Effect of EDFA Cross-Gain Saturation on the Transmission of Packetized Burst-Mode Data over WDM

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Abstract. In this paper, we demonstrate the importance of the number of WDM channels and the network traffic variability on the dynamics of a cascade of EDFAs fed by packet traffic in burst mode. The dynamics are determined using a numerical model incorporating time variation effects in the EDFA. Calculations are based on the solution of a transcendental equation describing the time evolution of the *reservoir*, i.e. the total number of excited ions, for each EDFA. Traffic on WDM channels is modeled as statistically independent ON/OFF time-slotted sources. We find that the cross-gain saturation effect depends on the number of WDM channels and also on network traffic variability. As the number of WDM channels increases, and even though each one is highly variable in time, the dynamics of the total input power exhibit less fluctuation, allowing the reservoir to have a more suitable behavior. In addition, the swings of the reservoir and the total output power decrease when we increase the network utilization factor. This positive effect is not felt on the output power excursion of an individual WDM channel. This is due to the fact that the cumulative effect of the reservoir fluctuations along a cascade will lead to further broadening of any individual channel power PDF. Finally, we investigate the effect of gain clamping of the first amplifier in the cascade – by implementing a ring laser and propagating the lasing power through the cascade – on the statistics of several measurable entities.

Keywords: Modeling, optical communication, optical fiber amplifiers, wavelength-division multiplexing, transient analysis

1. Introduction

Among the most important characteristics of erbium-doped fiber amplifiers (EDFAs) for wavelength division multiplexing (WDM) applications is a gain ripple over the required wavelength range. Therefore, factors such as the number of WDM channels, their input powers, or the network utilization factor, influence significantly the behavior of a cascade of several EDFAs. As for any design procedure, we must try to ensure optimal functioning for a cascade of EDFAs over a point-to-point link. For this to happen, it is important to verify the consequence of the above external parameters on the dynamics of the cascade.

An EDFA can be modeled as a dynamic non-linear system with only one state variable: the total number of excited ions in the amplifier,

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known as the *reservoir* (Bononi and Rusch, 1998). The reservoir is defined by $r(t) \overset{\Delta}{=} \rho A \int_0^\ell N_2(z,t)\, dz$, where $N_2(z,t)$ is the fraction of population in the $^4I_{13/2}$ metastable level, ℓ is the length of erbium-doped fiber (EDF), and ρ is the Er^{3+}-ion density in the doped fiber core of effective area A.

The response of EDFAs to non-periodic changes in the power of input channels (due to channel add/drop, network reconfiguration, fiber cuts, or packetized traffic) has been the subject of much recent research (Srivastava and Sun, 1997; Ziskind and Srivastav, 1996; Bononi and Tancevski, 1998). Due to changes in the input power, the gain excursion in an EDFA leads to the occurrence of wide swings in the output power and output optical signal-to-noise ratio (OSNR) (Karasek and Vallés, 1998; Tancevski and Bononi, 1999). Moreover, the gain of an EDFA is in general wavelength dependent, which leads to different gains among WDM channels. Hence, signals traversing a cascade of several amplifiers will experience an increasing output power spread among individual channels.

Any modification of the total input power of WDM signals is reflected in reservoir dynamics. If some channels are not present for a certain time, the total EDFA input power decreases. From a system perspective, the removal of input fluxes under constant pump conditions will lead to a rising reservoir level. Conversely, if some channels are added, the total input power increases, and the reservoir falls. EDFA gain fluctuations are a direct consequence of such reservoir variations (Bononi and Tancevski, 1998). The variations of one channel, hence, affects the gain of all the other channels, leading to excursions in individual channel output power, even though their input power is maintained constant. Such interaction is defined as *cross-gain saturation.*

In this work, we investigate the effect of traffic burstiness and of the number of WDM channels on the dynamics of an EDFA cascade.

