Cost Functions for CAC/RWA in Dynamic Optical Networks under GVD, SPM and XPM

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***Abstract*—The constraints of optical Quality of Service (QoS) in transparent optical networks are herein addressed through empirical cost functions. The joint effect of group velocity dispersion (GVD) and nonlinear effects Cross-Phase Modulation (XPM) and Self-Phase Modulation (SPM) are considered through extensive numerical simulation in single and multi-span systems. A representative cost function is then found to encompass the physical impairments of a given link utilization (i.e., launched power, wavelength grid, number of active channels, etc). Finally, this link-based approach is used to demonstrate the simplification of the algorithms for Connection Admission Control (CAC) integrated to the algorithm of Routing and Wavelength Assignment (RWA) in dynamic lightpath provisioning with end-to-end optical QoS guarantees.**

***Index Terms*—** Algorithms of route allocation and wavelength assignment, dynamic optical networks, nonlinear effects in optical fibers, optical QoS.

I. INTRODUCTION

Transparent optical end-to-end dynamic connections are enabled by the introduction of optical switching in some nodes of the network [1]. It is believed that the next generation networks will be characterized by domains of transparency, i.e., optical sub-networks having on their edges elements that carry out optical-electro-optical (O-E-O) conversions. Inside these domains of transparency the end-to-end signal quality needs to be preserved. The quality of service (QoS) perceived by electronic client networks are directly impacted by signal degradation of such connections [2]. Therefore, a mechanism for Connection Admission Control (CAC) integrated to the algorithm of Routing and Wavelength Assignment (CAC/RWA) must be put in place to manage the degradation caused by (nonlinear) interferences between lightpaths. A connection request that arrives at the optical network control plane will be served whenever the level of QoS provided by the optical layer meets the values demanded by the applications of the client networks [3]. Such levels of QoS are traded across the optical and the client networks through an Optical Service Level Assignment (OSLA), in which the aimed performance can be established from parameters like Bit Error Rate (BER).

Provision of QoS in dynamic optical networks has been extensively studied [2]-[8]. In particular,

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effects such as crosstalk in Optical Cross-Connects (OXCs) [4], accumulation of Amplified Spontaneous Emission (ASE) [5], and Polarization Mode Dispersion (PMD) [6], [8] are taken in account in RWA algorithms. However, all these strategies only deal with linear effects. Large fluctuations in BER may also appear after the activation (or deactivation) of lightpaths. Nonlinear effects, such as Four Wave Mixing (FWM), Cross-Phase Modulation (XPM), interweave the performance of the channels as long as there are links shared by lightpaths throughout the network.

The main limitation in the development of algorithms for CAC/RWA taking into account nonlinear effects in dynamic networks is its intrinsic complexity. Provided that it must take in account the global impact, i.e., across the whole set of lighpaths, during the admission of a new connection [7]. In this work it is proposed, for the first time, a methodology for the integration of the nonlinear effects of XPM and Self Phase Modulation (SPM), acting along with Group Velocity Dispersion (GVD), to the algorithms of CAC/RWA.

The method is based on the numerical simulation of Single Mode Fiber (SMF) optical links [9] arbitrarily varying the transmitted power, the length of span, the number of spans, the channel spacing, and the number of channels in the system. The single metric to summarize the diversity of scenarios is the eye-closing penalty. A methodology is proposed for the determination of appropriate cost functions. A CAC/RWA with low complexity is demonstrated and tested over diverse network topologies.

The remainder of this paper is organized as follows. Section II introduces the physical impairments XPM, SPM and GVD. Section III brings the methodology to compose the proposed cost function. A CAC/RWA algorithm based on cost function is presented in Section IV along with numerical results for different network scenarios. Finally, Section V brings a discussion on the limits of use for the cost function approach and the proposals for future works.

II. GVD, SPM AND XPM IN OPTICAL FIBERS

We illustrate the problem for one span WDM system with two wavelengths with optic carriers f_1 and f_2, that propagate through a single-mode fiber. The propagation is modeled with the pair of coupled nonlinear Schrödinger equations shown in (1) [10]

$$j\frac{\partial A_{1,2}}{\partial z}+\frac{j}{v_{gn}}\frac{\partial A_{1,2}}{\partial z}-\beta_{2n}\frac{\partial^2 A_{1,2}}{\partial T^2}+ +\gamma\left(\left|A_{1,2}\right|^2+2\left|A_{2,1}\right|^2\right)A_{1,2}=\frac{j\alpha}{2}A_{1,2} \tag{1}$$

where α is the attenuation and γ is the nonlinear coefficients of the fiber; z and T are, respectively, the distance and time; and A_n, v_{gn} and β_{2n} (n= 1 or 2) represent, respectively, the electric field, the group velocity and the parameter of group velocity dispersion for the signal of each optical carrier f_n.

