Impairment-Aware Offline RWA for Transparent Optical Networks

Konstantinos Manousakis, Konstantinos Christodoulopoulos, Emmanouel (Manos) Varvarigos
Computer Engineering and Informatics Department, University of Patras, Greece, and
Research Academic Computer Technology Institute, Patra, Greece
{*manousak*, *kchristodou*, *manos*}@ceid.upatras.gr

***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. We initially present an algorithm for solving the static RWA problem based on an LP relaxation formulation that tends to yield integer solutions. To account for signal degradation due to physical impairments, we model the effects of the path length, the path hop count, and the interference among ligthpaths by imposing additional (soft) constraints on RWA. The objective of the resulting optimization problem is not only to serve the connection requests using the available wavelengths, but also to minimize the total accumulated signal degradation on the selected lightpaths. Our simulation studies indicate that the proposed RWA algorithms select the lightpaths for the requested connections so as to avoid impairment generating sources, thus dramatically reducing the overall physical-layer blocking when compared to RWA algorithms that do not account for impairments.**

I. INTRODUCTION

In a WDM network each fiber link carries high-rate traffic at many 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* [1][2], where optical pulse-trains are transmitted through *lightpaths*, that is, all-optical WDM channels that may span multiple consecutive fibers. Given a set of connection requests, the RWA problem consists of selecting an appropriate path and a wavelength for each requested connection so as to minimize the network resources used or maximize the traffic served [1]-[4]. 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 static traffic matrix) the problem is referred to as *offline* or *static* RWA, while when the connections arrive randomly and are served on a one-by-one basis the problem is referred to as *online* or *dynamic* RWA. We will focus our study on offline RWA, which is known to be a $\mathcal{NP}$-hard problem. Offline RWA is more difficult than online RWA, since it jointly optimizes 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 in the literature assume an ideal physical layer where signal transmission is error free. However, signal transmission is significantly affected by physical limitations of fibers and optical components [1][2], and must be accounted for during connection establishment. We will refer to such phenomena as physical layer impairments (PLI). Due to the PLI the signal quality may degrade to the extent that the bit-error rate (BER) at the receiver may be so high that signal detection may be infeasible. For the remaining of this study we will refer to such a phenomenon as *physical-layer blocking*.

Since in offline RWA the assignment of paths and wavelengths (lightpaths) is to be decided for all requested connections simultaneously, interference among them has to be taken into account during lightpath selection. The offline RWA algorithms proposed to date do not handle the impairments that depend on the interference among lightpaths. In this paper, we start by presenting an algorithm for solving the static RWA problem based on an linear program (LP) relaxation formulation that has acceptable integrality performance [5][6]. We then extend this formulation in order to handle the physical layer impairments. More specifically, for each lightpath we describe as linear soft constraints (i) the path's length and the number of hops, (ii) the number of adjacent and second adjacent channels across all the links of the lightpath, and (iii) the number of intra-channel crosstalk sources (lightpaths crossing the same switch utilizing the same wavelength) along the lightpath. We present and evaluate two impairment-aware (IA)-RWA variations that differ on the number of surplus variables used to formulate the above parameters. The objective of the IA-RWA problem is not only to serve the connection requests with the available wavelengths, but also to minimize the total signal degradation accumulated on the established lightpaths.

It is worth noting that the aforementioned parameters, (i) - (iii) above, are the key parameters for the majority of the physical impairments [1][2]. More specifically, amplified spontaneous emission (ASE) noise depends on the number of amplifiers, which is related to the length of the links, and the number of hops (switches). Chromatic dispersion (CD), self-phase modulation (SPM) and polarization mode dispersion (PMD) also depend on the length of the path. Filter concatenation (FC) depends on the number of filters over the path, and since it is a general practice that each all-optical 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 cross-phase modulation (XPM), four-wave mixing (FWM) and inter-channel crosstalk (inter-XT). Finally, intra-channel 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 linearly on the parameters discussed, it is expected that trying to reduce these parameters would decrease the effect of all impairments. Our performance results, which use a Q estimator tool that uses detailed analytical models to evaluate the quality of transmission (QoT) of the selected lightpaths, indicate that this expectation is correct.

Our simulation results show that the proposed IA-RWA algorithms avoid impairment generating sources and choose lightpaths that have small length, traverse a small number of hops and also interfere among each other as little as possible. The proposed algorithms are shown to dramatically reduce the overall physical-layer blocking when compared to a "pure" RWA algorithm that does not consider impairments at all. Moreover, we also look-into the effect that the additional constraints have on the integrality of the algorithm.

The rest of the paper is organized as follows. In Section II we present previous work on RWA and impairment-aware RWA. In Section III we give the pure RWA formulation. We then extend it and propose in Section IV our impairment-aware RWA algorithm with physical impairment constraints. Simulation results are then presented in Section V. Our conclusions are given in Section VI.

