem [3], few IA-RWA algorithms that are not based on the worst-case interference assumption have been proposed, since the interference among lightpaths is difficult to formulate in a combinatorial optimization problem [7]. On the other hand, in online algorithms the interference among channels is easier to account for, since the utilization of the network is known when a new connection is requested, assuming centralized RWA decisions. Thus, analytical models or other approaches can be used for estimating the physical effects on the candidate lightpaths.

The effects of amplified spontaneous emission (ASE) noise and crosstalk (XT) on online RWA are examined in [10]. An IA-RWA algorithm is presented in [11] that consists of two phases: 1) a network-layer module to compute the routes, and 2) a separate physical-layer module to estimate the OSNR and polarization mode dispersion (PMD) of a candidate lightpath. A dynamic algorithm based on real-time  $Q$ -factor measurements from monitors is presented in [12]. In [13], an adaptive IA-RWA algorithm that models as noise the most important physical impairments and assigns additive noise variance parameters per link is proposed. Signaling protocols for the dynamic establishment of lightpaths in the presence of physical impairments are discussed in [19] and [20]. Online IA-RWA algorithms for translucent networks are proposed in [14], [15], and [18]. The authors in [14] propose algorithms that are either based on the worst-case assumption, or they use detailed physical-layer models to estimate the actual interference based on the current utilization state of the network. Our IA-RWA approaches take into account the utilization of the network in a more sophisticated way by defining impairment parameters per link that can be quickly combined using the multicost framework so as to evaluate the QoT of candidate lightpaths.

A multiconstraint approach with parameters being the OSNR, the number of free wavelengths, and the link cost is presented in [16]. The proposed approach sends control packets over candidate paths that acquire information on the aforementioned parameters at intermediate nodes, with the selection of the lightpath being performed at the destination. Lately, another multiconstraint approach has been presented in [17] as an extension to [11]. Instead of using a separate physical-layer evaluation module, as done in [11], [17] uses per-link additive linear impairment parameters in a multiconstraint formulation. In general, multicost and multiconstraint algorithms have been used for quality-of-service (QoS) routing problems [21]. To the authors' best knowledge, the present paper is the first time that the IA-RWA problem is addressed with multicost algorithms that consider the current utilization state of the network to determine the actual interference among lightpaths, thus performing a cross-layer optimization between the physical and the network layers. In contrast, the algorithm in [16] handles impairments

TABLE I  
PHYSICAL-LAYER IMPAIRMENTS CLASSIFICATION

Class 1: Impairments that affect the same lightpath	Class 2: Impairments that are generated by other lightpaths
Amplified Spontaneous Emission noise (ASE) Polarization Mode Dispersion (PMD) Chromatic Dispersion (CD) Filter concatenation (FC) Self-Phase Modulation (SPM)	Intra- and inter-channel Crosstalk (XT) Cross-Phase Modulation (XPM) Four Wave Mixing (FWM)

through OSNR, which is not affected by dispersion and nonlinear effects [1], [2], and does not consider interference at all. Also, the algorithm of [17] uses a worst-case interference assumption and treats all impairments separately without combining them into a single metric [such as the  $Q$ -factor or bit error ratio (BER)]. This may lead to decisions that are unnecessarily conservative, as for example to drop a lightpath when one impairment exceeds its margin, while the other effects are not significant and the BER is still acceptable.

A novelty of our proposed online IA-RWA algorithms, compared to previous works, is that our algorithms calculate all the feasible lightpaths that are nondominated with respect to the cost vectors they use for the given source–destination pair. In order to do so with low running times, we use an appropriate domination relationship to reduce the path space and also prune subpaths that have unacceptable QoT. Once we calculate the feasible and nondominated candidate lightpaths, we can select the one that optimizes any desired optimization function or policy. Note that some heuristic approaches may perform as well as the described algorithms, but can be reproduced by the proposed algorithms by defining appropriate optimization policies. Our aim is not only to find a specific optimization policy that minimizes blocking (this depends also on the physical-layer parameters, the bit rate and modulation format, the topology, and the traffic load), but to propose a general algorithm, a “framework,” that contains different optimization policies as subcases.

## III. PHYSICAL IMPAIRMENTS AND QUALITY OF TRANSMISSION

In transparent and translucent WDM networks, the signal QoT degrades due to the nonideal physical layer [1], [2]. PLIs are usually categorized into linear and nonlinear based on the way their effects depend on the power. However, when considering IA-RWA algorithms, we found it more useful to categorize the PLIs to those that affect the same lightpath and to those that are generated by the interference among lightpaths. Table I presents a classification of the most significant PLIs.

PLIs of the second class are more difficult to deal with in IA-RWA algorithms, making decisions for one lightpath to affect and be affected by decisions made for other lightpaths.

### A. Quality of Transmission, BER, and $Q$ -Factor

Several criteria can be used to evaluate the QoT of a lightpath. BER is the ultimate criterion taking all impairments into consideration. Assuming on–off keying and Gaussian-shaped noise, the  $Q$ -factor is related to the system's BER through

$$\text{BER}(Q) = 1/2\text{erfc}(Q/\sqrt{2}). \quad (1)$$

The higher the  $Q$ -factor value is, the smaller the BER, and thus the better the QoT. Typically, we use a  $Q$ -factor threshold

[e.g., 15.5 dB without forward error correction (FEC)] and consider a lightpath feasible, implying that its QoT is acceptable, if its  $Q$ -factor is higher than the given threshold.

The  $Q$ -factor is the electrical signal-to-noise ratio at the input of the decision circuit at the receiver. The  $Q$ -factor of a lightpath  $(p, w)$  that uses wavelength  $w$  on path  $p$  is given by

$$Q_{pw} = \frac{I_{1',pw} - I_{0',pw}}{\sigma_{1',pw} + \sigma_{0',pw}} = \frac{I_{1',pw}}{\sigma_{1',pw} + \sigma_{0',pw}} \quad (2)$$

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  $p$ ).

### B. Direct and Indirect IA-RWA Algorithms

To account for the physical-layer impairments in a cross-layer optimization manner, an IA-RWA algorithm has to incorporate impairment-related constraints at some point in its formulation. A distinction we make between IA-RWA algorithms is whether they address *directly* or *indirectly* the effects of the impairments. To give an example, PMD is proportional to the square root of the length of the path, and also other impairments, such as ASE noise, are affected by the path length. An algorithm that selects paths with small lengths would aim *indirectly* at achieving low PMD and ASE, but it would not be guaranteed to have acceptable QoT. On the other hand, an algorithm that uses analytical formulas to constrain *directly* the effects of PMD and ASE can be reasonably sure (depending on the accuracy of the models and the other effects that are accounted for) that a lightpath satisfying these constraints has acceptable QoT.

In this paper, we propose two multicost IA-RWA algorithms that follow these two approaches. The indirect *Multi-Parametric* algorithm records impairment-generating source parameters, such as the path length, the hop count, the number of crosstalk, and other interlightpath interfering sources. Reducing these parameters indirectly improves the QoT of a lightpath. The direct *Sigma-Cost* IA-RWA algorithm incorporates the evaluation of the QoT of a lightpath in its formulation, using analytical models to calculate directly the  $Q$ -factor of the candidate lightpaths. These calculations, however, assume a specific modulation format, bit rate, and values for the physical-layer parameters. Compared to the direct approach, the indirect approach is more generic and more easily applicable to different conditions (modulation formats, bit rates) since it does not use specific models for the impairments or specific parameter values. On the other hand, if the physical-layer parameters are accurately known and good impairment models for the specific network are used, the direct algorithm is bound to give much better solutions than the indirect approach, as our performance results will indicate.

### C. Estimating the Feasibility of a Lightpath

Compared to the offline planning problem of a WDM network, where we can afford to take long times, execution time is a crucial factor for an online algorithm since it adds to the waiting time of the connection request. The  $Q$ -factor is not readily available before a lightpath is actually set up, so models of physical impairments have to be used to estimate it in advance. In our paper, we use impairment-generating parameters in the indirect algorithm, or simplified impairment models in

the direct algorithm, as well as quick rules to combine these parameters in order to estimate the feasibility of candidate solutions. At the end of the algorithms, we verify the feasibility of the chosen lightpath using a more detailed  $Q$ -factor estimation module (Q-Tool), developed within the DICONET project [23], which uses detailed analytical models for all impairments listed in Table I. This verification is relatively important for the indirect algorithm, but can mostly be omitted for the direct algorithm, given that the simplified models the direct algorithm uses capture the most dominant effects. The models and assumptions used in the proposed algorithms are presented in Section IV and the Appendixes.

## IV. MULTICOST ONLINE IA-RWA ALGORITHMS

The WDM network is represented by a connected graph  $G = (N, L)$ , where  $N$  denotes the set of nodes (OXC switches), assumed not to be equipped with wavelength converters, and  $L$  denotes the set of single-fiber links. Each link  $l \in L$  supports  $m$  wavelengths,  $\lambda_1, \lambda_2, \dots, \lambda_m$ .

