A Multicost Approach to Online Impairment-Aware RWA

K. Christodoulopoulos, K. Manousakis, E. A. Varvarigos
Computer Engineering and Informatics Dep., University of Patras,
and Research Academic Computer Technology Institute,
Patra, Greece.
{*kchristodou*, *manousak*, *manos*}*@ceid.upatras.gr*

M. Angelou, I. Tomkos
Athens Information Technology,
Athens, Greece.
{*mang*, *itom*}*@ait.edu.gr*

***Abstract*—We design and implement a multicost impairment-aware routing and wavelength assignment algorithm for online traffic. In transparent optical networks the quality of a transmission degrades due to physical layer impairments. To serve a connection, the proposed algorithm finds a path and a free wavelength (a lightpath) that has acceptable signal quality performance by estimating a quality of transmission measure, called the Q factor. We take into account channel utilization in the network, which changes as new connections are established or released, in order to calculate the noise variances that correspond to physical impairments on the links. These, along with the time invariant eye impairment penalties of all candidate network paths, form the inputs to the algorithm. The multicost algorithm finds a set of so called non-dominated Q paths from the given source to the given destination. Various objective functions are then evaluated in order to choose the optimal lightpath to serve the connection. The proposed algorithm combines the strength of multicost optimization with low execution time, making it appropriate for serving online connections.**

I. Introduction

The most common architecture utilized for establishing communication in WDM optical networks is *wavelength routing* [1], where data are transmitted through *lightpaths*; that is, all-optical WDM channels, that may span multiple consecutive fibers. The effective establishment and usage of lightpaths is crucial, and, thus, it is important to propose efficient algorithms to select the routes of the requested connections and to assign wavelengths on each of the links along these routes, so as to optimize a certain performance metric. This is known as the *routing and wavelength assignment* (abbreviated RWA) problem.

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. *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. In this study we will focus on the online RWA problem.

The majority of offline and online 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 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 the signal degrades due to physical layer impairments [1][2].

In transparent or translucent WDM networks call blocking may occur due to (i) the non-ideal physical layer transmission media and component characteristics (*physical-layer blocking*), and (ii) the non-availability of a free wavelength due to the wavelength allocation of existing connections (*network-layer blocking*). A RWA algorithm designed for these types of WDM networks has to cope with both causes of blocking.

Routing and wavelength assignment algorithms have been extensively examined in the literature. The main focus of research has been offline RWA, which is a NP-hard optimization problem [3]. However, in offline RWA few impairment-aware algorithms have been proposed, since the interference among channels is hard to formulate [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 [5]. An impairment aware (IA)-RWA algorithm that uses a separate module to estimate the OSNR and PMD of a candidate lightpath is presented in [6]. A dynamic and adaptive QoS routing algorithm, based on real-time Q factor measurements from monitors is presented in [7]. 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 are not taken into account. [8] 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 [9], a adaptive IA-RWA algorithm that models as noise the most important physical impairments and assign additive noise variance parameters per link is proposed. A number of online IA-RWA algorithms for translucent networks, considering both linear and nonlinear physical effects, are evaluated in [10].

A multicost 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 multicost-related information at the intermediate nodes. Then the selection of the lightpath is performed at the destination. In general, multicost and multi-constrained algorithms have been used for QoS routing problems [12]. To the authors' best knowledge, the current work is the first time that the IA-RWA problem is addressed with a multicost algorithm that uses impairment-related cost parameters chosen so as to quickly calculate the Q factor of a lightpath. On the other hand, [11] handles impairments through OSNR which is not affected by dispersion and non-linear effects [2], and thus the Q factor approach that we adopt in this paper is more general. Moreover, the algorithm proposed in this paper selects the lightpath at the source (source routing), while in [11] the selection is performed at the destination.