II. Previous Work

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

RWA integer linear program (ILP) formulations were initially proposed in [7][8]. 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 few newer and more sophisticated RWA algorithms are presented in [5][6][9]. The LP relaxation formulations proposed in [5][6] are 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 [10]-[15]. Among these online algorithms there are approaches that consider the quality of transmission (QoT) problem separately from the RWA problem, that is, they first solve the RWA problem and then consider the effects of the impairments, evaluating the feasibility of the chosen lightpaths in a separate modeling module [10]-[12]. This approach may not yield a solution with acceptable quality of transmission, and iterations are usually performed in order to improve the physical-layer blocking performance. Other online approaches incorporate physical impairments into the cost function of the algorithm and also consider the interference among the lightpaths [13]-[15].

In the dynamic traffic case, where the connections are established on a one-by-one basis, the employed algorithm can examine the feasibility of a lightpath for a connection request. This can be done by calculating (through appropriate models) or measuring (through performance monitors) the interference of the already established lightpaths to the lightpath under examination. 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 consider inter-lightpath interference.

In [16], the authors solved the offline pure (without impairments) RWA problem and then evaluated in a post-processing phase the feasibility of the chosen lightpaths. For connection requests whose lightpaths do not have acceptable transmission performance, new solutions are found, by excluding from the set of candidate paths the ones that were previously considered. An offline impairment-aware RWA algorithm that assigns Q-factor costs to links before solving the problem is proposed in [17]. However, the proposed algorithm does not take into account the actual interference among lightpaths since it assumes a worst case interference scenario. In [18], 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.

The main contribution of our work is an (I)LP formulation with physical impairments that solves 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. Consequently, both linear and non-linear impairments are taken into account. In order to address path-related impairments we pose soft constraints on the path's length and the number of hops. Moreover, in order to decrease interference among lightpaths we pose soft constraints on the number of adjacent (and second adjacent) channels across all the links of a lightpath, and the number of intra-channel crosstalk sources (lightpaths crossing the same switch utilizing the same wavelength) along the lightpath. We argue that these are the key parameters for the majority of the physical impairments and validate our proposed formulation through simulations, using an evaluation module with detailed analytical formulas to model all the well known impairments.

III. Routing and Wavelength Assignment Problem

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 $C=\{1,2,\dots,W\}$ of W distinct wavelengths. The static version of RWA assumes an a-priori known traffic scenario given in the form of a matrix of non-negative integers Λ, called the traffic matrix. Then, Λ_{sd} denotes the number of requested connections from source s to destination d and there may be multiple connection requests for a given source-destination pair (s,d).

The algorithm is given a specific RWA instance; that is, a network topology, the set of wavelengths that can be used, and a static traffic scenario. It returns the instance solution, in the form of routed lightpaths and assigned wavelengths, as well as the blocking probability that accounts for requests that are not served for the given set of wavelengths.

A. The Algorithm in the Absence of Physical Impairments

The algorithm consists of four phases [6]. The first (pre-processing) phase computes a set of candidate paths to route the requested connections. The second phase utilizes Simplex algorithm 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 in order to obtain an integer solution. 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 doubled 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 other k-shortest path algorithms are also applicable. 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 $P=\bigcup_{s-d} P_{sd}$ is inserted to the next phase. The pre-processing 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 linear program (LP). The LP formulation used is presented in Section III.B. This LP is solved using the Simplex algorithm that is generally considered efficient for the great majority of all possible inputs. If the instance is feasible and the solutions are 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 solutions are fractional 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 (non-integer) solution, the third phase involves iterative fixing and rounding methods, as presented in Section III.D, in order to obtain an integer solution. The maximum number of iterations is the number of connection requests, which is polynomial on the size of the input. Rounding can increase the number of required wavelengths, in which case we are not able to find a feasible solution and 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 iteratively increasing the number of available wavelengths and re-executing Phases 2 and 3 until a feasible solution is obtained. 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. The removed wavelengths are those occupied by the minimum number of lightpaths, so as to minimize the number of requested 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 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 the next subsection). 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:

- $x_{p,w}$: an indicator variable, equal to 1 if path p occupies wavelength w, else 0
- F_l: the flow cost function value of link l

RWA LP FORMULATION

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

subject to the following constraints:

- Distinct wavelength assignment constraints,
  $$\sum_{\{p|l\in p\}} x_{p,w} \le 1, \text{ for all } l\in E, \text{ for all } w\in C$$
- Incoming traffic constraints,
  $$\sum_{p\in P_{sd}} \sum_{w} x_{p,w} = \Lambda_{sd}, \text{ for all } (s,d) \text{ pairs}$$
- Flow cost function constraints,
  $$F_l \ge f(w_l) = f\left(\sum_{\{p|l\in p\}} \sum_{w} x_{p,w}\right)$$
- The integrality constraint is relaxed to $0 \le x_{p,w} \le 1$.