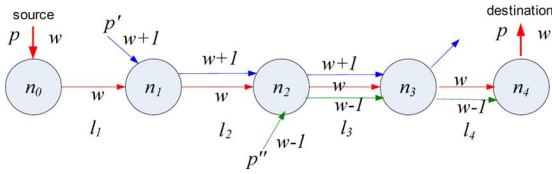
In the online (dynamic) version of the IA-RWA problem, we assume that connection requests arrive at random time instants and are served one by one by the algorithm. Therefore, along with the network  $G$ , the inputs to the algorithm are: 1) the source node  $s \in N$ ; 2) the destination node  $d \in N$ ; and 3) the utilization state of the network at the time of the request. Regarding the utilization state of the network, we assume that the node where the algorithm is executed has a picture of the wavelengths' utilization of all links. This is done by keeping for each link  $l \in L$  a Boolean wavelength availability vector  $\overline{W}_l$ , whose  $i$ th entry  $w_{li}$  is equal to 0 when wavelength  $\lambda_i$  is utilized by a lightpath, and equal to 1 when  $\lambda_i$  is free (available),  $i = 1, 2, \dots, m$ . If the algorithm runs in a centralized way, the network manager has all this information since it has made all RWA decisions. The algorithm may also be run in a distributed way, in which case we assume that the control plane is responsible for distributing the wavelength utilization information among the nodes. This is the information usually required by distributed RWA algorithms. Also, propagation or update delays may result in outdated utilization information, leading to performance deterioration due to conflict/race problems. We will not consider such issues in our study since these are of a more general nature, relating to the distributed versus centralized operation of the network. The reader is referred to [20] for an experimental quantification of the tradeoff between the delay and the blocking probability for centralized and distributed IA-RWA execution.

Given the above inputs, the IA-RWA algorithm returns a lightpath  $(p, w)$ , that is, a path  $p$  and a wavelength  $w$  that is free (unused) on all links  $l$  comprising the path  $p$ , to serve the connection request. Physical-layer impairments pose additional constraints on RWA: The selected lightpath  $(p, w)$  has to be feasible in terms of QoT (as evaluated by its  $Q$ -factor value  $Q_{pw}$ ), and also its establishment must not turn infeasible any of the already established connections.

In the following, we present two multicost IA-RWA algorithms that indirectly and directly consider the physical-layer impairments.

### A. MP Indirect IA-RWA Algorithm

1) *Computing the Cost Vector of a Path:* For a lightpath  $(p, w)$ , we identified the following parameters that


 Fig. 2. Adjacent channel interference on lightpath  $(p, w)$  by other lightpaths.

indirectly affect its signal quality: (i) the path's length  $d_p$ ; (ii) the number of hops  $h_p$  of the path; (iii) the number  $a_{pw}$  of active adjacent channels of wavelength  $w$  across all the links of path  $p$ ; (iv) the number  $sa_{pw}$  of active second-adjacent channels of wavelength  $w$  across all the links of path  $p$ ; (v) the number  $x_{pw}$  of intrachannel crosstalk sources of wavelength  $w$  across all the nodes of path  $p$ ; and (vi) the number  $fw_{pw}$  of four-wave mixing sources of wavelength  $w$  across all the links of path  $p$ .

The aforementioned parameters, (i)–(vi), are the key parameters for the majority of physical impairments [1], [2]. More specifically, ASE noise depends on the number of amplifiers, which is related to the length of the links, and the number of hops (switches). Accumulated residual dispersion due to possible nonideal compensation of chromatic dispersion (CD), PMD, and self-phase modulation (SPM) depends on the length and the number of hops of the path. Filter concatenation (FC) depends on the number of filters over the path, and thus it mainly depends on the number of hops and possibly the length of the path. Moreover, the interlightpath interference effects are accounted for in the parameters  $a_{pw}$ ,  $sa_{pw}$ ,  $x_{pw}$ , and  $fw_{pw}$ . Of course, the physical impairments do not all depend linearly on the parameters discussed. The Multi-Parametric algorithm, in the form that will be presented shortly, is rather coarse and does not capture some physical details, as opposed to the direct Sigma-Cost algorithm to be presented later. For example, it does not consider the variation of the distance between amplifiers, or different dispersion maps, on different links, etc. It could be improved by using weighted link-based cost parameters, but this lies outside the scope of this paper. The main premise in the Multi-Parametric IA-RWA algorithm is that trying to reduce these aforementioned parameters will *indirectly* decrease the effect of all impairments.

To explain the formulation of the interference among lightpaths, we present in Fig. 2 an example for the case of adjacent channel interference. A lightpath  $p$  from  $n_0$  to  $n_4$  is established using wavelength  $w$ . Let  $(p', w+1)$  be a lightpath crossing links  $l_2$  and  $l_3$ , and  $(p'', w-1)$  be a lightpath crossing links  $l_3$  and  $l_4$ . In this example, there are in total  $a_{pw} = 4$  adjacent channel interfering sources affecting lightpath  $(p, w)$ .

Link  $l$  is assigned a cost vector with  $2+5 \cdot m$  cost parameters:

- 1) the delay of the link, or equivalently, its length  $d_l$  (scalar);
- 2) the hop count of the link,  $h_l$  (scalar); by definition  $h_l = 1$ ;
- 3) a vector  $\overline{A}_l = (a_{l1}, a_{l2}, \dots, a_{lm})$  whose  $i$ th element  $a_{li}$  records the number of active adjacent channels on wavelength  $i$ ;
- 4) a vector  $\overline{SA}_l = (sa_{l1}, sa_{l2}, \dots, sa_{lm})$  whose  $i$ th element  $sa_{li}$  records the number of active second-adjacent channels on wavelength  $i$ ;

- 5) a vector  $\overline{X}_l = (x_{l1}, x_{l2}, \dots, x_{lm})$  whose  $i$ th element  $x_{li}$  records the number of intrachannel generating sources at the switch link  $l$  ends at;
- 6) a vector  $\overline{FW}_l = (fw_{l1}, fw_{l2}, \dots, fw_{lm})$  whose  $i$ th element  $fw_{li}$  records the number of four-wave mixing sources on wavelength  $i$ ;
- 7) the wavelengths' availability represented by a Boolean vector  $\overline{W}_l = (w_{l1}, w_{l2}, \dots, w_{lm})$ , whose  $i$ th element  $w_{li}$  is equal to 0 if wavelength  $\lambda_i$  is used, and equal to 1 if it is available.

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

$$V_l = (d_l, h_l, \overline{A}_l, \overline{SA}_l, \overline{X}_l, \overline{FW}_l, \overline{W}_l).$$

In Appendix A, we present a procedure to calculate the vectors  $\overline{A}_l$ ,  $\overline{SA}_l$ ,  $\overline{X}_l$ , and  $\overline{FW}_l$  from the wavelength utilization vectors  $\overline{W}_l$  of all links  $l \in L$ .

Similarly to a link, a path  $p$  is also characterized by a cost vector  $V_p$  with  $2+5 \cdot m$  parameters, in addition to one more parameter ( $*p$ ) that records the list of link identifiers that comprise the path. In particular, the cost vector of path  $p$  can be calculated by the cost vectors of the links  $l = 1, 2, \dots, k$ , that comprise it using the associative operator  $\oplus$

$$\begin{aligned} V_p &= (d_p, h_p, \overline{A}_p, \overline{SA}_p, \overline{X}_p, \overline{FW}_p, \overline{W}_p, *p) = \oplus_{l \in p} V_l \\ &= \left( \sum_{l=1}^k d_l, \sum_{l=1}^k h_l, \sum_{l=1}^k \overline{A}_l, \sum_{l=1}^k \overline{SA}_l, \sum_{l=1}^k \overline{X}_l, \sum_{l=1}^k \overline{FW}_l, \right. \\ &\quad \left. \&_{l=1}^k \overline{W}_l, *p = (1, \dots, k) \right) \end{aligned} \quad (3)$$

where “&” denotes the bitwise AND operation. Note that all operations (summation and &) between vectors have to be interpreted componentwise (that is, separately for each wavelength) and that by definition  $h_p = k$ . By calculating the cost vector  $V_p$ , we obtain the available lightpaths  $(p, w)$  over path  $p$  (wavelengths marked by 1 in  $\overline{W}_p$ ). We denote by  $V_{pw} = (d_p, h_p, a_{pw}, sa_{pw}, x_{pw}, fw_{pw})$  the cost vector of lightpath  $(p, w)$ .

