EDFA Adaptive Gain Control Effect Analysis over an Amplifier Cascade in a DWDM Optical System

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***Abstract*—In this paper, we analyze the EDFA adaptive gain control impact on 80 modulated C-band channels (10 Gbps NRZ) in a DWDM optical system composed of four cascaded amplifiers. System performance was evaluated in terms of channels optical signal-to-noise ratio (OSNR), noise figure (NF), bit error rate (BER), and gain flatness (GF) measurements. The adaptive EDFA scheme aims to optimize NF and GF spectra by adjusting its setpoint gain based on static information about these parameters and was improved here to prioritize NF when BER of the received signal remains under the FEC limit.**

I. Introduction

Due to the increasing global internet traffic, including several broadband applications, optical networks are becoming increasingly dynamic and complex to manage. One way for services providers and telecommunication carrier to overcome these issues is to minimize operators efforts, allowing the network to make some adjustments autonomously based on the overall system performance.

Aiming this goal, components of the optical network must have some degree of intelligence in order to act when a physical layer impairment or any other change occurs. This intelligence can be based on a static knowledge, previously stored in a memory (embedded in component or in centralized control), or by a cognitive process in which component or system learns and acts from its previous experience.

Some approaches that simplify and automate process configuring devices and network topologies in a dynamic environment including adaptive and cognitive procedures emerged in the network operation management [1]–[4]. These decisions must be taken always considering a system quality of service (QoS) parameter as bit error rate (BER) or optical signal to noise ratio (OSNR).

The erbium doped fiber amplifier (EDFA) is a device that plays a key role in optical networks responsible for regenerating the signal power. On the other hand, it is an important source of system noise. Moreover, other impairment that comes from the EDFA is that the gain depends on wavelength, thus leading a non-flat gain. The noise level added, associated to the noise figure (NF), and the gain flatness (GF) depend on the operating point of the amplifier, which can be adjusted by its setpoint gain. In essence, the EDFA setpoint gain can be automatically adjusted to provide optima NF and GF, according to its actual input power and a previous and static knowledge.

In [5], this approach was used to perform an EDFA adaptive gain control (AdGC) used in a cognitive EDFA scheme through a GMPLS control plane. In that scenario, a dynamic optical network with four C-band channels with different rates and modulation formats was experimentally accomplish. Some physical layer impairments attenuation were inserted in order to demonstrate EDFA AdGC efficiency in terms of BER improvements.

In this paper, the same EDFA AdGC is evaluated in terms of an amplifier cascaded system with a complete and modulated C-band load, comprising 80 dense wavelength division multiplexing (DWDM) channels in a 10 Gbps NRZ (non-return-to-zero) OOK (on-off keying) modulation format. This evaluation concerns measurements of OSNR, worst channel NF, GF, amplifiers output flatness and some channels BER, which allows to have a complete knowledge of the signal health. It will be demonstrated that, for cases when the signal degradation is severe, not allowing its detection, a GF degradation is acceptable in order to achieve a better performance in terms of BER measurements.

II. Adaptive EDFA

The EDFA AdGC scheme is based on the first two cognitive assumptions of being aware and adaptive (plan, decide and act) [2], [3] and its procedure is detailed as follows.

A. Amplifier characterization

The amplifier characterization is an automatized process to measure the amplifier performance for some operating points inside a region referred as the amplifier power mask [6]. This region is defined in the input and output power plane as shown in Fig. 1, and is limited by the amplifier maximum and minimum gains and maximum output and minimum input powers [7].

The characterization process consists of varying the amplifier input power composed of 40 flat and non modulated DWDM channels (full ITU-T C-band load) according to the setpoint gain adjusted in order to sweep all amplifier power mask operating points. It is necessary to define the sweep process step (measured point distance), which determines the characterization granularity. For each point, parameters as total input and output powers and their spectra are measured.

This process can be performed experimentally, as in [6], or by simulation. The main difference between these two

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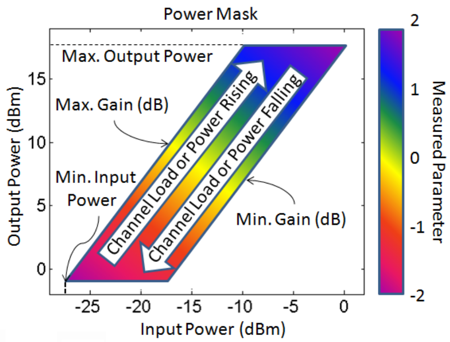


Fig. 1. Definition of the power mask region.

procedures is that the experimental characterization needs an extra step to compute channels NF and GF spectrum after all data acquisition. Otherwise, by simulation, these parameters are computed during the acquisition step by the software.

