Multi-Parametric Online RWA based on Impairment Generating Sources

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Abstract—**We propose and evaluate an impairment-aware multi-parametric routing and wavelength assignment algorithm for online traffic in transparent optical networks. In such networks the signal quality of transmission degrades due to physical layer impairments. In the multi-parametric approach, a vector of cost parameters is assigned to each link, from which the cost vectors of candidate lightpaths are calculated. In the proposed scheme the cost vector includes impairment generating source parameters, such as the path length, the number of hops, the number of crosstalk sources and other inter-lightpath interfering parameters, so as to indirectly account for the physical layer effects. For a requested connection the algorithm calculates a set of candidate lightpaths, whose quality of transmission is validated using a function that combines the impairment generating parameters. For selecting the lightpath we propose and evaluate various optimization functions that correspond to different IA-RWA algorithms. Our performance results indicate that the proposed algorithms utilize efficiently the available resources and minimize the total accumulated signal degradation on the selected lightpaths, while having low execution times.**

I. INTRODUCTION

In WDM optical networks data are transmitted through *lightpaths*; that is, all-optical channels that may span multiple consecutive fibers. From the network perspective, the problem of establishing a lightpath for a connection request is transformed to the problem of selecting a route (path) and a free wavelength. This problem is called *routing and wavelength assignment* (abbreviated RWA) problem. The objective of the RWA operation is to minimize the network resources used or maximize the traffic served with limited network resources. When no lightpath can be found to serve a connection, the connection is blocked, resulting in a *network-layer blocking*.

The majority of RWA algorithms proposed in the literature assume an ideal physical layer where signal transmissions are considered to be error-free. This is the case in opaque networks, where the signal is regenerated at each intermediate node along a lightpath via optical-electrical-optical (OEO) conversion. The network cost could be reduced in a translucent network where regenerators are only employed at some nodes. The ultimate goal is the development of an all-optical transparent network, where a data signal remains in the optical domain for the entire lightpath. However, in such network the quality of transmission (QoT) of the signal degrades due to physical layer impairments [1][2]. In particular, 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, resulting in a *physical-layer blocking*.

The RWA problem is usually considered under two alternative settings. *Static* or *offline* lightpath establishment addresses the case where the set of connections is known in advance and are jointly served and optimized. This problem usually appears in the planning phase of an optical network. *Dynamic* or *online* lightpath establishment considers the case where connection requests arrive at random time instances and are served on a one-by-one basis. This problem is important during network operation. In this study we will focus on the online RWA problem where the execution time of the algorithm is important since it determines the connection establishment delay. As a result it is desirable that an online impairment aware (IA)-RWA algorithm is able to handle efficiently and quickly both *physical- and network-layer blocking.*

The online IA-RWA algorithms we propose in this paper follow the *multi-parametric* or *multi-cost* approach, which is significantly more powerful than single-cost routing. In traditional single-cost routing each link is characterized by a scalar cost. On the other hand, in the multi-parametric approach a vector of cost parameters, which are related to different QoS parameters, is assigned to each link. Then, by defining appropriate operations between these cost parameters, we can calculate the cost vector of a path. In multi-parametric algorithms, operators like minimization and maximization can be used, something that is not possible in the single-cost approach. Moreover, single-cost routing calculates a single path between two nodes that optimizes a single-cost criterion, while in the multi-parametric approach more than one paths between two nodes are calculated, since the optimization parameters are more than one.

In the proposed multi-parametric scheme the cost vector of a path includes the utilization of wavelengths so as to be able to calculate the available lightpaths over that route. Moreover, the cost vector includes impairment generating source parameters, such as the path length, the number of hops, and various inter-lightpath interferer sources, so as to indirectly account for the physical layer effects. We propose and evaluate various optimization functions that correspond to different IA-RWA algorithms. The lightpaths calculated by our multi-parametric scheme are evaluated, in terms of physical layer blocking, using a function that combines these cost parameters. A lightpath is rejected if the value produced by the function is larger than a predefined threshold, which characterizes the lightpaths with acceptable QoT.

Generally, most of the related works choose lightpaths using analytical formulas and models in order to calculate the QoT of the candidate lightpaths. In contrast, in our proposed Multi-Parametric schemes we record parameters related to the impairment generating sources, and combine them in a function that we use as a measure of the QoT of the candidate lighpaths. The main benefits of this approach originate from the fact that these parameters are more easily and quickly calculated and also that they are independent of the modulation format used and the rate of each wavelength. Moreover, the function that we use to combine these parameters is more

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easily modeled and can also be adapted to an operational WDM network based on feedback provided by monitors.

