Impairment Aware RWA in Optical Networks: Over-provisioning or Cross Optimization?

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***Abstract*—In transparent and translucent wavelength routed optical networks the signal quality degrades due to physical layer impairments while the interference among lightpaths implies that routing decisions for one lightpath affect and are affected by the decisions made for other lightpaths. To establish a lightpath for a new connection two main approaches can be used. The most common approach is to select a lightpath that has acceptable transmission quality under a worst case interference assumption, ensuring that the selected lightpath will not become infeasible due to the possible establishment of future interfering connections. This approach sacrifices candidate path space for a quick and stable lightpath selection, which is appealing from a complexity viewpoint. The second approach is to consider the current network utilization and account for the actual interference among lightpaths, performing a cross layer optimization between the network and physical layers. In this case, however, the algorithm has to check whether the establishment of the new lightpath turns infeasible some of the already established connections. The question that arises is whether the performance benefits that can be achieved through the second approach are worth the added complexity introduced by the cross-layer optimization applied.**

***Index Terms*— Routing and Wavelength Assignment, transparent networks, translucent networks, physical layer impairments, network provisioning**

I. Introduction

In *opaque* networks the signal is regenerated at every intermediate node along a lightpath via Opto-Electro-Optical (OEO) conversion. The network cost could be reduced by employing regenerators only at specific nodes of the network. When regenerators are available, a lengthy end-to-end connection that needs regeneration at some intermediate node(s) is set up in a multi-segment manner so that it is served by two or more consecutive transparent lightpath-segments. Optical networks, where some lightpaths are routed transparently, while others go through a number of regenerators, are known as *translucent* optical networks. In some networks it is also feasible for the data signal to remain in the optical domain for the entire path and these networks are known as *transparent* networks.

In transparent and translucent networks, it is important to propose algorithms that select the routes for the connection requests and the wavelengths that will be used on each of the links along these routes, so as to optimize certain desired performance metrics. This is known as the routing and wavelength assignment (RWA) problem. An offline RWA algorithm is executed when the network is initially set up for network provisioning (i.e., planning phase of the network), and is also executed periodically, or when traffic changes substantially. An online RWA algorithm is executed for new connection requests that arrive sporadically and have to be served on demand, one by one (i.e., operational phase of the network).

The typical objectives of the RWA problem are to reduce both the blocking ratio and the network cost in terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). In transparent or translucent optical networks a connection blocking may occur (i) due to the unavailability of free wavelengths or links (network-layer blocking) and (ii) due to the physical layer impairments, introduced by the non-ideal physical layer, which may degrade the signal quality to the extent that the lightpath is infeasible (physical-layer blocking).

Physical layer impairments reduce the number of candidate paths that can be used for routing. Moreover, due to certain physical layer effects, routing choices made for one lightpath affect and are affected by the routing choices made for the other lightpaths. RWA algorithms that take physical layer impairments into account are referred to as impairment-aware (IA)-RWA algorithms.

There are two approaches to address the IA-RWA problem while accounting for the interference among lightpaths. In the first approach, the quality of transmission (QoT) of a new candidate lightpath is calculated under the assumption that all wavelengths on all links are fully utilized. This will be referred to as the worst case interference assumption. A lightpath chosen in this way is bound to have acceptable transmission quality during its entire duration, even if future interfering connections are established. However, this approach reduces the candidate path space available for routing, resulting in larger blocking probability and wasteful use of network resources. On the other hand, cross-layer optimization algorithms that use the current network utilization to estimate the actual interference among lightpaths are able to explore a larger path space. The drawback of this second approach is that the IA-RWA algorithm's operation becomes more complicated, since in this case the actual inter-lightpath interference has to be modeled, and, additionally, the algorithm has to

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evaluate if the establishment of a new lightpath will turn infeasible some of the already established connections.

In what follows we present in more details and evaluate through simulations typical algorithms that follow these two approaches. Our aim is to investigate the performance and tradeoffs involved when using worst case impairment estimates or actual impairment estimates in designing and operating an optical network. In particular, in Section II we report on previous work. In Section III we give a short description of the physical layer impairments. In Section IV we outline algorithms for transparent optical networks that follow the worst case interference assumption or estimate the actual interference among lightpaths so as to perform a cross-layer optimization of the solution between the network and physical layers. In Section V we describe algorithms for network provisioning in translucent networks following the two aforementioned approaches. Simulation results are presented in Section VI, where we evaluate whether the cross layer optimization algorithms, for transparent and translucent networks, exhibit performance benefits that compensate for their increased complexity. Our conclusions are given in Section VII.