In this paper we propose a multicost impairment-aware routing and wavelength assignment algorithm for online traffic. To serve a connection request, the proposed algorithm finds a path and a free wavelength (a lightpath) that has acceptable quality of transmission (QoT) performance by estimating the corresponding Q factor. We take into account the current utilization of the network, which changes as new connections are established or released, in order to calculate the noise variances of the links. These, along with the time invariant eye impairment penalties of all candidate paths, form the inputs to the algorithm. The proposed multicost algorithm consists of two phases. In the first phase, the algorithm finds the set of so called non-dominated Q paths from the given source to all the nodes of the network, including the given destination. In the second phase, an optimization function (or policy) is applied to the cost vector of the paths, in order to find the optimum solution. Various objective functions are proposed and evaluated through simulation experiments.

Our performance results indicate that the proposed algorithm with an optimization function that accounts for both the availability of wavelengths and the Q performance of the chosen solution exhibits a superior performance over the other policies examined, combining good network layer blocking and low rerouting rate of older connections. The execution time of the proposed algorithm is small, making it appropriate for serving online connections.

II. 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- 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. Assuming Gaussian shaped noise the Q-factor is related to the system's BER through:

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

Note that the higher the Q-factor value the smaller the BER and thus the better the quality of the signal. BER or Q factor is not readily available before a lightpath is actually set up.

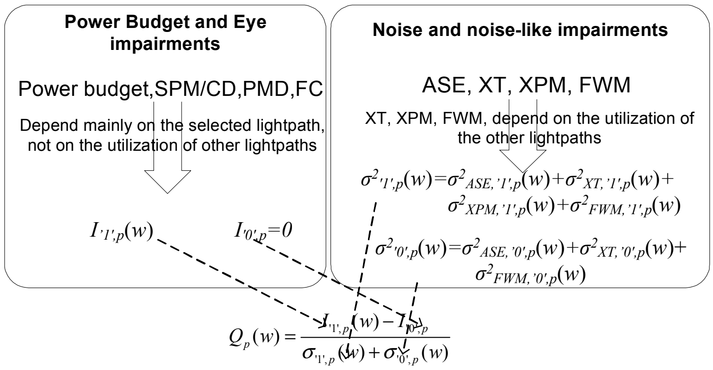

Figure 1: Q factor calculation.

Instead, models of physical-layer impairments can be used to estimate the Q factor in advance. Various analytical models for the linear and nonlinear impairments have been proposed in the literature. Since we are considering online traffic, the algorithm's execution time is a crucial factor. Therefore, we want to use simplified impairment models and quick rules to combine them in the process of the algorithm so as to quickly calculate the Q-factor of candidate solutions, and possibly use a more detailed Q estimation tool at the end, in order to verify the feasibility of the chosen lightpath. This is the approach that was followed in this paper. The simplified models and the assumptions used in the proposed multicost algorithm are presented in Sections III and IV. For the final verification of the solutions produced by the algorithm we used a detailed Q estimator tool that takes into account the effect of the most important impairments.

III. Q FACTOR OF A PATH AND Q FACTOR OF A LINK

The Q-factor is the electrical signal-to-noise ratio at the input of the decision circuit in the receiver's terminal. Assuming Gaussian shaped noise, the Q-factor of a lightpath (p,w), that is, wavelength w on path p is given by:

$$Q_p(w)=\frac{I_{'1',p}(w)-I_{'0',p}(w)}{\sigma_{'1',p}(w)+\sigma_{'0',p}(w)}=\frac{I_{'1',p}(w)}{\sigma_{'1',p}(w)+\sigma_{'0',p}(w)}, \quad (2)$$

where $I_{'1'}$ and $I_{'0'}$ are the mean values of electrical voltage of signal 1 and of signal 0, respectively, and $\sigma_{'0'}$ and $\sigma_{'1'}$ are their standard deviations, at the input of the decision circuit at the destination (end of path p).

