Considering Physical Layer Impairments in Offline RWA

Konstantinos Christodoulopoulos, Konstantinos Manousakis, and Emmanouel Varvarigos,
University of Patras and Research Academic Computer Technology Institute
Marianna Angelou, Athens Information Technology

Abstract

We consider the offline version of the routing and wavelength assignment problem in transparent all-optical networks. In such networks and in the absence of regenerators, the signal quality of a transmission degrades due to physical layer impairments. Certain physical effects cause choices for one lightpath to affect and be affected by the choices made for other lightpaths. This interference among 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. For this reason the majority of work performed in this field either neglects lightpath interactions or assumes a worst case interference scenario. In this article we present a way to formulate interlightpath interference as additional constraints on RWA and show how to incorporate these constraints in an IA-RWA algorithm that directly accounts for the most important physical layer impairments. The objective of the resulting cross-layer optimization problem is not only to serve the connection requests using the minimum number of wavelengths (network layer objective), but also to select lightpaths that have acceptable quality of transmission performance (physical layer objective).

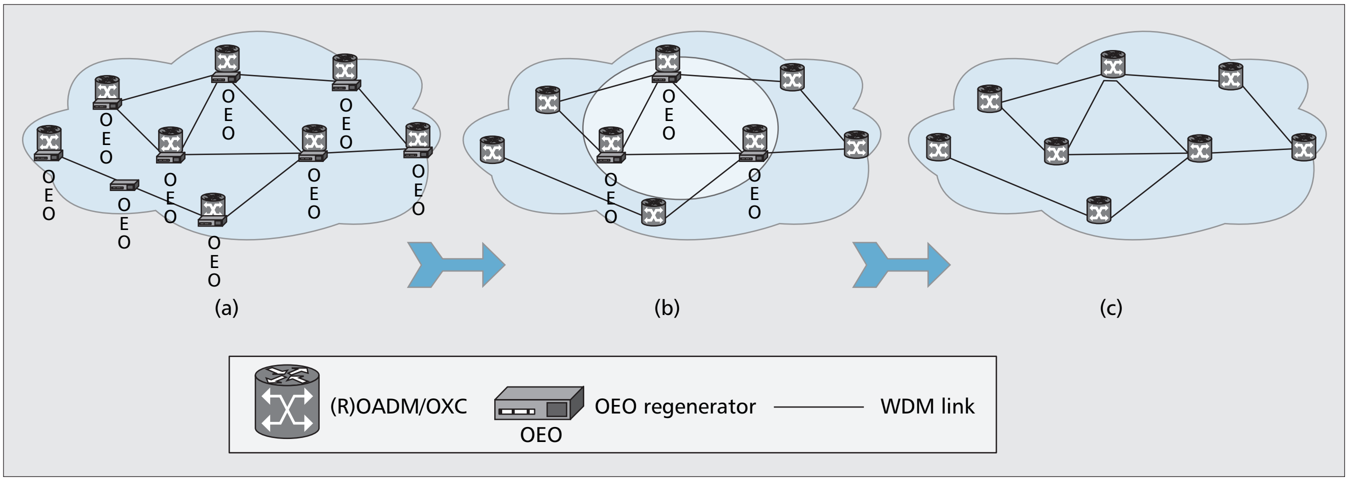
Optical networks offer the promise of meeting the high bandwidth requirements of emerging applications, by providing transmission rates that exceed those of copper networks by several orders of magnitude at very low bit error rates (BERs) and affordable cost. In a wavelength-division multiplexed (WDM) optical 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*, where optical pulse-trains are transmitted through *lightpaths*. The current optical technology employed in core networks is point-to-point (*opaque*), where the signal is regenerated at every intermediate node via optical-electronic-optical (OEO) conversion. In the past few years, the trend clearly shows an evolution toward low-cost high-capacity all-optical networks that do not utilize regenerators. Initially, the cost of an opaque network can be reduced by moving toward a network where regenerators are only employed at some nodes, which is usually referred to as a *translucent* (or managed reach) network. However, 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. It is the vision of the Dynamic Impairment Constraint Network for Transparent Mesh Optical Networks (DICONET) project [1] that future core networks will have a translucent and eventually *transparent* optical structure (Fig. 1).

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

A large number of research studies have been conducted on the RWA problem since it was introduced over a decade ago. Various RWA schemes have been proposed that differ in the assumptions made on the traffic pattern, the availability of wavelength converters, and the desired objectives. The RWA problem is usually considered under two alternative traffic models. When the set of connection requests is known in advance, the problem is referred to as *offline* or *static* RWA, while when the connections arrive at random times and are served one by one, the problem is referred to as *online* or *dynamic* RWA. Typically, an offline RWA algorithm is executed in the planning phase, when the network is initially set up. Online algorithms are used during network operation as new connection requests arrive. An offline algorithm can also be used periodically or when the traffic pattern changes substantially to adapt the state of the network to the evolving traffic. In terms of complexity offline RWA is more difficult than online RWA, since it has to jointly optimize all the light-

0890-8044/09/$25.00 © 2009 IEEE



■ Figure 1. *Evolution of optical networks: a) opaque everywhere; b) managed reach; c) all-optical.*

paths used, in the same way that the multi-commodity flow problem is more difficult than the shortest path problem in conventional networks. In this article we focus on offline RWA, which is known to be an NP-hard optimization problem [2]. However, the methodology and arguments presented in this article address many issues that are also common to the online RWA problem.

