On The Offline Physical Layer Impairment Aware RWA Algorithms in Transparent Optical Networks: State-of-the-Art and Beyond

(Invited Paper)

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***Abstract*—In transparent optical networks with no regeneration, the problem of capacity allocation to traffic demands is called "Routing and Wavelength Assignment". Much work on this topic recently has focused on the dynamic case, whereby demands arrive and must be served in real-time. In addition, due to lack of regeneration, physical impairments accumulate as light propagates and QoT may become inappropriate (e.g., too high Bit Error Rate). Considering the physical layer impairments in the network planning phase gives rise to a class of RWA algorithms: offline Physical Layer Impairment Aware- (PLIA-)RWA. This paper makes a survey of such algorithms, proposes a taxonomy, and a comparison between these algorithms for common metrics. We also propose a novel offline PLIA-RWA algorithm, called POLIO-RWA, and show through simulations that it decreases blocking rate compared with other PLIA-RWA algorithms.**

I. INTRODUCTION

The evolution of the optical networks as the main infrastructure for supporting new and future data-intensive applications is focused on the provision of more capacity in a cost-effective manner. With respect to the optical transmission systems, this evolution can be translated to higher line rate (e.g. 10 or 40 Gbps) and also denser WDM transmission systems (i.e. 80-160 wavelengths per fiber) [1], [2]. The evolution trend depicts a transformation towards lower cost (CAPEX and OPEX) and higher capacity for the next generation core networks.

To realize the vision of transparent optical networks, while offering efficient resource utilization and strict quality of service guarantees based on certain service level agreements, the core network should efficiently provide high capacity, fast and flexible provisioning of links, high-reliability, and intelligent control and management functionalities. At deployment time, all-optical core WDM network operators typically know how bandwidth should be allocated between the clients. In particular, the demand set is already at least partially known, enabling the network operator to perform the resource allocation task offline. Since, in all-optical networks, bandwidth is allocated under the form of *lightpaths* (i.e., the combination of a route between two clients or edge nodes, and a wavelength), the problem of pre-planned resource allocation in such networks is called *static* or *offline* Routing and Wavelength Assignment (RWA) problem [3], [4]. The other case, whereby traffic demands are assumed to arrive in a dynamic fashion, is referred to as the *online* or *dynamic* RWA problem. This paper focuses on the offline RWA problem.

In most RWA proposals, the optical layer is considered as a perfect medium and therefore all outcomes of the RWA algorithms are considered valid and feasible even through the Quality of Transmission (QoT) of some signals — as measured for instance in terms of Bit Error Rate (BER) — may be unacceptable. The incorporation of physical impairments in transparent optical network planning problem has recently received a lot of attention from the research community, leading to the development of a number of Physical Layer Impairment Aware RWA (PLIA-RWA) algorithms [5]. Since the RWA problem is known to be NP-Complete even when assuming a perfect transmission medium [3], [4], the offline PLIA-RWA problem is also NP-complete and heuristics are needed. In a previous work, we performed a comprehensive literature review on the proposed algorithms that address the online and offline PLIA-RWA problem [5]. Very few works target the offline case; in addition, those proposed offline PLIA-RWA algorithms are evaluated for different metrics and network topologies, making them impossible to compare.

In this work we provide a summary of the state-of-the-art algorithms proposed for offline PLIA-RWA problem along with a novel heuristic algorithm, which we call Pre-Ordering Least Impact Offline-RWA (POLIO-RWA), and also present the results of their performance under same assumptions. We show that POLIO-RWA perform better than previously proposed algorithms for relevant network dimensioning metrics.

This paper is organized as follows. In Section II we present the state-of-the-art and our novel algorithm for PLIA-RWA problem. The physical layer performance evaluator model is compiled in Section III. Performance evaluation results are presented in Section IV and Section V concludes this paper.

