Transient control for cascaded EDFAs by using a multi-objective optimization approach

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ABSTRACT

Erbium-doped fiber amplifiers (EDFA) have been used for some years now in building effective optical systems for the most diverse applications. For some applications, it is necessary to introduce some feedback control laws in order to avoid the generation of transients that could create impairments in the system. In this paper, we use a multi-objective optimization approach based on genetic algorithms, to study the introduction of proportional-derivative (PD) controllers into systems of cascaded EDFAs. We compare the use of individual controllers for each amplifier to the use of controllers to sets of amplifiers.

Keywords: Erbium-doped fiber amplifiers; Power transients

1. INTRODUCTION

Failures in some channels or add/drop of channels due network reconfiguration can cause power transients that lead to error bursts and impact on the network performance, which are unacceptable to service providers. In order to overcome this problem, several schemes to protect amplified networks against power transients have been developed [1]-[3].

The principle of most of these control methods can be explained using Fig. 1. Basically the EDFA gain increases as the pump power increases. When the EDFA gain is below 0 dB the gain increases as the signal power increases, whereas the gain decreases as the signal power increases when the gain is above 0 dB. The value of the threshold pump power, P_{th}, does not change when the signal power changes. To keep the gain at Gc when the signal power changes the control can be implemented through the variation of the pump power in way to oppose the gain variation. In this case if the signal power increases, then the gain tends to decrease, but if the pump power is increased by a certain amount of power it will compensate the higher signal power. Other way to compensate changes in the gain is introducing a signal probe that would compensate the signal power variation.

In this work we have used the pump control scheme. In the pump control scheme the gain of the EDFA is electronic controlled by adjusting the pump current in a way that the gain remains the same. For this method there are several ways to monitor the power transient and use this data to adjust the pump power, such as: (1) detection of the total signal power at the EDFA input [1], (2) detection of the output power of a surviving channel [2], (3) detection of the gain of a probe wavelength, (4) detection of the amount of ASE power, and (5) detection of the input and output pump power [3].

Section 2 presents the numerical modeling for dynamic EDFAs. Section 3 presents the structure of an auto-tuning scheme for PD controllers by using genetic algorithms. Section 4 presents the simulation description of the feedback loop and the last section presents simulation results for cases where a chain of EDFAs presents or not a transient control system.

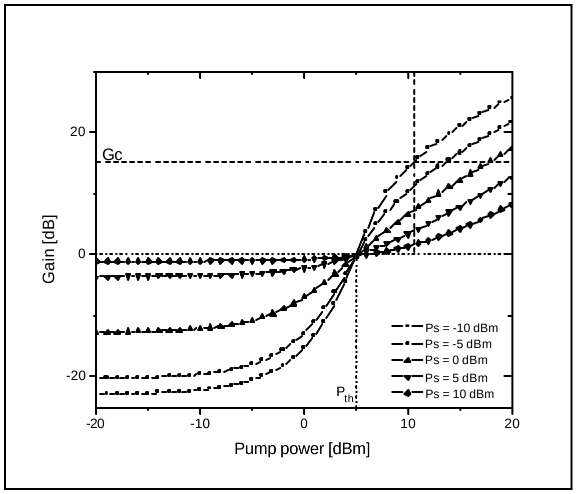


Figure 1 – Gain as function the pump power and signal power

2. NUMERICAL MODEL

The dynamics of EDFA were generally considered to be slow as a result of the low spontaneous lifetime of approximately 10 ms. For high data rate transmission, the gain of EDFAs is practically undisturbed by the signal modulation and it does not introduce intersymbol interference in single channel systems or cross-talk among channels in WDM systems. For this reason steady-state models have been used to model EDFA in transmission systems.

However, several events in static and dynamically switched networks can cause deviations in the power level of the channels. Even, when these power deviations are small the transients can become very large if they accumulate in a chain of EDFAs. To predict and analyze the possible impact of transients in the network performance it is necessary to use models that are able to reproduce and characterize the dynamic response of EDFAs. Several models were introduced in the literature [4][5][6] to describe the power transients; here we are going to present two models that were used along this work.

