Routing and wavelength assignment algorithms in survivable WDM networks under physical layer constraints

George Markidis and Anna Tzanakaki
Athens Information Technology (AIT), 68 Markopoulo Ave., Peania, Athens, Greece
{gmar,atza}@ait.edu.gr, Tel.: +30-210-6682766, Fax: +30-210-6682730

Abstract

This paper addresses the problem of survivable lightpath provisioning in wavelength division multiplexed networks taking into consideration the optical signal performance degradation triggered by the physical impairments of transparent optical networks as a routing constraint. This work proposes a resource efficient provisioning scheme that takes into consideration both working and protection traffic. In order to maximize the utilization of spare capacity the backup multiplexing technique is applied in combination with suitable wavelength assignment algorithms differentiating the two types of traffic. In addition, to provide the required quality guarantees an impairment aware routing algorithm that incorporates the main physical layer characteristics of large-scale optical networks into its path computation process is proposed. The performance of the proposed solution is investigated and compared to other conventional RWA algorithms (i.e shortest path, minimum hop and random wavelength assignment) through simulations of a typical mesh long-haul network.

1. Introduction

It is widely accepted that telecommunications networks and the Internet have grown from infrastructures that were initially only supporting some level of connectivity between end users into a very powerful economic/business paradigm with a significant socioeconomic impact for the whole globe. It is true to say that, when considering the extent and nature of the use of Today's and Future Internet, including activities such as commerce and businesses, a fundamental requirement that needs to be satisfied is to provide secure and trusted access to the end users. It is becoming increasingly important to offer the ability to carry out a wide spectrum of activities through a trustworthy network infrastructure-ensuring the security, reliability, and stability of increasingly critical and pervasive applications and services.

Optical networking exploiting wavelength division multiplexing (WDM) is extensively used in existing telecommunications infrastructures and is expected to play a significant role in next generation networks and the future Internet supporting a large variety of services having very different requirements in terms of bandwidth, latency, reliability, security and other features. In transparent WDM networks, signals are transported end-to-end optically without being converted to the electrical domain along their path. Connection provisioning of all-optical connections (lightpaths) between source and destination nodes is achieved utilizing specific routing and wavelength assignment algorithms (RWAs). The traditional RWA schemes and formulations make the routing decision based only on network level conditions such as connectivity and available capacity, without considering the details of the physical layer, relying on the assumption that all paths are of acceptable quality due to inherent optoelectronic regeneration available in the network. Therefore, when an available path and wavelength is identified, the connection is assumed to be feasible to be established. However, in future optical networks that are fully transparent or comprise large domains of transparency and support very high data rates the optical signal experiences the accumulation of physical impairments through transmission and switching. This is due to the analogue nature of this type of networks resulting in some cases in unacceptable signal quality [1]. In this case a more detailed consideration of the physical impairments when determining paths that can support high quality signals is required. In order to address this issue, RWA algorithms that consider the physical layer impairments and their impact on optical signal quality are proposed and constrain the routing of wavelength channels according to the physical characteristics of the paths. These algorithms are reported as Impairment Aware RWA [2] and ensure that connections are feasible to be established considering not only availability of network resources but also the equally important physical performance of the connections. The IA-RWA approach needs to jointly consider the physical layer impairments (linear such as amplifier induced noise, polarization mode dispersion, chromatic dispersion, in-band crosstalk, filter concatenation and non-linear such as self-phase modulation, cross-phase modulation and four wave mixing) and the networking aspects that capture and describe the overall performance of the optical network.

Another important aspect in the context of optical networks is fault-tolerance. As the deployment of WDM technology enables the routing of multiple lightpath connections utilizing different wavelength channels in an optical fiber, a single link failure may cause loss of services that carry enormous amounts of information that may lead to significant revenue reduction. Different approaches addressing resilience in WDM optical networks have been extensively reported in the literature [3].

