Impairment Aware based Routing and Wavelength Assignment in Transparent Long Haul Networks

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Abstract. We investigate new routing and wavelength assignment algorithms considering as constraints physical impairments that arise in transparent networks. Accounting both linear and nonlinear impairments we propose a scheme that integrates the routing and wavelength assignment to achieve an optimal combination of physical and networking performance. Through simulations of a typical long haul network the improvement achieved using the proposed approach compared to conventional RWA algorithms (i.e shortest path and first fit) is demonstrated and the significance of impairment aware routing and wavelength assignment schemes is recognized.

Keywords: Routing and Wavelength Assignment (RWA), Impairment Constraint Based Routing (ICBR), transmission impairments, transparent networks.

1 Introduction

Transparent WDM optical networks have gained strong importance, over the last years, and are considered as a viable solution to meet the rapidly increasing bandwidth demands imposed by the explosive growth of the Internet. In these networks signals are transported end-to-end optically, without being converted to the electrical domain along their path and a control mechanism is required to establish and tear down all-optical connections, called lightpaths, between source and destination nodes. This is known as connection provisioning and is achieved utilizing specific routing and wavelength assignment algorithms (RWA). The development of an intelligent control plane able to provide efficient connection provisioning is an important traffic engineering problem for minimizing the cost and improve the efficiency of resource utilization. The traditional RWA schemes and formulations [1][2] make the routing decision based only the network level conditions such as connectivity, capacity availability etc. and they don't include the impact of physical layer in the overall network performance. However, in transparent networks the transmitted signal has an analogue nature and when it propagates through optical fibers and OADMs/OXC nodes it experience impairments that accumulate.
Recently, various Impairment Aware Routing and Wavelength Assignment (IA-RWA) algorithms have been proposed that take into consideration the impact of the

physical network performance when assigning connections.[3][4][5][6] The challenges of an IA-RWA approach originate from the seemingly diverse nature of the networking and physical performance issues that have to be considered. From one hand there are the impairments that are existent in the physical layer and on the other hand there are the networking aspects (blocking probability, end-to-end delay, and throughput) that capture and describe the overall performance of the WDM optical network. It is evident, that all these heterogeneous issues have to be modeled and unified under a properly designed framework that will provide a solution for the RWA problem, which will be both feasible and efficient at the same time.

This paper extends the work presented in [7] by implementing an IA-RWA scheme for an all optical long haul network. This is achieved by also considering all the nonlinear degradations that are imposed on the signal when it transverses the fiber Therefore, the degradations due to cross-phase modulation (XPM), four-wave-mixing (FWM) and self phase modulation (SPM) have been analytically modeled and their combined influence has been integrated into the same figure of merit function, the Q-factor, along with the linear degradations. In addition, due to the wavelength dependence of nonlinear impairments, a novel wavelength assignment scheme is proposed to provide improve performance compared to conventional wavelength assignment schemes like first fit and random wavelength assignment.

2 Modeling of transmission induced impairments

2.1 Transmission link architecture

A challenging task in the engineering of transparent and dynamically reconfigurable optical networks, where regenerators are absent from the switching nodes is to deal with the accumulation of the impairments over the cascaded fiber sections. Different techniques to increase propagation distances and achieve transparency at least for a few links, have been identified by inserting specific devices, such as Raman amplification, dynamic gain equalizers [8], or dynamic dispersion compensators. This solution has the drawback of high cost, competing with the savings of optoelectronic interfaces. Alternatively, it was suggested to use dispersion management rules and EDFAs to achieve acceptable signal quality at the end of the path. In our simulation case the second approach is adopted by using a specific dispersion management scheme that eliminates the resonant built up of nonlinear penalties. Moreover it is simple and cost-effective to implement particularly in B&S OADM and OXC networks [9]. According to this scheme each amplifier span is under-compensated, whilst pre-compensators are required at the OADMs and OXC sites to reduce the total amount of the accumulated dispersion.

The schematic diagram of the transmission link that has been considered for this study is illustrated in fig. 1. At the end of each SMF span there is a double stage EDFA that is used to compensate the corresponding losses. Also, a DCF fibre module exists at the intermediate stage of the EDFAs to be used for the appropriate dispersion management. At the beginning of the link there is also a pre-compensating fiber module, whilst post-compensation may also be provided at the end of the link. The parameters P_{inSMF}, P_{inDCF}, $P_{inPRE,}$ and P_{inPOST} represent the peak power levels of the signal pulse-stream at the input of the SMF, DCF and PRE, POST fibers sections, respectively. The rest of their corresponding parameters are summarized in Table 1.

