Analysis of EDFA Gain Variation in Dynamic Optical Networks

Victor André P. de Oliveira, Fco A. de Oliveira Neto & Iguatemi Eduardo da Fonseca

***Abstract*— This paper presents an analysis of the Erbium-Doped Fiber Amplifier gain variation effect. To do this, it is presented an analytic model that can estimate the behavior of the variation in relation on its input power. To evaluate and help on the analysis, two routing and wavelength algorithms were implemented. The result of the numerical simulations indicate that the network performance can increase if a EDFA gain control is employed.**

***Index Terms*— Optical amplifiers, RWA algorithms, Transparent optical networks.**

I. INTRODUCTION

The accelerating growth of data traffic is motivating the research for more efficient, flexible and intelligent optical network architectures. In this direction, Transparent Optical Networks (TON) based in IP over Wavelength Division Multiplexing (WDM) technology is becoming accepted as one of the most promising candidates to fulfill these ever-increasing bandwidth demands. This happens not only because the required switching speed may turn to be higher than the one that can be supplied by electronics, but also because of the expressive amount of energy that would be consumed by these routers. However, the efficient use of the full capacity that is provided by TONs depends on factors such as: a) optical switching technology, b) traffic distribution, c) design of the network architecture, and d) deployment of new all-optical devices [1].

Despite all the advances achieved in last years, there are still challenges to be overcome for mass deployment of TON's and, therefore the efficient use of resources of these networks [2]. For example, in a TON with optical Erbium-Doped Fiber Amplifier (EDFA), the admission of a new lightpath can cause fluctuations in Bit Error Rate (BER) of the paths already presented in the optical network. These fluctuations occur due to the saturation effect of EDFA's, which causes variations in the gains of the amplifiers, affecting the power of connections and consequently the Optical Signal Noise Rate (OSNR) and the BER of these connections. Note that the saturation effect of EDFA's works the same way as the nonlinear effect in an optical network. That is, the admission of a connection causes interference to other connections already present on the network, so your treatment in the admission process connections on the network has considerable computational complexity [3].

Recently, more sophisticated RWA algorithms, named Impairments Aware RWA (IA-RWA), that take into account physical layer impairments, have been investigated [4] - [11]. In [4] - [6], the influence of Amplified-Spontaneous Emission noise (ASE) over Bit Error Rate (BER) in a TON was investigated. Nonlinear effects, as Four-Wave Mixing (FWM) and Cross-phase Modulation (XPM), and their impact over the Transmission Quality of Service (TQoS) in a TON were examined in [7] - [10]. In [11] - [12] Polarization Mode Dispersion (PMD) was studied in static and dynamic optical networks.

The purpose of this work is to investigate the impact of EDFA gain variation in a dynamic optical network impaired by ASE and saturation of the amplifiers. An analytical equation is derived to explain the gain variation when the network traffic grows. In addition to this, an IA-RWA algorithm is taken into account of the EDFA saturation and a gain variation is proposed and numerically analyzed. The numerical results show that, even under high traffic conditions, gain variation may be controlled if only one gain actualization is made in the amplifiers into the network.

The remainder of this paper is divided as it follows. In section II the EDFA gain variation is analyzed. Section III presents the proposal of an IA-RWA considering the analysis discussed before. In section IV, the simulations and results are presented. And finally, in section V, the conclusions are presented.

II. THE PROBLEM OF EDFA GAIN VARIATION

An important consideration in the design of optical systems is the EDFA saturation. This is because the amplifier output is limited due to both the input power over the project's own amplifier. As a result, the higher the energy input, the greater the gain and the lower the power output.

Ramaswami [13] defines that the gain of an amplifier (in dB) can be expressed by the equation:

$$G = 10\log\left(1 + \frac{P_{sat}}{P_{ent}} \times \ln\left(\frac{G_{max}}{G}\right)\right) \qquad (1)$$

in which, G_{max} is the unsaturated gain, G is the saturated gain of the amplifier, P_{sat} is the internal saturation power, and P_{ent} is the total input power in the amplifier (the total power from all wavelengths).

Figure 1 plots the amplifier gain as a function of input power in a typical EDFA. It is observed that for low input power, the

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amplifier gain is its unsaturated gain, and for high input power, the gain will tend to one ($G \rightarrow 1$) so that the power amplifier output is equal to the input power ($Pin = Pout$).