II. Previous Work

Different IA-RWA algorithms proposed in the literature model in different ways the interaction between the networking and the physical layer, optimizing their solutions either separately or jointly over these two layers. Regarding the operation phase of an optical network, various online IA-RWA algorithms have been proposed in the literature [2] - [5]. In [2] the authors decouple the RWA and the IA subproblems, by first deciding on the lightpath to serve a connection (RWA subproblem) and then evaluating the feasibility of the chosen lightpath on a separate module (IA subproblem). In [3] an IA-RWA algorithm that selects a lightpath and then uses analytical models to estimate its QoT is presented. An IA-RWA algorithm that is based on the shortest path or shortest widest path concept and uses analytical formulas to estimate the QoT of each candidate lightpath is presented in [4].

The multicost algorithm presented in our previous study [5] solves the IA-RWA problem jointly and takes into account the interference among the lightpaths, using the current network utilization. This is done by first calculating noise variance vectors per wavelength that are used as cost vectors for the links of the network. It then calculates the path parameter vectors by using appropriate associative operators to combine the corresponding link parameter vectors. During its operation the algorithm calculates the Q-factor of candidate lightpaths and prunes those that do not have acceptable QoT. In the end, it obtains a set of non-dominated paths from source to destination that all have acceptable QoT performance.

We turn now our attention to translucent networks, as opposed to transparent networks discussed above. The majority of RWA algorithms proposed so far for translucent networks assume a dynamic (online) traffic scenario. [6] presents a two-dimensional Dijkstra RWA algorithm for translucent optical networks that assumes a given placement for the regenerators and a constraint on the maximum transparent distance. When the length of a lightpath exceeds a maximum transparent distance bound, the lightpath is blocked. A different approach for dynamic resource allocation and routing is considered in [7] and [8], where spare transceivers (transmitter-receiver pairs or add-drop ports) at the nodes are used to regenerate signals. This case applies to networks where the lightpaths initiated and terminated at a node do not use up all its transceivers, so that some nodes will have spare transceivers that can be used for regeneration purposes. A Max-spare algorithm for selecting the regeneration nodes for a lightpath is proposed in [9] and compared to a Greedy algorithm used in conjunction with a wavelength-weighted and a length-weighted RWA algorithm. In [10], two online RWA algorithms for translucent networks with sparse regenerator placement are presented. These algorithms assume (i) worst-case physical penalties (corresponding to a fully loaded system), or (ii) take into account the current network status and the actual number of active channels.

In [11], the problem of maximizing the number of established connections, under a constraint on the maximum transparent length, is formulated as a mixed-integer linear program (MILP). Since MILP is NP-hard, the authors also propose a heuristic algorithm to route connections. However, [11] does not consider impairment effects other than the transparent length. A simple heuristic is given, for placing the fewest such regenerators to reach a given blocking probability for dynamic traffic, based on the ranked frequency of shortest-path routes transiting each node is given in [12]. In [13] the authors address the translucent network design problem by proposing several regenerator placement algorithms based on different knowledge of future network traffic patterns. A quality of transmission-based heuristic IA-RWA algorithm for translucent networks is presented in [14]. In the first phase of that algorithm a random search heuristic RWA algorithm is used and in the second phase regeneration placement is performed after estimating the BER of the lightpaths comprising the solution of the first phase. In our previous study [15], we examined the offline IA-RWA problem for translucent networks and proposed an algorithm that selects the regeneration sites and the number of regenerators that need to be deployed on these sites for the given set of requested connections. The problem of regenerator placement and regenerator assignment is formulated as a virtual topology design problem.

III. Physical Layer Impairments

Several criteria can be used to evaluate the signal quality of a lightpath. Among a number of measurable transmission quality attributes, 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 bit error rate (BER). The Q-factor is the electrical signal-to-noise ratio at the input of the decision circuit in the receiver's terminal [3][4]. Physical layer impairments (PLIs) are usually categorized to linear and non-linear, according to their dependence on the power. However, when we consider IA-RWA algorithms it is useful to categorize the PLIs to those that affect the same lightpath (Class 1) and to those that are generated by the interference among lightpaths (Class 2). Table I presents this classification.