In this work, this process is performed by simulation, and the results are presented in Fig. 2 for the two amplifier types used in this paper. These types are a preamplifier and a power amplifier with one EDFA stage. The unique difference between them is in term of maximum pump power. Fig. 2 (a) and (b) refers to the preamplifier with + 14 dBm of maximum output power, - 30 dBm of minimum input power, and gain varying from 14 to 24 dB, while Fig. 2 (c) and (d) to the power amplifier with + 21 dBm of maximum output power, - 25 dBm of minimum input power, and the same preamplifier gain range. Fig. 2 (a) and (c) shows worst channel NF values and Fig. 2 (b) and (d) present GF results with spectra information (Power (dBm) versus Frequency (THz)) for some gain values.

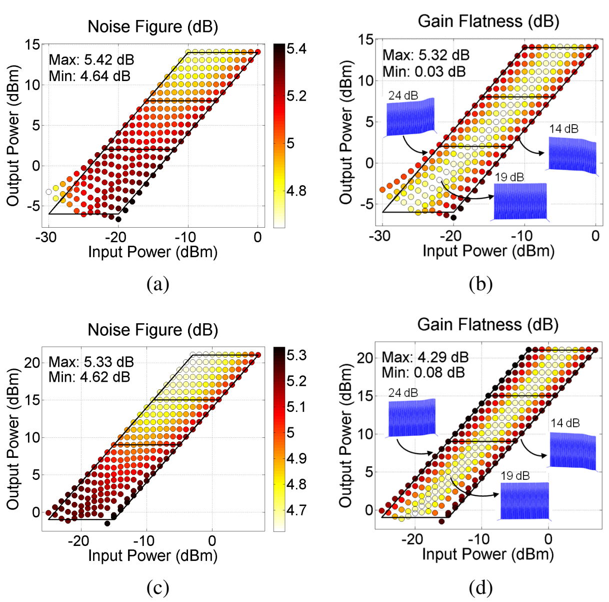


Fig. 2. Characterization results with information of optical EDFA preamplifier (a) worst channel NF, (b) spectrum GF, and optical EDFA booster amplifier (c) worst channel NF and (d) spectrum GF.

Also in Fig. 2, best NF and GF values are represented by white color. These values are concentrated in the upper left region for NF power mask, and around 19 dB setpoint gain region for GF spectrum power mask, which is the nominal gain for both amplifiers. Nominal gain refers to the setpoint gain which the gain flattening filter (GFF) component was designed, thus, leaving an optimal (flat) GF for this specific setpoint gain. For gain values greater than nominal gain, low C-band are more attenuated than high C-band, as shown if Fig. 2 (b) and (d) for 24 dB gain spectra. While for smaller gain values, high C-band are mode attenuated, as also in Fig. 2 (b) and (d) for 14 dB gain spectra.

B. *Fitness function and gain selection*

As EDFA AdGC main goal is to optimize simultaneously NF and GF, fitness function makes use of amplifier characterization results in terms of such parameters, as present in Fig. 3 (a) and (c), resulting in a multi-objective optimization problem [8]. These parameters, associated to an input power (-10 dBm in Fig. 3), are the axis of an objective space, build as in Fig. 3 (b) for the booster amplifier.