In the approach that we have adapted in this study (Figure 1), that is based on [8][10], $I_{'1',p}(w)$ depends on the transmitter's characteristics, the gains and losses of the amplifiers and links over the path, and the so called "eye impairments", namely, SPM/CD, PMD and FC. The remaining physical impairments are considered as noise or noise-like. Thus, for the noise variances of lightpath (p,w) we have:

$$\sigma^2_{'1',p}(w)=\sigma^2_{ASE,'1',p}(w)+\sigma^2_{XT,'1',p}(w)+\sigma^2_{XPM,'1',p}(w)+\sigma^2_{FWM,'1',p}(w), \quad (3)$$

$$\sigma^2_{'0',p}(w)=\sigma^2_{ASE,'0',p}(w)+\sigma^2_{XT,'0',p}(w)+\sigma^2_{FWM,'0',p}(w), \quad (4)$$

where σ^2_{ASE}, σ^2_{XT}, σ^2_{XPM} and σ^2_{FWM}, are the electrical noise variances due to ASE, XT, XPM and FWM, respectively. Note that XT, XPM and FWM depend on the utilization of the other wavelengths. Moreover, XPM and FWM are transmission impairments generated in the fiber links, while XT is related to the non-ideal switching fabric of the optical cross-connects (OXC). In what follows, by the term "link" we will refer to a link and the OXC switch that is connected at its end.

In the general case, the Q factor of a lightpath cannot be calculated directly by the Q factors of the links that comprise it. In order to estimate the Q factor of a lightpath we perform the following calculations that are based on the noise characteristics of the links that comprise the lightpath and the eye impairments of the end-to-end route.

We assign to each link parameters that correspond to the electrical noise variances of all noise or noise-like impairments. These link-related parameters can be added over a path, after accounting for the gains and losses of the amplifiers and the fiber segments over the path. More specifically, for a path p consisting of links l=1,2,…,k with known electrical noise variances $\sigma^2_{ASE,'1',l}(w)$, $\sigma^2_{ASE,'0',l}(w)$, $\sigma^2_{XT,'1',l}(w)$, $\sigma^2_{XT,'0',l}(w)$, $\sigma^2_{XPM,l}(w)$, $\sigma^2_{FWM,'1',l}(w)$ and $\sigma^2_{FWM,'0',l}(w)$ per wavelength w, and known gains or losses $G_l(w)$ (G_l is typically expressed in dB and accounts for the losses of the fiber segments and the components of the link l and the ending OXC, and the gains of the inline amplifiers of the link l and the ending OXC), we have:

$$\sigma^2_{'1',p}(w)=\sum_{l=1}^{k}\left(\sigma^2_{'1',l}(w)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right)=$$

$$\sum_{l=1}^{k}\left(\left(\sigma^2_{ASE,'1',l}(w)+\sigma^2_{XT,'1',l}(w)+\sigma^2_{XPM,'1',l}(w)+\sigma^2_{FWM,'1',l}(w)\right)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right),$$

$$\sigma^2_{'0',p}(w)=\sum_{l=1}^{k}\left(\sigma^2_{'0',l}(w)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right)=$$

$$\sum_{l=1}^{k}\left(\left(\sigma^2_{ASE,'0',l}(w)+\sigma^2_{XT,'0',l}(w)+\sigma^2_{FWM,'0',l}(w)\right)\cdot\prod_{i=l+1}^{k}10^{2\cdot G_i(w)/10}\right).$$

Note that the electrical noise variances from each link grow with the square of the remaining gain/loss up to the receiver.

The eye penalty impairments do not change with the utilization of the other wavelengths, but depend on the selected path. More specifically, the PMD penalty depends on the length of the path and does not depend on the utilization of the other wavelengths. FC penalty depends on the number of filters of the path. Typically, in a transparent WDM network a OXC switch is designed so as to have two filters, and, thus, in order to calculate FC effect we only have to count the number of OXCs (or hops) on the path. Finally, the effect of SPM/CD is the most complicated eye impairment to calculate (judging from the analytical models that are used to estimate it), and it usually has to be estimated for an end-to-end path. However, a transparent optical network is typically designed so that the effect of SPM/CD is fully compensated at the end of each link and thus under this assumption SPM/CD can be neglected.

