Dynamic Routing and Wavelength Assignment with Power Constraints

Gustavo Sousa Pavani and Helio Waldman

Resumo— **Este trabalho visa ao estudo do problema de roteamento e alocação de comprimento de onda (RWA) considerando restrições de potência no sinal óptico. Propõe-se dois algoritmos dinâmicos de roteamento (Simple e Smart RWA-P), os quais relacionam o ruído ASE e as restrições de potência, para examinar a probabilidade de bloqueio e a imparcialidade sob um tráfego não-estático. Os resultados obtidos sugerem que os atuais algoritmos de RWA devem considerar as restrições de camada física.**

Palavras-Chave— **Rede óptica transparente, roteamento e alocação de comprimento de onda, tráfego dinâmico, restrições de camada física, ruído ASE, restrições de potência.**

Abstract— **This work focuses on the Routing and Wavelength Assignment (RWA) problem while considering constraints on the optical signal power. We propose two dynamic routing algorithms (Simple and Smart RWA-P), which relate the ASE noise and these power constraints, in order to investigate the blocking probability and fairness in a non-static traffic scenario. The results obtained indicate current RWA algorithms should pay attention to physical impairments in the optical layer.**

Keywords— **Transparent optical network, routing and wavelength assignment, dynamic traffic, optical layer physical impairments, ASE noise, power constraints.**

I. INTRODUCTION

Routing and wavelength assignment (RWA) takes a central role in the management of an optical network. However, some works [1], [2], [3], [4], [5] pointed out the necessity of considering the optical layer physical impairments into the RWA to make it effective. In a transparent network, there is no signal regeneration, and the noise and signal distortion accumulate along the lightpath. Therefore, in an ultra-long-haul network, some routes cannot be feasible from the transmission point of view, because they do not have an acceptable transmission performance.

This work proposes an extension to [6], which integrates power constraints and Bit-Error Rate (BER) due to ASE noise into the RWA problem. That first work was limited to a static scenario, where the entire set of connections is known in advance. Now, a dynamic traffic is taken into consideration, in which a lightpath is set up for each connection as it arrives, and the lightpath is released after some amount of time. Indeed, the objective here is to minimize the blocking probabilities of the arriving connections.

In our case, we only treat the Amplified Spontaneous Emission (ASE) noise, because it is a limiting factor for ultra-long-haul systems [7], due to noise accumulation in a cascade of optical amplifiers, and it is easy to be modeled analytically. The maximum acceptable BER determines the minimum power of an optical signal in the network.

Other physical impairments, like fiber non-linearities, are much harder to treat [4] and are not included in this work. However, when the maximum power used in every component of the network is controlled, fiber non-linearities are indirectly managed due to their dependence on the signal power.

The rest of the paper is organized as follows. In Section II, we describe our routing and wavelength assignment problem with its power constraints. In Section III, we present the node architecture. In Section IV, we give the parameters used throughout this paper. In Section V, we describe the network and the traffic used. In Section VI, we detail the dynamic RWA algorithms. In Section VII, we report our simulation results. The paper concludes with Section VIII.

II. RWA WITH POWER CONSTRAINTS (RWA-P)

This paper studies a variant of the RWA problem, known as RWA with power constraints (RWA-P), which was first introduced by [3], [8] and extended by [6] for the static traffic. For a dynamic traffic scenario it can be stated as follows: given a network topology and a dynamic traffic, the objective is to minimize the blocking probability of the connections by routing, assigning wavelengths, and maintaining an acceptable level of optical power and adequate Signal-Noise Ratio (SNR) all over the network.

The minimum power constraint (which is also called sensitivity level) assures that the optical signal can be detected by all optical devices. The maximum power constraint guarantees the minimization of non-linear physical impairments, because it makes the aggregate power on a link to be limited to a maximum value.

One difficulty in this problem is that the gain of the optical amplifier is a traffic-dependent nondeterministic quantity [2]. In addition, the accumulated ASE noise saturates even more the amplifiers.

