Cross Layer Optimization of Static Lightpath Demands in Transparent WDM Optical Networks

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Abstract—**We consider the offline version of the impairment-aware routing and wavelength assignment (IA-RWA) problem in transparent all-optical networks as a cross layer optimization problem. In optical networks and in the absence of regenerators, optical signal quality degrades due to physical layer impairments. We initially present an algorithm for solving the RWA problem based on an LP relaxation formulation that has acceptable integrality performance. To account for signal degradation due to physical layer impairments we extend our RWA formulation and constrain the interference among lightpaths using noise variance related parameters. The objective of the resulting optimization problem is not only to serve the connection requests by minimizing the number of utilized wavelengths, but also to select lightpaths that have acceptable physical layer performance.**

Keywords- Routing and wavelength assignment, transparent all-optical networks, physical layer impairments, cross layer optimization.

I. INTRODUCTION

The most common architecture for establishing communication in WDM optical networks is *wavelength routing* [1], where optical pulse-trains are transmitted through WDM channels that may span multiple consecutive fibers, called *lightpaths*. Recent technological advances on optical devices and communication sub-systems have led to a profound transformation in all aspects of optical network communications. The trend clearly shows an evolution towards dynamic reconfigurable, low-cost and high capacity transparent (all-optical) WDM networks. When optimizing network design of such networks, there is a strong need for accounting for the interactions between the functions performed at different networking layers.

In transparent wavelength-routed WDM networks data is transferred between access stations in the optical domain without any intermediate optical to/from electronic conversion. This can be realized by determining a path in the network between the two edge nodes, and allocating a free wavelength on all of the links on the path, to form all-optical lightpaths. Since lightpaths are the basic switched entities of a WDM network architecture, their effective establishment and usage is crucial. It is thus important to propose efficient algorithms to select the routes for the connection requests and to 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* (abbreviated 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 constraint*).

The RWA problem is usually considered under two alternative traffic models. *Offline* (or *static*) lightpath establishment addresses the case where the set of connections is known in advance, usually given in the form of a traffic matrix that describes the number of lightpaths that have to be established between each pair of nodes. *Dynamic* (or *online*) lightpath establishment considers the case where connection requests arrive at random time instants, over a prolonged period of time, and are served upon their arrival, on a one-by-one basis.

In this paper we focus on offline RWA which is known to be a NP-hard optimization problem. 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]. For the rest of this paper 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.

Transparency reduces the ability of a client layer to interact with the physical layer, thus, leading to limitations on network design, planning, control and management. In particular, the need to account for the physical layer impairments constrains the kinds of paths that can be used for routing. To overcome this problem a number of cross-layer design approaches are emerging to solve the problems in this area, usually referred to as PLI-aware or simple IA-RWA algorithms.

An important distinction is how the IA-RWA algorithms define the interaction between the networking layer and the physical layer, and if they jointly optimize the solutions over these two layers. In the presence of physical layer impairments, routing choices made for one lightpath affect and are affected by the routing choices made for other lightpaths. This physical layer interference among the lightpaths is particularly difficult to formulate in the offline IA-RWA problem, since in this problem we start with no already established connections, and the utilization of lightpaths are the variables of the problem.

In this paper we propose a cross layer optimization approach with the objective to assign routes and wavelengths to the traffic demands so as to satisfy impairment constraints while also minimizing the number of wavelengths used. We start by presenting an LP relaxation formulation for the "pure" (not impairment aware) RWA problem [2] [3]. We then extend this LP formulation in order to handle the physical layer impairments. In particular, for each lightpath inserted in the LP

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formulation, we calculate a noise variance bound after accounting for the impairments that do not depend on the other lightpaths. We then express the interference among lightpaths by noise variance parameters. Using the noise variance bounds and these parameters we formulate new constraints and insert them in the RWA formulation. Solutions that satisfy these constraints are expected to exhibit acceptable transmission performance. We check our proposed IA– RWA formulation through simulations, using an evaluation module that incorporates analytical models for the most important physical impairments.