The provision of resilience in optical WDM networks is realized by either proactive protection [4] or reactive restoration [5]. The first computes one or more alternative paths to the primary routing path (backup paths) and the required network resources are reserved for it at the time of establishing the primary lightpath. A backup path is then activated at the occurrence of a failure on the primary path. On the other hand, restoration acts only after the detection of a failed path by computing and provisioning a new path that circumvents the point of failure. This procedure may fail in identifying a backup lightpath due to lack of available capacity and therefore does not guarantee successful recovery.

A further classification of the pre-designed protection method is based on link or path protection schemes. In the link based method the failed link is replaced by a new path which however includes the unaffected portion of the primary path. This method constrains the choice of the backup paths and requires more spare resources than the path-based method [6], which computes a complete end-to-end backup path from the source to the destination of the failed primary path. In the path-based method, wavelength channels on the backup path can be either dedicated or shared. If dedicated, the wavelength channels assigned to a specific backup path cannot be assigned to other backup paths. On the other hand in the shared method, backup paths can share wavelength channels under the single link failure assumption, if their primary paths are link-disjoint which is known as backup multiplexing and provides improved resource utilization [7].

The above and other design choices create interesting trade-offs, such as the balance between overall cost and degree of resilience in shared vs. dedicated protection [8]. The algorithm proposed in this paper employs path-based protection [9]. More specifically, survivability is provided by implementing the backup multiplexing technique under dynamic traffic demands where existing lightpaths cannot be rerouted and future lightpath requests are not known. The use of the backup multiplexing technique is selected in order to facilitate efficient resource sharing. In this framework different routing and wavelength assignment schemes that considerably enhance the spare capacity utilization are investigated and proposed. Through the proposed novel wavelength assignment scheme (that dedicates a consecutive number of wavelengths to protection lightpaths) a significant performance improvement compared to commonly used techniques is observed.

In addition, a routing algorithm for the discovery of primary and backup paths which takes into consideration the physical performance of the optical network has been incorporated in the simulations. More specifically not only the availability of optical connections is considered before they can be established but also the quality of these connections in terms of the quality factor Q. The analytical model of Q-factor for the performance evaluation of a static unicast IA-RWA introduced in [8] has been used to integrate different types of degradations triggered by various physical layer impairments and thus to reflect the overall signal quality. For the Q-factor evaluation performed in this work the impairments considered include the amplified spontaneous emission noise (ASE), cross-phase modulation (XPM) and four-wave mixing (FWM) assuming that they follow a Gaussian distribution. Also, optical filtering and the combined self-phase modulation/group velocity dispersion (SPM/GVD) effects were introduced through an eye closure penalty metric calculated on the most degraded bit-pattern.

2. Algorithm Specification

The work presented in this section solves the online version of the RWA/resilience problem, i.e. traffic requests arrive and get served sequentially without knowledge of future incoming requests [9,10]. This makes this contribution valid for usage both in the network design and – most importantly – the traffic engineering field. In addition it is assumed that only a single link could fail at any instance of time and re-routing of already established connections is not allowed. Last, the model does not take into consideration any wavelength conversion capability of the network and thus wavelength continuity across any path is a tight constraint in the problem definition.