In any case, since the eye impairments and the transmitters' power and amplifiers/links gains/losses do not change vastly as connections are established or released, we can pre-calculate the aforementioned effects so as to obtain $I_{'1',p}(w)$ for all candidate lightpaths (p,w) and store them in a database. Even though the temperature and other parameters may affect these values, we assume that a periodic process keeps this database up to date. Another approach is to use quick and efficient models to calculate $I_{'1',p}(w)$ as the algorithm is executed, something that is plausible especially under the assumption that SPM/CD is fully compensated.

IV. Multicost Impairment Aware Online RWA

A. Computing the cost vector of a path

We consider a WDM network with N nodes and L links, each of which uses m wavelengths, $\lambda_1,\lambda_2,...,\lambda_m$. The WDM network employs no wavelength conversion. We assume that the node where the algorithm is executed maintains a database with the parameters $I_{'1',p}(w)$ of all lightpaths (p,w), or can calculate them in a timely efficient manner. 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. Finally, we assume that the node that runs the algorithm maintains or calculates *vectors* that contain the electrical noise variances of signal 1 and signal 0 of all links l, denoted by $\overline{\sigma^2_{'1',l}}$, and $\overline{\sigma^2_{'0',l}}$, whose i^{th} entry denotes the corresponding variance for wavelength i, i=1,…,m. We have used a quick algorithm to calculate these vectors for a link that is not presented here due to size limitation.

1) Cost vector of a link

Each link l is assigned a cost vector that contains $1+4\cdot m$ cost parameters:

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

(ii) a vector $\overline{G_l}$ =($G_l(1)$,..., $G_l(m)$) with the gain/loss of the link for each of the wavelengths, in dB,

(iii) a vector $\overline{\sigma^2_{'1',l}}$ =($\sigma^2_{'1',l}(1)$,..., $\sigma^2_{'1',l}(m)$) with the electrical noise variances of signal 1 for each of the wavelengths,

(iv) a vector $\overline{\sigma^2_{'0',l}}$ =($\sigma^2_{'0',l}(1)$,..., $\sigma^2_{'0',l}(m)$) with the electrical noise variances of signal 0 for each of the wavelengths

(v) the availability of wavelengths in the form of a Boolean vector $\overline{W_l}$ =(w_l(1),...,$w_l(m)$), whose i^{th} element $w_l(i)$ is equal to 0 (false) when wavelength λ_i is used and equal to 1 (true) when λ_i is free (available).

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

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

2) Cost vector of a path

Similarly to a link, 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. Assume a path p with cost vector

$$V_p = (d_p,\ \overline{G_p},\ \overline{\sigma^2_{'1',p}},\overline{\sigma^2_{'0',p}},\overline{W_p},\ {*p}),$$

where d_p, $\overline{G_p}$, $\overline{\sigma^2_{'1',p}},\overline{\sigma^2_{'0',p}},\overline{W_p}$ 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:

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

where the operator "&" denotes the bitwise Boolean AND operation. Note that all operations between vectors have to be interpreted component-wise.

3) Checking the Q factor values of intermediate lightpaths

For a path p, we check if the available wavelengths of that path (marked by 1 in $\overline{W_p}$) have acceptable Q factor performance. To do so, we use the cost vector V_p to obtain $\overline{\sigma_{'1',p}}$ and $\overline{\sigma_{'0',p}}$, and we also use the list of links $*p$ to obtain the power $I_{'1',p}$ through a database lookup or quick calculation (Section III). Then, by using Eq. (2) we obtain the Q factor of each wavelength, that is, we obtain the vector $\overline{Q_p}=(Q_p(1),\ldots,Q_p(m))$. We finally check that the Q factor of the available wavelengths are higher than a given threshold (recall that the higher the Q factor, the better the signal quality is). For those wavelengths that do not satisfy the threshold we set the corresponding index of the utilization vector W_p equal to zero. In other words, we make these wavelengths unavailable due to poor QoT performance and not due to their being used by another lightpath. Note that we have assumed that the quality of the signal always degrades as we move down a path. Other approaches, such as sophisticated dispersion maps, etc, that can increase the signal quality later in the path 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, and thus compensation is usually performed on a per hop basis.