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 that we use inequalities is that we will use a piecewise linear cost function f that is inserted in the LP formulation by utilizing these inequalities. Also note that the wavelength continuity constraints are implicitly taken into account be 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 routing of the connections. We choose F_l to be a properly increasing function $f(w_l)$ of the number of lightpaths $w_l=\sum_{\{p|l\in p\}}\sum_w x_{p,w}$ crossing link l. $F_l = f(w_l)$ is also chosen to be convex (instead of linear), implying a greater degree of 'undesirability', when a link becomes highly congested. This is because it is preferable, in terms of network performance, to serve an additional unit of flow using several low-congested links, than to use a link that becomes totally congested. In particular, we utilize the following flow cost function:

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

The above (nonlinear) function is inserted to the LP in the approximate form of a piecewise linear function; i.e., a continuous non-smooth function, that consists of *W* consecutive linear parts (see Figure 1). The piecewise linear function is constructed as follows: we begin with $F_l(0)=0$, and iteratively set, for $i=1,\ldots,W$, $F_l^i(w_l)=a_i \cdot w_l+\beta_i$, $i\text{-}1 \le w_l \le i$, where $a_i=F_l(i)-F_l(i\text{-}1)$ and $\beta_i=(i\text{-}1)\cdot F_l(i)-i\cdot F_l(i\text{-}1)$.

Observe that the piecewise linear function is exactly equal to $F_l=f(w_l)$ at integer argument values ($w_l=1,2,\ldots,W$) and greater 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 [5]. 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 thus consist also of integer components. Since the Simplex algorithm moves from vertex to vertex of that polyhedron, there is a higher probability of obtaining integer solutions than using other methods (e.g., interior point methods). Our experimental results in [6] show that this is actually the case in most problem instances.

D. Iterrative Fixing and Rounding Teqnique

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 turn out to be non-integer. In such case we continue 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 integers with the same cost. Thus, if after successive fixings we reach an all-integer solution we are sure that it is an optimal solution. 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 the fixing process cannot be further pursued we proceed to the rounding process. We round a single variable, the one closest to 1, and continue solving the reduced LP problem. Rounding is inevitable when there is no integer solution with the same objective cost as the LP relaxation of the RWA instance. However, if after rounding the objective 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 which is polynomial on the size of the problem input.

IV. Transmission Impairments in WDM Networks

In transparent optical networks signal quality degrades due to physical layer impairments (PLIs). These PLIs depend on the characteristics of the fibers and the components used, but some of them also vary with network utilization. The dominant sources of degradation are: Amplified Spontaneous Emission (ASE) noise from erbium doped amplifiers (EDFAs), inter-channel crosstalk (inter-XT) from power leaking in optical crossconnects (OXCs), imperfect power isolation in the demultiplexers (intra-channel crosstalk or intra-XT), dispersion effects such as Polarization Mode Dispersion (PMD) and Chromatic Dispersion (CD), and Filter Concatenation (FC). Moreover, severe nonlinear impairments include Self Phase

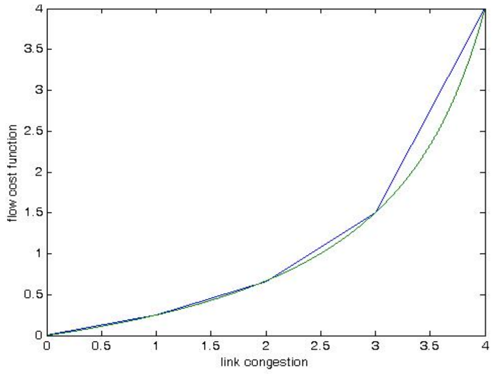

Figure 1: The flow cost function $F_l=f(w_l)$ (curved line) and the corresponding piecewise linear function.

Modulation (SPM), Cross Phase Modulation (XPM), and Four Wave Mixing (FWM). The impairments that accumulate may result in significant degradation of the signal quality at the destination, which may turn the lightpath infeasible. Therefore, avoiding physical impairments is a crucial consideration in designing transparent WDM networks.

A. Impairment-Aware RWA (IA-RWA) Formulation

In this section, we enhance the LP formulation presented in the previous section to take into consideration (i) the length and the number of hops of a path, (ii) the number of adjacent (and second adjacent) channels over all links of the lightpath, and (iii) the number of intra-channel generating sources (lightpaths crossing the same switch utilizing the same wavelength) along the lightpath. 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.

1) Constraining the path length and hop count

Our aim is to minimize the degradation from physical phenomena that are directly connected to the length and the number of nodes a lightpath traverses. More specifically, ASE noise is a linear impairment that depends only on the number of amplifiers on the path. PMD also depends on the length of the path, it is additive on a per link basis and does not depend on the utilization of the other wavelengths. The penalty of FC depends on the number of filters of the path and, since it is a common practice a OXC switch to have two filters, we only have to count the number of OXC switches (or hops) of the path in order to calculate the effect of FC.

To constraint the length and the number of hops of path *p*, we use the following constraints:

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

where a_l is a constant for link *l* that is related to its length. In our experiments we have chosen $a_l = \lfloor d_l/100 \rfloor + 4$, where d_l is the length of link *l* in km. This choice assumes that amplifiers are placed every 100 km of fiber, and each switch has 2 amplifiers (one input and one output amplifier) and 2 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 constrains are not treated as hard constraints in the above LP formulation; instead, we use the non-negative 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. Thus, the new cost objective is to minimize

$$\sum_l F_l + \sum_p S_p \,,$$

where the first term accounts for the cost of wavelength utilization on the links (penalizing more severely increasing utilization of individual links) and the second term accounts for path lengths and hop counts that exceed a certain threshold.