2.1 Assumptions and Definitions

Initially we introduce the main definitions and assumptions used by our algorithm. We assume that all requests have a bandwidth demand of one unit and for each request a link disjoint backup path is required along with its primary path to provide guaranteed protection. The physical bandwidth of each link l can be divided into the following three parts: A_l, B_l, and R_l [8]. A_l represents the total amount of reserved bandwidth dedicated to primary paths carried by link l and it is not allowed to be shared. B_l is the total bandwidth occupied by all backup paths on link l and unlike A_l it can be shared by some backup paths, provided that their associated primary paths are disjoint. Specifically if two primary paths share a common link (so they are not disjoint) they will be both affected by a single network fault on this link. Therefore, their backup paths cannot share any common bandwidth since it will be necessary for both paths to be activated simultaneously in case of their common primary link failure. Finally, the residual bandwidth R_l is the difference between the physical bandwidth on link l and the total consumed bandwidth (A_l + B_l). For any future primary path established on link l, R_l is the only available bandwidth that can be used whereas for setting up a backup path on link l for a new primary path a, the available bandwidth $S_l(a)$ consists of two components : the residual bandwidth R_l and the portion of B_l (denoted by γ_l (a)) that is able to be shared for carrying this backup path. Since primary paths do not share bandwidth their cost is the sum of the weight of each link they traverse. On the other hand the cost of a backup path depends also on the number of free wavelengths used by it on each link it traverses. If a wavelength is not free and it is currently used by some primary lightpath, it can not be used by the backup path. If a wavelength is not free and it is currently used by a set of backup lightpaths S, it can be used by the new backup path with no extra cost (zero cost) if and only if its primary path is link-disjoint with the primary route of each and every backup lightpath in S. If a wavelength is free, it can be used by the backup path with the cost value equal to the weight of its links. Unlike primary paths, the path cost of a longer backup path may cost less than that of a shorter one, because of bandwidth sharing. This cost function approach leaves a higher number of wavelengths available for use from future requests, thus improving the network performance.

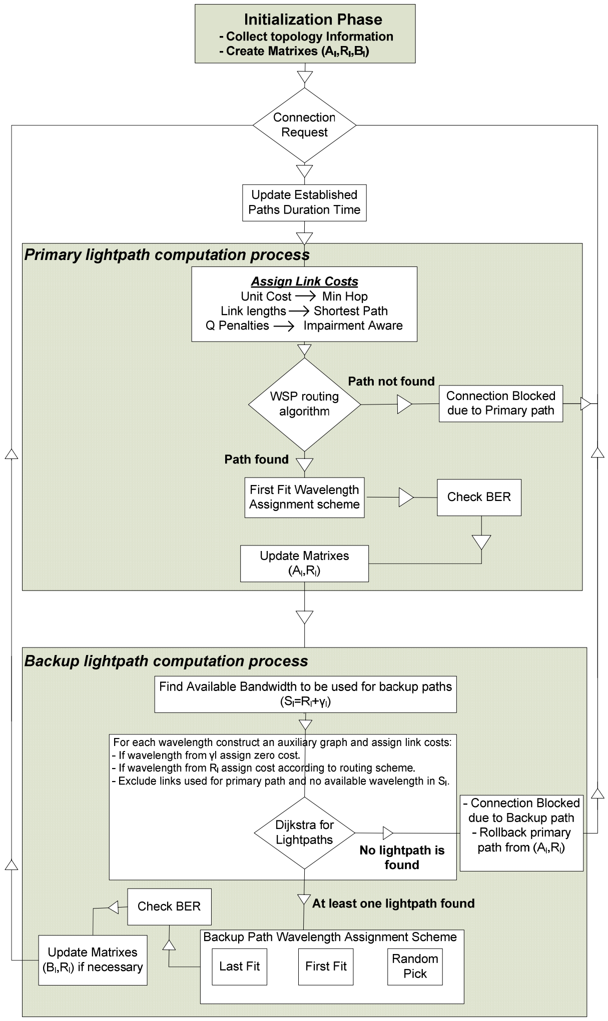


Fig.1 Flowchart of the proposed algorithm

2.2 Algorithm Description

The routing and wavelength assignment problems are solved in two separate steps. Routing is implemented based on the Dijkstra's algorithm to compute a primary and a backup path for a given demand. The wavelength assignment algorithm assigns wavelengths to the primary and backup paths favouring resource sharing between the current demand and the already established requests.

