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Offline Routing and Wavelength Assignment in Transparent WDM Networks

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***Abstract*—We consider the offline version of the routing and wavelength assignment (RWA) problem in transparent all-optical networks. In such networks and in the absence of regenerators, the signal quality of transmission degrades due to physical layer impairments. Because of certain physical effects, routing choices made for one lightpath affect and are affected by the choices made for the other lightpaths. This interference among the lightpaths is particularly difficult to formulate in an offline algorithm since, in this version of the problem, we start without any established connections and the utilization of lightpaths are the variables of the problem. We initially present an algorithm for solving the pure (without impairments) RWA problem based on a LP-relaxation formulation that tends to yield integer solutions. Then, we extend this algorithm and present two impairment-aware (IA) RWA algorithms that account for the interference among lightpaths in their formulation. The first algorithm takes the physical layer indirectly into account by limiting the impairment-generating sources. The second algorithm uses noise variance-related parameters to directly account for the most important physical impairments. The objective of the resulting cross-layer optimization problem is not only to serve the connections using a small number of wavelengths (network layer objective), but also to select lightpaths that have acceptable quality of transmission (physical layer objective). Simulations experiments using realistic network, physical layer, and traffic parameters indicate that the proposed algorithms can solve real problems within acceptable time.**

***Index Terms*—Cross-layer optimization, LP-relaxation, offline or static traffic, physical layer impairments, quality of transmission, routing and wavelength assignment (RWA), transparent all-optical networks, wavelength routed WDM networks.**

I. Introduction

IN a wavelength division multiplexing (WDM) network, each fiber link carries high-rate traffic at several different wavelengths, thus creating multiple channels within a single fiber. The most common architecture utilized for establishing communication in WDM optical networks is wavelength routing, where optical pulse-trains are transmitted through *lightpaths*, that is, all-optical WDM channels that may span multiple consecutive fibers [1], [2].

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Current optical core networks are mainly point-to-point (opaque) networks, where the signal is regenerated at every intermediate node via optical-electronic-optical (OEO) conversion. As the size of opaque networks increases, network designers have to consider more electronic terminating and switching equipments, which contribute to cost (CAPEX), heat dissipation, power consumption, physical space requirements, and operation and maintenance costs (OPEX). The trend in recent years shows an evolution toward low-cost and high-capacity all-optical networks that do not utilize OEO. Initially, the cost of an opaque network can be reduced by moving toward a network where OEO conversion is employed only at some nodes, which is usually referred to as a *translucent* (or managed reach) network. The ultimate goal is the development of an all-optical *transparent* network, where the data signal remains in the optical domain for the entire lightpath.

Since the lightpaths are the basic switched entities of a wavelength routed WDM network, their effective establishment and usage are crucial. Thus, it is important to propose efficient algorithms to select the routes for the requested connections and to assign wavelengths on each of the links along these routes. This is known as the *routing and wavelength assignment* (abbreviated RWA) problem. The constraints are that paths that share common links are not assigned the same wavelength (*distinct wavelength assignment*). Also, a lightpath, in the absence of wavelength converters, must be assigned a common wavelength on all the links it traverses (*wavelength continuity constraint*).

The RWA problem is usually considered under two alternative traffic models. When the set of connection requests is known in advance (for example, given in the form of a traffic matrix) the problem is referred to as *offline* or *static* RWA, while when the connection requests arrive at random times, over an infinite time horizon, and are served one by one, the problem is referred to as *online* or *dynamic* RWA. The offline problem pertains to the planning phase of the WDM network, while the online problem to the operational phase. We will focus our study on offline RWA, which is known to be an NP-hard problem [4]. Offline RWA is more difficult than online RWA since it aims at jointly optimizing the lightpaths used by the connections in the same way that the multicommodity flow problem is more difficult than the shortest-path problem in general networks.

The majority of offline RWA algorithms proposed to date assume an ideal physical layer where signal transmission is error-free [5]. However, in a transparent or translucent network, where the signal on a lightpath remains in the optical domain, the quality of transmission (QoT) is significantly affected by physical limitations of fibers and optical components, such as amplified spontaneous emission noise (ASE), chromatic dispersion (CD), polarization mode dispersion (PMD), filter concatenation

(FC), intra- and interchannel crosstalk (XT), as well as by nonlinear effects, such as self- and cross-phase modulation (SPM, XPM), four-wave-mixing (FWM), etc. [2], [3]. We will refer to such phenomena as physical layer impairments (PLIs). Because of these impairments, signal quality may degrade to the extent that the bit error rate (BER) at the receiver may be so high that signal detection is infeasible. For the remainder of this study. we will refer to such a phenomenon as *physical-layer blocking*, as opposed to the *network-layer blocking* that arises from the unavailability of an adequate number of wavelengths.

Clearly, the existence of physical impairments limits the number of paths that can be used for routing. This interdependence between the physical and the network layers makes the RWA problem in the presence of impairments a cross-layer optimization problem. To address this problem, a number of approaches are emerging, usually referred to as impairment-aware (IA)-RWA algorithms. An important distinction is how the IA-RWA algorithms define the interaction between the networking and the physical layers and if they jointly optimize the solutions over these two layers. Because of some particular interference-related impairments, routing decisions made for one lightpath affect and are affected by the decisions made for other lightpaths. This interference is particularly difficult to formulate in offline IA-RWA where there are no already established connections and the utilization of the lightpaths are the variables of the problem. It is because of this difficulty that the offline IA-RWA algorithms proposed to date do not handle interference-related impairments.

In this paper, we propose two IA-RWA algorithms for offline traffic that account for the physical impairments and the interference among lightpaths in their formulation and perform a cross-layer optimization between the physical and the network layers. The objective of the IA-RWA problem is not only to serve the connection requests using a small number of wavelengths (network layer objective), but also to select lightpaths that have acceptable QoT (physical layer objective).

We start by presenting an algorithm for solving the "pure" RWA problem (that is, without impairments) that uses path-related variables and is based on a linear programming (LP) relaxation formulation [6], [7]. To obtain good integrality performance, the proposed formulation uses a piecewise linear cost function and a random perturbation technique. If, even with these techniques, the returned solution is not integer, we use fixing and rounding iterations to obtain an integer solution. Our performance results show that this algorithm is able to find optimal solutions for the majority of input instances.

The pure RWA algorithm is next extended so as to also handle physical layer impairments. We propose two novel IA-RWA algorithms. The first algorithm considers *indirectly* the physical impairments. For each lightpath, we soft-constrain: 1) the path's length and the number of hops; 2) the number of adjacent and second adjacent channels across all the links of the lightpath; and 3) the number of intrachannel crosstalk sources (i.e., lightpaths crossing the same switch and utilizing the same wavelength) along the lightpath [8]. By constraining these impairment-generating parameters, the lightpaths comprising the solution are indirectly selected so as to exhibit good quality of transmission. The second IA-RWA algorithm considers *directly* the physical impairments. For each candidate lightpath inserted in the formulation, we calculate a noise variance bound based on the impairments that do not depend on the interference among lightpaths. We use this bound and noise variance parameters to define appropriate constraints that limit the total interference noise accumulated on a lightpath. If the selected lightpaths satisfy these constraints, they have, by definition, acceptable quality of transmission.

Our goal is to provide practical IA-RWA algorithms that can be used in real network and traffic scenarios [23]. Therefore, although the formulations presented here can be solved optimally by ILP for small problems, we focus on LP-relaxation combined with appropriate techniques for obtaining integer solutions that scale well and can give near-optimal solutions to realistic problems.

We assess the performance of the proposed IA-RWA algorithms using simulation experiments. To decide about the feasibility of the selected lightpaths, we use an estimation tool that models analytically the most important impairments so as to calculate the Q-factor values [2] of the selected lightpaths. Our simulation results show that the proposed IA-RWA algorithms can dramatically reduce physical-layer blocking when compared to a pure RWA algorithm that does not consider impairments at all. We present results for a realistic network and traffic load, showing that the proposed algorithms scale well and can solve real problems within acceptable time.

The rest of the paper is organized as follows. In Section II, we present previous works on RWA and IA-RWA. In Section III, we give our pure RWA formulation. We then extend it and propose in Section IV the indirect and the direct impairment-aware RWA algorithms. Simulation results are then presented in Section V. Our conclusions are given in Section VI.

II. Previous Work

The RWA problem has been extensively studied in the literature. The offline version of RWA is known to be an NP-hard optimization problem [4]. To make computations tractable, a common approach is to decouple the RWA into its constituent subproblems, by first finding routes for all requested connections and searching for appropriate wavelength assignment [1], [5]. Note that both subproblems are NP-hard: The routing subproblem for a set of connections corresponds to a multicommodity flow problem, while wavelength assignment corresponds to a graph coloring problem. Various efficient heuristics have been developed for both routing and wavelength assignment. However, such decomposition techniques suffer from the drawback that the optimal solution of the joint RWA might not be included in the solutions provided by the algorithms used for the two subproblems.

RWA integer linear programming (ILP) formulations were initially proposed in [10] and [11]. Since the associated ILP are very hard to solve, the corresponding relaxed linear programs (LP) have been used to get bounds on the optimal value that can be achieved. A review on various offline and online RWA algorithms can be found in [5]. A few newer and more sophisticated RWA algorithms are presented in [6], [7], and [12]. The LP-relaxation formulation proposed in [6], and also considered in [7], is able to produce exact RWA solutions in many cases, despite the absence of integrality constraints.

