Impact of Optical Switch and Amplifier Characteristics on Physical Impairment-based Wavelength-Routed Optical Networks

C. J. A. Bastos-Filho, S. C. Oliveira, E. A. J. Arantes, J. F. Martins-Filho

***Abstract* - We propose and demonstrate a novel dynamic routing algorithm (RWA) for transparent optical networks based on physical layer impairments such as switch loss, amplifier noise accumulation, amplifier gain saturation, amplifier bandwidth, wavelength dependent gain and device losses along lightpaths. Also, we study the influence of each impairment related to the amplifiers and switch elements, on the network performance. The metrics of our algorithm is based on the calculation of the noise figure using the well known formulation for cascade of elements in lightpaths. We assume no wavelength conversion capabilities in our network and we assign wavelengths using a first fit algorithm. For a given call our algorithm assigns the first available wavelength and calculates the best route (minimum noise figure). Upon the calculation of the noise figure of the lightpath we obtain the bit error rate (BER). Our algorithm blocks a call if there is no wavelength available or if the BER for the available wavelength is above a given level, which guarantees a pre-defined quality-of-service for the network operation. We present simulation results of dynamic traffic in a hypothetical meshed network in terms of blocking probabilities as a function of the available wavelengths number, switch loss, network load and amplifier characteristics. We demonstrate that our algorithm outperforms the traditional shortest path routing algorithm.**

***Keywords*— Optical networks, routing and wavelength assignment (RWA), optical amplifiers, optical communication, noise figure, routing algorithm, bit error rate (BER).**

I. INTRODUCTION

The rapidly increasing demands of Internet have been the driving force behind the recent development of the telecommunication industry. The early deployment of wavelength division multiplexing (WDM) technology was in a point-to-point manner to ease fiber exhaustion.

Upon the development of optical amplifiers and other devices more and more WDM channels could be transmitted close together to accomplish higher capacity optical links, in the so called dense wavelength division multiplexing (DWDM) technology. As more advanced sub-systems, such as optical add/drop multiplexers (OADMs) and optical cross-connects (OXCs) have matured, DWDM has become a network-level technology [1-4].

Optical networks can either be opaque or transparent (all-optical). In opaque networks every node regenerates the signal (conversion from optical to electronic and back to optical) to accomplish its functions. These networks have high costs due to the wavelength transponders and electronic circuitry. Moreover, they are bit-rate, protocol, and format dependent. In opaque networks the transmission and switching functions are independent and the accumulation of signal degradation due to physical impairments is much less important, because of the regeneration process. In transparent networks there is no regeneration, i.e. the signal remains in the optical domain from source to destination nodes. Since the network is bit-rate, protocol and format independent, it is more easily upgradable and can support different types of traffic, being more suitable for modern demands. However, intelligence must be included in the optical layer of the network to accomplish the switching of lightpaths and other functions. Moreover, these automatic switched optical networks (ASON) suffer from degradation of optical signal to noise ratio (OSNR) due to physical impairments, since the signal remains in the optical domain, accumulating noise and degradation as it travels through several optical components (fiber segments, EDFAs, OADMs, OXCs, MUX, DEMUX, etc) [1-4].

In these transparent optical networks one of the major factors that affect performance is the lightpath routing and wavelength assignment (RWA). The dynamic RWA problem involves algorithms for efficient route selection and wavelength assignment, including signaling mechanisms to request and establish lightpaths between source and destination nodes, and upgrade the network status when the connections are established and terminated, with minimum call blocking probability [5,6]. In some current work on optical routing it is usually assumed that all routes have adequate signal quality. This is not always the case, especially for large and heavily loaded networks. Although every point-to-point link in a network is designed to provide

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This work was supported by SIEMENS LTDA, Brazil (8o TA – Convênio 003/01 SIEMENS-UFPE/CAESER – Lei 10176/01). C. J. A. Bastos-Filho acknowledges scholarship support from the Brazilian Agency CNPq. S. C. Oliveira acknowledges scholarship support from the Brazilian Agency CAPES.

an adequate signal quality at its output, the dynamics of the network imposes drastic changes in optical parameters all the time. In [7,8] the performance of RWA algorithms based on distance (shortest path), hop count, available wavelengths, relative capacity loss and others are analyzed and compared. None of them take into account the transmission impairments. Ramamurthy et al [9] included BER calculations after a shortest path routing algorithm to take into account some physical impairments. It includes crosstalk in the wavelength-routing nodes, wavelength dependence and saturation of amplifier gains and ASE generation in EDFAs, along with receiver shot and thermal noise. Tang et al [10] considered polarization mode dispersion (PMD), crosstalk and nonlinear effects in a heuristic RWA algorithm. Levandovsky [11] presented a set of guidelines for a routing algorithm based on evaluation of the noise figure to take into account noise accumulation in the lightpath (no gain saturation is considered).