2. Simulation parameters

The numerical model used for the simulations is based on the dynamic model of EDFA described in detail in (Karasek and Bononi, 2000) and assumes homogeneously broadened gain medium and absence of excited-state absorption. The effect of amplified spontaneous emission (ASE) is taken into account. We consider a cascade of six identical single-stage amplifiers with typical *Lucent Technology* EDF pumped at 1480 nm. The pump power and the length of each EDFA are identical and are respectively $P_p = 25\,\mathrm{mW}$ and $l = 25\,\mathrm{m}$. All emission and absorption cross-sections are spectrally resolved in the region from 1450 to 1650 nm, subdivided into $N_{ASE} = 1000$ bins of $\delta\lambda = 0.2$ nm. The inter-amplifier loss is assumed to be 20 dB. For a typical transmission fiber loss of 0.25 dB/km, that represents a distance between neighboring amplifiers of 80 km.

In our analysis, we consider burst-mode packet data transmission, such as native mode ATM, Ethernet, or IP over WDM. Such traffic has been shown to be self-similar (Taqqu and Willinger, 1997; Leland and Taqqu, 1994), i.e., there exists a very high variability in the duration of the ON and OFF bursts on each channel. A self-similar traffic entails a wide variation of the total input power level over time scales comparable to the EDFA chain reaction time (Tancevski and Bononi, 1999). This can result in large variations in the EDFA gain level, and output power of the channels, due to the effect of EDFA cross-gain saturation.

The time varying bursty signals representing traffic of the WDM channels were randomly generated as independent ON/OFF sources, i.e., each as a succession of ON and OFF periods. The duration of each ON/OFF period is assumed to be a random variable with a rounded Pareto distribution (Tancevski and Bononi, 1999). Using a random number U uniformly distributed on [0, 1], statistically independent ON and OFF intervals (in units of slots) were generated for each WDM channel via

$$T_{i,\mathrm{ON}} = T_{slot}\left\lfloor \frac{1}{U^{1/\alpha_{\mathrm{ON}}}} \right\rfloor, \qquad T_{i,\mathrm{OFF}} = T_{slot}\left\lfloor \frac{1}{U^{1/\alpha_{\mathrm{OFF}}}} \right\rfloor \tag{1}$$

where α_{OFF} and α_{ON} are parameters regulating the burstiness of the traffic, and $\lfloor x \rfloor$ is the floor function. The elementary size of one ON/OFF period is 53 bytes, corresponding to one ATM cell, $T_{slot} = 2.83\,\mu s$. The average utilization of the aggregate WDM traffic is given by the utilization factor u

$$u = \frac{\sum_{i=1}^{NCH} E[T_{\mathrm{i,ON}}]}{\sum_{i=1}^{NCH} E[T_{\mathrm{i,\ ON}}] + \sum_{i=1}^{NCH} E[T_{\mathrm{i,OFF}}]} \tag{2}$$

where NCH is the number of WDM channels, $E[T_{\mathrm{i,ON}}]$, $E[T_{\mathrm{i,OFF}}]$ are the mean values of the ON and OFF bursts (in slot units) of individual WDM channels. Different network utilization factors u have been implemented in order to evaluate the behavior of a cascade with various traffic types and densities. In order to obtain different utilization factor, we must change the value of α_{ON} and α_{OFF}, which are indicators of the degree of variability of the traffic, as indicated in (Tancevski and Bononi, 1999).

In our simulations, we maintain the total input power to the cascade constant while the number of WDM channels varies. Indeed, we consider three cases: 2, 8 and 32 WDM channels centred at 1550 nm with a spacing of 0.4 nm. In these three cases, we assume that the average input power for an ON period is respectively $P_{ch}^{in} = -13, -19, -25\,\text{dBm}$ for each WDM channel. In addition, we assume that power of one ON period is not constant, as suggested in previous studies (Bononi and Tancevski, 1998; Tancevski and Bononi, 1999), where the ratio of "0" and "1" in the ON slots is assumed to be exactly 50% for each packet. On the contrary, we model the ON packet power as a binomial random variable due to two main reasons. The reservoir time response has not the same order as the packet time, and we suppose that the power in one ON slot is related to the number of "1" which can be supposed as a bernoulli random variable. Also, we have considered that during the OFF period, there is a fixed input value $P_{in}^{ch} = -50\,\text{dBm}$. This value is comparable with a thermal noise generated by the transmitter.

Alongside the WDM channels, we have added a continus wave (CW) placed before the WDM comb having a constant input power $P_{sur}^{in} = -25\,\text{dBm}$, corresponding to a single channel power in the case of 32 WDM channels. With such a low input power level, the effect of the CW channel on the behavior of the cascade is negligible. Besides the fact that it is an easily measurable quantity, the CW channel is an indicator of the gain excursion.