Recently, RWA algorithms that consider the impact of physical layer impairments have been the subject of intense research. Most of these studies consider the online (dynamic) version of the problem [13]–[18]. Among these online algorithms, there are approaches that consider the quality of transmission problem separately from the RWA problem, that is, they first solve the RWA problem and then evaluate the feasibility of the chosen lightpaths in a separate module [13]–[15]. Iterations are usually performed to improve the physical-layer blocking. Other online approaches incorporate physical impairments into their cost functions and also consider the interference among the lightpaths [16]–[18].

In the dynamic traffic case, where connections are served one by one, the employed algorithm must examine the feasibility of a lightpath that is about to be established. This can be done by calculating (through appropriate models) or measuring (through performance monitors) the interference caused by the already-established lightpaths to the candidate lightpath. However, this cannot be done in the static RWA case, where there are no already-established connections, and the utilization of lightpaths are the variables of the problem. For this reason, offline RWA algorithms proposed to date do not, to the best of our knowledge, consider interlightpath interference. Although it is possible to use online algorithms to solve the offline problem (by sequentially considering each connection in the given set of requests), this approach does not jointly optimize the solution for all the connections. Thus, combinatorial optimization algorithms, like the ones used in the current paper, are usually employed for offline problems.

In [19], the authors solve the pure (without impairments) offline RWA problem and then evaluate the feasibility of the chosen lightpaths in a post-processing phase. For connection requests whose lightpaths do not have acceptable transmission quality, new solutions are found by excluding from the set of candidate paths the ones previously considered. An offline impairment-aware RWA algorithm that assigns Q-factor costs to links before solving the problem is proposed in [20]. However, the proposed algorithm does not take into account the actual interference among lightpaths and assumes a worst-case interference scenario. In [21], the authors formulate the RWA problem by including the optical power so as to ensure that the power level at the beginning of each optical amplifier as well as at the end of each fiber is above a certain threshold.

A main contribution of our work is two (I)LP formulations that solve the offline IA-RWA problem in transparent networks, taking into account not only impairments that depend on the chosen lightpath, but also impairments that depend on the interference among lightpaths as additional constraints in RWA. In this way, cross-layer optimization of the solution over the physical and the network layers is performed.

III. Pure RWA Algorithm

A network topology is represented by a connected graph $G = (V, E)$. V denotes the set of nodes, which we assume not to be equipped with wavelength conversion capabilities. E denotes the set of (point-to-point) single-fiber links. Each fiber is able to support a common set $C = \{1, 2, \ldots, W\}$ of W distinct wavelengths. The static version of RWA assumes an *a priori* known traffic scenario given in the form of a matrix of nonnegative integers Λ, called the traffic matrix. Then, Λ_{sd} denotes the number of requested wavelengths from source s to destination d, which can be greater than one.

The algorithm takes as input a specific RWA instance—that is, a network topology, the set of wavelengths that can be used, and a traffic matrix. It returns the RWA instance solution, in the form of routed lightpaths and assigned wavelengths, as well as the blocking probability, in case the connection requests cannot be served for the given set of wavelengths.

A. Pure RWA Algorithm

The pure RWA algorithm consists of four phases [7]. The first (preprocessing) phase computes a set of candidate paths to route the requested connections. RWA algorithms that do not use any set of predefined paths but allow routing over any feasible path (using multicommodity flow formulations) have also been proposed in the literature. These algorithms are bound to give at least as good solutions as the algorithms that use precalculated paths, such as the one proposed here, but use a much higher number of variables and constraints and do not scale well. In any case, the optimal solution can be also found with a RWA algorithm that uses precalculate paths, given a large enough set of paths. The second phase of the proposed algorithm utilizes Simplex to solve the LP that formulates the given RWA instance. If the solution returned by Simplex is not integer, the third phase uses iterative fixing and rounding techniques to obtain an integer solution. Note that a noninteger solution is not acceptable since a connection is not allowed to bifurcate between alternative paths or wavelength channels. Finally, Phase 4 handles the infeasible instances so that some (if all is not possible) requested connections are established.

Phase 1: In this phase, k candidate paths for each requested connection are calculated using a variation of the k-shortest path algorithm: At each step, a shortest path is selected, and the costs of its links are increased (doubled in our experiments) so as to be avoided by the paths found in subsequent steps. The paths obtained in this way tend to use different edges, so that they are more representative of the path solution space, but they are not always disjoint—and certain good edges can be reused. Therefore, our approach lies between the k-shortest and k-disjoint paths approaches. Note that by changing the way the cost of the links is increased, we can obtain a range of options between these two approaches and control the tradeoff between the reusability of the links and the number of disjoint paths produced. In any case, the proposed RWA algorithm is general and can function with any k-shortest path algorithm. By selecting an appropriately large number for k, the solution space is expected to contain an optimal RWA solution with large probability. After a set P_{sd} of candidate paths for each commodity pair s–d is computed, the total set $P = \cup_{s\text{–}d} P_{sd}$ is inserted to the next phase. The preprocessing phase clearly takes polynomial time.

Phase 2: Taking into account the network topology and number of available wavelengths, the traffic matrix, and the set of paths identified in Phase 1, Phase 2 formulates the given RWA instance as a LP. The LP formulation used is presented in Section IV-B. This LP is solved using the Simplex algorithm that is generally considered efficient for the majority of inputs and has additional advantages, as we will see, for the problem at hand. If the instance is feasible and the solution is integer, the algorithm terminates by returning the corresponding optimal solution in the form of routed lightpaths and assigned wavelengths and blocking equal to zero. If the instance is feasible but the solution is noninteger, we proceed to Phase 3. If the instance is infeasible, meaning that it cannot be solved with the given number of wavelengths, we proceed to Phase 4.

Phase 3: In case of a fractional (noninteger) solution, the third phase involves iterative fixings and roundings, as presented in Section IV-D, to obtain an integer solution. The maximum number of such iterations is the number of connection requests, which is polynomial on the size of the input. Rounding can turn the problem infeasible, and then we proceed to Phase 4. If we find a feasible solution, the algorithm terminates and outputs the routed lightpaths and assigned wavelengths.

Phase 4: This phase is used when the LP instance is infeasible for the given number of wavelengths W. Infeasibility is overcome by progressively increasing the number of available wavelengths and re-executing phases 2 and 3 until a feasible solution is obtained. Then, at the end of Phase 4, we have to select which connections should be blocked so as to reduce the number of wavelengths to the given set. The wavelengths removed are those occupied by the smallest number of lightpaths so as to minimize the number of connections that are blocked. The algorithm terminates and outputs the routed lightpaths and assigned wavelengths, along with the blocking probability, which is in that case strictly greater than zero.

B. RWA LP Formulation

The proposed LP formulation aims at minimizing the maximum resource usage, in terms of wavelengths used on network links. Let $F_l = f(w_l)$ denote the flow cost function, an increasing function on the number of lightpaths w_l traversing link l (the used formula is presented in Section III-C). The LP objective is to minimize the sum of all F_l values. The following parameters, constants and variables are used:

Parameters:
- $s, d \in V$: network nodes;
- $w \in C$: an available wavelength;
- $l \in E$: a network link;
- $p \in P_{sd}$: a candidate path.

Constant:
- Λ_{sd}: the number of requested connections from node s to d.

Variables:
- x_{pw}: An indicator variable, equal to 1 if path p occupies wavelength w, that is if lightpath (p, w) is activated, and equal to 0, otherwise.
- F_l: the flow cost function value of link l

$$\textbf{Minimize}: \sum_l F_l$$

subject to the following constraints:
- Distinct wavelength assignment constraints

$$\sum_{\{p|l\in p\}} x_{pw} \leq 1, \text{ for all } l \in E \text{ and all } w \in C$$

- Incoming traffic constraints

$$\sum_{p\in P_{sd}} \sum_{w} x_{pw} = \Lambda_{sd}, \text{ for all } (s,d) \text{ pairs}$$

- Flow cost function constraints

$$F_l \geq f(w_l) = f\left(\sum_{\{p|l\in p\}} \sum_{w} x_{pw}\right), \text{ for all } l \in E$$

- The integrality constraints are relaxed to

$$0 \leq x_{pw} \leq 1, \text{ for all } p \in P \text{ and all } w \in C.$$

Note that using inequalities for the flow cost function constraints in the above formulation is equivalent to using equalities since these constraints will hold as equalities at the optimal solution. The reason we use inequalities is that they will be more convenient when we employ a piecewise linear cost function f in the LP formulation, as will be presented in Section III-C. Also note that the wavelength continuity constraints are implicitly taken into account by the definition of the path-related variables. In Section IV, we will extend the above LP formulation so as to take into consideration the physical layer impairments.

C. Flow Cost Function

The variable F_l expresses the cost of congestion on link l for a specific selection of the routes. We choose F_l to be a properly increasing function $f(w_l)$ of the number of lightpaths crossing link l. $F_l = f(w_l)$ is chosen to also be strictly convex (instead of, e.g., linear), implying a greater degree of "undesirability," when a link becomes highly congested. This is because it is preferable, in terms of overall network performance, to serve an additional unit of flow using several low-congested links than using a link that is close to saturation. In particular, we utilize the following flow cost function, but other convex functions are also applicable [6], [7]:

$$F_l = f(w_l) = \frac{w_l}{W + 1 - w_l}.$$

The above (nonlinear) function is inserted to the LP in the approximate form of a piecewise linear function, i.e., a continuous function, that consists of W consecutive linear parts. The piecewise linear approximation is constructed as follows. We begin with $F_l(0) = 0$ and iteratively set, for $i = 1, 2, \ldots, W$, $F_l^i(w_l) = a_i \cdot w_l + \beta_i$, $i - 1 \leq w_l \leq i$, where $a_i = F_l(i) - F_l(i-1)$ and $\beta_i = (i-1) \cdot F_l(i) - i \cdot F_l(i-1)$. We insert in the LP formulation W linear constraints of the form

$$F_l^i(w_1) = a_i w_l + \beta_i \leq F_l, \quad i = 1, 2, \ldots, W$$

defined by the corresponding a_i and β_i values for each link l. Since the LP objective is to minimize the cost $\sum_l F_l$, for a specific value of w_l, one of these W linear cost functions, and in particular the one that yields the highest $F_l(w_l)$, is satisfied with equality at the optimal solution of the LP. All the remaining linear functions are deactivated; that is, they are satisfied as strict inequalities at the optimal solution (Fig. 1).

