Power Consumption of Hybrid EDFA/Raman Amplified Systems

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Abstract *We analyze the power consumption in hybrid EDFA/Raman amplified links along with the trade-off of span distance and the use of FEC. A simple model provides some guidelines for the choices to be made.*

Introduction

The rapid growth of the Internet has highlighted the issue of the power consumption of the network equipment, including that of the optical backbone network. The power consumption of the optical amplifiers is not insignificant in long-haul systems[1], and the choice of amplification scheme is related to the use of power consuming forward error correction (FEC) in a trade-off fashion where a decreased amplifier count leads to higher complexity FEC to maintain the same throughput and bit-error rate (BER).

One method for improving the optical signal-to-noise ratio (OSNR) and thus the BER is the use of distributed Raman amplification, which can be used to compensate for the whole or parts of the span loss in combination with erbium-doped fiber amplifiers (EDFA). Such hybrid amplification schemes have to the best of our knowledge so far only been investigated from a performance point of view[2], and not from a power consumption perspective. Previous studies of the power consumption of optical systems[1,3] has only included EDFA-based amplification.

In this paper, using simple performance and power consumption models we investigate the effect on the optical amplifier power consumption from adding a Raman pump in the backward direction. We further investigate potential system-level power savings by trading the improved OSNR for a power consumption decrease in other system components, e.g., the FEC.

System model

We consider a system according to Fig. 1, where the span loss is completely compensated for with a combination of distributed Raman amplification and lumped EDFA. We can then introduce a Raman gain ratio $0 < \beta_R < 1$ that describes the fraction of the span loss in dB that is compensated for by distributed amplification, so that $G_{R,dB} = \beta_R G_{tot,dB}$, where $G_{tot} = e^{\alpha_s L}$ is the total span loss. Pure Raman corresponds to $\beta_R = 1$ and pure EDFA corresponds to $\beta_R = 0$. If depletion of the Raman pump is neglected, the Raman gain can be written[5] $G_R = \exp(g_R P_{p,R}(1-e^{-\alpha_p L})/\alpha_p)$, where $P_{p,R}$ is the Raman pump power, α_p is the loss coefficient at the pump wavelength and g_R is the Raman gain efficiency. We have assumed SMF with $\alpha_s = 0.2\,\mathrm{dB/km}$, $\alpha_p = 0.25\,\mathrm{dB/km}$ and we have measured $g_R = 0.41\,/\mathrm{W/km}$. The amplified spontaneous emission (ASE) noise in this system will then have contributions from both the Raman amplification and the EDFA, so that the total ASE spectral density is $S_{ASE} = S_{ASE,E} + G_E S_{ASE,R}$. The EDFA ASE contribution $S_{ASE,E}$ can be found from the gain and n_{sp}[4] and the Raman contribution $S_{ASE,R}$ by numerically integrating the noise over the fiber length[5]. Here we used $n_{sp} = 1.58$ for the EDFA ASE and $n_{sp,R} = 1.13$ for the Raman ASE[5]. We neglect multi-path interference caused by distributed Rayleigh back scattering, since it is low for moderate pump powers[6].

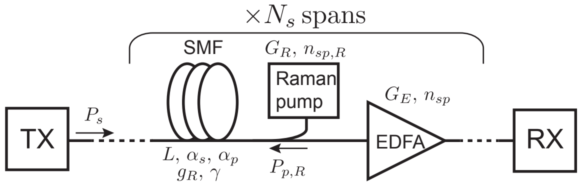

Fig. 1: The considered system.

In systems without inline dispersion compensation, nonlinear interference (NLI) is approximately Gaussian noise[7], and can also be included in the expression for the OSNR. The NLI noise takes the form $S_{NLI} = k_{NLI} P_s^3$, where k_{NLI} depends on the spectral shape of the channels, the fiber parameters and the signal power evolution along the fibers. The NLI is increased with the Raman pump power due to the higher average signal power in the fiber, but for moderately backward-pumped systems the OSNR decrease this causes is under 0.5 dB[2]. For simplicity the value was assumed to be equal to the one found for an equivalent EDFA based span. We assumed an 80 channel square-spectrum system in the entire C-band and used $\gamma = 1.3\,/\mathrm{W/km}$ to calculate k_{NLI}.