In this paper we propose and demonstrate a novel dynamic routing algorithm for transparent optical networks based on physical layer impairments, including amplifier noise accumulation, amplifier gain saturation, wavelength dependent gain and losses along lightpaths. Similar to [11], the metrics of our algorithm is based on the calculation of the noise figure of the lightpaths. However, we use the simple and well known formulation for cascade of elements to obtain it [12]. Different from [9] our algorithm selects the route based on lowest physical impairments and than calculates BER to check for the QoS. We assume circuit-switched bidirectional connections and no wavelength conversion capabilities in our network and we assign wavelengths using an intelligent first fit algorithm. We present simulation results of dynamic traffic in a hypothetical meshed network in terms of blocking probability as a function of network load and amplifier characteristics. We show that our algorithm outperforms the traditional shortest path routing algorithm. We also show that optical amplifier and switch characteristics greatly affect network performance.

II. ALGORITHM DESCRIPTION

Figure 1 shows the block diagram of our proposed routing algorithm. For a given call our algorithm assigns the first available wavelength between the source and destination nodes and calculates the best route (minimum noise figure). Upon the calculation of the noise figure of the lightpath we obtain the bit error rate (BER). Noise figure and BER calculation will be described in Section III. Our algorithm blocks a call if there is no wavelength available or if the BER for the available wavelength is above a given level, which guarantees a pre-defined quality-of-service (QoS) for the network operation. The blocked calls are lost. The blocking probability is obtained upon the simulation of a set of requested calls (10^5 calls). We use Poisson distribution for call arrivals and for call holding time. The source-destination node pair for each call follows a uniform distribution. The BER threshold was set as 10^{-12}. We implemented our algorithm in MATLAB®. The simulation of 5×10^4 calls takes approximately 2 minutes.

For comparisons we also determine the route and blocking probability for the shortest path routing algorithm. In this case call blocking occurs if there is no available wavelength or if the BER for the chosen route exceeds the BER threshold.

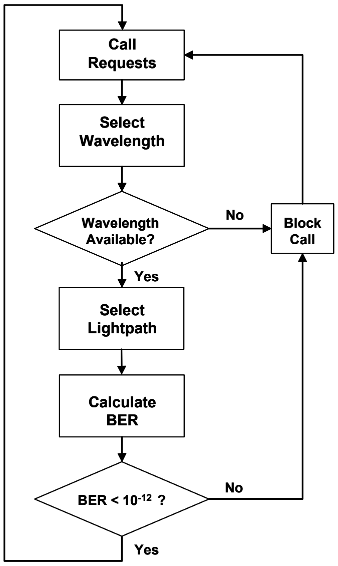

Fig. 1. Block diagram of our routing algorithm.

III. SIMULATION MODELS

Figure 2 shows the configuration of the wavelength routing nodes used in our simulations, which is similar to the ones in [9]. The metrics of our algorithm is based on the calculation of the noise figure for the link between each pair of nodes in the network using the well known formulation for cascade of elements in an optical link [12]. The noise figure (NF) is defined as

$$NF = 10\log F \quad , \tag{1}$$

where F is the noise factor, which is defined in terms of the input and output optical signal to noise ratios as

$$F = \frac{OSNR_{in}}{OSNR_{out}} \quad , \tag{2}$$

There are two main contributions to the noise factor in a single link [12]: an additive term, the spontaneous to signal beat noise (3) caused by the beating between signal and ASE, and a multiplicative term, the shot noise (4). These two terms are given by:

$$F_{LINKsig,sp_i} = F_{AMP} + \frac{F_{AMP} P_{FIBER+2TAP}}{G_{AMP}} \tag{3}$$

$$F_{LINKshot_i} = \frac{P_{SW+MUX} P_{FIBER+TAP} P_{DEMUX+SW}}{G_{AMP}^2} \qquad (4)$$

In (3) and (4)   is the amplifier noise factor,   is the linear loss of the transmission fiber plus the input and output tap losses,   is the linear amplifier gain obtained from figure 3,   is the linear loss of the switch plus the multiplexer loss and   is the linear loss of the demultiplexer plus the switch loss.

