System impact of EDFA gain fluctuation in WDM optical packet networks

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Today optical networks are all based on continuous data stream transmission (SONET/SDH, Gigabit Ethernet): the optical layer does not handle data packets.

Future true all-optical packet networks will handle data packet at optical level: no power is transmitted on empty slots.

Fast signal power transient at the input of EDFA cause time dependent saturation effects generating significant output power fluctuations.
EDFA dynamic behaviour

**Fast modulation (bit)**
2.5 Gbit/s

**Slow modulation (packet)**
1 μs

Fast modulation is not “seen” by the population inversion. Indeed, slow modulation is “followed” by the inversion, resulting in gain modulation.
Packetized transmission using non controlled EDFAs: dynamic gain variation strongly affect the signal and the system performance.
The proposed gain locking technique

- A strong CW signal is added to the WDM signals carrying packetized traffic: it will be called **locking signal**

- The locking signal power must be high enough in order to saturate the EDFA

- The aggregate power of all WDM signals must be small with respect to the locking signal power

- WDM signals will experience a small signal gain, without dynamic fluctuations, around the bias point fixed by the locking signal
The proposed gain locking technique

**CW locking signal**

\[ P_{lock} \]

\[ \lambda_{lock} \]

\[ \lambda \]

\[ N_{ch} \] WDM signals with packetized traffic

\[ P_{lock} \]

\[ P_{WDMsignal} \]

\[ P_{out} \]

\[ P_{in} \]

If \( N_{ch} \cdot P_{WDMsignal} \ll P_{lock} \)

\[ G_{WDMsignal} = \frac{dP_{out}}{dP_{in}} \bigg|_{P=P_{lock}} \]
Packetized transmission with gain locking

Packetized transmission with gain locked EDFAs. The dynamic gain fluctuation is negligible: system performance is not affected.
Measuring the impact: a new parameter

\[ Q_{\Delta G} = \frac{E}{\sigma_{\Delta G}} = \frac{m_1 - m_0}{(\sigma_{tot}^1 - \sigma_{noise}^1) - (\sigma_{tot}^0 - \sigma_{noise}^0)} \]

WITHOUT PACKETS

WITH PACKETS

\[ \sigma_{noise}^1 \]

\[ \sigma_{noise}^0 \]

no gain fluctuations

gain fluctuations: increased \( \sigma \)
Experimental setup

The 4 channel packet transmitter

Packet generator #1
Laser #1 $\lambda=1548.91$ nm

Packet generator #2
Laser #2 $\lambda=1549.72$ nm

Packet generator #3
Laser #3 $\lambda=1551.32$ nm

Packet generator #4
Laser #4 $\lambda=1552.93$ nm

Polarization Maintaining
4x1 Coupler

Lithium Niobate Modulator

Bit generator
2.5 Gbit/s

Independent packet generators at 1Mbit/s (slot time 1 $\mu$s). Packet arrival process is modeled using geometrically distributed random number generators.

Array of 4 lasers, spaced 200 GHz (1.6 nm) on the ITU grid, directly modulated by packet generators.

A $2^{20}-1$ pseudorandom bit stream is overwritten on packets.
Experimental setup

The amplified link with three cascaded EDFA

- **Locking laser** \(\lambda_{\text{lock}} = 1545\,\text{nm}\)
- **VOA**
- **EDFA**
  - G = 20 dB
  - \(\alpha = 20\,\text{dB}\)
  - G = 20 dB
  - \(\alpha = 20\,\text{dB}\)
  - G = 20 dB
  - \(\alpha = 20\,\text{dB}\)
- **Optical Filter** \(\lambda = 1551.32\,\text{nm}\)
- **Optical Coupler**
- **PIN**
- **BER meter**
- **Oscilloscope**

- \(P_{\text{ch}}\): transmitted power per channel
- \(P_{\text{rx}}\): received power per channel

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Traffic description

Slot ON, marked with 1: packet transmission
Slot OFF, marked with 0: no transmission

\[ \begin{array}{cccccccccccccccc}
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\
\end{array} \]

- \( T_{\text{off}} \) and \( T_{\text{on}} \) are geometrically distributed random numbers
- \( T_{\text{on}} \) is the average number of consecutive slot ON
- \( T_{\text{off}} \) is the average number of consecutive slot OFF
- \( T_{\text{on}}/(T_{\text{off}} + T_{\text{on}}) \) is the average traffic load
- \( T_{\text{off}} + T_{\text{on}} \) gives an indication of the traffic burstiness
$Q_{\Delta G}$ vs. $P_{ch}$: gain locking improvement

$T_{on} + T_{off} = 400$ slots; Load = 50%

$P_{lock} = -16$ dBm
For each value of $P_{ch}$, set using the variable optical attenuator (VOA) after the transmitter, a BER vs. $P_{rx}$ curve is obtained sweeping $P_{rx}$ by mean of the VOA after the receiver filter.

Measuring BER with packet ON and OFF, we get a sensitivity penalty at a reference bit-error-rate set to $10^{-9}$.

At each penalty we relate the newly introduced parameter $Q_{\Delta G}$, in order to obtain the relationship between sensitivity penalty and $Q_{\Delta G}$ curve.
BER measurements

![Graph showing BER measurements with and without packet, and sensitivity penalty.]

- \(P_{\text{ch}} = -22 \text{ dBm}\)
- Sensitivity Penalty
- Without packet: \(10^{-9}\)
- With packet: Log(BER) vs. \(P_{\text{rx}}\) [dBm]
Correlating Penalty and $Q_{\Delta G}$

Rule of thumb: $Q_{\Delta G}$ should be greater than 18-20 dB in order to have a sufficiently low system impact.
$Q_{\Delta G}$ traffic dependence: burstiness

Load = 50%

$P_{rx}$ [dBm] vs. $Q_{\Delta G}$ [dB] for different values of $Ton + Toff$: 20, 200, and 400.
$Q_{\Delta G}$ traffic dependence: load

$T_{on} + T_{off} = 200$ slots

$P_{\text{rx}}$ [dBm] vs. $Q_{\Delta G}$ [dB] for different loads (50%, 10%, 70%).
Conclusions

- We experimentally addressed the impact of bursty input optical signals on the gain fluctuation of EDFA amplifiers.
- We introduced a new and easily measurable parameter that allow to quantify the effect.
- We related this parameter to the system sensitivity penalty.
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