We perform a number of experiments where we show that the proposed Multi-Parametric algorithms utilizes efficiently the available resources and minimize the total accumulated signal degradation on the selected lightpaths, thus, dramatically reducing the overall physical- and network-layer blocking. We also show that it is possible to preserve QoT without the need of a QoT estimator, by appropriately designing the algorithm. Moreover, the execution time of the proposed algorithms is kept at low levels, making these algorithms applicable to serve online traffic.

The rest of the paper is organized as follows. In Section II we report on previous work. In Section III we give a short description of the physical layer impairments. We identify the impairment generating sources from a network perspective and define appropriate parameters to be used in our algorithms. In Section IV we present the Multi-Parametric scheme and describe several variations. Simulation results are presented in Section V. Our conclusions are given in Section VI.

II. Related Work

RWA algorithms have been extensively examined in the literature. Regarding offline RWA, which is known to be a NP-hard optimization problem [3], few impairment-aware algorithms have been proposed, since the interference among channels is hard to formulate in a combinatorial optimization problem [4]. On the other hand, in online algorithms the utilization of the network is known or can be found when a new connection request arrives. Thus, analytical models or other approaches can be used for estimating the effect of the physical impairments on a candidate lightpath solution.

The effects of amplified spontaneous emission noise and crosstalk on online RWA are examined in [6]. An impairment aware (IA)-RWA algorithm that uses a separate module to estimate the OSNR and PMD of a candidate lightpath is presented in [7]. A dynamic and adaptive QoS routing algorithm, based on real-time Q factor measurements from monitors is presented in [8]. Each link is assigned a Q factor related metric and shortest-path algorithms are then applied. However, inter-lightpath interference and the effect of the newly established lightpaths on existing lightpaths is not taken into account. [9] evaluates two path establishment algorithms that are variations of the shortest path and the shortest widest path algorithms, with link costs being any of the physical parameters. Analytical formulas are used to estimate the Q factor of the chosen lightpath. In [10], an adaptive IA-RWA algorithm that models as noise the most important physical impairments and assign additive noise variance parameters per link is proposed.

In general, multi-cost and multi-constrained algorithms have been used for QoS routing problems [12]. A multi-cost approach with cost parameters being the OSNR, the number of free wavelengths, and the link cost, is presented in [11]. The proposed approach sends control packets over candidate paths that acquire multi-cost-related information at the intermediate nodes. The main differences of our approach to [11] is that, in our case, the choice of the lightpath is performed at the source, and we also take into account parameters such as the interference among the channels that are important and are neglected in the OSNR approach adopted in [11].

In [5] we investigated dynamic IA-RWA algorithms that use complex formulas in order to take directly into account the effects of the physical impairments, by calculating the Q factor of the candidate lightpaths. On the other hand, in this work, we use a multi-parametric approach that considers impairment generating source parameters, such as the path length, the number of hops, the number of crosstalk and other inter-lightpath interferer sources. In this way, the quality of transmission (QoT) of each lightpath is characterized by several cost parameters that do not measure directly the impairments, but the sources that generate them. These parameters can be quickly and accurately calculated, taking into account the current utilization of the network, which changes as new connections are established or released. Compared to [5], this approach is more generic, more easily applicable to different conditions (topologies, modulation formats, transmission rate) and does not use specific models for the impairments or known impairment-parameters.

To calculate if a lightpath is feasible certain assumptions have to be made for the modulation format and the transmission rate, since a number of physical layer parameters have to be accurately known in order to use specific analytical models. As a result these analytical models have to change when these parameters also change. This may be undesirable, both for current networks where the operation of different layers should remain independent, so that changes in one layer do not (significantly) affect the other and for future networks where parameters like modulation and rate will be more easily tunable and decided upon the routing process.

III. Physical impairments and Quality of transmission

In transparent WDM networks the signal quality degrades due to the non-ideal physical layer [1][2]. Linear and non-linear physical layer impairment can be categorized to those that affect the same lightpath that generated them, and to those that affect and are affected by the other lightpaths:

- **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),
- **Impairments that are generated by other lightpaths**: Crosstalk (XT) (intra-channel and inter-channel crosstalk), Cross-Phase Modulation (XPM), Four Wave Mixing (FWM).

The second class of impairments is more difficult to deal with in RWA algorithms, since, because of these impairments, decisions made for setting up one lightpath affect and are affected by decisions made for other lightpaths.

