A Comparison of Offline IA-RWA Approaches

(Invited paper)

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We present two offline IA-RWA algorithms developed within the DICONET project. An evaluation module with analytical models to account for the physical layer impairments (to be referred to as Q-Tool) is used to estimate the quality of transmission of the lightpaths. Specifically, we present (i) a combinatorial IA-RWA algorithm that is based on a LP-relaxation formulation with piecewise linear cost functions that directly accounts for the physical impairments by introducing additional constraints in its RWA formulation, and (ii) a sequential heuristic IA-RWA algorithm that orders the connections and serves them one-by-one, using the Q-Tool to evaluate the feasibility of the continuously evolving solution. We compare the performance of these algorithms to that of a pure RWA algorithm that routes the connections over their shortest paths so that they have acceptable transmission quality.

1. 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 networks. The trend clearly shows an evolution towards dynamic reconfigurable, low-cost and high capacity transparent (all-optical) WDM networks. It is the vision of the DICONET project [2] that future core networks will eventually have a transparent optical structure (Figure 1).

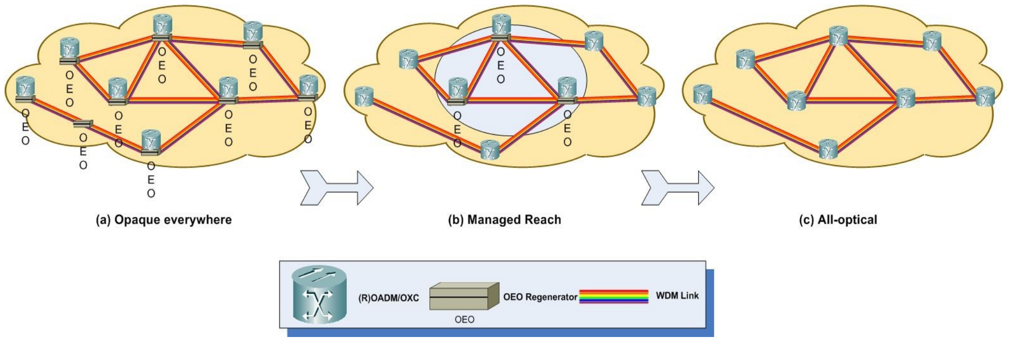

Figure 1: Evolution of wavelength routed optical core networks.

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. This is known as the *routing and wavelength assignment* (abbreviated RWA) problem. 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 and *online* (or *dynamic*) 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 study 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 [1]. However, signal transmission is significantly affected by physical limitations of fibers and optical components [3], usually referred to as *physical layer impairments* (PLI). Due to the PLIs 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. 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.

The need to account for the PLIs constrains the kinds of paths that can be used for routing. To address this problem a number of cross-layer design approaches are emerging, usually referred to as PLI-aware or impairment-aware (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 PLIs, routing decisions made for one lightpath affect and are affected by the routing decisions made for other lightpaths.

Most IA-RWA algorithms that have appeared in the literature consider the online version of the problem, while the corresponding work on offline traffic is quite limited. This is because even the pure (without PLIs) offline RWA problem is NP-hard and becomes even more complicated when PLIs are included. In the dynamic traffic case where the connections are established one-by-one, the employed algorithm can examine the feasibility of a candidate lightpath by calculating the interference by/to the already established lightpaths. However, this cannot be done in the offline RWA case, where there are no already established connections and the utilization of lightpaths are the variables of the problem. For this reason, offline IA-RWA algorithms proposed to date do not consider inter-lightpath interference [4].

Generally, there are two approaches to solve the offline RWA problem. The problem can be solved by applying a combinatorial optimization algorithm or by applying an online algorithm that serves one-by-one the given set of connections. In order to use an online algorithm to solve the offline problem the algorithm has to be adaptive and take into account the effect of the evolving solution to each new connection it serves. In general, such online approaches do not optimize the solution for all connections requests jointly, and thus their performance is suboptimal. Thus, the order in which the connections are considered is particularly important for obtaining a good final solution.

In this study we present two offline IA-RWA algorithms that have been developed within the DICONET project [2] that use different algorithmic techniques, and in particular (i) a combinatorial optimization algorithm that is based on an LP-relaxation formulation and (ii) a heuristic algorithm that serves the connections one-by-one. We compare these IA-RWA algorithms to a pure RWA algorithm that routes the connections only over their shortest paths, so as to exhibit acceptable quality of transmission performance. To evaluate the feasibility of the chosen lightpaths we use a module that incorporates analytical models to account for the PLIs (to be referred to as Q-Tool) developed within DICONET. The key difference between the IA-RWA algorithms presented here to the offline algorithmic approaches found in the literature is that the proposed algorithms take into account almost all the dominant PLIs and also consider, to a certain degree, the interference among the lightpaths, which is particularly difficult for this type of traffic. Also, the proposed algorithms scale well and were proven applicable to solve problems under realistic network and traffic loads.

