EDFA Gain Variation Problem in Transparent Optical Networks

Victor A. P. Oliveira, and Iguatemi E. Fonseca

***Resumo*— Este trabalho apresenta um estudo sobre o impacto que a variação do ganho dos Amplificadores Óticos a Fibra Dopada com Érbium (EDFA) tem sobre o desempenho de redes óticas dinâmicas. É proposto um modelo analítico para estimar a variação de ganho dos EDFA's considerando a potência de entrada dos amplificadores. Dois algoritmos de alocação de rota e comprimento de onda com restrições da camada física são também propostos. As simulações numéricas sugerem que o desempenho da rede pode ser melhorado com a eliminação da variação de ganho dos amplificadores. É também verificado que o modelo analítico proposto captura satisfatoriamente o comportamento da variação de ganho dos EDFA's.**

***Palavras-Chave*— Variação do ganho de EDFA, Algoritmos de Alocação de Rota e Comprimento de Onda, Redes Óticas.**

***Abstract*— This work presents a study about the impact of Erbium-doped Fiber Amplifier (EDFA) gain variation problem may have on the performance of Dynamic Optical Networks. An analytical model to estimate the EDFA gain variation considering amplifier input power is proposed. Two Impairment Aware RWA algorithms are also proposed. Numerical simulations suggest that network performance can be improved with the elimination of amplifiers gain variations. Results also indicate that proposed analytical model satisfactorily captures the behavior of EDFA's gain variation.**

***Keywords*— EDFA Gain variation; Routing and Wavelength Assignment Algorithm; Optical Networks.**

I. INTRODUCTION

The increasing demand of IP traffic had motivated researchers to look for a strategy that is capable of providing a appropriate bit rate that supports all types of traffic. Networks that perform Optical-Electro-Optical conversion (OEO) may not be capable of streaming traffic and dynamic from a wide range of applications such as VoIP, video on demand, etc [1]. Moreover, OEO conversion causes the network to be opaque, i.e., there is no transparency regarding signal modulation and protocol [2]. The so-called Transparent Optical Networks (TON) using wavelength division multiplexing (WDM) have shown to be strong candidates to solve these problems [3].

Although it has achieved some progress in recent years, there are still challenges to overcome for mass deployment of TON [1]. For example, there are fundamental problems when using EDFAs in a TON. For example, the admission of a connection (or even a connection drop) can cause fluctuations in the lightpath Bit Error Rate (BER) [4]. These fluctuations occur due to the EDFA saturation, which causes variations in the amplifiers gains, therefore affecting the Optical Signal to Noise Ratio (OSNR) of the lightpaths present in the network. As these connections may share common links with others connections, the OSNR of other connection is also affected. Thus, one may consider that the EDFA saturation works as a nonlinear effect.

Recently, more sophisticated Routing and Wavelength Assignment (RWA) algorithms, called Impairment Aware RWA (IA-RWA), which take into account physical impairments, have been studied [3] - [10]. In [4], [5], [6] the influence of ASE noise on the BER in a TON was investigated. However, the amplifiers saturation effect has been little studied [4]. The impact of nonlinear effects, such as Four-Wave-Mixing and Cross Phase Modulation, over the Quality of Transmission (QoT) in a TON was presented in [7], [8]. The influence of Polarization Mode Dispersion over an optical network was examined in [9]. A review describing IA-RWA techniques in transparent optical networks is presented in [10], notice that there is few paper considering EDFA gain variation problem.

In order to study the impact of the EDFA's gain variation effect over the performance of a dynamic transparent optical network, this paper proposes a simple analytical model that estimates the behavior of EDFA gain variation regarding input power and, indirectly, the dynamics of network traffic. In addition, two IA-RWA's algorithms that consider the EDFA gain saturation are presented.

II. GAIN VARIATION AND MATHEMATICAL MODELLING

Figure 1 plots the amplifier gain, denoted by G, as a function of input power in a typical EDFA.