The majority of offline RWA algorithms proposed in the literature [3, 4] assume an ideal error-free physical layer. However, signal transmission 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 (intra- and inter-XT), and nonlinear effects such as self- and cross-phase modulation (SPM and CPM), four-wave-mixing (FWM), and so on [5]. We refer to such phenomena as physical layer impairments (PLIs). These impairments may degrade signal quality to such an extent that the BER at the receiver may be so high as to make signal detection infeasible. This gives rise to *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 PLIs limits the number of paths that can be used for routing. This interdependence between the physical and 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 PLI-aware or simply impairment-aware (IA)-RWA algorithms. An important distinction is how IA-RWA algorithms define the interaction between the networking and physical layers, and if they jointly optimize the solutions over these two layers. The IA-RWA problem has so far been considered mainly in its easier online version [6, 7], while the corresponding work on offline algorithms is quite limited. In the dynamic traffic case, where connections are established one by one, the employed algorithm can examine the feasibility of a lightpath for each new connection request by calculating (using analytical models) or measuring (using appropriate monitors) the effect of already established lightpaths to any candidate solution. However, this cannot be done in the static traffic case, where the assignment of lightpaths is to be decided for all connection requests simultaneously, and interference among them cannot be avoided afterward. For this reason, offline RWA algorithms proposed to date do not consider inter-lightpath interference, but either neglect it or assume a worst case interference scenario [8, 9]. Finally, it is worth noting that online algorithms, through repetitive execution, can also be used to solve the offline problem. However, such sequential approaches do not optimize the utilization of wavelengths for all connections requests jointly, and their performance is suboptimal, especially for heavy traffic.

In this article we start by giving a description of the PLIs, focusing on their effect on routing decisions, and then we discuss how these effects can be accounted for in an offline IA-RWA algorithm. Since the most difficult part for offline traffic is to handle the interference among lightpaths, we initially present an IA-RWA algorithm that prunes candidate lightpaths assuming a worst case interference scenario. Taking a different approach, we then present ways to formulate the various types of interference by considering the number of adjacent and second-adjacent channels across all the links of a lightpath and the number of intra-XT generating sources at intermediate nodes along a lightpath. Finally, we propose an IA-RWA algorithm that combines these effects using noise variance related parameters and constrain the total interference noise accumulated on the selected lightpaths. In this way cross-layer optimization over the physical and network layers is accomplished. We argue that using algorithms which include in their formulation the interference among lightpaths, such as the one presented in this article, can minimize the number of wavelengths required to satisfy all connection requests with zero physical layer blocking better than algorithms that do not account for impairments or are based on a worst case interference scenario.

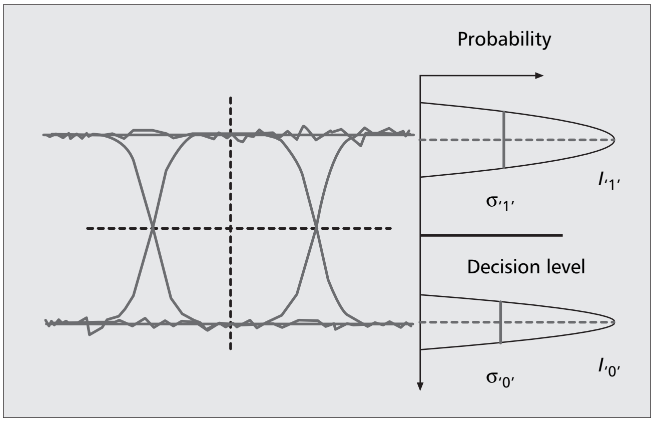
Physical Layer Impairments

In transparent (all-optical) and translucent WDM networks the signal quality of transmission (QoT) degrades due to the nonideal physical layer [5]. Several criteria can be used to evaluate the signal quality of a lightpath. Among a number of measurable optical transmission quality attributes, such as optical power, optical signal-to-noise ratio, CD, and PMD, the Q-factor seems to be more suitable as a metric to be integrated in an RWA algorithm because of its immediate relation 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. Assuming Gaussian shaped noise, the Q-factor of a lightpath (p,w) (i.e., wavelength w on path p) is given by

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

where $I_{'1'}$ and $I_{'0'}$ are the mean values of electrical voltage of signals 1 and 0, respectively, and $\sigma_{'0'}$ and $\sigma_{'1'}$ are their standard deviations at the input of the decision circuit at the des-



■ Figure 2. *Eye diagram and Q factor.*

tination, which in this case is the end of path *p*. Figure 2 illustrates the relation between an eye diagram and the Q-factor. The higher the value of the Q-factor, the smaller the BER and the better the quality of the signal. Generally, a path has acceptable QoT performance when the Q-factor at the destination is higher than 15.5 dB. When forward error correction is employed, a connection can be accepted with even smaller Q values.

PLIs are usually categorized as linear and nonlinear according to their dependence on power. However, when we consider IA-RWA algorithms, it is useful to categorize the PLIs as those that affect the same lightpath that generated them and those that are generated by the presence of other lightpaths (also referred to as *multichannel effects*), resulting in the following two classes for the most important PLIs:

- **Class 1 — Impairments that affect the same lightpath**: ASE, PMD, CD, FC, SPM
- **Class 2 — Impairments that are generated by other lightpaths**: XT (intra-XT and inter-XT), XPM, FWM

Considering PLIs in RWA

In this section we discuss ways in which PLIs can be incorporated in the RWA problem. PLIs that belong to class 1 depend only on the selected lightpath and can be accounted for quite easily. We assume that we are using a typical RWA algorithm that takes as input a set of candidate lightpaths and selects an appropriate subset of lightpaths to satisfy the connection requests. Then for each candidate lightpath we can precalculate the effects of the PLIs that belong to class 1, using, for example, analytical models, and discard those that have unacceptable QoT performance. In this way the RWA algorithm can be fed with candidate solutions that are acceptable at least for the impairments of class 1.