2) *Estimating the Feasibility of the Available Lightpaths:* We define a Quality Of Transmission Estimate (QUOTE) metric as a function  $g$  of the cost vector  $V_{pw}$  of lightpath  $(p, w)$

$$\text{QUOTE}(p, w) = g(V_{pw}) = g(d_p, h_p, a_{pw}, sa_{pw}, x_{pw}, fw_{pw}).$$

The function  $g$  is assumed to be monotonically increasing with respect to each of these impairment generating sources and can be chosen so as to take into account their relative importance. For example, in a network where intrachannel crosstalk is low,  $x_{pw}$  can be neglected or included with a very small weight. In particular, the function used in our experiments was a weighted sum of the parameters of interest

$$\begin{aligned} \text{QUOTE}(p, w) &= c_1 \cdot d_p + c_2 \cdot h_p + c_3 \cdot a_{pw} \\ &\quad + c_4 \cdot sa_{pw} + c_5 \cdot x_{pw} + c_6 \cdot fw_{pw} \end{aligned} \quad (4)$$

where the  $c_i$ 's are coefficients that are used to declare the relative importance of each parameter (impairment). Using the above function and a threshold  $\text{QUOTE}_{\max}$ , we can decide if a lightpath has acceptable transmission performance or not. The QUOTE function's weights and the corresponding  $\text{QUOTE}_{\max}$  threshold have been selected based on tuning

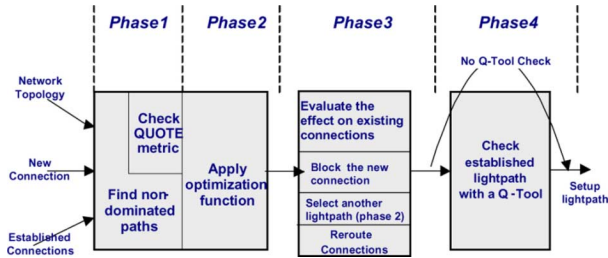


Fig. 3. Input/output and the phases of the Multi-Parametric algorithm.

experiments to be described later in the performance results of Section V-A. Note that we have also developed an automatic process to efficiently tune the QUOTE function using particle swarm optimization (PSO) [25]. A particle of the swarm is formed by the coefficients of the impairment-generating parameter of each link. We execute an experiment using these coefficients for a number of connection establishments, and we take as output the corresponding physical-layer blocking, using Q-tool as the QoT evaluation module. The coefficients are then adjusted using PSO, the same experiments are reexecuted, and the process iterates until we find coefficients that yield near-zero physical-layer blocking.

The QUOTE function is used to prune the solution space. For a path  $p$ , we check if the available wavelengths  $w$  of that path (marked by 1 in vector  $\overline{W}_p$ ) have a QUOTE( $p, w$ ) value that is smaller than the predefined threshold QUOTE<sub>max</sub>. For lightpaths that do not satisfy the threshold, we set the corresponding index of the utilization vector  $\overline{W}_p$  equal to zero. In other words, we make these wavelengths unavailable due to poor QoT performance and not due to their being used by another lightpath. Paths that do not have at least one available wavelength ( $\overline{W}_p = \mathbf{0}$ ) are not extended further during the execution of the algorithm.

It may seem easier to measure each impairment source separately and have a different threshold for each one, as done in [17]. This choice is not ruled out and is a special case of our Multi-Parametric algorithm. However, we believe that this approach will not be efficient since it may discard paths due to a single parameter violation, while the rest of the parameters may be very good and the total QoT may be acceptable.

3) *Algorithm Description*: The proposed Multi-Parametric IA-RWA algorithm consists of four phases, three basic and one optional (Fig. 3).

*Phase 1: Computing the Set of Nondominated Paths  $P_{n-d}$* : The goal of this phase is to find a set of good, in terms of the QUOTE metric, candidate lightpaths to efficiently serve the connection. Our scheme uses the algorithm presented in Fig. 4. This algorithm utilizes, in addition to the QUOTE metric and the related QUOTE<sub>max</sub> threshold, a *domination* relationship between paths that have the same source and end node in order to reduce the number of paths considered. In particular, we say that a path  $p_1$  dominates a path  $p_2$  with the same source and end nodes (notation:  $p_1 > p_2$ ) if the following relation holds:

$$p_1 > p_2 \text{ iff } (d_{p_1} \leq d_{p_2} \text{ and } h_{p_1} \leq h_{p_2} \text{ and for all } i : w_{p_2i} \geq w_{p_1i} \\ \text{and } w_{p_2i} \cdot a_{p_1i} \leq a_{p_2i} \text{ and } w_{p_2i} \cdot s_{a_{p_1i}} \leq s_{a_{p_2i}} \\ \text{and } w_{p_2i} \cdot x_{p_1i} \leq x_{p_2i} \text{ and } w_{p_2i} \cdot f_{w_{p_1i}} \leq f_{w_{p_2i}}). \quad (5)$$

---

**Notation:**

The network is defined as a directed graph  $G=(N,L)$ :  $N$  is the set of nodes, and  $L$  is the set of links.

The connection request has source node  $s \in N$  and destination node  $d \in N$ .

$V_l$  is the cost vector of link  $l \in L$  and  $V_p$  is the cost vector of path  $p$ .

$M_i$  is the set of cost vectors of the paths from  $s$  to a node  $n_i \in N$ , and  $M = \cup_{i \in S} M_i$  is the set of all vectors.  $M' \subseteq M$  is the subset of all final vectors for all the nodes, and  $M'_i \subseteq M_i$  is the set of final vectors for node  $n_i$ .

---

$P_{n-d} \leftarrow \text{Compute\_the\_Set\_of\_Non\_Dominated\_Paths}(G, s, d, V_l)$

## Initialization

$M' = \{\}, M = \{\}$

for all links  $l \in L$  starting at  $s \in N$ ,  $M = M \cup V_l$

while  $M \neq M'$

## Choose the optimum label

find path  $p$  in  $M$  whose vector  $V_p$  has minimum 1<sup>st</sup> cost parameter  
in case of tie, select the one with minimum 2<sup>nd</sup> parameter, etc.  
 $n \in N \leftarrow$  ending node of path  $p$

$M' = M' \cup V_p$

## Obtain new paths and discard dominated paths

for all  $n_j \in N$  neighbors of  $n$  (connected through link  $l=(n, n_j) \in L$ )

## Obtain the cost vector of the new path  $p_j'$

$V_{p_j'} = V_p \oplus V_l$  ( $\oplus$  is the associative operator)

## Evaluate the Quality of Transmission of new path  
for all wavelengths  $i$

calculate QUOTE <sub>$p_j', i$</sub>  (or  $Q_{p_j', i}$ ), using the cost vector  $V_{p_j'}$

if QUOTE <sub>$p_j', i$</sub>  < QUOTE<sub>max</sub> (or  $Q_{p_j', i} > Q_{min}$ )

set  $V_{p_j'} \rightarrow w_{p_j', i} = 0$  (make wavelength  $i$  unavailable)

end if

end for

## Discard a path without a free wavelength

if  $\overline{W}_{p_j'} = \mathbf{0}$

check the next neighbor  $n_j$  (discard the new path  $p_j'$ )

end if

## Discard dominated paths

for all  $V_{p_j} \in W$  ( $p_j$  are paths ending at  $n_j$ )

if  $p_j > p_j'$  (" $>$ " is the domination relationship)

check the next neighbor  $n_j$  (discard the new path  $p_j'$ )

else if  $p_j' > p_j$

$M = M - \{V_{p_j}\}$  (discard the old path  $p_j$ )

end if

end for

$M = M \cup \{V_{p_j'}\}$  (add the new path  $p_j'$  to the set of paths)

end for

end while

**end algorithm** (return  $P_{n-d} \equiv M'_d$ )

---

Fig. 4. Pseudocode of the algorithm that computes the set of nondominated paths from the given source to the given destination.

Note that we only consider the impairment parameters for the wavelengths  $i$  of path  $p_2$  that are available ( $w_{p_2i} = 1$ ). A path that is dominated by another path has worse delay, wavelength availability, and impairment-generating parameters than the latter, and there is no reason to consider it further. In particular, since the optimization function  $f$  that will be applied to the cost vectors of the paths in the second phase of the algorithm is monotonic in each of the cost components, the dominated paths would never be selected. Discarding dominated paths reduces the solution space in a safe way (so as not to discard good solutions), along with the execution time of the algorithm.

The algorithm described in Fig. 4 is a generalization of Dijkstra's algorithm that only considers scalar link costs. It first obtains a nondominated path between the origin and a direct neighbor. This path is selected so as to have the smallest first cost parameter or, in case of a tie, the smallest second parameter, etc. By definition, this path is nondominated since the parameters that comprise the cost vectors are additive and nonnegative and this path has at least one parameter smaller than the other paths. The algorithm extends this path through the outgoing links of its end node so as to calculate new paths and their cost vectors, using the associative operator  $\oplus$  of (3). Then, the algorithm selects a nondominated path between the origin and one of its neighbors, or between the origin and one of the neighbors of the previously considered neighbor, extends it using the corresponding outgoing links, calculates new paths, and so on. For each new path that is calculated, the algorithm applies the domination relationship (5) between the new path and all the paths with the same end node that have been previously calculated. The new path is discarded if it is dominated by one of the previously calculated paths; otherwise, it is added to the set of nondominated paths of the specific end node, and all the previously calculated paths that are dominated by it (if any) are discarded. The basic difference with Dijkstra's algorithm is that a set of nondominated paths between the source  $s$  and each node is obtained instead of a single path; a node for which a path has already been found is not finalized (as in the simple Dijkstra case) since it may have to be considered again later. The algorithm finishes when no more paths can be extended and returns the set of nondominated paths  $P_{n-d}$  that has been calculated between the source  $s$  and the destination  $d$ . Note that when extending a path, we check if it has at least one available wavelength, and discard it if this is not the case. In this way, each path in the set of nondominated paths  $P_{n-d}$  passed to the second phase has at least one available wavelength.