In figure 1 the flow chart of the algorithm is presented. First the initialization phase takes place, in which the algorithm collects network topology information (i.e. number of nodes, number of links, wavelengths per fiber, network connections, backup path wavelength assignment scheme) and the relevant physical layer parameters, required for the Q-penalty evaluation of each bidirectional link [2]. The required matrices to monitor the network state (A_l, B_l and R_l) are constructed, and connection requests arrive for random source and destination pairs following a Poisson arrival process with time duration that follows an exponential distribution. In the primary computation phase a primary lightpath is provisioned for each request. Three routing algorithms are available in this phase, which differentiate in terms of the weights that are assigned as link costs. By consulting the Rl matrix (that monitors the wavelength availability of each link) the following approaches are considered: If a link has no free wavelengths, its cost is set to infinite and it is not considered by the Dijkstra algorithm for the path computation. If available wavelengths exist on the link, the cost is set according to the selected routing strategy. More specifically in case of shortest path routing, link length is considered as the link cost and for impairment aware routing Q penalty is used. Finally to enable minimum hop routing, links are assigned a unit cost.

After weights are assigned to the network links, the Dijkstra algorithm is deployed on the weighted graph to calculate the shortest path for which at least one common free wavelength exists on its links. If no path is found, the connection is blocked. If at least one path is found, a list of possible wavelengths that can be allocated is identified and the first wavelength is chosen (assuming that they are sorted in increasing order) to form the primary lightpath. Furthermore a module that monitors the bit error rate (BER) of the provisioned primary path is involved that check the path quality and decides whether the path satisfies the quality constraints or not. After the primary lightpath is ready to be established, the A_l and R_l matrixes are updated to reserve the appropriate wavelength for the requested time duration.

After each request is provisioned the flow control moves to the backup computation phase. Here the available bandwidth $S_l(a)$ consisting of the residual bandwidth (R_l) and the portion of the backup bandwidth (γ_l) that can be shared is first identified excluding the links utilized by the primary path. Based on this available bandwidth, for each wavelength an auxiliary graph is generated representing the current network state. For this new topology formulation link costs are assigned based on the following strategy: On the links for which the wavelength under consideration belongs to γ_l a zero weight is assigned and if it belongs to R_l the link weight (as described above for the three different routing schemes) is assumed. On the other hand links on which the wavelength is already allocated (by primary lightpaths) are not considered in the auxiliary graph and cannot be used for the backup calculation. An attempt to find a lightpath for each wavelength follows. If no lightpath is found for any wavelength, the connection is blocked due to backup path blocking, requesting from the algorithm to roll back the updates of Al and Rl previously performed by the primary path computation phase. In case of multiple backup lightpaths computations the algorithm must allocate one, based on the selected wavelength assignment scheme. If the random pick (RP) wavelength assignment scheme is selected the lightpath is chosen randomly from the set of the available lightpaths. For the last fit (LF) scheme the lightpaths with minimum cost are identified and the last one (when sorted in increasing order) is selected, whereas for the first fit (FF) the first one from the minimum cost lightpaths is allocated. In the final step of the algorithm the BER module is involved to check the quality of the provisioned backup path (in case primary path has acceptable quality) and Bl and Rl matrices are updated for the links which residual bandwidth is used. Also for each simulation time unit the time duration of existing paths is updated and if their duration expires, primary and backup (if not shared with longer lived requests) resources are released.

3. Performance Study

The results presented in this section, are generated based on the Pan-European test network defined by COST 239 [11] that comprises 11 nodes and 26 links (figure 2) each with capacity of 16 wavelengths. Links are considered bidirectional and if a link failure occurs the traffic flow in both directions will be disrupted. Lightpaths comply with the wavelength continuity constraint and connection requests are equally likely to have any of the network nodes as source or destination. Also we assume that calls arrive with exponential inter-arrival times and their duration follows exponential distribution. A connection is blocked if a primary or a backup path cannot be provisioned whereas the quality of the established primary and backup paths is examined and if the bit error rate of the transmitted signal is less than 10^{-15}, the connection is considered failed. The results shown in the following figures are the average values over 20 independent repetitions of the described simulation configuration.