II. Previous Work

The routing and wavelength assignment (RWA) problem has been extensively studied in the literature. Recently, RWA algorithms that consider the impact of physical layer impairments (PLI) have also been the subject of intense research. Most IA-RWA algorithms that have appeared in the literature consider the online (dynamic) version of the problem [4][5], while the corresponding work on offline traffic is quite limited. This is because even the pure (without physical impairments) offline RWA problem is NP-hard and the problem becomes even more complicated when PLI are included. 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 each connection request by calculating the effect of the already established lightpaths. 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 [6] a LP-relaxation algorithm that uses link formulation to solve the IA-RWA problem in a transparent network is proposed. In particular, a set of k candidate shortest paths is pre-calculated using a single physical impairment as link cost parameters and then a pure RWA formulation is used. Finally, in a post-processing phase the feasibility of the chosen lightpaths is evaluated and the ones that are not accepted are rerouted. An impairment-aware offline RWA algorithm that assigns Q-factor costs to links before solving the problem is proposed in [7]. However, the proposed algorithm does not take into account the actual interference among lightpaths since it assumes a worst case interference scenario. Some more specific problems involving impairment constraints combined with multicast transmission and traffic grooming formulated as ILP are studied in [8] and [9]. However, in most related work the physical layer impairments are only indirectly taken into account, through the length of the chosen paths. Finally, online algorithms, through repetitive execution, have also been used to solve the offline problem, by considering the connections sequentially and serving them one by one. In general, such online approaches do not optimize the utilization of wavelengths for all connections jointly, and thus their performance is suboptimal.

The key difference between the IA-RWA algorithm presented in this paper to the offline algorithmic approaches found in the literature is that the proposed algorithm performs a joint cross-layer optimization between the physical and the network layers. In [10] we have proposed an *indirect* IA-RWA algorithm that uses separate constraints for the sources that generate the impairments and takes into account the interference among the lightpaths, which is particularly difficult to formulate for this type of traffic. In this paper, we proceed further and propose an IA-RWA algorithm that takes *directly* into account all the dominant impairment effects. 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. Then, we use this bound to constraint the interfering noise caused by other lightpaths by introducing appropriate constraints in the RWA formulation. The proposed algorithm was proven applicable to solve problems under realistic network and traffic loads, since it avoids heavy ILP formulations like the ones of [8] and [9].

III. RWA in Transparent WDM Networks

A. Network Layer Problem

The network topology is represented by a connected, simple graph $G=(V,E)$. V denotes the set of nodes, which we assume not to be equipped with wavelength conversion capabilities. E denotes the set of (point-to-point) single-fiber links. Each fiber is able to support a common set $C=\{1,2,\ldots,W\}$ of wavelengths. The static version of RWA assumes an a-priori known traffic scenario given in the form of a matrix of nonnegative integers Λ, called the traffic matrix. We denote by Λ_{sd} the number of requested connections from source s to destination d, that may be larger than one in case that there are multiple connection requests for a given source-destination (s,d) pair.

We start by computing a set of k candidate paths P_{sd} for each (s,d) pair. We then formulate the RWA problem as a Linear Program (LP). The proposed LP formulation aims at minimizing the resource usage, in terms of the number of wavelengths used over the network links. The following types of 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 for source-destination pair (s,d)

Constant:

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

Variables:

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

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

subject to the following constraints:

- Distinct wavelength assignment constraints,

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

- Incoming traffic constraints,

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

- Cost function,

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

- The integrality constraints are relaxed to $0 \leq x_{pw} \leq 1$.

We use the flow cost function F_l to express the penalty incurred for congestion on link l. F_l is taken to be a function f of the total number w_l of lightpaths crossing link l. It is natural to assume that f is a properly increasing function of w_l, since increased congestion is obviously undesirable. Also, f should be convex, so as to imply a greater amount of 'undesirability', when a link becomes highly congested. This is because it is often preferable, in terms of network performance, to serve an additional unit of flow using several low-congested links, than to use a single link that becomes totally congested [2]. Various flow cost functions have been examined in [3]. For this study we utilize the following flow cost function:

$$F_l = f\left(w_l\right) = \frac{w_l}{W+1-w_l},\ 0 \leq w_l \leq W,$$

which is inserted in the LP in the form of piecewise linear costs as presented in Figure 1. Inserting such a piecewise linear function to the LP objective, results in the identification of integer optimal solutions by Simplex, in most cases. 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 [11], there is a higher probability of obtaining integer solutions than using other methods (e.g., interior point methods). Our experimental results show that this is actually the case in most problem instances [3].

B. *Random Perturbation and Fixing and Rounding Teqniques*

Non-integer solutions for the flow variables are not acceptable, since a connection is not allowed to bifurcate between alternative paths or wavelength channels. 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. To increase the number of integer solutions obtained we use a random perturbation technique and iterative fixing and rounding methods.