A. Sensitivity level

The minimum power or sensitivity level in each component of the network is calculated based on the ASE noise and can be determined by the following equation [6]:

$$P_{sen} = 4\gamma^2 N_{sp} h f_c B_e \left\{ 1 + \sqrt{1 + \frac{\frac{B_o}{B_e} - \frac{1}{2}}{4\gamma^2}} \right\} \qquad (1)$$

where N_{sp} is the spontaneous emission factor, f_c is the frequency of the optical carrier, h is the Planck's constant

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($\because hf_c$ is the energy of the photon), G is amplifier's gain and, B_o is the optical bandwidth (which is at most the spacing of the frequency grid in WDM systems), B_e is the electrical bandwidth of the low-pass filter after the photodetector. Let $\gamma = Q^{-1}(BER)$ and Q function can be numerically evaluated [7]:

$$Q(t) = \int_t^{\infty} \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}}\, dx \tag{2}$$

The Q factor is commonly used in the receiver performance specification, because it is related to Signal-Noise Rate (SNR) necessary to achieve a certain Bit-Error Rate (BER). For example, for a BER of 10^{-15} we have, approximately, $\gamma = 8$. Nowadays, a BER of 10^{-15} is a common requirement for new WDM systems.

B. Amplifier Cascading: Equivalent Pre-amplifier Model

Consider that the receiver gets the signal from a link with cascading amplifiers, numbered as $1, 2, \ldots$ starting from the receiver, as shown in figure 1. The pre-amplifier can be considered as the amplifier number 0 of the cascade. Let G_i be the gain of amplifier i e $N_{sp\,i}$ its spontaneous emission factor. The span between the i-th and the $(i-1)$-th amplifier has attenuation L_i. Let P_i the mark power at the input of the i-th amplifier.

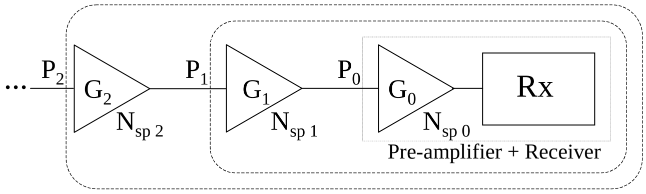

Fig. 1. Cascading of amplifiers.

The minimum value of P_i can be obtained by doubling the value of equation 1 and it can be represented by the cascade, from the input of amplifier i until the output of pre-amplifier, as an equivalent pre-amplifier of gain G_i^{eq} and spontaneous emission factor $N_{sp\,i}^{eq}$. As demonstrated in [6], equation 3 gives the equivalent spontaneous emission factor:

$$N_{sp\,1}^{eq} = \frac{N_{sp\,1}(G_1 - 1)L_1 G_0 + N_{sp\,0}(G_0 - 1)}{G_1 L_1 G_0 - 1} \tag{3}$$

Finally, the value of $N_{sp\,1}^{eq}$ replaces N_{sp} in equation 1 to calculate the minimum value of P_1. Calculating recursively $N_{sp\,i}^{eq}$ one can find all sensitivity levels in a connection request.

C. Other approach

In [4], the ASE noise is also considered in the RWA phase as shown in equation 4. However, it just gives an upper bound on the number of optical amplifiers in a lightpath, which may overestimate the blocking probability due to ASE noise. A future work will compare equation 1 and equation 4 approaches.

$$M \leq \left\lfloor \frac{P_L}{2SNR_{min} n_{sp} h\nu (G-1) B_o} \right\rfloor, \tag{4}$$

where M is the number of optical amplifiers, P_L is the average transmitting power, n_{sp} is the spontaneous emission factor, h is the Planck's constant, B_o is the optical bandwidth, G is the amplifier gain and SNR_{min} is the minimum signal-noise relation.

III. NODE ARCHITECTURE

An optical network is formed by the interconnection of wavelength routing nodes (WRNs), by pairs of unidirectional fibers. A WRN is composed by many components, such as taps, optical amplifiers, multiplexers/demultiplexers, etc. Also, the local station and the optical cross-connect (OXC) are regarded as a part of WRN.