The first EDFA dynamic model is based on the numerical solution of the rate and propagation equations, which are written below

$$\frac{d\overline{n_2}(z,t)}{dt} = \sum_{k}^{n} \frac{a_k(n_k)\cdot\overline{n_t}}{hn_k\cdot z\cdot t}\cdot P_k(z,t) - \sum_{k=1}^{n} \frac{a_k(n_k)\cdot\overline{n_2}(z,t)}{hn_k\cdot z\cdot t}\cdot P_k(z,t) - \sum_{k=1}^{n} \frac{g_k(n_k)\cdot\overline{n_2}(z,t)}{hn_k\cdot z\cdot t}\cdot P_k(z,t) - \frac{1}{t}\cdot\overline{n_2}(z,t) \quad (1)$$

$$\frac{dP_k(z)}{dz} = u_k\cdot P_k(z)\cdot\left(\left(g_k(n_k)+a_k(n_k)\right)\cdot\frac{\overline{n_2}}{\overline{n_t}} - a_k(n_k) - l_k\right) + u_k\cdot P_{0k}\cdot g_k(n_k)\cdot\frac{\overline{n_2}}{\overline{n_t}} \quad (2)$$

Where h is the Planck constant, t is the metastable lifetime parameter, n_k is the frequency and P_k is the power of the kth beam, each beam propagates in the forward ($u_k = 1$) or backward ($u_k = -1$) direction, l_k is the background loss, and n_t is the local erbium ion density. P_{0k} means the spontaneous emission contribution from the local metastable population n_2.

$P_{0k} = m\cdot h\cdot n_k\cdot\Delta n_k$, where the normalized number of modes **m** is normally 2 and Δn_k is the frequency bandwidth of each noise component.

The Er^{3+} absorption coefficient (a_k), gain coefficient (g_k), and a fiber saturation parameter (z) are parameters that can be obtained by conventional fiber measurement techniques [7].

The saturation parameter z can be defined theoretically as [8]

$$z = p \cdot b_{eff}^{2} \cdot n_t / t \tag{3}$$

and the absorption and gain coefficients are expressed in terms of distributions of the ions and optical modes, for a uniform ion distribution the absorption and gain coefficients can be simplified as [8]

$$a_k(n_k) = \Gamma(n_k) \cdot \bar{n}_t \cdot s_a(n_k) \tag{4}$$

$$g_k(n_k) = \Gamma(n_k) \cdot \bar{n}_t \cdot s_e(n_k) \tag{5}$$

The numerical solution is based on solving the time-dependent rate equations assuming the atomic populations remain constant during the time step Δt. The solution is separated in two steps: a spatial integration with density populations fixed during the time interval Δt, followed by time integration. The steady-state solutions are used as initial condition for the time evolution. This model is referred here as "Full approach".

To demonstrate the transient effects caused by the add-drop of channels in an EDFA using the model above, the system shown in Fig. 2 was simulated. The system is copumped at 980 nm with 55 mW of pump power and the signals are at 1536 nm (Tx1) and 1552nm (TX2). The signal at 1552 nm is modulated by a square waveform to simulate the adding/dropping of channels in the system.

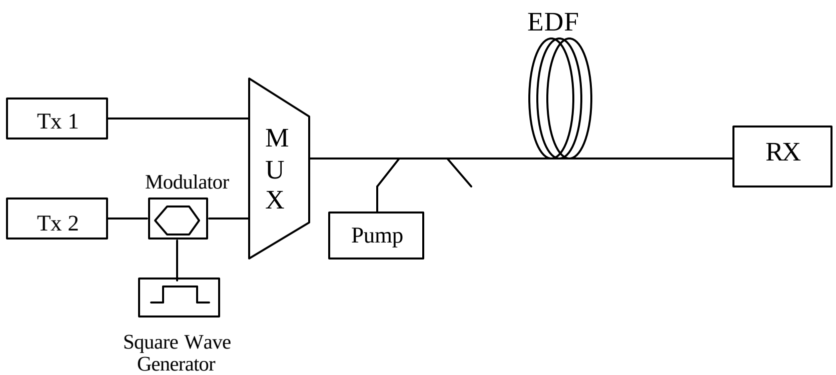


Figure 2 – System schematic to simulate the add and drop of channels in a WDM system