TABLE I: PHYSICAL LAYER IMPAIRMENTS CLASSIFICATION

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

IV. WORST-CASE VERSUS ACTUAL-CASE DESIGN OF TRANSPARENT NETWORKS IN THE PRESENCE OF PLIS

In this section we discuss ways that can be used to incorporate physical layer impairments (PLIs) into the RWA problem. PLIs of Class 1 depend only on the selected lightpath and can be treated quite easily. Assume that for a new connection request we can pre-calculate a set of candidate lightpaths, using some cost criterion. For each candidate lightpath we can calculate the effects of the PLIs of Class 1, using, e.g., analytical models, and discard those with unacceptable QoT performance.

PLIs of Class 2 are more difficult to be accounted for, since they make decisions for one lightpath depend on decisions made for other lightpaths. These computations, using analytical formulas, are time consuming for an online algorithm. Moreover, due to these impairments, the establishment of future connections may turn infeasible some previously established lightpaths. An obvious simplification is to consider a “worst case scenario”, that is, to assume that all wavelengths in the network are active, and calculate the worst case interference accumulated on each candidate lightpath. Then, the lightpaths that do not have acceptable QoT performance under this worst case assumption can be discarded, ensuring that the chosen lightpath is feasible, irrespectively of the actual utilization of the network. This approach does not choose the lightpath that is optimal for the current utilization of the network, but acts as if the network was fully utilized. In practice, the wavelength continuity constraint limits the maximum achievable network utilization, except for the degenerate case where all connections are between adjacent nodes. Thus, the key drawback of the worst case interference assumption is that it results in discarding candidate lightpaths that are not really infeasible. The actual feasibility or not of these lightpaths depends on the lightpaths that are active in the network.

To illustrate this, we quantify through an example case the degree to which the routing solution space is reduced when physical layer impairments are considered. We assume the generic Deutsche Telekom (DTnet) topology, shown in Figure 1, with physical layer parameters chosen to have realistic values. We have also used a quality of transmission evaluation module (Q-Tool) developed within the DICONET project [16] that uses analytical models to account for the most important physical layer effects and in particular all the physical layer impairments presented in Table I. We assume that there is a single connection request for each source-destination pair in the network for a total of $N(N-1)$ connection requests, where N is the number of nodes in the network. For this set of connection requests, we calculate, initially, k-shortest length paths, for different values of the parameter k, and then we prune this set of candidate paths using the Q-Tool by eliminating paths that are estimated to be infeasible. In doing so, we either assume an empty network, discarding lightpaths that are infeasible due to impairments of Class 1, or we assume a fully utilized network, discarding lightpaths that are infeasible due to impairments of Class 1 and of Class 2 under the worst case interference scenario. Table II shows that the path population obtained after eliminating candidate paths due to the impairments of Class 1 (column (b)) is considerably larger than that obtained when we use the worst case interference assumption for the impairments of Class 2 (column (c)).

An IA-RWA algorithm that assumes a worst-case interference and explores the solution space that corresponds to column (c), is expected to obtain zero physical-layer blocking, since lightpaths will only be rejected due to lack of available wavelengths (network-layer blocking). Moreover, it is guaranteed that the selected lightpaths will not become infeasible due to the establishment of future connections. However, such an algorithm explores a smaller solution space and unnecessarily restricts the RWA choices, when compared to an algorithm that takes into account the actual utilization state of the network and explores the solution space that corresponds to column (c). This may lead to deterioration in the performance of the IA-RWA algorithm that assumes a worst-case interference (higher network layer blocking). We will come back and quantify this performance difference later in this article.

TABLE II:
THE REDUCTION IN THE SOLUTION SPACE DUE TO PLIS OF CLASS 1 AND CLASS 2 (UNDER THE WORST CASE INTERFERENCE ASSUMPTION), FOR THE CASE OF THE GENERIC DT NETWORK TOPOLOGY AND THE REFERENCE TRAFFIC MATRIX.

	(a)Initial path population (k-shortest length paths)	(b)Population after discarding paths due to impairments of Class 1	(c)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

A. k-SP worst case IA-RWA algorithm

In this section we outline a simple IA-RWA that follows the worst case interference approach. We assume that for each source-destination pair, the algorithm pre-calculates a set of k-shortest length paths (k=5 in our simulation experiments). Using analytical models for all

PLIs described in Section III and under the worst case interference assumption the algorithm prunes the set of candidate paths so as to finally keep only the paths that have acceptable QoT performance (paths belonging to column (c) of Table II). The current network utilization state is only considered in order to identify the free wavelengths that are available to serve a new connection. In particular, when a new connection request for source-destination pair (*s*,*d*) arrives, the algorithm searches the candidate paths of (*s*,*d*) for free wavelengths and selects from the paths that have at least one available wavelength, the one that uses the path with the smallest number of hops, and from the wavelengths of that path, the wavelength that is utilized most in the network. This follows the *shortest-hop* and *most used wavelength* approach that is widely used in RWA algorithms [1].