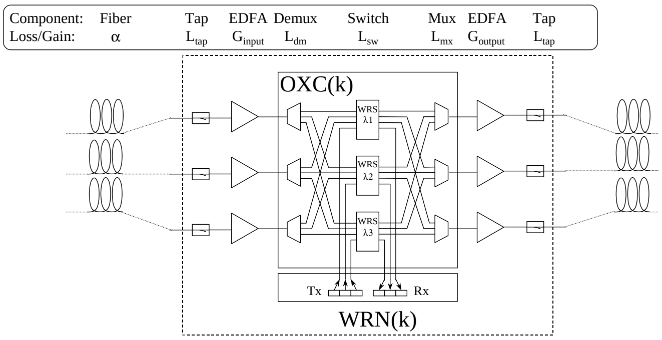

Fig. 2. WRN architecture.

Figure 2 shows a representative WRN. This 4×4 WRN has one local station attached to it, represented by the receivers and transmitters. The OXC inside the WRN contains multiplexers/demultiplexers and a wavelength routing switch (WRS), which is responsible for routing the traffic.

In this example, there are 3 WRS in the node and each WRS is dedicated to one wavelength, so this node holds 3 wavelengths. The optical signal entering the WRN passes by many components that contributes for the gain or loss of the signal power. The loss caused by a WRS can be calculated with the following expression [9]:

$$L_{sw} = 2\lceil \log_2(D_i) \rceil L_s + 4L_w, \tag{5}$$

where D_i is the node degree, i.e., the number of links and stations attached to this node; L_s is the loss due to the switch element insertion loss and L_w is the loss due to the waveguide/fiber coupling loss.

A. Amplifier gain

The gain of the amplifier is calculated as follows [10]:

$$G = 1 + \frac{P^{sat}}{P_{in}} \ln \frac{G_{max}}{G}, \tag{6}$$

where G_{max} is the small-signal gain of amplifier, P^{sat} is the amplifier's internal saturation power, and P_{in} is the total input signal power.

IV. PARAMETERS

In table I, we present the system/device parameters used throughout this paper.

Parameter	*Symbol*	*Value*
Maximum aggregate power on a link	P_{max}	1 mW (0 dBm)
Maximum transmitter power	P_{max}^{xmit}	1 mW (0 dBm)
Small-signal gain of inline amplifier	G_{inline}	20 dB
Small-signal gain of pre/input amplifier	G_{input}	12 dB
Small-signal gain of output amplifier	G_{output}	12 dB
Fiber attenuation	α	0.2 db/km
Tap loss	L_{tap}	1 dB
Multiplexer loss	L_{mx}	4 dB
Demultiplexer loss	L_{dm}	4 dB
Switch element insertion loss	L_s	1 dB
Waveguide/fiber coupling loss	L_w	1 dB
Optical carrier frequency	f_c	193 THz (1.55 μm)
Planck's constant	h	6.63×10^{-34} J/Hz
Optical bandwidth	B_o	100 GHz
Bit rate	B	2.5 Gbps
Electrical bandwidth	B_e	2 GHz
N_{sp} of inline amplifier	N_{sp}^{inline}	2
N_{sp} of pre/input amplifier	N_{sp}^{input}	2
N_{sp} of output amplifier	N_{sp}^{output}	2
Saturation power of inline amplifier	P_{inline}^{sat}	13.7 mW
Saturation power of pre/input amplifier	P_{input}^{sat}	13.7 mW
Saturation power of output amplifier	P_{output}^{sat}	13.7 mW
Parameter of function Q	γ	8

TABELA I

SYSTEM/DEVICE PARAMETERS AND VALUES USED IN RWA-P PROBLEM.

V. SMALL OPTICAL NETWORK AND TRAFFIC

In this work, we used a small optical network that is shown in figure 3. The stations are depicted by circles, the switches are represented by the hexagons and the optical amplifiers by triangles.