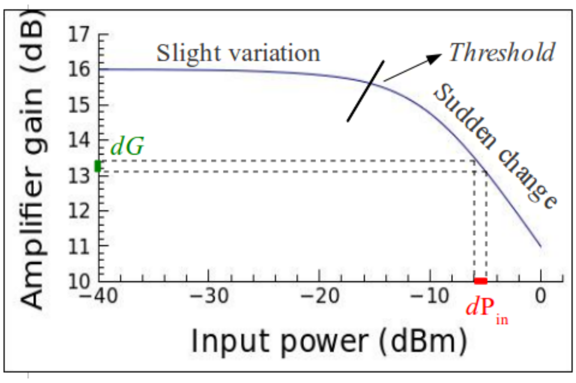

Fig. 1. A typical EDFA Gain.

Observe that for low input power the amplifier gain is its unsaturated gain. Note that threshold mark delimits the region

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of abrupt gain variation. EDFA gain (in *dB*) can be expressed by

$$G = 10 * \log(1 + \frac{P_{sat}}{P_{in}} * \ln(\frac{G_{max}}{G})) \qquad (1)$$

where, P_{sat} is the amplifier saturation power, G_{max} is the unsaturated gain and P_{in} is the amplifier input power, i.e., the sum of power from all connections passing through the EDFA [2].

EDFA gain variation problem in a dynamic optical network can be explained as follows. Consider a network whose initial state is composed only by the connection that occupies the wavelength λ_1, according Fig. 2.

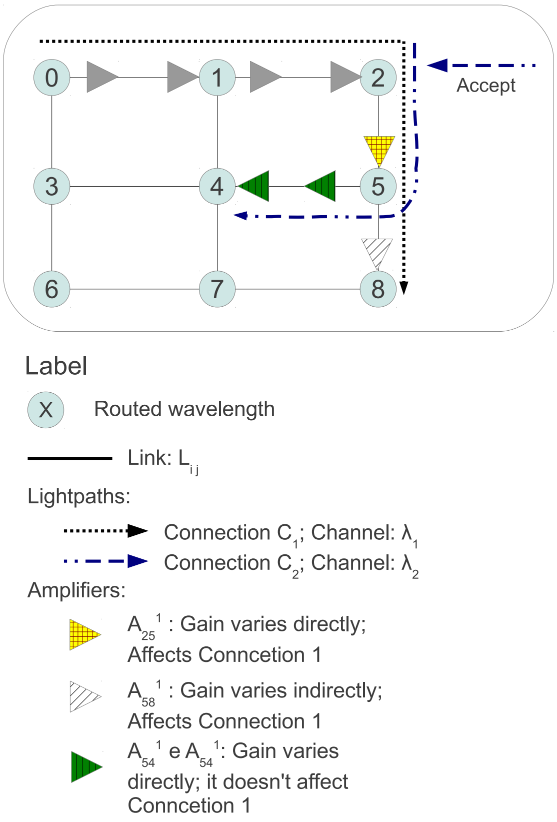

Fig. 2. EDFA gain variation when adding a connection.

Now consider that a new connection is admitted at the wavelength λ_2, and that this connection shares a link (which connects nodes 2 and 5) with the first. Since the two connections share the same amplifier (A_{25}^1), its gain tends to decrease due to increased EDFA input power. This means that amplifier output power for the same connection λ_1 is not the same anymore. Thus, all amplifiers that cycled through the amplifier A_{25}^1 in the connection path in λ_2 have changed their gains, e. g., the amplifier A_{58}^1, which although not on the route in which the new connection was accepted, will have its gain changed. The gain variation problem can also occur when a connection is removed from the network, or if it was considered that the optical path at wavelength λ_2 was removed.

At first glance, when analyzing (1), one might believe that when network traffic is high, EDFA gain variation will be high, since the heavier the traffic, the greater the number of connections passing through the amplifiers and, thus, greater their input power. Calculating the derivative of the gain as a function of input power, one can obtain information about the behavior of the EDFA gain variation regarding input power. To calculate the derivative, the method of derivation of implicit functions is used [11], which can be expressed by

$$\frac{\partial G}{\partial P_{in}} = \frac{\frac{-\partial(G,P_{in})}{P_{in}}}{\frac{\partial(G,P_{in})}{\partial G}}, \qquad (2)$$

$$\frac{\partial G}{\partial P_{in}} = \frac{-G * P_{sat} * \ln(\frac{G_{max}}{G})}{G * P_{in}^2 + P_{sat} * P_{in}}. \qquad (3)$$

Equation (3) shows the final result of the derivative. Note that gain variation decreases with the square of EDFA input power. Thus, one can expect that when dynamic optical networks operate under high traffic, i.e., when EDFA input power is high, the instability caused by the EDFA gain variation problem decreases. This is confirmed in the simulations presented in the Section IV.