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In general, (1) needs to be solved numerically. However, an illustrative analytical solution can be found for the case of CW (continuous-wave) signal propagation, as shown in (2)

$$A_1(L) = \sqrt{P_1}\,\exp[j\phi_1] \tag{2}$$

Where L is the length of the fiber, P_1 is the incoming power in the fiber for the optical frequency f_1 and ϕ_1 is the nonlinear phase deviation given by (3)

$$\phi_1 = \gamma\left[\frac{1-\exp(-\alpha L)}{\alpha}\right](P_1 + 2P_2) \tag{3}$$

It is noteworthy that (3) is a combination of SPM (term proportional to P_1 itself), and XPM (term proportional to P_2).

Thus, XPM leads the optic phase of a channel to become modulated by the launched power of the other channel. The role of GVD is to convert these fluctuations of phase into amplitude variations, generating what is called crosstalk [11]. The same phenomenon occurs when there are more than two channels interacting, as in typical WDM systems. In this case, a specific channel has its phase modulated according the transmitted power of the other channels and their proximity in the wavelength grid. The SPM interacting with GVD will cause variations in the format of the bit itself (it is also able to compress the bit reducing the inter symbol interference). Thus, XPM, SPM and GVD interact with each other in the determination of the optical link performance as a whole.

III. METHODOLOGY FOR DETERMINATION OF COST FUNCTIONS

It is well known that nonlinear effects in general, and the effects of XPM and SPM in single mode fibers in particular, are heavily dependent on transmitted power levels and channel spacing. Moreover, the optical fiber length and system bit rate also have an influence on the power penalty caused by these effects [10]. Provided that the cost functions must be an appropriate representation of nonlinear effects, it is essential that the weighting of the parameters described above reflects their real impact on system performance.

A proposal for an empirical cost function is presented in this Section. It will be used in the algorithm for CAC/RWA to estimate the impact (eye-closure penalty) of the physical layer on blocking probability, which is a key metric in the performance of dynamic optical networks. The empirically found equation given in (4) properly translates system parameters into a cost variable. It is indicated by the high correlation coefficients between (4) and eye-closure penalty values for single and multi-span lightpaths obtained from extensive numerical simulations.

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$$C = 0{,}6F_{spacing}(F_{power} + F_{channels}) + 0{,}2F_{fiber\_length} + 0{,}2F_{br} \quad (4)$$

$F_{spacing}$ is the factor that includes the influence of channel spacing and, similarly, F_{power} weighs the transmitted power, $F_{channels}$ assesses the overall use of neighboring channels in relation to the channel that is being analyzed, and finally, F_{fiber_length} accounts for the length of the fiber while F_{br} considers the system bit rate.

TABLE I. WEIGHTS TO THE CHANNEL SPACING

Spacing Factor	
Channel Spacing (*GHz*)	$\mathbf{F_{spacing}}$
50	1,0
100	0.8
200	0.4

TABLE II. WEIGHTS TO THE TRANSMITTED POWER

Power Factor	
Power (*dBm*)	$\mathbf{F_{power}}$
0	0.3
7	0.7
10	1.0

TABLE III. WEIGHT TO THE LENGTH OF THE FIBER

Length Factor	
Length of the fiber (*km*)	$\mathbf{F_{fiber\_length}}$
L	L/10

TABLE IV. WEIGHT TO THE BIT RATE

Bit Rate Factor	
Bit Rate (*Gb/s*)	$\mathbf{F_{br}}$
T	T/100

The $F_{channels}$ factor depends on the arrangement of neighboring channels. The penalty imposed on a channel can be neglected if a given channel is far from the one under analysis [12]. For the sake of simplicity, we define 3 regions of interest, as shown in Fig. 1, given by multiples of the spacing grid employed. For instance, considering that the WDM system has 50 *GHz* channel spacing, region 1, 2 and 3 comprise, respectively, the channels that are at 50 *GHz*, 100 *GHz* and 150 *GHz* from the channel under analysis. The channels beyond region 3 will have little or no influence on the channel under analysis for the levels of power considered, thus they are neglected in the present investigation. Therefore, there are 3^3 link use combinations with the corresponding $F_{channels}$, which are given in the Appendix A.

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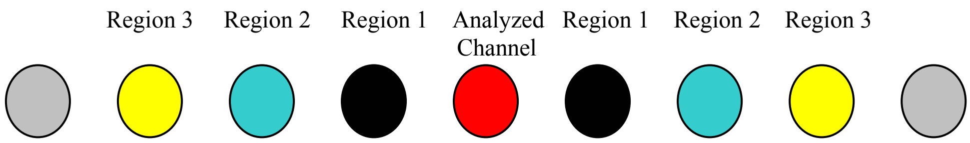

Fig. 1 - Regions to be considered to calculate the channel factor.