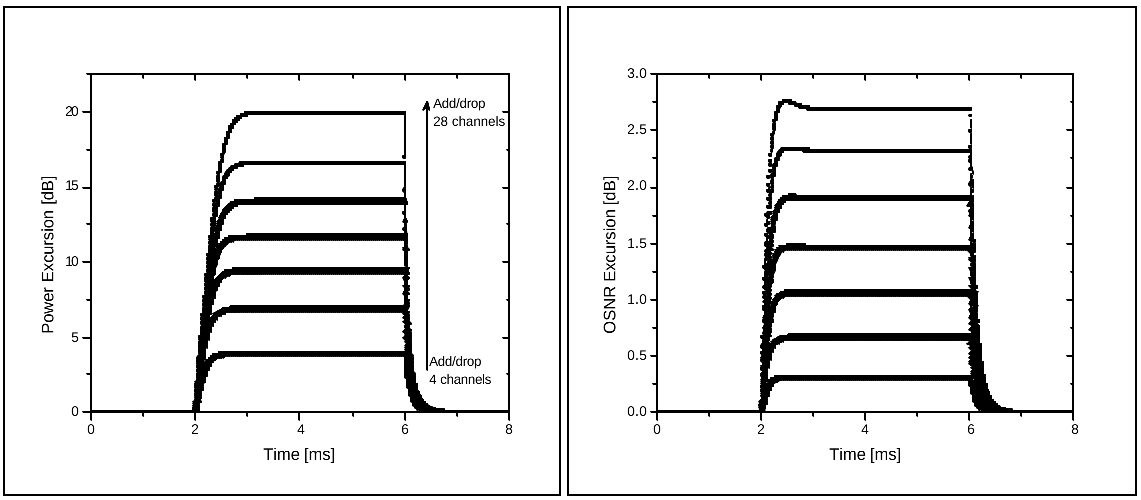
The signal at 1536 nm represents the surviving channel and has the input power correspondent to a certain number of surviving channels. The signal at 1552 represents the add-drop channel and has the input power correspondent to the number of channels to be added/dropped in the system. It is assumed that the sum of the input powers of the channels is kept at -2 dBm, which would correspond to 32 channels with input power of -17 dBm each. The CW signal of the add-drop channel is modulated to represent an addition of channels at the time of 2 ms and drop at 6 ms. Power distribution between the signals and the corresponding number of channels added/dropped is shown in the table below.

Table 1 – Power distribution between the channels

Number of Channels to add/drop	4	8	12	16	18	24	28
Input Power of the Surviving channel (dBm)	-2.58	-3.25	-4.04	-5.01	-6.26	-8.02	-11.03
Input Power of the add-drop channel (dBm)	-11.03	-8.02	-6.26	-5.01	-4.04	-3.25	-2.58

The simulations for each pair of input powers were done using the "full approach" model. Fig. 3 shows the power and the optical signal noise ratio (OSNR) evolution of the surviving channel for the different number of add/drop channels. As expected the add/drop of channels in the system caused power transients in the output signals. The amplitude of the power excursion is proportional to the number of channels dropped and is related to the amplifier saturation. Some time after the channel being dropped (less than 1ms) the survival channels in the system reach a new steady-state level, but now in a larger output power. When the channels are added back, the system goes back to the original steady-state value.

The OSNR evolution presents a lower excursion in comparison with the power excursion. This lower OSNR excursion is due to the fact that when the channels are dropped the noise tends to increase, as the total input power that is saturating the amplifier is lower. This interplay avoids the OSNR evolution follow the same behavior of the power excursion.



(a) (b)

Figure 3 - Evolution of the output (a) power excursion and (b) OSNR excursion of the signal channel at 1536 nm for add/drop of 4, 8, 12, 16, 20, 24 and 28 channels.