PLIs that belong to class 2 are more difficult to consider by offline algorithms. This is because these impairments make decisions made for one lightpath affect and be affected by decisions made for other lightpaths. An obvious simplification is to consider a worst case scenario (i.e., to assume that all wavelengths on all links are active) and calculate the worst case interference accumulated on each lightpath. Then again, the lightpaths that do not have acceptable QoT performance under this worst case assumption can be discarded before the RWA algorithm is executed, ensuring that the solution is feasible irrespective of the final selection of lightpaths.

However, this approach does not optimize the problem for the given traffic, but solves it as if the network was fully utilized, something that will never happen. In practice, the wavelength continuity constraint limits the maximum achievable network utilization, except for the degenerate case where all connections are between adjacent nodes. The key drawback of the worst case interference assumption is that it results in discarding candidate lightpaths that are not really infeasible. The feasibility of these lightpaths depends on the lightpaths that are finally selected in the solution, which are not known before RWA algorithm execution. By formulating the interference among lightpaths in the RWA algorithm, we may be able to use these lightpaths and let the algorithm choose the solution so that the interference among them does not make them infeasible.

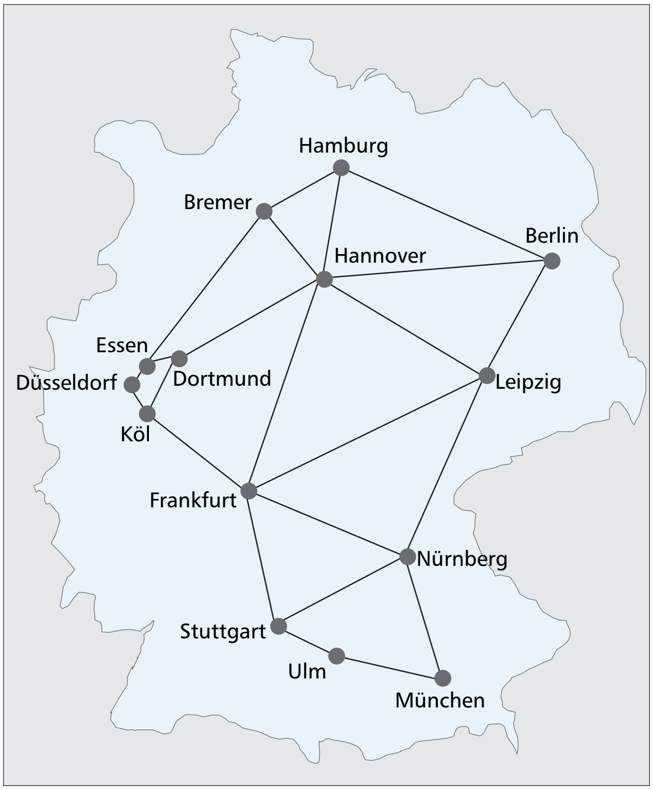
In the following we quantify through a realistic example the degree to which the routing solution space is reduced when PLIs are considered. We assume the generic Deutsche Telekom topology, shown in Fig. 3, with physical layer parameters chosen to have realistic values. We have also used a QoT evaluation module (Q-Tool) developed within the DICONET project [1] that uses analytical models to account for the most important physical layer effects. As already mentioned, we assume an offline RWA algorithm that takes as input a set of candidate paths and selects a subset of them to satisfy the demands. In this example we assume that all source-destination pairs require a connection of one wavelength (this corresponds to what is usually called the reference traffic matrix) for a total number of connection demands equal to 182. Initially, we calculate the *k*-shortest length paths for different values of the parameter *k*, and then we prune the set of candidate paths using the Q-Tool. To do so, we assume either an empty network, discarding lightpaths that are infeasible due to impairments of class 1, or a fully utilized network, discarding lightpaths that are infeasible due to impairments of class 1 and class 2 under the worst case interference scenario.

In Table 1 we see the reduction in the routing solution space after considering the PLIs. As we increase the initial path population size by increasing the parameter *k*, the percentage of paths that are discarded increases. This was expected since the path length largely determines the physical layer effects, so as we move from the shortest to more lengthy paths, an increasing percentage of these paths turn out to be infeasible. Eventually, beyond some value of *k*, all paths will turn out to be infeasible ,and the population reported in columns b and c will stabilize. In any case, Table 1 shows that the path population obtained after eliminating candidate paths due to the impairments of class 1 (column b) is considerably larger than when we use the worst case interference assumption for the impairments of class 2 (column c).

An IA-RWA algorithm that takes into account the actual interference among lightpaths can use as input the paths that correspond to column b, while an algorithm that assumes a worst case interference scenario is bound to use as input the paths that correspond to column c. This reduction in the solution space unnecessarily restricts the choices the RWA algorithm can make and leads to deterioration of its performance.