A. *Quality of transmission, BER and Q factor*

There are several criteria that could be used to evaluate the signal quality of a lightpath. Bit-error ratio (BER) is a very appropriate criterion because it is a comprehensive parameter that takes all impairment effects into consideration. The Q-factor is the electrical signal-to-noise ratio at the input of the decision circuit in the receiver's terminal, and, under the assumption of Gaussian shaped noise, is related to the system's BER through the function:

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

Thus, the higher the Q-factor value the smaller the BER and the better the quality of the signal. Q factor is not readily

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available before a lightpath is actually set up. Instead, models of physical-layer impairments can be used to estimate the BER or the Q factor in advance. Various analytical models for the linear and nonlinear impairments have been proposed in the literature and different methodologies exist for calculating the Q-factor.

B. *Impairment Generating Parameters*

Calculating the quality of transmission (QoT) through models for the physical impairments and the Q factor, can be quite difficult and time consuming. For this reason in this work we are interested in identifying and measuring the network parameters that generate the impairments, which we call impairment generating parameters, so as to indirectly account for the physical layer effects.

Assuming a lightpath (p,w), that is wavelength w on path p, we have identified the following parameters that might affect the signal quality of this lightpath: (i) the path's length (L_p), (ii) the number of hops of the path (H_P), (iii) the number of active adjacent channels (A_{pw}) of wavelength w across all the links of the lightpath, (iv) the number of active second adjacent channels (SA_{pw}) of wavelength w across all the links of the lightpath, (v) the number of intra-channel crosstalk sources (X_{pw}), which is the number of lightpaths crossing the same switches and utilizing the same wavelength w along the lightpath.

It is worth noting that the aforementioned parameters, (i) - (v) above, are the key parameters for the majority of the physical impairments [1][2]. More specifically, amplified spontaneous emission (ASE) noise depends on the number of amplifiers, which is related to the length of the links, and the number of hops (switches). Chromatic dispersion (CD), self-phase modulation (SPM) and polarization mode dispersion (PMD) also depend on the length of the path. Filter concatenation (FC) depends on the number of filters over the path and thus it mainly depends on the number of hops and possibly the length of the path. Moreover, all the network parameters that act as sources for the inter-lightpath interference effects are accounted for in the parameters A_{pw}, SA_{pw} and X_{pw}. Although the above physical impairments do not all depend linearly on the parameters discussed, it is expected that trying to reduce these parameters would decrease the effect of all impairments.

To explain how we formulate the interference among lightpaths we present in Figure 1 an example for the effect of the adjacent channel interference. A lightpath p from n_0 to n_4 is established using wavelength w. Let (p',w+1) be a lightpath that crosses links l_2 and l_3, and (p'',w-1) be a lightpath that crosses links l_3 and l_4. In this example there are in total A_{pw}=4 adjacent channel interfering sources affecting the signal quality of lightpath (p,w). We can observe that we can count the number of adjacent channel interferer sources by knowing the current state of the network. In a similar manner we can calculate the sources for the other interference related effects.

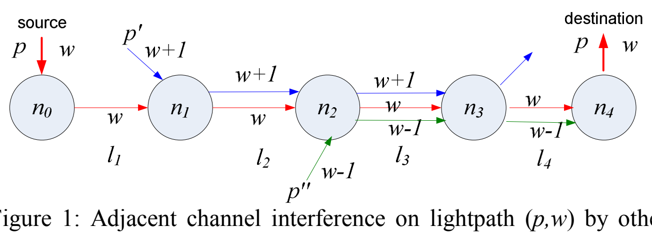

Figure 1: Adjacent channel interference on lightpath (p,w) by other lightpaths.

Having identified the impairment generating parameters of lightpath (p,w) we can map its quality of transmission performance (TP) with a function f as follows:

$$TP(p,w) = f(L_p, H_p, A_{pw}, SA_{pw}, X_{pw}) .$$

The function f can be chosen as to take into account specific impairment related characteristics of the network. For example, in a network where intra-channel crosstalk is low, X_{pw} can be neglected or included with a very small weight. In this work, we used a function f that adds almost all the parameters of interest, normalizing them when needed:

$$TP(p,w) = c_1 \cdot L_p + c_2 \cdot H_p + c_3 \cdot A_{pw} + c_4 \cdot SA_{pw} + c_5 \cdot X_{pw} \quad (1)$$

where c_i's are coefficients that are used to declare the relative importance of each parameter (impairment). Assuming that $c_i<c_j$, the parameter multiplied by the coefficient c_j is more important and contributes with a higher weight to the *TP* metric than the parameter multiplied by c_i. Moreover, the definition of the *TP* metric can change so as to include various physical layer parameters that differ from one link to the other [15]. We can use the above function and a threshold $TP_{\max}$ in order to decide if a lightpath has acceptable transmission performance or not. One could argue that it may be more beneficial to measure each impairment source separately and have a different threshold for each one of them. This choice is not ruled out and can also be applied in our Multi-Parametric algorithm. However, we believe that this approach will not be efficient, since this way it is possible to discard paths based only on a single bad parameter, even though the rest are very good. As our performance experiments indicate, a single metric (*TP*) and a single threshold ($TP_{\max}$) are quite efficient, in order to measure and preserve the QoT of the ligthpaths.