*Phase 2: Selecting the Optimal Lightpath:* The available wavelengths of a nondominated path  $p \in P_{n-d}$  (wavelengths marked by 1 in  $\overline{W}_p$ ) with cost vectors  $V_{pw}$  form the set of candidate lightpaths  $(p, w)$  over path  $p$ . In the second phase of the algorithm, we apply an optimization function or policy  $f(V_{pw})$  to the cost vector  $V_{pw}$  of all candidate lightpaths calculated in the first phase. The function  $f$  yields a scalar cost per candidate lightpath in order to select the optimal one. The function  $f$  can be different for different connections, depending on their QoS requirements and other considerations. Note that the optimization function  $f$  has to be monotonic in each of the cost components. For example, it is natural to assume that the objective function is increasing with respect to delay, hop count, number of crosstalk sources, etc. In this paper, we propose and evaluate the following objective functions, each of which can be viewed as a different IA-RWA algorithm.

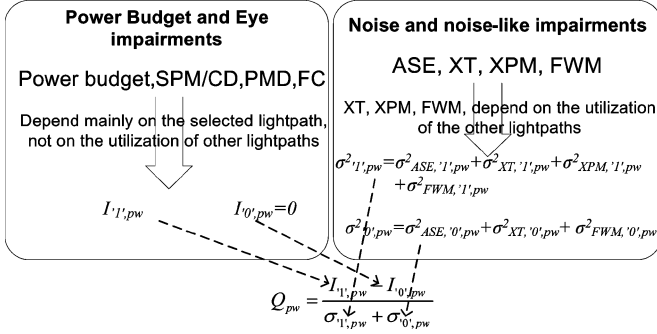
- 1) *Most Used Wavelength (MUW):* Given the existing connections, we order the wavelengths in decreasing utilization order and choose, among the candidate lightpaths, the one whose wavelength is most used. This corresponds to the well known "most used wavelength" method [4], which has been shown to exhibit good network-layer blocking (that is, blocking due to limited wavelength resources) assuming ideal physical layer. This approach does not differentiate between the QUOTE values of the solutions as long as they are acceptable and may choose lightpaths close to the

threshold that would become infeasible when new connections are admitted (see Phase 3 of the algorithm).

- 2) *Better parameter QUOTE value (minQUOTE):* Among the candidate lightpaths, we select the one with the smallest QUOTE value. This approach does not consider the utilization of wavelengths, possibly making it more difficult to serve future requests due to network-layer blocking.
- 3) *Worse parametric QUOTE value (maxQUOTE):* Among the candidate lightpaths, we select the one with the largest acceptable QUOTE value. Since the larger the QUOTE value is, the worse the QoT of the lightpath, this rule yields lightpaths that have "just" acceptable quality. The rationale is to try to pack the chosen lightpaths (of at least acceptable quality), hoping that this will make it easier to find available wavelengths for future requests. As in the *MUW* policy, the QUOTE value of the lightpath selected may deteriorate to unacceptable levels when new connections are established.

*Phase 3: Evaluate the Effect on the Established Connections:* As previously discussed, XT, XPM, and FWM (i.e., impairments of class 2 in Table I) depend on the utilization of the other lightpaths. Thus, when a new lightpath is established, the QoT of some existing lightpaths may become unacceptable. This is the penalty we pay for avoiding use of the worst-case interference assumption when calculating the feasibility of lightpaths, as described in the Introduction. To address this issue, before establishing a new lightpath, we always evaluate if any existing connections will obtain QUOTE values that are larger than a given rerouting threshold  $QUOTE_r$  (which can be different than the threshold  $QUOTE_{max}$  used for examining the feasibility of a new lightpath, even though in our results we assume  $QUOTE_r = QUOTE_{max}$ ). When this case arises, we can either: 1) block the new connection; 2) select a different lightpath to serve the new connection (reexecute the second phase of the algorithm); or 3) reroute the affected existing connections. A connection that is rerouted may trigger more reroutings, resulting in a chain reaction effect that can be controlled by limiting the rerouting depth. Generally, we want to avoid a rerouting since it involves tearing down a lightpath that would interrupt the service of the connection.

*Phase 4: Q-Tool Estimator (Optional):* At the end of the algorithm, we evaluate the feasibility of the lightpaths using a  $Q$ -factor estimator (Q-Tool) that incorporates detailed analytical models for the impairments listed in Table I. The Q-Tool we used has been developed within the DICONET project [23]. The Q-Tool takes as input the new and the existing lightpaths, calculates their  $Q$ -factors, and returns if any of them have unacceptable QoT. If more than one lightpath has unacceptable QoT, the new connection is blocked, or we can consider a different candidate lightpath, similarly to phase 3. In general, our goal is to use the Q-Tool as little as possible to reduce the execution time of our algorithm. In case we decide not to use the Q-Tool, we establish the new connection assuming that the feasibility decision taken based on the QUOTE function is correct. We found that by using a training procedure to fine-tune the parameters of QUOTE function (shortly described in the performance results in Section V-A) we can significantly reduce the probability that the Q-Tool rejects as infeasible a lightpath that the test based on QUOTE found feasible.


 Fig. 5.  $Q$ -factor calculation.

### B. Sigma-Cost Direct IA-RWA Algorithm

We now take a different approach and propose a direct IA-RWA multicost algorithm that uses the  $Q$ -factor to directly estimate the feasibility of the lightpaths.

1) *Q-Factor of a Path and Q-Factor of a Link*: The mean value  $I_{1',pw}$  of electrical voltage of signal '1' in the  $Q$ -factor definition (2) depends on the transmitter's characteristics, the gains and losses of the amplifiers and links over the path, and the SPM/CD, PMD, and FC, regarded as eye penalty impairments [2], [14]. The remaining physical impairments are considered as noise. Fig. 5 presents a conceptual view of how to calculate the  $Q$ -factor from the values of  $I_{1',pw}$  and the noise variances. Note that XT, XPM, and FWM depend on the utilization of the other lightpaths (class-2 impairments; see Table I). Also, XPM and FWM are transmission impairments generated in the fiber links [1], [2], while XT is related to the nonideal switching fabric of the OXCs [10]. Thus, for conciseness, in what follows, by the term "link" we will refer to a link and the OXC switch that is connected at its end.

The  $Q$ -factor of a lightpath cannot be calculated directly by the  $Q$ -factors of the links that comprise it since it is not an additive parameter. 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 penalty impairments of the end-to-end route. We assign to each link parameters that correspond to the electrical noise variances of all noise 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. More specifically, for a path  $p$  consisting of links  $l = 1, 2, \dots, k$  with known electrical noise variances  $\sigma_{ASE,1',lw}^2$ ,  $\sigma_{ASE,0',lw}^2$ ,  $\sigma_{XT,1',lw}^2$ ,  $\sigma_{XT,0',lw}^2$ ,  $\sigma_{XPM,lw}^2$ ,  $\sigma_{FWM,1',lw}^2$ , and  $\sigma_{FWM,0',lw}^2$  per wavelength  $w$ , and known gains or losses  $G_{lw}$  ( $G_{lw}$  is typically expressed in decibels and accounts for the losses of the fiber segments and optical components and the gains of the in-line amplifiers of link  $l$  and the ending OXC), we have

$$\begin{aligned} \sigma_{1',pw}^2 &= \sum_{l=1}^k \left( \sigma_{1',lw}^2 \cdot \prod_{l'=l+1}^k 10^{2 \cdot G_{l'w}/10} \right) \\ &= \sum_{l=1}^k \left( (\sigma_{ASE,1',lw}^2 + \sigma_{XT,1',lw}^2 + \sigma_{XPM,1',lw}^2 + \sigma_{FWM,1',lw}^2) \cdot \prod_{l'=l+1}^k 10^{2 \cdot G_{l'w}/10} \right) \end{aligned} \quad (6)$$

$$\begin{aligned} \sigma_{0',pw}^2 &= \sum_{l=1}^k \left( \sigma_{0',lw}^2 \cdot \prod_{l'=l+1}^k 10^{2 \cdot G_{l'w}/10} \right) \\ &= \sum_{l=1}^k \left( (\sigma_{ASE,0',lw}^2 + \sigma_{XT,0',lw}^2 + \sigma_{FWM,0',lw}^2) \cdot \prod_{l'=l+1}^k 10^{2 \cdot G_{l'w}/10} \right). \end{aligned} \quad (7)$$

Note that the electrical noise variances of a link are multiplied with the square of the remaining gain/loss up to the receiver.

The eye penalty impairments do not depend on the utilization of the other channels, but only on the selected path (these impairments belong to class 1 of Table I). In any case, since the eye impairments and the transmitters' power and amplifiers/links gains/losses do not change significantly when a new connection is established or released, we can precalculate offline (between requests) so as to obtain  $I_{1',pw}$  for all candidate lightpaths and store them in a database. Another approach is to use quick and efficient models to calculate  $I_{1',pw}$  as the algorithm is executed, something that is relatively simple especially under the assumption that CD is fully compensated and SPM effect is low and negligible for the network under study [14].

2) *Computing the Cost Vector of a Path*: We assume that the node where the algorithm is executed maintains a database with the parameters  $I_{1',pw}$  of all lightpaths ( $p, w$ ) or can calculate them in a timely manner. We also assume that the node that runs the algorithm maintains or calculates the *vectors* containing the electrical noise variances  $\sigma_{1',l}^2$ , and  $\sigma_{0',l}^2$  of signal '1' and signal '0' of all links  $l$ , respectively, whose  $i$ th entries denote the corresponding variances for wavelength  $i$ . We have used a quick algorithm to calculate these vectors that is presented in Appendix B.