Tables I-IV show the values that each factor must assume depending on the characteristics of simulated WDM system. These values have been empirically adjusted so that the cost function best represents the penalties obtained in the simulations. The Split-Step Fourier method is used to solve the nonlinear Schrödinger equation [10]. Actually, the propagation through nonlinear Schrödinger equation is used for the whole electric field of the set of channels in WDM system, instead of the coupled equations system in (1).

SMFs with the following parameters are considered: attenuation of 0.25 *dB/km*, nonlinear refractive index of 2.45×10^{-20} m^2/W, dispersion at 1550 *nm* of 17 *ps/nm-km,* chromatic dispersion curve slope of 0.056 ps/nm^2-*km* and effective area of 78.5×10^{-12} m^2. The bit rate is set at 10 *Gb/s* for (NRZ external modulated) sequences with 128 bits. The fiber spans vary from 10 to 50 *km*, and we consider up to five channels sharing the same span. Although the approach using the electric field of the whole set of channels enables also FWM effect to be analyzed, its impact on the system is negligible due the high value of GVD in SMFs.

The main goal is to perform extensive simulations in order to evaluate different link use scenarios. We consider a particular link use scenario: the number of channels and their location in wavelength grid in use, and the link length itself. This scenario can be represented by the corresponding eye-closure penalty due to the joint effect of GVD, XPM and SPM on the channel under analysis. The next step is to test different cost functions. The metric used is the correlation between the empirical expression and the eye closure penalty. For each simulated scenario we obtain a corresponding cost by feeding (4) with the parameter in Table I-V, accordingly, for diverse link use scenario in both single and multi-span analysis. Although equation (4) yielded very satisfactory outcomes, there may be other cost functions with equal or better results.

Provided that the objective is the use of the cost functions in transparent optical networks, wavelength grid, power per channel, and bit rate are considered as invariable parameters. The arbitrarily chosen variables for the investigation to design the cost function shown in (4) are: i) fiber length, since each span crossed by a lightpath may vary in length; ii) number of channels simultaneously transmitted in each span, once in dynamic optical networks this number changes over time.

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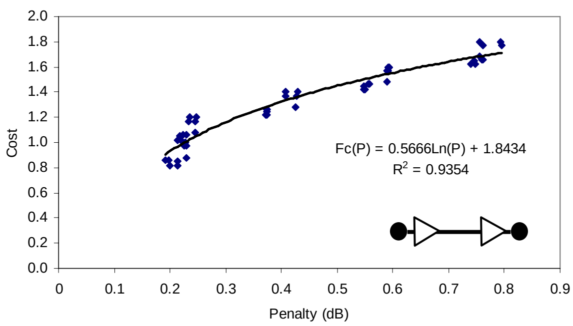
Moreover, the relationship between penalties for single and multi-span lightpaths is capital for extrapolating the proposed link analysis to RWA/CAC in transparent optical networks. The aim is to use cost accumulation as a proxy for signal degradation simplifying, as a result, the procedures for selecting best (available) routes across the network.

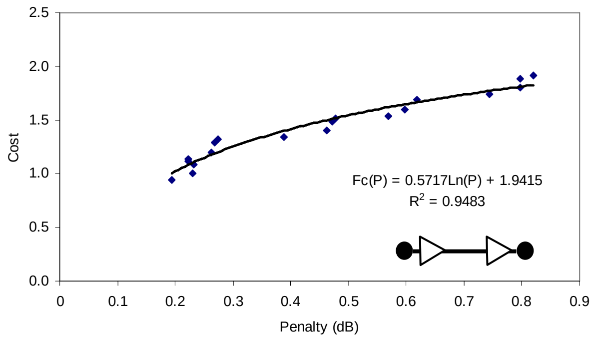
A. Single-span analysis

The Fig. 2 shows scatter plots for cost vs. penalty and a fitting function for lightpaths crossing a single span for different wavelength grids and transmitted power. The abscissa brings the eye-closure penalty for a given link use scenario. The ordinate represents the value of the calculated cost in accordance with (4) using the same parameters of the simulated WDM system.

Although the link span ranges from 10 to 50 *km* and the number of wavelengths in use varies from 0 to 5, the corresponding cost values from (4) are not widely scattered. This means that the penalty is very well represented by the proposed cost function. This allow us to fit a simple (and easily invertible) $f_c(P)$ function which relates cost and penalty with significantly high levels of correlation (R^2 above of 0.9) for all the simulated cases. In addition, these functions point to trends in the relationship between cost and penalty. Such trends can be used to estimate end-to-end signal degradation in multi-hop lightpaths through the equivalence of cost accumulation along their hops and power penalty. However, before that, the cost function must be also evaluated in multi-span scenarios. Moreover, multi-span results must be related to single-span penalties in order to check the validity of the single-span cost accumulation approach.