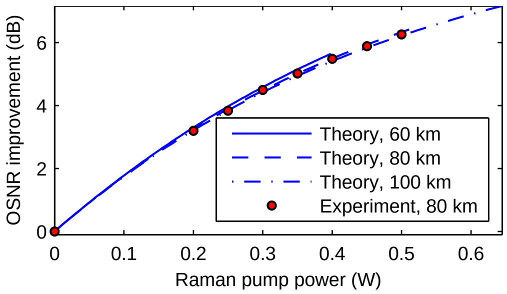

Fig. 2: The OSNR improvement as a function of the pump power, not including NLI.

If NLI is taken into account, there is an optimal signal power that maximizes the OSNR, depending on the amount of ASE and NLI[2]. When the amount of ASE is decreased by using Raman amplification the optimal signal power is decreased, which leads to a reduction in the achievable OSNR improvement. It can be shown that the maximum OSNR improvement is only 2/3 of the ASE reduction in dB[2].

Power consumption models

In earlier estimates the power consumption of an EDFA unit is assumed to consist of one part proportional to the pump power and one fixed part for monitoring and management electronics[3]. We extend this model to also include the Raman pump power so that

$$P_{\text{span}} = \frac{1}{\eta_e}(P_{p,E} + P_{p,R}) + P_{MM}, \tag{1}$$

where η_e is the electrical power conversion efficiency, which we assume to be the same for both the EDFA and Raman pump. We also assume that the monitoring and management power consumption P_{MM} is not affected by adding a Raman pump. The Raman pump power can be found directly from the equation for the Raman gain, and the EDFA pump power is[4]

$$P_{p,E} = \frac{1}{\eta_{PC}}(P_{out} - P_{in}) = \frac{P_s}{\eta_{PC}}\left(1 - \frac{1}{G_E}\right), \tag{2}$$

where η_{PC} is the power conversion efficiency between the EDFA pump and the output power. This equation assumes that the EDFA is operated in the saturation regime. We have used $\eta_{PC} = 40\,\%$[3] and $\eta_e = 5\,\%$[1].

Single hybrid span characteristics

It is convenient to normalize the Raman induce OSNR improvement with respect to the EDFA-only OSNR. The normalized OSNR is improved according to Fig. 2 when the Raman pump power is increased. We have verified this by measuring the OSNR increase of a -10 dBm CW laser at the output of an 80 km hybrid amplified span, also plotted in Fig. 2. The low signal power means that pump depletion was negligible and the theory and experiments are in good agreement. Due to the attenuation of the Raman pump in the transmission fiber, the normalized ASE reduction is almost unaffected by the span length. Note that if the system is operated at the optimal signal power with respect to NLI the OSNR improvement is 2/3 of the ASE reduction.

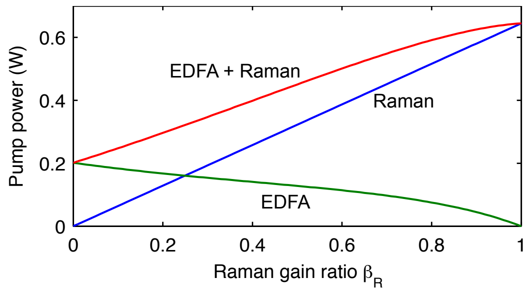

Fig. 3: The pump powers as a function of the Raman gain ratio for a 100 km span, including the effect of the reduced optimal signal power.

The increased power consumption of the Raman pump is counteracted by the reduction of EDFA power consumption due to the reduced gain of the EDFA. With the assumption that $\eta_{PC} = 40\,\%$, the former effect is stronger and increasing Raman gain increases overall the power consumption. If the system is operated at the optimal signal power with respect to NLI, the EDFA power consumption is reduced further by the decrease of the signal power. The pump power variations are plotted in Fig. 3.

System-level power consumption trade-offs

In this section, the power consumption of the Raman induced OSNR increase is traded against other system components. In both examples, NLI is taken into account.

Number of spans: In a link of total length L_{tot}, the noise reduction from Raman amplification allows for a reduced number of spans, while keeping the OSNR constant. The total power consumption of such a system is $P_e = N_s P_{\text{span}}$. In Fig. 4 the number of spans needed for a system of length 2400 km operated at an OSNR of 17 dB is plotted as a function of the Raman gain ratio. Note that above $\beta_R = 0.78$ no further reduction in span count can be achieved at the desired OSNR. When the span count is increased, the increased Raman gain results in a higher total pump power for a single amplifier unit. This is counteracted by the decrease in number of amplifier units needed.