B. k-SP current state IA-RWA algorithm

This algorithm again pre-calculates *k*-shortest length paths, but this time analytical models only for Class 1 impairments (see Table I) are used to prune the candidate path space (the path space corresponds to column (b) of Table II). Then the algorithm considers the current utilization state of the network and uses analytical models for Class 2 impairments (see Table I) to calculate the interference among lightpaths. The selection process of the lightpath is slightly altered. From the set of candidate lightpaths the algorithm selects the *shortest-hop*, *most used wavelength* lightpath that does not turn infeasible some of the already established lightpaths. Since the last criterion can be time consuming we set a limit to the number of lightpaths that are checked (this limit is set to 5 in the simulation experiments).

C. Multicost IA-RWA algorithm

Assuming that the network supports m wavelengths, the multicost IA-RWA algorithm presented in [5] uses the utilization state of the network in order to calculate a cost vector per link l that has $1+4 \cdot m$ cost parameters,

$$V_l = (d_l, \overline{G_l}, \overline{\sigma^2_{'1',l}}, \overline{\sigma^2_{'0',l}}, \overline{W_l}),$$

where $\overline{G_l}$, $\overline{\sigma^2_{'1',l}}$, $\overline{\sigma^2_{'0',l}}$ and $\overline{W_l}$ are vectors of size m that record the gain, noise variance of bit 1 and bit 0, and the utilization per wavelength. To calculate the noise variances of bit 1 and bit 0 for all wavelengths on all links we use analytical models to account for ASE, XT, XPM and FWM. These vectors can be calculated offline (in-between connections).

Similarly to the link cost vector, a path has a cost vector with $1+4 \cdot m$ parameters, in addition to the list of labels of the links that comprise the path. The cost vector of p can be calculated by the cost vectors of the links l=1,2,..,n, that comprise it as follows:

$$V_p = (d_p, \overline{G_p}, \overline{\sigma^2_{1,p}}, \overline{\sigma^2_{0,p}}, \overline{W_p}, {*p}) = \left(\begin{array}{l} \sum_{l=1}^{n} d_l, \sum_{l=1}^{n} \overline{G_l}, \sum_{l=1}^{n} \left(\overline{\sigma^2_{1,l}} \cdot \prod_{i=l+1}^{n} 10^{2 \cdot \overline{G_i}/10} \right), \\ \qquad \sum_{l=1}^{n} \left(\overline{\sigma^2_{0,l}} \cdot \prod_{i=l+1}^{n} 10^{2 \cdot \overline{G_i}/10} \right), \mathop{\&}_{l=1}^{n} \overline{W_l}, (1,2,\ldots,n) \end{array} \right).$$

Using this cost vector a path, we can calculate the Q factor of the available lightpaths over that path. To do so we use the noise variance vectors $\overline{\sigma^2_{'1',l}}, \overline{\sigma^2_{'0',l}}$ and account also for eye penalties (due to PMD, SPM/CD and FC). Eye penalties depend on the path (identified by the last parameter of the cost vector) and are calculated offline, in between connections.

The multicost algorithm consists of two phases:

Phase 1: In the first phase, the algorithm computes the set $P_{n\text{-}d}$ of non-dominated paths from the given source to all network nodes (including the destination). This algorithm can be viewed as a generalization of Dijkstra's algorithm that only considers scalar link costs. The basic difference is that instead of a single path, a set of non-dominated paths between the origin and each node is obtained. Two mechanisms are used to prune the solution space and reduce the running time of the algorithm. As the paths are extended by adding new links, we combine the cost parameters to calculate the Q-factor of candidate lightpaths and make unavailable those with unacceptable QoT. We also do not extend paths that have no free wavelengths. Finally, we use a domination relationship to prune paths that are worse with respect to all parameters than other calculated paths to the same end-node.