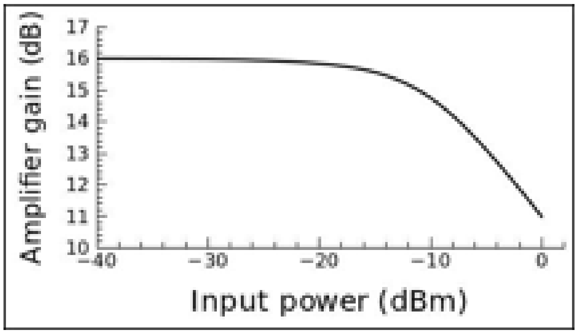


Fig. 1. Gain saturation in a typical EDFA. Unsaturated gain = 16 dB and saturation power = 10 dBm.

Although there is no fundamental problem in an EDFA operating in saturation [13], this operation could generate instability in the network due to the dynamics of input and output connections in WDM networks.

This instability can lead to momentary loss of information that is traveling across the network at the time of instability. In computer simulations, this problem needs to be taken into account, for the results obtained in simulation are as close as possible to a real optical network. Moreover, analyzing this problem in a numerical simulation, a solution can be proposed to minimize the impact of gain variation in these amplifiers.

To a better understanding of this problem, three situations are being considered. In the first one, consider a network whose initial state is composed only by the connection that occupies the wavelength λ_1, according to Figure 2. Now consider that a new connection is admitted to the wavelength λ_2, and that this connection shares the link (L_{25}) with the first. As the two connections share the same amplifier (A^1_{25}), its gain tends to decrease due to the increased input power amplifier. This means that the output power amplifier for the same connection λ_1 is not the same anymore. Thus, all amplifiers that succeed the amplifier A^1_{25} in the connection path in λ_1 have changed their gains, e. g., the amplifier A^1_{58}.

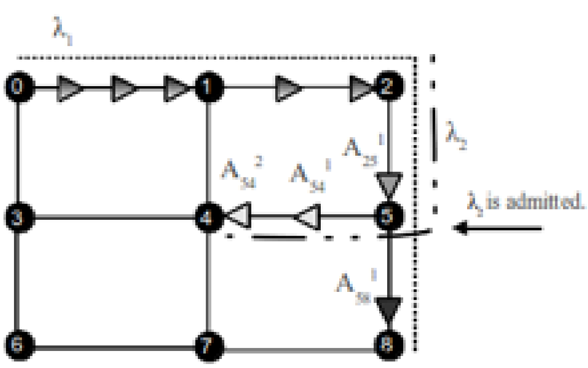


Fig. 2. Gain variation when admitting a new lightpath.

The same thing can happen when a connection is removed from the network, as illustrated in Figure 3. In this case, the initial state is composed by two connections admitted in λ_1 and λ_2 respectively. Both share the link connection between node number two and node number five (L_{25}). Assuming that the connection allocated in the wavelength λ_2 is withdrawn, the A^1_{25} amplifier power is decreased. Consequently, its gain will increase so that the power of connections that come from it will also increase. Therefore, all the amplifiers that follow the path of the connection allocated to the wavelength λ_1 undergo a change in its gain, in this case, the amplifier A^1_{58}.

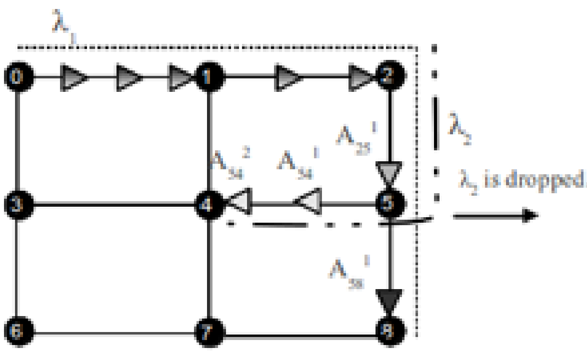


Fig. 3. Gain variation when a lightpath is dropped.

Another situation of the gain variation can be illustrated in Figure 4. Suppose there is a connection in λ_1 and its lightpath passes through links $L_{87} - L_{74} - L_{41} - L_{12}$. A looping condition occurs when a new connection is accepted, in λ_2 for example, and shares any two nonconsecutive links. As an example, assume that the connection order in in λ_2 is $L_{12} - L_{25} - L_{58} - L_{87}$. Thus, the links L_{12} and L_{87} will be shared; L_{12} and L_{87} as the first and last link, respectively, in the connection on λ_2, L_{87} and L_{12} as the first and last link, respectively, in the connection admitted on λ_1.