4) Checking if the path is further extendable

We check if path p has at least one available wavelength.

$$\text{If } \overline{W_p} = \mathbf{O} \text{ (all zero vector), then path } p \text{ is rejected.} \quad (5)$$

5) Domination relationship

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

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

$$d_{p_1} \le d_{p_2} \text{ and } \overline{W_{p_1}} \ge \overline{W_{p_2}} \text{ and } \overline{Q_{p_1}} \ge \overline{Q_{p_2}} . \quad (6)$$

The "≥" relationship for vectors $\overline{W}$ and $\overline{Q}$ 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.

Even though we focus only on transparent networks, the presence of 3R regenerators could also be included in the above formulation: when we cross a 3R we can check the Q factor of the wavelengths and for the wavelengths that have an acceptable Q factor performance we make the corresponding noise variance entry equal to zero by using that regenerator. If the number of regenerators is limited, an additional parameter must be included in the cost vector of the paths, indicating the number of regenerators used, and the algorithm has to be modified accordingly. Another possible variation of the algorithm is to use a pseudo-domination relationship (instead of the domination relationship of Eq. (6)), so that smaller algorithmic complexity is obtained [13]. The pseudo-domination relationship could be defined so as to have more relaxed requirements, so that more paths are (pseudo)-dominated (pruned) and not considered further. These possible variations will be explored in future works.

B. Multicost Impairment Aware RWA Algorithm

The multicost impairment aware routing and wavelength assignment algorithm we propose consists of two phases: given a source-destination pair, the set $P_{n\text{-}d}$ of non-dominated paths between them is calculated first, and then an optimization function $f(V_p)$ or policy is applied to the cost vector of each path $p\in P_{n\text{-}d}$ to select the optimal lightpath.

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

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 $P_{n\text{-}d}$ 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. (6), and that when we expand a path we check the Q factor of its wavelengths (Section IV.A.3) and if the path is further extendable (Section IV.A.4).

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 Q factor performance, since lightpaths with unacceptable Q factor were made unavailable in the process of the algorithm.

2) Phase 2: Choosing the optimal lightpath from $P_{n\text{-}d}$

In the second phase of the proposed 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 function f yields a scalar cost per path and wavelength (per lightpath) in order to select the optimal one. The function f can be different for different connections, depending on their QoS requirements. Note that the optimization function f 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, increasing with increased noise variance, etc. For the context of this study, we have evaluated the following policies:

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 Q factors of the solutions. By the way the paths are calculated, all the available lightpaths have at least acceptable Q factor. However, the chosen lightpath can have a Q value close to the threshold, which can become unacceptable when new connections are established (see next section about rerouting).

ii) Better Q performance (bQ)

For each non-dominated lightpath we calculate its Q factor and select the lightpath with the higher Q 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) Mixed better Q and wavelength utilization (bQ-MUW)

This approach is a combination of approaches (ii) and (i). We start by finding the highest Q value as in (ii). Then, from the set $P_{n\text{-}d}$ we find the lightpaths that have Q factors close to that highest value (e.g., keeping the lightpaths with Q factor no less than 0.5 dB from the highest Q). From this set we finally select the lightpath whose wavelength is used more in the network, similarly to (i).