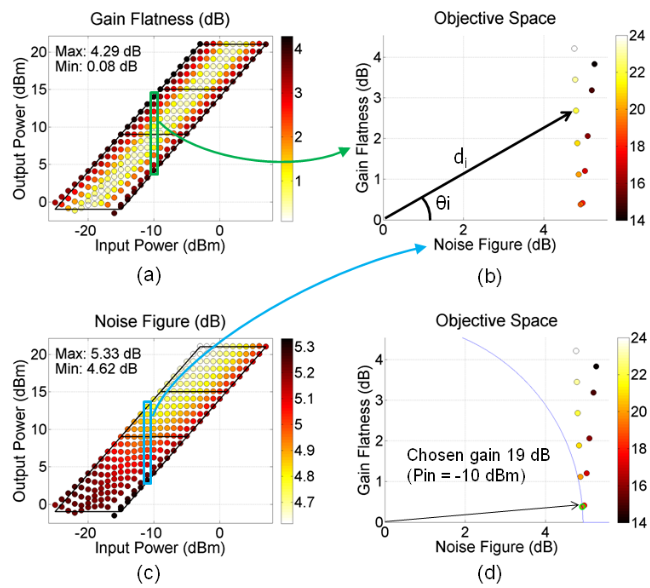


Fig. 3. Objective space build description from the (a) GF and (c) NF power masks for the power amplifier. In (b) is the objective space for -10 dBm input power illustrating the Euclidian distance d_i and the angle θ_i, used to compute the fitness value and (d) shows the gain setpoint selected for the same input power and the circle whose radius is the lowest distance.

Also in Fig. 3 (b), the Euclidian distance from each point to the origin, d_i, and the angle θ_i in the objective space are defined. They are used to compute fitness values, based on target vector optimization [9], as

$$fitness_i = d_i^{-1} \angle \theta_i \tag{1}$$

where d_i^{-1} is the module, d_i is the Euclidian distance, and θ_i is the argument, defined as

$$d_i = \sqrt{NF_i^2 + GF_i^2} \tag{2}$$

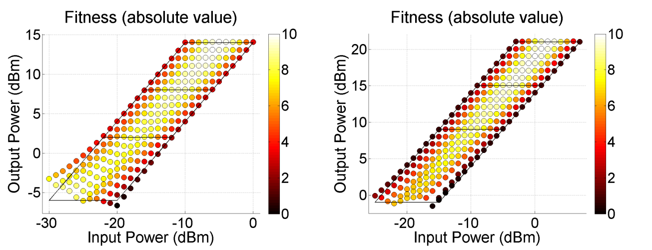
$$\theta_i = arctan\left(\frac{NF_i}{GF_i}\right) \tag{3}$$

Objective space in Fig. 3 (b) helps one to understand how the fitness function, computed as in in Eq. 1, works: amplifier operating point with the lowest distance has the best fitness value. Otherwise, the highest is the distance, the lowest (poorest) is the fitness value associated to it.

EDFA AdGC needs to select a gain setpoint according to the amplifier input power optimizing NF and GF simultaneously. This is possible by selecting the gain with the best fitness value or, based on the objective space, the gain with the lowest distance to the origin, which represents the best trade off between NF and GF. Fig. 3 (d) exemplifies this selection for a power amplifier with -10 dBm of input power and which results in a 19 dB setpoint gain selected. Other gain values must be located outside the circle represented in the Fig. 3 (d), which radius is the lowest distance from the selected point to the origin.

When, for the same input power, two operating points have the same fitness value, the selection is made based on the argument value θ_i. If NF is more critical to the system, the fitness value with maximum angle should be selected. Otherwise, the fitness with smallest angle must be selected.

Finally, fitness values, computed by means of Eq. 1, are normalized from zero to ten and presented inside power mask in Fig. 4 for the two amplifier models used in this work.



(a) (b)

Fig. 4. Power mask with information fitness values for (a) preamplifier and (b) booster amplifier.

For the two amplifier models presented in Fig. 4, best fitness values are concentrated in the region around 19 dB gain setpoint (yellow and white colors). Thus, highlighting the behavior of GF than NF. This occur because GF varies from near zero to 5 dB, while NF varies approximately 1 dB, with values from 4.5 to 5.5 dB inside all power mask for both amplifier models. Therefore, GF has a stronger influence in the fitness value because of the greater variation.

C. Parameters weight

Fitness values inside power mask are more like GF than NF because of the greater values variation of GF parameter. Thus, when the EDFA AdGC selects a setpoint gain, it is surely the best GF, but it is also possible to have best NF values for other setpoint gains with some GF degradation. This situation is clearly observed in Fig. 3 (d), that shows the setpoint gain selected, 19 dB, which has the best (minimum) GF value, while all gains greater than 19 dB present a better (smaller) NF.

Although, in some cases, a suboptimal GF is acceptable in order to have a better NF when the signal is very degraded. Thus, to meet such cases, fitness function present in previous subsection should be modified.

To improve the EDFA AdGC including these cases, we assign different weights to each parameter emphasizing one of them, before the optimization process. Each parameter has its value multiplied by its respective weight, which assumes values from zero to one, decreasing its variation (maximum and minimum values) and thus reducing its influence in fitness function result.