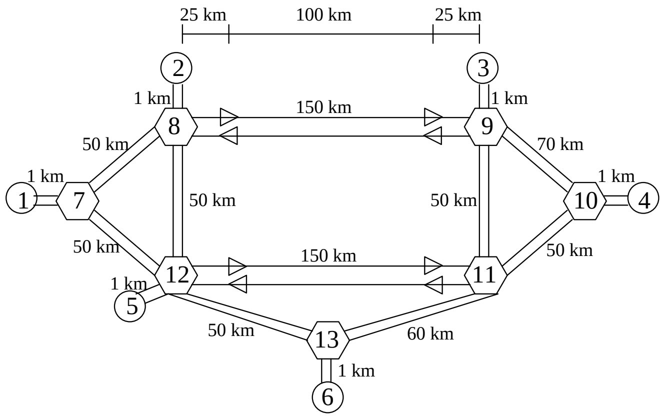

Fig. 3. Small optical network.

Each station has an equal probability to be selected as the source station, but a non-uniform probability of being choosed as a destination station as shown in equation 7, where $T_{i,j}$ is the relative weigth bias of a given station i as the source node to choose the station j as the target.

$$T = \begin{bmatrix} 0 & 3 & 2 & 0 & 2 & 1 \\ 0 & 0 & 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 3 \\ 1 & 3 & 2 & 0 & 3 & 2 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 1 & 2 & 3 & 1 & 2 & 0 \end{bmatrix} \qquad (7)$$

Finally, we used a memoryless traffic: Poissonian arrivals with exponentially distributed service time. We varied the total load of the network from 1 to 20 Erlangs.

VI. DYNAMIC RWA ALGORITHMS

Although the combined problem of routing and wavelength assignment is a very hard problem, it can be decoupled in two separate subproblems: the routing subproblem and the wavelength assignment subproblem. Due to the lack of uniformity of the literature, throughout this section, we will use the definitions from [11].

For the routing subproblem, we used a fixed-alternate routing approach. In this strategy, each node in the network maintain a routing table containing an ordered list of a number of fixed routes to each destination node. For instance, these routes may include the shortest-path route, the second-shortest-path and so on. For calculating the k-shortest paths in this work, we used the Yen's algorithm [12], restraining its number to 3.

For the wavelength assignment subproblem, we used a First-Fit (FF) approach. In this scheme, all wavelengths are numbered. When searching for a available wavelength, a lower-numbered is considered before a higher-numbered wavelength. The first available wavelength is then selected. This approach is used due to its simplicity and low computation cost. Also, this scheme performs well in terms of blocking probability and fairness.

For the RWA-P problem, however, even if we can allocate a path with an available wavelength, we have to verify if this lightpath can be established, i.e., if the connection does not violate the minimum and maximum power constraints.

We developed two different strategies for connection establishment. The first one, which is shown in Algorithm 1 and called Simple RWA-P, takes the first available path and verifies if the connection can be established. If the connection does not violate the power constraints, the connection is set up. Otherwise, the connection is rejected. The second one, which is shown in Algorithm 2 and called Smart RWA-P, tries others paths if the current route cannot meet the power restrictions, until the connection can be set up or the number of pre-calculated paths (K) is reached.

These two approaches uses a iterative method for finding the transmitting power for each connection. They start with -30 dBm of transmitting power and at each iteration they increase their power by 1 dBm. The iteration ends when the power in all components are above the sensitivity level or the transmitting laser has reached its maximum power (P_{max}^{xmit}).

VII. RESULTS

For comparing the Simple RWA-P and Smart RWA-P approaches, we also simulated the RWA considering only its topological aspect. All simulations were carried with 8 wavelengths available in the network. As the simulations were very time consuming, we limited our simulations to 10^5 connection requests, except for the figures 5 and 7 where the topological RWA was calculated with 10^7 requests.

