Fair Power Distribution Among WDM Channels in a Transparent Linear Network

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Summary—Transparent optical networks are those in which the signal remains in the optical domain from source to destination. Due to amplifiers saturation, ASE noise and non-linearities, a fair power distribution among channels is necessary due to lightpaths having different links distances.

***Index Terms*—Transparent optical network, WDM, EDFA, Fair power distribution.**

I. INTRODUCTION

A transparent network provides connections called lightpaths, that are wavelength routes from source to destination. If there are some nodes capable of wavelength conversion, there is no need to have the same λ available in all links of the connection. The eletronic bottleneck of very high bandwidth networks is mitigated in transparent networks because they eliminate the O-E-O conversions of traditional optical networks (opaque networks), thus making protocol independent.

To compensate the signal attenuation through the link, erbium doped fiber amplifiers (EDFA) are used, but they generate ASE noise. Even with just one amplifier, signal-ASE beat noise can be the dominant noise among others like thermal and shot noise at the electronic receiver. Other types of signal impairment such as dispersion, crosstalk and non-linearities like FWM, as well as penalties like extinction ratio, are covered by the system margin. Reed-Solomon Forward Error Correction (239,255) is assumed, providing a coding gain of about 6 dB [1], which is essential for long distance WDM transparent links using IM-DD technology, because it enables a longer communication link without regeneration.

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Fig. 1 shows the EDFA model used in the simulation. The flat gain assumption is used (approximately 1545 – 1560 nm), so that all the wavelengths in the specific EDFA experience the same gain, and the gain is a function only of the total input power (the signals powers plus the noise power). Using the least square regression, the transcendental equation $G = 1 + (P_{SAT}/P_{IN})\ .\ \mathrm{Ln}\ (G_{MAX}/G)$, for $P_{SAT} = 10$ mW and $G_{MAX} = 26$ dB, is approximated by to the polynomial $G = 14.535 - 0.736\ P_{IN} - 0.0067\ P_{IN}^2 + 0.00043\ P_{IN}^3 + 1.08 \times 10^{-5}\ P_{IN}^4 + 7.1 \times 10^{-8}\ P_{IN}^5$.

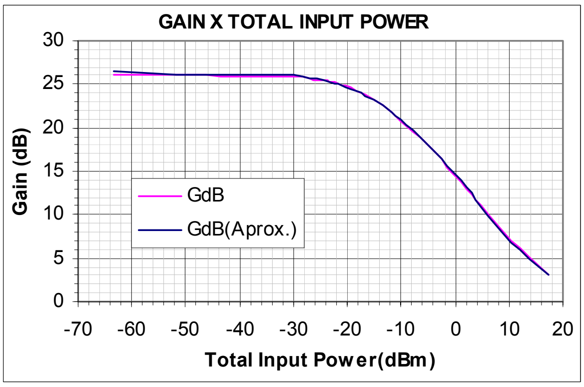


Fig. 1 : EDFA Model

III. LINEAR NETWORK

A linear network was simulated with 4 nodes, unequally spaced along a line. As shown in Fig. 2, each node represents a Brazilian city, and the distances were approximated to multiples of 100 kilometers, which is the distance between amplifiers.

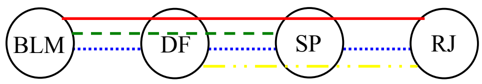


Fig. 2: Linear Network Interconnecting 4 Cities

The acronyms BLM, DF, SP, RJ stand for Belém, Brasília, São Paulo and Rio de Janeiro respectively, and the disposal and the number of optical amplifiers, as well as the allocation of the wavelengths are:

Wavelength 1 - λ_1
Wavelength 2 - λ_2
Wavelength 3 - λ_3
Wavelength 4 - λ_4

BLM-DF: 1600 km – 16 EDFA´s
$P1_{BLM-RJ} + P2_{BLM-SP} + P3_{BLM-DF}$

DF-SP: 1000 km – 10 EDFA´s
$P1_{BLM-RJ} + P2_{BLM-SP} + P3_{DF-SP} + P4_{DF-RJ}$

SP-RJ: 400 km – 4 EDFA´s
$P1_{BLM-RJ} + P3_{SP-RJ} + P4_{DF-RJ}$

IV. BER MODEL

The bit error rate (BER) model used in the simulations is the same as proposed in [1]. It is adequate for amplified systems with ASE as the dominant noise, and $2 \times B_O >> B_e$. The parameters of the system are shown in Table 1.