Phase 2: In the second phase of the algorithm we apply an optimization function or policy $f(V_p)$ to the cost vector, V_p, of each path $p \in P_{n\text{-}d}$. The optimization policy f has to be monotonic in each of the cost components, and yields a scalar cost per path and wavelength (that is, per lightpath) in order to select the optimal one. Various optimization policies that correspond to different IA-RWA algorithms are presented and evaluated in [5]. For this study we assume that we use the *shortest-hop*, *most used wavelength* policy, which is also used in the *k*-SP algorithms presented above. When making a routing and wavelength assignment decision, we check if the establishment of the new lightpath will turn infeasible some of the already established lightpaths. In case this happens, there are two options: (i) reroute the connections that are turned infeasible or (ii) resort to the second selection choice (the second best lightpath with respect to the optimization policy), and if this also turns some established lightpaths infeasible, resort to the third choice, and so on. To obtain a fair comparison, in this study we have assumed that we follow the latter approach and set a limit on the number of candidate lightpaths that are checked (in particular, in the simulation experiments the limit was set to 5). Note that in order to evaluate the effect of the new lightpath on the already established ones, we use the link cost vectors and the associated operators described above for a rapid and efficient way to perform this calculation.

The reason we use a multicost algorithm is threefold. The first is that we do not use complicated analytical formulas to account for the interference among lightpaths during the execution of the algorithm, but we pre-calculate the noise variances of each wavelength on each link and keep these values in cost vectors. The cost vector of each path is then calculated by combining the cost vectors of the links that comprise it, using simple and quick operations so that the algorithm runs fast. The second reason derives from the multicost algorithm's nature. The lightpaths calculated have, by the definition of algorithm operations, acceptable quality of transmission performance so the IA-RWA problem is solved in a joint manner. Third, having found the complete set of candidate lightpaths we can explore the whole lightpath space and apply any optimization policy when selecting the optimal solution.

In Section VI, we compare the performance, in terms of connection blocking and execution time, of the three online IA-RWA algorithms presented. Our results quantify the benefits of the actual interference approach.

V. Worst-Case versus Actual-Case Design of Translucent Networks in the Presence of PLIs

In this section we focus on translucent networks and on the number of regenerators required in such networks to serve a given traffic matrix, under the worst or actual interference assumptions. In translucent optical networks, regenerators are employed at some but not all the network nodes. Some of the connections established are routed transparently, while others, typically those served by lengthy paths, may need to utilize one or more regenerators to restore their signal's quality. The offline IA-RWA algorithms proposed for these networks decide the lightpaths but may also select the regeneration sites and the number of regenerators that need to be deployed on these sites, so as to serve the given traffic matrix.

In order to provision the network we compare two different approaches that are based on the same IA-RWA algorithm presented in [15]. In particular, we compare (i) a worst case interference IA-RWA algorithm, where the physical layer constraints are confronted by over-provisioning the network in terms of regenerators required, with (ii) an IA-RWA algorithm that calculates the actual interference among lightpaths, relaxing in this way the demand for regenerators at the cost of an increased algorithmic complexity. In both approaches a traffic matrix is given as the input to the algorithm and the number of regenerators required to serve this traffic is recorded as the output of the algorithm.

The IA-RWA algorithm we use under both the worst-case and the actual-case interference approaches, consists of three phases. In the first phase, the connection demands are distinguished into those that can be served transparently and those that are served using regenerators. In the actual interference approach, in order to find the pairs of transparently connected regeneration sites it is assumed that the network is empty and that only Class 1 impairments affect the QoT of the paths. In contrast, in the worst case interference approach, it is assumed that the network is fully loaded. In both approaches the quality of transmission evaluation estimator module (Q-Tool) developed within the DICONET project [16] is used for assessing the QoT of lightpaths. Next, the non-transparent connections are transformed into a sequence of transparent connections by routing them through a series of regenerators. To do so, the algorithm formulates a virtual topology problem. The virtual topology consists of the original network's regeneration sites, with (virtual) links between any pair of transparently connected regeneration sites. Each virtual link of the paths chosen in the virtual topology to serve a connection, corresponds to a transparent sub-path (lightpath) in the physical topology (Figure 3). The algorithms used for routing the non-transparent traffic demands in the virtual topology, are based on a *k*-shortest path algorithm, with link costs defined in two different ways:

1. *Virtual-Hop (**VH**) shortest path algorithm*. In this algorithm all the links of the virtual graph have cost equal to 1, and the cost of a virtual path is equal to the number of regenerators it crosses. The optimal virtual path is the one consisting of the fewest regenerators (virtual hops).
2. *Physical-Hop (**PH**) shortest path algorithm.* Here the cost of a virtual link is equal to the number of physical links (physical hops) it consists of. With this definition, the optimal virtual path is the one that traverses the minimum number of physical nodes.