Algorithm 1 SIMPLE RWA-P

```
$P^{xmit} \leftarrow$ - 30 dBm
for $i \leftarrow 1$ to $K$ do
    $path \leftarrow$ GETPATH($i$)
    $wavelength \leftarrow$ GETWAVELENGTH($path$)
    if Available lightpath then
        while $P^{xmit} < P^{xmit}_{max}$ do
            if Above sensitivity level in all components of the network then
                return True
            end if
            $P^{xmit} \leftarrow P^{xmit}$+ 1 dBm
        end while
        return False
    end if
end for
return False
```

Algorithm 2 SMART RWA-P

```
$P^{xmit} \leftarrow$ - 30 dBm
for $i \leftarrow 1$ to $K$ do
    $path \leftarrow$ GETPATH($i$)
    $wavelength \leftarrow$ GETWAVELENGTH($path$)
    if Available lightpath then
        while $P^{xmit} < P^{xmit}_{max}$ do
            if Above sensitivity level in all components of the network then
                return True
            end if
            $P^{xmit} \leftarrow P^{xmit}$+ 1 dBm
        end while
    end if
end for
return False
```

The results for the Smart RWA-P with K=1 are exactly the same for the Simple RWA-P with K=1, since there are no alternate routes to be tested.

An alternate route significantly improves the blocking probability, as seen for the Smart RWA-P with K=2 over the curve for the Simple RWA-P. Clearly, the Smart RWA-P outperforms the Simple RWA-P approach, since the latter does not take full advantage of the alternate routing.

Under higher load, occasionally the Simple RWA-P presented slighter more blocking probability for values of K equals to 2 and 3 than for K equal to 1. The same behavior was observed for the Smart RWA-P, where K equals to 3 had sometimes a slight higher blocking than with K equals to 2, for a total load greater than 15 Erlangs in the network. For sake of clarity, all these curves are not shown in the figure 4, since the variations are very small $(< 1\%)$.

A. Fairness

Though important, average blocking probability (computed over all connection requests) does not always capture the full effect of a particular dynamic RWA algorithm on other aspects of network behavior, in particular, fairness. In this context, fairness refers to the variability in blocking probability experienced by lightpath requests between the various edge node pairs, such that lower variability is associated with a higher degree of fairness. In general, any network has the property that longer paths are likely to experience higher blocking than shorter ones. Consequently, the degree of fairness can be quantified by defining the unfairness factor as the ratio of the blocking probability on the longest path to that on the shortest path for a given RWA algorithm [13].

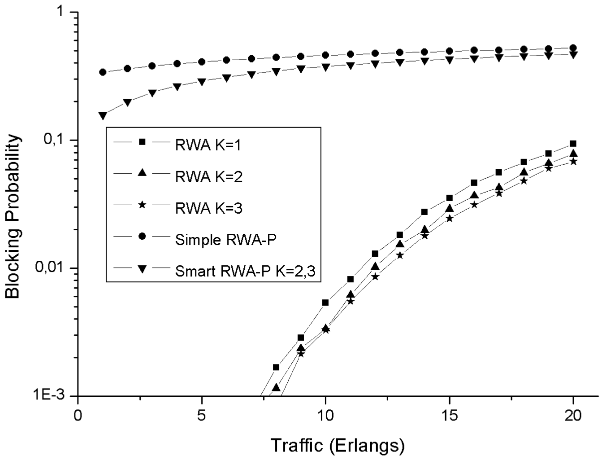

Fig. 4. Blocking probabilities.

In figure 5, we depicted the blocking probabilities for the topological RWA versus the distance covered by the lightpath.

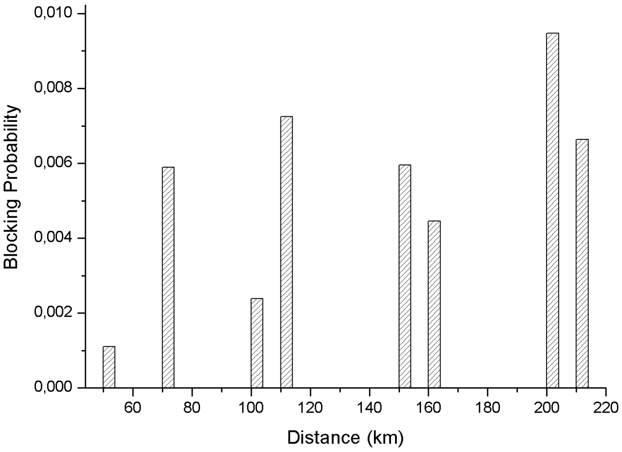

Fig. 5. Blocking probabilities for the topological RWA with K=1.

