Cross Layer RWA in WDM Networks: is the Added Complexity Useful or a Burden?

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ABSTRACT

In transparent wavelength routed optical networks, the signal quality degrades due to physical layer impairments. Certain physical effects make routing decisions made for one lightpath affect and be affected by the decisions for other lightpaths. To safely 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 the worst case interference assumption. This ensures that the selected lightpath will not become infeasible due to the possible establishment of future interfering connections, but it sacrifices candidate path space for a quick and stable lightpath selection process. The second approach is to consider the actual current network utilization and account for the interference among lightpaths so as to perform a cross layer optimization between the network and physical layers. In the latter approach, the algorithm has to evaluate and check if 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 obtained through the second approach are worth the added complexity introduced by the cross-layer optimization required.

Keywords: Routing and Wavelength Assignment, transparent all optical networks, physical layer impairments, online (dynamic) traffic.

1. INTRODUCTION

We consider the dynamic version of the RWA problem in WDM optical networks where connection requests arrive at random time instances and are served on a one-by-one basis. The typical objective of this problem is to reduce the blocking ratio over an infinite time horizon. In transparent or translucent WDM networks call blocking may occur due to (i) the non-availability of a free wavelength due to the wavelength allocation of existing connections (*network-layer blocking*) and (ii) the physical layer impairments, introduced by the non-ideal physical layer, which may degrade the signal quality to the extend that the lightpath is infeasible (*physical-layer blocking*).

The need to account for the physical impairments constrains the kinds of paths that can be used for routing. To address this problem a number of approaches are emerging, usually referred to as impairment-aware (IA)-RWA algorithms. Due to certain physical layer effects, routing decisions made for one lightpath affect and are affected by the routing decisions made for the other lightpaths. This interdependence between the physical and the network layers makes the RWA problem in the presence of physical impairments a cross-layer optimization problem.

An important distinction is how the IA-RWA algorithms define the interaction between the networking layer and the physical layer, and if they try to jointly optimize the solutions over these two layers. Various IA-RWA algorithms for online traffic have been proposed in the literature [2]-[5]. In [2] the authors decouple the RWA and the IA subproblems, decide on the lightpath to serve a connection (RWA subproblem) and then evaluate 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 quality of transmission (QoT) is presented. An IA-RWA algorithm that is based on a shortest path or shortest widest path and uses analytical formulas to estimate the QoT of each candidate lightpath is presented in [4]. The multicost algorithm presented in [5] solves the IA-RWA problem jointly and takes into account the interference among the lightpaths, using the current network utilization to calculate noise variance vectors per wavelength that are assigned to the links of the network. Using these cost vectors as input and by defining appropriate associative operators to combine link parameter vectors so as to obtain corresponding path parameter vectors, the algorithm calculates the Q factor of candidate lightpaths as it is executed, and uses it to prune the paths that do not have acceptable transmission quality. In the end, it obtains a set of non-dominated paths from the source to the destination that all have acceptable QoT performance.

There are two approaches to address the online IA-RWA problem while accounting for the interference among lightpaths. In the first approach, to serve a new connection request a lightpath is selected under a worst case interference assumption, assuming that all wavelengths on all links are fully utilized and calculating the transmission quality of the candidate lightpaths under this assumption. A lightpath that is chosen in this way is bound to have acceptable transmission quality during its entire duration, even if future connections that interfere with it are established. However, such an approach reduces the candidate path space and may results in a larger blocking probability for a given number of available wavelengths. On the other hand, cross-layer optimization algorithms that use the current network utilization to account for the actual interference among lightpaths are able to explore a larger path space. The drawback of this second approach is that the problem becomes more complicated, since the actual inter-lightpath interference has to be modelled in the RWA algorithms, and the algorithm also has to evaluate if the establishment of the 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.

2. PHYSICAL IMPAIRMENTS AND QUALITY OF TRANSMISSION

Several criteria can be used to evaluate the signal quality of a lightpath but the Q-factor seems to be more suitable to be integrated in an RWA algorithm, because of its immediate relation to the bit error rate. 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, based on the way they 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 and to those that are generated by the interference among lightpaths:

- **Class 1** - Impairments that affect 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).

3. CONSIDERING PHYSICAL LAYER IMPAIRMENTS IN RWA

In this section we discuss ways that can be used in order to incorporate PLIs into the RWA problem. PLIs that belong to Class 1 depend only on the selected lightpath and can be accounted for quite easily. Assume that for a new connection request we can pre-calculate a set of candidate lightpaths and then select an appropriate one from this set to serve the request. Then, for each candidate lightpath we can calculate the effects of the PLIs of Class 1, using, for example, analytical models, and discard those that have unacceptable QoT performance.

PLIs that belong to Class 2 are more difficult to be accounted for because 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 of the 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. However, this approach does not choose the lightpath that is optimal for the current network state, 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, but their feasibility depends on the utilization of the network.

To illustrate this, we quantify through an example the degree to which the routing solution space is reduced when PLI are considered. We assume the generic Deutsche Telekom topology, shown in Figure 1(a), 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 [6] that uses analytical models to account for the most important physical layer effects. We assume that there is a single connection request for all source-destination pairs 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 considered 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 1 shows that the path population obtained after eliminating candidate paths due to the impairments of Class 1 (column (b)) is considerably larger than when we use the worst case interference assumption for the impairments of Class 2 (column (c)).