IV. Multi –Parametric Impairment Aware Online RWA

The proposed multi-parametric algorithms consist of four phases that are divided in two basic and two optional phases (Figure 2) that will be analyzed in the subsequent subsection. In contrast to traditional single-cost approach, where each link is characterized by a scalar, in the multi-parametric approach a vector of cost parameters is assigned to each link, from which the parameter vectors of candidate lightpaths are calculated.

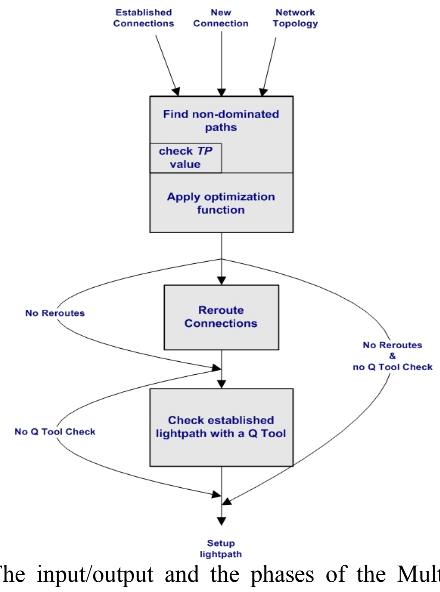

Figure 2: The input/output and the phases of the Multi-Parametric algorithm.

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A. Computing the cost vector of a path

We consider a WDM network with N nodes and L links, each of which carries m wavelengths, $\lambda_1, \lambda_2, \ldots, \lambda_m$. The WDM network employs no wavelength conversion. We also assume that the node where the algorithm is executed (in a decentralized or centralized architecture) has a picture of the wavelengths' utilization of all links. Although the algorithm may run in a decentralized way, and thus due to propagation delays utilization information might be outdated, we will not focus on such problems.

1) Cost vector of a link

Each link l is assigned a cost vector that contains $2+5 \cdot m$ cost parameters:

(i) the delay of the link, or equivalently, its length L_l (scalar);

(ii) the hop count of the link, H_l (scalar), which is by definition equal to 1 (but it will help us to count the number of hops of a path);

(iii) a vector $\overline{A_l}=(a_{l1},a_{l2},\ldots,a_{lm})$ whose i^{th} element a_{li} records the number of active adjacent channels on wavelength i of the link;

(iv) a vector $\overline{SA_l}=(sa_{l1},sa_{l2},\ldots,sa_{lm})$ whose i^{th} element sa_{li} records the number of active second-adjacent channels on wavelength i of the link;

(v) a vector $\overline{X_l}=(x_{l1}, x_{l2},\ldots,x_{lm})$ whose i^{th} element x_{li} contains the number of intra-channel generating sources at the switch that link l ends;

(vi) the availability of wavelengths in the form of a Boolean vector $\overline{W_l}=(w_{l1}, w_{l2},\ldots,w_{lm})$, whose i^{th} element w_{lm} is equal to 0 (false) if wavelength λ_i is used and equal to 1 (true) when λ_i is free.

Thus, the cost vector characterizing a link l is given by

$$V_l = (L_l, H_l, \overline{A_l}, \overline{SA_l}, \overline{X_l}, \overline{W_l}).$$

2) Cost vector of a path

Similarly to a link, a path has a cost vector with $2+5 \cdot m$ parameters, in addition to the list of labels of the links that comprise the path. Assume a path p with cost vector

$$V_p = (L_p, H_p, \overline{A_p}, \overline{SA_p}, \overline{X_p}, \overline{W_p}, *p),$$

where L_p, H_P, $\overline{A_p}$, $\overline{SA_p}$, $\overline{X_p}$, and $\overline{W_p}$ are as previously described, and $*p$ is the list of identifiers of the links that comprise path p. The cost vector of p can be calculated by the cost vectors of the links l=1,2,..,k, that comprise it as:

$$V_p = \left(\sum_{l=1}^{k} L_l, \sum_{l=1}^{k} H_l, \sum_{l=1}^{k} \overline{A_l}, \sum_{l=1}^{k} \overline{SA_l}, \sum_{l=1}^{k} \overline{X_l}, \underset{l=1}{\overset{k}{\&}} \overline{W_l}, (1,2,\ldots,k) \right),$$

where the operator & denotes the bitwise AND operation. Note that all operations between vectors have to be interpreted component-wise and that by definition $H_p=k$.