To evaluate the noise figure of the lightpaths we use the expression:

$$F_{LIGHTPATH} = \sum_{i=1}^{n} \frac{F_{LINKsig,sp_i}}{\prod_{j=0}^{i-1} G_{LINK_j}} + \prod_{i=1}^{n} F_{LINKshot_i} \qquad (5)$$

where,

$$G_{LINK_i} = \begin{cases} 1, i = 0 \\ \dfrac{G_{AMP}^2}{P_{SW+MUX} P_{FIBER+2TAP} P_{DEMUX+SW}}, i \neq 0 \end{cases} \qquad (6)$$

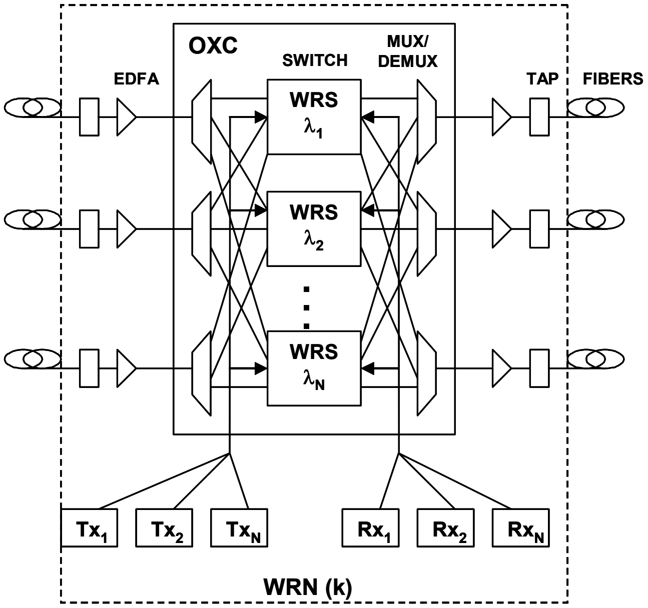

Fig. 2. Configuration of the wavelength routing node (WRN), composed of erbium doped fiber amplifiers (EDFA), monitoring couplers (TAP), and a optical cross-connect (OXC), which consists of multiplex-demultiplex couplers (MUX/DEMUX), ad-and-drop transceivers (Tx and Rx), and a wavelength routing switch (WRS) for each wavelength.

In our simulations we have used the typical values of network components shown in table 1.

Since we are interested in studying the effects of the amplifier impairments in an optical network we used the first order Lorentzian functions to model the spectral gain curve of the EDFA, with different gain bandwidths, which are shown in figure 3. It is important to notice that we have also included the gain compression effect, by using the formulation described in [13].

TABLE I

Typical values used to simulate our optical network.

Component	Typical Loss
Multiplexer	$2L_W + M_\lambda L_R$ (dB)
Demultiplexer	$2L_W + M_\lambda L_R$ (dB)
Switch (For N fiber)	$2\log 2NL_S + 4L_W$ (dB)
Amplifier Gain	23.7 dB
Amplifier noise Figure	5 dB
Tap	0.5 dB
Transmission fiber	0.2 dB/km

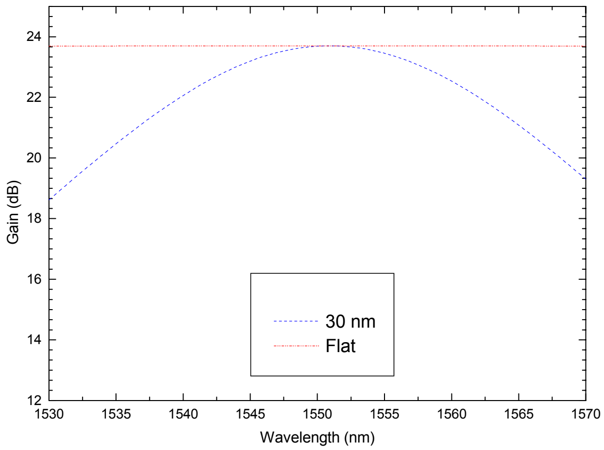

Fig. 3. Lorentzian functions used to model the gain spectrum of an EDFA with a 3dB bandwidth of 30 nm and also flat-band.