Following the above discussion, an IA-RWA algorithm that accounts for the actual interference among lightpaths by performing cross-layer optimization over the physical and network layers is expected to require fewer wavelengths to serve the given traffic than an IA-RWA algorithm that assumes a worst case interference scenario. We quantify this performance difference later in this article. Note that the reduction in the solution space due to the physical effects depends on the topology and traffic profile. For example, in a small network that consists of short links, the physical layer effects are negligible, and the difference between the population sizes that correspond to columns a, b, and c would be small, even for high values of parameter *k*. Thus, the above discussion is valid when the physical effects are significant enough, which is the case of interest in this article.

A typical argument in favor of the worst case interference



■ Figure 3. *Generic DT network topology, consisting of 14 nodes and 23 links (46 uni-directional links).*

scenario is that a network configured based on this assumption is more reliable, since future connections will not render the already established lightpaths infeasible. In current operational WDM networks changes in the traffic matrix are usually slow and incremental. The increase of the average traffic between two nodes will eventually require an additional wavelength, but the average traffic increase is small compared to the granularity of the wavelength, and the frequency of such incremental changes is low, on the order of a couple of new connections per year. For slowly changing traffic, an online IA-RWA algorithm is executed to adjust the previous solution to the new traffic demands, and/or an offline algorithm can be periodically re-executed after a certain time or a certain number of new established lightpaths to optimize the utilization of the wavelengths for the new traffic demands. It stands to reason that under the worst case interference assumption the establishment of new lightpaths would continue to utilize the available wavelengths inefficiently, and the network will reach the point where it cannot serve more connections earlier than when an IA-RWA that accounts for the actual inter-lightpath interference is used.

RWA Algorithm

Various algorithms have been proposed in the literature to solve the offline RWA problem [3]. In this article we assume we are using a typical algorithm that formulates the offline RWA problem as an integer linear program (ILP) using path-related variables [4]. The ILP algorithm is given an RWA instance (i.e., a network topology, its node and link characteristics, and a traffic matrix), and returns the paths and assigned wavelengths for all connections served, with the objective of minimizing the number of wavelengths required to serve the connections.

We assume that for each connection request we compute a set of k candidate paths using a variation of a k-shortest path algorithm. A lightpath in the ILP formulation is represented by a flow variable x_{pw}, which takes value equal to 1 if wavelength w of path p is used (i.e., if lighpath (p,w) is activated) and equal to 0 if lightpath (p,w) is not activated. Given the set of candidate paths and the set of available wavelengths, the variables for all candidate lightpaths are identified. The ILP algorithm selects which candidate lightpaths to activate by setting the corresponding x_{pw} variable to 1, with the objective of minimizing the number of wavelengths used, subject to a number of constraints that are innate to the RWA problem. In particular, these constraints include wavelength assignment constraints, wavelength continuity constraints, incoming traffic constraints, and certain specific constraints to formulate the objective cost.

Since ILP is NP-hard, heuristic algorithms must be used to obtain solutions in acceptable (nonexponential) time. In the simulation experiments reported at the end of this article we used a linear programming (LP) relaxation formulation combined with a specifically designed piecewise linear cost function, as presented in [10], that was shown to yield integer optimal solutions for a large number of RWA input instances, despite the absence of integrality constraints. Note that noninteger solutions for the flow variables x_{pw} are not acceptable, since a connection is not allowed to bifurcate between alternative paths or wavelength channels. Thus, if LP relaxation does not yield an integer solution, appropriate rounding techniques are used, and the optimality is no longer guaranteed.

We refer to the ILP algorithm that was outlined above as a *pure* RWA algorithm, in the sense that it ignores PLIs. Using this pure RWA algorithm and pruning the candidate paths under the worst case interference assumption in the preprocessing phase, we obtain an impairment-aware RWA algorithm to which we refer as worst-case (WC)-IA-RWA. Note that the only difference between the pure RWA and WC-IA-RWA algorithms is the set of candidate lightpaths they use as input.

Cross-Layer Impairment-Aware RWA Formulation

In this section we extend the preceding pure RWA algorithm by formulating the interference among lightpaths as additional constraints to make the algorithm impairment-aware. We start by presenting an *indirect* way to account for impairments, which constrains the number of adjacent and second-adjacent channel interfering sources and the number of intra-XT interfering sources. We then proceed to propose an alternative way to *directly* constrain impairments using noise-related parameters. More specifically, for each candidate lightpath, 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). Then we use this bound to constrain the interfering noise caused by other lightpaths (impairments of class 2) by introducing appropriate constraints in the RWA formulation.

Constraining Adjacent Channel Interference

Impairments due to inter-XT and nonlinear physical impairments (FWM and XPM) depend not only on the topology of the considered lightpath, but also on the load of the links comprising the lightpath. In particular, inter-XT has to do with the power leaking between neighboring channels. XPM is more severe between adjacent channels, becoming less significant as we move away from the channel under examination. FWM depends on the utilization of certain sets of wave-

	(a)	(b)	(c)
	Initial population (*k*-shortest length paths)	**Population after discarding paths due to impairments of class 1**	**Population after discarding paths due to impairments of class 1 and class 2 — assuming worst case interference**
k = 1	182	182	182
k = 2	364	359	333
k = 3	546	528	427
k = 4	728	653	479
k = 5	910	751	506
k = 6	1092	817	513

■ Table 1. *The reduction in the solution space due to the PLIs of class 1 and class 2 (under the worst case interference assumption), for the case of the DT network topology and reference traffic matrix.*

lengths and is more severe when the adjacent channels are active. As a consequence, avoiding the utilization of adjacent and next-to-adjacent channels would have a positive effect in the quality of transmission of a lightpath.