3) Rerouting connections

As previously discussed, XT, XPM and FWM impairments depend on the utilization of the other lightpaths. To this end, when a new lightpath is established, the QoT of some existing lightpaths may become unacceptable. To address this issue, in the proposed multicost algorithm each time we take the decision of establishing a new lightpath we always evaluate how many of the existing connections have unacceptable Q factor and reroute the ones that fall beneath the given threshold. 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. In case that reroutings are prohibited, we can either block the establishment of a new lightpath that would lead to at least one rerouting, or we can continue using the existing lightpaths with an inferior QoT.

4) QoS differentiation and extensions

Based on the optimization policies and the above discussion about reroutings, a number of approaches to provide Quality of Service differentiation using the proposed multicost algorithm are available. For example, we can assume a number of classes of service, where established lightpaths of class 1 are not allowed to be rerouted at all, established lightpaths of class 2 are allowed to be rerouted only by new connections of class 1, etc. Also, depending on the optimization policy that is used, different features can be delivered. For example, bQ policy is designed to select a lightpath that has a low probability of being rerouted in the future, while MUW policy is designed so as to exhibit low network layer blocking that would be desirable for ensuring high service probability for real-time applications for which QoT is not that critical. In any case, the multicost algorithm is general and there are a lot of options, such as using the path's delay or the number of hops in the optimization function, extending the definition of the cost vector to keep track of the number of available wavelengths of intermediate links or include a cost for using a link, etc., that are left to be explored in the future.

V. PERFORMANCE RESULTS

In order to evaluate the performance of the proposed algorithm we have conducted simulation experiments in Matlab. The experiments were performed assuming the Generic DT network topology (Figure 2), which is a transparent candidate network, as identified by the DICONET project [14].

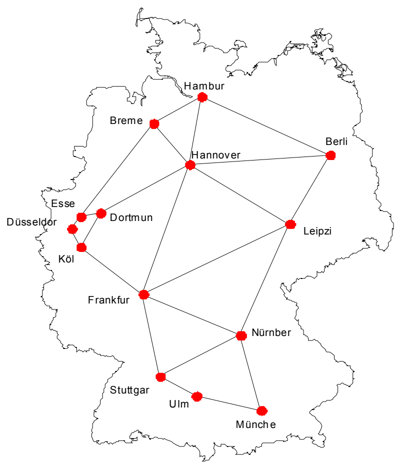

Figure 2: Generic DT network topology, with 14 nodes and 23 links (we assumed 46 directional links).

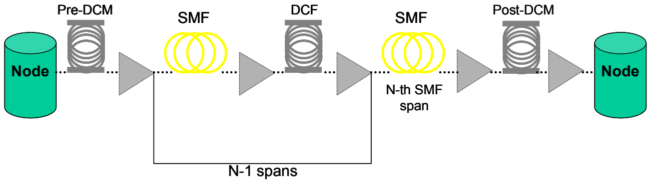

Figure 3: Link model.

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.

The link model of the reference network is presented in Figure 3. We assumed 10Gbps transmission rates and channel spacing of 50 GHz. The span length in each link was set to 100 km. Each link was assumed to consist exclusively of SSMF fibers with dispersion parameter D=17 ps/nm/km and attenuation parameter a=0.25 db/km. For the DCF we assumed parameters a=0.5 dB/km and D=-80 ps/nm/km. The launch power was set to 3 dBm/ch for every SMF span and -4 dBm/ch for the DCF modules. The EDFAs' noise figure was set to approximately 6 dB with small variations (±0.5 dB) and each EDFA exactly compensates for the losses of the preceding fiber span. We assumed a switch architecture similar to [5] and a switch-crosstalk ratio X_{sw}=32 dBs with small variations per node (±1 dB). Regarding the dispersion management scheme, a pre-compensation module was used in order to achieve better transmission reach: every span was under-compensated by a value of 30 ps/nm to alleviate non-linear effects, and the accumulated dispersion at the input of each switch was fully compensated to zero with the use of an appropriate post-compensation module at the end of the link.