The effect of the bursty packetized traffic is evaluated statistically. The probability density function (PDF) histograms of the reservoir, the total output power, the CW output power, and also the output power of the reference wavelength are determined along the cascade.

To suppress eventual large gain and output power variations, we examine the use of all optical gain-clamping (Dai and Pan, 1997). The first EDFA in the chain is clamped by a ring laser configuration, with two 10:90 couplers in the input and in the output. In the feedback loop of the AOGC EDFA, an optical band-pass filter centered at the lasing wavelength of $\lambda_l = 1543\,\text{nm}$, and having a Gaussian transmittivity was simulated. The ring configuration at the first EDFA creates a lasing signal that counteracts the fluctuations in the input channel power level, and tends to stabilize the doped fiber inversion level to the steady-state value. Lasing power from the first gain-clamped EDFA is allowed to propagate down the cascade, thus stabilizing to some extent the successive EDFAs.

3. results and Discussion

This section is divided into three parts. First, a transient analysis gives considerable insight into the effects of cross-gain saturation and their dependence on the number of channels. In the following part, the implications of cross-gain saturation are analyzed in detail from a statistical point of view. Clamping results are depicted in the last subsection.

3.1. TRANSIENT ANALYSIS

We start with the time evolution of the CW output power and the total output power at the end of the first EDFA for a time period of 340 μs with a network utilization factor $u = 0.5$ ($\alpha_{ON} = \alpha_{OFF} = 1.2$). Figure 1a shows the high variability of the CW channel in case of 2 and 32 WDM channels with the same power budget.

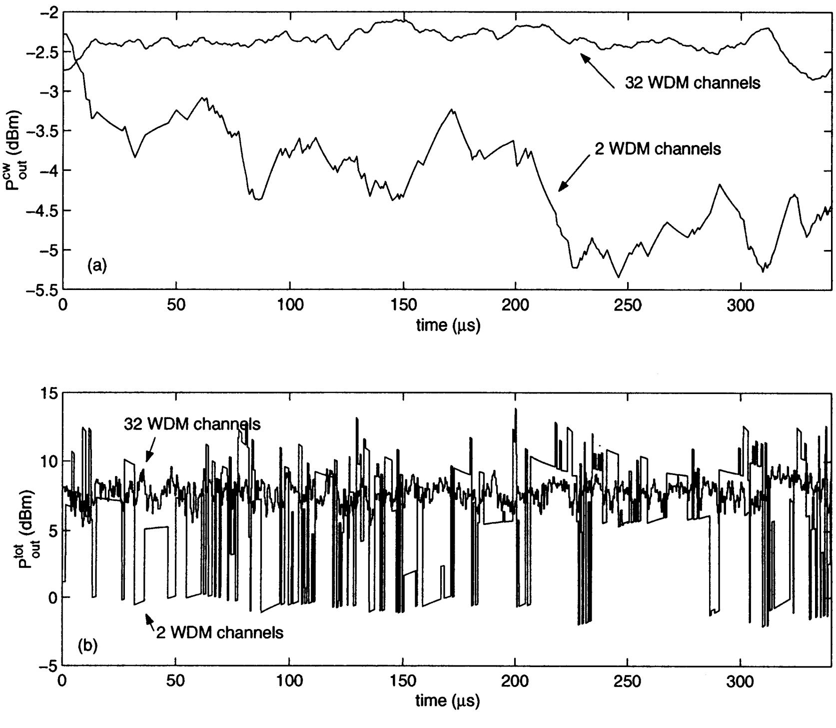

Figure 1. (a) Time evolution of continuous wave at the output of an EDFA with 2 and 32 WDM channels. (b) Time evolution of total output power at the output of an EDFA with 2 and 32 WDM channels.

The significant CW power swings in the case of only 2 WDM channels are caused by large input power variations. If in one of the two channels a long OFF period occurs, input power to the amplifier drops by 50 %. This gives the EDFA enough time to acquire gain greatly exceeding the average value. With increasing number of channels the probability of concurrent occurrence of long OFF periods in several channels decreases which results in the decrease of gain fluctuations. Figure 1b plots time evolution of total output power when 2 and 8 WDM channels are transmitted.