Figure 4a presents an example to illustrate the adjacent channel interference effect. A lightpath on path p from n_0 to n_4 is established using wavelength w. Let p_1 be a lightpath that uses links l_2, l_3, and wavelength $w + 1$, and p_2 be a lightpath that uses links l_3, l_4 and wavelength $w - 1$. These two lightpaths affect the signal quality of lightpath (p,w). In this example there is one adjacent channel interfering source on link l_2 and link l_4, and two interfering sources on link l_3.

Let $n_{\text{adj},l}(p,w)$ denote the number of adjacent channels interferer sources on link l for lightpath (p,w). Based on the path related variables we can calculate this number by counting the active paths p' that cross the same link and utilize one of the adjacent channels:

$$n_{\text{adj},l}(p,w) = \sum_{\{p' | l \in p'\}} x_{p',w-1} + x_{p',w+1}.$$

Then by summing $n_{\text{adj},l}(p,w)$ over all the links l that comprise path p, we can constrain the total number of adjacent channel interfering sources over the whole lightpath to be less than a maximum acceptable value $N_{\text{adj-max}}$. In a similar manner we can calculate the number $n_{\text{adj-2},l}(p,w)$ of second-adjacent channels of link l for lightpath (p,w) and constrain the total number of second-adjacent channel interfering sources over the lightpath to be less than a maximum acceptable value $N_{\text{adj-2-max}}$.

Constraining Intra-XT Interference

Node intra-XT is the 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 [6]. Figure 4b presents an example to illustrate the effect of intra-XT. A lightpath p from node n_0 to node n_4 is established using wavelength w. Let (p_1,w), (p_2,w), and (p_3,w) be three lightpaths that use nodes n_2, n_2, and n_3, respectively, and the same wavelength w. These lightpaths affect the signal quality of lightpath (p,w). In this example there are two intra-XT interfering sources on node n_2, and there is one interfering source on node n_3.

Based on the above, we can calculate $n_{XT,n}(p,w)$ as the number of intra-XT interfering sources on node n for lightpath (p,w). Then by summing $n_{XT,n}(p,w)$ over all nodes that comprise the lightpath, we can constrain the total number of intra-XT interfering sources over the whole lightpath to be less than a maximum acceptable value $N_{XT\text{-max}}$.

Using the above formulations we can obtain an IA-RWA algorithm that constrains both the number of adjacent and second-adjacent channels, and the number of intra-XT interfering sources [11]. This algorithm considers the interference among lightpaths indirectly in the sense that it constrains the number of interfering sources and not their actual effects. We proceed now to present an alternative algorithm that directly accounts for these effects.

Constraining the Interference among Lightpaths

Based on the classification of impairments presented earlier, we can use analytical formulas in order to calculate the effects of the impairments that belong to class 1, which do not depend on the utilization of the other lightpaths, on a given candidate lightpath. We assume that we use approximations in order to model as noise the effects of the class 2 impairments, such as the model for intra-XT presented in [6], and models for XPM and FWM presented in [12]. Based on the above and a given threshold for the Q-factor, say 15.5 dB, we can calculate for a given lightpath (p,w) a bound on the interference noise variance it can tolerate due to XT, XPM, and FWM, after accounting for the impairments that do not depend on the utilization of the other lightpaths.

$$\sigma^2_{XT,\text{‘1’}}(p,w) + \sigma^2_{XPM,\text{‘1’}}(p,w) + \sigma^2_{FWM,\text{‘1’}}(p,w) \leq \sigma^2_{\max,\text{‘1’}}(p,w),$$

where σ^2_{XT}, σ^2_{XPM}, and σ^2_{FWM} are the electrical variances of the intra-XT noise, XPM, and FWM degradations. Since it is difficult to find a very accurate $\sigma^2_{\max,\text{‘1’}}(p,w)$bound that incorporates all the class 1 impairments, and we also do not take into account the interference on signal 0 (typically negligible), we use a value for the bound that is somewhat higher than the one actually calculated. Also, since taking into account that FWM would require additional variables and further complicate the algorithm, we assume that FWM contributes a constant c_{FWM}. Since the noise FWM contributes is generally rather smaller than the effects of the other impairments, c_{FWM} can be chosen as the worst case FWM contribution.

We assume that for each link l and the OXC switch n it ends, we know the following electrical noise variance parameters:

- $s^2_{XPM,l}$: The electrical noise variance of signal 1 due to XPM from an active adjacent channel
- $s^2_{XPM\text{-}2,l}$: The electrical noise variance of signal 1 due to XPM from an active second-adjacent channel

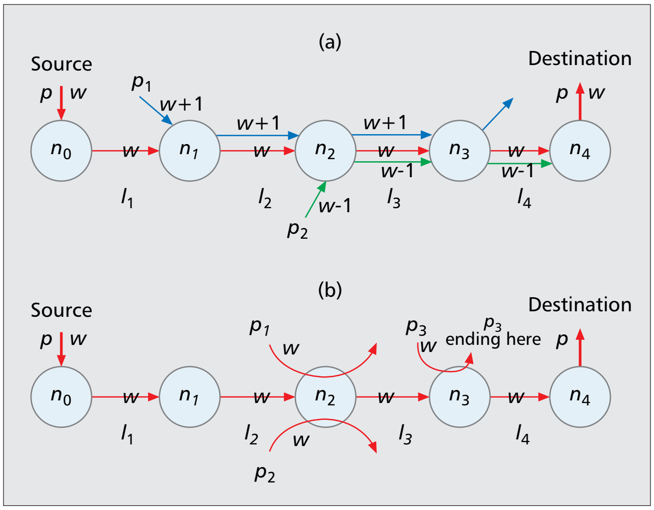


Figure 4. *a) Adjacent channel interference on lightpath* (p, w)*; b) intra-channel XT interference on lightpath* (p, w)*, by other lightpaths.*