(a)



(b)

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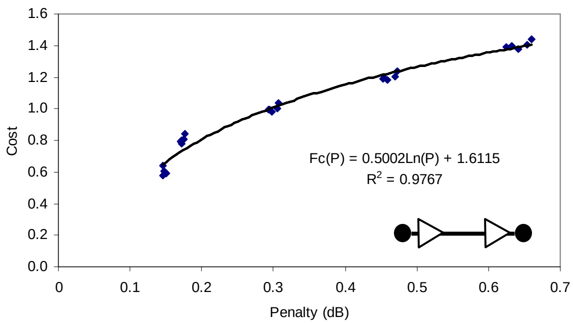

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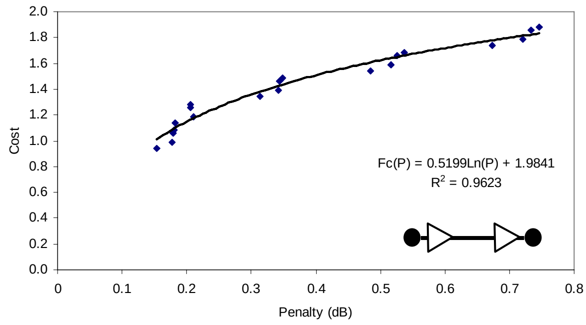
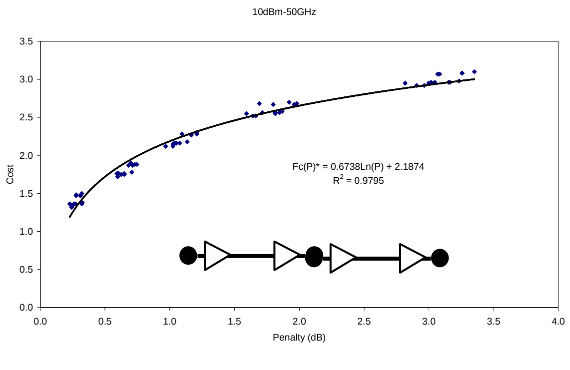


(d)

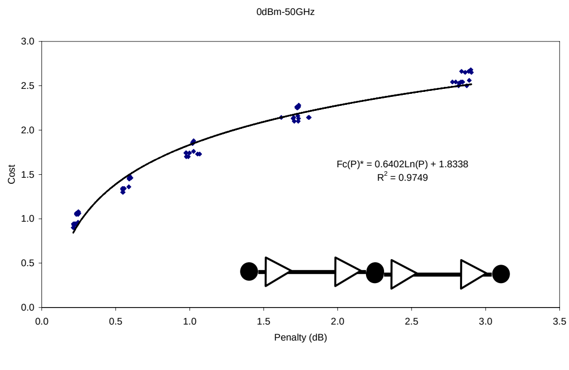
Fig. 2 - Cost x penalty for single-span lightpaths at 10 *Gb/s*: (a) channel spacing of 50 *GHz* and power of 0 *dBm*; (b) channel spacing of 50 *GHz* and power of 7 *dBm*; (c) channel spacing of 200 *GHz* and power of 10 *dBm*; (d) channel spacing of 100 *GHz* and power of 10 *dBm*.

B. Multi- span analysis

Figs. 3a and 3b show the scatter plot and the fitting function relating cost and penalty for transparent lightpaths crossing two spans. The total length in this case is between 20 and 100 *km* while the results for four-span connections, in Figs. 3c and 3d, the total distance range from 10 to 100 *km*. The number of active channels, as in the single-span analysis, is between 0 and 5. It is clear from results in Fig. 3 that equation (4) also holds for multi-span connections as a means of representing the degradation of signal quality. Simple log functions also fit the data with the high correlation levels similar to the ones found for single-span systems. Therefore, cost functions can be used for both single and multi-span links connecting the OXCs. Furthermore, lightpaths sharing multi-spans may now be taken as a representative (and somehow pessimistic) case for the multi-hop transparent connections enabled by the concatenation of single-span links between OXCs.