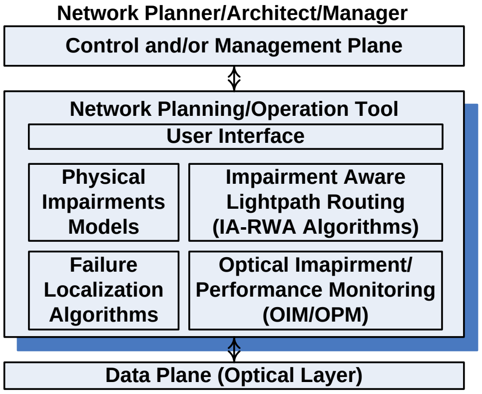

Fig. 1. DICONET framework

II. PLIA-RWA ALGORITHMS FOR NETWORK PLANNING

A. Framework

The DICONET framework [6] for a physical layer impairment aware network planning and operation tool is depicted in Fig. 1. The key innovation of the proposed framework is the development of a network planning/operation tool, which reside in the core network nodes. This tool incorporates real-time measurements of optical layer performance into PLIA-RWA algorithms and is integrated into a unified control plane. It serves as an integrated framework that considers both physical layer parameters and networking aspects and optimizes automated connection provisioning in transparent optical networks.

B. State-of-the-Art PLIA-RWA

Fig. 2 presents a classification of the algorithmic approaches that can be followed in order to solve the PLIA-RWA problem. This classification is applicable for both online and offline algorithms [5].

Class A concerns plain RWA (impairment unaware) algorithms. Generally, the RWA problem can be either solved jointly or by decomposing it to the routing (R) and wavelength assignment (WA) subproblems (R+WA). To take into account the Physical Layer Impairment (PLI) performance, a further step, the PLI verification, is added. This step can be added at the end of the RWA solution (class A-3) or between the R and WA sub-problems (classes A-1 and A-2). If the outcome of the PLI verification step shows that the quality of the lightpath(s) chosen is not satisfactory, a re-attempt of computing the route(s) can be triggered. Class B includes algorithms that address the RWA problem jointly with the PLI. Constraints related to the impairments can be either added in the R sub-problem (class B-1), in the WA sub-problem (class B-2), or in both R and WA (class B-3). Note that algorithms of Class B-3 can address the RWA problem jointly or by decomposing it into its R and WA sub-problems. Class C is the combination of classes A and B. In addition to the PLI constraints in the RWA solution, the PLI verification step is also added.

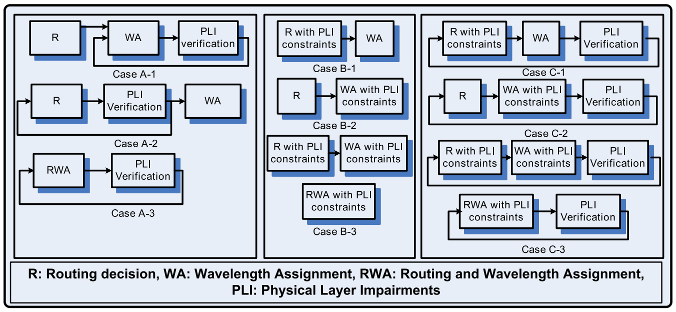

Fig. 2. Taxonomy of PLIA-RWA algorithms

Most of the algorithms proposed in the literature consider the online (dynamic) version of the problem. In contrary, there are few works in the literature regarding the offline PLIA-RWA problem [5]. In general the algorithmic approach for the PLIA-RWA problem can be categorized either as sequential approach based on some heuristic or global optimization, which searches for an optimal solution. In [7] a link-path formulation to solve an Integer Linear Programming (ILP) problem of RWA in a transparent network is proposed. Impairment constraints are taken into account indirectly, in a pre-processing phase, while a post-processing phase is used to evaluate the quality of the obtained solution. In particular, a set of k candidate paths is pre-calculated with the assistance of a (variation of a) shortest path algorithm that uses either a single physical impairment [7] or a Q-Penalty [8] as the link cost parameter[1]. Then, limiting the search in this set of candidate paths, a physical layer agnostic RWA formulation is used in both works. Finally, in a post-processing phase the feasibility of the chosen lightpaths is evaluated. These algorithms fall in case C-3 of our PLIA-RWA algorithms taxonomy.

An impairment-aware offline RWA algorithm that assigns Q-factor costs to links before solving the problem is proposed in [9]. In this work, k-shortest routes are computed considering a Q-penalty value as the link costs. Then, the wavelength that maximizes the Q value is selected to serve each connections request. Since the wavelength assignment is not performed jointly for all connections, a worst case assumption for the interference among lightpaths is used. Therefore, the proposed algorithm does not take into account the actual interference among lightpaths and does not truly optimize the performance, since it assumes worst case interference. This work adopts the case C-1 of our classification.