3.2. STATISTICAL ANALYSIS

The results of the simulation in a cascade of six EDFAs are shown in Fig. 2. In this figure, the rows correspond to the number of WDM channels in the system. Three different configurations were considered: 2, 8, and 32 WDM channels. The three columns represent the three network utilization factors implemented: $u = 0.25$ ($\alpha_{ON} = 1.91, \alpha_{OFF} = 1.2$), $u = 0.5$ ($\alpha_{ON} = 1.2, \alpha_{OFF} = 1.2$) and $u = 0.75$ ($\alpha_{ON} = 1.2, \alpha_{OFF} = 1.91$). For each number of WDM channels and network utilization factor, the PDFs of the reservoir of the 1^{st}, 3^{rd}, and 6^{th} EDFAs are plotted. The first general observation is that the fluctuations of the

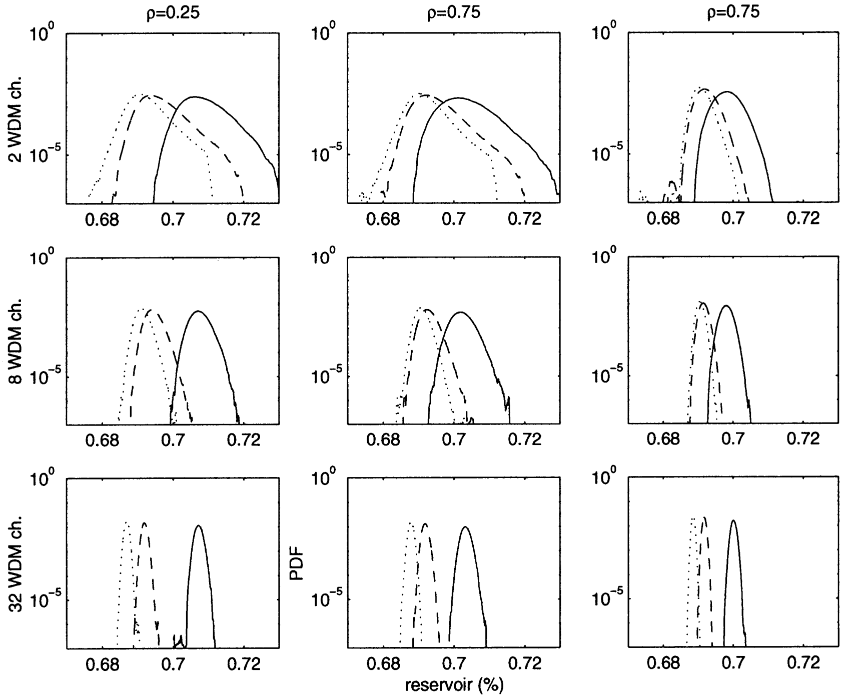

Figure 2. Probability density function of the reservoir for an unclamped cascade for different numbers of WDM channels and different utilization factors. Amplifier 1, 3 and 6 are represented by the solid, dashed and dot line, respectively.

reservoir decrease along the cascade in all the cases. We also observe that the mean value of the reservoir decreases along the cascade due to the propagation of ASE. We remark also that the excursion of the reservoir decreases when we increase the utilization factor or the number of WDM channels. However, the narrowing is more significant with the increase of the number of channels. In both cases, the decrease of reservoir fluctuations is best explained with total power arguments, as we will see below.

In order to realize the importance of cross-gain saturation on the behavior of a cascade of several EDFAs, we evaluate statistically the PDF of the total output power along the cascade as shown in Fig. 3. The three distinct maxima of the two-channel case are due to the frequent occurrence of the three extreme cases: "all OFF", "1 ON" or "all ON". As the number of WDM channels increases, the intermediate states become more frequent, and the PDFs approach a gaussian shape. In addition, it is interesting to mention that the probability of having