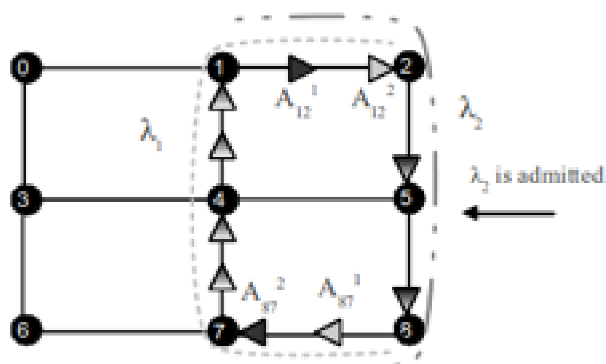


Fig. 4. Gain variation: looping condition.

The major problem in this situation is the following. In accepting the connection on λ_2, the A^1_{12} amplifier gain decreases, affecting the power entering in the A^1_{12} amplifier of the same loop (analogous to the scheme shown in Figure 3). The question in this situation is from the another link (L_{87}), whose A^1_{87} amplifier gain will also change, but this time due to connection on λ_2. With the A^1_{87} amplifier gain being changed, all other amplifiers that follow the connection λ_1 also will be changed. As the end of the connection in λ_1 coincides with the beginning of the connection in λ_2, the whole cycle begins again.

At first glance, when seeing the Fig. 1, we are tempted to believe that when network traffic is high, the variation of the amplifiers gain will also be high. Since the higher the traffic, the greater the number of connections passing through the amplifiers and also the higher the input power. Calculating the derivative of the gain as a function of input power, information about the behavior of the EDFA gain variation concerning the input power can be obtained.

In Eq. 1, the G variable is in both sides of the equation, meaning its a transcendental equation; that is, G is function of P_{ent} and G itself. Thus, the derivative was obtained from the implicit derivation method, as showed by [14] and can be expressed by

$$\frac{\partial G}{\partial P_{ent}} = \frac{\dfrac{-\partial f(G, P_{ent})}{\partial P_{ent}}}{\dfrac{\partial f(G, P_{ent})}{\partial G}} \tag{2}$$

The resolution of the derivative is beyond the scope of this work. Therefore, Eq. 3 shows only the final result of the derivative calculation.

$$\frac{\partial G}{\partial P_{ent}} = \frac{-G \cdot P_{sat} \cdot \ln\left(\dfrac{G_{max}}{G}\right)}{G \cdot P_{ent}^2 + P_{sat} \cdot P_{ent}} \tag{3}$$

III. Proposal of IA-RWA

Aiming to evaluate the impact of variation gain on EDFA's under a dynamic optical network, two RWA algorithms were developed.

A. IA-RWA taking into account EDFA gain saturation

The IA-RWA algorithm proposed in this paper evaluates the blocking probability of connections not only in terms of continuity, but also in terms of a predefined QoT metric. Thus, if a request requires a given level of QoT, it will be admitted if and only if: (a) it is not blocked by the restriction of continuity, (b) if it has a level of QoT at or above the level of QoT asked in the request, and (c) if the new connection does not violate the quality of connections already present on the network. In fact, the requirements (b) and (c) could be merged into one, since they cannot be measured separately due to the EDFA's saturation be a nonlinear effect. Thus, the new connection must be established temporarily in order to evaluate its behavior and other previously established connections.

Figure 5 shows the flowchart of the algorithm. As can be seen, it is first generated a connection request. The route is found after considering the shortest path, where the link cost is the distance in kilometers. Then the algorithm performs the test of continuity using the First Fit heuristic [15]. At this point, if there is no free wavelength, the connection is immediately rejected. Otherwise, the connection is admitted only to pre-compute the QoT and examine whether such a connection does not interfere so as to degrade the already established connections in the network. If so, the connection must be removed and discarded. Otherwise, the connection is finally admitted. Note also that, as shown in the flowchart, the gain and power are adjusted once the connection is pre admitted (and if it is rejected). For, as discussed in previous section, the gain of EDFA depends on the total input power, and this update is necessary to obtain consistent results with simulations in real optical network.