III. IA-RWA'S

In order to evaluate the impact of EDFA gain variation over a dynamic transparent optical network, three RWA algorithms were implemented. The proposed IA-RWA algorithms evaluate blocking probability of connections requests not only in terms of wavelength continuity constraint, but also in terms of a QoT metric. If a request requires a given QoT level, it will be admitted if and only if: (a) it is not blocked by the wavelength continuity constraint; (b) it has a QoT level at or above the QoT level requested, and (c) the new connection does not violate the QoT of connections already present on the network.

Figure 3 shows the flowchart of the IA-RWA 1.

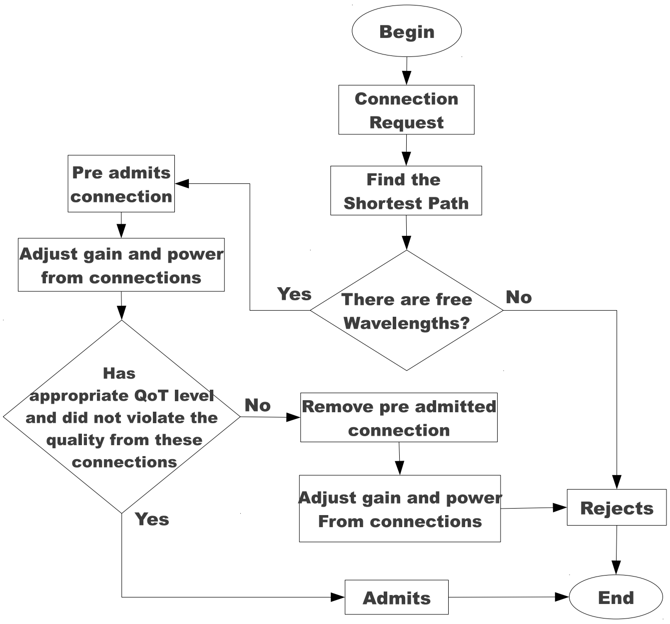

Fig. 3. IA-RWA 1 algorithm.

As can be observed, the route is found after considering the shortest path, where the link cost is the distance in kilometers. Then, the algorithm performs the wavelength continuity constraint test using the First-fit heuristic [12]. At this point, if there are no free wavelength, the connection is rejected. Otherwise, the connection is admitted only to be pre-computed the QoT level and is then examined whether such connection does not degrade the already established connections in the network. If so, the connection must be removed and discarded. Otherwise, the connection is finally admitted. Note that, as shown in the flowchart, the power connections are adjusted once the connection is pre admitted (and if it is rejected). Thus, as discussed in Section II, as EDFA gain depends on the total input power, this update is necessary to obtain results consistent with a real dynamic optical network.

IA-RWA 2 was implemented similar to the previous. Instead of using the distance to find the shortest path (fixed-routing), an adaptive routing based on lower noise accumulation was used. It can be captured by the following equation

$$LC = \frac{1}{OSNR} = \frac{1}{\frac{P_{signal}}{P_{ASE}}} = \frac{P_{ASE}}{P_{signal}}, \quad (4)$$

where, LC is the link cost, OSNR is the optical signal to noise ratio, P_{signal} is the sum of all signals power or connections power at the end of the link, and P_{ASE} is the accumulated ASE noise power in the link. For a single EDFA, P_{ASE} is given by [13]

$$P_{ASE} = 2 * \eta_{sp} * h * f_c * (G-1) * B_0. \quad (5)$$

Where, η_{sp} is the constant called the spontaneous emission factor, h is Planck's constant, f_c is the optical carrier frequency, and B_0 is the optical filter bandwidth.

A traditional RWA algorithm was implemented, the so called Blind RWA [7]. Note that Blind is much simpler that IA-RWA and does not check the QoT of the connections; it simply accepts a connection if it finds an available optical path. Blind RWA uses routing based on the minimum distance in kilometers and the First-fit algorithm to assign wavelengths.