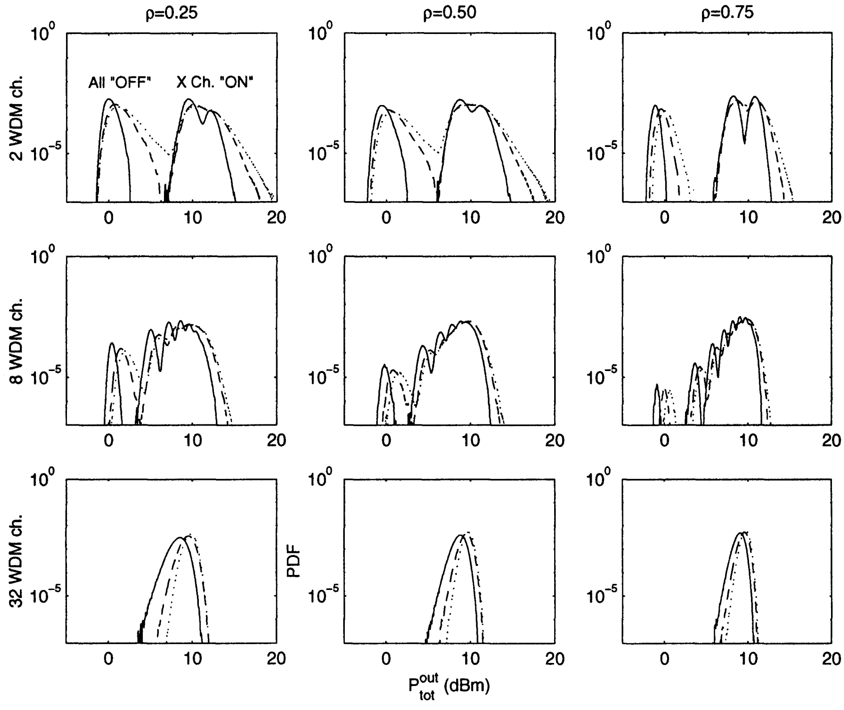

Figure 3. Probability density function of the total output power for an unclamped cascade for different numbers of WDM channels and different utilization factors. Amplifier 1, 3 and 6 are represented by the solid, dashed and dot line, respectively.

all channels in the OFF state (represented by the left-hand PDF peak) decreases as the network utilization factor increases, as can be expected.

We note that the general behavior of the total output power is the same as that observed for the reservoir histograms: First, the excursion of the total output power decreases along the cascade; second, we notice that as the utilization factor increases, the fluctuation of the total output power decreases. In contrast to the reservoir statistics, we observe that the mean value of the total output power increases along the cascade due to growing ASE.

A comparison between Fig. 2 and Fig. 3 shows clearly the dependence of reservoir excursions on the variability of total input power. Indeed, the reservoir dynamics are directly related to the total input flux. As the number of WDM channels or the network utilization factor increase, the variability of the total input power becomes less pronounced which allows a more stable reservoir behavior.

Let us now verify whether a high number of WDM channels and a high utilization factor will affect the dynamics of a single WDM channel. We evaluate, in Fig. 4, the output power PDF of the reference channel at $\lambda_{ref} = 1550\,\mathrm{nm}$.

It is clear from Fig. 4 that the excursion of output power of the reference channel increases along the cascade, for any number of WDM channels and network utilization factor. We note that the excursion of each PDF decreases, but not significantly, as the utilization factor increases. It is important to notice that, in contract with the total power PDFs, the reduction in fluctuation of individual output powers due to the increasing number of channels or having a denser traffic were not so substantial. This can be explained by two main reasons. First, the input power of each channel is highly variable along time. The second reason lies in the relation between the output power and the reservoir shown below:

$$\begin{aligned} P_{\lambda_i}^{(k,out)}(t) &= P_{\lambda_i}^{(k,in)}(t) \,.\, \exp\left(B_i r^{(k)}(t) - A_i\right) \\ &= P_{\lambda_i}^{(k,in)}(t) \,.G_i^{ss}.\, \exp\left(B_i \Delta r^{(k)}(t)\right) \end{aligned} \tag{3}$$

with G_i^{ss} is the gain value at λ_i at the steady-state and $\Delta r^{(k)}(t) = r^{(k)}(t) - r^{(k,ss)}$ as the difference between the level of the the actual value and steady-state.