3) Checking the TP values of intermediate lightpaths

For a path p, we check if the available lightpaths of that path (marked by 1 in vector $\overline{W_p}$) have a TP value that it is smaller than a predefined threshold $TP_{\min}$. In particular, given vector V_p we use Eq. (1) to obtain the TP value of each lightpath, that is the vector $\overline{TP_p}=(TP_{p,1}, TP_{p,2},\ldots,TP_{p.m})$. For those lightpaths that do not satisfy the threshold we set the corresponding index of the utilization vector $\overline{W_p}$ equal to zero. In other words, we make these wavelengths unavailable due to poor performance and not due to their being used by another lightpath. Note that we have assumed that the quality of the signal always decreases as we move down a path. Other approaches, that can increase the signal quality later in the lightpath have to be treated differently (in that case a subpath not satisfying the threshold may satisfy it later when it is extended). However, in a dynamic transparent network such approaches are not usually adopted due to the dynamic nature of the traffic, and thus compensation is usually performed on a per hop basis.

We then check if path p has at least one available wavelength. If $\overline{W_p} = \mathbf{O}$ (all zero vector), path p is rejected.

4) Domination relationship

We also define a *domination* relationship between two paths that can be used to reduce the number of paths considered by the multi-parametric algorithm. In particular, we will say that

p_1 dominates p_2 (notation: $p_1 > p_2$) **iff**

$$L_{p_1} \le L_{p_2} \text{ and } H_{p_1} \le H_{p_2} \text{ and } \overline{W_{p_1}} \ge \overline{W_{p_2}} \text{ and } \overline{A_{p_1}} \le \overline{A_{p_2}} \text{ and } \overline{SA_{p_1}} \le \overline{SA_{p_2}} \text{ and } \overline{X_{p_1}} \le \overline{X_{p_2}} \quad (2)$$

The "$\ge$" relationship for vectors $\overline{W}$, $\overline{A}$, $\overline{SA}$, $\overline{X}$ should be interpreted component-wise. A path that is dominated by another path, has worse delay, wavelength availability, and QoT than the other path, and there is no reason to consider it or extend it further.

B. Multi-Parametric Impairment Aware Online RWA Algorithm

The multi-parametric impairment aware online routing and wavelength assignment algorithm we propose consists of four phases, two basic and two optional.

1) Phase 1: Computing the set of non-dominated paths P_{n-d}

The algorithm that computes the non-dominated paths from a given source to all network nodes (including the destination) 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. Thus a node for which one path has already been found is not finalized (as in the Dijkstra case), since we can find more "non-dominated" paths to that node later. An algorithm for obtaining the set P_{n-d} of non-dominated paths from a given source to all nodes is given in [13]. The differences from the algorithm of [13] are that the domination relationship that is used is the one given in Eq. (2), and that we check the TP values of the wavelengths (Section III.A.3) before applying the domination relations.

By definition, for the given source and destination, the non-dominated paths that the algorithm returns have at least one available wavelength. Moreover, the paths and available wavelengths have at least acceptable TP performance, since lightpaths with unacceptable TP values were made unavailable in the process of the algorithm.

The goal of this first phase is to find a set of good candidate lightpaths, which can efficiently serve the connection.

2) *Phase 2: Choosing the optimal lightpath from P_{n-d}*

In the second phase of the proposed algorithm we apply an optimization function or policy $g(V_p)$ to the cost vector, V_p, of each path $p \in P_{n-d}$. The function g yields a scalar cost per path and wavelength (per lightpath) in order to select the optimal one. The function g can be different for different connections, depending on their QoS requirements. Note that the optimization function g applied to the cost vector of a p has to be monotonic in each of the cost components. For example, it is natural to assume that it is increasing with respect to delay, hop count, number of crosstalk sources, etc. For the context of this study we have proposed and evaluated the following objective functions, which essential correspond to different IA-RWA algorithms.

i) Most Used Wavelength (MUW)

Given the connections already established, we order the wavelengths in decreasing utilization order and choose the lightpath whose wavelength is most used. This approach is the well known "most used wavelength" algorithm [3], proven to exhibit good network–layer blocking assuming ideal physical layer. Note that this approach does not differentiate between the *TP* values of the solutions. By the way the paths are calculated, all the available lightpaths have at least acceptable *TP* values. However, the chosen lightpath can have an *TP* value close to the threshold, which can become unacceptable when new connections are established (see next section about rerouting).

ii) Better parameter TP value (minTP)

For each non-dominated lightpath we calculate its *TP* value and select the lightpath with the smaller *TP* value. This approach does not consider the utilization of wavelengths in the network, making it more difficult for future connections to be served due to network-layer blocking.

iii) Worse parametric TP value (maxTP)

For each non-dominated lightpath we calculate its *TP* value and select the lightpath with the larger *TP* value. This way in contrast to the *minTP* optimization function, we consider the utilization of wavelengths in the network, making it more easy for future connections to be served. However, as in the *MUW* selection policy, the chosen lightpath can have an *TP* value close to the threshold, which can become unacceptable when new connections are established (see next section about rerouting).