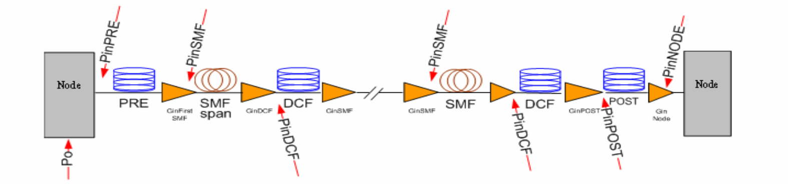


Fig. 1. The transmission link architecture.

Parameters	SMF	DCF
Attenuation a (dB/km)	0.25	0.5
Nonlinear index coefficient n (m^2/W)	2.6 10^{-20}	3.5 10^{-20}
Chromatic Dispersion Parameter D(s/m^2)	17 10^{-6}	-80 10^{-6}
Dispersion Slope dD/dλ(s/m)	0.085 10^{3}	-0.3 10^{-3}
Effective Area A_{eff}(m^2)	65 10^{-12}	22 10^{-12}

Table 1. Parameters of the fibers used on each link

2.2 Q factor formulation

As the signal propagates through a transparent network it experiences the impact of a variety of degrading phenomena that introduce different types of distortions. For example, there are distortions of almost "deterministic" type related only to the single channel's pulse stream, such as the interplay of SPM and GVD or the optical filtering introduced by the MUX/DEMUX elements at the OXC/OADMs. The other category includes degradations of pertubative nature, introduced by the ASE noise, WDM nonlinearities such as Four-Wave-Mixing (FWM) and Cross-Phase-Modulation (XPM) and finally crosstalk.
To incorporate the physical layer impact of a WDM network into the routing procedure there is a need the corresponding impairments to be evaluated in an accurate and time efficient way. Numerical modeling of a long haul WDM network is computationally a very heavy procedure that might take several hours to produce a single result. On the other hand, analytical or semi-analytical models can be also derived for each degradation to provide an instantaneous estimation of their relative influence. What should be noted in this case is the way all the different types of degradations can be integrated to a single physical layer performance metric.
In this work, Q-factor metric has been used to integrate all the different types of degradations and thus to reflect the overall signal quality. Several assumptions have been considered to achieve this. The first is that any interplay among the different

types of degradations is ignored. Furthermore, the statistics of the distortions that have pertubative nature (such as ASE, Crosstalk, FWM and XPM) follow a Gaussian distribution. Finally, concerning the SPM/GVD and optical filtering effects, these are introduced through an eye closure penalty metric calculated on the most degraded bit-pattern. The corresponding Q-factor penalty on the k-link into the network is then given according to the following equation (1).

$$Q_k = \frac{pen_k \cdot P}{\sqrt{\sigma^2_{ASE,k} + \sigma^2_{crosstalk,k} + \sigma^2_{XPM,k} + \sigma^2_{FWM,k}}} \tag{1}$$

where pen_k is the relative eye closure attributed to optical filtering and SPM/group velocity dispersion (GVD) phenomena, calculated semi-analytically through single channel simulations according to the model proposed in [10]. Furthermore, $\sigma^2_{XPM,k}, \sigma^2_{FWM,k}$ represent the electrical variances of the XPM and FWM induced degradations, which are calculated according to [11], [12], and are added to the corresponding electrical variances of the ASE noise $\sigma^2_{ASE,k}$ and the generated crosstalk $\sigma^2_{crosstalk,k}$.

3 Proposed IA-RWA Scheme

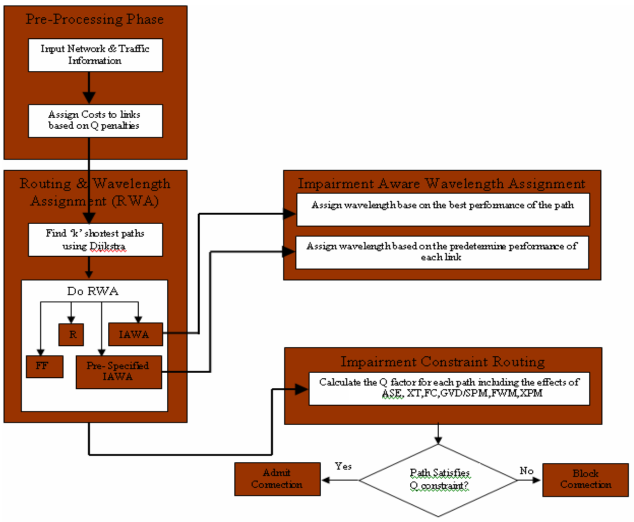


Fig. 2. Flow chart of proposed IA-RWA.