Table 1: System Parameters

Parameter	Value
Number of wavelengths	4
Bit Rate (Rb)	2,5 Gbps
Electrical Bandwidth (B_e)	0,7 Rb
Optical Bandwidth (B_O)	10 GHz
ASE Factor (N_{SP})	2
Fiber Attenuation	0,25 dB/Km
Span Length	100 km

The following equations are necessary to evaluate BER, where P_{ASE} means the ASE power.

$$BER = Q(\gamma) \qquad (1)$$

$$Q(\gamma) = \frac{1}{\sqrt{2\pi}} \int_{\gamma}^{\infty} e^{-\frac{1}{2}z^2} dz \qquad (2)$$

$$\gamma = \frac{2 \times OSNR \times \sqrt{\frac{B_O}{B_e}}}{1 + \sqrt{4 \times OSNR + 1}} \qquad (3)$$

$$OSNR = P_{SIGNAL}/P_{ASE} \qquad (4)$$

$$P_{ASE} = 2 \times P_N \times (G-1) \times B_O \qquad (5)$$

$$P_N = N_{SP} \times h \times f_C \qquad (6)$$

In equation (6), h is the Planck constant with value 6.63×10^{-34} J.Hz, and f_C is the carrier frequency with value ~ 193.1 THz.

V. SYSTEM DESIGN

System design requires careful budgeting of the power for different impairments. Here a design is sketched out for a transmission system with optical amplifiers. First the ideal value of the parameter γ is determined. It is assumed that a BER of 10^{-12} is desired, so we need $\gamma = 7$, or $20 \log \gamma = 17$ dB. This is the case of an ideal system, but due to impairments some penalties must be added onto this ideal value γ, as shown in Table 2. The required γ after adding all the considered impairments and coding gain is 20 dB. This is the value that must be obtained if an ideal system is assumed to start with, and γ is computed only from optical amplifier noise accumulation [1].

Table 2: System Design

Impairment	Allocation (dB)
Ideal γ	17
Transmitter	1
Crosstalk	0.5
Dispersion	1
Nonlinearities	0.5
Circulator (worst case)	3
Margin	3
Coding Gain	(6)
Required γ	20

VI. SYSTEM CALCULATIONS

Two cases were simulated, the former considering input mean power of 0,5 mW for each channel, and the latter considering different input mean power in each channel. The power distribution in the latter case is a function of the link distance and the EDFA saturation.

A. *Same Power for All Channels*

In this case an input mean power of 0,5 mW for each channel was considered, regardless of the link distance.

B. *Unequal Channel Powers*

The amplifier model used in this problem is such that when the gain provided by EDFA is just sufficient to compensate the span attenuation, the output power of the amplifier is about 2.16 mW. So in a fair power distribution, this 2.16 mW should be distributed among all channels in each hop. In reality, at least in the first hop (fiber link between Belém and Brasília), because after this hop there is a great probability that the EDFA would be in a saturation state (with input power about -22 dBm), so with the insertion of new channels (and drop of others) this limit can be exceeded and the gain provided by the EDFA will be less than 25 dB that is necessary to compensate the span attenuation. Even though the value 2.16 is not the ideal one, it will be used as a base to find the other channels powers.

Belém node is used as reference, so that the connection to Brasília has 1600 km, connection to São Paulo has 2600 km and to Rio de Janeiro has 3000 km. To distribute 2.16 mW power in a fair way, for each channel was attributed a power proportional to its link distance, so:

$P_{BLM\text{-}BRA} = (1600 / 7200) \times 2.16 \text{ mW} = 0.48 \text{ mW}$

$P_{BLM\text{-}SP} = (2600 / 7200) \times 2.16 \text{ mW} = 0.78 \text{ mW}$

$P_{BLM\text{-}RJ} = (3000 / 7200) \times 2.16 \text{ mW} = 0.9 \text{ mW}$

$P_{BRA\text{-}SP} = (1000 / 7200) \times 2.16 \text{ mW} = 0.3 \text{ mW}$

$P_{BRA\text{-}RJ} = (1400 / 7200) \times 2.16 \text{ mW} = 0.42 \text{ mW}$

$P_{SP\text{-}RJ} = (400 / 7200) \times 2.16 \text{ mW} = 0.12 \text{ mW}$

C. Results

Figs. 3, 4 and 5 describe the variations of several parameters when the transmitted power in each path is set at 0,5 mW. In Figs. 6, 7 and 8, the same parameters are calculated when the transmitted powers are set according with the fairness criterion in *B*.