The dynamic model introduced before has presented a very good accuracy. However, this accuracy has a price, which is the large time spent in the calculation. As for each time step there is a spatial integration along the longitudinal fiber length. Therefore, when simulating high dense WDM systems with long chains of EDFAs, the system simulation with this model may become very slow. In order to have an option to the "full approach" model a second method is introduced here to simulate dynamic EDFAs in a faster way, it is known as "average inversion" model [6]. In this case the average ion density population inversion, along the fiber length is taken into account.

Neglecting the loss and ASE in (2) and substituting it into (1),

$$\left(\frac{d\overline{n_2}(z,t)}{dt} + \frac{1}{t}\cdot\overline{n_2}(z,t)\right) = -\frac{1}{p\cdot b_{eff}^2}\cdot\left(\sum_k \frac{dP_k(z)}{dz}\cdot u_k\right) \tag{6}$$

Integrating this equation over z, along the fiber length, it becomes

$$\left(\frac{d}{dt}+\frac{1}{t}\right)\cdot\int_0^L \overline{n_2}(z,t)\cdot dz = -\frac{1}{p\cdot b_{eff}^2}\cdot\int_0^L\left(\sum_k \frac{dP_k(z)}{dz}\cdot u_k\right)\cdot dz \tag{7}$$

Defining here the average ion density population at the metastable level as

$$\overline{n_2}_{Avg} = \frac{1}{L}\int_0^L \overline{n_2}(z,t)\cdot dz \tag{8}$$

And substituting it into (7), that becomes

$$\frac{d\,\overline{n_2}_{Avg}}{dt} = -\frac{\overline{n_2}_{Avg}}{t} - \frac{1}{L\cdot p\cdot b_{eff}^2}\cdot\sum_k \left(P_k(L,t) - P_k(0,t)\right) \tag{9}$$

As stated in the deduction of the average inversion model, the spontaneous emission was neglected in the calculation of the n_2. Which makes the model less accurate for cases where ASE becomes significant, e.g. for low input powers (less than –20 dBm, depending on the gain and signal wavelengths). In these cases the accuracy can be improved using an equivalent ASE input [6][9].

$$\frac{d\,\overline{n_2}_{Avg}}{dt} = -\frac{\overline{n_2}_{Avg}}{t} - \frac{1}{L\cdot p\cdot b_{eff}^2}\cdot\sum_k \left(P_k(L,t) - P_k(0,t) + P_{ASE}(t)\right) \tag{10}$$

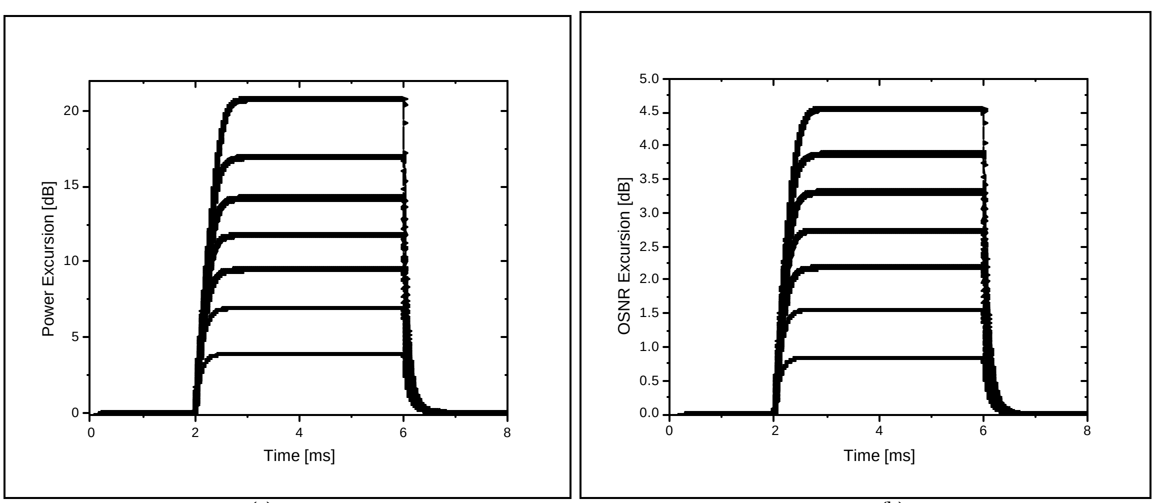
Where P_{ASE} is defined by

$$P_{ASE} = 4\cdot\sum_{k=1}^{n} n_{spk}\cdot\left(G(v_k)-1\right)\cdot\Delta v \tag{11}$$