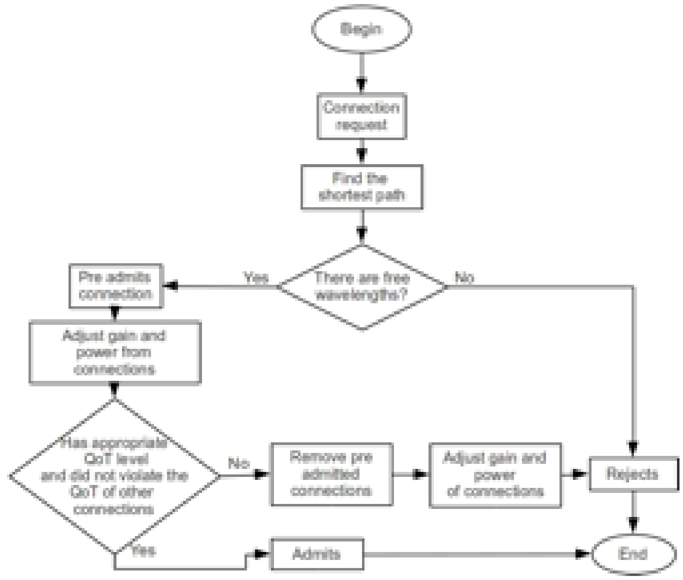


Fig. 5. The proposed IA-RWA flowchart.

B. The Blind RWA

It was also implemented a Traditional RWA algorithm, also called Blind RWA [3]. It is simpler compared to the IA-RWA and does not check the connections QoT; simply accepts if it finds an available optical path. The Blind RWA in question uses routing based on the minimum distance in kilometers and assignment of wavelengths using the algorithm First-Fit. Figure 6 shows its flowchart.

IV. Simulations

A. Simulation Environment

Through a simulation environment , implemented in C/C++ programming language, was simulated in a dynamic scenario, in which were generated 100,000 requests for connections that have an uniform traffic pattern across the network nodes and follow a Poisson distribution with duration of exponential distribution (mean = 1s). The Optical Network used is transparent, i.e., and it has no optical-electrical-optical conversion, and it has 19 nodes. All links are bidirectional and they have a ranging length from 240 to 480 km. The length of a span is 80 km. A set of W = 16 wavelengths in an optical network was used without wavelength conversion.

The simulated network topology is illustrated in Figure 7. Simulations were made with transmission rates of 10 and 40 Gbps. From the parameters presented in Table 1, the number of rejected connections among the total number of connection

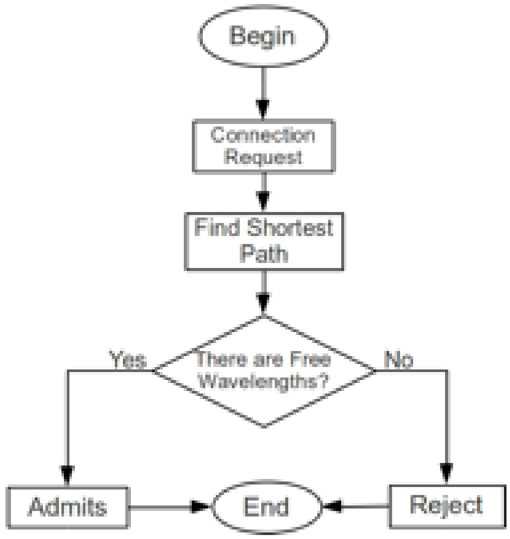


Fig. 6. The Blind RWA flowchart.

requests arriving at the optical network is the network blocking probability.

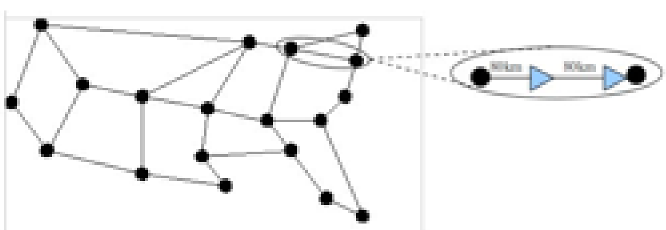


Fig. 7. The network topology.

TABELA I

SIMULATION PARAMETERS.