IV. NUMERICAL SIMULATIONS

A. Simulation Environment

Using an ad hoc simulator, implemented in C/C++ programming language, a dynamic transparent optical network, in which are generated 100,000 connection requests, was simulated. The requests have an uniform traffic pattern across the 19-node NSFnet network topology and follow a distribution with duration with exponential distribution (mean = 1s). All links are bidirectional with a length among 80 - 240 *km*. The length of a span, i.e. the distance between two EDFA's, is 80 *km*. A set of 16 wavelengths under the ITU-T grid was used and there is no wavelength conversion in the network. Simulations were made with transmission rates of B=10 and 40 *Gbps*. The number of rejected connections among the total number of connection requests arriving at the network is the network blocking probability. Fiber attenuation, BER_{TH} (QoT level required), lightpath input power, G_{max}, P_{sat}, η_{sp}, optical and electrical filter bandwidths are, respectively, 0.22 *dB/km*, 10^{-12}, 0 *dBm*, 16 *dB*, 10 *dBm*, 4, 50 *GHz*, and $0.8 * B$. Lightpath *Q* factor is calculated using the Gaussian model [2].

A new metric was used to compute the average of gain variation every time a connection is admitted or dropped in the network. As discussed in Section II, gain variation depends on amplifier input power and, since the network traffic is dynamic, the input power tends to vary greatly. This behavior can be captured by

$$G_j = \frac{\sum_{i=0}^{A}(\Delta G_j^i)}{A} \quad (6)$$

where, the ΔG_j^i is the gain variation of the $i-th$ amplifier, j is the number of EDFA gain update, and A is the number of amplifiers that suffer gain variation when a connection is admitted or dropped in the network. Observe that A is incremented every time the network state changes when a connection is admitted or dropped.

B. Gain Variation and Proposed IA-RWA's

Figure 4 shows the results obtained from the simulation with the initial variation gain (G_0) and after two amplifier gain updates (G_1 and G_2). Blind RWA, IA-RWA's 1 and 2 are investigated in a network operating at a transmission rate of 40 *Gbps*. The results are similar to 10 *Gbps* and are therefore not presented here. As can be seen, G_0 has behavior that can be captured by (3). When traffic is low, the gain variation is high, and as traffic increases, G_0 tends to decrease inversely proportional to amplifier input power. It is understood that when traffic is heavy the network has many connections. Thus, it was concluded that if the traffic is low, it means the amplifiers input power is also low, otherwise, if traffic is high, amplifiers input power will also be high. 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 G_1, the first update, and G_2, the second update, illustrated in Fig. 4. Observe that two updates were necessary for the gain variation becomes negligible and ensure that the connections on the network were stable.

In order to illustrate the benefits of the updating process to network performance, network scenarios with (w in the legend) and without (wo in the legend) gain update are analyzed. Figures 5, 6 and 7 show the comparative results of the proposed IA-RWA's with the Blind RWA, which serves as a reference only, since it does not block connections without QoT. Notice that in scenarios in which gain update is used, network performance is improved, and the higher the transmission rate, the greater the improvement in performance. For example, there is a considerable reduction in blocking probability when network operates with IA-RWA 1 or IA-RWA 2 at 40 *Gbps* in Fig. 6. This can be explained by the great reduction in blocking due to QoT in Fig. 7 for scenarios with gain update. Observe also that, IA-RWA 1 with gain update performs similarly to Blind RWA at 10 and 40 *Gbps*.One should remember that it is possible that when the network operates with Blind RWA, connections without QoT requirements, i.e., with $BER > 10^{-12}$, may be admitted in the network. Even admitting connection only with QoT requirements, IA-RWA 1 has a similar blocking probability than Blind RWA.

Moreover, it was observed that IA-RWA 2 has gotten a worse blocking probability than IA-RWA 1, showing that it is better to use a routing based on the link distance instead a routing based on the cost specified by (4). And so, this can also bring one benefit in sense of algorithm complexity, since IA-RWA 1 use fixed routing, thus do not demand the actual network state to compute a route. In opposition, IA-RWA 2 uses the actual network state to compute a route. The IA-RWA 2 performance is not good because when it computes the route with less ASE noise, it tends to find paths with more hops than the ones find by IA-RWA 1. And so, future requests may be blocked by wavelength continuity constraint, as is verified in Fig. 7. Note that the use of gain update by IA-RWA 2 causes a higher blocking due to continuity, but decreases significantly blocking due to QoT. IA-RWA 1 presents the same benefit.