(a)



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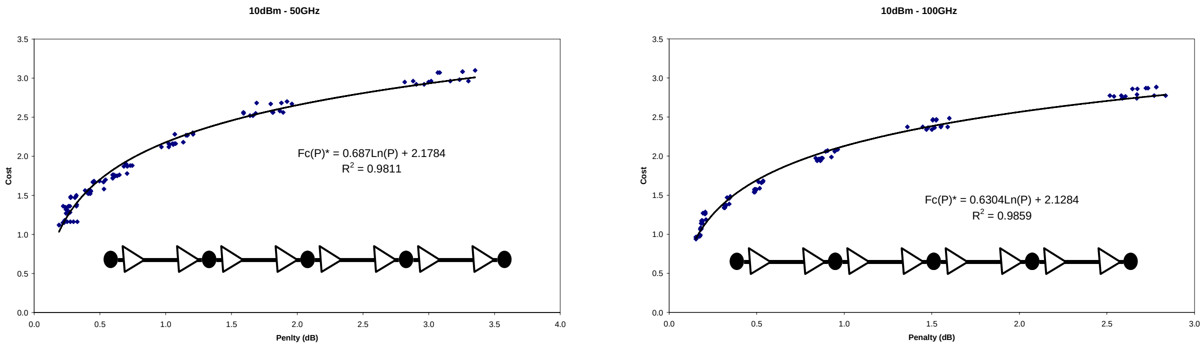

(c) (d)

Fig. 3 - Cost x penalty for multi-span lightpaths at 10 *Gb/s*: (a) channel spacing of 50 *GHz,* power of 10 *dBm* and 2 spans; (b) channel spacing of 50 *GHz*, power of 0 *dBm* and 2 spans; (c) channel spacing of 50 *GHz,* power of 10 *dBm* and 4 spans; (d) channel spacing of 100 *GHz*, power of 10 *dBm* and 4 spans.

C. Cost accumulation and end-to-end penalty in networks built with single-span links

Whether cost accumulation appropriately represents end-to-end penalty in a multi-hop network built with single span links is herein investigated. Fig. 4 presents the analyzed equivalence of lightpaths setups.

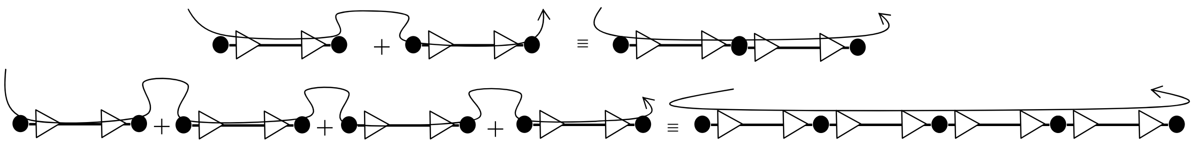

Fig. 4 – The process of accumulation cost across H hops

The accumulation of cost across *H* hops is transformed into penalty values using the inverse from fitting function $f_c(P)$ for single-span systems as given in (5).

$$P_{ca} = f_c^{-1}\left(\sum_h C_h\right) \tag{5}$$

Provided the fitting produces a logarithmic function, the accumulation of cost will result in a product of individual penalties. This may lead to very pessimistic analysis. However, a tighter bound can be found by relating the penalty results from multi-span simulations (P_{ms}) and the ones through accumulated cost calculations P_{ca}. Fig. 5 presents the scatter plot for P_{ms} vs. P_{ca}. A linear fitting yields $f_p(P_{ca})$ for each network scenario allowing more realistic end-to-end penalties (P_T) for signal quality in multi-hop lightpaths; as given in (6) and shown in Fig. 5 for each link use scenario.