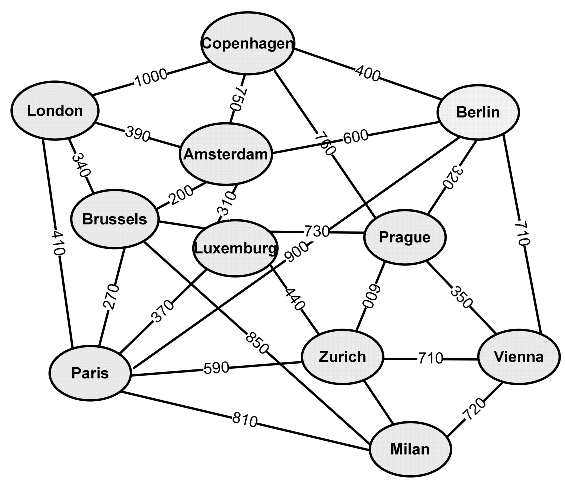
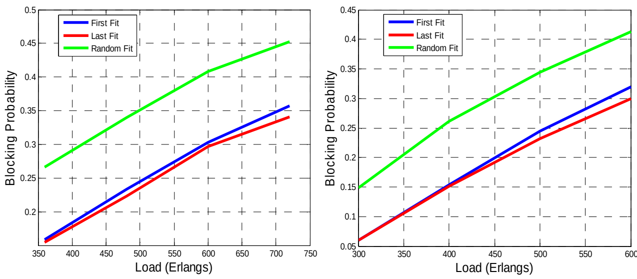


Fig. 2: Pan-European test network COST 239

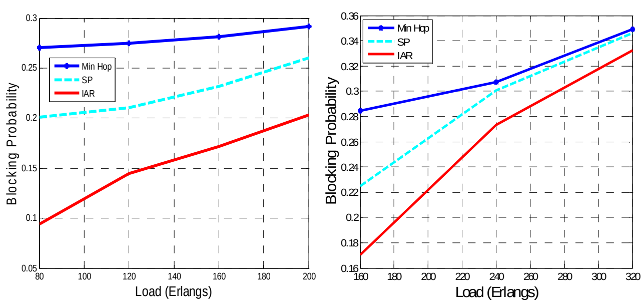
First the behaviour of the three wavelength assignment schemes i.e. Last Fit, Random Pick and First Fit when applied for the backup lightpath establishment is investigated. First fit is the wavelength assignment scheme used for the primary path establishment through all simulation results presented. In figure 3 the average blocking probabilities for Last Fit, First Fit and Random Pick are compared under different traffic loading conditions without considering signal degradation due to optical impairments. LF wavelength assignment scheme provides improved network performance compared with FF of around 2% for high network loads and significantly outperforms RP since it can offer a blocking improvement of 12% for a wide range of traffic conditions. These observations can be explained by the difference in the restoration capacity occurring from the various wavelength assignment schemes.



(a) (b)

Fig.3 Network performance for the three backup path wavelength assignment schemes under different loading conditions (a) λ=60 and μ=6,8,10,12 (b) μ=10 and λ=30,40,50,60

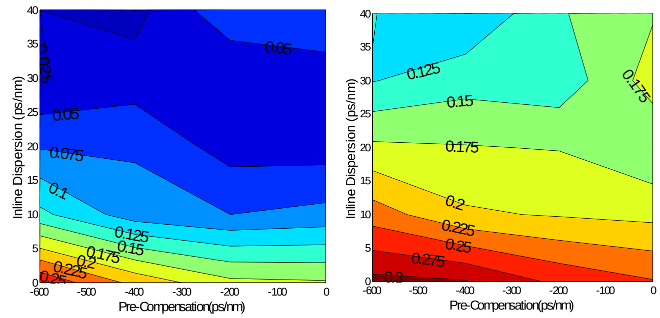
A relevant analysis [9] has shown that the Last Fit wavelength assignment algorithm maximizes the backup path link reuse although a small number of links are dedicated for backup paths that are used more than once compared to the case of the Random Pick algorithm. The increase in restoration capacity of the Last Fit over the Random Pick scheme constitutes the main reason of the lower blocking probability of the Last Fit scheme. Last Fit is a simple and fast wavelength assignment scheme able to increase considerably the backup link reuse by dedicating a small but consecutive portion of the wavelength band to backup paths, allowing a large amount of the precious residual bandwidth for the primary paths that are allocated based on a First Fit scheme.