Link  $l$  is assigned a cost vector with  $1 + 4 \cdot m$  cost parameters:

- 1) the delay of the link, or equivalently, its length  $d_l$  (scalar);
- 2) a vector  $\overline{G}_l = (G_{l1}, G_{l2}, \dots, G_{lm})$  with the gain/loss of the link for each of the wavelengths, in decibels;
- 3) a vector  $\overline{\sigma_{1',l}^2} = (\sigma_{1',l1}^2, \sigma_{1',l2}^2, \dots, \sigma_{1',lm}^2)$  with the electrical noise variances of signal '1' for each wavelength;
- 4) a vector  $\overline{\sigma_{0',l}^2} = (\sigma_{0',l1}^2, \sigma_{0',l2}^2, \dots, \sigma_{0',lm}^2)$  with the electrical noise variances of signal '0' for each wavelength;
- 5) a Boolean vector  $\overline{W}_l = (w_{l1}, w_{l2}, \dots, w_{lm})$  to record wavelength availability.

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

$$V_l = (d_l, \overline{G}_l, \overline{\sigma_{1',l}^2}, \overline{\sigma_{0',l}^2}, \overline{W}_l).$$

Similarly to a link, a path has a cost vector with  $1 + 4 \cdot m$  parameters, in addition to the list of identifiers ( $*p$ ) of the links that comprise it. The cost vector of path  $p$  can be calculated using (6) and (7) by the cost vectors of the links  $l = 1, 2, \dots, k$  that comprise it. The related associative operator  $\oplus$  is defined as

$$V_p = \bigoplus_{l \in p} V_l = \left( \sum_{l=1}^k d_l, \sum_{l=1}^k \overline{G}_l, \sum_{l=1}^k \left( \overline{\sigma_{1',l}^2} \cdot \prod_{l'=l+1}^k 10^{2 \cdot \overline{G}_{l'}/10} \right), \sum_{l=1}^k \left( \overline{\sigma_{0',l}^2} \cdot \prod_{l'=l+1}^k 10^{2 \cdot \overline{G}_{l'}/10} \right), \& \overline{W}_l, (1, 2, \dots, k) \right). \quad (8)$$



As previously, all operations between vectors are interpreted componentwise.

3) *Estimating the Feasibility of Available Lightpaths*: In the indirect Multi-Parametric algorithm (Section IV-A2), we estimate the feasibility of a lightpath using the indirect quality of transmission metric QUOTE, while in the direct Sigma-Cost algorithm we use directly the  $Q$ -factor. For a path  $p$ , we check if the available wavelengths of that path (marked by 1 in  $\overline{W}_p$ ) have acceptable  $Q$ -factor performance. In particular, for a candidate lightpath  $(p, w)$ , we use the cost vector  $V_{pw}$  to obtain  $\sigma_{1',pw}$  and  $\sigma_{0',pw}$ , and the list of links  $*p$  to obtain  $I_{1',p}$  [through a database lookup or quick calculation (Section IV-B1)]. Then, by using (2), we obtain the  $Q$ -factor  $Q_{pw}$  of this lightpath and check if it is higher than a given threshold  $Q_{\min}$  (recall that the higher the  $Q$ -factor, the better the signal quality is). For the wavelengths of path  $p$  that do not satisfy the threshold, we set the corresponding index of the utilization vector  $\overline{W}_p$  equal to zero so as to make them unavailable due to poor QoT.

*Algorithm Description*: Similarly to the indirect Multi-Parametric algorithm presented in Section IV-A3, the direct Sigma-Cost IA-RWA algorithm consists of three basic and one optional phases.

In the first phase of the algorithm, we compute the set of non-dominated paths  $P_{n-d}$  from the given source to the given destination. To do so, we use the algorithm presented in Fig. 4, the associative operator  $\oplus$  of (8), and the following definition of the domination relationship between two paths:

$$p_1 \text{ dominated } p_2 (\text{notation: } p_1 > p_2) \text{ iff } (d_{p_1} \leq d_{p_2} \text{ and for all } i: w_{p_1 i} \geq w_{p_2 i} \text{ and } w_{p_2 i} \cdot Q_{p_1 i} \geq Q_{p_2 i}). \quad (9)$$

Again in the domination relationship, the  $Q$ -factor is compared only for the wavelengths of path  $p_2$  that are active.

In the second phase, we apply an optimization function or policy  $f(V_{pw})$  to the cost vector  $V_{pw}$  of the lightpaths  $(p, w)$  that are available over paths  $p \in P_{n-d}$ . Similarly to the Multi-Parametric algorithm, we evaluated the following policies: 1) MUW; 2) *Better Q performance* (bQ); and 3) *Mixed better Q and wavelength utilization* (bQ-MUW). The difference is that for a lightpath, instead of the transmission performance QUOTE metric, we calculate and use its  $Q$ -factor value. Also, we should emphasize that the larger the  $Q$ -factor value is, the better is the QoT of a lightpath, while the opposite is true for the QUOTE metric.

In the third phase of the algorithm, we evaluate the effect of the new lightpath on the already established lightpaths. If one or more lightpaths are turned infeasible, we either: 1) reject the new lightpath; 2) select another candidate lightpath; or 3) reroute the old connections.

Finally, the fourth phase involves the verification of the solution through a detailed Q-Tool estimator. As already mentioned, this phase is typically performed in the case of the Multi-Parametric algorithm and is typically omitted in Sigma-Cost algorithm, at least when the simplifying models and assumptions used are accurate and do not overestimate the quality of the signal (see the discussion in Section III-C).

### C. Algorithms Complexity

The complexity of a multicost algorithm depends on the number and type of the cost parameters comprising the cost vector [21]. The  $m$ -dimensional Boolean vector  $\overline{W}_p$  recording the wavelengths' utilization on path  $p$  can take  $2^m$  different

values, where  $m$  is the number of wavelengths per link. A path  $p$  that has worse values for both  $d_p$  and  $Q_p$  than another path may not be dominated if its  $\overline{W}_p$  vector is not dominated.

We focus on a particular path  $p$  and let  $Z_k$  be the set of utilization vectors with  $k$  "ones" ("one" marks an available wavelength slot). It is easy to see that  $Z_k$  is a set of nondominated utilization vectors, and that the vectors in  $Z_k$  dominate all the vectors with  $k-1$  or less available slots. Any utilization vector with higher than  $k$  available slots would dominate more than one vector in  $Z_k$ . It can be shown that the set  $Z_{\lfloor m/2 \rfloor}$  obtained for  $k = \lfloor m/2 \rfloor$  is the nondominating set with the highest cardinality. Thus, the set of nondominated utilization vectors may have cardinality up to

$$\binom{m}{\lfloor m/2 \rfloor} \approx \frac{\sqrt{2 \cdot \pi \cdot m} \cdot \left(\frac{m}{e}\right)^m}{\left(\sqrt{2 \cdot \pi \cdot m/2} \cdot \left(\frac{m/2}{e}\right)^{m/2}\right)^2} = \frac{2}{\sqrt{2 \cdot \pi}} \cdot \frac{2^m}{\sqrt{m}} \quad (10)$$

which is exponential in  $m$ . All these nondominated vectors may have to be calculated by the proposed multicost algorithms, meaning that, in the worst case, their running times would be nonpolynomial in the size of the input. However, in realistic networks cases, such a high number of nondominated paths are seldom encountered due to the correlation of the link cost vectors imposed by the wavelength continuity constraint [24].

A possible variation of the proposed algorithms is to use a *pseudo-domination* relationship [instead of the domination relationships of (5) and (9) in the indirect and the direct algorithms, respectively] to reduce algorithmic complexity [22]. The pseudo-domination relationship could be defined to have more relaxed requirements so that more paths are (pseudo-)dominated and thus pruned and not considered further in the execution of the algorithm. For example, instead of comparing the utilization of each wavelength separately in  $\overline{W}_p$ , we can compare the total number of available wavelengths, which can take at most  $m$  values. Additionally, in the Sigma-Cost algorithm, *usually* (but not always) the better (smaller)  $d_p$  is, the better (larger)  $Q_p$  also is, and therefore the paths that are better with respect to one of these two criteria and worse with respect to the other will not be that many. Similarly, in the domination relation of the Multi-Parametric algorithm, we can use for each vector  $\overline{A}_i$ ,  $\overline{SA}_i$ ,  $\overline{X}_i$ ,  $\overline{FW}_i$  its worst value, alleviating the dependence on  $m$ , obtaining polynomial running time algorithms. Since under all examined cases (see Section V) the execution times of the algorithms were acceptable and low, this possibility was not pursued further and can be explored in future works.