Where Δn is the spectral width of the noise bins. The spontaneous emission factor is given by

$$n_{spk} = \frac{\overline{n_2}_{Avg}}{\overline{n_2}_{Avg} - \overline{n_1}_{Avg}\cdot s_a(n_k)/s_e(n_k)} \tag{12}$$

To verify the accuracy of this model, the same system showed in Fig. 2 was simulated using the average inversion model. The results found are shown in Fig. 4, the EDFA response for the “average inversion” model has basically the same dynamic characteristics presented by the “full approach” model. The only difference of behavior was found when we compare the OSNR evolutions.



(a) (b)

Figure 4 - Evolution of the output (a) power excursion and (b) OSNR excursion of the signal channel at 1536 nm for add/drop of 4, 8, 12, 16, 20, 24 and 28 channels.

As it was told before, the main advantage of the "average inversion" model is the simulation speed, which is an important factor when we have to simulate dense WDM systems and/or long links that would demand large amounts of calculation.

3. CONTROLLER TUNING

As described in the numerical model section, the numerical solving of the equations (1) and (2) are carried out in two steps: the first for the steady-state and the second for the time integration. Once the first step is complete, the second one (where the control loop is performed) can be rewritten as:

$$\dot{p} = Ap + Bu \qquad (13)$$

where p is the power for each signal, A is related to the steady-state power distribution, B is the control matrix, and u is the new input on time for each channel being propagated in the fiber.

Assuming a PD controller [10], and since the only inputs that can be controlled are the pumps, the feedback-loop may be closed by using:

$$\dot{p}_{pump} = p_{pump} - (K_P\,(p_{sur} - p_0) + K_D\,\dot{p}_{sur}) \qquad (14)$$

where p_{pump} is the pump channels, p_{sur} is the power of the surviving channel chosen at the time t considered, p_0 is the power of the surviving channel at steady-state, and K_D and K_P are the gains of the proportional and differential errors used in the feedback control loop.

If we restate the problem above, the requirement is to find the coefficient matrices K_D and K_P in order to minimize the transient for the surviving channels in general and, specifically, for the surviving channel chosen to monitor the control strategy. Karásek and Menif [10], proposed a procedure based on the Ziegler-Nichols method [11] to solve this problem. However, two other problems arise from the solution they proposed. Firstly, it is necessary to have a complete, in-depth knowledge of the characteristics of the system to be controlled. Secondly, it appears to work just for one pump.

To address these stated issues, we used genetic algorithms to obtain the gain matrices K_D and K_P. The following two objectives are stated for design [12]:

- Minimize the maximum overshoot of the output:

$$f_1 = \max_t \left| p_{sur} - p_0 \right| \qquad (15)$$

- Minimize the settling time of the output: ($(|p_{sur} - p_0|) \leq 2\% \, p_0$):

$$f_2 = t_s \qquad (16)$$

These two criteria are used to find the fitness of each individual in the population. Each one of the functions above were transformed and normalized, because we are looking for a minimum, i.e., we want the values of f_1 and f_2 to go towards zero. The fitness function then becomes [12]:

$$f(x) = \sum_{i=1}^{2} \left| \frac{(r_i - w_i\, f_i(x))}{r_i} \right| \qquad (17)$$

Where r_i is the maximum value allowed for each function and w_i is a weight function. Clearly, in our case, the maximum fitness for an individual will be 2.

In the last section, using some numerical simulations that utilize the described strategy, we will show that the gain matrices can be easily found without any *a priori* analysis of the problem (other than the limits of each coefficient, which are easily distinguishable).