2. Quality of Transmission

In transparent (all-optical) WDM networks the signal quality of transmission (QoT) degrades due to the non-ideal physical layer. When we consider IA-RWA algorithms it is useful to categorize the physical layer impairments (PLIs) to those that affect the same lightpath and to those that are generated by the interference among lightpaths:

- **Class 1** - Impairments that are generated by the same lightpath: Amplified Spontaneous Emission noise (ASE), Polarization Mode Dispersion (PMD), Chromatic Dispersion (CD), Filter concatenation (FC), Self-Phase Modulation (SPM),
- **Class 2** - Impairments that are generated by interference among lightpaths: Crosstalk (XT) (intra-channel and inter-channel crosstalk), Cross-Phase Modulation (XPM), Four Wave Mixing (FWM).

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.

3. Offline IA-RWA algorithms

An instance of the offline RWA problem is defined by the network topology and the set of connection requests given in the form of a traffic matrix. The objective of the problem is to serve all the connection requests with the minimum number of wavelengths (network layer objective) and also to select lightpaths that have acceptable quality of transmission performance (physical layer objective).

3.1 Sigma-bound IA-RWA Algorithm (SB-LP-IA-RWA)

In [4] we 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 offline traffic. In this study we proceed further and present 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.

3.1.1 Network Layer Problem

We start by calculating for each connection request a set of *k*-shortest length paths. These are then used in order to formulate the RWA instance as a Linear Programming (LP) problem. A variable x_{pw} in the LP formulation represents a lightpath (p,w) and takes value equal to 1, if (p,w) is utilized in the solution, and equal to 0, otherwise. Typically, the RWA is formulated as an integer linear programming (ILP) problem. Since ILP is NP-hard, to obtain solutions in acceptable (non-exponential) time we relax the integrality constraint and solve the LP-relaxation combined with a specifically designed piecewise linear cost function that makes Simplex algorithm yield integer optimal solutions for a large number of RWA input instances [4]. Note that non-integer 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 the LP-relaxation does not yield an integer solution, appropriate rounding techniques are used and the optimality of the solution is no longer guaranteed.

3.1.2 Physical Layer Problem

Following the classification of the impairment that was presented in Section 2 and given a threshold for the Q factor, say 15.5 dB, we 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 of class 1.

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

Since it is difficult to find an accurate $\sigma^2_{max,'1'}$ bound and we also make some simplification assumptions, we use a bound that is somewhat higher than the one actually calculated. Also, since taking into account FWM would require additional variables and would complicate the algorithm, we assume that FWM contributes a constant c_{FWM} ; since the effects of FWM are generally rather small compared to the other effects, c_{FWM} can be chosen as the worst case FWM contribution.

In order to account for the physical impairments we have to identify the network parameters that generate these effects. Assuming a lightpath (p,w), XPM is more severe if an adjacent channel is activated, and becomes less significant as we move away from the channel under examination. Node intra-channel 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.

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

- $s^2_{1\text{-}XPM,'1',l}$, $s^2_{2\text{-}XPM,'1',l,}$: the noise variance of bit 1 due to XPM from an active adjacent channel, and from an active second adjacent channel.
- $s^2_{XT,'1',n}$: the intra-XT noise variance of bit 1 due to a lightpath that also crosses switch n and uses the same wavelength.

Analytical models can be used to obtain these parameters (note that the algorithm can also use wavelength dependent parameters).

To account for the interference among lightpaths, for each lightpath (p,w) that is selected in the solution the following constraint is introduced in the LP:

$$\sum_{\{l\in p|n\,\mathrm{end\,of}\,l\}}\left(\overbrace{s^{2}_{XT,n}\cdot\left(\sum_{\{p'|n\in p'\}}x_{p',w}\right)}^{\text{intra-XT}}+\overbrace{s^{2}_{XPM,l}\cdot\left(\sum_{\{p'|l\in p'\}}x_{p',w-1}+x_{p',w+1}\right)}^{\text{XPM from adjacent channels}}+\overbrace{s^{2}_{2-XPM,l}\cdot\left(\sum_{\{p'|l\in p'\}}x_{p',w-2}+x_{p',w+2}\right)}^{\text{XPM from second adjacent channels}}\right)+c_{FWM}\leq s^{2}_{\max,'1'}(p,w)$$

The lightpaths that satisfy the corresponding constraint are expected to have acceptable quality of transmission performance. In this way the LP algorithm performs a cross-layer optimization of the solution over the network and the physical layers.