3) *Phase 3: Rerouting connections*

This is an optional phase of our Multi-Parametric scheme. As previously discussed, XT, XPM and FWM impairments depend on the utilization of the other lightpaths. Thus, when a new lightpath is established, the QoT of some existing lightpaths may become unacceptable. To address this issue, in the proposed Multi-Parametric algorithm each time we consider establishing a new lightpath we always evaluate whether any of the existing connections will obtain unacceptable *TP* values and reroute the ones that fall beneath the given threshold $TP_{\max}$. Rerouting is a process that we want to avoid, since it involves tearing down the previous lightpath, re-executing the algorithm and establishing a new lightpath, which would interrupt the service of the connection. If rerouting is not used (it is either prohibited or we do not want to endure the corresponding time overhead), we can either continue using the existing lightpaths with an inferior QoT, or we can block the establishment of the new lightpath that would lead to at least one rerouting. The former is the action we assume in our simulation experiments when reroutings are not performed.

4) *Phase 4: The Q-Tool estimator*

This is also an optional phase of our Multi-Parametric scheme. In particular, in the end of the algorithm and in order to evaluate the feasibility of the lightpaths we use a Q-factor estimator that uses detailed analytical models to account for the most important impairments. The Q estimator takes as input the new lightpath and the already established lightpaths, calculates their Q factors, and returns how many of them have unacceptable transmission quality. In case more than one lightpaths have unacceptable QoT, then we block the corresponding connection request. In general, our goal is to use the Q-Tool as less as possible, in order to reduce the execution time of our algorithm and the dependence on various network related parameters (e.g., modulation formats, rates, etc). In case we decide not to use the Q-Tool, then we establish the connections based only on the previous steps of the Multi-Parametric scheme, assuming that the decision taken based on the impairment generating source parameters are correct.

V. PERFORMANCE RESULTS

In order to evaluate the performance of the proposed algorithms we have conducted simulation experiments in Matlab. The experiments were performed assuming the DT network topology, which is a transparent candidate network, as identified by the DICONET project [14] that has 14 nodes and 23 edges (we assumed 46 directed links). The link model of the reference network is the same as the one used in [5]. We assumed 10Gbps transmission rates and channel spacing of 100 GHz. The span length in each link was set to 100 km.

Connection requests (each requiring bandwidth equal to 10Gbps) are generated according to a Poisson process with rate λ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. The duration of a connection is given by an exponential random variable with average $1/\mu$ (time units). Thus, λ/μ gives the total network load in Erlangs.

Also, we have chosen the following values for the coefficients of Eq. (1), c_1=1/100, c_2=0, c_3=1, c_4=1 and c_5=1:

$$TP(p,w) = \frac{L_p}{100} + A_{pw} + SA_{pw} + X_{pw}\ .$$

The choice of c_2=0 assumes that the number of hops of the path is ignored, and c_1=1/100 is chosen to count the number of amplifiers of link, since we assume that amplifiers are placed every 100km. Experiments have also shown that the selection of different values for these coefficients can improve the performance of the proposed algorithms.

In Figure 3 we observe the blocking probability of the *MUW*, *minTP* and *maxTP* algorithms for different number of available wavelength in each link and different network loads. We observe that the *minTP* algorithm outperforms the others in both sets of experiments. The *minTP* algorithm handles better the physical layer blocking, which becomes almost zero when the number of the available wavelengths is large (Figure 3.a). Also, even for heavy network load the *minTP* algorithm outperforms the other algorithms, since as the load increases the impairments in the network also increase due to additional number of lightpaths that are activated (Figure 3.b).