This formulation has the added advantage that we do not get an infeasible instance. By using surplus variables, even if some lightpaths chosen in the solution cannot satisfy the above constraint we shall still obtain a solution. In contrast, if we used hard constraints, Simplex would fail to produce any (not even partial) solutions if the aforementioned length and hop constraints could not be satisfied for all connection requests.

2) Constraining adjacent channel interference

Impairments due to inter-channel crosstalk and non linear physical impairments (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. In particular, inter-channel crosstalk has to do with the power leakage between neighboring channels at the OXCs. The effect of cross-phase modulation is more severe between adjacent channels and deteriorates as we move away from the channel under examination. Four-wave mixing depends on the utilization of certain sets of wavelengths and is more severe on a given channel if its adjacent channels are also active. 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.

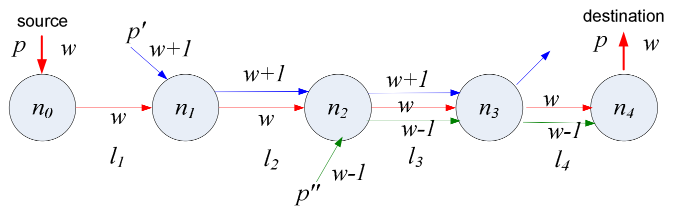

Figure 2: Adjacent channel interference on lightpath (p,w) by other lightpaths.

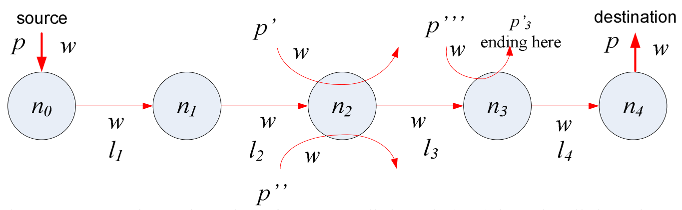

Figure 3: Intra-channel XT interference on lightpath (p,w) by other lightpaths.

In Figure 2 the effect of adjacent channel interference is depicted. 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 $(p'',w\text{-}1)$ be a lightpath that crosses links l_3 and l_4. In this example there are in total 4 adjacent channel interfering sources affecting the signal quality of lightpath (p,w).

To avoid adjacent channel interference we use the following constraints.

$$\left(\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w-1}+\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w+1}\right)+B\cdot x_{pw}-S_p{}'\leq$$
$$N_{adj-acceptable}+B, \quad \text{for all } p\in P, \text{ for all } w\in C,$$

where

- B is a constant (taking large values).
- $N_{adj\text{-}acceptable}$ is a threshold on the number of adjacent interfering channels for a lightpath.
- $L_{pp'}=\{l \mid l\in p\cap l\in p'\}$ is the set of links that are common to paths p and p', and $|\cdot|$ denotes the cardinality of a set.
- $\left(\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w-1}+\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w+1}\right)$ is the total number of adjacent interfering sources that affect the signal of lightpath (p,w).

The reason for introducing constant B is the following:

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

$$\left(\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w-1}+\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w+1}\right)-S_p{}'\leq N_{adj-acceptable}$$

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

$$\left(\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w-1}+\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w+1}\right)-S_p{}'\leq N_{adj-acceptable}+B,$$

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 utilized, and inactive (always true), otherwise.

In a similar manner, the constraint for the next to adjacent channels is formulated as follows.

$$\left(\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w-2}+\sum_{p'}\left|L_{pp'}\right|\cdot x_{p',w+2}\right)+B\cdot x_{p,w}-S_p{}''\leq$$
$$N_{next-adj-acceptable}+B, \quad \text{for all } p\in P, \text{ for all } w\in C.$$

We again employ soft constraints by including in the optimization function the surplus variables $S_p{}'$ and $S_p{}''$ that appear in the constraints on the number of adjacent and second-adjacent channels used, respectively.

3) Constraining intra-channel crosstalk

Node intra-channel crosstalk is related to the non-ideal switching matrix of an optical cross-connect switch [10]. In particular, inter-channel crosstalk is the effect of power leakage between lightpaths crossing the same switch and using the same wavelength due to non-ideal isolation of the inputs/outputs of the switching fabric. Note that intra-channel crosstalk cannot be filtered out, since the interfering signal is on the same wavelength as the one affected.

In Figure 3 the effect of intra-channel XT is depicted. A lightpath p from n_0 to n_4 is established using wavelength w. Let (p',w), (p'',w), (p''',w) be lightpaths that 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). In particular, in this example there are in total 3 intra-channel XT interfering sources.