### D. QoS Differentiation and Algorithms Extensions

Based on the optimization policies and the discussion about reroutings, a number of approaches to provide QoS differentiation among connections become apparent. One possibility is to define several classes of service, where lightpaths of class 1 are not allowed to be rerouted; lightpaths of class 2 may be rerouted for establishing a new class-1 connection, etc. Also, depending on the optimization policy used, different features can be delivered. For example, the bQ policy (Section IV-B4) tends to select lightpaths that have a low probability of being rerouted in the future, while the MUW policy is designed so as to exhibit low network-layer blocking and high service probability, which are important for real-time applications with relaxed QoT requirements. In any case, the multicost algorithms proposed here

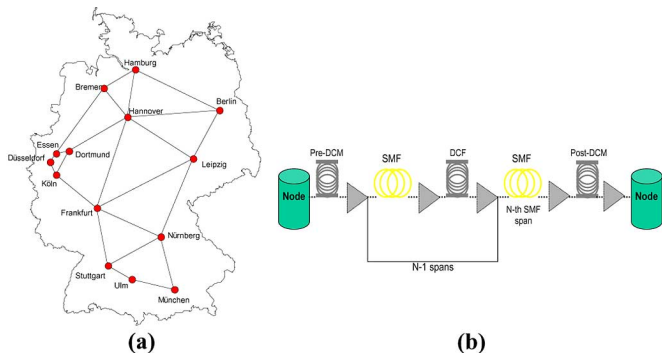


Fig. 6. (a) Generic DT network topology with 14 nodes and 46 directional links. (b) Link model used in the simulation experiments.

are general and can support many options and selection criteria, such as using the path's delay or hop count in the optimization function, extending the definition of the cost vector to include an energy cost for using a link, etc., that are left to be explored in the future.

Even though we focus only on transparent networks in this paper, the presence of wavelength converters or 3R regenerators can also be included in the formulation of our multicost algorithms [26]. In particular, assume that we extend a subpath  $p$  ending at a node  $n$ , where regenerators are available by adding an outgoing link  $l$ . When extending  $p$ , we then have two options: 1) use one of the available regenerators, or 2) do not use one. Thus, we create two paths and accordingly define their cost vectors. In particular, when regeneration is not used, we add to the cost vector of  $p$  the cost vector of link  $l$  as done in this paper using (8). Meanwhile, when a regenerator is utilized, the impairments are compensated and the wavelength continuity constraint is relaxed at node  $n$ . Then, the cost vector of the path is set equal to the cost vector of the outgoing link  $l$ , and we can also store the cost vector of the path up to that point for future use. Both these paths are considered by the algorithm. An additional parameter indicating the number of used regenerators can also be included in the cost vector and in the optimization function to regulate the use of the regenerators in the network.

## V. PERFORMANCE RESULTS

In order to evaluate the performance of the proposed algorithms, we conducted simulation experiments in MATLAB. The simulations were performed for the Generic DT network topology [Fig. 6(a)], which is a transparent candidate network, as identified by the DICONET project [23]. The feasibility of the selected lightpaths is evaluated using a  $Q$ -factor estimator (the  $Q$ -Tool developed within the same project [23]) that uses detailed analytical models. The  $Q$ -Tool takes as input the new and the already established lightpaths, calculates their  $Q$ -factors, and determines which of them have unacceptable QoT.

The link model of the reference network is presented in Fig. 6(b). We assumed 10-Gb/s transmission rates and channel spacing of 50 GHz. The span length on each link was set to 100 km. Each link was assumed to consist of single-mode fiber (SMF) with dispersion and attenuation parameters  $D = 17$  ps/nm/km and  $a = 0.25$  dB/km, respectively. For the dispersion compensation fiber (DCF), we assumed parameters  $D = -80$  ps/nm/km and  $a = 0.5$  dB/km. The launch power was set to 3 dBm/ch for every SMF span and  $-4$  dBm/ch for

the DCF modules. The erbium-doped fiber amplifiers' (EDFA) noise figure was set to approximately 6 dB with small variations ( $\pm 0.5$  dB), and each EDFA exactly compensates for the losses of the preceding fiber span. We assumed a switch architecture similar to [10] and a switch-crosstalk ratio  $X_{sw} = 32$  dBs with small variations per node ( $\pm 1$  dB). Regarding dispersion management, a precompensation module was used in order to achieve better transmission reach: Every span was under-compensated by a value of 30 ps/nm to alleviate nonlinear effects, and the accumulated dispersion at the input of each switch was fully compensated to zero using an appropriate post-compensation module. Note that the physical-layer assumptions presented do not constrain the applicability of the proposed algorithms, which are general and can also be used in cases where the links do not follow the amplification and the dispersion strategy previously described.

Connection requests of a single wavelength (10 Gb/s) are generated according to a Poisson process with rate  $\lambda$  requests/time unit. The source and destination of a connection are uniformly chosen among all nodes. The duration of a connection is exponentially distributed with average  $1/\mu$  time units. Thus,  $\lambda/\mu$  gives the total network load in Erlangs.

### A. Tuning the Parameters of the Multi-Parametric Algorithm

We start by fine tuning the parameters of the Multi-Parametric indirect IA-RWA algorithm of Section IV-A.

Based on a large number of (trial and error) tests performed, we ended up with the following QUOTE function:

$$\text{QUOTE}(p, w) = d_{pw}/100 + h_{pw} + 1.25 \cdot a_{pw} + sa_{pw} + 1.5 \cdot x_{pw} + 0.3 \cdot fw_{pw}. \quad (11)$$

We found that these coefficient values result in very satisfactory performance in terms of the blocking probability achieved for the network and physical parameters under study.

We now present the procedure followed in order to decide the  $\text{QUOTE}_{\max}$  threshold's value, below which a candidate lightpath is considered to have adequate QoT. In Fig. 7, we plot the performance of the MUW, minQUOTE, and maxQUOTE schemes as a function of the used  $\text{QUOTE}_{\max}$  threshold. In particular, along with the total connection blocking, we also separately record the following two constituent kinds of blockings. The first, to be referred to as Phase 1 blocking, corresponds to the case where no candidate lightpath is found in Phase 1 of the Multi-Parametric algorithm (Fig. 3), either due to wavelength unavailability or due to not being able to meet the  $\text{QUOTE}_{\max}$  threshold. The second kind of blocking, to be referred to as Phase 4 blocking, corresponds to the case where the lightpath considered to be feasible in Phase 1 of the Multi-Parametric algorithm was later found by the  $Q$ -Tool in Phase 4 to have unacceptable  $Q$ -factor. The number of total blockings is equal to the sum of the Phase 1 and Phase 4 blockings. We observe that as the  $\text{QUOTE}_{\max}$  threshold increases, the number of connections blocked due to the QUOTE function in Phase 1 decreases, while the number of connections blocked due to the  $Q$ -Tool in Phase 4 increases. This is because when using a smaller (more restrictive)  $\text{QUOTE}_{\max}$  threshold, many candidate lightpaths are discarded in Phase 1 of the algorithm, and those that are not rejected have very good QoT, usually accepted by the  $Q$ -Tool. On the other hand, when we use a large (more permissive)  $\text{QUOTE}_{\max}$  threshold, many lightpaths

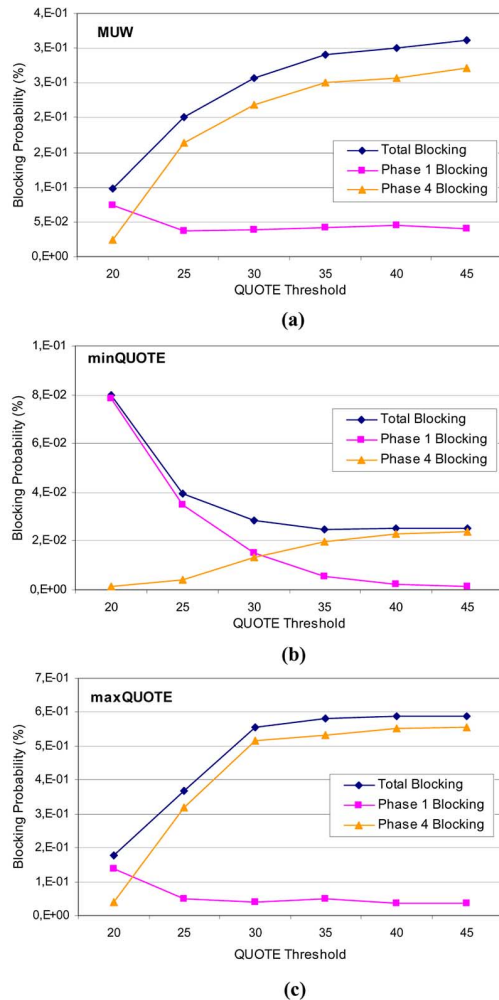


Fig. 7. Total blocking, the Phase-1 and the Phase-4 induced blocking, for (a) MUW, (b) minQUOTE, and (c) maxQUOTE optimization functions of the Multi-Parametric algorithm for fixed load equal to 100 Erlangs,  $W = 16$  available wavelengths, as a function of  $QUOTE_{max}$  threshold values.

pass the test of Phase 1, but some of them have actually unsatisfactory QoT and are rejected in Phase 4. We also observe that, in the minQUOTE scheme, the intersection of the Phase 1 and Phase 4 blocking plots occurs for a larger  $QUOTE_{max}$  value than in the MUW and maxQUOTE schemes, meaning that the number of connections blocked by the Q-Tool in Phase 4 is kept small for a large range of  $QUOTE_{max}$  threshold values. Based on these graphs, we decided to set the  $QUOTE_{max}$  threshold equal to 30 for the minQUOTE scheme and equal to 20 for the MUW and the maxQUOTE schemes. These results also indicate that it is possible to achieve acceptable QoT in the Multi-Parametric scheme without using the Q-Tool, thereby omitting Phase 4 of the algorithm. Generally, we would like to use the Q-Tool in some initial executions of the algorithm to tune the QUOTE function and  $QUOTE_{max}$  threshold (this will depend on the modulation format, rate, etc.). After the tuning procedure, the Q-Tool is no longer necessary in practice, and the Multi-Parametric scheme can be executed without it.

