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A New Method to Equalize Static and Dynamic OSNR in Cascades of EDFAs without In-Line Optical Filters

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ABSTRACT

In this paper, we present a new method to equalize the optical signal-to-noise ratio (OSNR) of all wavelength division multiplexed channels at the end of a cascade of several erbium-doped fiber amplifiers (EDFAs), by use of pre-emphasis and the proper choice of EDFA design parameters. Identical OSNR at the end of the cascade ensures better signal detection and quality of service

Keywords: Cascade of EDFAs, WDM System, Equalization, Pre-emphasis, OSNR, and Self-similar traffic.

1. INTRODUCTION

Erbium doped fiber amplifiers (EDFAs) are a key enabling technology for wavelength division multiplexing (WDM) communications. Amplifiers provide the necessary gain across all information channels to overcome fiber attenuation.

The response of EDFAs to non-periodic changes in the power of the input channels (due to channel add/drop, network reconfiguration, fiber cuts, or packetized traffic) has been the subject of much recent research [1, 2, 3]. The gain excursion in an EDFA due to changes in the input power leads to possibly wide swings in the output power and output optical signal-to-noise ratio (OSNR) [4, 5].

The gain of an EDFA is in general wavelength dependent, leading to different gains among WDM channels. Signals traversing a cascade of several amplifiers will experience an increasing OSNR spread among channels. Different equalizing schemes [6, 7] have been suggested to overcome this effect.

We present here a novel equalizing method that combines pre-emphasis with equal amplifier inversion to achieve perfect output OSNR equalization at the end of the EDFA chain, without resorting to any optical equalizing filter.

Finally, we examine the performance of the equalizing method when the input WDM channels carry burst-mode packetized data traffic with high variability in the burst duration.

2. PRE-EMPHASIS FOR STEADY STATE EQUALIZATION

Our aim is to determine the EDFAs parameters (inversion level, doped fiber length, pump powers, input signal powers) to achieve equal OSNR on all channels to ensure better signal detection and to achieve the required quality of service for all WDM channels at the end of the cascade.

Since the OSNR is a tractable indicator of signal quality in preamplified direct-detection, we use it as the determining parameter in our approach. Hence, our aim is to obtain identical steady state OSNR on all WDM channels at the end of the cascade.

The proposed chain design method assumes the doped fibers of all the EDFAs in the chain have identical physical characteristics, except for their length. We further assume that the wavelength allocation of the WDM channels is given.

Our design begins with the arbitrary choice of a reference channel among the WDM channels. For this channel we use known criteria for optimizing the gain levels down a chain in which a single channel is

propagated, allowing for non-uniform inter-amplifier losses. Using such criteria, for a fixed target OSNR, the reference channel power out of each EDFA is the lowest possible. This is to ensure minimal nonlinear effects during propagation in the fiber between successive EDFAs. This also ensures the smallest pump levels.
If all WDM channels behave like the reference channel, then the design is optimal even for the multi-channel case. For this to happen we select the same inversion for all the doped fiber sections, so that all the EDFAs in the chain have the same spectral profile (This in general requires that pump levels are unequal down the chain). Such inversion can be optimized so as to obtain the flattest overall gain across the channels' wavelength range. Finally, we use pre-emphasis to perfectly equalize the OSNR of all WDM channels at the end of the chain, as illustrated in Figure **1**.