The effect of intra-channel crosstalk for each path p and wavelength w is formulated as follows:

$$\sum_{p'} \left|N_{pp'}\right| \cdot x_{p',w} + B \cdot x_{p,w} - S_p''' \le N_{XT-acceptable} + B,$$
$$\text{for all } p \in P, \text{ for all } w \in C,$$

where $N_{pp'} = \{n \mid n \in p \cap n \in p'\}$ is the set of nodes that are common to paths *p* and *p'*. As previously, we use constant *B* to activate or deactivate this constraint for a given lightpath (*p*,*w*). The surplus variables are again carried in the objective.

B. Optimization Functions

Our overall objective is to minimize the number of requests that are blocked for a given number of available wavelengths *W*. 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 do not have acceptable quality of transmission performance. In order to consider both of the above factors that affect blocking we use the following cost functions, which try to penalize both the wavelength usage and the violation of impairment related thresholds but differ in the number of surplus variables they use:

- 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 related impairments of path p.
- Minimize $\sum_{l} F_l + \sum_{p \in P} S_p + \sum_{p \in P}\sum_{w \in C} S_{pw}' + \sum_{p \in P}\sum_{w \in C} S_{pw}'' + \sum_{p \in P}\sum_{w \in C} S_{pw}'''$,
  where $S_{pw}', S_{pw}'', S_{pw}'''$ define the excess of the impairments of path *p* on a specific wavelength *w*, and S_p is as previous.

The formulations presented in Section IV.A used one surplus variable S_p per path *p* (irrespective of the chosen wavelength *w*); the modifications needed to include one surplus variable S_{pw} per lightpath (*p*,*w*) is straightforward and is omitted for brevity. Note that the impairments discussed in Section IV.A.1 do not have these two different versions since the length/hop constraint does not change with the selected wavelength *w*. We denote by IA-RWA-p the algorithm that uses one surplus variable S_p per path *p* and by IA-RWA-pw the algorithm that uses one surplus variables S_{pw} per lightpath (*p*,*w*)

Note that in the two optimization objectives described above the impairment-related parameters are equally penalized. A weighted combination of these could improve the blocking performance of the algorithm. For example, if the network under examination has high ASE and FC noise, and thus the length and the number of hops of the lightpaths is more important, we could use a higher weight to penalize the surplus variables S_p. However, the focus of the proposed IA-RWA algorithms is to formulate the impairment-related parameters that affect the quality of transmission of the lightpaths. Different ways to combine these parameters and the choice of appropriate weights are left for future work.

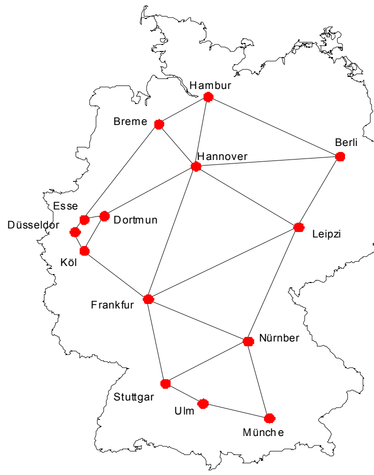

Figure 4: Generic DT network topology. 14 nodes, 23 links (we assumed 46 directed links).

Table I shows the number of variables and the number of constraints required by the proposed algorithms. For the IA-RWA-p and IA-RWA-pw algorithms we have assumed that we apply all the impairment constraints (path length and hop count, adjacent and second adjacent channel interference, and intra-XT interference) presented in Section IV.A simultaneously, using the above minimization cost functions. We can see that RWA uses the fewest variables (since it does not use any surplus variables), IA-RWA-pw uses the highest number of variables, and IA-RWA-p comes in between. IA-RWA-p and IA-RWA-pw have the same number of constraints. The difference in the number of constraints between the RWA and the IA-RWA-p/ IA-RWA-pw formulations are due to the additional impairment-related constraints described in Section IV.A.

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 we used the glpk library [19] to solve the corresponding LP problems. We compared the proposed IA-RWA algorithms of Section IV to the "pure" RWA algorithm, presented in Section III, which does not consider physical impairments.

The network topology used in our simulations was the generic Deutsche Telekom network (DTnet), shown in Figure 4, which is a candidate transparent network, as identified by the DICONET project [20]. The capacity of a wavelength was assumed equal to 10Gbps.

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	=	≤
RWA (Section III)	$k\rho N^2 W+L$	-	$(\rho N^2)_1$	$(L W)_2+(L W)_3$
IA-RWA-p	$k\rho N^2 W+L$	$4 k\rho N^2$	$(\rho N^2)_1$	$(L W)_2+(L W)_3+(k\rho N^2)_4+(k\rho N^2 W)_5+(k\rho N^2 W)_6+(k\rho N^2 W)_7$
IA-RWA-pw	$k\rho N^2 W+L$	$3 k\rho N^2 W+k\rho N^2$	$(\rho N^2)_1$	$(L W)_2+(L W)_3+(k\rho N^2)_4+(k\rho N^2 W)_5+(k\rho N^2 W)_6+(k\rho N^2 W)_7$

$N=|V|$: number of nodes
$L=|E|$: number of links
$W=|C|$: number of wavelengths
k: number of shortest paths for each connection
ρ: load (percentage of total connections)