This piecewise linear function is equal to the nonlinear function $F_l = f(w_l)$ at integer argument values $(w_l = 1, 2, \ldots, W)$

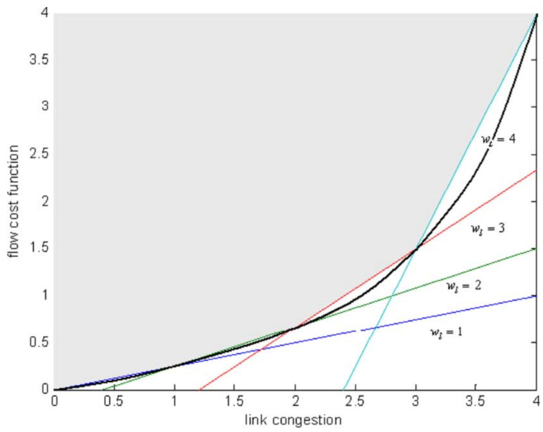

Fig. 1. The set of linear constraints that are inserted in the LP formulation. We use inequality constraints to limit our search in the colored area. Since the objective that is minimized is the flow cost, we finally search for solutions only at its lower bounds, which identify the piecewise linear approximation of the flow cost function $F_l = f(w_l)$ (black line).

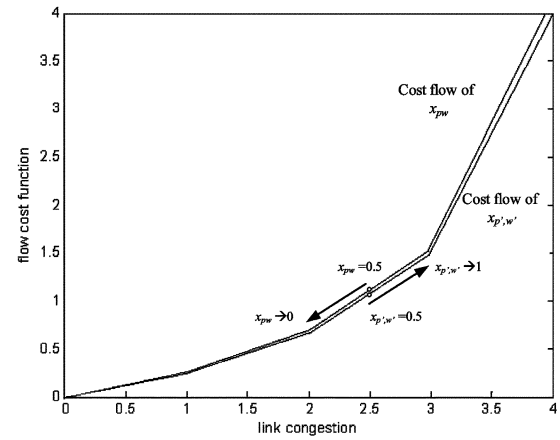

Fig. 2. Random perturbation mechanism. The first derivatives of the two variables x_{pw} and $x_{p',w'}$ are not equal on a specific link. Thus, the variable with the smaller derivative is selected (set to one), yielding an integer solution.

and greater than that at other (fractional) argument values. Inserting such a piecewise linear function to the LP objective results in the identification of integer optimal solutions by Simplex, in most cases [6]. This is because the vertices of the polyhedron defined by the constraints tend to correspond to the corner points of the piecewise linear function and tend to consist also of integer components. Since the Simplex algorithm moves from vertex to vertex of that polyhedron [9], there is a higher probability of obtaining integer solutions than using other methods (e.g., interior point methods). Our experimental results presented in Section V show that this is actually the case in most problem instances.

D. Random Perturbation Technique

Although the piecewise linear cost function presented above is designed so as to yield good integrality characteristics, that is, solution variables that are mostly integer, there are still cases where some of the solution variables of the LP-relaxation turn out to be noninteger. Remember that noninteger solutions for the flow variables are not acceptable.

To increase the number of integer solutions obtained, we use the following random perturbation technique. In the general multicommodity flow problem, given an optimal fractional solution, a flow that is served by more than one paths has equal sum of first derivatives of the costs of the links comprising these paths [25] (see Appendix A for a more detailed explanation). The objective function that we utilize in our RWA formulations sums the flow costs of the links that comprise a lightpath, and thus a request that is served by more than one lightpaths has equal sums of first derivates over the links of these lightpaths. Note that the derivative of the cost on a specific link is given by the slope of the linear or piecewise linear flow cost function used. To make the situations where two lightpaths have equal first derivative lengths over the links that comprise them less probable, and thus obtain more integer solutions, we multiply the slopes on each link with a random number that differ to 1 in the sixth decimal digit (see Fig. 2).

E. Iterative Fixing and Rounding Techniques

If, even with the piecewise linear cost function and the random perturbation technique, we do not obtain an integer solution, we continue by "fixing" and "rounding" the variables.

We start by fixing the variables; that is, we treat the variables that are integer as final and solve the reduced problem for the remaining variables. Fixing variables does not change the objective cost returned by the LP, so we move with each fixing from the previous solution to a solution with equal or more integer variables with the same cost. This is because when some variables are fixed and the RWA problem is reduced, Simplex uses different variables and constraints and starts from a different basic feasible solution (bfs) [9]. Thus, it ends with the same objective cost, but with a solution that might consist of an equal or a higher number of integer variables. Since the objective cost does not change, if after successive fixings we reach an all-integer solution, it is an optimal one. On the other hand, fixing variables is not guaranteed to return an integer optimal solution, if one exists, since the integer solution might consist of different integer values than the ones gradually fixed.

When we reach a point beyond which the process of fixing does not increase the integrality of the solution, we proceed to the rounding process. We round a single variable, the one closest to 1, and continue solving the reduced LP problem. While fixing variables helps us move to solutions that have more integer variables and the same value of the objective cost, rounding makes us move to higher objective values and search for an integer solution there. However, if after rounding the objective cost changes, we are not sure anymore that we will end up with an optimal solution.

Note that the maximum number of fixing and rounding iterations is the number of connection requests that is polynomial on the size of the problem input.

IV. Impairment-Aware RWA Algorithms

In this section, we extend the preceding pure RWA algorithm so as to make it impairment-aware. We start by giving a short introduction on physical layer impairments and defining the Q-factor, which is the metric that we use to estimate the quality of transmission of the lightpaths. We then proceed to

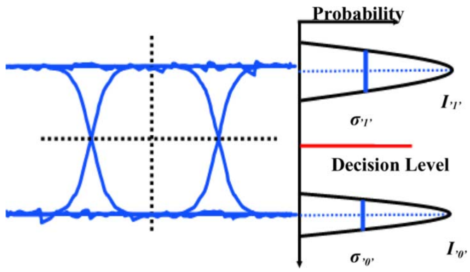

Fig. 3. Eye diagram and Q-factor.

propose our IA-RWA algorithms. We start by presenting an *indirect* way to account for physical impairments in which we constrain the sources that generate these effects (Section IV-B). Then, we propose a *direct* way that constrains the impairments using noise-variance-related parameters (Section IV-C).

A. Physical Layer Impairments

In transparent and translucent WDM networks, the signal QoT degrades due to the nonideal physical layer [2], [3]. Several criteria can be used to evaluate the signal quality of a lightpath. Among a number of measurable optical transmission quality attributes, the Q-factor seems to be more suitable as a metric to be integrated in a RWA algorithm because there are models to estimate it, and it is directly and monotonically related to the BER.

The Q-factor is the electrical signal-to-noise ratio at the input of the decision circuit in the receiver's terminal [3]. Assuming Gaussian-shaped noise, the Q-factor of a lightpath (p, w), that is, wavelength w on path p, is given by

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

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) [2]. Fig. 3 illustrates the relation between an eye diagram and the Q-factor. The higher the value of the Q-factor, the smaller the BER is, and the better the QoT.

Physical layer impairments (PLIs) are usually categorized as linear and nonlinear according to their dependence on the power. However, when considering IA-RWA algorithms, it is useful to categorize the PLIs into those that affect the same lightpath and those that are generated by the interference among lightpaths, resulting in the following two classes for the most important PLIs:

- **Class 1: Impairments that affect the same lightpath**: amplified spontaneous emission noise (ASE), polarization mode dispersion (PMD), chromatic dispersion (CD), filter concatenation (FC), self-phase modulation (SPM);
- **Class 2: Impairments that are generated by the interference among lightpaths**: crosstalk (XT) (intrachannel and interchannel crosstalk), cross-phase modulation (XPM), four-wave mixing (FWM).

PLIs that belong to Class 2 are more difficult to be considered by offline algorithms. This is because these impairments make decisions for one lightpath affect and be affected by decisions made for other lightpaths.

1) Direct and Indirect IA-RWA Algorithms:

To account for the physical layer impairments in a cross-layer approach, an algorithm has to incorporate impairment-related constraints at some point in its formulation. An important distinction is whether these impairment-related constraints address *directly* or *indirectly* the effects of the impairments. To give an example, polarization mode dispersion (PMD) is proportional to the square root of the length of the path, and also other impairments, such as amplified spontaneous emission (ASE) noise, are affected by the path length. An algorithm that chooses paths with small lengths is bound to exhibit lower PMD and ASE effects; such an algorithm would be treating impairments indirectly. However, when the network is heterogeneous, the length of a path can be misleading even for PMD. Such an algorithm would not ensure that a path with small length also has acceptable QoT since the impairment effects are not directly verified. On the other hand, an algorithm that includes constraints that bound directly the effects of PMD and ASE in its formulation using, e.g., analytical formulas can be sure (to a certain degree, depending on the other effects that are accounted for) that a lightpath satisfying these constraints has acceptable QoT.