From eq.(3), it is clear that any perturbation in the reservoir level leads to a broadening of the output power PDF following the exponentiel relation. Recall that an ON power for each packet is modeled as a uniform variable, hence generating a broad PDF. Any variability, even slight, in the reservoir will lead to further broadening of that PDF. That explains the observation that although reservoir PDFs get nar-

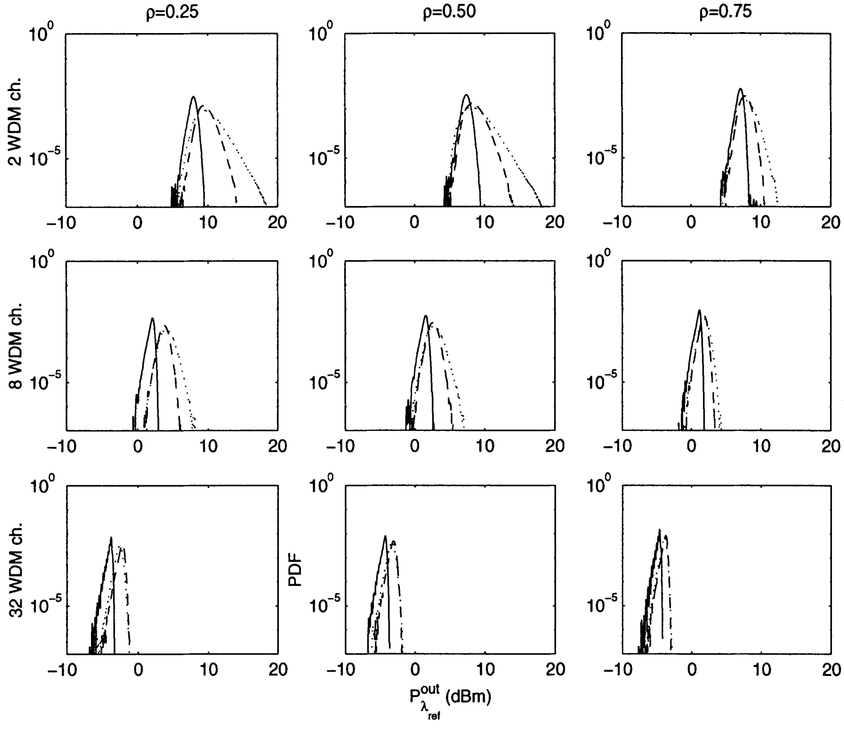

Figure 4. Probability density function of the output power of the reference channel for an unclamped cascade for different numbers of WDM channels and different utilization factors. Amplifier 1, 3 and 6 are represented by the solid, dashed and dot line, respectively.

rower along the cascade (due to cross-gain saturation), the cumulative effect of the reservoir fluctuations after several EDFAs leads to the broadening of the individual channel power PDFs. The growth of the output power fluctuations along the cascade is better visualized in the CW channel as illustrated in Fig. 5. Besides, the CW channel can be used experimentally to measure the gain and the reservoir fluctuations. Fig. 5 shows the PDF of the output power of the CW channel for a cascade of 8 WDM channels and a utilization factor $u = 0.5$.

The broadening of individual channel power PDFs and the narrowing of reservoir and total power PDFs along the cascade are not contradictory. The fact that individual channel power fluctuations do not necessarily imply similar variations on total output power is due to cross-gain saturation. Indeed, the switching of a single channel to the OFF state, for instance, induces the increase in gain, hence output power, of all other channels. The output power decrease in the dropped