- $s^2_{XT,n}$: The electrical intra-XT noise variance a lightpath crossing node n contributes to another lightpath that also crosses n and uses the same wavelength

We assume that these noise variance parameters are the same, irrespective of the examined wavelength, although this assumption is not restrictive, and we could have used different parameters per wavelength. To obtain these parameters, analytical models for the specific impairments can be used.

Based on the above, we can constrain the interference accumulated over a lightpath (p,w) that is selected in the solution by introducing the following constraint:

$$\sum_{\{l\in p|n \text{ end of } l\}} \left(\begin{array}{l} \overbrace{s^2_{XT,n}\cdot n_{XT,n}(p,w)}^{\text{intra-XT}} \\ + \; \overbrace{s^2_{XPM,l}\cdot n_{\text{adj},l}(p,w)}^{\text{XPM from adjacent channels}} \\ + \; \overbrace{s^2_{XPM-2,l}\cdot n_{\text{adj-2},l}(p,w)}^{\text{XPM from 2nd adjacent channels}} \end{array} \right) + c_{FMW} \le \sigma^2_{\max,'1'}(p,w).$$

For a given lightpath the above constraint counts the number of interfering sources at each intermediate link and node, and multiplies this number with the related noise variance parameter. In this way it calculates the noise variance that is accumulated over the lightpath due to the interference of the other lightpaths and constrains it by a bound determined by the impairments that do not depend on the utilization of the other lightpaths. The lightpaths that satisfy the corresponding noise variance constraint are expected to exhibit acceptable quality of transmission performance.

In the performance results section that follows, we call Sigma-Bound IA-RWA (SB-IA-RWA) the algorithm that utilizes the above constraints to directly include the physical layer effects in its formulation.

Simulation Results

In order to evaluate the performance of the proposed IA-RWA algorithm, we carried out a number of simulation experiments. We implemented the pure RWA formulation and the proposed IA-RWA formulations in Matlab, and used the LINDO-API library to solve the corresponding LP-relaxations [10]. To evaluate the feasibility of the lightpaths, we used the Q-Tool developed within the DICONET project [1].

We compared the performance of three algorithms:

- The pure RWA algorithm that does not consider physical impairments at all
- The WC-IA-RWA algorithm that prunes the candidate paths based on the impairments of class 1 and class 2 under the worst interference scenario
- The cross-layer SB-IA-RWA algorithm that takes into account the interference among lightpaths in its RWA formulation, presented above

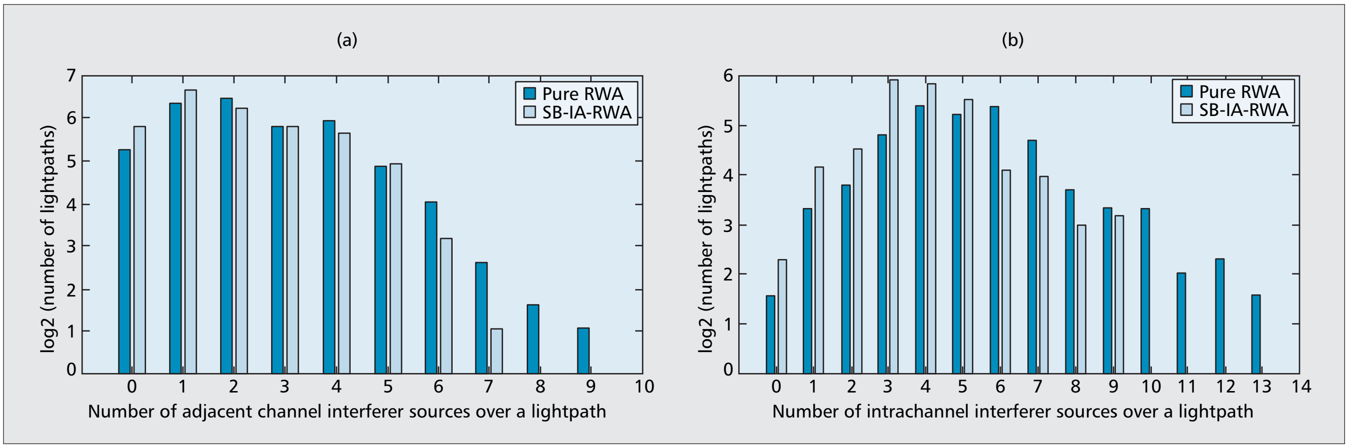
A key difference of these algorithms is the set of candidate paths they take as input. In particular, referring to Table 1, the pure RWA algorithm takes as input the set of paths that correspond to column a, the WC-IA-RWA algorithm the set of paths that correspond to column c, and the proposed cross-layer SB-IA-RWA algorithm the set of paths that correspond to column b. To make the comparison fairer, we used $k = 3$ for the pure RWA and proposed SB-IA-RWA algorithms, and $k = 4$ for WC-IA-RWA.