Some more specific problems involving physical layer impairment constraints into the optimization problem were studied as well. A Mixed-ILP (MILP) formulation of the RWA problem for multicast connections in the presence of optical power constraints is proposed in [10]. 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. This technique follows the case C-3 of our classification chart. RS-RWA is a heuristic algorithm that was proposed in [11]. This algorithm falls into case A-3 of our taxonomy. We describe [11] in more depth in the next section, along with our novel offline RWA algorithm.

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[1] Q is a QoT metric related to BER, and will be presented in more details in Section III.

C. Selected offline PLIA-RWA algorithms

In this work we evaluate the performance of three offline IA-RWA algorithms that were proposed in the literature, namely, a Random Search RWA (RS-RWA) algorithm [11], and an Integer Linear Programming-based RWA (ILP-RWA) algorithm [8], and the novel POLIO-RWA algorithm. The selection of algorithms from the literature is motivated by their different approach to address the PLIA-RWA problem, and their performance under assumed conditions. Therefore we consider them as the state-of-the-art PLIA-RWA algorithms [5].

ILP-RWA is an optimization-based algorithm that was studied in [7], [8]. It is a global optimization algorithm which for a given set of lightpath requests finds an optimal RWA over available paths and wavelengths. The set of paths consists of k-shortest paths (between each pair of nodes) which are calculated based on some PLI-aware link cost metric. The link costs correspond either to individual impairments [8], or are calculated as a link Q-factor [7]. The RWA problem is formulated as an Integer Linear Program (ILP) problem. The optimization criterion is the minimization of link usage subject to the network layer constraints.

The main idea in [11] is to perform a sequential search to compute lightpaths for a given permutation of the demand set. The set of available paths is an arbitrary set of k alternate shortest paths which are given for each pair of source destination nodes. The wavelengths are assigned according to a First-Fit policy. Among a number of permutations the one that achieves the lowest lightpath blocking, is selected. Once a set of accepted lightpaths is found, the physical signal quality is verified. A variation of the RS-RWA algorithm can address the problem of lightpath establishment with regenerator placement. However, PLIA-RWA algorithms for translucent optical networks are not investigated in this paper.

D. A novel heuristic PLIA-RWA Algorithm: POLIO-RWA

In this section we present our novel heuristic algorithm. We define a “demand” as a triplet (s, d, W) where s and d are the source and destination of the demand, and W is the number of wavelengths requested to satisfy the demand. A single demand may require more than one wavelength $(W > 1)$ to be fulfilled if the needed data rate exceeds the channel capacity. We assume customers accept that only a fraction of their requested bandwidth W is granted. We establish lightpaths in a pre-defined sequence. The order in which the demands are considered plays an important role in the performance of the proposed algorithm. Hence, the first building block in our algorithm is a *demand pre-processing ordering* module. We propose two strategies to order the demands. We assess the a-priori distance between two nodes s and d by the length of the shortest path between s and d. Then, we order lightpaths according to this shortest distance in increasing order (shortest path first). Ties are broken randomly in this pre-processing step. The *routing engine* uses the Breadth-First-Search (BFS) Shortest path algorithm. Another key building block in our algorithm is the *physical layer performance evaluator* described in Section III. We compute the QoT of a lightpath through its BER. This performance evaluator is used to guarantee the QoT of the selected lightpath. The idea is to compute the Q factor of the candidate lightpath and only accept those, which have a Q factor value above a given threshold. The flow of proposed algorithm is depicted in Fig. 3. With respect to the taxonomy of PLIA-RWA approaches, the proposed algorithm falls in Case C-3.