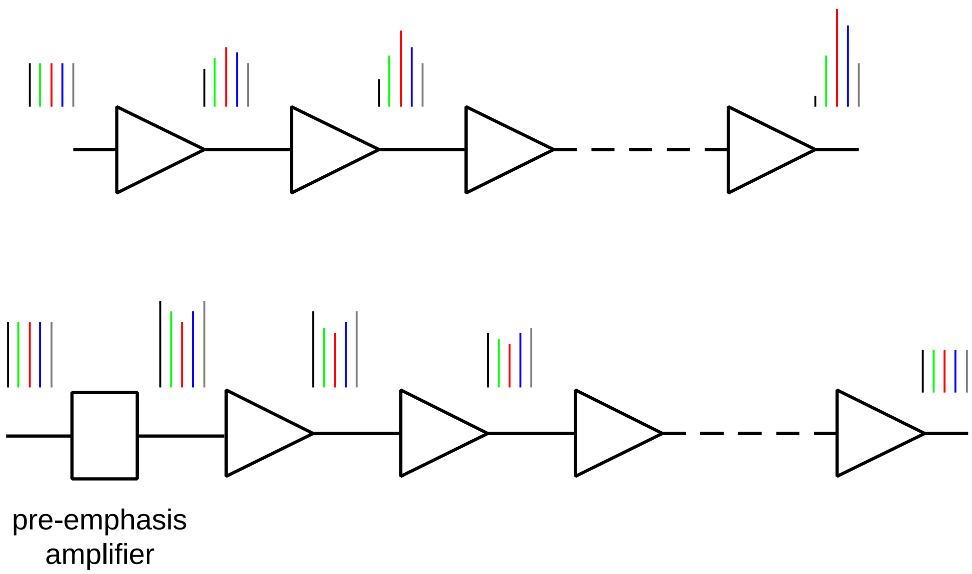

Figure 1. Effect of the use of pre-emphasis in the flat output at the end of a cascade.

To implement the above ideas, the chain design consists of the following steps:
1) We first determine the inversion level needed in each doped fiber to achieve the minimal gain spread among the WDM channels (Figure **2**). Indeed, an inappropriate choice of the inversion level can lead to a large inter-channel spread for power and OSNR (Figure **3**).
2) We fix a reference channel, generally in the middle of the WDM comb, and determine for it, according to the single-channel criteria mentioned above, the gain required at each amplifier in the cascade and thus fix the length of all doped fibers.
3) Knowing the gain of each EDFA, we determine, in analytical closed form, the WDM input power distribution (called pre-emphasis) that achieves the same OSNR as the reference channel for all the remaining WDM channels, at the end of the chain.
4) Finally, we determine the pump power needed at each EDFA to achieve the planned inversion with the pre-emphasized input channels obtained from point 3. The pump levels are calculated assuming that all the WDM channels are present.

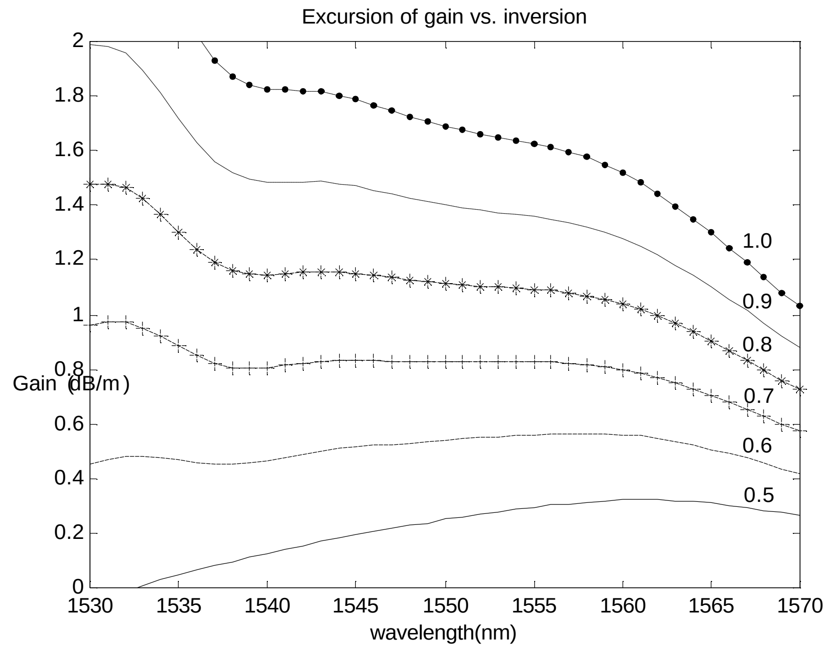

Figure 2. Non-flat gain versus wavelength profile for different inversion level.