From the above, we can observe that the average power of the signal is maintained and that SPM/CD is fully compensated at the end of each link. This makes the calculation of the eye penalties (Section III) much easier and faster, since we only have to consider the PMD and FC effects. Note that the assumptions of the physical layer parameters, presented above, do not constrain the applicability of the proposed algorithm. The proposed algorithm is general and can also be used in cases where the links do not follow the amplifier strategy mentioned above, or where SPM/CD is not fully compensated and must also be considered.

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.

In Figure 4(a) we graph the blocking probability for the three examined optimization policies as a function of the network load, assuming that there are 20 available wavelengths per link. We can observe that the most used wavelength (MUW) policy exhibits the best blocking performance. However, as Figure 4(b) indicates, MUW exhibits a high number of reroutings. This policy does not account for the Q factor of the establishing lightpaths, tends to "pack" the lightpaths so as to use the same wavelengths in order to avoid network layer blocking, and a lot of already established lightpaths turn out to have unacceptable transmission performance after establishing a new lightpath. If reroutings were not allowed, then this policy would exhibit a very high blocking probability. On the other hand, the bQ policy has the worst blocking probability performance. The bQ policy wastes a lot of wavelengths trying to establish a lightpath that is not affected by the others (the one with the highest Q value), and the network blocking is increased. However, since the lightpath that is established every time has the highest Q value and future connections do not appreciably affect it, bQ exhibits the best rerouting performance. The mixed bQ-MUV policy that combines the good network blocking probability of MUV policy and the low rerouting probability of bQ policy seems the best solution, since it gives the most balanced results.

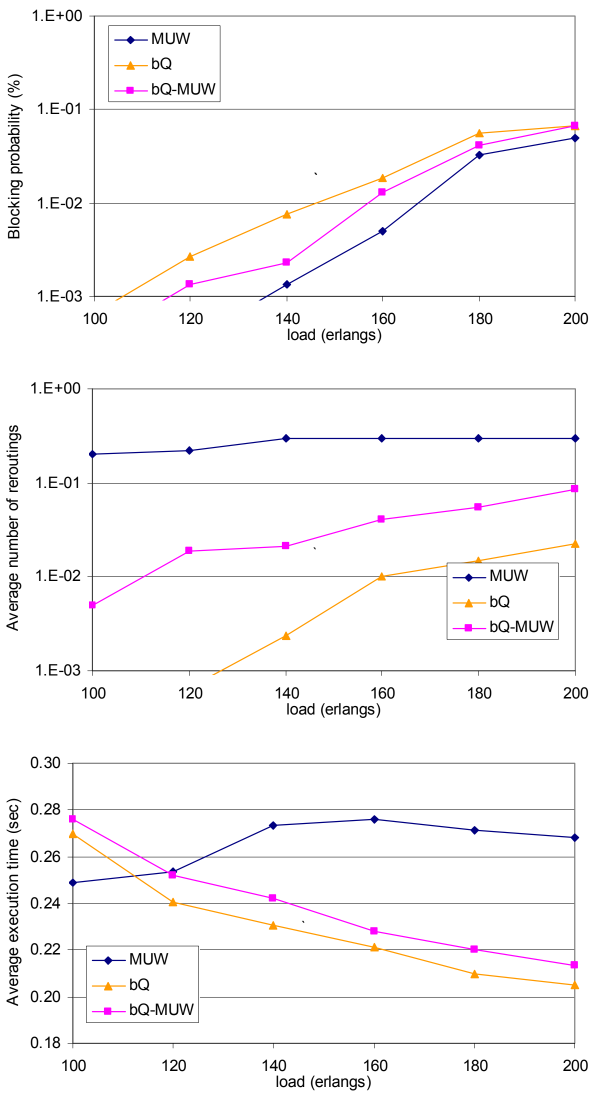

Figure 4: (a) blocking probability, (b) average number of reroutings per connection, and (c) average execution time per connection, vs. network load, assuming 20 available wavelengths per link.