In Fig. 8, we plot the blocking performance of the MUW, minQUOTE, and maxQUOTE policies, with  $QUOTE_{max}$  threshold set to the better performing values, as previously observed, and in particular equal to 20, 30, and 20, respectively. These experiments were performed for load equal to 100 Erlangs and

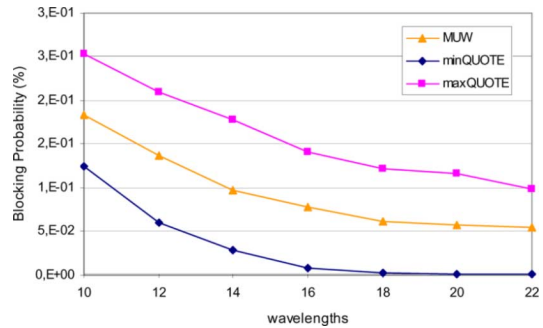


Fig. 8. Blocking probability of the Multi-Parametric policies as a function of the number of available wavelengths  $W$  for 100-Erlangs network load.

different values for number of available wavelengths  $W$ . We observe that the minQUOTE scheme yields the smallest total blocking, followed by the MUW and the maxQUOTE schemes. As expected, more connections are successfully served as  $W$  increases. In the following comparisons, we chose to consider only the minQUOTE scheme since it was shown in these experiments to outperform the other two Multi-Parametric schemes.

### B. Comparing the Performance of the Multicost Algorithms

In this section, we compare the performance of the proposed online IA-RWA algorithms to that of a typical  $k$ -shortest path IA-RWA algorithm. In particular, we compare the following algorithms: 1) the Multi-Parametric algorithm using the minQUOTE optimization function tuned as previously described, in two variations—MP\_Q and MP\_no\_Q—that correspond to using or not using the Q-tool (optional fourth phase); 2) the SC multicost algorithm, presented in Section IV-B, using the better performing mixed bQ-MUW optimization functions (the MUW and bQ policies are not displayed to make the figures more readable); and 3) the  $k$ -SP-Q ( $k = 3$ ) algorithm. The  $k$ -SP-Q algorithm calculates  $k$ -shortest length paths and selects the shortest that has a free wavelength; if more than one wavelength is available over that path, the MUW wavelength is selected.

Both the  $k$ -SP-Q algorithm and the MP\_Q variation of the Multi-Parametric algorithm that makes use of the optional fourth phase use the Q-Tool to check the QoT of their chosen lightpaths. In case the Q-Tool rejects the selected lightpath, another lightpath is chosen from the set of candidate lightpaths. This is repeated up to four times in these experiments. In the case of the MP\_Q scheme, this is done by choosing the second, third, etc., best lightpath with respect to the optimization function used (minQUOTE) from the set of nondominated paths calculated in Phase 1 of the algorithm. Note that this approach was not applied in the previous Multi-Parametric experiments (Section V-A), where a connection was blocked after the Q-Tool rejected the selected lightpath, since in those experiments our objective was to evaluate the performance of the different optimization policies. In the case of the  $k$ -SP-Q algorithm, when the Q-Tool rejects the selected lightpath, the next MUW wavelength is selected, and when no more wavelengths are available on the shortest path, we move to the next shortest path, etc. The  $k$ -SP-Q algorithm makes heavy use of the Q-Tool in order to select a feasible path from a set of candidate lightpaths consisting of the  $k$ -shortest paths. Note that in the case of the direct SC algorithm and the MP\_no\_Q variation, the Q-Tool is not used. In these algorithms, when

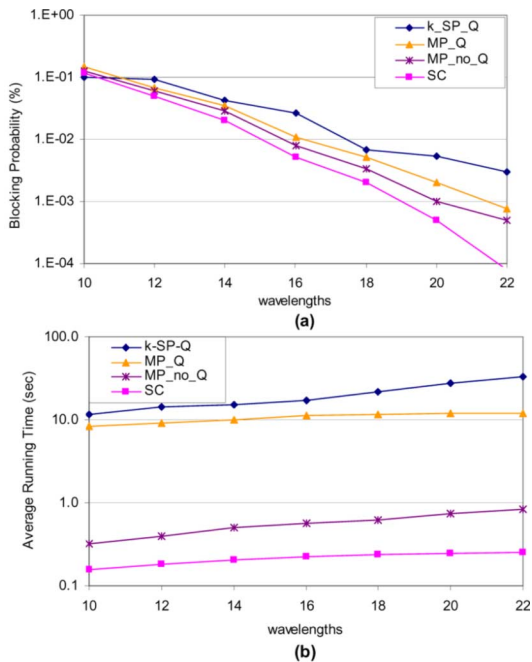


Fig. 9. (a) Blocking probability and (b) average running time per connection in seconds, as a function of the number of available wavelengths  $W$  for fixed network load equal to 100 Erlangs.

the interference caused by the chosen lightpath makes some already established connections (third phase) infeasible, the algorithms return to the second phase and select the second lightpath, which is in turn evaluated in the third phase, and so on, for a total of up to four times. No reroutings were allowed in this set of experiments.

Fig. 9(a) shows the blocking rate of the evaluated algorithms. We observe that the SC algorithm produces the best results, while the  $k$ -SP-Q algorithm produces the worst. The blocking of the MP-Q variation is slightly higher than that of the same algorithm without using Q-tool (MP\_no-Q). Essentially, this difference corresponds to the error of not using the Q-tool. The MP\_no-Q variation relies only on the QUOTE metric to evaluate the QoT feasibility of the lightpaths, and despite the tuning procedure, there are some cases where it misjudges the QoT feasibility of the lightpaths. In any case, the error of not using Q-Tool is quite small and can be tolerated, given the significant gains obtained in the running time [see Fig. 9(b)]. As expected, the number of connections blocked decreases when the number of available wavelengths increases, and most of the algorithms are able to achieve near-zero blocking when enough wavelengths are available. The MP-Q and MP\_no-Q algorithms indirectly take into account the impairments (through the impairment generating sources and the QUOTE function). As a result, some of the QoT feasible paths may not be considered, resulting in a reduced solution space, or some candidate paths may be QoT infeasible and be blocked (if chosen) in the fourth phase, which would result in selecting the second, third, etc., lightpath solution. Thus, the performance of the indirect MP algorithms is worse than that of the direct SC algorithm. However, as discussed in Section III-B, this indirect approach of the MP algorithms makes it more generic and easily applicable to different conditions (modulation formats and bit rates).

In Fig. 9(b), we observe that the average running times of the proposed SC and MP\_no-Q algorithms are quite small, in

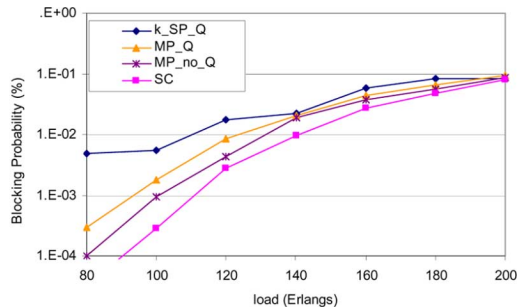


Fig. 10. Blocking probability as a function of the network load, for fixed number of available wavelengths  $W = 20$ .

the order of a few hundreds of milliseconds. These are comparable and even lower than the corresponding average execution times reported in the literature [14], [18]. Despite its simplicity, the  $k$ -SP-Q algorithm has very high running time, in the order of few tens of seconds, because it relies heavily on the detailed Q-Tool. This is also the case for the MP-Q variation. The execution of the detailed Q-Tool is the dominant delay factor in these experiments. The improvement in the running time of the MP algorithm when using the Q-tool (MP-Q) compared to the case where it does not use it (MP\_no-Q) is significant, up to three orders of magnitude. As discussed in Section V-A, after tuning the QUOTE function and QUOTE<sub>max</sub> threshold, the Q-Tool rarely rejects a selected lightpath, and the error of not using it is rather small [see Fig. 9(a)]. Thus, the Q-tool (phase 4) may be omitted, dramatically reducing the running time. In all cases, the running times of the algorithms increase with the number of available wavelengths since then: 1) fewer connections are blocked and the Q-Tool has to treat a larger number of established lightpaths, and 2) more nondominated paths are found in the first phase of the MP and SC algorithms.

In Fig. 10, we compare the performance of the  $k$ -SP-Q and the proposed multicost algorithms as a function of the network load for a fixed number of wavelengths. The results are qualitatively similar to the ones presented in Fig. 9. Increasing network load deteriorates the algorithms' blocking performance as expected. The SC algorithm exhibits the best blocking performance, followed by the MP\_no-Q and MP-Q algorithms, while  $k$ -SP-Q comes last.