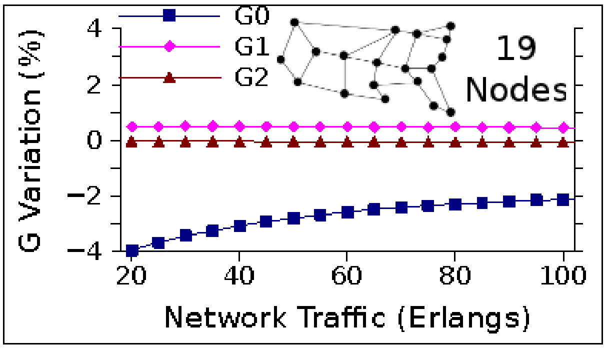

Fig. 4. Gain variation without updates (G_0) and with one (G_1) and two (G_2) updates to 40 *Gbps*.

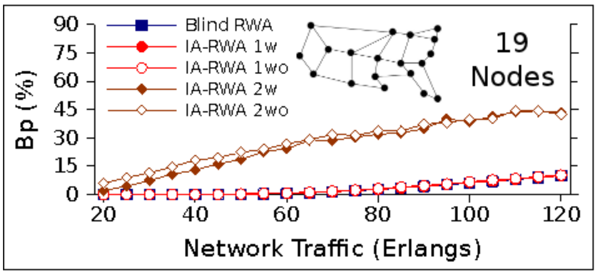

Fig. 5. Blocking Probability to 10 *Gbps*.

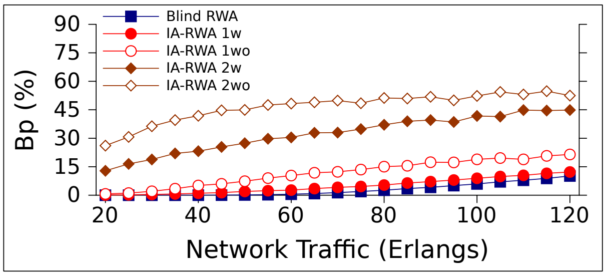

Fig. 6. Blocking Probability to 40 *Gbps*.

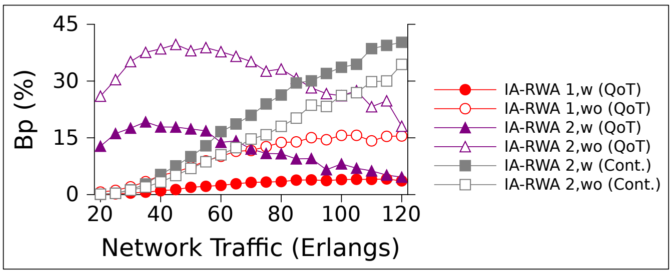

Fig. 7. Blocking only due to QoT (QoT in the legend), and only due to wavelength continuity constraint (cont.). With (w) and without (wo) gain update to 40 *Gbps*.

In order to analyze algorithms performance under a low blocking probability, the dynamic optical network has been simulated operating with 24 wavelengths to 10 *Gbps*. Observe in Fig. 8 that the results present the same behavior, i.e., IA-RWA's with gain update keep better performance than the scenario without gain update. Figure 9 shows only the results for IA-RWA 1 and Blind algorithm. Observe that, for 100 Er, IA-RWA 1 with gain update (w in the legend) presents blocking probability near to 1% or 0.01, while the same algorithm in a network scenario without gain update (wo in the legend) present blocking close to 4% or 0.04. For 50 Er, IA-RWA 1 in network scenarios with gain update shows similar performance to Blind algorithm, with blocking probability close to 0.1% or 0.001.