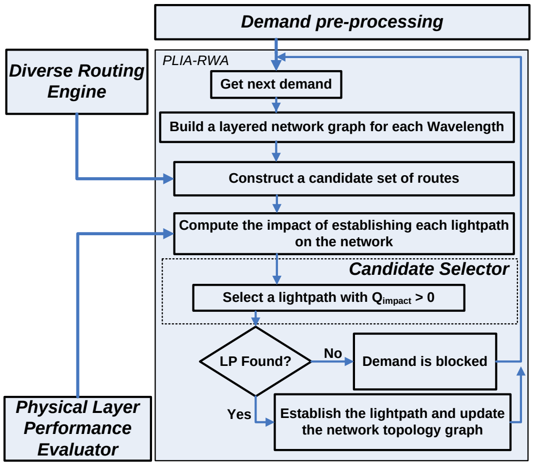

Fig. 3. Proposed heuristic algorithm

For each demand, in turn, we construct a layered network graph (LNG) as follows. The network topology for a given WDM optical network is defined by $G(N, L, W)$ where N is the set of nodes in the network, L is the set of bidirectional links, and W is the set of wavelengths per fiber. A layered network graph $LNG(V, E)$ is a directed graph constructed from G. Each node $i \in N$ in G is replicated W times in the LNG. These nodes are denoted by $v_i(1), \ldots, v_i(|W|)$. If $L_{i,j} \in L$ connects node i to node j, then vertices $v_i(w)$ and $v_j(w)$ are connected by two edges $e_{i,j}(w)$ and $e_{j,i}(w)$ for all $w \in W$. The representation of a LNG is shown in Fig. 4.

The diverse routing engine then constructs a set of diverse routes in each wavelength layer of the LNG graph. This is similar to the “adaptive routing” approach [12]. In order to control the diversity level of routes, we define two parameters k and δ where k determines the number of computed shortest paths between two nodes, and δ defines the number of node- and/or link-disjoint diverse paths. Results are obtained using $k = 10$ and $\delta = 2$. At the end of this step, we have a set of “candidate lightpaths” $\mathcal{C}$ containing at most $W(k + \delta)$ lightpaths. After constructing the pool of candidate paths, we exploit our physical layer performance evaluator (i.e. Q factor estimator) to compute the *margin* of each candidate route (with respect to the minimum allowed Q factor $Q_{threshold}$, on the currently established lightpaths. The margin is computed by subtracting $Q_{threshold}$ from the Q factors of all active lightpaths (including the candidate path) and finding the minimum value, as expressed in (1), where $\mathbf{Q}$ is a vector that includes the Q factors of all active lightpaths:

$$Q_{margin} = \min\left(\mathbf{Q} - Q_{threshold}\right). \tag{1}$$

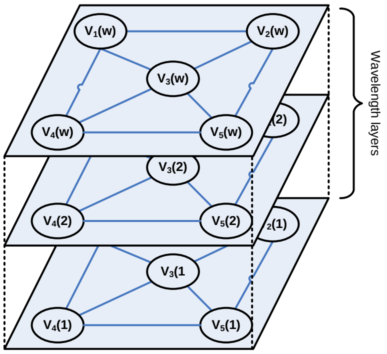

Fig. 4. Layered network graph

The next step is to select a lightpath from the candidate lightpath list. We consider a heuristic, by which the candidate lightpath with highest non-negative Q_{margin} is selected. If this lightpath is found then the lightpath will be established and the network topology graph will be updated to reflect the wavelength and route allocation. Since we have decomposed the network graph to different wavelength layers and for each layer we are finding a diverse set of candidate paths, we actually try to find a lightpath that affects least the already active lightpaths as far as the Q factor metric is concerned. If a proper lightpath is not found, then the demand is blocked.

III. PHYSICAL LAYER IMPAIRMENTS MODELING

To estimate the QoT of a signal carried by a lightpath, we use a metric called “Q factor” which is directly related to the Bit-Error Rate of a signal via the following relationship, in the case of on-off keying intensity modulated signals:

$$BER = \frac{1}{2}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right). \tag{2}$$

The Q factor is defined as [13]:

$$Q = \frac{P_1 - P_0}{\sigma_1 + \sigma_0}. \tag{3}$$

where P_0, P_1 are the means of the distributions of the received “0” and “1” symbols after photodetection, respectively, and σ_0 and σ_1 their standard deviations. We developed a “Q tool” able to estimate the Q factor of a lightpath based on the network topology and information about the physical network components. The Q tool incorporates the main impairments that affect signal propagation. In particular, we account for the following impairments: Amplifier Spontaneous Emission (ASE) noise, filter concatenation, Polarization Mode Dispersion (PMD), Cross-Phase Modulation (XPM), Four-Wave Mixing (FWM), and optical crosstalk originating from optical leaks within the optical crossconnects.