	(a) Initial 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 of Class 2 - assuming worst case interference
k=1	182	182	182
k=3	546	528	427
k=5	910	751	506

Table 1: The reduction in the solution space due to the PLIs of Class 1 and Class 2 (under the worst case interference assumption), for the case of the generic DT network topology, considering single wavelengths requests between all source-destination pairs.

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.

3.1 *k*-SP worst case IA-RWA algorithm

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. Then, under the worst case interference assumption the algorithm prunes the set of candidate paths so that it finally keeps only the paths that have acceptable QoT performance (corresponds to column (c) of Table 1). The current utilization network 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 between source-destination pair arrives, the algorithm searches its candidate paths for free wavelengths and selects from the paths that have at least one available wavelength, the path that uses 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 path/most used wavelength approach that is widely used in dynamic RWA algorithms [1].

3.2 *k*-SP current state IA-RWA algorithm

This algorithm uses again *k*-shortest length pre-calculated paths, but this time the set of paths is pruned by considering the physical impairments that belong to class 1 (corresponds to column (b) of Table 1). Then the algorithm considers the current utilization state of the network and uses analytical models 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 one that has the shortest hop path, the most used wavelength, and does not turn infeasible some of the already established lightpaths.

3.3 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,

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

where $\overline{G_l}$, $\overline{s^2_{'1',l}}$, $\overline{s^2_{'0',l}}$ 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. 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:

$$V_p = (d_p, \overline{G_p}, \overline{s^2_{1,p}}, \overline{s^2_{0,p}}, \overline{W_p}, {*p}) = \left(\sum_{l=1}^{n} d_l,\ \sum_{l=1}^{n} \overline{G_l},\ \sum_{l=1}^{n} \left(\overline{s^2_{1,l}} \cdot \prod_{i=l+1}^{n} 10^{2\cdot \overline{G_i}/10} \right), \sum_{l=1}^{n} \left(\overline{s^2_{0,l}} \cdot \prod_{i=l+1}^{n} 10^{2\cdot \overline{G_i}/10} \right), \underset{l=1}{\overset{n}{\&}} \overline{W_l}, (1,2,\dots,n) \right),$$

The multicost algorithm consists of two phases:

Phase 1: In the first phase, the algorithm computes the set 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 in order to calculate the Q factor of candidate lightpaths and make unavailable those that do not have acceptable QoT. We then stop extending the paths that do not have at least one free wavelength. We also use a domination relation to prune paths that are worse in 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 computed in Phase 1. The optimization policy *f* yields a scalar cost per path and wavelength (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, also used in the *k*-SP algorithms presented above. When choosing a new lightpath, we check if its establishment turns 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, we assumed that we follow the latter approach and set a limit on the number of candidate lightpaths that are checked (limit=5 in the simulations). 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 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, but we pre-calculate the noise variances of each wavelength on each link to form cost vectors. The cost vector of each path is then calculated by combining the cost vectors of the links that comprise it, using simple associative operations so that the algorithm runs fast. The second reason derives from the multicost algorithm's nature. The lightpaths calculated have, by definition, acceptable QoT so the IA-RWA problem is solved in a jointly manner. Third, having the complete set of candidate lightpaths we explore the whole lightpath space and we can apply any optimization policy when selecting the solution.

4. SIMULATION EXPERIMENTS

We compared the performance of three 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 generic DTnet topology of Figure 1(a), with capacity per wavelength assumed to be 10Gbps. We used a random traffic generator to produce connection requests according to a Poisson process with exponentially distributed durations and uniformly distributed source-destination nodes.

Figure 1(b) 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 1(c) 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 of the multicost algorithm is due to the quick way that we use to evaluate the interference among lightpaths and the limit we have set on the repetition of this process.

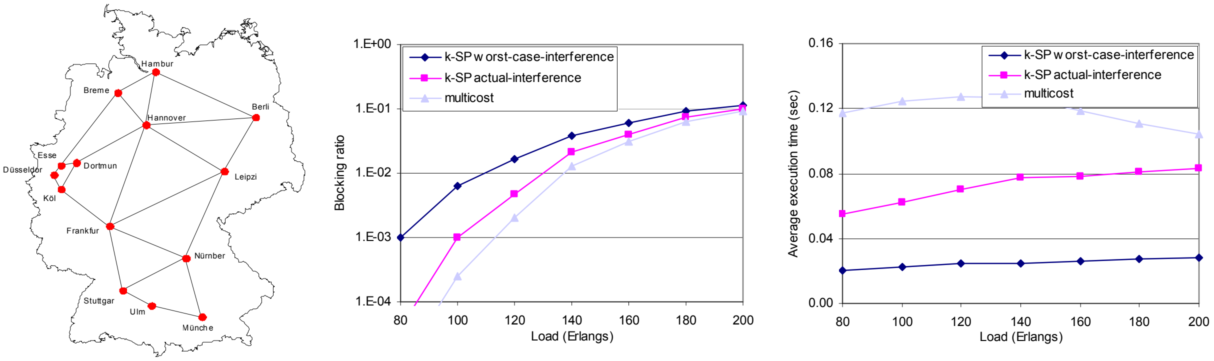

Figure 1: (a) DTnet topology used in the simulation experiments. (b) Blocking ratio and (b) average execution time as a function of network load assuming *W*=16 available wavelengths.

5. CONCLUSIONS

Due to certain physical effects, routing decisions made for one lightpath 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 QoT under the worst case interference assumption, guaranteeing that the lightpath will be feasible independently of the establishment of future connections. 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 than an algorithm that assumes a worst case interference, while sophisticated techniques can keep the execution time low and acceptable. The added complexity of the second approach seems to be justified by the performance benefits obtained.

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