Then the algorithm selects the routes to be followed by non-transparent connections by minimizing one of the following: i) the maximum number of regenerators used among all network nodes, or ii) the total number of regenerators used in the network, or iii) the number of regeneration sites. To perform this optimization, the virtual topology problem is formulated as an integer linear program (ILP).

By the end of the first phase the initial traffic matrix is transformed into a new traffic matrix whose source-destination pairs can, in principle, be transparently connected.

In the second phase, when the actual interference approach is followed, an IA-RWA algorithm for transparent networks is applied, with input the transformed transparent traffic matrix, in order find the RWA solution. On the other hand, in the worst interference approach, an impairment unaware RWA algorithm is applied. This is because the fully loaded network assumption applied in the first phase of the algorithm, results in all lightpaths having acceptable QoT. Finally, in the third phase of the algorithm, which is necessary only for the actual interference approach, the connections that were rejected in the second phase due to physical-layer blocking are rerouted through the remaining (unused in the first phase) regenerators.

In general, the CAPEX (Capital expenditure) and OPEX (Operational expenditure) of a translucent network depend not only on the number of wavelengths but also on the number of regenerator sites and regenerators used. The basic IA-RWA used [15], distinguishes between minimizing the maximum number of regenerators used among the sites and minimizing the total number of regenerators used or minimizing the number of regeneration sites. Each of these objectives can be used to obtain good solutions, depending on the criterion that we want to optimize. In addition, in our work, the use of the worst and the actual interference assumptions introduces a trade-off between the fast execution time and the over-provisioning of the resources on one hand and the higher execution time and efficient use of the available resources on the other. This trade-off is examined in the simulation results that follow.

VI. Simulation Experiments

In this section we compare the performance of the worst and the actual interference approaches under the transparent and translucent network scenarios.

A. Transparent Networks

We compared the performance of three online IA-RWA algorithms outlined in the previous section: (i) the *k*-SP worst-case-interference algorithm with *k*=5, (ii) the *k*-SP actual-interference algorithm with *k*=5, and (ii) the multicost algorithm. The topology used in our simulations was the DTnet topology of Figure 1, with capacity per wavelength assumed to be 10Gbps. The physical layer parameters were taken from deliverable D2.1 of Diconet [16]. We assumed *W*=16 available wavelengths per fiber link. We used a random traffic generator to produce connection requests according to a Poisson process (rate λ requests/time unit) with exponentially distributed durations (average $1/\mu$ time units) and uniformly distributed source-destination nodes. The network load is defined as λ/μ (in Erlangs). For each examined load 5000 connections were generated.

Figure 2(a) shows the blocking ratio as a function of the network load. The multicost algorithm exhibits the best blocking performance with the performance of the *k*-SP actual-interference algorithm coming quite close. The difference between the multicost and the *k*-SP actual-interference algorithm is due to the larger path space that the multicost algorithm explores. Typically, the multicost algorithm corresponds to the *k*-SP actual-interference algorithm with infinite *k*, with the path space adjusted and pruned precisely according to the utilization of the network and the QoT of the calculated lightpaths so as to have acceptable running time. On the other hand the difference between the *k*-SP worst-case-interference and *k*-SP actual-interference is more than one order of magnitude for light loads and decreases as the load increases. This is expected, since as the network load increases, the routing options that can be explored by the *k*-SP actual-interference algorithm are reduced due to the unavailability of wavelengths. Figure 2(b) shows the average execution time of the algorithms. As expected the average execution time of *k*-SP worst-case-interference algorithm is the lowest. However, from this graph we can see that the *k*-SP actual-interference and the multicost algorithms also have acceptable execution time that is kept less than 0.15 sec. This good running time is due to the sophisticated and quick way that we use to evaluate the interference among lightpaths and the limit we have set on the repetition of this process.

B. Translucent Networks

We carried out a number of simulation experiments, evaluating the performance of several offline IA-RWA algorithms for translucent networks under both the worst interference assumption and the actual interference assumption. The network topology used in our simulations was the Geant-2 network, shown in Figure 3, which is a candidate translucent network, as identified by the DICONET project [16] with 34 nodes and 54 bidirectional links (for our simulations we assumed 108 directional links) and a realistic traffic matrix considered of a total of 400 connections. We assumed *W*=80 available wavelengths per fiber link. All single-hop connections were able to be served transparently, but some multi-hop connections were not, making the use of regenerators necessary. We assumed that the number of regeneration sites is not restricted; that is, every node is capable of accommodating regenerators. It was up to the proposed algorithms to solve the regeneration placement problem, in order to decide the regeneration sites and the number of regenerators to deploy on each site.