3.2 Sequential Heuristic IA-RWA Algorithm (S-H-IA-RWA)

In the previous section we presented a combinatorial algorithm to solve the IA-RWA problem for all demands simultaneously. Taking a different approach in this section, we establish lightpaths by considering the connection requests sequentially, in a defined order. To serve the connections, we use an adaptive heuristic algorithm that in each iteration takes into account the utilization state of the network up to that point [5].

The order in which the demands are considered plays an important role in the performance of the proposed algorithm. The demands are ordered and served in increasing shortest length path order, since it is more difficult to accommodate calls between nodes that are far apart (because such paths require more resources). The algorithm calculates *k*-shortest length paths for each connection request. Note that the parameter *k* can be seen as a tuning parameter that controls the tradeoff between the blocking performance and the running time of the algorithm, since the candidate lightpath are checked for QoT adequacy through Q-Tool and these computations are time-consuming. The algorithm runs as follows. It extracts one connection request from the ordered list and checks its *k*-shortest length paths one after another for free wavelengths (taking into account the previous served lightpaths). When it finds a free wavelength it evaluates its Q-factor with the Q-tool and stops the first time it finds a lightpath with acceptable QoT. The connection is served by this lightpath, the utilization state of the network is updated and the algorithm continues to the next request. An additional feature of this algorithm is that it can provide different levels of protection according to the QoS requirements of the request.

4. Performance Evaluation

We compare the performance of the IA-RWA algorithms for transparent networks that were presented in the previous subsections to that of a typical offline pure RWA that does not consider physical impairments in its formulation. In particular, we have used a pure RWA algorithm that serves all connection requests over their shortest paths and uses the Smallest Last graph colouring heuristic algorithm to assign wavelengths. In this comparison section we will refer to this algorithm as SP-RWA algorithm. SP-RWA algorithm exhibits only network-layer blocking, since in the used network all connections requests could always be established over their shortest path, irrespective of the degree of interference among the lightpaths.

The network topology that was used is the generic DT network topology (DTnet) shown in Figure2(a), consisting of 14 nodes and 46 directed links. The link model of the reference network is presented in Figure2(b) and the physical parameters were chosen to take realistic values. With respect to the traffic, we define the load as the ratio of the number of connection requests included in the traffic matrix over the number of single wavelength requests between all source-destination pairs. We used two different types of traffic generators, (i) a random traffic generator to produce 50 traffic matrices of loads and ρ ranging form 0.5 up to 1 with 0.1 step (ii) a realistic traffic generator to produce traffic matrices that resemble the real traffic of DTnet, as reported in [2], by scaling up/down the real traffic matrix of DTnet which corresponds to load slightly larger than 2.05 (note that a source-destination pair may request more than one wavelength and thus the load can be higher than 1).

As presented in the corresponding sections, both algorithms use variations of the *k*-shortest path algorithm in order to compute a set of candidate paths from which they choose their solutions. For this performance comparison SB-LP-IA-RWA and S-H-IA-RWA algorithms used *k*=3 and *k*=10 shortest paths, respectively. Note that the heuristic S-H uses a high number of candidate paths, and thus searches rather exhaustively the path space. Recall that S-H is a sequential heuristic algorithm that calculates the candidate paths for each connection request one at a time, while the SB-LP-IA-RWA algorithm is combinatorial. Also, note that the SB-LP algorithm uses certain constraints in its formulation that directly take into account the Q-factor of the lightpaths, while the S-H algorithm, at some intermediate phase, utilize Q-Tool to validate the feasibility of intermediate solutions.

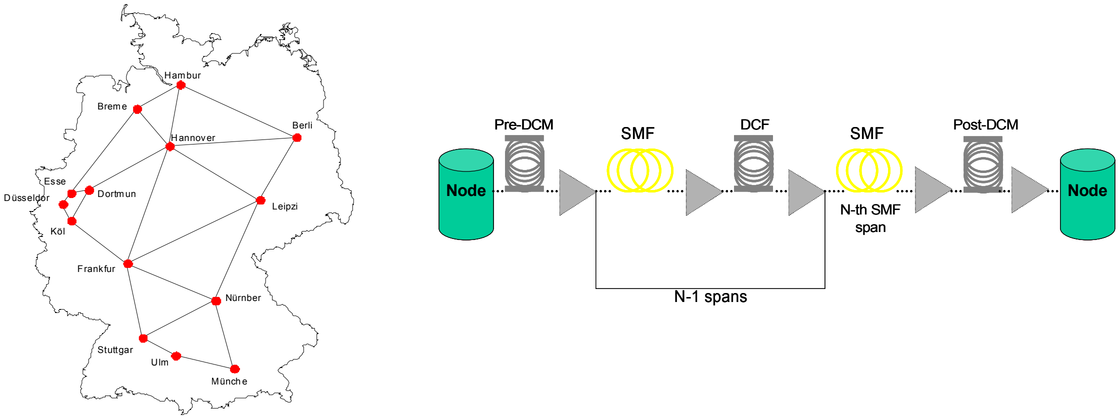

Figure 2: (a) link model and (b) DT network topology, with 14 nodes and 23 links (46 directed links).