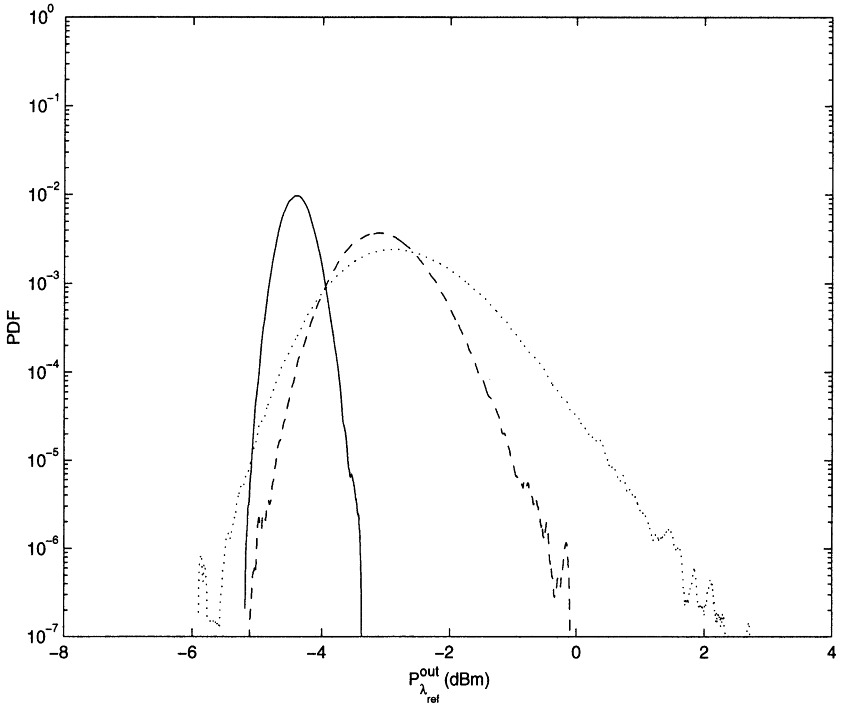

Figure 5. Probability density function of the continuous wave for an unclamped cascade with 8 WDM channels and $u = 0.5$. The outputs of amplifiers 1, 3 and 6 are represented with solid, dashed and dot lines, respectively.

channel is, in a sense, balanced by the increase in the output power of the other channels. Those variations are therefore reflected on the dynamics of individual channels rather than on the total output power (or the reservoir), as is clear from the PDFs of Fig. 2 and Fig. 4.

The fluctuations in the reservoir level have been identified as the direct cause of gain instability in EDFAs and EDFA cascades. The effect of cross-gain saturation depicted in Fig. 2 is therefore beneficial for it results in the reduction of reservoir excursions. However, it has no effect on individual output power swings (see Fig. 4 and Fig. 5). In order to stabilize them, any reservoir fluctuations must be suppressed, especially at the beginning of the cascade, where the largest reservoir fluctuations occur. All-optical gain clamping has been proposed and demonstrated for that purpose (Dai and Pan, 1997; Zirngibl, 1991). In the following, we examine the effect of using AOGC on the the statistics of the reservoir and reference channel output power.

3.3. CLAMPING EFFECT

The advantages of clamping the first EDFA are shown in Fig. 6. This figure shows the PDF of the reservoir of the 1^{st}, 3^{rd}, and 6^{th} EDFAs for a unclamped (Fig. 6a) and clamped (Fig. 6b) cascade with 8 WDM channels and an utilization factor $u = 0.5$. First, we note that the reservoir mean values are slightly lower in the clamped case due to the decrease in gain caused by the propagation of lasing power. More importantly, the largest spread of the reservoir probability at the level of 10^{-6} is less than 0.5% along the cascade, in contrast with 3% in the unclamped cascade, corresponding to the first EDFA. Nevertheless, the effect of cross-gain saturation is still visible in the clamped cascade, for reservoir excursions decrease along the cascade.