(a) (b)

Fig. 4: Comparison of the three routing schemes for different traffic utilizations (a) λ=20 and μ=4,6,8,10 (b) μ=8 and λ=20,30,40,50

In the next step of our analysis we considered the physical layer constraints in our simulations. In figure 4 a comparison of the three routing schemes is provided for the case in which only the BER of the primary path is considered. The network performance when the proposed impairment aware routing scheme is used is significantly improved compared to the commonly used shortest path and minimum hop algorithms that are unaware of the optical layer parameters especially under low traffic utilization. For these conditions, requests are blocked mainly due to signal degradation and therefore IAR that is able to avoid low quality links demonstrates a blocking improvement of 5-10% compared with shortest path and 9-27% compared with minimum hop routing.

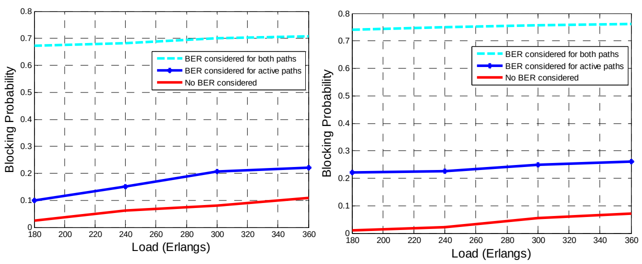


(a) (b)

Fig. 5: Blocking probabilities as a function of dispersion mapping including inline dispersion compensation and pre-compensation when (a) Impairment Aware routing or (b) shortest path routing is implemented for the calculation of the primary paths.

In figure 5 we investigated the blocking probabilities of the network as a function of the pre and inline dispersion parameters when impairment aware (fig.5a) and shortest path (fig.5b) routing are involved and BER calculation is enabled only for the primary path. The improved performance of the proposed IAR scheme comparing with the typical shortest path is quite considerable. The wide regions of optimum performance that are identified when the impairment aware scheme is implemented designate flexible dispersion engineering. A wide spectrum of the implemented dispersion maps results in a blocking percentage that varies between 0 and 15% for the IAR scheme whereas this range of blocking percentage values can be observed only for a small range of dispersion parameters when shortest path is used.

Finally we explore the blocking probabilities for IAR and MH routing under different optical impairment assumptions. As observed in figure 6, when no signal degradation is considered minimum hop routing, outperforms impairment aware routing due to its ability to allow a form of load balancing in the network. Even for moderate loading conditions MH offers an improvement of about 5%. This benefit of MH disappears when impairments come into play. In this case IAR demonstrates an improvement varying from 12 to 5% when BER is considered as a constraint to the established connection. In addition we investigate the behaviour of the network when signal quality constraints are enabled in both primary and backup paths with the same high threshold (BER must be less that 10^{-15} to accept the connection) for both paths. As depicted in figure 6 this causes a significant increase in the network blocking of around 50%.



(a) (b)

Fig.6: Blocking probabilities as a function of loading when impairments are not considered, impairments are considered only for the primary path and impairments are considered for both primary and backup paths for (a) IAR and (b) MH routing

This is an important result with regards to the network performance when the signal quality of both the working and the protection paths is taken into consideration. More specifically it indicates that although when focusing on the impairments of the working paths the blocking probability that the network suffers due to the combination of availability of resources and physical layer performance can be quite low it significantly increases with the inclusion of the protection paths which are most commonly longer than the working paths.

4. Conclusions

In this paper the problem of efficiently provisioning reliable lightpaths in a dynamic WDM network environment, considering physical layer constraints was addressed. The routing and wavelength assignment problems were solved in two stages and various algorithm options for the wavelength assignment and the routing schemes were evaluated. Simulations shown that the overall network performance can be improved when wavelength assignment algorithms able to offer high spare capacity utilization are implemented. In addition the proposed impairment aware routing algorithm incorporated in the provisioning of protected lightpaths is able to provide guaranteed quality connections in a highly efficient manner.

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