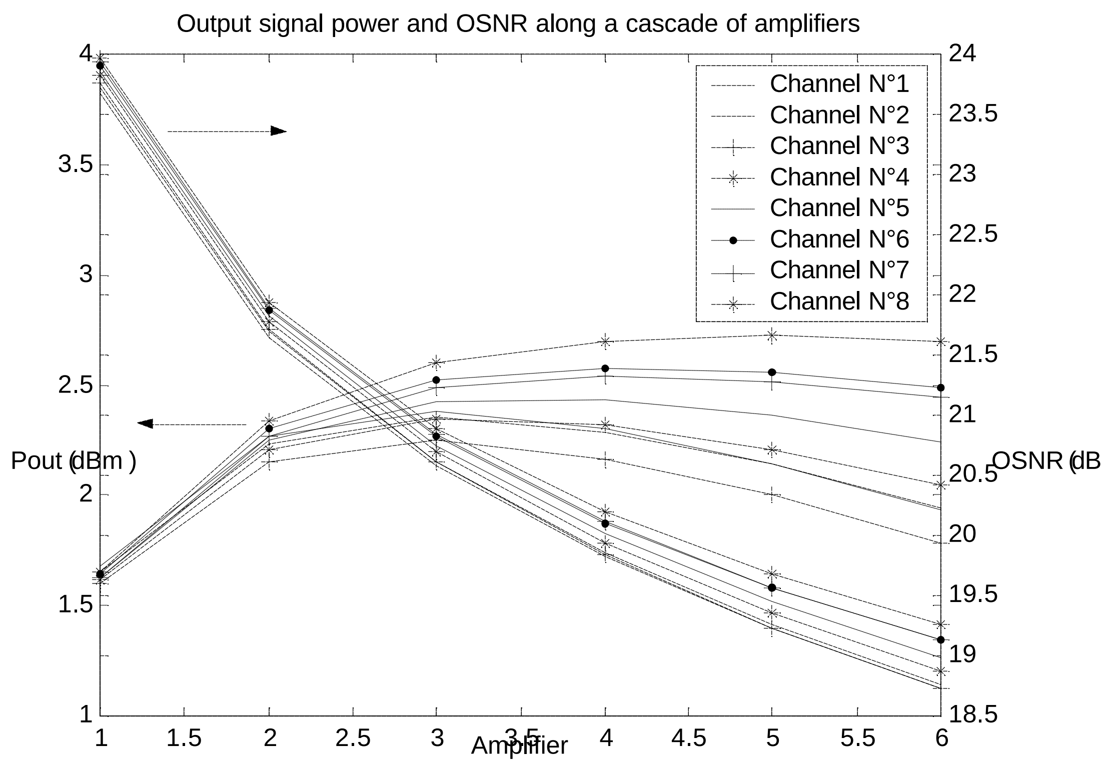

Figure 3. Evolution of output signal power and OSNR at steady state along a cascade of amplifiers without pre-emphasis.

3. SIMULATIONS

We consider a cascade of six EDFAs having 8 WDM channels, placed from 1547 to 1554 nm, with spacing of 1nm. Applying our equalizing design method described in the previous section, with all channels present and at steady-state, we obtain a perfectly equalized OSNR for all channels at the end of the sixth EDFA, as shown in Figure **4**. With preamplified direct detection, a uniform OSNR implies the same BER performance for all WDM channels, even though the received power slightly differs among WDM channels.