4. CONTROL SYSTEM

We have simulated an analogue controller in our simulation [9]. To simulate that, the proportional and derivative parts of the control law were represented by operational amplifiers configured as a differential amplifier and a differentiator respectively.

In the simulation of the differential amplifier the signal monitored passed through a low pass filter in order to simulate the frequency response of the amplifier, and then the signal is multiplied by a constant that represents the DC gain of the differential amplifier.

For the differentiator simulation, a high-pass filter was used and the output was multiplied by a constant that represents the high-frequency gain of the differentiator.

To complete the feedback loop control, a low-pass filter was used to simulate the effect of the monitoring receiver bandwidth. All filters used in the simulations were implemented by FIR filters with the impulse response in accordance with the parameters defined for each component.

5. SIMULATION RESULTS AND CONCLUSIONS

To investigate the power transients in EDFA chains the WDM system shown in Fig. 5 was simulated. The chain has 5 C-band EDFAs and between each EDFA there is an attenuator to simulate the losses due the fiber link.

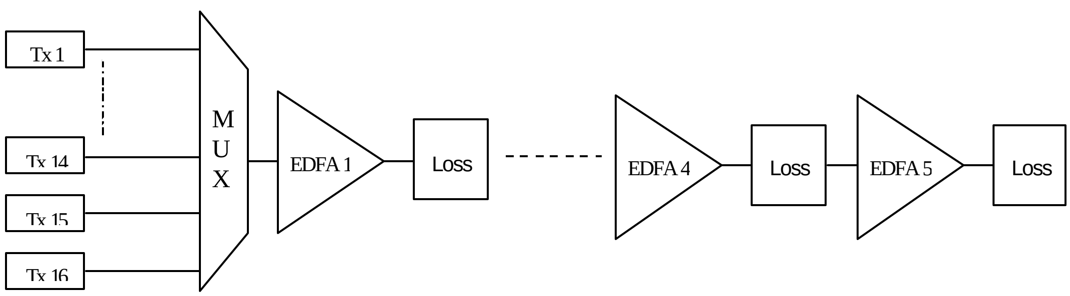


Figure 5 – System schematic to simulate a WDM system containing an EDFA chain.

The WDM system has 16 channels spread linearly from 1539.72 nm to 1563 nm (channel space of 1,6 nm) and input power per channel is –16 dBm. Each EDFA is counter-pumped at 980 nm with the pump power of 18 dBm and there is a filter in the EDFA output to equalize the gain of all channels. After each EDFA the signals are attenuated by the same amount of gain they had gotten, approximately 16 dB. In this way, the input powers of the signals are kept approximately constant for all EDFAs inputs.

Half of the channels, the even channels, were modulated by a square wave to simulate the drop of channels at $t = 100\,ms$ and verify the power transients caused by it. Fig. 6 shows the output power excursion of the channel at 1539.72 nm.

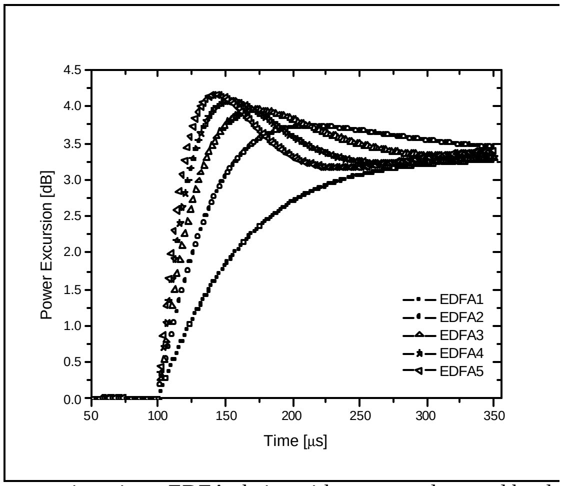


Figure 6 – Power transients in an EDFA chain, without control, caused by drop of channels.