These changes impacts only (2) and (3), that are rewritten as

$$d_i = \sqrt{(NF_W.NF_i)^2 + (GF_W.GF_i)^2} \tag{4}$$

$$\theta_i = arctan\left(\frac{NF_W.NF_i}{GF_W.GF_i}\right) \tag{5}$$

where NF_W and GF_W are NF's and GF's weights, respectively. Fitness is computed by means of (1) as usual.

As a result, Fig. 5 shows some objective spaces and fitness power mask for some GF's weight values for the power amplifier used in this work. NF's weight remains unchanged as one.

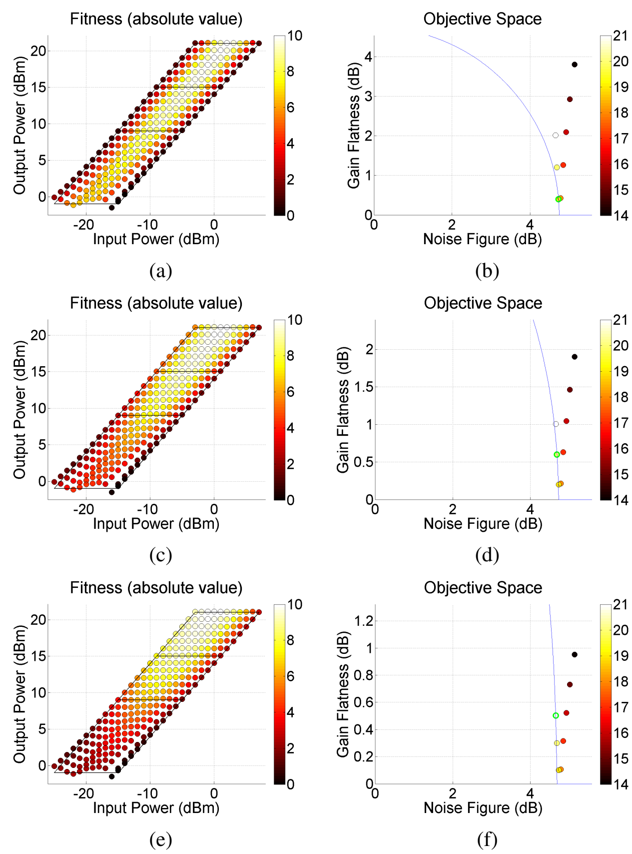


Fig. 5. Power amplifier objective space for Pin = 0 dBm and fitness power mask for different values of NF weight: (a) and (b) GF weight = 1, (c) and (d) GF weight = 0.5 and (e) and (f) GF weight = 0.25.

Fig. 5 (a), (c) and (e) show fitness values distribution inside the power mask for GF's weight values of 1, 0.5 and 0.25, respectively. These figures show that as GF's weight decrease from 1 to 0.25, fitness values change its distribution inside power mask, become more and more like NF's power mask in Fig. 2 (c), once GF influence is minimized by weight values less than one. Thus, in Fig. 5 (a), with GF's weight equals to one, best fitness values are concentrated around 19 dB setpoint gain, as in GF power mask in Fig. 2 (d), and move to the upper

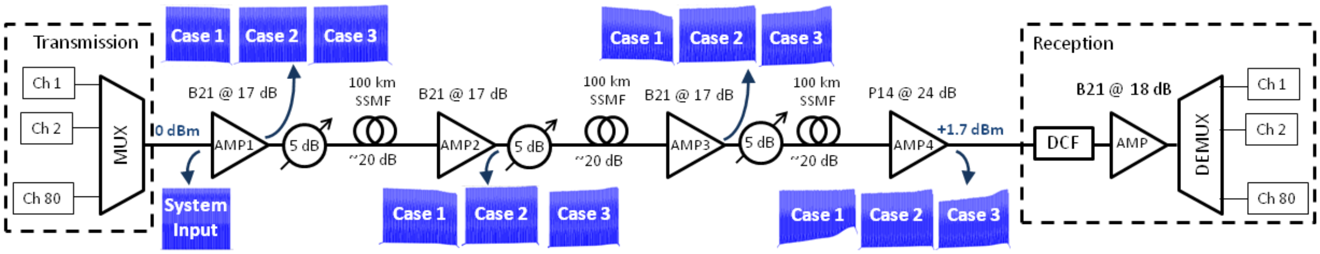


Fig. 6. Simulation setup with amplifier output spectra, Power (dBm) versus Frequency (THz), for all cases and initial information of system total input/output powers.

left region as in NF power mask in Fig. 2 (c) for GF's weight 0.25 (Fig. 5 (e)).