The BER for the lightpath is obtained from standard formulation [13,14] using the OSNR at the destination node, which is obtained from the noise figure using equation (2) by assuming an OSNR of 35dB at the input node. This is a worse case scenario, since typical values obtained from commercial transmitter specifications range from 35 to 50dB.

In figure 4 we show a typical meshed optical network configuration [14], which we used in our simulations. Node distances are given in kilometers. Notice that we have tried to create an asymmetric network to evaluate the efficiency of our routing algorithm. We assume circuit-switched bidirectional connections and no wavelength conversion capabilities in our network. The node configuration is given in figure 2.

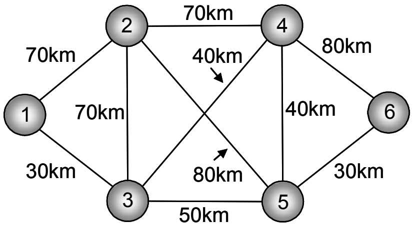

Fig. 4. Configuration of the meshed optical network used in the simulations.

IV. SIMULATION RESULTS AND DISCUSSION

In figure 5 we show the blocking probability as a function of the available wavelengths, for a load of 30 Erlangs. In all the cases our algorithm, based in the minimum noise figure path, outperformed the traditional shortest path algorithm. The blocking probability curves for our RWA algorithm is either lower (for low blocking probability) or equal to those for the shortest path algorithm. Figure 5 clearly shows that there is a minimum value for the blocking probability as a function of the number of wavelength channels. The blocking probability is high for too little wavelengths available, as expected. However, the blocking probability increases for higher wavelength channels due to the multiplexer/demultiplexer losses. As the number of wavelength (M_λ) channels increases it is necessary to increase the number of ports in the multiplexer, leading to higher losses, as given in Table I. As the gain no longer compensates for the losses in the lightpaths the BER increases, leading to higher blocking probabilities. For the simulations of figure 5 we used a switch loss element (L_S) and insertion loss (L_W) of 1 dB, internal reflection loss (L_R) of 0.1dB, an amplifier bandwidth of 30 nm and amplifier saturation power of +16dBm.

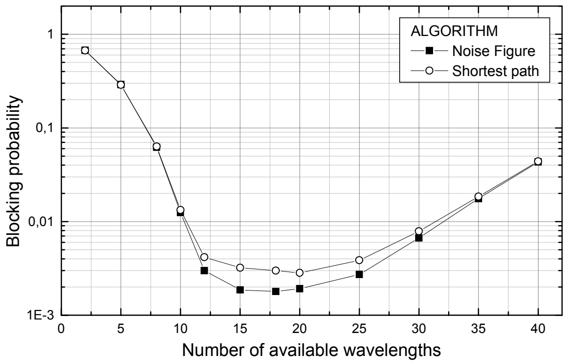

Fig. 5. Blocking probability as a function of the number of available wavelengths, for load of 30 Erlangs, for the algorithm based in the noise figure (squares) and the algorithm using the shortest path (circles). Optical switch loss element (L_S) and insertion loss (L_W) are 1 dB, internal reflection loss L_R=0.1dB, amplifier bandwidth is 30 nm and amplifier saturation power is +16dBm.

In figure 6 we analyze the influence of two amplifier characteristics: the gain bandwidth and the saturation output power, using our proposed noise figure based routing algorithm only. We used a Lorentzian shape gain spectrum with a 3 dB bandwidth of 30 nm and a flat gain spectrum. And we used two values of amplifier saturation power, +16 dBm and +20 dBm. Figure 6 shows that the amplifier bandwidth does not impact the network performance. It is because network performance is limited by BER constraints due to switch losses and amplifier saturation. Indeed, by changing the amplifier output saturation power from 16 dBm to 20 dBm we observe that the blocking probability decreases. For the simulations in figure 6 we used a switch loss element (L_S) and insertion loss (L_W) of 1 dB in both cases, $L_R = 0.1$dB and a 20 Erlang traffic load.