B. Indirect IA-RWA Formulation

In this section, we present an *indirect* way to account for the physical layer effects [8]. In this approach, we consider: 1) the length and the number of hops of a path; 2) the number of adjacent (and second adjacent) channels over all links of the lightpath; and 3) the number of intrachannel generating sources. We use surplus variables in order to "soft" constrain these parameters to be less than a predefined threshold and carry the surplus variables in the objective cost of the RWA formulation.

It is worth noting that the aforementioned parameters are the key parameters for the majority of physical impairments [2], [3]. 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 CD, SPM, and PMD effects depend on the length and the number of hops of the path. FC depends on the number of filters on the path, and since it is a general practice that each switch employs two filters, FC depends on the number of hops. Moreover, the effects of the impairments that depend on the utilization of the other lightpaths are more severe when the interfering sources are on the two adjacent channels. This is the case in XPM, FWM, and interchannel crosstalk (inter-XT). Finally, intrachannel crosstalk (intra-XT) depends on the utilization of the same wavelength by lightpaths crossing the same switch. Although the above physical impairments do not all depend in a simple manner on the parameters considered here, it is expected that trying to reduce these parameters will indirectly decrease the effect of all impairments.

1) Constraining the Path Length and Hop Count:

Our aim is to minimize the degradation from physical phenomena that are connected to the length and the number of nodes a lightpath traverses. To constrain the length and the number of hops, we use the following constraints:

$$\sum_{w}\sum_{l\in p} a_l \cdot x_{p,w} - S_p \le A_{\text{path-max}},\ S_p \ge 0,\ \text{for all } p \in P$$

where a_l is a constant for link l that is related to its length. In our simulation experiments, we have chosen $a_l = \lfloor dl/100 \rfloor + 4$,

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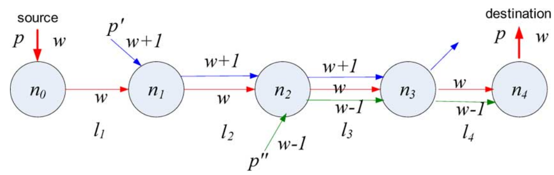

Fig. 4. Adjacent channel interference on lightpath (p, w) by other lightpaths.

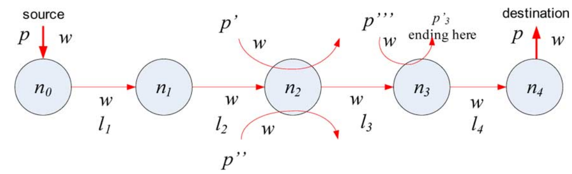

Fig. 5. Intrachannel XT interference on lightpath (p, w) by other lightpaths.

where d_l is the length of link l in kilometers. This choice assumes that amplifiers are placed every 100 km of fiber, and each switch has two amplifiers (one input and one output amplifier) and two filters. Note that by summing over all the links that comprise a path, we also count the number of hops, with a weight equal to 4 with the above definition of a_l.

The length and hop constraints are not treated as hard constraints in the LP formulation; instead, we use the nonnegative surplus variable S_p to represent the excess of physical degradation a path undergoes due to its length and number of hops. We carry the surplus variables of all paths in the objective (see the following Section IV-B2 about the objective).

2) Constraining Adjacent Channel Interference: Impairments due to interchannel crosstalk and nonlinear physical impairments, such as four-wave mixing and cross-phase modulation, depend not only on the considered lightpath, but also on the (dynamic) load of the links comprising the path. These effects are more severe between adjacent channels and deteriorate as we move away from the channel under examination. As a consequence, avoiding adjacent and next-to-adjacent (second adjacent) channels would have a positive effect on the quality of transmission of a lightpath.

Fig. 4 depicts an example of the adjacent channel interference effect. A lightpath p from n_0 to n_4 is established using wavelength w. Let $(p', w+1)$ be a lightpath that crosses links l_2 and l_3, and $(p'', w-1)$ be a lightpath that crosses links l_3 and l_4. We denote by $n_{\text{adj},l}(p,w)$ the number of adjacent channel interfering sources on link l for lightpath (p,w). Thus, in Fig. 4 there are $n_{\text{adj},l_2}(p,w) = 1$, $n_{\text{adj},l_3}(p,w) = 2$, and $n_{\text{adj},l_4}(p,w) = 1$ adjacent channel interfering sources affecting the signal quality of lightpath (p,w) on links l_2, l_3, and l_4, respectively, and the total number of interfering sources is four.

We constrain the number of adjacent channel interfering sources as follows:

$$\sum_{l\in p}\left(\sum_{\{p'|l\in p'\}} x_{p',w-1}+x_{p',w+1}\right)+B\cdot x_{pw}-S'_p\leq N_{\text{adj-max}}+B,$$

for all $p \in P$ and all $w \in C$, where we have the following:

- B is a constant (taking large values).
- $N_{\text{adj-max}}$ is a threshold on the number of adjacent interfering channels for a lightpath.
- $n_{\text{adj},l}(p,w) = \sum_{\{p'|l\in p'\}} x_{p',w-1}+x_{p',w+1}$ is the number of adjacent channel interfering sources that affect the signal of lightpath (p,w) on link l.

The reasons for introducing constant B are the following.

1) In case lightpath (p,w) is selected in the solution $(x_{pw} = 1)$, we have $B \cdot x_{pw} = B$, and the above constraint becomes

$$\sum_{l\in p}\left(\sum_{\{p'|l\in p'\}} x_{p',w-1}+x_{p',w+1}\right)-S'_p\leq N_{\text{adj-max}}$$

2) In case lightpath (p,w) is not selected $(x_{pw} = 0)$, we have $B \cdot x_{pw} = 0$, and the above constraint becomes

$$\sum_{l\in p}\left(\sum_{\{p'|l\in p'\}} x_{p',w-1}+x_{p',w+1}\right)-S'_p\leq N_{\text{adj-max}}+B$$

which always holds when the constant B is large enough.

Thus, constant B is used to make the constraint active when lightpath (p,w) is chosen, and inactive (always true) otherwise.

Similarly, we constrain the number of next-to-adjacent channel interfering sources as follows:

$$\sum_{l\in p}\left(\sum_{\{p'|l\in p'\}} x_{p',w-2}+x_{p',w+2}\right)+B\cdot x_{pw}-S''_p$$
$$\leq N_{\text{2-adj-max}}+B,\ \text{for all } p\in P \text{ and all } w\in C.$$

We again employ soft constraints by including in the optimization function the surplus variables S'_p and S''_p.

Note that, depending on the significance of XPM, we can define constraints to consider a higher number of adjacent channels than the first two (adjacent and second adjacent) presented above. For our simulation experiments, we have considered the effects of the first two adjacent channels, which seems appropriate for the network and physical layer parameters used.

3) Constraining Intrachannel Crosstalk: Intrachannel crosstalk is related to the nonideal switching matrix of an optical cross-connect switch [13]. In particular, interchannel crosstalk is the effect of power leakage between lightpaths crossing the same switch and using the same wavelength due to nonideal isolation of the inputs/outputs of the switching fabric. Note that intrachannel crosstalk cannot be filtered out since the interfering signal is on the same wavelength as the one affected. Fig. 5 depicts an example of the intrachannel crosstalk effect. A lightpath p from n_0 to n_4 is established using wavelength w. Lightpaths (p', w), (p'', w), (p''', w) cross nodes n_2, n_2, and n_3, respectively, using the same wavelength w. These lightpaths affect the signal quality of lightpath (p,w). We denote by $n_{\text{XT},n}(p,w)$ the number of intra-XT interfering sources on node n that is the end of link l for lightpath (p,w). In this example, there are $n_{\text{XT},n_2}(p,w) = 2$, and $n_{\text{XT},n}(p,w) = 1$ intra- XT interfering sources on nodes n_2 and n_3, respectively, and the total number over the lightpath is three.

We constrain the number of intra-XT interfering sources as follows:

$$\sum_{\{l\in p, n \text{ end of } l\}}\ \sum_{\{p'|n\in p'\}} x_{p',w}+B\cdot x_{pw}-S'''_p\leq N_{\text{XT-max}}+B,$$

for all $p \in P$ and all $w \in C$.

Note that $n_{\text{XT},n}(p,w) = \sum_{\{p'|n\in p'\}} x_{p',w}$ is the number of intra-XT sources that affect the signal of lightpath (p,w) on node n. As previously, we use constant B to activate or deactivate this constraint for a given lightpath (p, w). The surplus variables S_p''' are again carried in the minimization objective.

4) Optimization Functions: There are two reasons a connection may be blocked. The first has to do with not having enough wavelengths to serve all the connections; this is the *network-layer blocking* also present in the pure (without physical impairments) RWA problem (Section III). The second is *physical-layer blocking*, which corresponds to selecting lightpaths that have unacceptable quality of transmission. To consider both of the above factors that affect blocking, we use the following objective, which penalizes both the wavelength usage and *indirectly* the quality of transmission (by penalizing the violation of the impairment-generating parameters):

$$\textbf{Minimize} \sum_l F_l + \sum_{p\in P} S_p + \sum_{p\in P} S_p' + \sum_{p\in P} S_p'' + \sum_{p\in P} S_p'''$$

where S_p, S_p', S_p'', S_p''' define the excess of the impairment-generating parameters of path p.

This formulation has the added advantage that we never get an infeasible instance due to physical effects. By using surplus variables, even if some lightpaths in the solution cannot satisfy the corresponding constraint, we still obtain a solution. In contrast, if we used hard constraints, Simplex would fail to produce any (not even partial) solutions if all the constraints could not be satisfied for all connection requests.