In the general multicommodity flow problem, given an optimal fractional solution, a flow that is served by more than one paths has equal sum of first derivatives of the costs of the links comprising these paths. The reason is that if they were not equal, one could shift some small flow δ from one path to the other, reducing the total cost, which would mean that we do not have an optimal solution. The objective function that we utilize in our RWA formulations sums the flow costs of the links that comprise a lightpath, and thus a request that is served by more than one lightpaths has equal sums of first derivates over the links of these lightpaths. Note that the derivative of the cost on a specific link is given by the slope of the linear or piecewise linear flow cost function that we utilize. To make the situations

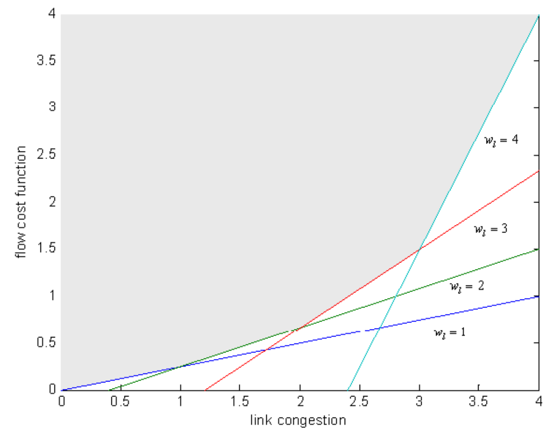

Fig. 1: The set of linear constraints that are inserted in LP formulation. We use inequality constraints to limit our search in the colored area. Since the objective that is minimized is the flow cost, we finally search for solutions only at its lower bounds, which identify the piecewise linear approximation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

where two lightpaths have equal first derivative lengths over the links that comprise them less probable, and thus obtain more integer solutions, we multiply the slopes on each link with a random number that differ to 1 in the sixth decimal digit.

If we still have non-integer variables, we start by fixing the variables, that is, we treat the variables that are integer as final and solve the reduced problem for the remaining variables. Fixing variables does not change the objective cost returned by the LP, so we move with each fixing from the previous solution to a solution with equal or more integer variables that has the same cost. 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 we reach a point beyond which the process of fixing does not increase the integrality of the solution, we proceed to the rounding process. We round a single variable, the one closest to 1, and continue solving the reduced LP problem. 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 a 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 variables which is polynomial on the size of the problem input.

C. *Physical Layer Problem*

In transparent (all-optical) and translucent WDM networks the signal QoT degrades due to the non-ideal physical layer [1]. Among a number of measurable optical transmission quality attributes the Q-factor appears to be more suitable as a metric, due to its close correlation with the bit error rate (BER). Under the assumption of Gaussian shaped noise, the Q-factor of a lightpath (p,w) (that is wavelength w over path p) is given by:

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

where $I_{'1'}$ and $I_{'0'}$ are the mean values of electrical voltage of signal 1 and of signal 0, respectively, and $\sigma_{'0'}$ and $\sigma_{'1'}$ are their standard deviations, at the input of the decision circuit at the destination, which in this case is the end of path p.

In the approach adapted [7], $I_{'1',p}(w)$ depends on the transmitter's power, the gains and losses over path p, and the "eye impairments": self-phase modulation (SPM), chromatic dispersion (CD), polarization mode dispersion (PMD) and filter concatenation (FC). The remaining impairments are considered as noise [12]. For the noise variances of bits 1 and 0 we have:

$$\sigma^2_{'1'}(p,w)=\sigma^2_{ASE,'1'}(p,w)+\sigma^2_{XT,'1'}(p,w)+\sigma^2_{XPM,'1'}(p,w)+\sigma^2_{FWM,'1'}(p,w),$$

$$\sigma^2_{'0'}(p,w)=\sigma^2_{ASE,'0'}(p,w)+\sigma^2_{XT,'0'}(p,w)+\sigma^2_{FWM,'0'}(p,w),$$

where σ^2_{ASE}, σ^2_{XT}, σ^2_{XPM} and σ^2_{FWM}, are the electrical noise variances due to amplified spontaneous emission (ASE), intra-channel crosstalk (XT), cross-phase modulation (XPM) and four-wave mixing (FWM), respectively.

1) Calculating the noise variance bound of a lightpath

We classify the physical layer impairments to those that are generated from the chosen lightpath and those that are generated due to the interference among lightpaths. Crosstalk (XT), cross-phase modulation (XPM) and four-wave mixing (FWM), belong to the second class. Due to these impairments choices made for one lightpath affect and are affected to choices made for the other lightpaths.