### C. Random Networks Experiments

The set of experiments reported in this section aims at evaluating the scalability of the proposed IA-RWA algorithms. Toward this end, we have created 10 random networks with  $N = 10, 20, 30,$  and  $40$  nodes (40 networks in total) and average connectivity degree equal to 3.5. For each network, we find the number of hops  $h_{max}$  of the longest hop path and set the distance between two adjacent nodes constant and equal to  $1200 \text{ km}/h_{max}$ . The physical-layer parameters were similar to those assumed for the DT network. In Fig. 11, we present the blocking probability and the running time required to serve a single connection, averaged over the 10 random networks for each value of  $N$ . We have assumed traffic of 200 Erlangs and  $W = 20$  wavelengths per link. As the number of nodes increases, the blocking probability decreases since the same load is divided in a larger network and link congestion is less probable. The SC algorithm exhibits the best blocking performance, with that of the MP algorithms (with and without

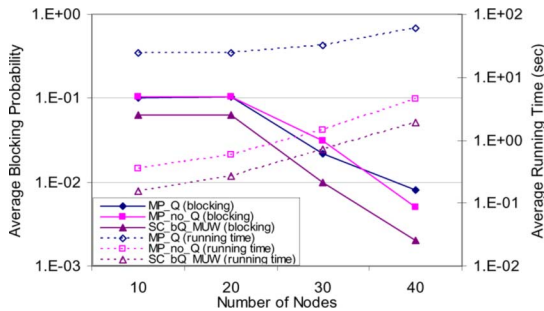


Fig. 11. Average blocking probability and average running times for random networks with 10, 20, 30, and 40 nodes, traffic load equal to 200 Erlangs, and  $W = 20$  available wavelengths per link.

the use of Q tool) coming quite close. As expected, the average running time increases with the number of nodes. Again, the MP\_with\_Q algorithm that uses the slow Q-tool evaluation module exhibits the highest running times. The running times of the proposed multicost algorithms scale well with the number of nodes. Remember that the number of paths that can be calculated by the algorithm in the worst case can be exponential in the size of the input, but, at least for the examined scenarios, the problem is still tractable within reasonable time (up to a few seconds for 40-node networks). In any case, the complexity of the algorithms can be reduced to polynomial by applying pseudo-dominance relationships, as described in Section IV-C.

## VI. CONCLUSION

We proposed two multicost impairment-aware routing and wavelength assignment algorithms for online traffic. The first Multi-Parametric (or indirect) IA-RWA algorithm includes in its cost vector network-layer parameters that act as impairment-generating sources. The Multi-Parametric algorithm uses a function to combine these parameters into a scalar cost, and a threshold to evaluate the feasibility of a lightpath. A lightpath that has a small number of impairment-generating sources and satisfies the corresponding threshold is indirectly expected to exhibit good QoT. The second Sigma-Cost (or direct) multicost IA-RWA algorithm, uses noise variance-related cost parameters. These can be combined in order to calculate the  $Q$ -factor of a candidate lightpath, so as to directly evaluate its QoT feasibility. To serve a connection, the proposed algorithms calculate a set of nondominated lightpaths, based on the parameters they incorporate, and then apply an objective function or (selection policy) to choose the optimal lightpath. Various objective functions that correspond to different IA-RWA algorithms were proposed and evaluated. The indirect Multi-Parametric algorithm after a tuning procedure was able to provide good solutions to the IA-RWA problem without using specific analytical models for the physical-layer impairments. When analytical models and the corresponding parameters are available, the direct Sigma-Cost algorithm provided even better solutions. Our results indicated that the proposed IA-RWA algorithms can efficiently serve the online traffic in a transparent network so as to guarantee the transmission quality of the lightpaths with low running times.

### APPENDIX A

#### COMPUTING LINK INTERFERENCE PARAMETERS

We show how to compute the interference parameters of link  $l$  ending at node (OXC switch)  $n$ , and in particular how to compute the vectors of active adjacent channels  $\overline{A}_l$ , active second

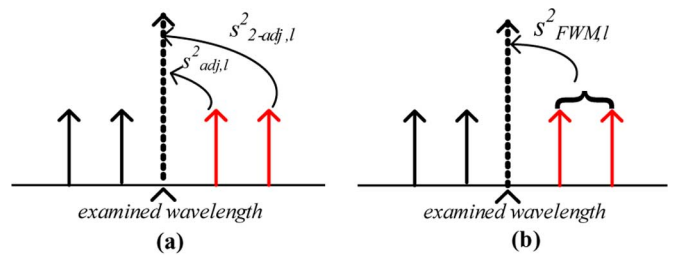


Fig. 12. (a) Noise variance contribution due to XPM from the adjacent and next-to-adjacent channels. (b) Noise variance contribution due to FWM when the two adjacent channels are active (degenerate FWM).

adjacent channels  $\overline{SA}_l$ , intra-XT generating sources  $\overline{X}_l$ , and four-wave-mixing generating sources  $\overline{FM}_l$ .

We assume that we know the wavelength utilization vector  $W_l$  of all links  $l \in L$  of the network. The wavelength utilization vector  $\overline{W}_l$  of link  $l$  has its  $i$ th entry  $w_{li}$  equal to 0 when wavelength  $\lambda_i$  is used, and equal to 1 when  $\lambda_i$  is free (available),  $i = 1, 2, \dots, m$ . We also denote  $w'_{li} = 1 - w_{li}$ .

For link  $l$  ending at node  $n$ , we have the following.

- The number of active adjacent channels on wavelength  $i$  is  $a_{li} = w'_{l,i-1} + w'_{l,i+1}$ .
- The number of second adjacent channels on wavelength  $i$  is  $sa_{li} = w'_{l,i-2} + w'_{l,i+2}$ .
- The number of intra-XT generating sources is  $x_{li} = \sum_{l' \neq l} w'_{l',i}$ , where  $l' \neq l$  are links ending at node  $n$ .
- The number of FWM generating sources is  $f_{mi} = (w'_{l,i-1} \cdot w'_{l,i-2}) + (w'_{l,i+1} \cdot w'_{l,i+2})$ . Note that we only consider degenerate FWM effect.

### APPENDIX B

#### COMPUTING LINK NOISE VARIANCE PARAMETERS

In this appendix, we show how the noise variances of signal '1' and '0' of link  $l$  ending at node (switch)  $n$  are computed.

We assume that for link  $l$  we know the following values:

- $\sigma_{ASE,1',l}^2 (\sigma_{ASE,0',l}^2)$ : the ASE noise variance of '1' (or '0') due to  $l$  inline amplifiers and the amplifiers of switch  $n$ ;
- $s_{XT,1',l}^2 (s_{XT,0',l}^2)$ : the intrachannel XT noise variance of '1' (or '0') due to a lightpath crossing switch  $n$  that uses the same wavelength with the examined wavelength;
- $s_{adj,l}^2 (s_{2-adj,l}^2)$ : the noise variance due to XPM from an active adjacent (or second adjacent) channel [Fig. 12(a)];
- $s_{FWM,1',l}^2 = s_{FWM,0',l}^2 = s_{FWM,l}^2$ : the noise variance due to FWM that two active adjacent channels contribute [Fig. 12(b)].

Note that, in this approach, we assume that  $s_{XT,1',l}^2, s_{XT,0',l}^2, s_{adj,l}^2, s_{2-adj,l}^2, s_{FWM,1',l}^2$  and  $s_{FWM,0',l}^2$  are the same, irrespective of the examined wavelength (but this is not restrictive, and we can use wavelength-dependent parameters). This is an acceptable assumption that permits us to perform fast calculations. The notation  $s^2$  is used instead of  $\sigma^2$  to stress that  $s^2$  corresponds to the contribution of a "single" impairment source while  $\sigma^2$  denotes the total contribution of the corresponding impairment. In our experiments, these parameters were found using corresponding analytical formulas, but values obtained from appropriate monitors could also be used.

Based on the interfering parameters of link  $l$ ,  $\overline{A}_l$ ,  $\overline{SA}_l$ ,  $\overline{X}_l$ , and  $\overline{FM}_l$ , as computed in Appendix A, we can calculate the noise variance parameters as follows.

- $\sigma_{1',XT,li}^2 = x_{XT,li} \cdot s_{1',XT,l}^2$  and  $\sigma_{0',XT,li}^2 = x_{XT,li} \cdot s_{0',XT,l}^2$ .
- $\sigma_{XPM,li}^2 = a_{adj,li} \cdot s_{adj,li}^2 + x_{2-adj,li} \cdot s_{2-adj,l}^2$ .
- $\sigma_{FWM,1',li}^2 = x_{FWM,li} \cdot s_{FWM,l}^2$  and  $\sigma_{FWM,0',li}^2 = x_{FWM,li} \cdot s_{FWM,l}^2$ .

Regarding XPM and FWM, note that we consider the contribution of only the two adjacent channels from each side of the examined wavelength  $i$ , and we also assume that their contribution is symmetrical. In general, the noise contribution of the active channels is reduced as we move away from the examined wavelength. Recall that in the context of an online algorithm, accuracy is not the main issue, but simplicity and efficiency are. (A more accurate estimate of the  $Q$ -factors of the chosen lightpaths can be used in the final validation phase of the algorithm to decide if a lightpath is feasible or not.)

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