Note that in the indirect IA-RWA algorithm described, the impairment-generating parameters are equally penalized. A weighted cost could improve the performance of the algorithm. This is done in a slightly different manner in the direct IA-RWA algorithm that is going to be presented.

For the remainder, we will refer to the described indirect IA-RWA algorithm as *parametric* or *P-IA-RWA*.

C. Direct IA-RWA Formulation

We now proceed to describe a *direct* IA-RWA algorithm. For each candidate lightpath inserted in the RWA formulation, we calculate an upper bound on the interference noise variance it can tolerate, after accounting for the impairments that do not depend on the utilization of the other lightpaths (impairments of Class 1, Section IV-A). Then, we use this bound to constrain the interfering noise variance caused by other lightpaths (impairments of Class 2).

1) Calculating the Noise Variance Bound of a Lightpath: We start from the definition of Q-factor that was presented in equation (1) of Section IV-A. In the approach adapted, $I_{`1',p}(w)$ depends on the transmitter's power, the gains and losses over path p, and the "eye impairments": SPM, CD, PMD, and FC. The remaining impairments are considered as noise or noise-like. For the noise impairments and bits 1 and 0, we have

$$\begin{aligned}\sigma^2_{`1'}(p,w) &= \sigma^2_{\mathrm{ASE},`1}(p,w) + \sigma^2_{\mathrm{XT},`1'}(p,w)\\ &\quad + \sigma^2_{\mathrm{XPM}}(p,w) + \sigma^2_{\mathrm{FWM},`1'}(p,w) \qquad (2)\\ \sigma^2_{`0'}(p,w) &= \sigma^2_{\mathrm{ASE},`0'}(p,w) + \sigma^2_{\mathrm{XT},`0'}(p,w)\\ &\quad + \sigma^2_{\mathrm{FWM},`0'}(p,w) \approx \sigma^2_{\mathrm{ASE},`0'}(p,w) \qquad (3)\end{aligned}$$

where σ^2_{ASE}, σ^2_{XT}, σ^2_{XPM} and σ^2_{FWM} are the electrical noise variances due to ASE, intrachannel XT, XPM, and FWM, respectively. Note that the noise variances $\sigma^2_{\mathrm{XT},`0'}$, $\sigma^2_{\mathrm{FWM},`0'}$ of bit 0 are low and negligible compared to $\sigma^2_{\mathrm{ASE},`0'}$ and especially compared to the corresponding noise variances of bit 1. Also, note that XT, XPM, and FWM depend on the utilization of the other lightpaths (Class 2 impairments).

Let $Q_{\min}$ be the acceptable threshold for the QoT of a lightpath. Since we do not consider all the physical impairments and we also make various simplifying assumptions (such as not considering XT and FWM for bit 0 and XPM generated by channels of distance more than 2), we will use $Q_{\mathrm{acc}} = Q_{\min} + Q_{\mathrm{margin}}$ that is a margin Q_{margin} higher than the desired threshold $Q_{\min}$. Using the definition of the Q-factor presented in (1), and (2) and (3), we have

$$\begin{aligned}&\frac{I_{`1'}(p,w)}{\sigma_{`1'}(p,w)+\sigma_{`0'}(p,w)} \geq Q_{\mathrm{acc}}\\ &\Rightarrow \sigma^2_{`1'}(p,w) \leq \left(\frac{I_{`1'}(p,w)}{Q_{\mathrm{acc}}} - \sigma_{`0'}(p,w)\right)^2\\ &\Rightarrow \sigma^2_{\mathrm{XT},`1'}(p,w) + \sigma^2_{\mathrm{XPM},`1'}(p,w) + c_{\mathrm{FWM}}\\ &\quad \leq \left(\frac{I_{`1'}(p,w)}{Q_{\mathrm{acc}}} - \sigma_{\mathrm{ASE},`0'}(p,w)\right)^2 - \sigma^2_{\mathrm{ASE},`1'}(p,w)\\ &\Rightarrow \sigma^2_{\mathrm{XT},`1'}(p,w) + \sigma^2_{\mathrm{XPM},`1'}(p,w) + c_{\mathrm{FWM}} \leq \sigma^2_{\max}(p,w)\end{aligned} \qquad (4)$$

where

$$\sigma^2_{\max}(p,w) \stackrel{\mathrm{def}}{=} \left(\frac{I_{`1'}(p,w)}{Q_{\mathrm{acc}}} - \sigma_{\mathrm{ASE},`0'}(p,w)\right)^2 - \sigma^2_{\mathrm{ASE},`1'}(p,w) \qquad (5)$$

assuming that FWM contributes a constant c_{FWM}. c_{FWM} is relatively small compared to the other effects and could be chosen as the worst-case FWM contribution, that is assuming all wavelengths on all links are active (which even in a fully loaded network is not likely to happen due to wavelength continuity constraint). In this way, we are making sure that the actual FWM contribution is less than the used c_{FWM}.

For a lightpath (p, w), the above inequality gives a bound $\sigma^2_{\max}(p, w)$, based on the impairments that do not depend on the interference among lightpaths (class-1 impairments), that constrains the total interference noise variances of the impairments that depend on the utilization of the other lightpaths (class-2 impairments).

2) Defining the Noise Interference Constraints: We assume that for each link l, and the optical cross connect (OXC) switch n it ends at, we know the following noise variance parameters:

- G_l (in dB): the power loss/gain of the link/OXC due to fiber attenuation, power leakage, and amplifiers' gains;
- $s^2_{1-\mathrm{XPM},`1',l}$, $s^2_{2-\mathrm{XPM},`1',l}$: the noise variance due to XPM for bit 1 from an active adjacent and second adjacent channel, respectively;
- $s^2_{\mathrm{XT},`1',n}$: the intra-XT noise variance for bit 1 that is contributed to a lightpath that also crosses switch n and uses the same wavelength.

We assume that $s^2_{1-\mathrm{XPM},`1',l}$, $s^2_{2-\mathrm{XPM},`1',l}$, $s^2_{\mathrm{XT},`1',n}$ are the same irrespectively of the examined wavelength w, but the algorithm can be extended to consider different parameters per wavelength. To obtain the above parameters, analytical models for the specific impairments can be used. For example, for NRZ modulation, we can use models described in [13] and [22].

TABLE I
NUMBER OF VARIABLES AND CONSTRAINTS FOR THE PROPOSED IMPAIRMENT-AWARE RWA FORMULATIONS

Formulation	Number of Variables		Number of constraints	
	RWA Variables	Surplus Variables	=	≤
"pure" RWA (Section III)	$k\cdot\rho\cdot N\cdot(N-1)\cdot W+L$	-	$[\rho\cdot N\cdot(N-1)]_1$	$[L\cdot W]_2+[L\cdot W]_3$
P-IA-RWA	$k\cdot\rho\cdot N\cdot(N-1)\cdot W+L$	$4\cdot k\cdot\rho\cdot N\cdot(N-1)$	$[\rho\cdot N\cdot(N-1)]_1$	$[L\cdot W]_2+[L\cdot W]_3+[k\cdot\rho\cdot N\cdot(N-1)]_4+[k\cdot\rho\cdot N\cdot(N-1)\cdot W]_5+[k\cdot\rho\cdot N\cdot(N-1)\cdot W]_6+[k\cdot\rho\cdot N\cdot(N-1)\cdot W]_7$
SB-IA-RWA	$k\cdot\rho\cdot N\cdot(N-1)\cdot W+L$	$k\cdot\rho\cdot N\cdot(N-1)$	$[\rho\cdot N\cdot(N-1)]_1$	$[L\cdot W]_2+[L\cdot W]_3++[k\cdot\rho\cdot N\cdot(N-1)\cdot W]_8$

$N=|V|$: number of nodes
$L=|E|$: number of directed links
$W=|C|$: number of wavelengths
k: number of shortest paths pre-calculated for each connection
ρ: load (loads higher than 1 take the value ρ=1 in this Table)

Constraints:
1: incoming traffic constraints
2: distinct wavelength assignment constraints
3: flow cost function constraints
4: path length and number of hops constraints
5-6: adjacent and 2nd adjacent channel interference constraints
7: intra-XT interference constraints
8: Sigma-bound's noise variance constraints

For a path p that consists of links $l=1,2,\ldots,m$, we have

$$\sigma^2_{\mathrm{XT},`1'}(p,w)+\sigma^2_{\mathrm{XPM},`1'}(p,w) = \sum_{\{l=1|n\text{ end of }l\}}^{m}\Bigg(\Bigg(s^2_{\mathrm{XT},`1',n}\cdot n_{\mathrm{XT},n}(w)+s^2_{1-\mathrm{XPM},`1',l} \cdot n_{\mathrm{adj},l}(w)+s^2_{2-\mathrm{XPM},`1',l}\cdot n_{2-\mathrm{adj},l}(w)\Bigg)\cdot\prod_{i=l+1}^{m}10^{2\cdot G_l/10}\Bigg) \tag{6}$$

where $n_{\mathrm{XT},n}(w)$ is the number of intra-XT generating sources on switch n and wavelength w, and $n_{\mathrm{adj},l}(w)$ and $n_{2-\mathrm{adj},l}(w)\{0,1,2\}$ are the number of utilized adjacent and second-adjacent channels on link l and wavelength w, respectively (see Figs. 4 and 5).

Based on (6) and (4), we constrain the interference accumulated over the lightpaths by introducing the constraints shown in the equation at the bottom of the page.