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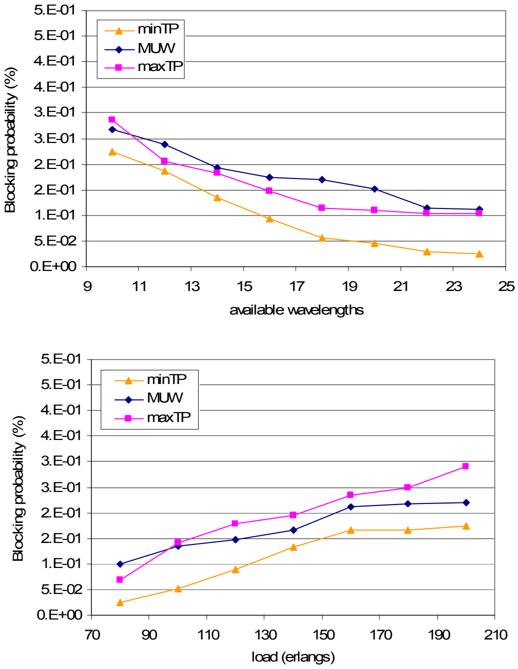

Figure 3: (a) The blocking probability vs. the number of available wavelengths and (b) blocking probability vs. the load in the network.

In Figure 4 we evaluate the performance of the *MUW*, *maxTP* and *minTP* algorithms and plot the percentage of connections blocked due to the *TP* threshold and due to the Q estimator that is applied in the fourth phase of the algorithm. In these experiments we alter the threshold of the *TP* value for which a candidate lightpath is consider to have an acceptable QoT. Generally, we observe that as the *TP* threshold increases the number of *TP* blocked connections decreases, while the number of Q blocked connection increases. On the one hand, using a small (restrictive) *TP* threshold, many candidate lightpaths are discarded by the algorithm. In this case, the lightpaths that are not rejected have very good QoT, that is usually accepted by the Q estimator. On the other hand, when we use a large (permissive) *TP* threshold, many lightpaths get accepted. However, some of them do not have acceptable QoT and are rejected by the Q estimator. We also observe that in the *minTP* algorithm (Figure 4.b) the intersection of the two plots occurs for a larger *TP* threshold. This indicates that by using the *minTP* algorithm we can handle better the physical impairments occurring in the network. Also, in the *minTP* algorithm for a large range of *TP* thresholds, the number of connections blocked by the Q estimator is small, indicating that it is also possible to perform the Multi-Parametric scheme without using the Q-Tool in the fourth phase. This way we will be able to execute our scheme faster and without the needed of a Q-Tool and anything else this entails (e.g., dependence on specific modulation formats, rates, etc). Moreover, as we observe in Figure 4.d the *minTP* algorithm produces the smallest total number of connections blocked. The *MUW* and *maxTP* algorithms perform similarly, with the *MUW* algorithm to result in most cases in a smaller number of blocked connections.

We also performed experiments using the *minTP* algorithm, with and without the Q estimator and confirmed that both Multi-Parametric variations perform similarly. This indicates that it is indeed possible to achieve QoT without using a Q-Tool. Generally, we can use the Q-Tool in some initial executions of the algorithm to experiment and see which *TP* threshold value performs better (this will depend on modulation format, rate etc). After tuning the *TP* threshold parameter, the Q-Tool is essentially no longer necessary and the Multi-Parametric scheme can be executed without it.

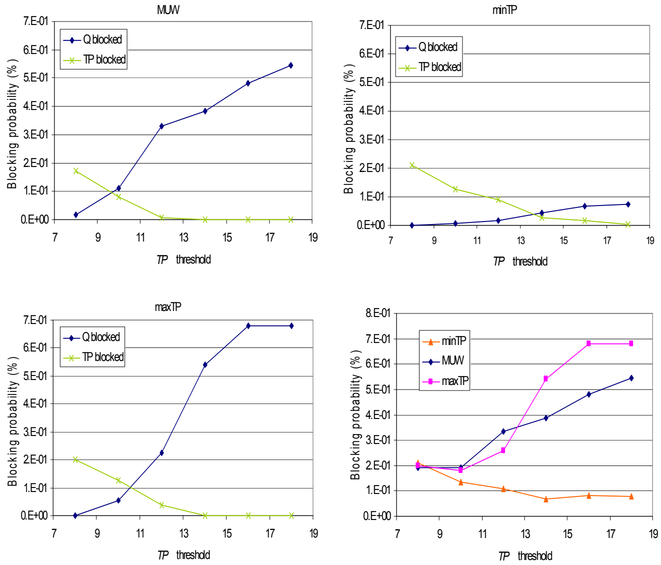

Figure 4: The number of blocked connections due to the Q estimator, due to the *TP* threshold and their total number for the Parametric algorithms a,d) *MUW*, b,d) *minTP* and c,d) *maxTP*, for network load equal to 100 Erlangs.