Parameters	Values
Blocking type	Continuity + QoT
Routing type	Fix
BERTH	10-12
Fiber attenuation	0.2 dB/km
Input Power (P)	0 dBm
Max Amplifier Gain (Gmax)	16 dB
Saturation Power (Psat)	10 dBm
Amplifier Spontaneous Emission Factor (Nsp)	4
Optical Filter Bandwidth	50 GHz
Electrical Filter Bandwidth	Bit Rate x 0.8

B. Simulation Environment

In this work we used four metrics. They were used to evaluate the performance of an optical network operating with RWA and IA-RWA algorithms. The four are: i) the EDFA gain variation, ii) Threshold Violation Probability (TVP) of QoT, iii) Critical Violation Probability (CVP) of QoT, and iv) the Blocking Probability.

1) EDFA Gain Variation: A new metric was used basically to compute the gain average change every time a connection enter or leaves the network. For, as stated earlier, the gain variation is entirely dependent on optical amplifier input power and as dynamically connections arrive, the input power tends to vary greatly. This behavior can be captured by Eq. 4

$$\Delta G_j = \frac{\sum_{i=0}^{A} \Delta G_j^i}{A} \tag{4}$$

in which, the ΔG_0^i is the gain variation of the i-th amplifier, and A is the number of amplifiers that suffer gain variation during the arrive or leave of a connection.

2) Threshold Violation Probability: The Threshold Violation Probability means the probability of at least one active connection in the entire network has their BER above BERth after the change of state of an optical path in the network, i.e. upon activation or termination of a network connection [3]. This metric can be expressed as: Let pX = Prob $\{$X = x$\}$ the probability of having x = 0,1,2, ... active connections with its BER above the maximum allowed after a connection is established or terminated on the network. The TVP is the probability that at least one active connection is degraded, i.e. TVP = [1-pX (x = 0)]. The TVP can be useful to give an overall representation of the network QoT, it provides a measure for the preservation and provision of statistical QoT. QoT deterministic is reached as TVP$\rightarrow$0, in other words, the process of establishing and closing connections never violates the OSNR of other active connections in the entire network (in addition to meeting its own demand for quality).

C. Critical Violation Probability

In order to monitor excessive BER degradation, Critical Violation Probability is used. CVP is a measure similar to TVP, but with BERth equals to 10-3 for all optical paths and according to the metrics already defined Excessive Error Defect (dEXC) by the SDH in ITU-T G.806 [16]. It is considered that CVP should be less than 0.01% for the mechanisms of protection and restoration of the network not very often activated.

D. Blocking Probability

One metric that is used to measure the performance of proposed algorithms is the network blocking probability. This represents the number of optical paths rejected before the total number of requests that reach the optical network. The blocking probability is the most used metric in literature, and it is used to evaluate the performance of RWA algorithms in dynamic optical networks.

E. Analysis of Gain Variation

Figures 5a-5b illustrate the results obtained from the simulation with the initial variation gain (G0) and after two gains power amplifier updates connections (G1 and G2). They are considered the Blind RWA and IA-RWA in a network operating at a transmission rate of 40 Gbps. The results are similar to 10 Gbps and they are therefore not presented here. As can be seen, the G0 has remained virtually the same and its behavior can be captured by Eq. 3. When traffic is low, the variation is higher, and as traffic increases, the variation of the G0 tends to decrease inversely proportional to the input power amplifier. Note that, although on the charts there is not explicit power entrance, it is understood that, when traffic is heavy, the network has many connections to stay longer in the network. Thus, it was concluded that if the traffic is low, it means that the input power amplifiers is also low, otherwise, if traffic is high, the input power of the amplifiers will also be high.