We again use constant B to activate/deactivate the constraints and carry the surplus variables S_p in the objective cost. If the selected lightpaths satisfy these constraints they have, by definition (and assuming that the models available for calculating the noise variance parameters and the Q-factor are accurate), acceptable quality of transmission. Although we assumed that the signal power is totally compensated at the end of each link and each OXC, this assumption is not restrictive, and the constraints can be modified for nonzero power gains or losses.

We will refer to the described direct IA-RWA algorithm as *sigma bound* or *SB-IA-RWA* algorithm.

D. Number of Variables and Number of Constraints

Table I shows the number of variables and the number of constraints required by the proposed algorithms, and in particular the pure RWA algorithm presented in Section III, the indirect P-IA-RWA algorithm presented in Section IV-B, and the direct SB-IA-RWA presented in Section IV-C. The number of variables and constraints utilized is important in determining the computational effort required to solve the corresponding ILP or LP (e.g., the running time of Simplex has been found experimentally to be roughly proportional to the product of the number of variables and the number of constraints, when the coefficients for the Simplex tableau are chosen randomly). We let $N=|V|$ be the number of network nodes, $W=|C|$ the number of available wavelengths, $L=|E|$ the number of links, k the number of candidate paths for each connection request that we precalculate in phase 1 of the RWA algorithms. We also let ρ be the *traffic load*, defined as the ratio of the total number of connection requests over the number of single lightpath requests between all possible source–destination pairs, that is

$$\rho=\frac{\sum\limits_{(s,d)\mathrm{pairs}}\Lambda_{sd}}{N\cdot(N-1)} \tag{7}$$

where Λ_{sd} is the number of lightpaths that have to be established for source–destination pair (s,d).

Both IA-RWA algorithms are extensions of the pure RWA algorithm and employ additional constraints in order to account for the physical layer. Since the indirect P-IA-RWA algorithm separately limits the path length and hop count, the number of

$$\sum_{\{l\in p,n\text{ end of }l\}}\left(\overbrace{s^2_{\mathrm{XT},`1',n}\cdot\sum_{\{p'|n\in p'\}}x_{p',w}}^{\text{intra-XT}}+\overbrace{s^2_{1-\mathrm{XPM},`1',l}\cdot\left(\sum_{\{p'|l\in p'\}}x_{p',w-1}+x_{p',w+1}\right)}^{\text{adjacent channel XPM}} \overbrace{+s^2_{2-\mathrm{XPM},`1',l}\cdot\left(\sum_{\{p'|l\in p'\}}x_{p',w-2}+x_{p',w+2}\right)}^{\text{second adjacent channel XPM}}\right)+c_{\mathrm{FWM}}+B\cdot x_{pw}-S_p\le\sigma^2_{\max}(p,w)+B,$$

for all $p\in P$ and all $w\in C$

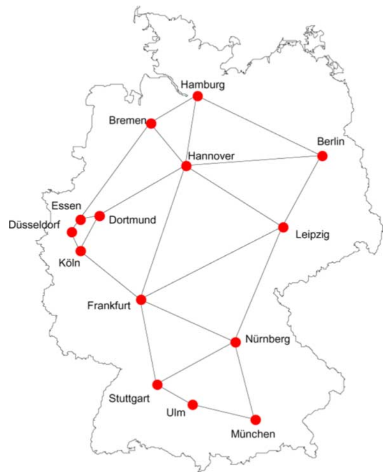

Fig. 6. Generic DT network topology (DTnet) with 14 nodes, 23 undirected links (in our simulations we assumed 46 directed links).

adjacent and second adjacent channel interfering sources, and the number of intra-XT interfering sources, it needs $(k\cdot\rho\cdot N^2)+3\cdot(k\cdot\rho\cdot N^2\cdot W)$ additional constraints and $4\cdot k\cdot\rho\cdot N^2$ surplus variables. The direct IA-RWA algorithm utilizes considerably fewer constraints and surplus variables since it combines all the physical effects in a single noise variance constraint per ligthpath. Thus, it only needs $k\cdot\rho\cdot N^2\cdot W$ additional constraints and $k\cdot\rho\cdot N^2$ surplus variables.

V. Simulation Results

To evaluate the performance of the proposed IA-RWA algorithms, we carried out a number of simulation experiments. We implemented all the algorithms in Matlab and used LINDO [24] to solve the corresponding LP and ILP problems.

We start, in Section V-A, by presenting results for the pure RWA algorithm. We evaluate the integrality and optimality performance of the proposed LP-relaxation algorithm and the random perturbation technique (Section III) by comparing it to a typical min-max RWA formulation. We then, in Section V-B, turn our attention to the RWA problem in the presence of physical impairments. We evaluate the performance of the two proposed IA-RWA algorithms of Section IV and compare it to that of the pure RWA LP algorithm of Section III with respect to the total blocking performance, including network- and physical-layer blocking.

The network topology used in our simulations was the generic Deutsche Telekom network, shown in Fig. 6, which is a candidate transparent network identified in DICONET [23]. The capacity of a wavelength was assumed equal to 10 Gb/s.

A. Pure RWA Performance Results

In this section, we evaluate the performance of the pure RWA algorithm that is based on the LP-relaxation formulation presented in Section III. To have a reference point, we also executed the same simulations using a typical min-max formulation (a formulation whose objective is to minimize the maximum number of wavelengths used), which was solved using the ILP branch-and-bound algorithm of [24]. Note that the piecewise linear cost function used in the proposed LP RWA algorithm (Section III-C) tries to approximate the min-max objective, while also being continuous and piecewise linear, so as to exhibit a good integrality performance when the Simplex algorithm is used. Thus, the ILP-min_max algorithm sets the criterion in terms of optimality. We also used the same min-max formulation and solved its LP-relaxed version followed by iterative fixing and roundings. This LP-min_max algorithm sets a comparison criterion in terms of integrality and execution time since its difference to our proposed LP algorithm lies on the piecewise linear cost function that we utilize and the random perturbation technique. For all algorithms, we have used $k=3$.

The results were averaged over 100 simulation experiments corresponding to different random static traffic instances of a given traffic load [for the definition of load ρ, please refer to Equation (7)]. More specifically, we have performed simulations for loads ranging from 1 up to 3 with a step of 1.

To evaluate the performance we used the following metrics.

a) The number of used wavelengths averaged over all simulations. This is the objective we want to minimize.
b) The fraction of instances we obtained an integer solution by the LP execution (without any fixing and rounding iterations).
c) Average number of "fixings" and "roundings" required to obtain integer solutions that are guaranteed to be optimal; this is the average number of fixings and roundings to move from (b) to (d).
d) The fraction of instances that we are sure to have found an optimal solution (corresponding to instances for which there was no increase in the objective cost of the LP).
e) Average number of "fixings" and "roundings" for the cases that we are not sure to obtain an optimal solution; this is the average number of fixings and roundings to move from (d) to (f).
f) The fraction of instances that we found an integer solution after fixings and roundings, irrespective of the optimality. (f) is always 1 since we always succeeded in obtaining an integer solution.
g) Average running time (in seconds): the average running time of the simulation experiments, including the tableau creation, the LP (or ILP) execution and the fixing and rounding iterations until we obtain integer solutions.

Table II presents the corresponding results. We can see that the proposed LP-piecewise algorithm finds solutions [column (a)] that are closer to the optimal ones [as expressed by column (a) of the ILP-min_max algorithm] than those obtained by the LP-min_max algorithm. The random perturbation technique seems to improve the performance of the algorithm, being able to find in some cases better solutions that use a smaller maximum number of wavelengths. This is because the random perturbation technique yields more integer solutions without fixings [column (b)] and solutions that are guaranteed to be optimal [column (d)] than the LP-piecewise algorithm without it. When using the random perturbation technique, for all the simulation experiments performed, the optimality was lost only for one instance for load $\rho=1$ and two instances for load $\rho = 3$. The random perturbation technique reduces the number of fixing and rounding iterations [columns (c) and (e)] that are performed and has similar running time [column (g)]. The execution time of the LP-min_max algorithm is higher than that of the proposed LP-piecewise algorithm due to its bad integrality performance and the high number of fixing and rounding iterations it performs to obtain an integer solution.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
PERFORMANCE OF THE PURE RWA ALGORITHMS

Load	Cost Function	a	b	c	d	e	f	g
1	ILP-min-max	14.01	1	n/a	n/a	n/a	n/a	91.93
	LP-min-max	14.03	0	9.78	0.63	16.77	1	22.5
	LP-piecewise	14.02	0.08	2.14	0.88	5.92	1	7.72
	LP-piecewise + random perturbation	14.02	0.75	1.18	0.98	3	1	5.17
2	ILP-min-max	26.66	1	n/a	n/a	n/a	n/a	869.7
	LP-min-max	26.68	0	10.75	0.46	14.14	1	38.44
	LP-piecewise	26.68	0.02	2.46	0.88	3.45	1	30.85
	LP-piecewise + random perturbation	26.66	0.48	1.28	0.98	4	1	30.84
3	ILP-min-max	37.24	1	n/a	n/a	n/a	n/a	4375.2
	LP-min-max	37.34	0	12.23	0.36	14.68	1	122.34
	LP-piecewise	37.31	0.02	3.12	0.84	5.18	1	93.15
	LP-piecewise + random perturbation	37.26	0.28	1.45	0.95	4.33	1	96.22

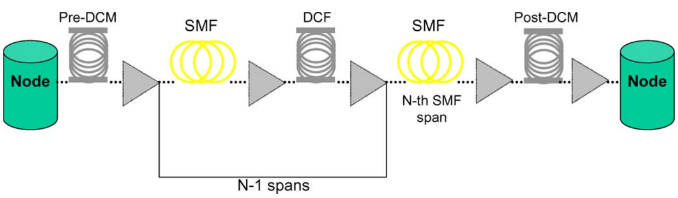

Fig. 7. Link model.