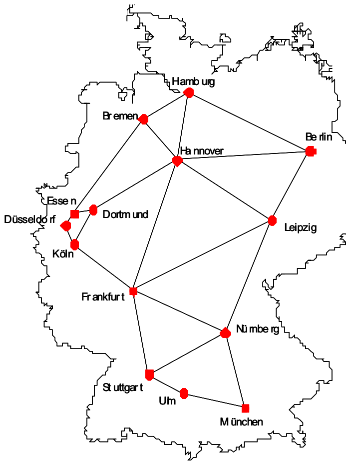

Figure 1: DTnet topology used in the simulation experiments.

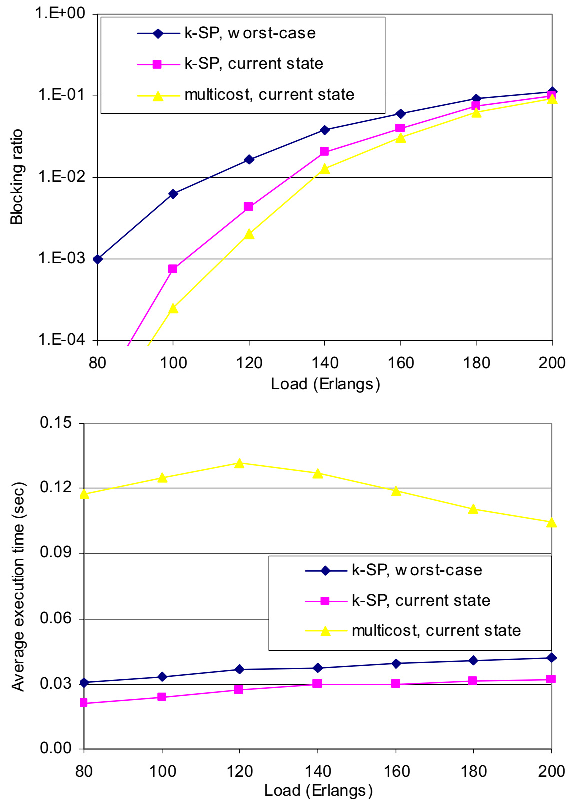

Figure 2: (a) Blocking ratio and (b) average execution time as a function of network load assuming *W*=16 available wavelengths

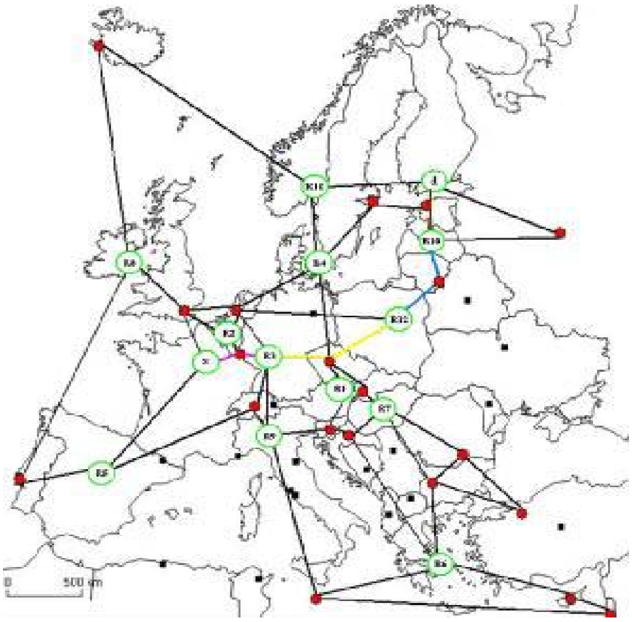

Figure 3: The non-transparent connection request between source-destination pair (*s*, *d*) can be broken into four transparent sub-path requests: *s-R3*, *R3-R12*, *R12-R10 and R10-d*. Each of the three sub-path requests can be served using a different wavelength.