The topology used in our simulations was the Deutsche Telekom network (DTnet), shown in Fig. 3, with capacity per wavelength channel assumed to be 10 Gb/s. We used a random traffic generator to produce 100 traffic matrices for loads between 0.5 and 1 (we define the traffic load as the total number of connection requests over the number of connections when all source-destination pairs require a single wavelength). We also executed experiments with realistic traffic for the DTnet that includes 374 10 Gb/s connection requests, with some source-destination pairs requiring more than one lightpaths.

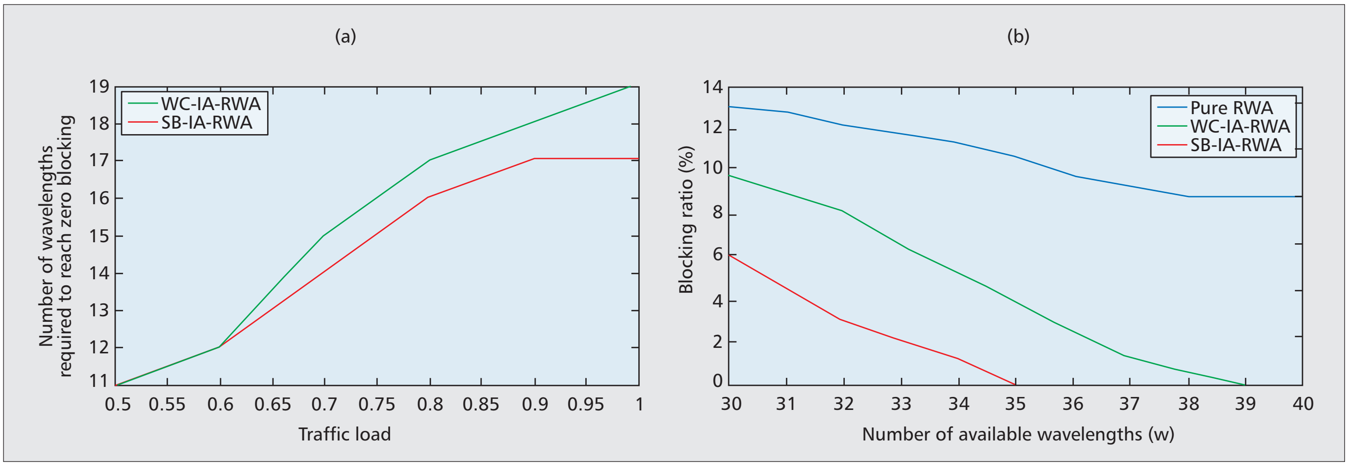
First, we present our results in the form of histograms that graph the probability mass distributions of the number of adjacent channels (Fig. 5a) and the number of intra-XT interfering sources of the selected lightpaths (Fig. 5b) when we use the proposed cross-layer SB-IA-RWA and pure RWA algorithms. In these figures a left shift in the probability distributions is observed when using the proposed SB-IA-RWA algorithm, meaning that physical impairment generating sources are fewer, and signal quality is improved.

Figure 6a shows the number of wavelengths required to achieve zero (physical and network) blocking for the WC-IA-RWA and proposed SB-IA-RWA algorithms using the traffic matrices produced by the random traffic generator. We do not graph the performance of the pure RWA algorithm since this algorithm was unable to obtain zero-blocking solutions due to physical blocking. We observe that the proposed SB-IA-RWA achieves zero blocking using fewer wavelengths than WC-IA-RWA. WC-IA-RWA is only affected by network layer blocking, since all candidate paths that are fed to the algorithm have acceptable QoT performance. However, the set of candidate paths WC-IA-RWA uses turns out to be inferior, resulting in a solution that consumes more wavelengths than the SB-IA-RWA algorithm. Note that the path population is not the only parameter that affects performance. Even more important is the distribution of the number of different candidate paths that are available for each source-destination pair. Since, in the case of WC-IA-RWA, some paths are unnecessarily discarded, the choices on the routes that can be used for certain connections are very restricted. In contrast, the proposed cross-layer SB-IA-RWA has more options in selecting lightpaths of acceptable quality to serve the traffic.

Figure 6b shows the average blocking probability vs. the number of available wavelengths per link for all examined algorithms, assuming the realistic DTnet traffic matrix. The pure RWA algorithm has the highest blocking rate since it



■ Figure 5. *a) Distribution of the number of adjacent channel interfering sources per lightpath; b) distribution of the number of intra-channel crosstalk interfering sources per lightpath, assuming realistic traffic and* W *= 35 wavelengths.*



■ Figure 6. *a) Number of wavelengths required to reach zero blocking for various loads obtained using the random traffic generator; b) blocking probability vs. number of available wavelengths* W *per link for realistic traffic load.*

cannot avoid physical layer blocking. The WC-IA-RWA algorithm exhibits only network layer blocking, while the SB-IA-RWA algorithm exhibits both physical and network blocking. The SB-IA-RWA algorithm outperforms the WC-IA-RWA algorithm in terms of rejected calls, and is able to reach zero blocking using fewer wavelengths. In particular, the difference between these two algorithms is four wavelengths for this realistic traffic load, a difference that is substantial. Comparing the results presented in Figs. 6a and 6b, we can deduce that the improvements obtained by the SB-IA-RWA algorithm are more pronounced when the traffic load is heavy since at these loads the number of interfering sources is higher and cross-layer optimization is more important.