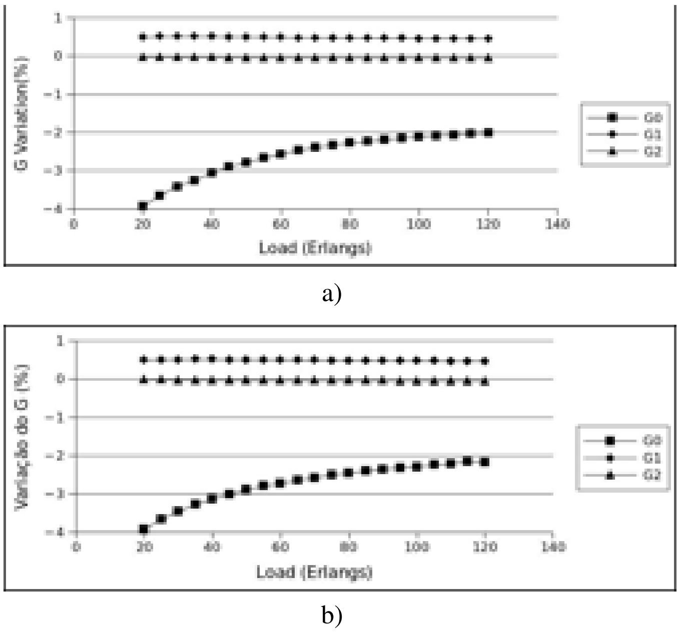


Fig. 8. Gain variation in simulations without updates (G0) and with one (G1).and two (G2) updates to 40 Gbps. a) Blid RWA; b) IA-RWA.

Even if the gain variation decreases when traffic is high, it is necessary to update the gain and input power for all the connections on the network come into equilibrium. This behavior was captured by G1, the first update, and G2, the second update, illustrated in Figures 8a - 8b. Note that the two updates were needed to the gain variation be negligible and to ensure that the connections on the network are even.

F. Advantages for network performance

To illustrate the benefits the updating process of the EDFA's gain can bring to network performance, we analyzed network scenarios with and without updating of gain, and operating with algorithms IA-RWA and Blind RWA and transmission rates 10 and 40 Gbps.

Figures 9a-9d show the comparative results of the proposed IA-RWA with the Blind RWA, which serves as a reference only, since it does not block connections without QoT. Namely, that is possible when the network operates with the Blind RWA algorithm, without QoT connections, i.e., with BER¿ 10-12, this may be admitted to the network. Note that in scenarios in which the updates of the gains are used, network performance has improved. For example, comparing Figures 9c and 9d, there is a reduction of approximately 20% of the network blocking probability when traffic is something (e.g. 100 Er), from 0.27 to 0.22. Similar improvement in performance occurs when the network operates at 10 Gbps, Figures 9a and 9b. Note that the higher the rate of transmission network, the greater the improvement in performance.

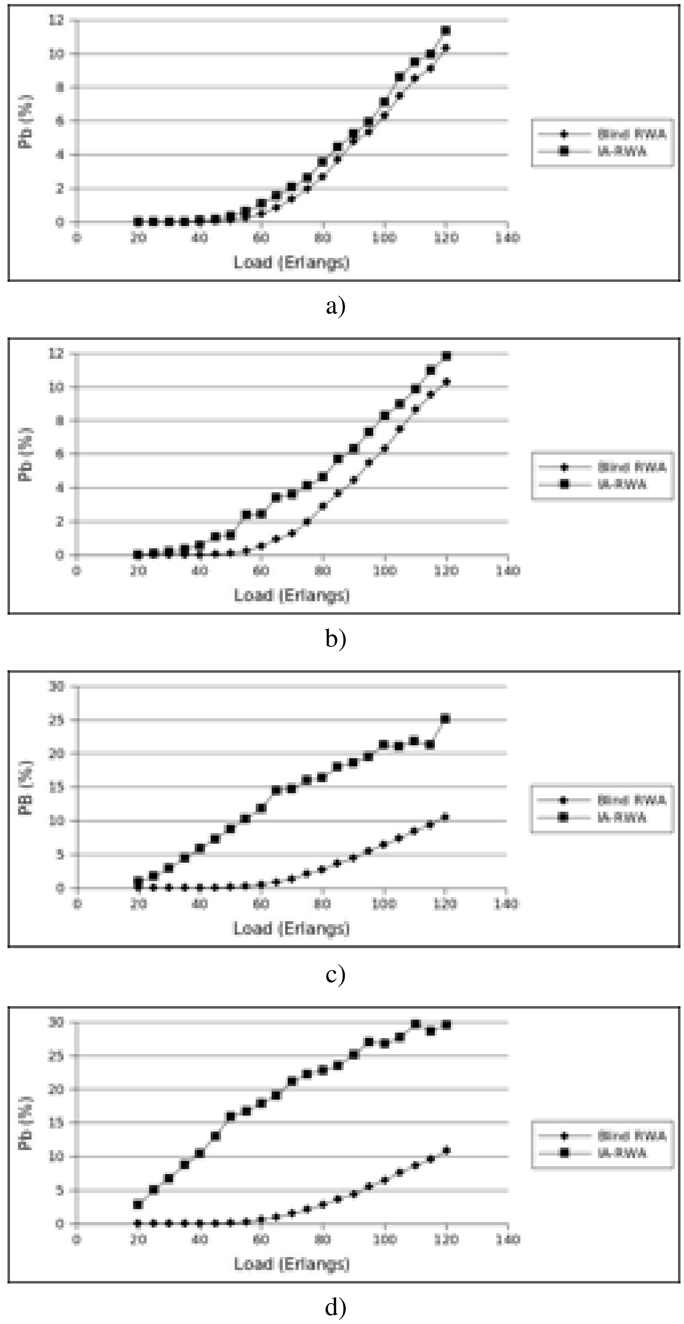
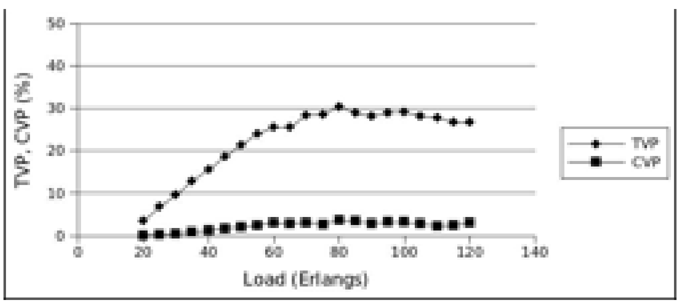