Noticing that $P_0 \ll P_1$ and following [14], we actually model filter concatenation through a penalty on P_1, yielding a new quantity P_1' that accounts for the eye closure incurred by filter concatenation. The PMD effect is modeled through a penalty on Q via a multiplicative factor η_{PMD} [15]. Hence Q is actually defined as:

$$Q_{est} = \frac{\eta_{\text{PMD}} P_1'}{\sigma_1 + \sigma_0}. \tag{4}$$

We model ASE noise, node crosstalk, XPM and FWM through noise variances:

$$\begin{aligned} \sigma_1^2 &= \sigma_{1,\text{ASE}}^2 + \sigma_{1,\text{XT}}^2 + \sigma_{\text{XPM}}^2 + \sigma_{\text{FWM}}^2, && (5) \\ \sigma_0^2 &= \sigma_{0,\text{ASE}}^2 + \sigma_{0,\text{XT}}^2.. && (6) \end{aligned}$$

The contribution of XPM and FWM within σ_0 are negligible and we model these two effects via the variances σ_{XPM}^2 and σ_{FWM}^2 in (5) using the models developed in [16]–[18]. Crosstalk is modeled as in [19] within both σ_1 and σ_0 via $\sigma_{1,\text{XT}}^2$ and $\sigma_{0,\text{XT}}^2$, as is ASE noise via $\sigma_{1,\text{ASE}}^2$ and $\sigma_{0,\text{ASE}}^2$.

Although some effects depend solely on the network topology and physical parameters (ASE noise, PMD, filter concatenation), other effects (crosstalk, XPM, FMW) depend on the network state, that is, on which lightpaths are established in the network, thereby introducing QoT interdependence between the lightpaths established in the network.

IV. PERFORMANCE EVALUATION

A. Assumptions

The network topology in our simulation studies is Deutsche Telekom national network (DTNet). This network has 14 nodes and 46 bidirectional links, with an average node degree of 3.29. The line rate in this network is assumed to be 10Gbps. The traffic load in the network is defined as:

$$Load = \frac{\sum_{i \in Demands} W_i}{N(N-1)}. \tag{7}$$

The evaluation is performed for the values of traffic load between 0.5 and 1.0 with a step of 0.1. For each load value, a set of 50 matrices of random (static) lightpath demands is given. The unit traffic load corresponds to the demand set where between each pair of (distinct) source-destination nodes there is a lightpath request. For example the number of lightpaths in the demand set for DTNet with the unit load is 182. The input power to the links is -4dBm and 3dBm per channel for DCF and SSMF fibers respectively. We also assumed that pre-dispersion compensation of 400ps/nm is considered in the links. The SSMF amplifier span length in each link was set at 100km, followed by a DCF segment that under-compensates the dispersion of the preceding SSMF of a value of 30ps/nm/km. At the end of each link the accumulated dispersion is fully compensated. It was assumed that the SSMF fibers have a dispersion parameter of D=17ps/nm/km and attenuation a=0.25db/km. The DCF segments have a dispersion parameter of D=80ps/nm/km and an attenuation of 0.5dB/km. The channel spacing was set at 50GHz. The noise figure of the amplifiers that compensate for the loss of the preceding fiber segment was set at NF=6dB with small variations. The signal-to-crosstalk ratio in nodes was set around -32dB with small variations in each node. The threshold value for computing the impact on Q factor (i.e. $Q_{Threshold}$) is 15.5dB (corresponding to BER=10^{-9} without FEC).

We implemented two versions of the RS-RWA algorithm [11]. In a plain RS-RWA algorithm the signal verification is performed as the ultimate algorithm’s step after the permutation procedure finds a best RWA solution. On the contrary, in