Fig. 3 shows that in the first spans, the signals received an extra gain (more than 25 dB that is necessary to compensate each span attenuation). It is due to the EDFA not being in a saturated state as in Fig. 6, where signals remain almost constant in the first hop, and fall slightly due to ASE power participating in the EDFA saturation. In both figures, in the second hop (DF-SP), the gain provided by the amplifiers is not sufficient to compensate the fiber loss due to the adding of 2 new signals and the drop of just one, saturating the optical amplifier. In the last hop (SP-RJ) the opposite occurs, adding of just one signal (with low power), and drop of two signals with relatively high power, so extra gains are provided.

Figs. 4 and 7 show ASE signals growing almost linear, mainly in Fig. 7, because the ASE signal is proportional to G-1, and as the gain is very close along the amplifiers in each hop, the ASE progression grows almost as a straight line.

In Fig. 5, the "short connection" between São Paulo-Rio de Janeiro has a BER of 10^{-47}, but other longer connections like Belém-São Paulo, has a 10^{-8} BER. To counteract this unfairness, a power distribution among the signals were applied. Fig. 8 shows that the BER of 10^{-12} is unreachable, but at least all connections reach the destination with BER of 10^{-10} or a little better, so applying power distribution, bit error rate can be improved from 10^{-8} for the worst case to 10^{-10}. If a BER of 10^{-10} is acceptable, then this fair power distribution can be used, otherwise some regeneration must be done, and the network should be called translucent network, instead of transparent network.