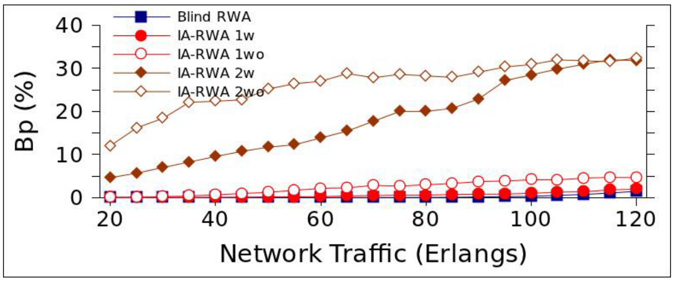

Fig. 8. Blocking Probability to 10 *Gbps* and 24 wavelengths.

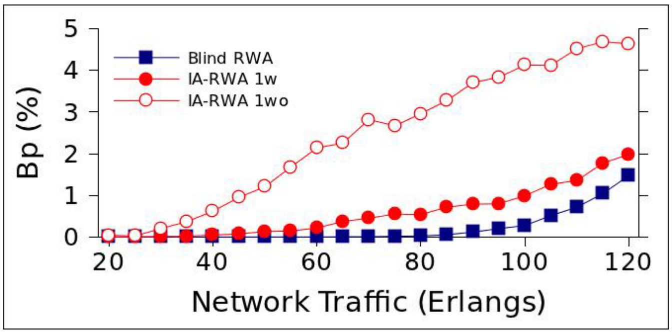

Fig. 9. Blocking Probability to 10 *Gbps* and 24 wavelengths. Blind and IA-RWA 1 algorithms.

V. CONCLUSION

This work presented a study on the benefits that the elimination of EDFA's gain variation can bring to the performance of a dynamic transparent optical network. EDFA's without gain variation can be implemented by using optical amplifiers equipped with Automatic Gain Control (AGC) [14]. Future works will investigate other possibilities for routing strategies as bio-inspired algorithms or meta-heuristics. Reducing of the number of EDFA‘s with AGC will be also studied.

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 Journal of Lightwave Technology*, vol. 27, pp. 1816 – 1826, June 2009.

[2] R. Ramaswami and K. Sivarajan, *Optical networks: a practical perspective*, 3rd ed. Academic Press, 2010.

[3] I. Tomkos, S. Azodolmolky, D. Klonidis, M. Aggelou, and M. Margariti, “Dynamic impairment aware networking for transparent mesh optical networks: Activities of EU project DICONET,” in *10st IEEE International Conference on Transparent Optical Networks. ICTON*, 2008, pp. 2 – 12.

[4] T. Deng and S. Subramaniam, “Source power management in transparent wavelength-routed mesh networks,” in *IEEE International Conference on Communications. ICC 2004*, june 2004, pp. 1664 – 1668.

[5] B. B. Ramamurthy and e. al., “Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks,” *IEEE/OSA Journal of Lightwave Technology*, vol. 17, pp. 1713–1723, oct. 1999.

[6] J. F. Martins-Filho and e. al., “Novel routing algorithm for transparent optical networks based on noise figure and amplifier,” in *IEEE International Microwave and Opticelectronics Conference. IMOC 2003*, sept. 2003, pp. 919 – 923.

[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] R. C. Almeida Jr., D. R. Campelo, A. V. T. Cartaxo, and H. Waldman, “Efficient wavelength assignment policy for XPM-impaired WDM networks,” *IEEE Communications Letters*, vol. 12, pp. 791 – 793, oct. 2008.

[9] M. Ali and 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.

[10] A. G. Rahbar, “Review of dynamic impairment-aware routing and wavelength assignment techniques in all-optical wavelength-routed networks,” *accept to IEEE Communications Surveys & Tutorials*, pp. 1 – 25, 2011.

[11] G. J. Etgen and S. L. Salas, *Cauculus: one variable*, 10th ed., ser. ISBN-13 978-0470073339. Wiley, 2006.

[12] 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.

[13] J. Rebola and A. V. T. Cartaxo, “Power penalty assessment in optically preamplified receivers with arbitrary optical filtering and signal-dependent noise dominance,” *IEEE/OSA Journal of Lightwave Technology*, vol. 20, pp. 401 – 408, mar. 2002.

[14] J. C. R. F. Oliveira, “Amplificadores opticos com controle automatico de ganho em redes opticas,” Tese de Doutorado, UNICAMP, 2007.