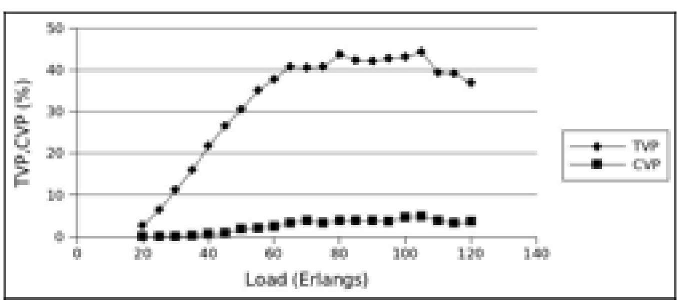
Fig. 9. Blocking probability in scenarios with and without gain update. a) 10 Gpbs with update; b) 10 Gbps without update; c) 40 Gbps with update; d) 40 Gbps without update.

Figures 10a - 10b show TVP and CVP for the network operating with the traditional RWA algorithm with a transmission bit rate of 40 Gbps. The results are similar to 10 Gbps. Note that in the scenario without gain actualization, the result of TVP is better than the scenario with update gain. For example, when network traffic is high (e.g., Er 100), the TVP for the scenario without update is about 29%, and 43% for the scenario with updating gain, i.e., an increase of 48%. This means that when the network operates with a traditional RWA algorithm, if the gains of the EDFA's are not updated, the probability of having connections in the network without QoT can be much higher than that measured by traditional RWA algorithm. This may have negative implications for the service offered to networks clients. A high value of TVP means that there is a high probability that the QoT of connections in the network are violated, i.e., their BER's can be high and degrade the quality of the information transmitted over the network.

Figures 7a - 7b also contain other interesting information. Note that from 80 Er, i.e., high network traffic, the values of TVP stabilize around 30% with no update gain, and 42% for the case with update gain. That is, although the number of connections is increasing on the network, the probability of having no connections QoT is not changed. The explanation for this lies in the fact that when traffic is high, the gain variations of the EDFA's also stabilize at a certain value, as can be seen in Fig. 8a and is also predicted by (3). Note that, in Fig. 8a, between 80 and 120 Er, EDFA gain variation practically remains around -2.2%. This seems to be a feature of the EDFA's saturation effect, which can be viewed as a nonlinear effect. The TVP caused in the network is due to other nonlinear effects, such as the FWM increases in proportion to the network traffic increase, with no significant points of stabilization values [3]. In other words, the growth curve is monotonic.



a)



b)

Fig. 10. TVP and CVP for Blind RWA at 40 Gbps. a) without gain actualization; b) with gain actualization.