The flowchart of the proposed IA-RWA scheme is shown in Fig. 2. Initially the preprocessing phase collects all the information related to the network and the traffic demands. Information such as the topology of the network, the link capacities, the fiber characteristics, dispersion map applied (pre, post and inline dispersion compensation), span lengths, attenuation of each span, the launched powers at each fiber segment, the noise figure of the amplifiers, the nodes architecture, the channel spacing and the link capacities are required by the algorithm for the physical impairments evaluation. Moreover information concerning the number of requests, the bit rate and the source destination pairs are required to identify the traffic demands for the static routing that is considered here. Then, based on the collected information a Q-factor penalty is assigned (according to eq.1) as a cost parameter to each link reflecting the corresponding degradation on the signal quality.

The RWA phase is initiated once the link costs have been found. This phase assigns paths (incorporating the physical impairments as weight of the links or applying conventional shortest path by utilizing link lengths as link weights) and wavelengths to all the demands. The RWA problem is handled in two steps. In the first step it is treated as a single-joint optimization problem as this has been shown to be the optimum approach [3], [13]. In order to simplify the optimization task and reduce the computation complexity the following approach was taken: The "*Find k shortest paths*" part of the algorithm identifies the *k* shortest paths for each source-destination pair. These *k* paths are the input for the "*Do RWA*" module (Fig. 2), which gives to the algorithm the flexibility to select the optimum path among the *k* input paths in terms of load balancing and physical layer performance. We should note that the *k* parameter is set to 3 since this value proved to be a good compromise between efficiency and computational overhead. At the end of this step the algorithm identifies the minimum number of wavelengths required to carry the requests and specifies the paths that should be established. If this number is less than the wavelengths that are available in the network then an additional blocking percentage due to lack of network resources is calculated at this stage.

Having identified the minimum number of required wavelengths along with all the established paths, the algorithm may be used to implement the specific wavelength assignment scheme. This may include either conventional strategies that are unaware of the physical performance status of the connection, (such as first fit (FF), and random fit (RF)) or strategies that take into consideration the corresponding impairments. For the later case two different schemes were examined, a direct implementation of the Impairment Aware Wavelength Assignment-(IAWA), as well as, a Pre-Specified (IAWA) scheme which for the first time is proposed here.

In the first fit (FF) scheme all wavelengths that are numbered and among those available on every link of the path the one with the highest number is selected. In the Random wavelength assignment (RF) scheme, the space of the wavelengths that are available on the required path is firstly identified and then one wavelength is randomly chosen.

In the Impairment Aware Wavelength Assignment (IAWA) scheme, the lightpaths are established according their Q-factor performance. More specifically, each potential lightpath, among those available on the path, is characterized in terms of Q-factor taking into consideration the already established wavelength connections. The one having the optimum performance is finally selected.

A novel Pre-Specified Impairment Aware Wavelength Assignment scheme (PS-IAWA) that offers an advanced performance in terms of computational efficiency has been also considered. According to this scheme, and prior to the wavelength assignment process, all the wavelength locations on per link basis are characterized and ordered in terms of their Q-factor value. Then the algorithm will define the paths and for each one of them the space of the common wavelengths that are available across its links. The final selection will be made based on the pre-specified order created at the beginning.

After the wavelength assignment is completed the control is transferred to the Impairment Constraint Based Routing module which verifies the Q factor constraint considering all the physical impairments involved across the path. In this case the overall Q factor for each selected lightpath is calculated considering the accumulated amount of degradation A path is accepted when the Q-factor value at the destination node is higher than 11.6dB, which corresponds to a BER of 10^{-15} after forward error correction (FEC) is utilized at 10Gbit/s and the connection is established, in any other case the path is rejected and the connection is blocked.

4 Transparent Network Simulations

The performance of our proposed IA-RWA scheme was compared with other RWAs under a Long Haul network representing a core Pan-European network.

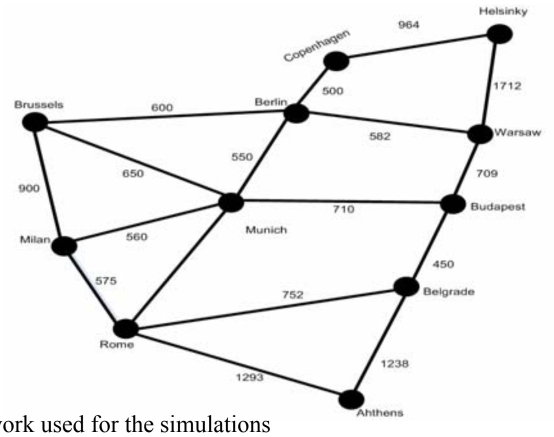


Fig. 3. The network used for the simulations

The network topology as illustrated in Fig. 3 consists of 11 nodes corresponding to 11 different European cities interconnected by 16 bidirectional links. Link lengths cover a range from 400 to 1750km, with the average link length being 813km. We assume that there are connection requests between every possible pair of nodes and therefore 55 end-to-end connections are requested to be established.