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

First, we present our results in the form of histograms that show the effect of the constraints described on Section IV.A on the solutions obtained by the RWA algorithms. More specifically, given the solution to an RWA instance, we graph the probability mass distributions of the lengths, the number of hops, the number of adjacent channels and the number of intra-XT interfering sources of the selected lightpaths. Then, we apply all the constraints presented in Section IV.A together, utilizing the objectives described in Section IV.B, and evaluate network performance using the blocking probability as the measure of interest. As already mentioned, the blocking probability generally includes both network-layer and physical-layer blocking. In our experiments we were more interested in the physical-layer blocking. Thus, all the experiments were performed assuming an adequate number of wavelengths so that if no physical impairments were present, all connections would be served. Thus, the blocking that is reported is equal to the physical-layer blocking.

For assessing the feasibility of lightpaths we used a Q-factor estimator that was developed within DICONET project [20] that uses analytical formulas to model all the well known impairments. The model of a link is the one presented in [20], having spans of length equal to 100 km (amplifiers placed every 100 km). The dispersion compensation map and the parameters of the physical impairments were realistically chosen assuming recent fibers and optical components.

Based on experiments performed with the Q estimation module on the DTnet, we used the following thresholds:

$A_{path\text{-}acceptable}$=16, $N_{adj\text{-}acceptable}$=6, $N_{next\text{-}adj\text{-}acceptable}$=6, $N_{XT\text{-}acceptable}$=5.

The results were obtained using (i) a series of traffic matrices produced by a random traffic generator and (ii) a realistic traffic scenario. We define the traffic load as the ratio of the number of requested connections to the total number of possible connections. For example traffic load ρ=0.5 corresponds to the case were half of the entries of the traffic matrix are equal to 1 and half equal to 0. For the experiments with the random traffic generator we performed 100 RWA executions corresponding to different random traffic instances for a given traffic load. We have also performed a single execution with the actual traffic matrix of DTnet as reported in [20], which corresponds to a load $\rho\approx 2.05$ (the traffic matrix consists of 374 connection requests of 10 Gbps). Note that in this traffic matrix for many source-destination pairs we have to establish more than one (in particular up to five) lightpaths.

A. Avoiding Impairments Generating Sources – Single Constraint Performance

We report the histograms of the distribution of certain characteristics of the paths obtained by RWA algorithm and the proposed IA-RWA algorithms for traffic load ρ=0.5, assuming W=16 available wavelengths. Note that the constraints presented in Sections IV.A.1, IV.A.2, IV.A.3 were used separately in the experiments of this section.

In Figures 5 and 6 we provide comparison results between the pure RWA and the IA-RWA-p algorithms. We do not report the results of IA-RWA-pw, since the length/hop constraint does not change with the selected wavelength w, and thus there is no difference between IA-RWA-p and IA-RWA-pw. When the IA-RWA-p algorithm is used, paths with shorter lengths, fewer nodes and therefore better quality of transmission characteristics are selected. The objective of the pure RWA algorithm is to minimize the total number of used

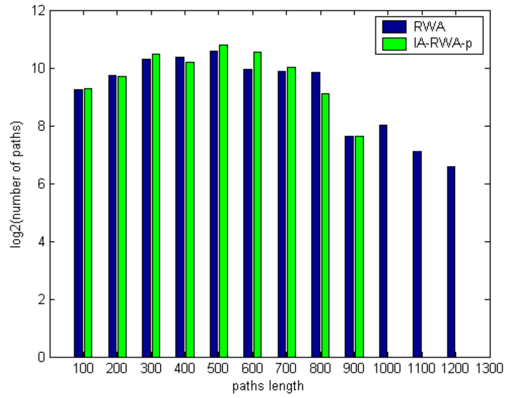

Figure 5: Histogram showing the distribution of the path lengths (the path distances in IA-RWA-p are constrained).

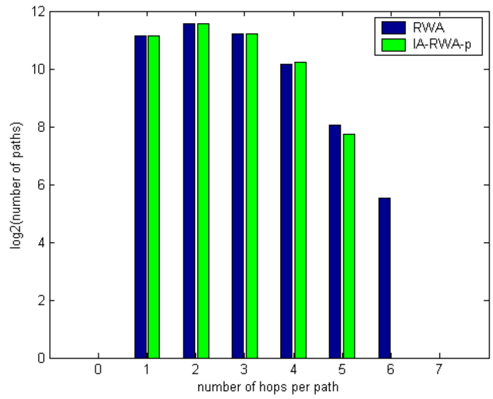

Figure 6: Histogram showing the distribution of the path hop count (the number of hops in IA-RWA-p are constrained).