From the above, we can deduce that the proposed LP-piecewise algorithm has superior overall performance. It finds with high probability an optimal solution while maintaining low execution times. The proposed random perturbation technique makes the proposed LP-piecewise algorithm even better since it increases its integrality performance in comparable running time. The good optimality performance of the proposed algorithm is maintained irrespectively of the load.

B. IA-RWA Performance Results

We now turn our attention to the case where physical layer impairments are present, and we evaluate the performance of the two proposed IA-RWA algorithms, namely, the indirect P-IA-RWA and the direct SB-IA-RWA algorithms.

To evaluate the feasibility of the lightpaths in terms of QoT, we used a Q-factor estimator (Q-Tool) that relies on analytical models to account for the most important impairments. The link model of the reference network is presented in Fig. 7. We assumed NRZ-OOK modulation format, 10-Gb/s transmission rates, and 50 GHz channel spacing. The span length on each link was set to 100 km. Each link was assumed to consist 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. The launch power was 3 dBm/ch for every SMF span and -4 dBm/ch for the DCF modules. PMD coefficient was assumed equal to $D_{\rm PMD} = 0.15$ ps/km$^{1/2}$. The EDFAs' noise figure was 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 [13] and a switch-crosstalk ratio $X_{\rm sw} = 32$ dBs with small variations per node (± 1 dB). Regarding dispersion management, a precompensation module was used to achieve better transmission reach: Initially the dispersion was set to -400 ps/nm, every span was undercompensated by a value of

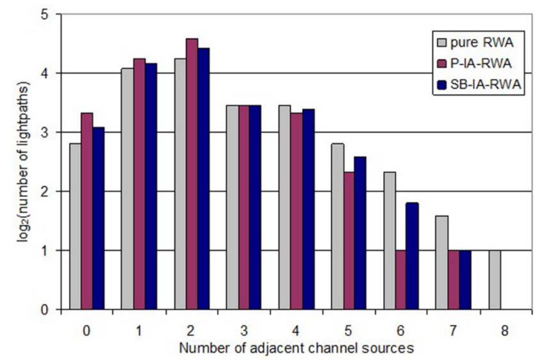

Fig. 8. Histogram showing the distribution of the number of adjacent channel interfering sources for the pure RWA and the P-IA-RWA and SB-IA-RWA algorithms, assuming realistic load $\rho = 2.05$ and $W = 40$ available wavelengths.

30 ps/nm to alleviate nonlinear effects, and the accumulated dispersion at each switch input was fully compensated to zero using an appropriate post-compensation module at the end of the link. The acceptable Q-factor limit was taken equal to $Q_{\rm min} = 15.5$ dB and the safety margin (Section IV-C1) equal to $Q_{\rm margin} = 0.3$ dB.

In the simulations, we have used $k = 3$ for all algorithms. The bounds for the P-IA-RWA algorithm were set to $A_{\text{path-max}} = 16$, $N_{\text{adj-max}} = 6$, $N_{\text{2-adj-max}} = 6$, and $N_{\text{XT-max}} = 7$.

1) Avoiding Impairments Generating Parameters: First, we show the effect of the additional constraints described in Section IV on the impairment-generating parameters of the obtained solutions. More specifically, given the solution to an RWA instance, we graph the probability mass distributions of the number of adjacent channels (Fig. 8) of the selected lightpaths. These results were obtained for the actual traffic matrix of DTnet, consisting of 381 connection requests (corresponding to load $\rho \approx 2.05$), as reported in the DICONET project [23], assuming $W = 40$ available wavelengths per link.

We compare the performance of the two proposed IA-RWA algorithms with that of the pure RWA algorithm. In this figure, a left shift in the probability distributions is observed when using the IA-RWA algorithms, meaning that impairment-generating parameters tend to be smaller. Similarly, left shiftings in probability distributions were observed for the other impairment-generating parameters (number of second adjacent channels, number of intra-XT sources). As a consequence, the impact of XPM, FWM, and intra-XT is indirectly reduced and signal quality is improved. We observe that the indirect P-IA-RWA algorithm exhibits better performance than the direct SB-IA-RWA. This is because the P-IA-RWA constrains these impairment-generating parameters, while the SB-IA-RWA algorithm is a direct algorithm and considers the actual effects generated by these parameters. For example, the SB-IA-RWA algorithm is more flexible and allows a lightpath to have a high number of intra-XT interfering sources if the other effects are not significant.

The objective of the pure RWA algorithm is to minimize the total number of used wavelengths. In trying to do so, it may select some long paths, use the same wavelength for as many connections as possible, and when this is not feasible, it will pack the lightpaths to neighboring wavelengths. These would have a negative effect on the QoT performance of the lightpaths. On the other hand, the proposed IA-RWA algorithms favor paths with

TABLE III
PERFORMANCE OF THE IA-RWA ALGORITHMS FOR REALISTIC LOAD

Algorithm	a	b	c	d	e	f	g
Pure RWA	28	0	2	1	n/a	1	31
P-IA-RWA	40	0	0	0	33	1	10846
SB-IA-RWA	35	0	0	0	24	1	916

small length and hop count. Moreover, to avoid the interference effects, the IA-RWA algorithms tend to spread the lightpaths over the available wavelengths. Clearly, there is a tradeoff between the number of utilized wavelengths and the QoT of the selected lightpaths: To avoid excessive impairment effects, some additional wavelength space is required. This is however acceptable since the objective of the IA-RWA problem is not only to minimize the number of wavelengths used, but also to select lightpaths with acceptable transmission quality.

In Table III, we report the performance of the algorithms in terms of integrality and execution times, using the metrics introduced in Section V-A. As also reported in Table II, the pure RWA algorithm has good integrality performance and very low execution time. The integrality of the IA-RWA algorithms is decreased due to the additional constraints that account for the physical layer. Usually, for the proposed LP-relaxed IA-RWA algorithms, a noninteger solution can be found with the same objective as the pure RWA that also satisfies the physical layer constraints. Roundings are used in order to obtain an integer acceptable solution [column (e)]. Roundings spread the lightpaths and use more wavelengths [column (a)], and thus the solution obtained is not sure to be optimal. However, as the results in Section V-B3 will show for the SB-IA-RWA algorithm, for a high number of input instances, the algorithm manages to find optimal solutions. The direct SB-IA-RWA algorithm requires fewer wavelengths than the indirect P-IA-RWA. Also, we see from column (g) that the running times of the proposed IA-RWA algorithms are acceptable low, with SB-IA-RWA algorithm being much faster than P-IA-RWA, due to the fewer number of surplus variables and constraints that it utilizes (see Table I) and the fewer number of fixings and roundings that it performs (see column (e) of Table III).

2) Blocking Performance for Constant Number of Wavelengths: We report here the blocking performance of the pure RWA algorithm and of the proposed IA-RWA algorithms assuming a constant number of wavelengths is available in the network, and in particular $W = 16$ wavelengths. As traffic, we used 100 traffic matrices of loads between 0.5 and 1 with a step of 0.1. After obtaining a solution, we use, in a post-processing phase, a Q-factor estimator module to evaluate the QoT of the chosen lightpaths. The Q-factor estimator takes as input the lightpaths selected by the algorithm, calculates their Q-factor, and determines which of them have unacceptable QoT. The blocking ratio is defined as the ratio of the number of blocked connections, after the use of the Q evaluation module, over the total number of connections (for a given traffic matrix). Note that the blocking of the pure RWA algorithm is due to the Q-factor estimator (physical blocking), while the blocking of the two IA-RWA algorithms cannot be distinguished to network- and physical-layer blocking due to the joint optimization between these layers that these IA-RWA algorithms perform.

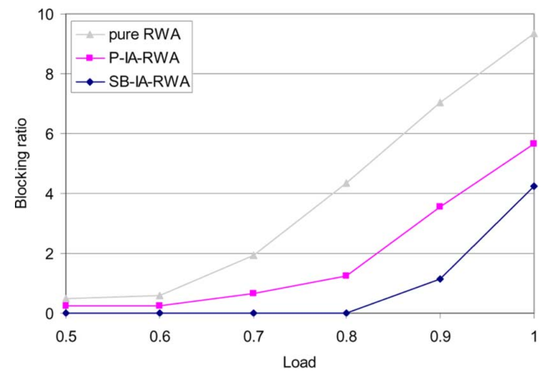

Fig. 9. Blocking ratio versus load ρ, assuming $W = 16$ available wavelengths.

From Fig. 9, we can observe that the blocking ratio of all the algorithms increases as the load increases. The pure RWA algorithm exhibits the higher blocking since it does not account for the physical impairments. As the load increases and more lightpaths are activated, the interference among them increases, and the physical-layer blocking of the pure RWA algorithm also increases. The indirect P-IA-RWA algorithm has significantly better blocking ratio than the pure RWA algorithm. Being an indirect algorithm, it cannot ensure zero physical-layer blocking for all instances, even for load 0.5. The blocking performance improvements are more pronounced for light traffic loads since then the available wavelengths are practically enough and the P-IA-RWA algorithm has more freedom to select the lightpaths so as to avoid interference among them. The direct SB-IA-RWA algorithm exhibits the best blocking performance over all algorithms examined. It is the only algorithm that can obtain a zero-blocking solution (thanks to its directly accounting for the impairment effects). Zero-blocking is maintained up to $\rho = 0.8$ load, after which point the number of utilized lightpaths is high and the interference-related constraints cannot all be satisfied. We also note that in all the cases where the SB-IA-RWA algorithm finished without violating its interference related constraints, the Q evaluation module (post-processing phase) accepted all the lightpaths provided by this algorithm, validating in this way the assumptions of Section IV-C.