Conclusions

Incorporating PLIs in offline RWA results in a cross-layer optimization problem that is important in achieving transparency in WDM networks. We investigate (I)LP formulations combined with appropriate constraints on the effect of impairments to address this problem. We initially classify the PLIs into two classes and discuss how these can be accounted for in an offline impairment-aware RWA algorithm. Since the most difficult part for offline traffic is to handle the interference among lightpaths, we initially show how to constrain the number of adjacent and second-adjacent channel interfering sources, and the number of intra-XT interfering sources accumulated over the links/nodes of a lightpath. Then we present a way to combine these constraints using noise related parameters in order to directly constrain these effects. Using realistic traffic scenarios and network topologies, our simulation results quantify the performance improvements that can be obtained by using an IA-RWA algorithm that takes into account the actual interference among lightpaths, as opposed to algorithms that do not consider impairments or consider impairments assuming a worst case interference scenario.

Acknowledgments

This work has been partially supported by the European Commission through the FP7-DICONET project. The authors would like to thank Dr. K. Yiannopoulos for his valuable comments.

References

[1] Dynamic Impairment Constraint Network for Transparent Mesh Optical Networks (DICONET) project, FP7-ICT-GA 216338; http://www.diconet.eu
[2] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications: An Approach to High-Bandwidth Optical WANs," *IEEE Trans. Commun.*, vol. 40, 1992, pp. 1171–82.
[3] H. Zang, J. P. Jue, and B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks," *Optical Net.*, vol. 1, 2000.
[4] R. Ramaswami and K. N. Sivarajan "Routing and Wavelength Assignment in All-Optical Networks," *IEEE/ACM Trans. Net.*, vol. 5, no. 3, Oct. 1995, pp. 489–501.

[5] G. P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed., Wiley-Interscience, 2002.
[6] B. Ramamurthy *et al.*, "Impact of Transmission Impairments on the Teletraffic Performance of Wavelength-Routed Optical Networks," *IEEE/OSA J. Lightwave Tech.*, vol. 17, no. 10, 1999, pp 1713–23.
[7] J. He *et al.*, "QoT Aware Routing in Impairment-Constrained Optical Networks," *Proc. IEEE GLOBECOM*, 2007, pp. 2269–74.
[8] I. Tomkos *et al.*, "Performance Engineering of Metropolitan Area Optical Networks through Impairment Constraint Routing," *IEEE Commun. Mag.*, vol. 42, no. 8, 2004, pp. 40–47.
[9] A. Hamad and A. Kamal, "Routing and Wavelength Assignment with Power Aware Multicasting in WDM Networks," *Proc. IEEE BROADNETS*, vol. 1, 2005, pp. 31–40.
[10] K. Christodoulopoulos, K. Manousakis, and E. Varvarigos, "Comparison of Routing and Wavelength Assignment Algorithms in WDM Networks," *IEEE GLOBECOM,* 2008.
[11] K. Manousakis, K. Christodoulopoulos, and E. Varvarigos, "Impairment-Aware Offline RWA for Transparent Optical Networks," *IEEE INFOCOM 2009*.
[12] S. Pachnicke *et al.*, "Fast Analytical Assessment of the Signal Quality in Transparent Optical Networks," *J. Lightwave Tech*, vol. 24, 2006, pp. 815–24.

Biographies

KONSTANTINOS CHRISTODOULOPOULOS (kchristodou@ceid.upatras.gr) received a Diploma in electrical and computer engineering from the National Technical University of Athens, Greece, in 2002, an M.Sc. degree in advanced computing from Imperial College London, United Kingdom, in 2004, and a Ph.D. degree from the Computer Engineering and Informatics Department, University of Patras, Greece, in 2009. His research interests are in the areas of protocols and algorithms for optical networks and grid computing.

KONSTANTINOS MANOUSAKIS (manousak@ceid.upatras.gr) received a Diploma degree in 2004 and an M.Sc. degree in computer science and engineering in 2007 from the Computer Engineering and Informatics Department, University of Patras. He is currently a Ph.D. candidate at the same department. His research activities focus on optimization algorithms for high-speed and optical networks.

EMMANOUEL (MANOS) VARVARIGOS (manos@ceid.upatras.gr) received a Diploma in electrical and computer engineering from the National Technical University of Athens in 1988, and M.Sc. and Ph.D. degrees in electrical cngineering and computer Science from the Massachusetts Institute of Technology in 1990 and 1992, respectively. He has held faculty positions at the University of California, Santa Barbara (1992–1998, as an assistant and later associate professor) and Delft University of Technology, the Netherlands (1998–2000, as an associate professor). In 2000 he became a professor in the Department of Computer Engineering and Informatics, University of Patras, where he heads the Communication Networks Lab. He is also the director of the Network Technologies Sector (NTS) at the Research Academic Computer Technology Institute (RA-CTI). His research activities are in the areas of high-speed networks, protocols, network architectures, distributed computation, and grid computing.

MARIANNA ANGELOU (mang@ait.edu.gr) received a degree in computer science from Aristotle University of Thessaloniki, Greece, in 2005, and an M.Sc. in information and telecommunication technologies from Athens Information Technology in 2008. She is currently pursuing a Ph.D. degree. Her research activities focus on the physical layer modeling of fiber impairments and their impact on the quality of transmission.