Fig. 5 (b), (d) and (f) show objective space for input power (Pin) equals to 0 dBm and the selected gain varying from 19, 20 and 21 dB also for GF weight 1, 0.5 and 0.25, respectively. Selected points are green detached, and the circles whose radius is the distance from each selected point to the origin indicates that it is really the low distance as all other points are outside this circle.

For the amplifier models used in this article, no matter the NF's weight (from zero to one), fitness power mask remains the same as in Fig. 4. It is not possible to obtain better values for NF when minimizing the influence of NF beyond the values concentrated around 19 dB gain setpoint region, as they are the best values.

III. Simulation Setup

Fig. 6 shows the simulation setup used to analyze the AdGC effects on an amplifier cascaded DWDM optical system, which was performed in OptiSystem software, a commercial optical link simulator [10]. All amplifiers were tuned with real laboratory components, thus leading to a simulation aligned with real experimental measurements. The setup consists of 80 C-band channels (ITU-T grid) modulated by 10 Gbps NRZ OOK, and with 0 dBm of total input power, passing through four cascaded amplifiers: three booster amplifiers (Amp #1, #2 and #3) and one preamplifier (Amp #4), which NF and GF power masks were previous shown in Fig. 2. Each 100 km of standard single mode fiber (SSMF) span, with 0.2 dB/km attenuation, begins with a 5 dB attenuation that represents a ROADM loss, resulting in approximately 25 dB of link loss. Reception comprises a dispersion compensating fiber (DCF) with 30.6 km length, 0.6274 dB/km attenuation, -167.354 ps/nm/km dispersion at 1550 nm and -0.3 ps/nm^2/km of dispersion slope. Total DCF attenuation, 18 dB, is compensate by an amplifier placed right after it.

All amplifiers operate with a feed-forward gain control [11], which pump powers are adjusted to provide the desirable setpoint gain. This control was accomplished using a Matlab script co-simulated with OptiSystem. Feed-forward gain control was performed using a previous characterization that varies input and pump powers, relating these values with gain setpoints by a first degree polynomial function ($f(x) = ax + b$), which have input and pump powers as independent and dependent variables, respectively. Different polynomial function coefficients a and b are associated to each gain setpoint. Thus, when a gain setpoint is adjusted, independent variable x is substituted by input power in the polynomial equation associated with the respective setpoint gain and the function returns the pump power to be set.

AdGC algorithm is also accomplish in a Matlab script component. It runs before feed-forward gain control to determine the gain setpoint selected from the algorithm.

Three different cases with respect to each amplifier setpoint gain are performed. Initially, in case 1, the gains of the amplifiers are set to compensate total link loss (3 x 25 = 75 dB), thus all booster amplifiers are set to 17 dB and preamplifier to24 dB (3 x 17 + 24 = 75 dB), as shown in Fig. 6, resulting in +1.7 dBm of system total output power. When AdGC is applied, in case 2, these gains are adjusted according to each amplifier input power in order to optimize NF and GF. Finally, in case 3, AdGC is also running, but now prioritizing NF. The following section describes all measurements and spectra present in Fig. 6.

IV. Results

To evaluate AdGC performance, besides total input/output powers and spectra measurements for each amplifier and entire system, BER values are also obtained for four DWDM channels: C26 (192.6 THz), C41 (194.1 THz), H48 (194.85 THz) and C57 (195.7 THz).

Tables I and II summarize the results for all evaluated cases. Table I shows some measured parameters for all amplifiers: input/output powers (Pin/Pout), gain setpoint adjusted (G_{set}), GF spectra, maximum channel NF (NF_{max}), output flatness spectrum ($Flat_{out}$) and minimum channel OSNR ($OSNR_{min}$). Differences between cases 2/3 with respect to case 1 are shown in brackets (increase: plus signal; decrease: minus signal). In case 1, received signal (Amp #4 output) has 6.04 dB of $OSNR_{min}$, with AdGC application, not only Amp #4 output $OSNR_{min}$ enhance +8.66 dB, but all amplifiers NF_{max}, GF, $Flat_{out}$ and $OSNR_{min}$ improve from case 1 to 2, as signal values in brackets indicate, showing AdGC algorithm efficiency.