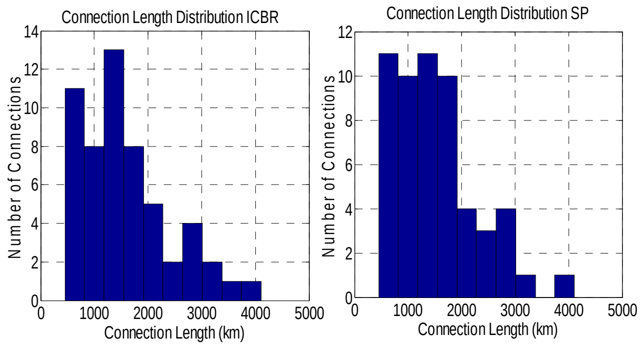


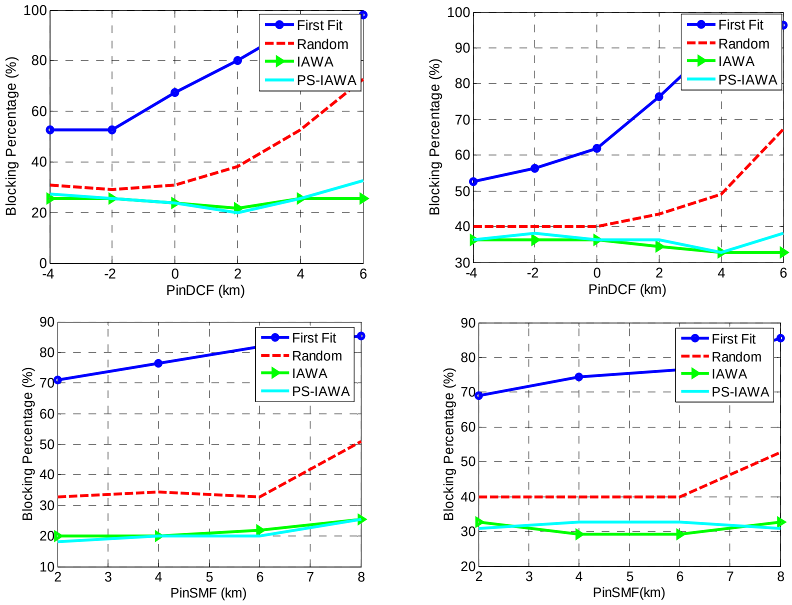
Fig. 4. The connection length distribution for ICBR and Shortest Path (SP).

The distributions of the lengths of these connections are depicted in Fig. 4 when Impairment Constraint Based Routing (ICBR) and Shortest Path (SP) algorithms are used to establish the connections. The average connection length when SP is used is 1480km and for the case where ICBR is used to satisfy the requests the average connection length is a bit higher at 1518km.

Based on the topology introduced above the network performance is evaluated in terms of blocking percentage which is defined as the ratio of the total number of connections that are unable to be established due to capacity and performance constraints divided by the total number of connections requests. In the following simulations we have considered that 40 wavelengths can be located at each link in a 50GHz channel spacing. Initially for a specific dispersion map where the residual dispersion after each 80 km SMF-DCF segment is 30ps/nm and the amount of pre dispersion is -400ps/nm, the overall blocking percentage is calculated as a function of the channel power levels at the input of the inline modules. The corresponding results are presented in figures 5a,c and 5b,d for both ICBR and shortest path (SP) routing schemes.