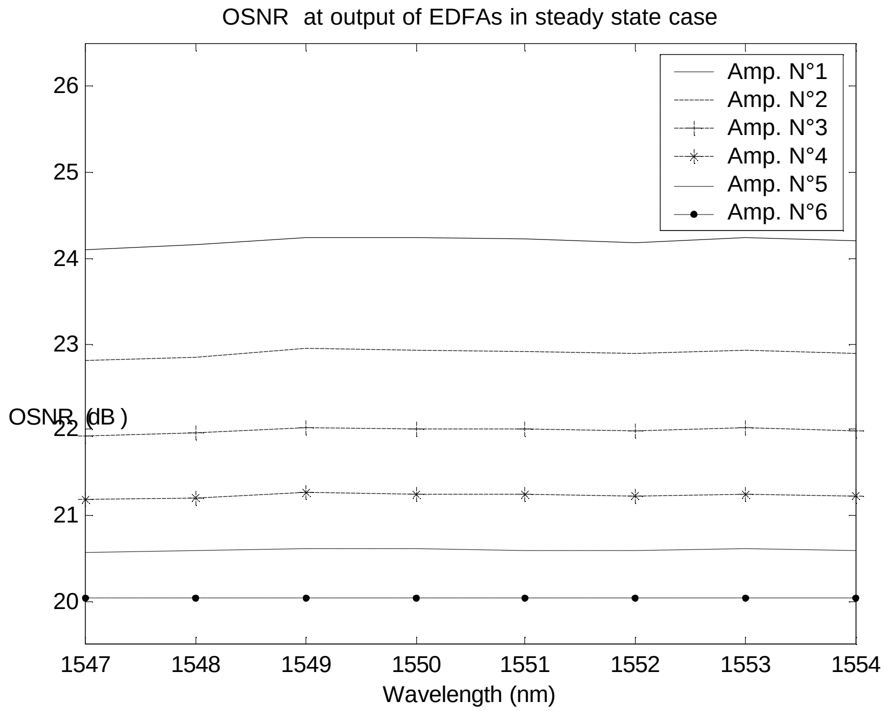

Figure 4. Evolution of the OSNR through a cascade of 6 amplifiers in steady state case.

While the equalizing design allows for flat output OSNR at steady state (i.e., with WDM channels modulated at high bit rate, without power discontinuities, or bursts), the OSNR will vary in burst mode operation, as the input power cycles between an activity mode (ON burst, during which packets are present back to back) and an inactivity mode (OFF burst, during which the source is idle, and no power is present on the channel).

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 [8, 9], that is, there exists a very high variability in the duration of the ON and OFF bursts on each channel. A self-similar traffic entails a wild variation of the total input power level over time scales comparable to the EDFA chain reaction time, and can result in large variations in the EDFA gain level, and thus of the channels output power and OSNR through the process of cross-gain modulation.

We also examine the use of all optical gain-clamping to combat such gain and OSNR variations [10]. To test the effect of the variability of packet inter-arrival times on the power and OSNR swings, we simulate the dynamic behavior of the same cascade we presented previously at steady-state.

The first EDFA in the chain is clamped by a ring laser configuration, as shown in Figure **5**. The time varying, bursty signals simulating the traffic from 8 WDM channels were randomly generated as 8 independent ON/OFF sources, i.e., each is a succession of ON and OFF periods (or bursts). The duration of each ON/OFF period is assumed to be a random variable with a rounded Pareto distribution [1].

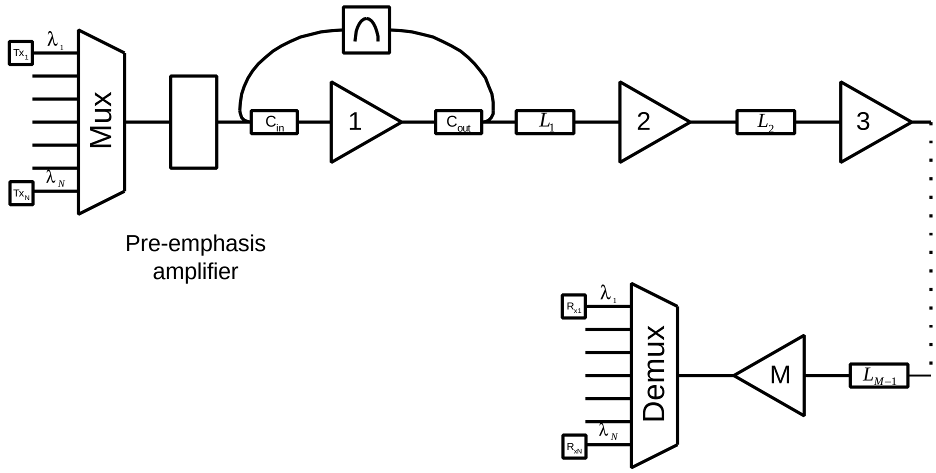

Figure 5. Schematic diagram of a cascade of EDFAs to form an optical point-to-point network.