Figure 4(c) shows the average execution time per connection (including re-execution of the algorithm in case of reroutings). First of all, from this figure we can observe that the algorithm exhibits quite low execution time, in the order of a few hundreds of msec, which is acceptable for serving this type or dynamic traffic. The average execution times of bQ and bQ-MUW policies decrease as the load increases. This is because we have assumed a constant number of wavelengths and as the load increases the network becomes congested and the algorithm prunes a lot of paths because it cannot find free wavelengths (Section IV.A.4). On the other hand, the average execution time of MUW policy starts to increase as the load increases, due to the increase in the average number of reroutings (Figure 4(b)). After some point, that the average number of reroutings stabilize, the average execution time of MUW policy starts to decrease due to the decreasing number of lightpaths that are available as the load increases.

VI. Conclusions

We proposed a multicost impairment-aware routing and wavelength assignment algorithm for online traffic. To serve a connection, the proposed algorithm finds a lightpath that has acceptable quality of transmission performance by estimating its corresponding Q factor. Various objective functions (selection policies) were proposed to choose the optimal lightpath for a connection. Our performance results indicate that the bQ-MUW policy that accounts for both the availability of wavelengths and the Q performance of the chosen solution exhibits a superior performance, combining low blocking with low rerouting probability of established connections. The execution time of the proposed algorithm is acceptable, making it appropriate to serve online connections.

Acknowledgements

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

References

[1] R. Ramaswami, K. N. Sivarajan: "Optical Networks: A Practical Perspective", 2nd ed., Morgan Kaufmann, 2001.
[2] G. Agawal, "Fiber-Optic Communication Systems", 3rd ed., Wiley, 2002.
[3] H. Zang, J. P. Jue, B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks," Optical Networks Magazine, vol. 1, Jan. 2000.
[4] K. Manousakis, K. Christodoulopoulos, E. Varvarigos, "Impairment-Aware Offline RWA for Transparent Optical Networks", to appear IEEE INFOCOM 2009.
[5] B. Ramamurthy, D. Datta, H. Feng, J. Heritage, B. Mukherjee, "Impact of Transmission Impairments on the Teletraffic Performance of Wavelength-Routed Optical Networks", IEEE/OSA Journal of Lightwave Technology, 1999.
[6] Y. Huang, J. Heritage, and B. Mukherjee, "Connection provisioning with transmission impairment consideration in optical WDM networks with high-speed channels," IEEE/OSA Journal of Lightwave Technology, 23(3), 2005.
[7] T. Deng, S. Subramaniam, "Adaptive QoS Routing in Dynamic Wavelength-Routed Optical Networks", IEEE Broadnets 2005.
[8] V. Anagnostopoulos, C. Politi, C. Matrakidis, A. Stavdas, "Physical layer impairment aware routing algorithms based on analytically calculated constraints", Optics Communications, 2006.
[9] J. He, M. Brandt-Pearce, Y. Pointurier, S. Subramaniam: "QoT-Aware Routing in Impairment-Constrained Optical Networks" IEEE Globecom, 2007.
[10] S. Pachnicke, T. Paschenda, P. Krummrich , "Assessment of a constraint based routing algorithm for translucent 10Gbps DWDM networks considering fiber nonlinearities", OSA Journal of Optical Networking, Vol. 7, Is. 4, 2008.
[11] A. Jukan, G. Franzl, "Path selection methods with multiple constraints in service-guaranteed WDM networks", IEEE/ACM Transactions on Networking, 2004.
[12] Z. Wang, J. Crowcroft, "Quality-of-service routing for supporting multimedia applications", Journal on Selected Areas in Communication, vol. 14, no. 7, 1996.
[13] E. Varvarigos, V. Sourlas, K. Christodoulopoulos, "Routing and Scheduling Connections in Networks that Support Advance Reservations", Computer Networks (58), 2008.
[14] Dynamic Impairment Constraint Network for Transparent Mesh Optical Networks (DICONET), FP7 - GA 216338. http://www.diconet.eu