It can be noticed that by selecting a proper wavelength assignment scheme the overall blocking percentage of the network can be considerably improved. Our proposed PS-IAWA outperforms first fit and random fit schemes and exhibits similar performance behavior with the more computational intensive IAWA. This is because the latter scheme calculates the Q factor of all potential wavelengths that can be used to establish a lightpath each time a path is considered, whereas the PS-IAWA does not require any further calculation once the order of wavelengths has been defined at the beginning. For low power levels in the DCF segment (-4dB to 2dB) the observed improvement is around 5% between the IAWA schemes and the random WA scheme, and more than 20% compared with first-fit scheme. The significant advantage of IAWA schemes is viewed when the power levels of the DCF increase. In such cases, a considerable improvement of 20% to 40% is earned by introducing the IAWA schemes compared with the random fit-case. This is even more for the first fit wavelength assignment scheme. Similar conclusion can be derived as the power in the SMF fiber increases. For this case the benefit is more than 10% for the majority of the input powers between the IAWA schemes and the random WA. Therefore by applying the proposed IAWA schemes in the network a wider range of input powers can be tolerated in both SMF and DCF segments. Also introducing our ICBR algorithm for the path computation procedure proves to be beneficial against the conventional shortest path as demonstrated by comparing figures 5a and 5c with 5b and 5d respectively. An appreciable improvement, around 10% is indicated at least for cases where the blocking percentage is at an acceptable level as it appears when IAWA schemes are implemented. Conclusively, the combination of a proper WA assignment scheme with an ICBR algorithm provides significant performance improvement in the network.

(a) (b)



(c) (d)

Fig. 5. Blocking percentage for ICBR (a,c) and SP (b,d) as a function of the power level at the DCF and the SMF segments for different Wavelength Assignment schemes.

In the next step of our analysis we investigate the blocking percentage of the network as a function of the pre and inline dispersion parameters. The results depicted in Fig. 6 represent the blocking percentage for each of the considered wavelength assignment schemes when the ICBR algorithm is involved. The advantage of the proposed PS-IAWA scheme comparing with the typical first fit and random-fit is quite considerable. The wide regions of optimum performance that are identified when impairment aware schemes are implemented designate flexible dispersion engineering. The whole spectrum of the implemented dispersion maps results in a blocking percentage that varies between 20% and 35% for both IAWA schemes. This range of blocking percentage values is impossible to be obtained using first-fit assignment, whilst and it can be observed only for a small range of dispersion parameters when random WA scheme is used.

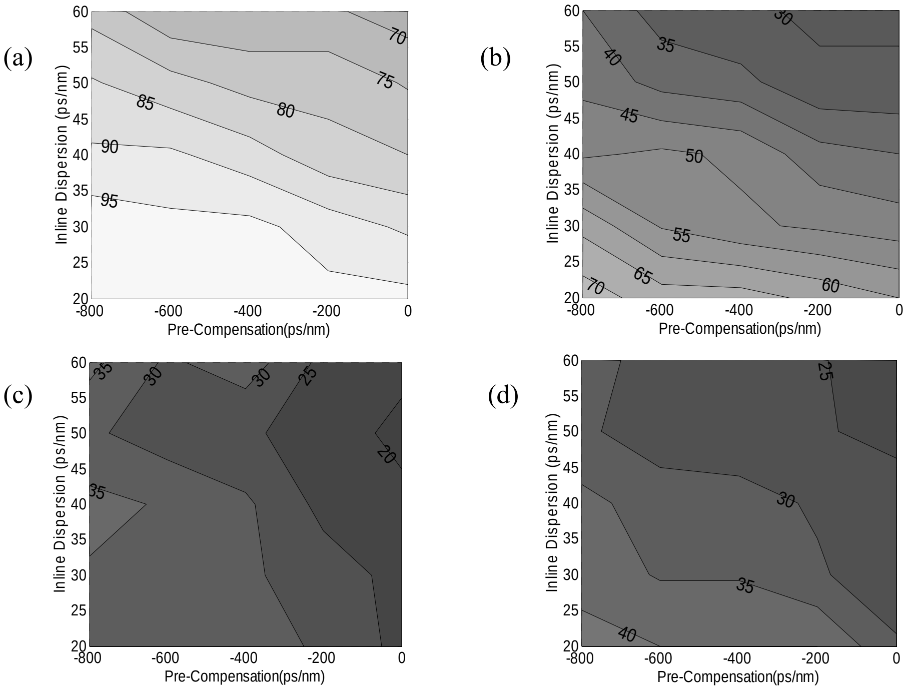


Fig. 6. Blocking percentage as a function of the dispersion mapping implementing (a) First Fit (b) Random Wavelength Assignment (c) Impairment Aware Wavelength Assignment and (d) Pre Specified IAWA scheme in combination with the ICBR algorithm

5 Conclusions

In this study a new Impairment Aware Routing and Wavelength Assignment algorithm was developed applicable for long haul applications. A number of linear and nonlinear impairments have been taken into account including ASE noise, crosstalk, filtering effects, SPM/GVD, cross phase modulation and four wave mixing. Through extensive simulations it is shown that the overall network performance can be significantly improved if ICBR in combination with Impairment Aware Wavelength Assignment is used to establish the connections.

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