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 in the neighborhood of a steady state value. A fraction of the lasing signal from the first clamped EDFA is allowed to propagate down the cascade, thus stabilizing to some extent each successive EDFA.

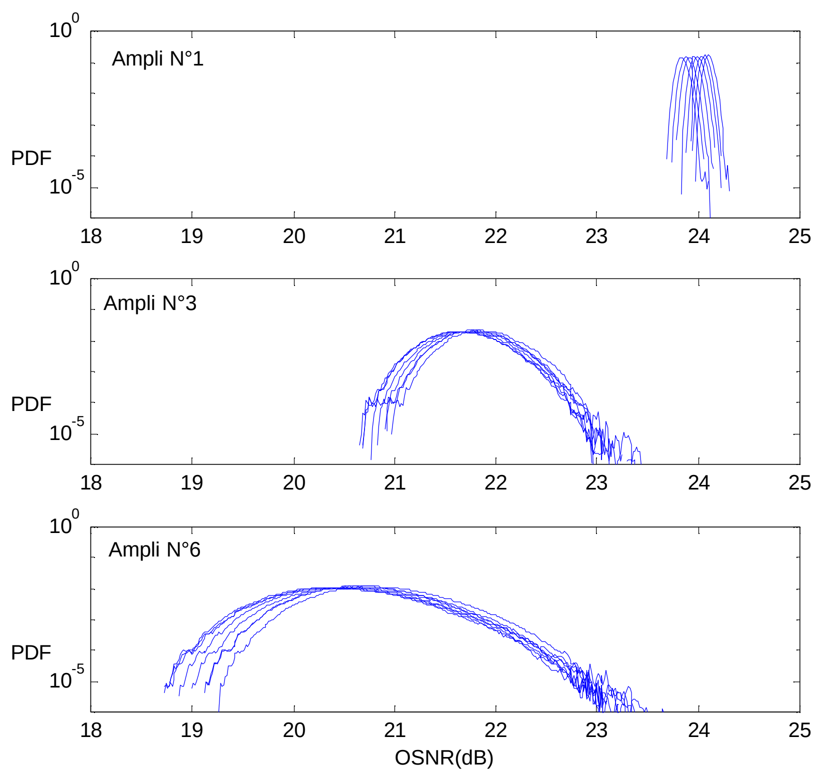

Figure 6. Evolution of the OSNR through an unclamped cascade over the 8 signal wavelengths at the 1st, 3rd and 6th amplifier.

The effect of the bursty packetized traffic has been evaluated statistically. The histogram estimate of the probability density function (PDF) of the output power and OSNR at the end of the cascade has been determined for three different chains:

1) a chain without our OSNR equalizing design, and without clamping;
2) a chain without our OSNR equalizing design, but with clamping of the first EDFA; and
3) a chain with our equalizing design, and with clamping of the first EDFA.