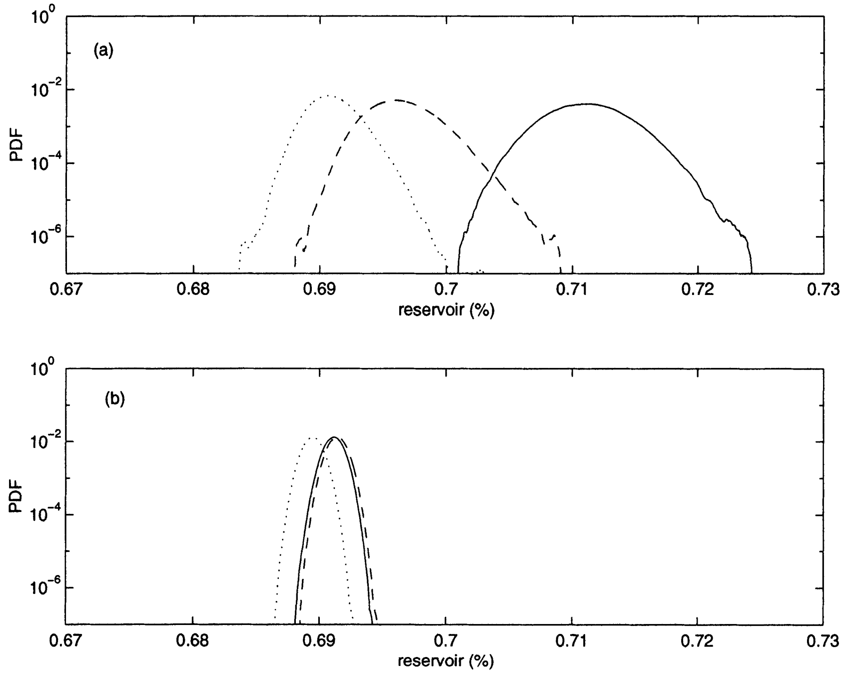

Figure 6. Probability density function of the reservoir for an unclamped (a) and clamped (b) cascade with 8 WDM channels and $u = 0.5$ at the amplifier 1, 3 and 6 with solid, dashed and dot line, respectively.

In Fig. 7a, b, the histograms of signal power of reference channel at the 1^{st}, 3^{rd}, and 6^{th} EDFAs are plotted for an unclamped and clamped cascade, respectively. The PDFs are plotted for a 0.5 utilization factor, a cascade of 6 EDFAs and 8 WDM channels, an ON average power of -19 dBm, and a fixed OFF power of -50 dBm.

We notice that also for the clamped cascade, the output power fluctuations grow along the cascade. However, a significant improvement is perceptible. Reduction of at least 4 dB is achieved with respect to the unclamped cascade. The width of the reference channel output power PDF at the end of the unclamped cascade, at the level of 10^{-6}, is 6.75 dB. For the clamped cascade, we obtain only 3.75 dB.

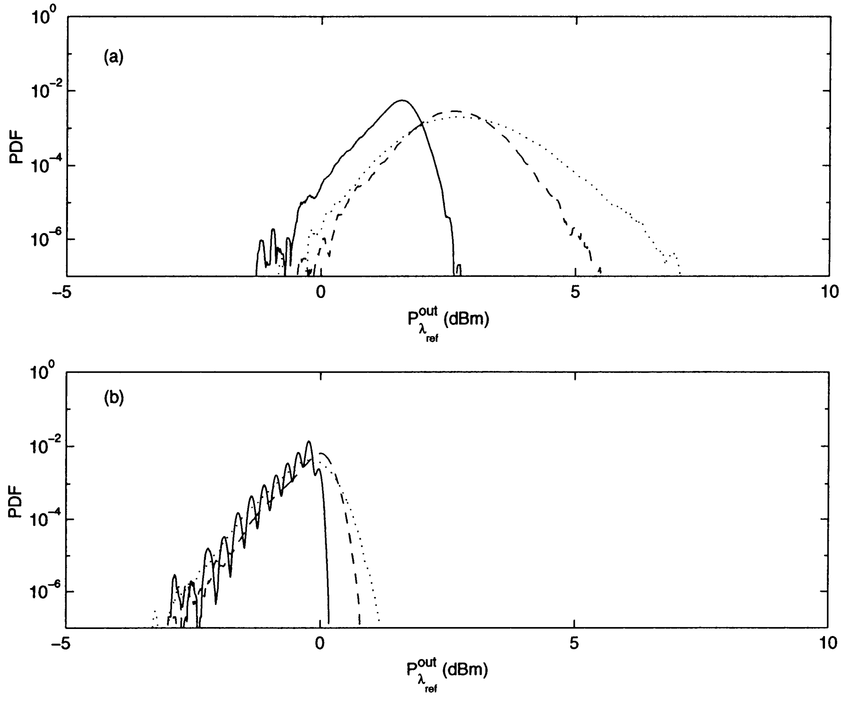

Figure 7. Probability density function of the output power of the reference WDM channel for an unclamped (a) and clamped (b) cascade representing ON periods with 8 WDM channels and $u = 0.5$ at the amplifier 1, 3 and 6 with solid, dashed and dot line, respectively.

4. Conclusion

We have shown that the effect of cross-gain saturation depends on the number of WDM channels, and also on network traffic variability. Indeed, the swing of the reservoir and the total output power decreases when we increase the number of WDM channels or the network utilization factor. As the number of WDM channels increases, the dynamics of the total input power no longer reflects the individual channel power fluctuations, thus allowing the reservoir to have less excursions. This advantage does not affect individual output power excursions. In fact, the cumulative effect of the reservoir fluctuations along a cascade will lead to further broadening of all individual channel power PDFs.

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