Figure 5 shows the blocking probability and the execution time of several variations of the *minTP* Multi-Parametric scheme for different number of available wavelengths in each link. In particular we compare the following schemes: scheme i) where the *TP* threshold of the candidate paths is checked and the rerouting phase is not performed, scheme ii) where the *TP* threshold of the candidate paths is not checked in the first phase of the Multi-Parametric scheme and no reroutings are perfomed, scheme iii) where the *TP* threshold of the candidate paths is not checked in the first phase of the Multi-Parametric scheme and rerouting are performed and scheme iv) where the *TP* threshold of the candidate paths is checked in the first phase of the Multi-Parametric scheme and rerouting are performed. By comparing the schemes (i) and (ii) we observe that by not discarding any lightpath due to the *TP* threshold, in the first phase of the algorithm, then a smaller blocking probability is achieved. However, this comes in the cost of a very large execution time as it can be seen in Figure 5.b, since the number of candidate lighpaths that are evaluated by the consecutive phases of the algorithm is large. Similar are our observations for the schemes (iii) and (iv). Moreover, by comparing the schemes (i) and (iv), we observe that the rerouting operation results in smaller blocking probability, since it helps in the defragmentation of the links/wavelengths utilization, so as to better handle the upcoming connection requests. The rerouting operation also increases the execution time of the scheme (iv) as it can been seen in Figure 5.b, however, this increase is not so large. The same observations, hold for the schemes (ii) and (iii). In general, we note the importance of pruning the connections that violate the *TP* threshold in the first phase of the algorithm and the importance of the rerouting operation. Executing both of these operations is in most cases beneficial in terms of the blocking probability and the execution time, than any other combination.

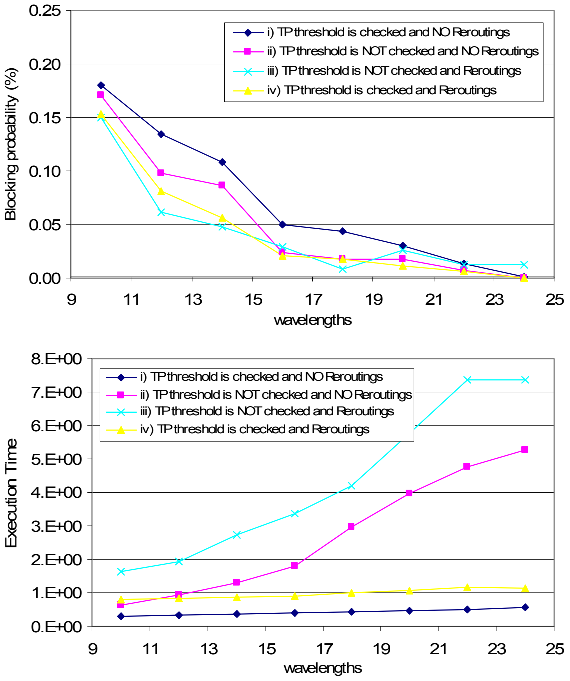

Figure 5: (a) The blocking probability, (b) the average execution time (in seconds) per connection request, vs. the number of available wavelengths, for several Multi-Parametric variations, for network load equal to 100 Erlangs.

VI. CONCLUSIONS

We proposed an online Multi-Parametric impairment-aware routing and wavelength assignment (RWA) scheme for dynamic traffic. To serve a connection, the proposed scheme finds a lightpath that has acceptable quality of transmission (QoT) performance by estimating the values of several impairment generating sources. For this purpose we define the transmission performance (*TP*) metric and validate the candidate lightpaths against a predefined *TP* threshold. Our Multi-Parametric scheme consists of a number of optional phases such as the validation against the *TP* threshold, the rerouting phase and/or the application of the Q-Tool estimator. These optional phases introduce trade-offs between the ability of our scheme to detect the most impairment efficient lightpaths and its execution time. We evaluated a number of Multi-Parametric algorithms with different optimization goals and observed that the *minTP* algorithm performs best, in terms of network and physical blocking and execution time, making it appropriate to serve online connections. Finally, our results indicate that it is possible to perform efficiently impairment routing and wavelengths assignment without the need of a Q estimator, except for an initial training period where the Q-Tool or real measurements provided by monitors can be used to fine tune the *TP* function and the threshold used. This reduces further the execution time of our algorithm and makes the algorithm easy to adapt when the modulation formats used are changed, or the rate of a wavelength is upgraded.

ACKNOWLEDGEMENTS

This work has been supported by the European Commission through DICONET project. K. Christodoulopoulos was supported by GSRT through PENED project 03EΔ207, funded 75% by the European Commission and 25% by the Greek State and the private sector.

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978-1-4244-4148-8/09/$25.00 ©2009
This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2009 proceedings.