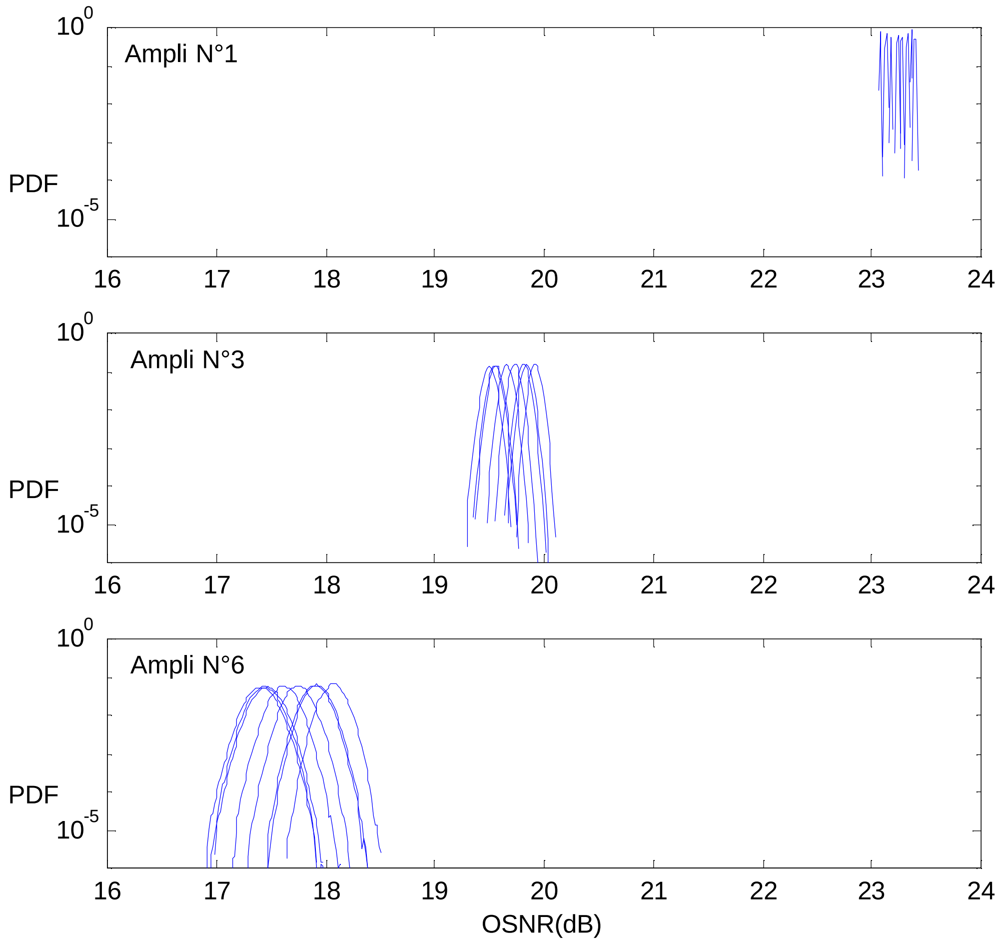

Figure 7. Evolution of the OSNR through clamped cascade over the 8 signal wavelengths at the 1st, 3rd and 6th amplifier.

For the first chain, figure 6, we notice two main features. Firstly, there are large excursions on the order of 1 dB at the first amplifier and 5 dB at the end of the cascade. Secondly, we observe a large separation of the mean values of OSNR for each WDM channel.

For the second chain, Figure 7, we note an improvement in the smaller gain spread (1.5 dB at the end of the clamped cascade compared to 5 dB in the unclamped one), but there is still a wide spread of the mean values of OSNR for each WDM channel.