4.1 Experiments using the random traffic generator

In Figure 3 we report the number of wavelengths that are required in order to reach zero blocking and the corresponding average running time. From these figures we can see that the combinatorial SB-LP-IA-RWA algorithm exhibits the best performance with respect to the number of wavelengths it requires to serve the generated RWA instances, and the lowest average running time. The SB-LP algorithm uses constraints that directly bound the interference among lightpaths in its LP formulation so that the lightpaths that comprise the solution have acceptable QoT performance. This was verified in the experiments, since when the SB-LP algorithm finished with zero blocking, no lightpath was dropped by the Q-Tool. The sequential heuristic S-H-IA-RWA algorithm has good wavelength utilization performance that deteriorates as the traffic load increases. This is expected since this algorithm does not optimize the solution jointly for all connections requests, but serves them one at a time. Since the lightpath chosen to serve a connection is affected by the previously chosen lightpaths, as the load increases the performance of the algorithm deteriorates, when compared to the combinatorial SB-LP algorithm. To compensate for this, S-H uses the highest number of candidate paths and thus performs a rather exhaustive lightpath search for each request it sequentially serves. The running times of the S-H is high and is dominated by the execution time of the Q-Tool. Since the evaluation module Q-Tool that was uses was not optimized with respect to its running time, its execution time performance can be improved. The wavelength performance of the SP-RWA algorithm is the worst, since it explores a small candidate path space (use only the shortest path for each connection), and thus requires a higher number of wavelengths to serve the connections. On the other hand, due to its simplicity, its execution time is the lowest.

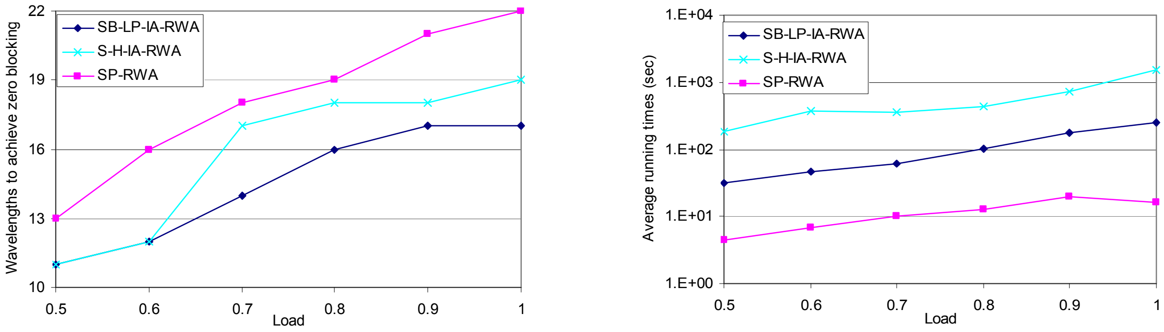

Figure 3: (a) Number of wavelengths required to reach zero blocking, and (b) average running times vs. load using the random traffic generator.

In Figure 4 we graph the average blocking ratio and the average running time as a function of the traffic load *ρ* assuming that a constant number of wavelengths, and in particular *W*=16, are available in the network. From these figures we can see that the combinatorial SB-LP-IA-RWA algorithm exhibits the lowest blocking performance, but the sequential S-H-IA-RWA is also very close. The running time of SB-LP increases rapidly when the blocking is non-zero, since for these cases the SB-LP algorithm searches longer time to find a zero-blocking solution. The S-H algorithm exhibits very high running times that also increase rapidly for high loads, where the blocking is non-zero. Since the number of wavelengths in this set of experiments is fixed, as the load increases, less candidate paths have acceptable Q-factor and the S-H algorithm has to call the Q-tool more times to evaluate the feasibility of additional candidate lightpaths. The blocking performance of the pure SP-RWA is the worst. Note that SP-RWA exhibits only network layer blocking since for the connections that it establishes the QoT is always acceptable. Contrary to the other algorithms the average running time of SP-RWA is slightly affected by the load.