V. Final comments

This article presented a study on the benefits that the elimination of EDFA's gain variation can bring to the performance of an optical network. For the gain of EDFA's will not suffer variations, optical amplifiers equipped with automatic gain control can be used in the network [17]. The results of numerical simulations suggest that the network performance can be improved with the elimination of variations in the gain of amplifiers. As future work will investigate other possibilities for IA-RWA and the possibility of reducing the number of amplifiers equipped with automatic gain control.

Referências

[1] M. L. F. Abbade, J. D. Marconi, R. L. Cassiolato, V. Ishizuca, I. E. Fonseca, and H. L. Fragnito, 'Field-Trial Evaluation of Cross-Layer Effect Caused by All-Optical Wavelength Converters on IP Network Applications", IEEE/OSA J. Ligthwave Technology, vol. 27, pp. 1816 - 1826, june 2009.

[2] R. Ramaswami, "Optical Networking Technologies: What Worked and What Didn't", IEEE Communications Magazine, pp. 132 - 139, Sept. 2006.

[3] I. E. Fonseca, "Uma abordagem para Aprovisionamento e Diferenciação de QoS Óptico na Presença de FWM em Redes Ópticas Transparentes", Tese de Doutorado, FEEC/Unicamp, Abril 2005.

[4] B. Ramamurthy, et al., "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks," IEEE/OSA J. Ligthwave Technology, vol. 10. pp. 1713-1723, Oct. 1999.

[5] J. F. Martins-Filho, C. J. A. Bastos-Filho, E. A. J. Arantes, S. C. Oliveira, L. D. Coelho, J. P. G. Oliveira, R. G. Dante, E. Fontana, F. D. Nunes, "Novel Routing Algorithm for Transparent Optical Networks Based on Noise Figure and Amplifier", in Proc. IEEE IMOC2003, Sept 2003.

[6] T. Deng, S. Subramaniam, "Source Power Management in Transparent Wavelength-Routed Mesh Networks", in Proc. IEEE ICC'04, Jun 2004.

[7] I. E. Fonseca, M. R. N. Ribeiro, R. C. Almeida Jr., and H. Waldman, "Preserving Global Optical QoS in FWM Impaired Dynamic Networks", IEE Electronics Letters, Vol. 40, pp. 191-192, Feb 2004.

[8] I. E. Fonseca, M. R. N. Ribeiro, R. C. Almeida Jr., and H. Waldman, "Meeting Optical QoS in Dynamic Networks with Reduced Complexity", in Proc. IEEE ECOC'04, Sept 2004.

[9] R. C. Almeida Jr., D. R. Campelo, A. V. T. Cartaxo, K. M. Guild, and H. Waldman, "Efficient Wavelength Assignment Policy for XPM-Impaired WDM Networks", IEEE Communication Letters, vol. 12, pp. 791 - 793, Oct. 2008.

[10] U. S. P. Filho, M. R. N. Ribeiro, C. P. Maioli, M. Freitas, and I. E. Fonseca, "Cost functions for CAC/RWA in dynamic optical networks under gvd, spm and xpm", Journal of Microwave and Optoelectronics, vol. 6, pp. 249-262, jun. 2007.

[11] M. Ali, L. Tancevski, "Impact of Polarization-Mode Dispersion on the Design of Wavelength-Routed Networks", IEEE Photonics Technology Letters, Vol. 14, pp. 720-722, May 2002.

[12] R. Martinez, C. Pinart, J. Comellas, G. Junyent, "Routing Issues in Transparent Optical Networks", in Proc. IEEE ICTON 2006, Jun 2006.

[13] R. Ramaswami,K.N. Sivarajan,G.H.Sasaki, "Optical Networks: A practical Perpective". Third Edition, Morgan Kaufmann. 893 p.

[14] H. L. Guidorizzi, "Um curso de cálculo", LTC, Rio de Janeiro, LTC, 2008.

[15] H. Zang, J. P. Jue, and B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks", SPIE Optical Network Magazine, Vol. 1, pp. 47-60, Dec 2000.

[16] ITU-T Rec. G.806 (2000) "Characteristics of Transport Equipment - Description Methodology and Generic Functionality".

[17] J. C. R. F. Oliveira, "Amplificadores Ópticos com Controle Automático de Ganho para Aplicação em Redes Ópticas", Tese de Doutorado, FEEC/Unicamp, 2007.

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