Based on this classification, and given a 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.

$$s^2_{XT,'1'}(p,w)+s^2_{XPM,'1'}(p,w)+s^2_{FWM,'1'}(p,w)\le s^2_{\max,'1'}(p,w).$$

Since it is difficult to find a very accurate $s^2_{\max,'1'}(p,w)$ bound and we also do not take into account the interference on signal 0 (which is typically less significant), we will use a value for the bound that is somewhat higher than the one actually calculated. Also, since taking into account FWM would require additional variables and would complicate further the algorithm, we will assume that FWM contributes a constant c_{FWM} (which is generally rather small compared to the other impairments, and c_{FWM} can be chosen as the worst case FWM contribution).

We assume that for each link l, and the optical cross connect (OXC) switch n that it ends, we know the following parameters:

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

Note that we assume here for simplification that $s^2_{1\text{-}XPM,'1',l}$, $s^2_{2\text{-}XPM,'1',l}$, $s^2_{XT,'1',n}$ are the same irrespective of the examined wavelength w, but we can also use wavelength dependent parameters. To obtain the above parameters, analytical models for the specific impairments can be used [11].

For a path p that consists of links l=1,…,m, we have:

$$s^2_{XT,'1'}(p,w)+s^2_{XPM,'1'}(p,w)=\sum_{\{l|l\in p,n\text{ end of }l\}}\Bigg(\Big(s^2_{XT,'1',n}\cdot n_{XT,n}(w)+ + s^2_{1-XPM,'1',l}\cdot n_{1-XPM,l}(w)+s^2_{2-XPM,'1',l}\cdot n_{2-XPM,l}(w)\Big)\cdot\prod_{i=l+1}^{m}10^{2\cdot G_i/10}\Bigg),$$

where $n_{XT,n}(w)$ is the number of intra-XT generating sources on switch n and wavelength w (number of lightpaths crossing n and utilizing wavelength w), $n_{1\text{-}XPM,l}(w)$ and $n_{2\text{-}XPM,l}(w)\in\{0,1,2\}$ is the number of utilized adjacent and second-adjacent channels of wavelength w on link l, respectively.

In Figure 2a a lightpath (p,w) is established from n_0 to n_4. 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 $n_{1\text{-}XPM,l_2}(w)$=1, $n_{1\text{-}XPM,l_3}(w)$=2, $n_{1\text{-}XPM,l_4}(w)$=1 adjacent channel interferer sources on links l_2, l_3, l_4, respectively.

Similarly, in Figure 2b the effect intra-channel crosstalk is depicted. Intra-XT is the 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 In this example there are $n_{XT,n_2}(w)$=2, $n_{XT,n_3}(w)$=1 intra-XT interferer sources on nodes n_2, n_3, respectively.

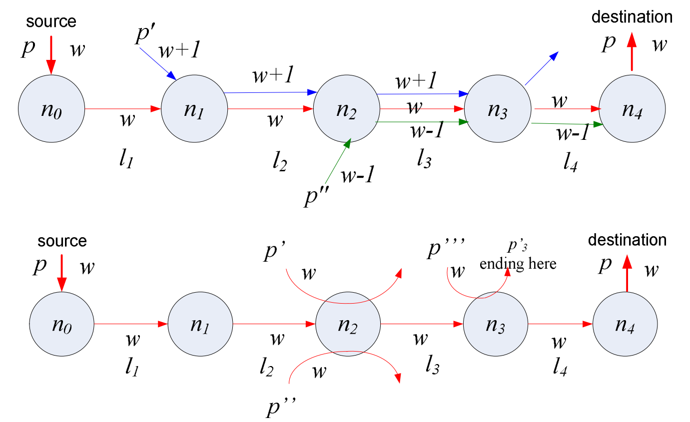

Fig 2: (a) Adjacent channel interference on lightpath (p,w) by other lightpaths, and (b) Intra-channel XT interference on lightpath (p,w) by other lightpaths.

2) Constraining the interference among lightpaths

We extend the LP formulation presented in Section III.A by adding the following constraint per lightpath (p,w):

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

where,

- B is a large constant used to activate/deactivate the constraint depending on whether lightpath (p,w) is utilized, or not. If lightpath (p,w) is selected, then $B\cdot x_{pw}=B$, and the above constraint is activated. If (p,w) is not selected, $B\cdot x_{pw}=0$, and the constraint holds always for B large enough.
- S_p is the excess of noise variance a path undergoes due the physical layer impairments.

Note that we can extend the above constraint in order to take into account the power losses/gains over the links.