3) Zero-Blocking Simulation Experiments: When designing a wavelength routed WDM network (offline problem) we are usually searching for a zero-blocking solution. As seen earlier, the direct SB-IA-RWA algorithm can find a zero-blocking solution given enough wavelengths, while the P-IA-RWA algorithm cannot ensure this, unless it uses very tight $A_{\text{path-max}}$, $N_{\text{adj-max}}$, $N_{\text{2-adj-max}}$, and $N_{\text{XT-max}}$ bounds, something that would result into an unacceptably large number of additional wavelengths. In this set of experiments, we focus on zero-blocking solutions. For this reason, we examine the performance only of the SB-IA-RWA algorithm and solve: 1) the proposed LP-relaxation algorithm using iterative fixings and roundings to obtain an integer solution; and 2) the ILP version with a branch and bound method.

In Fig. 10, we report on the average number of wavelengths required to obtain zero-blocking for 100 traffic matrices for loads between 0.5 and 1 with a step of 0.1. For the ILP execution of the algorithm, we were able to track solutions for loads up to $\rho = 0.7$ in a time limit of 5 h per instance. We can see that the average number of wavelengths required by the proposed LP-relaxation algorithm is quite close to that

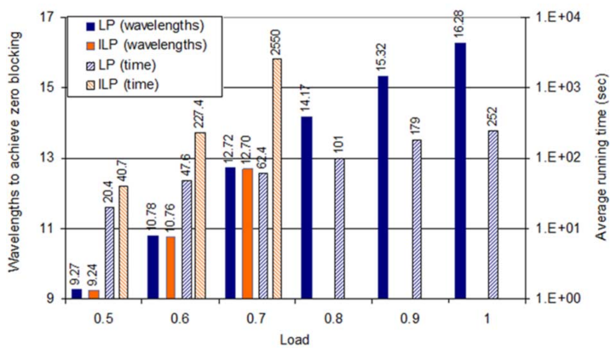

Fig. 10. Average number of wavelengths required to obtain zero blocking, and corresponding average running time for the SB-IA-RWA algorithm, solved using the proposed LP-relaxation technique and ILP.

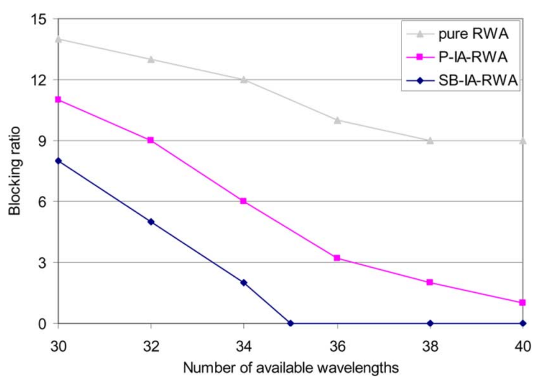

Fig. 11. Blocking ratio versus number of available wavelengths, for realistic traffic load $\rho \approx 2.05$.

required by the optimum ILP. With respect to the execution times, we see that the proposed LP-relaxation algorithm has superior performance, maintaining the running times within a few hundreds of seconds, while the ILP algorithm cannot solve certain hard instances even at medium load. Note that as the load increases, more lightpaths are activated and the interfering sources among them increase, making the problem more complicated and difficult to solve.

4) Realistic Traffic Matrix Simulation Experiments: In Fig. 11, we graph the blocking performance of the pure RWA algorithm and the proposed P-IA-RWA and SB-IA-RWA algorithms, as a function of the number of available wavelengths W, assuming the actual traffic matrix of DTnet ($\rho = 2.05$). We can see that the proposed IA-RWA algorithms reduce significantly the blocking ratio as compared to the pure RWA algorithm. The SB-IA-RWA algorithm can obtain a zero-blocking solution for $W = 35$, while the pure RWA has blocking equal to 10%, which is reduced to about 3.2% using P-IA-RWA. The running time of the pure RWA for $W = 35$ was around 30 s. The corresponding running time for the SB-IA-RWA algorithm was about 15 min, and that of the P-IA-RWA was about 3 h. Note that for this traffic load and $W = 35$, P-IA-RWA algorithm utilizes 21 338 variables and 61 278 constraints. The SB-IA-RWA algorithm utilizes fewer variables and substantially fewer constraints (19 700 and 22 512, respectively) and, thus, has much better running time.

Fig. 12 shows the number of wavelengths required to obtain a zero-blocking solution by the SB-IA-RWA algorithm, with input the realistic traffic matrix scaled uniformly so as to generate matrices of loads between 0.5 and 3, with a step of 0.5. We observe that SB-IA-RWA algorithm scales well with the load.

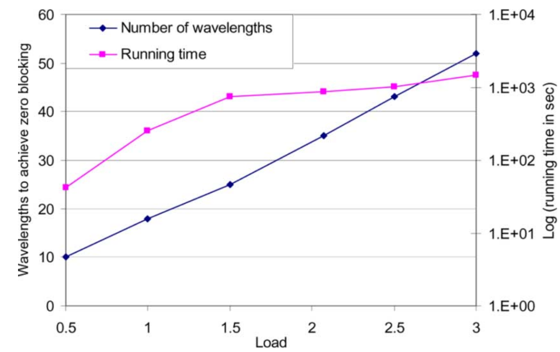

Fig. 12. Wavelengths required to find a zero-blocking solution and running time of the SB-IA-RWA algorithm, by scaling the realistic traffic matrix.

VI. Conclusion

We presented an algorithm for solving the static RWA problem based on a LP-relaxation formulation that provides integer optimal solutions despite the absence of integrality constraints for a large subset of RWA input instances. We then extended the RWA formulation and proposed two impairment-aware (IA) RWA algorithms that model the physical layer impairments as additional constraints in their formulation. The P-IA-RWA algorithm takes the physical layer indirectly into account, by constraining (actually, penalizing) the impairment-generating parameters. The second algorithm, SB-IA-RWA, is a direct algorithm that constrains the interference among the lightpaths so as to obtain acceptable transmission quality as defined by the Q-factor. Using realistic traffic scenarios, our results quantified the performance improvements obtained by the proposed IA-RWA algorithms over the pure RWA algorithm. The direct SB-IA-RWA algorithm was shown to exhibit very good wavelength utilization performance, can find a zero-blocking solution given enough wavelengths, and has acceptably low execution times.

Appendix

In the general multicommodity flow problem, given an optimal fractional solution, a flow that is served by more than one path has equal sum of first derivatives of the costs of the links comprising these paths [25]. To be more precise, assume a general multicommodity minimization problem

$$\begin{aligned} \text{minimize} \quad & D(x) \\ \text{subject to} \quad & x \in X \end{aligned}$$

where $x = (x_1, x_2 \ldots, x_n)$ is a solution consisting of n flow variables, and D is a differentiable convex function. Now, assume that we have an optimal solution x^* where two paths both serve a connection request, each of them carrying a fractional flow. For example, let x_p and $x_{p'}$ be two variables carrying fractional flows with $x_p \neq 0$ and $x_{p'} \neq 0$, where both paths p and p' serve the same source–destination pair. If we move a small fraction of flow $\delta > 0$ from x_p to $x_{p'}$, so as to obtain $x_p - \delta$ and $x_{p''} + \delta$ for the corresponding flow values, the increase ΔD in the objective cost would be

$$\Delta D = \delta \cdot \left(\frac{\partial D(x^*)}{\partial x_{p'}} - \frac{\partial D(x^*)}{\partial x_p} \right)$$

where $\partial D(x^*)/\partial x_p$ is the first derivative of D with respect to the coordinate (path flow) x_p evaluated at x^*. For x^* to be optimal, ΔD should be greater than or equal to zero, so that such a shifting of flow from one path to the other does not increase the cost. Since both $x_p \neq 0$ and $x_{p'} \neq 0$, a similar argument can be made by assuming that flow δ is moved from x_p' to x_p. This means that must also be less than or equal to zero. Therefore, the following relation must hold at the optimal solution when both flow variables x_p and $x_{p'}$ are nonzero:

$$\frac{\partial D(x^*)}{\partial x_{p'}} = \frac{\partial D(x^*)}{\partial x_p}$$

indicating that at an optimal solution, a flow that is served by more than one paths must have equal sums of their first derivative lengths over the corresponding paths.

Now, if we turn our attention to the RWA problem that we examine, a flow variable corresponds to a candidate lightpath (p, w). The objective function $D(x)$ that we utilize in our RWA formulations sums the flow costs of the links that comprise a lightpath, and thus a request served by more than one lightpath has equal sums of first derivates over the links of these lightpaths. The derivative of the cost on a specific link is given by the slope of the linear or piecewise linear flow cost function that we utilize. To make this more precise, let two lightpaths $x_{p,w}$ and $x_{p',w'}$ serve a connection request. Also, let a_l be the slope of the flow cost $f(w_l)$ on link l for a given solution. At an optimal solution where $x_{p,w}$ and $x_{p',w'}$ are both nonzero and both serve the same source–destination pair, the following holds:

$$\sum_{l\in p} \frac{\partial f(w_l)}{\partial x_{pw}} = \sum_{l\in p'} \frac{\partial f(w_l)}{\partial x_{p',w'}} \Rightarrow \sum_{l\in p} a_l = \sum_{l\in p'} a_l.$$

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