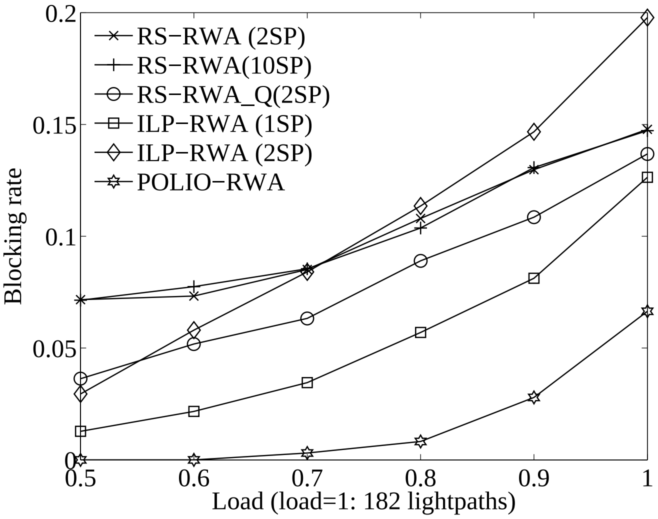

Fig. 5. Blocking rate of PLIA-RWA for 16 wavelengths per link.

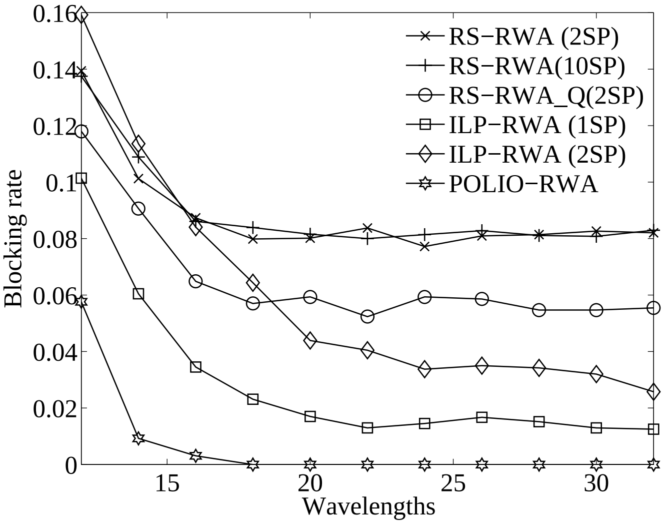

Fig. 6. Blocking rate of PLIA-RWA for a fixed load of 0.7.

an RS-RWA with Q-factor check (RS-RWA-Q) algorithm the verification of signal QoT is performed for each permutation. In both cases 10 permutations are examined.

Our formulation of the ILP problem in the ILP-RWA algorithm had to be slightly modified with respect to the one presented in [8]. The reason is that authors of [8] assume that there is no link capacity constraint imposed and, therefore, all the requests are assumed to be served by the network. On the contrary, the link capacity is constrained in our evaluation scenario and the resulting RWA problem concerns the minimization of the number of connections blocked among all the connections offered to the network.

The candidate shortest paths (SP) are calculated and ordered according to the physical distance. The number of paths that we consider between each pair of source-destination nodes is $k = \{2, 10\}$ for RS-RWA, $k = 2$ for RS-RWA-Q, and $k = \{1, 2\}$ for ILP-RWA. Note that for $k = 1$ the routing subproblem of ILP-RWA is relaxed and the algorithm performs as a wavelength assignment algorithm.

B. Results

The blocking rate of the algorithms as a function of traffic load for DTNet with 16 wavelengths per link is depicted in Fig. 5. Recall that a unit load corresponds to a demand set of 182 lightpath requests. We observe that POLIO-RWA outperforms other offline PLIA-RWA by a large margin. The blocked demands in POLIO-RWA are those who cannot satisfy the required QoT threshold. Also the performance of the RS-RWA algorithm does not depend significantly on the number of available routing paths (2SP and 10SP for $k = 2$ and $k = 10$ paths). Moreover, the enhanced RS-RWA-Q algorithm offers better performance than RS-RWA since it includes the Q-factor verification procedure into the RWA subroutine. As a result the RWA, which achieves the lowest blocking rate subject to both wavelength availability and signal QoT signal compliance is selected among all permutations.

Regarding the ILP-RWA algorithm, we can observe that the best overall blocking rate for the performed set of experiments is achieved for a relaxed version of the algorithm, i.e., with only 1 shortest path given. The deterioration of the algorithm performance, for $k > 1$, is due to the desire to accept as many lightpath requests as possible in the RWA processing step by optimal exploring of insufficient network link resources. In this case the cost of such strategy is a possible increase of the average path length. Thus, the ILP optimization procedure does not differentiate among all feasible candidate paths. Still, this decision results in the increase of link-dependent impairments and degradation of signal QoT if one path is longer than the other.