In Figure 4 we graph the total number of regenerators and the total number of regeneration sites required in the network, to reach zero blocking. The performance of each algorithm is closely related to the metric it minimizes. In our results we observe that the PH-based algorithms need a smaller number of wavelengths to reach zero blocking, but utilize more regenerators and regeneration sites. On the other hand, the VH-based algorithms need more wavelengths to reach zero blocking, but make better use of the regenerators. In particular, PH algorithms calculate paths that minimize the number of physical hops utilized, which tends to give good wavelength utilization performance, since shorter physical hop paths utilize less links/wavelengths. This is the reason shorter physical hop paths are widely used in pure (without impairments) RWA problems. However, these paths are not directly related to the virtual topology and thus the ILP algorithm that runs over the virtual topology does not produce the best results in relation to its objectives (minimization of the regenerators). On the other hand, the VH-based algorithms use as input virtual paths, which are not related to the physical topology. As a result, the ILP algorithm, though it places efficiently regenerators in the network, it selects longer physical hop paths that waste wavelength resources.

Moreover, as depicted in Figure 4 the IA-RWA algorithms for translucent networks that use estimates of the actual interference exhibit better performance when compared to the algorithms that provision the network under the worst interference assumption. The worst interference-based algorithms need to use considerably more regenerators (more than twice and in many cases even more) in order to satisfy the same demand matrix. The difference in the required number of regenerators can be explained as follows. Algorithms under the worst interference assumption, overuse the available resources in order to minimize the physical layer blocking, since they are based on a quite pessimistic assumption that will only occur if the network is fully loaded. On the other hand, by using the actual interference approach, network over-provisioning is relaxed and make better usage of the network resources. Based on the results of Figure 4, it is beyond any doubt that using sophisticated algorithms for network provisioning that account for the interference among lightpaths is an efficient way to reduce the waste of resources.

With respect to execution times, for offline traffic that pertains to the planning phase of the network, there are no strict time requirements. Since the problem is NP-hard, acceptable running time usually means that we are able to track solutions, which is particularly difficult for large NP-hard problems. In our case, a time limit of a few hours (5 hours) was set for all offline experiments and the execution time of the IA-RWA algorithms under the actual interference assumption were always within limit.

VII. CONCLUSIONS

Due to certain physical effects, routing decisions made for one lightpath affect and are affected by decisions made for other lightpaths. To establish a lightpath for a new connection we explored two approaches. One approach is to select a lightpath that has acceptable quality of transmission (QoT) under the worst case interference assumption, guaranteeing that the lightpath will be feasible independently of the establishment of future connections. This approach is appealing because of its simplicity and the fact that it does not require any

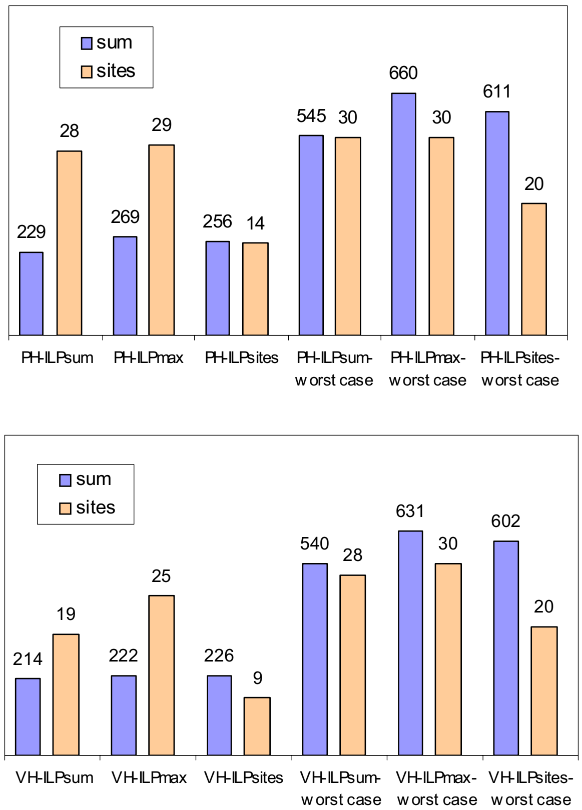

Figure 4: Total number of regenerators and total number of regeneration sites for 400 connection demands, *W*=80 available wavelengths and unrestricted regeneration sites. (a) PH and (b) VH based algorithms.

checks on the effect the establishment of a new connection will have on existing connections; however, it tends to overuse the wavelength and regenerator resources. The second approach is to take into account the current network utilization and perform a cross layer optimization between the network and physical layers. The second approach explores a larger path space and performs significantly better, in terms of blocking ratio and resources utilized, than algorithms that follow the worst case interference approach, but has increased complexity. We proposed and evaluated sophisticated techniques that follow the second cross-layer optimization approach. Our results indicated that we can keep the execution times low, comparable to those of algorithms that follow the worst-case assumption, and also obtain significant performance benefits.

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