Improvements from case 1 to case 2 can also be observed in Fig. 6 spectra, especially in Amp #4 output. At this point, for case 1, ASE levels are too high, despite a flattened output spectrum. This flatness occurs due to all booster amplifiers are set to 17 dB gain, which is less than nominal gain. Thus, Amp #3 output flatness is the result of accumulated GF in the same direction. Otherwise, Amp #4 are set to 24 dB gain (greater than nominal gain), therefore, its GF is in the opposite

TABLE I. RESULT: AMPLIFIERS PARAMETERS MEASURED

Amp #1	**Case 1**	**Case 2**	**Case 3**
Pin (dBm)	0	0	0
Pout (dBm)	17.12	19.16	20.15
G_{SET} (dB)	17	19	20
GF (dB)	1.57	0.42 (-1.15)	1.20 (-0.36)
NF_{max} (dB)	4.85	4.74 (-0.11)	4.69 (-0.16)
$Flat^{out}$ (dB)	1.56	0.48 (-1.08)	1.28 (-0.28)
$OSNR^{out}_{min}$ (dB)	**34.04**	**34.13(+0.09)**	**34.17 (+0.13)**
Amp #2	**Case 1**	**Case 2**	**Case 3**
Pin (dBm)	-7.88	-5.85	-4.84
Pout (dBm)	9.37	13.35	15.32
G_{SET} (dB)	17	19	20
GF (dB)	1.53	0.45 (-1.08)	1.22 (-0.31)
NF_{max} (dB)	4.98	4.82 (-0.16)	4.75 (-0.23)
$Flat^{out}$ (dB)	3.16	0.97 (-2.19)	2.49 (-0.67)
$OSNR^{out}_{min}$ (dB)	**24.40**	**27.16 (+2.76)**	**27.75 (+3.35)**
Amp #3	**Case 1**	**Case 2**	**Case 3**
Pin (dBm)	-15.63	-11.65	-9.68
Pout (dBm)	2.13	7.67	10.51
G_{SET} (dB)	17	19	20
GF (dB)	1.48	0.45 (-1.03)	1.16 (-0.32)
NF_{max} (dB)	5.21	4.99 (-0.22)	4.88 (-0.33)
$Flat^{out}$ (dB)	4.61	1.42 (-3.19)	3.70 (-0.91)
$OSNR^{out}_{min}$ (dB)	**15.11**	**20.87 (+5.76)**	**22.02 (+6.91)**
Amp #4	**Case 1**	**Case 2**	**Case 3**
Pin (dBm)	-22.87	-17.33	-14.50
Pout (dBm)	1.73	1.79	5.71
G_{SET} (dB)	24	19	20
GF (dB)	3.41	0.45 (-2.96)	0.98 (-2.43)
NF_{max} (dB)	5.48	5.23 (-0.25)	5.08 (-0.40)
$Flat^{out}$ (dB)	1.69	1.40 (-0.29)	4.65 (+2.96)
$OSNR^{out}_{min}$ (dB)	**6.04**	**14.70 (+8.66)**	**16.49 (+10.45)**

direction of booster amplifiers, thus, compensating the previous accumulated output flatness. In this same point, when AdGC is applied (case 2), ASE levels are reduced and spectrum remains flat, improving OSNR for all channels. Still in Fig. 6, it is possible to observe in all amplifiers output spectra, an improvement in terms of flatness.

Table II presents BER measurements for the four DWDM channels previously mentioned and summarizes system parameters (measured from Amp #1 input to Amp #4 output points) in terms of GF (GF^{sys}) and maximum channel NF (NF^{sys}_{max}). BER measurements show that, for case 1, measured channels are not able to be received because their BER values are too high, reflected by low $OSNR^{out}_{min}$ values in Amp #4 output (Table I). Then, when AdGC is applied to all amplifiers in cascade (Case 2), BER measurements decrease. However, for channels C26 and C41, values remain above FEC (forward error correction) limit value (3.8E-3), not allowing their right detection, although GF^{sys} and NF^{sys}_{max} improve 0.3 and 8,6 dB, respectively, with AdGC application.