The overall blocking rate as a function of the number of available wavelengths per links under a traffic load of 0.7 is presented in Fig. 6. Again, POLIO-RWA outperforms all other algorithms. In particular, it is seen that only 18 wavelengths are needed to accommodate a load of 0.7 to guarantee 0% blocking rate in a network running POLIO-RWA, while no other technique can achieve a 0 blocking rate for the given load. This is because other algorithms only verify, rather than incorporate in the decision-making process, the QoT compliance of lightpaths. In addition, we observe that the overall blocking rate hardly depends on the number of available routing paths in the RS-RWA algorithm. Also, the performance of the RS-RWA-Q algorithm is always at least as good as that of the RS-RWA algorithm, thanks to its quality-of-signal verification enhancement in the RWA procedure. We can observe that the relaxed version of the ILP-RWA combinatorial algorithm (i.e., with $1SP$) outperforms the sequential RS-RWA(-Q) algorithm. Although in both cases the overall blocking rate drops down when the number of wavelengths is increased, still it does not reach 0%. The characteristics obtained for ILP-RWA decay slowly when more wavelengths are provided. This can be attributed to the reduction of crosstalk effect since the wavelength assignment is more likely to be spread. The stability of results with respect to the number of wavelengths, as observed for the RS-RWA(-Q) algorithm, can be easily explained. Since

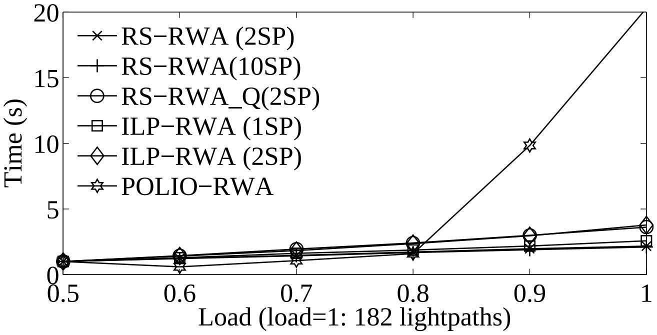

Fig. 7. Running time of the PLIA-RWA for 16 wavelengths per link.

the algorithm performs a First Fit-like search for available wavelength resources it will most likely assign consecutive wavelengths what, in turn, will increase the crosstalk effect. Note that above a certain number it does not matter how much wavelengths are available since the RWA routine always starts searching from the wavelength with smallest index.

Finally, in Fig. 7 we present the relative computation times, expressed in seconds, for each of the algorithm processing steps, namely, for the RWA procedure (denoted as ’RWA’ in the legend of Fig. 7) and the Q-verification procedure (denoted as ’Q’) versus different load values and for 16 available wavelengths per link. computation times are normalized to the one for load=0.5. For each algorithm, except RS-RWA-Q, the computation of RWA for a set of lightpath requests takes less time than further verification of their quality. Still the time is in the order of fractions of seconds up to some tens of seconds. As for the RS-RWA-Q algorithm, the computation time of RWA is considerably high, comparing with the others algorithms, and it results from the involvement of Q-factor calculation into the RWA procedure. Indeed, for each permutation of lightpath requests that is processed by the RWA procedure, the verification of signal QoT is performed. We notice that POLI-RWA does not scale well with load; however, for realistic load values, the running time remains acceptable for an offline scheme.

V. CONCLUSION

In this work we presented a taxonomy of various PLIA-RWA approaches from the literature. We have performed a number of experiments for selected static IA-RWA algorithms that have been proposed in the literature. Specifically, we have studied a random search RWA algorithm and an integer linear programming-based RWA algorithm (ILP-RWA). The former was implemented in two versions, as a plain random search RWA algorithm (RS-RWA) and, in its enhanced version, with a verification of signal quality performed in the RWA subroutine (RS-RWA-Q). We also propose a novel heuristic offline PLIA-RWA algorithm called POLI-RWA, which is shown to exhibit lower blocking rate compared to other algorithms. The obtained results justify the need for an impairment-aware RWA algorithm for optical network planning.

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