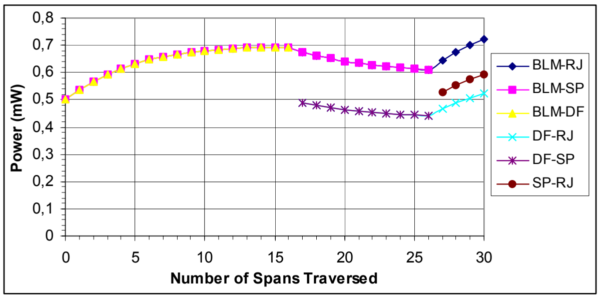


Fig. 3: Power in Each Link

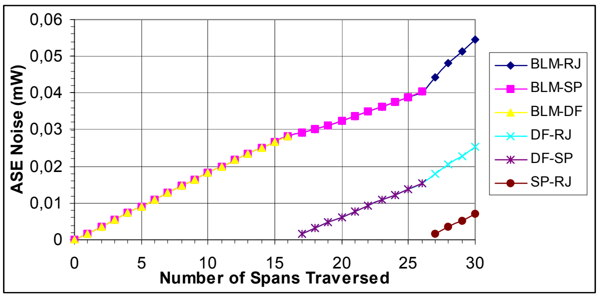


Fig. 4: Progression of ASE Noise in Each Link

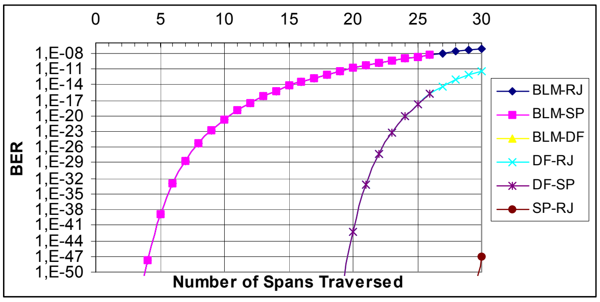


Fig. 5: BER Along the Network

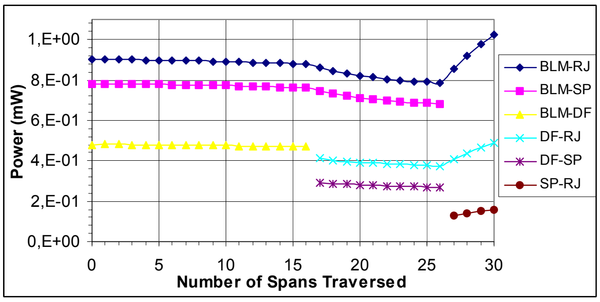


Fig. 6: Power in Each Link

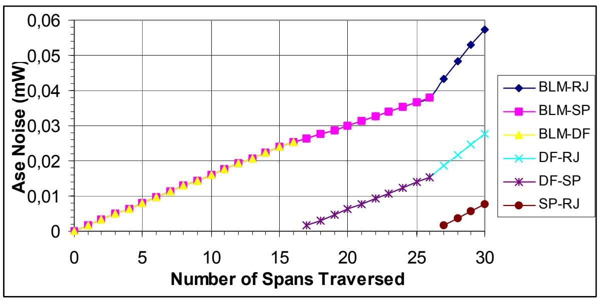


Fig. 7: Progression of ASE Noise in Each Link

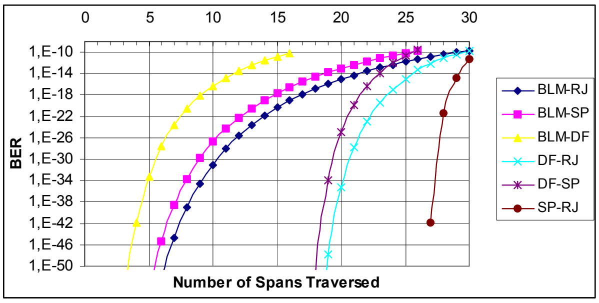


Fig. 8: BER Along the Network

VII. Conclusion

Currently, most of the optical networks installed, provide full regeneration (3R) to each signal in every node. This makes the network very expensive, besides being dependent of protocol and technologies, that is, it has a very rigid implementation. The most used transport technology is SDH, so SDH equipment is necessary at each node, for example, regenerators and ADMs. In transparent networks, all equipment would be independent to the signals types.

It is widely accepted that a fully transparent nation-wide optical network is not feasible, and a more realistic scenario is the interconnection of all-optical domains via an opaque nation-wide network. This scenario received the name of translucent network [2].

The present model shows that, it would be possible to have very long-haul networks with O-E-O conversions just in the source and in the destination, and to guarantee an acceptable BER (sometimes this is not possible) it is necessary to make input powers dependent of the distances and of the aggregate power of all lightpaths sharing each hop. This aggregate power dependence is due to fiber non-linearities and optical amplifier saturation.

This work suggests that longer linear network links in a WDM system can be achieved if a fair power distribution is used for each lightpath. For this, a simple method was used that assigns to each lightpath a power proportional to its distance, all this with intention to reduce the network cost.

In future works, the linear network will be upgraded to a mesh network and the transparent network will be a translucent one, where a specific node would be transparent for some signals but opaque for others.

References

[1] R. Ramaswami e K.N. Sivarajan, Optical Networks: A Practical Perspective. San Francisco, CA: Morgan Kaufmann Publishers, 1998.

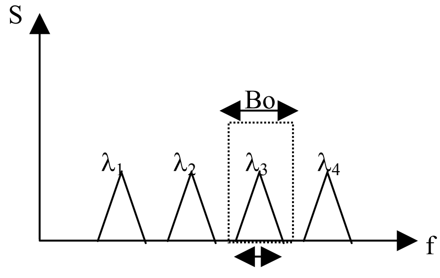
[2] M. Ali, Transmission-Efficient Design and Management of Wavelength-Routed Optical Networks. Kluwer Academic Publishers, 2001.

[3] B. Ramamurthy, et al. "Impact of transmission on the teletraffic performance of wavelength-routed optical networks" IEEE/OSA Journal of Lightwave Technology, October 1999.

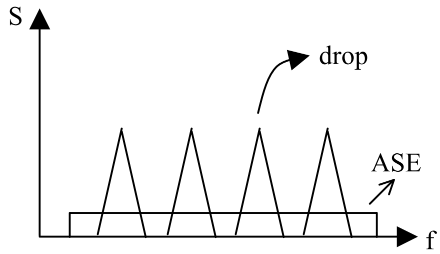
Appendix

Spectral Behavior Which Had Filtering and Optical Amplification

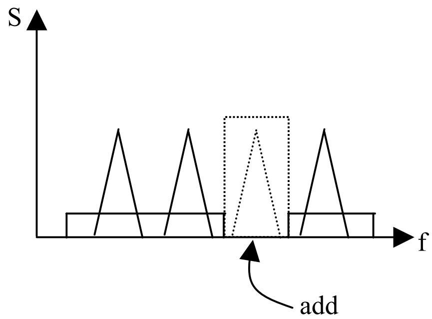
It is shown below, that when a channel is dropped and another one is added in the same wavelength, it will find the ASE spectrum cleaned in its band.



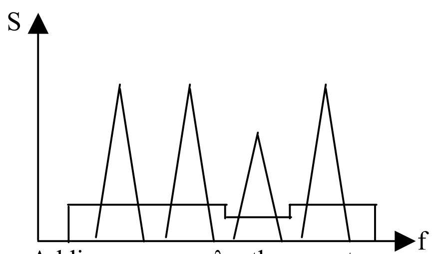
Consider that 4 λ's are inserted in the same node.



After passing by the EDFA, the power spectrum of ASE, will be ideally flat.



Because of the filter (Bragg grating), the spectrum was cleaned, appearing a gap.



Adding a new λ, the spectrum will have bands with different ASE levels.