TABLE II. RESULT: SYSTEM AND RECEIVER PARAMETERS MEASURED

Parameter	**Case 1**	**Case 2**	**Case 3**
C26 (192.6 THz) BER	1 (LOS)	8.06E-03	1.23E-03
C41 (194.1 THz) BER	1 (LOS)	4.44E-03	4.47E-04
H48 (194.85 THz)BER	1 (LOS)	3.00E-03	2.80E-04
C57 (195.7 THz) BER	1 (LOS)	3.20E-03	2.19E-04
GF^{sys} (dB)	1.69	1.39 (-0.30)	4.59 (+2.90)
NF^{sys}_{max} (dB)	32.86	24.22 (-8.64)	22.44 (-10.42)

Aiming to improve channels C26 and C41 BER values, we change GF weight, reducing its influence in the fitness function, thus, prioritizing NF in order to improve OSNR and, consequently, BER values. In case 3, the unique change in AdGC is a GF weight reduction from 1 to 0.5.

As expected, case 3 results in Table I show a more pronounced improvement in NF_{max} and $OSNR_{min}$ parameters than in GF and $Flat_{out}$ and even a worsening in Amp #4 $Flat_{out}$. This worsening is due to the good GF balance between amplifiers due to their setpoint gain is case 1, which compensates output flatness but leaves a high ASE level that degrades the signal BER. In Table II, NF^{sys}_{max} also improves with GF^{sys} degradation.

Although these degradation in terms of system/amplifier GF and output flatness, all channels have BER values less than FEC limit, thus, they are able to be detected in case 3. Thereby, a little degradation in GF is allowable in order to improve NF (OSNR) and BER values in the receiver.

V. CONCLUSION

EDFA AdGC effects on an amplifier cascade performance in a DWDM optical system with a full C-band load are favorable when we just monitor OSNR, NF and GF. Otherwise, when we focus on BER values, degradation appears for some channels. The results show that, with no AdGC, all the four measured channels were not able to be detected due to their high BER values. When AdGC is applied, half of measured channels remain undetected in terms of BER values. Thus, it is acceptable a little degree of degradation in GF in order to improve NF and give some strength to these channels to achieve a better OSNR and, consequently, improving BER values. Then, when we reduce GF influence in fitness function in a new AdGC scheme, although a little GF spectra degradation, all measured channels have BER values under FEC limit.

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REFERENCES

[1] Mahmoud, Q. H. Cognitive networks. John Wiley & Sons Limited, 2007.

[2] G.S. Zervas and D. Simeonidou, "Cognitive optical networks: Need, requirements and architecture," in Proc. ICTON We.C1.3, 2010.

[3] I. de Miguel et al., "Cognitive Dynamic Optical Networks," in OFC Conference, OSA Technical Digest (online) (Optical Society of America, 2013), paper OW1H.1.

[4] P. V. N. K. Chaitanya and D. Datta, "Some Schemes for Controlling Gain Dynamics of EDFA Chains in Wavelength-Routed Optical Networks", IEEE 3rd Int. S. on Advanced Netw. and Telecom. Sys., pp. 52-54, 2009.

[5] J. Oliveira et al., "Demonstration of EDFA Cognitive Gain Control via GMPLS for Mixed Modulation Formats in Heterogeneous Optical Networks," in OFC Conference, OSA Technical Digest (online) (Optical Society of America, 2013), paper OW1H.2.

[6] U. Moura et al., "Caracterizador Automatizado de Máscara de Potência de Amplificadores Ópticos para Redes WDM Reconfiguráveis," in SBrT 2012, Brasília, DF, Brasil (in Portuguese).

[7] Multichannel Erbium-Doped Fiber Amplifier (EDFA), JDSU, 2009. Available at www.jdsu.com.

[8] K. Deb, "Multi-objective optimization using evolutionary algorithms," New York, John Wiley & Sons, 2001.

[9] C.-H. Ko and S.-F. Wang, "Precast production scheduling using multi-objective genetic algorithms", Expert Systems With Applications, v. 38, n. 7, pp. 8293-8302, 2011.

[10] Optisystem, Optiware: http://www.optiwave.com

[11] J. Oliveira et al., Amplificador óptico hbrido para redes WDM reconfiguráveis com formatos de modulação avançados e recepção coerente. Cadernos CPQD tecnologia, v. 7, p. 59-74, 2011 (in Portuguese).