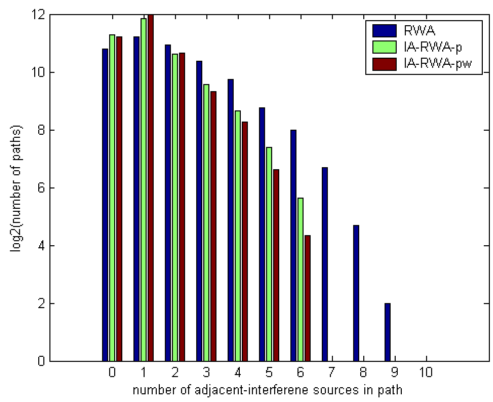

Figure 7: Histogram showing the distribution of the number of adjacent channel interferers per lightpath (the number of adjacent channel interferers in IA-RWA-p and IA-RWA-pw are constrained).

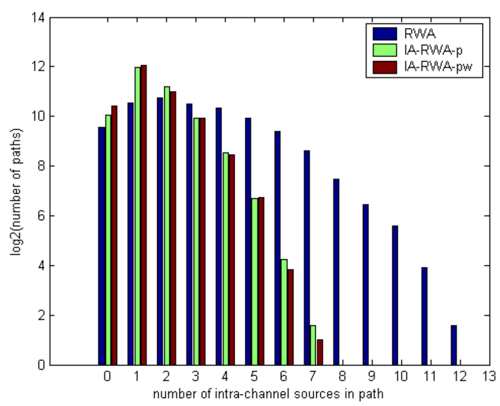

Figure 8: Histogram showing the distribution of the number of intra-channel crosstalk sources per lightpath (the number of intra-channel crosstalk interferers in IA-RWA-p and IA-RWA-pw are constrained).

wavelengths and in order to do so it can select long paths from the set of candidate paths. On the other hand, the proposed IA-RWA algorithms would favorably select shortest length and hop paths in order to avoid the violation of the corresponding threshold, in the possible expense of utilizing a higher number of wavelengths.

Figure 7 plots the distribution of the number of adjacent interference sources per path. Comparing the results obtained by the RWA, IA-RWA-p, and IA-RWA-pw, it can be observed that lightpaths selected by IA-RWA-p and IA-RWA-pw algorithms interfere less with other lightpaths and as a consequence the impact of XPM, FWM and inter-XT is reduced. Similarly, Figure 8 illustrates the distribution of the number of intra-XT interfering sources per lightpath. The improvements obtained by the IA-RWA algorithms in minimizing intra-channel crosstalk are evident.

In all these figures a left shift in the probability distributions is observed when using the IA-RWA algorithms, meaning that physical impairment generating sources are fewer, and signal quality is improved. We can observe that IA-RWA-pw exhibits better performance than IA-RWA-p, since the corresponding probability distributions of the former are more tilted to the left than those of the latter.

B. Integrality, Execution Time and Blocking Performance – Simultaneous use of Multiple Constraints

In this set of experiments we apply simultaneously all the constraints presented in Section IV.A and evaluate the performance of the algorithms through the blocking probability. Before doing so, however, we compare the running times and the integrality of the solutions produced by the algorithms using the following metrics [6]:

(a) The fraction of solutions for which we obtained an integer solution by the LP execution (without any fixing and any rounding iterations)

(b) The number of "fixings" required to obtain integer solutions (without any rounding iterations), averaged over all experiments; this is the average number of fixing iterations performed to move from (a) to (c)

(c) The fraction of solutions that are integer after fixing iterations (without any rounding iterations)

(d) Average number of fixing and rounding iterations for the cases that we performed a single rounding iteration (this is the average number of fixing and rounding iterations performed to move from (c) to (e))

(e) The fraction of solutions that are integer after fixing and rounding iterations

(f) Average running time (in sec): the average running time of the algorithms, including the tableau creation, the LP execution and the fixing and rounding iterations until we obtain integer solutions.

In Table II we present the performance of the algorithms in terms of integrality and execution time for the RWA, IA-RWA-p, IA-RWA-pw formulations, for load ρ=0.5 and W=16 wavelengths per link. The pure RWA algorithm has good integrality performance. From column (c) we can see that the pure RWA manages to obtain integer solutions for all problem instances, with the given number of wavelengths W, only by fixing the variables (therefore, without losing optimality). The RWA algorithm also has the best execution time, as expected, due to the absence of the impairment constraints present in IA-RWA-p and IA-RWA-pw. However, running times are also acceptable for the IA-RWA algorithms, and especially for the IA-RWA-p algorithm. In contrast to the RWA algorithm, the IA-RWA-p/IA-RWA-pw algorithms resort to rounding (column (d)), but as the following results will show, this does not negatively affect their blocking performance.

TABLE II: INTEGRALITY AND RUNNING TIME PERFORMANCE FOR LOAD 0.5

Formulation	(a)	(b)	(c)	(d)	(e)	(f)
RWA	0.22	1.7	1	0	1	4.5
IA-RWA-p	0	0	0	23	1	112
IA-RWA-pw	0	0	0	31	1	362

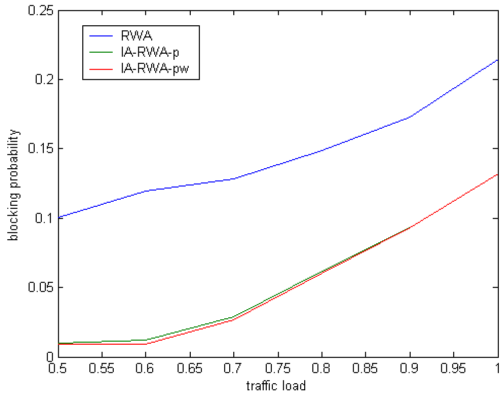

Figure 9: Blocking ratio as a function of load ρ, assuming that there are W=16 available wavelengths.