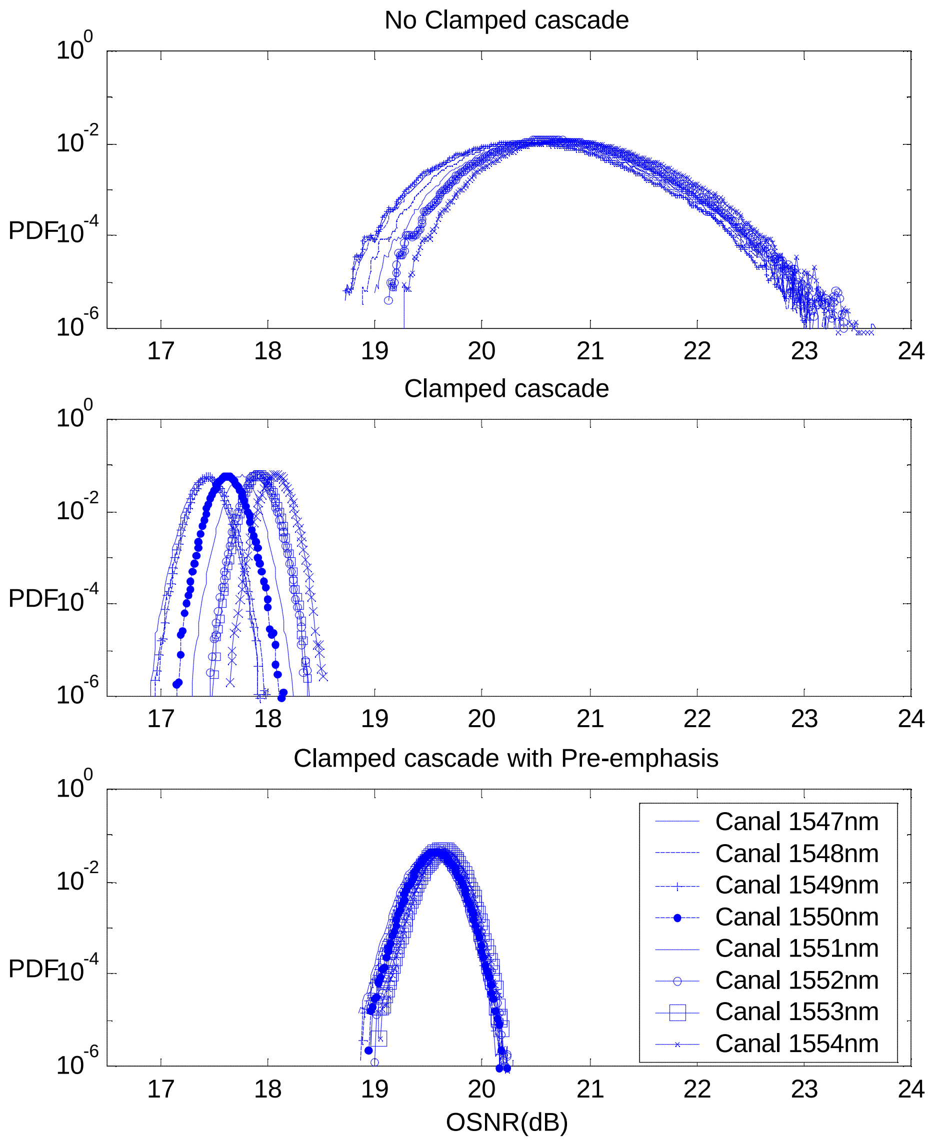

Figure 8. PDF of OSNR at the end of the cascade for the three cases (no clamped, clamped, and clamped with pre-emphasis) over the 8 channels.

For the third chain, Figure 8, the PDF curves of the eight channels almost perfectly overlap (to within 0.25 dB) at the end of the cascade. This ensures equalized quality of service for all 8 WDM packetized channels.

From Figure 8, we see two types of improvement. The first one is provided by clamping, which allows the reduction of the OSNR excursion for each channel from 5 dB in the unclamped case to only 1 dB in the clamped case. The second improvement is achieved by our equalizing design: the PDF curves are the same for all channels, implying an equal quality of service for all channels.

While clamping reduces the overall PDF spread for each signal (Figure 8.b), we also note that clamping of the first EDFA and propagation of the clamping laser makes the channel more unbalanced than the unclamped case of the first chain.

It is only in the third chain that uses our equalizing design that (even in a dynamic setting in which the input powers are varying randomly) the performance for each channel remains statistically equalized.

4. CONCLUSION

We have shown that it is possible to achieve OSNR equalization for a WDM system by the use of pre-emphasis and a judicious choice of EDFA parameters, without resorting to equalizing optical filters. More importantly, our equalizing design method ensures that the performance of the WDM channels is statistically equalized even in a dynamic scenario like burst-mode IP over WDM.

5. REFERENCES

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