$$P_T = f_P\left(P_{ca}\right) \tag{6}$$

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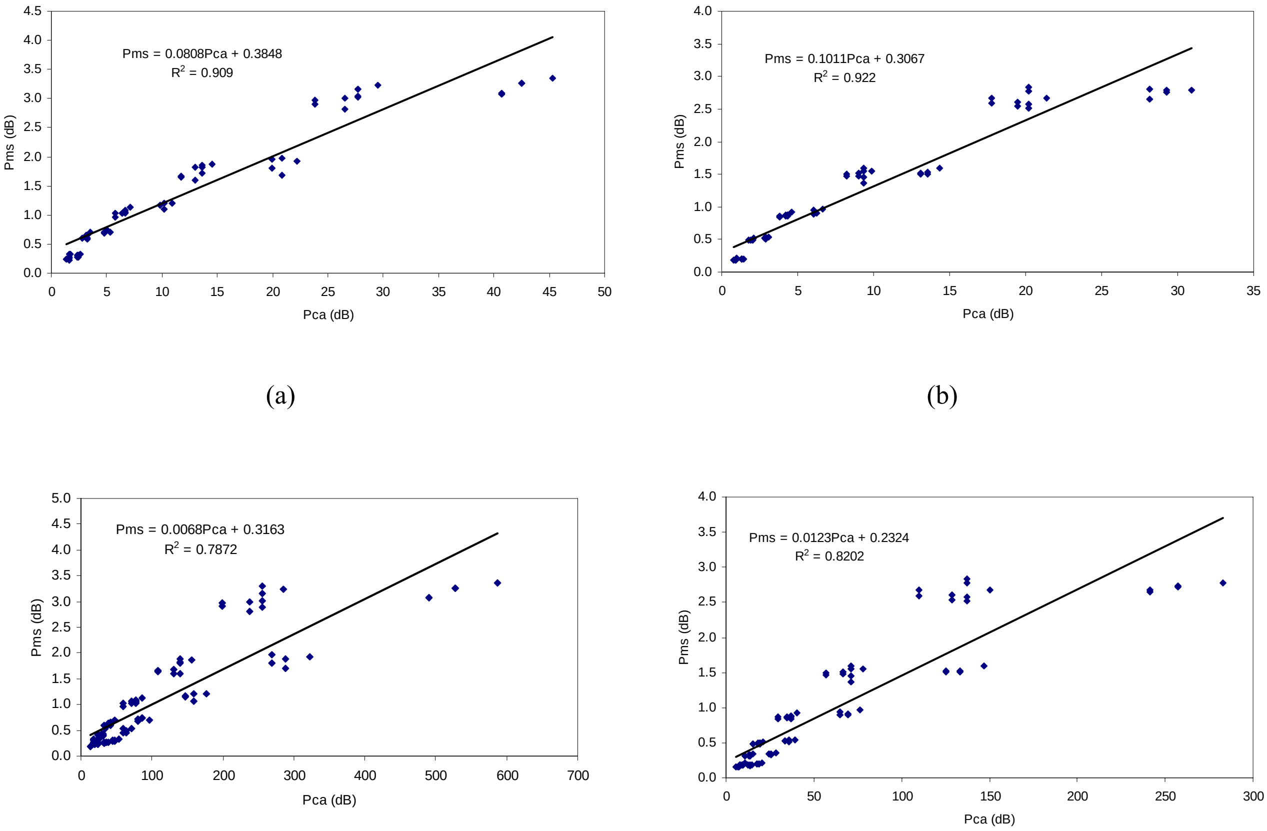

(a) (b)

(c) (d)

Fig. 5 - Scatter plot for P_{ms} vs. P_{ca} : (a) channel spacing of 50 *GHz*, power of 10 *dBm* and 2 span; (b) channel spacing of 100 *GHz*, power of 10 *dBm* and 2 span; (c) channel spacing of 50 *GHz*, power of 10 *dBm* and 4 span; (d) channel spacing of 100 *GHz*, power of 10 *dBm* and 4 span

IV. Study Case

The simulations presented in this Section were made for the three physical topologies, namely, American, ring and square, which are shown in Fig 6. Uniform traffic was adopted between the nodes. Lightpath requests arrive at a centralized control plane following a Poisson distribution with the holding time according to an exponential distribution. The fiber attenuation in each span connecting the nodes is fully compensated by ideal optical amplifiers (without ASE noise) working in boost and pre-amp configurations.

The cost function proposed was used in the Dijkstra´s algorithm for selecting the best, i.e., the least impaired available, route. The routing algorithm is based on the classic principle of discovering the minimum accumulated cost, which in our case implies in the minimal accumulated penalty, between the origin and destination nodes. After choosing such a route, the algorithm of wavelength assignment will attribute a channel for the lightpath request, once again seeking the wavelength that is least impacted by the physical layer. These two steps are performed as follow:

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Step 1: the $C_{ij,w}$ cost for one available wavelength w (at the moment the control plane receives a connection request) in a span connecting node i to node j of the network is calculated using (4);

Step 2: the cost of the span ij will be then given by (7):

$$C_{ij} = \max\left(C_{ij,w}\right) \quad \forall \quad w \tag{7}$$

The use of the worst case in (7) as the link cost is intended to prevent the use of spans that are already with high levels of penalty. This aims at preventing that active connections to be impaired by the establishment of new connections sharing such spans. In addition, the use of routes with lower penalty may also allow a better space distribution of traffic across the network;

Step 3: the best route, amongst the k possible between the source and the destination of the lightpath, is the one with the minimum cost (C_R) accumulated across its n hops (spans), as shown in (8) where n_k represents the number of hops in route k;

$$C_R = \min\left(C_k\right) = \min\left(\sum_{m=1}^{n_k} C_{ij}\right) \quad \forall \quad k \tag{8}$$

Step 4: Now the wavelength to be used by the new connection has to be chosen in the route C_R. Note that we can have up to w wavelengths that match the continuity criterion. Among them the one with the least amount of physical impairments should be chosen. Thus, the picked wavelength along this route will be the one that possesses the final cost (C_F) in (9).