After solving the RWA problem, we use a Q-factor estimator to evaluate the feasibility of the chosen lightpaths. The Q-factor estimator takes into account all the most known impairments (linear and non-linear) through analytical models. In particular, the Q-factor estimator is used at the end of the algorithm (post-processing) and takes as input the lightpaths selected by the algorithm, calculates their Q-factor, and returns how many of them have unacceptable transmission quality.

Figure 9 shows the average blocking ratio as a function of the traffic load ρ, assuming W=16 available wavelengths, for the impairment-aware and the pure RWA algorithms. The IA-RWA algorithms outperform the pure RWA algorithm in terms of rejected calls. As seen in Figures 5 to 8, the proposed IA-RWA algorithms avoid the impairment generating sources and as a result return lightpaths that exhibit better quality of transmission performance than pure RWA. The improvements are more pronounced at low traffic loads for the given constant number of wavelengths. At low load the available wavelengths are practically enough and the proposed IA-RWA algorithms have more freedom to select the lightpaths so as to avoid interference among them. As the load increases, given the constant number of wavelengths, in order to avoid network layer blocking the IA-RWA algorithms cram the lightpaths and thus higher physical layer blocking is observed.

Comparing the IA-RWA-p and IA-RWA-pw algorithms, we observe that they exhibit similar blocking performance. This is in contrast to the results presented in the previous section, where IA-RWA-pw seemed to be better. This has to do with the presence of all constraints (while in the previous section we evaluated separately each of them), the rounding process, and the high number of variables IA-RWA-pw utilizes. Indeed, as can be seen in Table II, IA-RWA-pw exhibits worse rounding performance (column (d)). Moreover, as column (f) indicates, IA-RWA-pw execution time is much higher than that of IA-RWA-p. Taking all considerations into account, IA-RWA-p seems to be the most preferable impairment aware algorithm from the two variations examined here.

C. *Experiments with Realistic DTnet Traffic Load*

We also performed experiments assuming the actual traffic matrix of DTnet, with corresponding load $\rho\approx 2.05$ as reported in the DICONET project [20]. We obtained results only for the IA-RWA-p algorithm. As in the previous experiments, the IA-RWA-p algorithm reduces significantly the blocking ratio as compared to the pure RWA algorithm. In particular, for W=50 wavelengths, the pure RWA has blocking equal to 21%, which is reduced to about 1.5% using IA-RWA-p. The running time of the pure RWA for W=50 was around 476 sec (≈8 min). The corresponding running time for IA-RWA-p was about 10750 sec (3 hours). Note that for this traffic load and W=50 the optimization problem formulated by IA-RWA-p consists of 28984 variables and 59928 constraints in total (see Table I), which is a very large optimization problem and requires a lot of memory and processing power to be solved. On the other hand, IA-RWA-pw utilizes almost W times these variables (see Table I), making it impossible to be solved using a typical personal computer (PC). This is the reason for which we report only the results of IA-RWA-p algorithm. Concluding, IA-RWA-p seems to be again the preferable impairment aware algorithm from the two formulations proposed in this paper.

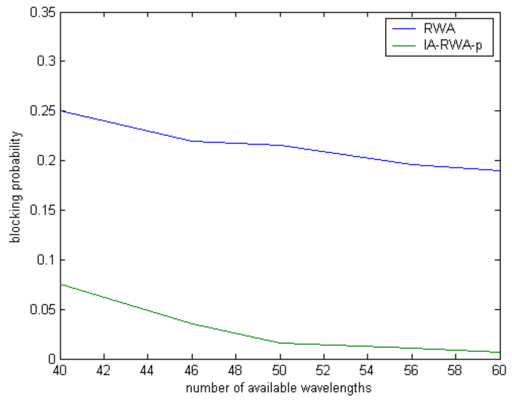

Figure 10: Blocking probability vs. number of available wavelengths per link, for realistic traffic load (load $\rho\approx 2.05$).

VI. CONCLUSION

We presented an algorithm for solving the static RWA problem based on an 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 so as to model the physical layer impairments as additional constraints on RWA. We described by linear constraints the degradation of the transmission quality of a lightpath due to the length of the path, the number of hops, the interference among adjacent and second adjacent channels over all links, and the interference among lightpaths crossing the same switch utilizing the same wavelength (intra-channel crosstalk sources) along the lightpath. Using realistic traffic scenarios, our results quantified the blocking performance improvement obtained by the proposed impairment-aware RWA algorithm when compared to a typical algorithm that solves the pure RWA problem and considers impairments only in the post-processing phase.

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