In accordance with Fig. 6, the time response of the surviving channels can in general be divided in 4 regions [6]: Initial linear region, the overshoot region, the oscillation region, and the final steady-state region. It can be seen that the slope in the linear region increases with the number of EDFAs, the same happens with the overshoot peak and oscillations. The maximum power excursion reached almost 4.5 dB in this chain.

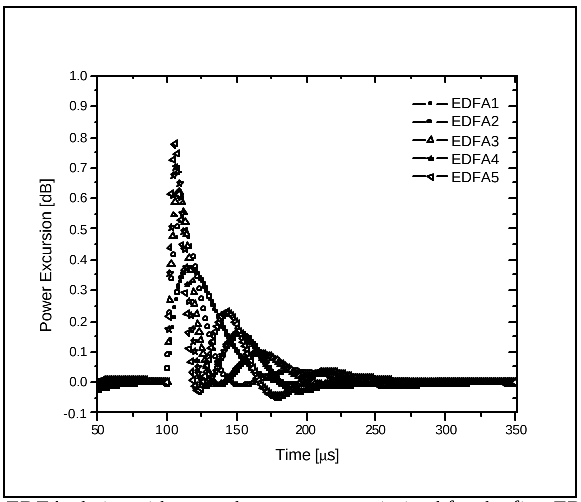


Figure 7 – Power transients in an EDFA chain, with control parameters optimized for the first EDFA, caused by drop of channels.

Using the monitoring method of detecting a surviving channel and using this information to control the pump power of each EDFA the results found are shown at Fig. 7. The proportional and differential coefficients used in the PD control were optimized for the first EDFA using the A.G. technique described in section 3. The coefficients found for the first EDFA were used in all 5 EDFAs

The results found with this gain control scheme had shown a decrease in the output power excursion values for all EDFAs. For the EDFA-1 the excursion decreased from 3.25 dB to less than 0.5 dB when the control is active. The same have happened for the other surviving channels, the maximum power excursion reached was lower than 0.8 dB. It can be noticed that excursion peak increased with the number of EDFAs when using the control. This happens because the power transients become faster when the number of amplifiers increases and it takes to the new power excursion peaks, which can take to a limitation on the number of EDFAs in the link.

To verify the possibility of a better response of the control scheme used in each EDFA, we have used the same optimization method for each EDFA to find the better proportional and differential coefficients. We have done the same procedure for EDFA-1, EDFA-2 and EDFA-3. The results found in the optimization were used again in the simulation of the chain and the coefficients utilized for the EDFA-4 and 5 were the same found for EDFA-3 since we had not optimized those.

As can be seen in Fig. 8 the simulation results were better than before, with the maximum gain excursion getting lower than 0.8 dB. The results would be even better if the EDFA-4 and 5 controls were optimized. Another important characteristic of these new results is the minimization of the oscillations that were seen in Fig. 7 for EDFA-1 to 3.

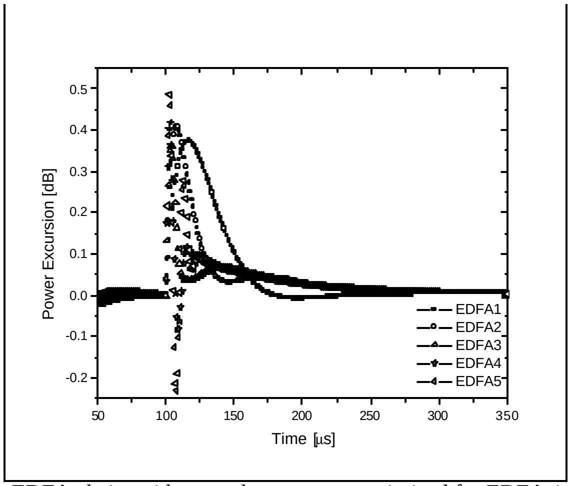


Figure 8 – Power transients in an EDFA chain, with control parameters optimized for EDFA-1 to 3, caused by drop of channels.

From these results we can conclude that a better optimization of the control parameters for each amplifier in the optical link will allow a better performance of the system since it would become more robust to impact of power transients due to the add and drop of channels in the system.

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