$$C_F = \min\left(C_{R,w}\right) \quad \forall \quad w \tag{9}$$

Step 5: However, to serve a lightpath request the admission control still needs to verify if the **restriction of QoS** is satisfied, i.e., if the eye-closure penalty does not exceed acceptable levels. In our case we use 3 *dB* as the maximum penalty for a lightpath. Note that typical level of penalty used in links (e.g., 1 *dB*) would be too severe for transparent networks built with single span SMFs without dispersion compensation. The total penalty P_T is obtained from (10) (see Equations (5) and (6)). The lightpath is established if $P_T < 3$ *dB* and blocked otherwise. Obviously, blocking also takes place when there is no continuous wavelength between source and destination.

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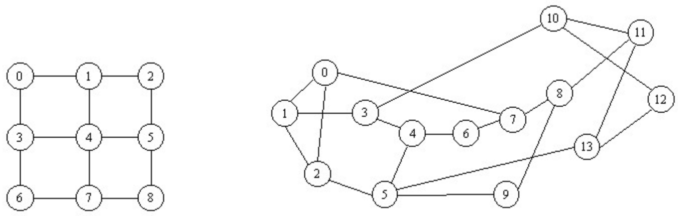
$$P_T = \begin{cases} f_c^{-1}(C_R)\, for\, n_k = 1 \\ f_P(f_c^{-1}(C_R))\, for\, n_k > 1 \end{cases} \quad (10)$$

The following considerations have been made for the simulations: bit rate of 10 *Gb/s*, 50 and 100 *GHz* channel spacing, and 10 wavelengths per link. The expressions for the case of 2 spans (seen in Fig. 5a-b) were adopted as $f_p(P_{ca})$ in (10). Bear in mind that the spans are built with SMF presenting already considerable values of penalty due to GVD at 10 *Gb/s*.

The dynamic routing without considering the physical layer is also implemented for comparison purposes. This algorithm is called blind RWA, i.e., does not have physical layer visibility. However, the spatial distribution of traffic in the network for blind RWA has implemented for the sake of fairness. The costs of the spans, in this case, are given by the inverse relation of the number of available wavelengths (11). This cost function is used instead of (7), and the assignment of wavelength is performed by randomly picking one out the set with the available that meet the continuity constraint in the chosen route (instead of using (9)).

$$C_{ij}^* = \left(\Omega_{ij} - \omega_{ij}\right)^{-1} \quad (11)$$

Ω_{ij} represents the total number of wavelengths in the link *ij* and ϖ_{ij} the number of wavelengths that are being used in this span at the time of the lightpath request.



(a) (b) (c)

Fig. 6 – Network topologies: (a) Square with 9 nodes; (b) American with 14 nodes; (c) Ring with 9 nodes

The blocking probability results are shown in Fig 7. These outcomes may allow network designer to choose the right combination between transmitted power and wavelength grid for a given network topology. In the diverse studied scenarios, blocking probability may be severely impacted by the RWA/CAC constraints to avoid excessive physical layer impairments. Especially in network with low connectivity (e.g., ring topology in Fig. 7c). This occurs due to the high value of interference length, i.e. average number of shared spans, between the lightpaths as traffic load increases.

As the transmitted power reaches 0 *dBm* in Fig. 7d, the blocking probability tends to values next to RWA with no physical layer impairments (blind algorithm) as expected. Link span is an important