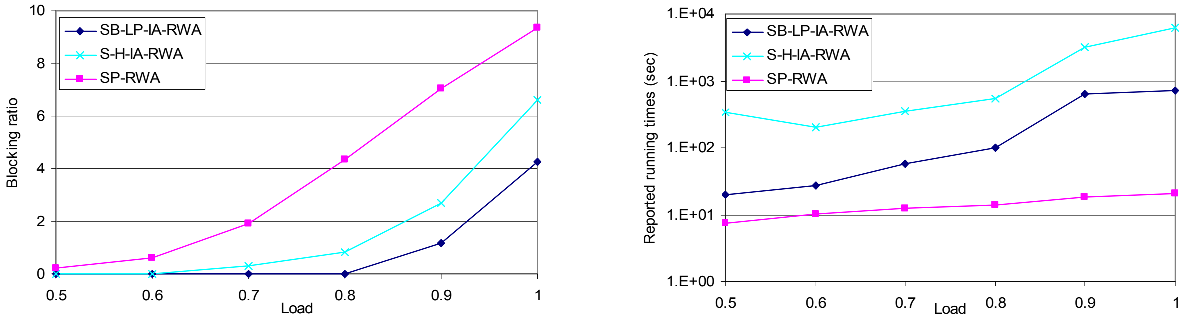

Figure 4: (a) Blocking ratio (b) average running times vs. load using the random traffic generator.

4.2 Experiments using the realistic traffic generator

In Figure 5 we report the number of wavelengths that are required in order to reach zero blocking and the corresponding average running time using as input the traffic matrices that were generated with the realistic traffic generator. As in the previous experiments, the SB-LP-IA-RWA algorithm exhibits the best performance. The performance of the sequential S-H-IA-RWA algorithm is very good for low loads and deteriorates as the load increases. In particular, for load *ρ*=0.5 the S-H algorithm finds a zero blocking solution for 10 wavelengths, the same number required by SB-LP. However, the difference between these two algorithms increase and reach up to 6 wavelengths for load ρ=3. As discussed above, this is because the S-H algorithm does not jointly optimize the solution. Again SB-LP algorithm exhibits lower average running times than S-RWA-Q. The wavelength performance of the pure SP-RWA algorithm is very low and deteriorates vastly as the load increases. As previously explained this is due to the small path space that it utilizes. Considering the realistic traffic loads, both SB-LP and S-H algorithms are able to find good solutions within acceptable time, for offline traffic.

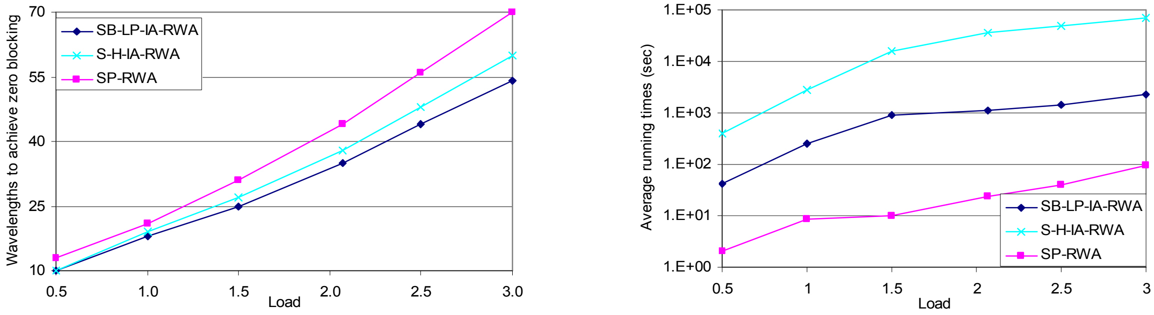

Figure 5: (a) Number of wavelengths required to reach 0 blocking, and (b) average running times vs. load using the realistic traffic generator.

5. Conclusion

We presented two IA-RWA algorithms for transparent networks, developed within the DICONET project and compared them with a pure RWA algorithm that routes the connections over their shortest paths. The proposed algorithms proved their applicability and showed that they can obtain good solutions within acceptable time for realistic inputs. The combinatorial SB-LP algorithm was shown to exhibit the best wavelength utilization and running time performance. This is because the SB-LP algorithm takes directly into account the physical impairments by constraining the interference among lightpaths in its formulation. The sequential heuristic S-H algorithm exhibits good performance that deteriorates as the load increases, since it does not jointly optimize the lightpaths for all requests, but serves them one-by-one. Its running time was high but can be improved by using a validation module that is optimized towards lower execution time and not towards accuracy.

Acknowledgements

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