In figure 6 is shown the the blocking probabilities for the Simple RWA-P versus the distance covered by the lightpath.

One can notice that when the power constraints are introduced in the RWA, the longer paths suffer from much higher

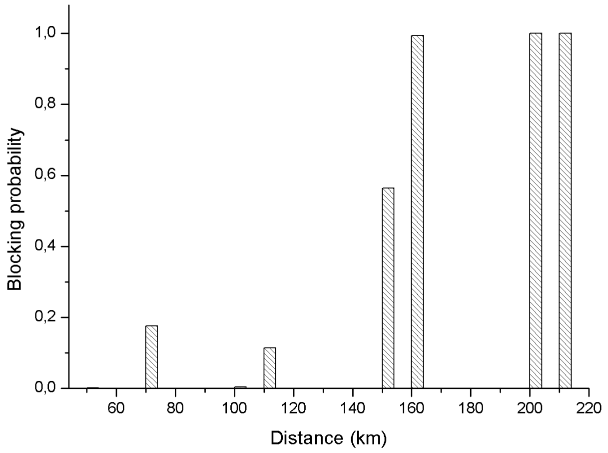

Fig. 6. Blocking probabilities for the Simple RWA-P with K=1.

probabilities of being blocked. Indeed, routes bigger than 200 km has a 100% chance of being blocked.

The comparison of the fairness between the topological RWA and the Simple RWA-P shown in figure 7 indicates the high degree of unfairness of the Simple RWA-P algorithm.

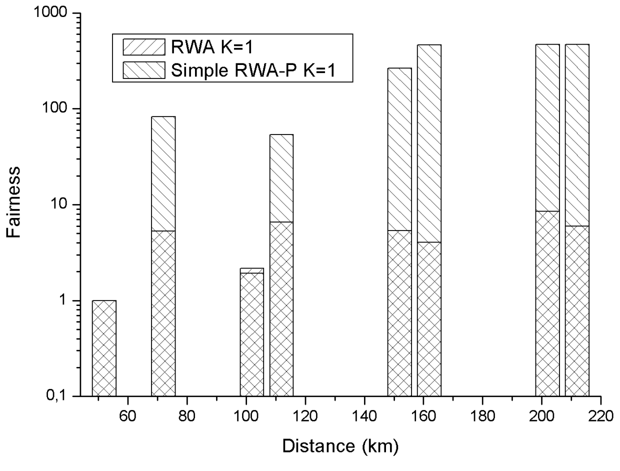

Fig. 7. Fairness comparison between topological RWA and Simple RWA-P with K=1.

The high unfairness of the Simple RWA-P algorithm was expected, because the ASE noise tends to accumulate along the lightpath due to amplifier cascading, penalizing the longer paths. This property may have a cascading effect which can result in an unfair treatment of the connections between more distant edge node pairs: blocking of long lightpaths leaves more resources available for short lightpaths, so that the connections established in the network tend to be short ones.

VIII. CONCLUSIONS

We confirmed the importance of incorporating optical layer physical impairments into the RWA algorithm. Indeed, the noise generated in the normal operation of the optical network may impair the establishment of lightpaths with an acceptable BER. As seen in this work, more than a half of the connections requests can be blocked due to ASE noise. This number may be even greater with we consider other kinds of physical impairments.

As a future work, an algorithm that introduces fairness in the RWA-P algorithm is planned and welcomed.

ACKNOWLEDGMENTS

This work was supported by FAPESP, CNPq and the Research and Development Center, Ericsson Telecomunicações S.A., Brazil.

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