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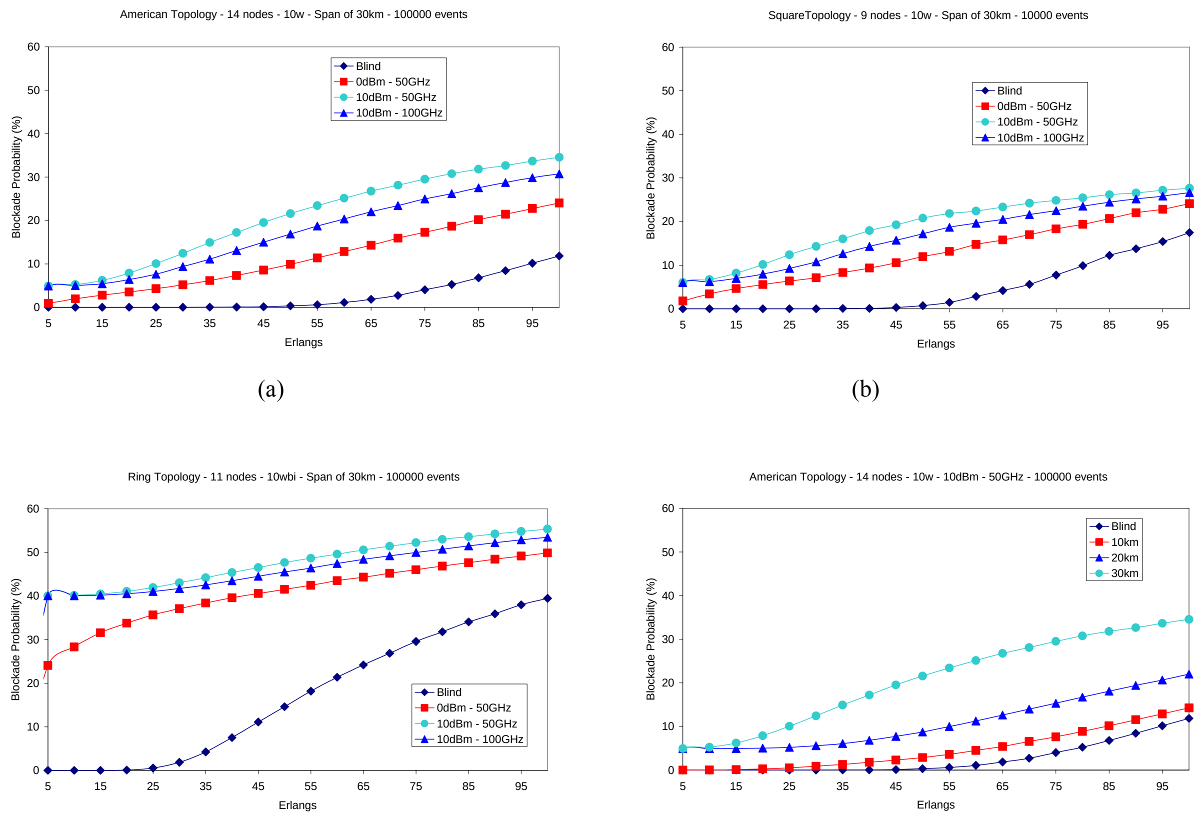
aspect as far as GVD, XPM, and SPM are concerned, but even under tight channel spacing (50 *GHz)* and high transmitted power (10 *dBm*), result for short links (10 *km*) approaches the outcomes from blind algorithm, possibly due to path diversity existent in the American topology. Blocking floors are observed for low traffic loads (below 10 *Er*) when nonlinear effects are pronounced, i.e., high transmitted power combined with tight grid, for all scenarios in Fig. 7. This is the results of blocking long distance lightpaths requests due to high levels (above 3 *dB*) physical layer impairments.



(c) (d)

Fig. 7 - - Blocking Probability X Total Traffic in the network in Erlangs: (a), (b) and (c) Blind and with different channel spacing, different power levels and topologies; (d) Blind and with 10 dBm of power, 50GHz channel spacing, American topology and different span size.

V. CONCLUSION

In this paper a new methodology for determination of cost functions in dynamic optic networks under the influence of GVD, XPM, and SPM was presented. The main contribution of the work is to present a simple way to design, from the analysis of single and multi-span WDM links, cost functions that relate a value of cost with a value of penalty of eye-diagrams. Therefore, their application significantly reduces complexity of control plane implementations in dynamic optical networks equipped with CAC/RWA algorithms capable of considering nonlinear effects.

Future work will investigate the effect of new solicitations on the active channels in the network, aiming not only to verify the restriction of QoS in admission process, but also throughout its holding

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period. Generalized cost functions for multi-span to improve the process of penalty accumulation are under investigation. The application of dispersion management techniques as means to mitigate the limitation of transparency imposed by GVD is being considered.

APPENDIX A

Each region can assume three values: 0 represents no active channel in the region; 1 represents only one active channel; and 2 represents two active channels in the region. Table V shows the corresponding values for $F_{channels}$.

TABLE V. WEIGHTS TO THE CHANNEL NEIGHBORING

Channels Factor			
Region 1	**Region 2**	**Region 3**	$\mathbf{F_{channels}}$
0	0	0	0
0	0	1	0.01
0	0	2	0.02
0	1	0	0.05
0	1	1	0.1
0	1	2	0.11
0	2	0	0.15
0	2	1	0.2
0	2	2	0.21
1	0	0	0.5
1	0	1	0.52
1	0	2	0.53
1	1	0	0.55
1	1	1	0.57
1	1	2	0.58
1	2	0	0.65
1	2	1	0.68
1	2	2	0.69
2	0	0	0.6
2	0	1	0.62
2	0	2	0.63
2	1	0	0.75
2	1	1	0.77
2	1	2	0.78
2	2	0	0.8
2	2	1	0.83
2	2	2	0.84

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