The power consumption of the amplifier units is typically dominated by the monitoring and man-

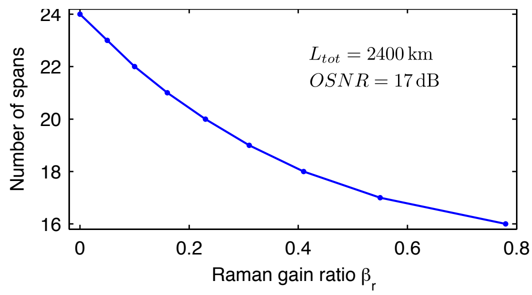

Fig. 4: The span count as a function of the Raman gain ratio.

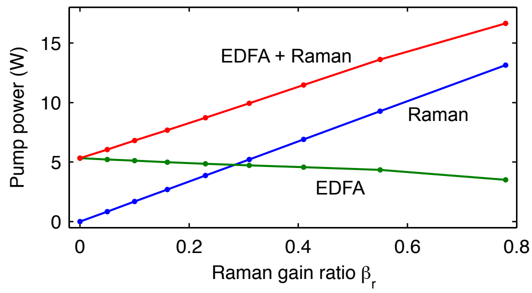

Fig. 5: The total pump powers summed over all amplifier units in the system in Fig. 4.

agement power P_{MM}[3]. In theory this could be reduced to an arbitrarily low value, while the pump power consumption is directly linked to the optical performance of the system and can be considered as a lower limit on the amplifier power consumption.

Even when taking the decrease of the number of spans into account, adding a Raman pump increases the total pump power needed, as can be seen in Fig. 5. This means that Raman amplification cannot be used to reduce the power consumption of the pump lasers alone. However, the monitoring and management power consumption P_{MM} has a big impact on which amount of Raman amplification is the most beneficial. Previous studies estimate $P_{MM} = 55\,\mathrm{W}$, so we varied P_{MM} from 0 to 70 W. As can be seen in Fig. 6, the Raman gain ratio that achieves the lowest power consumption increases with P_{MM}.

Forward error correction: It has been estimated[1] that significant power savings can be made in the transmitter and receiver if the pre-FEC BER can be improved from 10^{-2} to 10^{-4}, since a complex soft-decision FEC circuit consuming 13 W then can be replaced with a circuit using a simpler hard decision code consuming 0.13 W.

For a 100 Gbit/s PM-QPSK system we can use the theoretical BER–OSNR relation to find that a reduction in pre-FEC BER from 10^{-2} to 10^{-4} corresponds to an OSNR increase of 4.1 dB. This can be achieved by adding a 0.5 W Raman pump to each amplifier unit at the cost of 8 W in extra power consumption. Applying this to the 2400 km

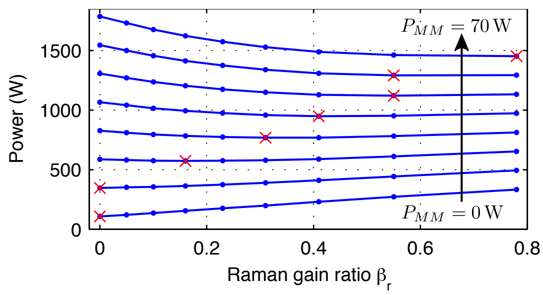

Fig. 6: The total amplifier power consumption for the system in Fig. 4, for different P_{MM}. The red crosses mark the minimum power consumption for each curve.

80 channel system with 24 amplifiers used in the specific estimate[1] results in a 200 W increase of the power consumption due to the added pump power. To make a fair comparison it should be noted that this extra pump power is shared between all the 80 channels of the system, while the power consumption of the FEC circuits is per channel. As a result of the decreased pre-FEC BER the total FEC power consumption can be reduced almost 1 kW.

Conclusions

Using simple system performance and power consumption models we have studied the power consumption implications of supplementing the EDFA gain with distributed Raman amplification to increase the OSNR. Assuming an EDFA operated in saturation, the improved OSNR comes at the cost of increased pump laser power consumption. However, if the increased OSNR can be used to reduce power consumption of other components in the system, for example FEC or managing electronics, a decrease in power consumption could be possible.

Acknowledgements

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