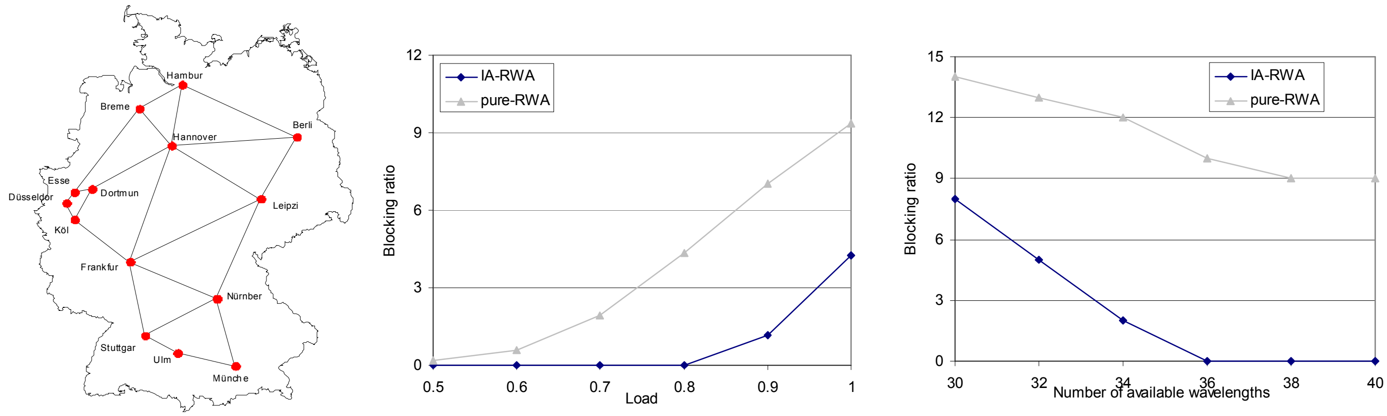

Fig. 3: (a) Generic DT network topology. 14 nodes and 23 links (we assumed 46 directed links). (b) Blocking probability vs. load assuming W=16 available wavelengths. (c) Blocking probability vs. the number of available wavelengths W, for realistic traffic load.

Physical impairments are not treated as hard constraints in our LP formulation; instead, we use the non-negative surplus variable S_p that equals to the excess of noise variance a lightpath undergoes. If the noise variance bounds are satisfied (S_p=0, for all p), it is expected that the lightpaths that comprise the solution will exhibit acceptable transmission performance. The surplus variables S_p are carried in the LP objective so that the resulting optimization problem aims not only at serving the requests by minimizing the available wavelengths, but also at selecting lightpaths that have acceptable quality of transmission performance. In particular, the objective becomes:

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

IV. Performance Results

We evaluated the performance of the proposed cross layer optimization algorithm through simulations and compared it to the pure RWA algorithm that does not consider physical layer impairments, as presented in Section III.A. We used Matlab and LINDO API to solve the related LP problems. The experiments were performed for the generic DTnet topology (Figure 3a), which is a transparent candidate network as indicated in DICONET project [13]. The capacity of a wavelength was assumed equal to 10Gbps. To evaluate the feasibility of the lightpaths we used a physical layer evaluation module that was developed within DICONET and uses analytical models to account for the most important impairments.

Figure 3b presents the blocking ratio as a function of the traffic load, assuming W=16 available wavelengths. In these experiments we used a random traffic generator to produce 100 traffic matrices for the examined loads. From this graph we can observe that the proposed IA-RWA outperforms the pure RWA that does not consider the physical layer impairments in its formulation. The proposed IA-RWA algorithm manages to serve all the traffic matrices up to load ρ=0.8 with zero physical and network layer blocking with the given number of wavelengths.

Figure 3c presents the blocking ratio as a function of the available number of wavelengths W. We have used a realistic traffic matrix for the DTnet as reported to [13] that corresponds to a load ρ=2.05 (remember that some connections can request more than one wavelengths). The proposed cross layer algorithm outperforms the pure RWA and in particular, for W=35, the pure RWA algorithm has blocking equal to 10%, while the IA-RWA algorithm routes all connections without any physical-blocking. The running time of IA-RWA for W=44 was about 20 min. Thus, the proposed IA-RWA has acceptable running time, considering the size of the input that corresponds to realistic traffic.

V. Conclusions

We presented a cross-layer optimization algorithm that minimizes the number of wavelengths used in the network and also selects lightpaths with acceptable quality of transmission performance based on an LP-relaxation formulation. Using a realistic scenario, our simulation results quantified the blocking performance improvements obtained by the proposed algorithm when compared to a typical RWA algorithm that considers physical impairments only in the post-processing phase.

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