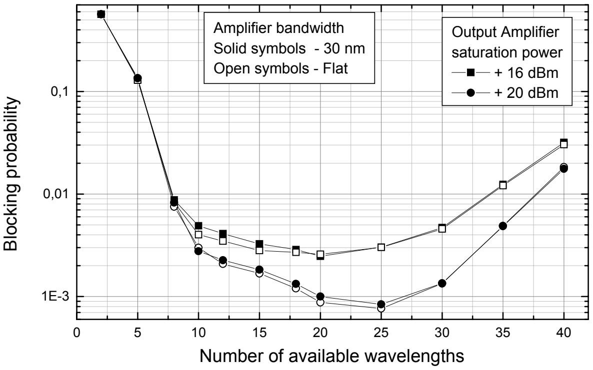

Fig. 6. Blocking probability as a function of the number of available wavelengths for a flat (squares) and 30nm bandwidth gain spectrum (circles), using two amplifier saturation powers, +16dBm (open symbols) and +20dBm (closed symbols). We used a switch loss element (L_S) and insertion loss (L_W) of 1 dB in both cases, L_R=0.1dB and a 20 Erlang traffic load.

In figure 7 we examined the influence of switch loss on network performance by varying the switch loss (L_S) and the insertion loss (L_w). For both we used values ranging from 0.50- to 1.25 dB. We clearly see that they have a dramatic impact on network performance. Figure 7 also shows that for switch losses ranging from 0.75 to 1 dB, the ideal number of wavelengths for the requested traffic is 10, since the blocking probability is below 1%. One can also notice that the blocking probability is higher for the lowest switch loss. This is due to unbalanced amplifier gain, since for low losses the optimum amplifier gain is lower than for the high loss case. For too high amplifier gain the signals experience excessive gain in the amplifier at the beginning of the path, causing saturation to the amplifiers at the end of the lightpath, increasing the BER. As the number of available wavelengths increases the losses increase, decreasing the signal power at the beginning of the lightpath, no longer causing gain saturation. Figure 7 also show that for the highest switch loss case (1.25dB) the blocking probability is high for any number of available wavelengths. In this case the high losses are not being compensated by the amplifiers gain, which leads to a high BER.

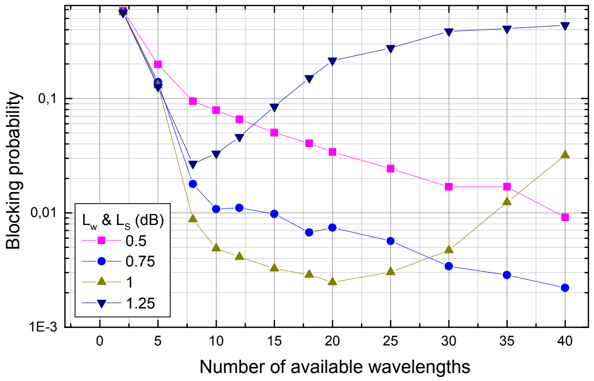

Fig. 7. Blocking probability as a function of the number of available wavelengths, for different switch element losses. We used a 30nm bandwidth amplifier, saturation power of +16dBm and a 20 Erlang traffic load.

V. CONCLUSIONS

In conclusion, we have proposed and demonstrated a novel dynamic routing algorithm for transparent optical networks based on physical layer impairments such as amplifier gain and noise accumulation, amplifier bandwidth, amplifier gain saturation, wavelength dependent gain and switch losses, which are all accounted for in the noise figure of the lightpaths. Our RWA algorithm selects the route based on the minimum noise figure, leading to lower blocking probabilities compared to the shortest path routing algorithm.

Our network simulation results demonstrated that there is an optimum number of wavelengths that minimizes the blocking probability, for a given network traffic load. We have also analyzed the influence of physical impairments such as optical amplifier bandwidth and saturation power, and optical switch losses in the blocking probability. Our results indicate that increasing the amplifier saturation output power has a significant impact on network performance, whereas the amplifier bandwidth has little impact. However, this should not be the case when one increases the total transmission bandwidth by using separate amplifiers in the S and L bands. This will be subject of future work. Our results clearly show that the most important impairment analyzed here was the switch loss. It indicates the importance of the research and development of low loss switches for the accomplishment of efficient, cost-effective, high capacity WDM transparent optical networks.

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