Performance Scaling Rules for Raman Amplification in Coherent Transmission Systems

Simple scaling rules are derived for backward Raman amplification that enable an estimation of maximum reach in coherent systems.

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Introduction

It is well known that Raman amplification can improve system performance, but by what amount? I recently have written a review article on Raman amplification [1] based on an Invited Tutorial presented at OFC 2015 [2]. This article provides a good overview on how Raman amplification works in real systems and describes a method to calculate the nonlinear transmission penalties in coherent links. It also describes the implementation and control of Raman modules.

In this White Paper, I show how the relative benefit of Raman compared to EDFA-only amplification can be easily calculated for backward Raman. This analysis can be used for any fiber type and span loss.

Optical Performance

The modelling of the amplified optical line system is based on simple signal and noise power which been presented in the review article [1]. The noise is defined at the optical receiver where the signal-to-noise ratio (SNR) defines the bit error rate of the data transmission. The changes in SNR after passing through an amplifier is further quantified by the noise figure (NF) which is the ratio of input to output SNR. In the optical domain, an optical SNR (OSNR) is defined as the ratio of optical signal power to optical noise. The NF (in linear units) of a span of loss, L_{span}, followed by an EDFA with noise figure, NF_{EDFA}, is

$$NF_{total} = L_{span} \cdot NF_{EDFA} \,. \qquad (1)$$

NF_{EDFA} is typically about 4.5 to 5 dB (2.8 to 3.2 in linear units).

With backward Raman amplification followed by an EDFA, the NF becomes

$$\begin{aligned} NF_{total} &= L_{span}\left[NF_{BR} + \frac{NF_{EDFA} - 1}{G_{BR}} \right] \qquad (2) \\ &= L_{span} \cdot NF_{R+E} \end{aligned}$$

where NF_{BR} and G_{BR} are the NF and on/off Gain of the backward Raman amplifier and NF_{R+E} is the combined Raman + EDFA NF. One can immediately see that the ratio of NFs [equation (1) divided by (2)] is independent of the span loss and equal to $NF_{ratio} = NF_{EDFA}/NF_{R+E}$. This ratio is about 3.5 (5.4 dB) in SMF at the short wavelength side of the spectrum (worst channel typically) using Xtera's 10-dB Raman Module (SE10C). Plots of NF_{BR} for two of Xtera's Raman modules is shown in Fig. 1.

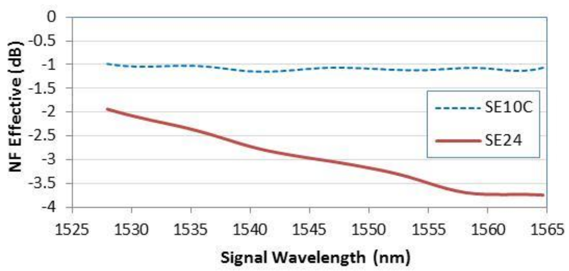

Fig. 1. Effective NF (NF_{BR}) of Xtera's SE10C and SE24 across the C-band. The NF of an EDFA is about 4.5 to 5 dB (not shown).

The NF relates to the more commonly used OSNR through the formula

$$OSNR = \frac{P_s}{P_{ASE}} = \frac{P_s \cdot G_{total}}{(G_{total} \cdot NF_{total} - 1) h \nu_s \, \Delta\nu} \qquad (3)$$

where P_s is the signal transmit power into the span, P_{ASE} is the noise power after the EDFA, $\Delta\nu$ equals 12.5 GHz for 0.1-nm bandwidth, and G_{total} is the total gain of the span plus amplifier (typically = 1.0). The total NF for a span and amplifier is usually large (a 20-dB span with EDFA has a NF > 300) so that the amplified spontaneous emission (ASE) noise is simply

$$P_{ASE} = NF_{total} \cdot h \nu_s \, \Delta\nu \,. \qquad (4)$$

For a dispersion-uncompensated coherent system, the nonlinear power, P_{NL}, may be analytically calculated [3] to get an effective OSNR which is the final performance metric:

$$OSNR_{eff} = \frac{P_s}{P_{ASE} + P_{NL}} \,. \qquad (5)$$

The nonlinear power has a simple scaling law [3] relative to the signal power:

$$P_{NL} = \eta \, P_s^{\,3} \qquad (6)$$

where η is the nonlinear term (units of 1/W^2) which does not depend on the span loss for typical spans of 17 dB or more [exp($-\alpha L$) << 1, where α is the fiber attenuation and L is span length]. Finally, the optimum signal power can be calculated from the ASE power

$$P_{s,opt} = \left(\frac{P_{ASE}}{2\eta} \right)^{1/3} . \qquad (7)$$

which occurs when the nonlinear power is one half the ASE power. As discussed in my review article [1], the value of η does not change significantly with backward Raman when followed by an EDFA of 15 dB gain or more.

Putting these equations together and assuming we are operating at the optimal signal power, the effective OSNR per span can be related simply to the NF as

$$OSNR_{eff} = \tfrac{1}{3} \eta^{-1/3} (h\nu \, \Delta\nu / 2)^{-2/3} NF_{total}^{\;-2/3} . \qquad (8)$$

Converting this to dB units and using a frequency corresponding to 1528 nm (short wavelength side of the C-band), the effective OSNR (within 0.1-nm bandwidth) per span is

$$OSNR_{eff-dB} = 55.8 - \tfrac{1}{3}\eta_{dB} - \tfrac{2}{3}NF_{dB}\,. \qquad (9)$$

The total effective OSNR for N spans is the per-span $OSNR_{eff\text{-}dB}$ minus the number of fiber spans in dB.

$$OSNR_{eff-dB}(N) = OSNR_{eff-dB} - 10 \cdot log_{10}(N) \qquad (10)$$

The maximum reach is just the span effective OSNR in dB minus the transponder OSNR threshold in dB converted to the linear number of spans, i.e., set $OSNR_{eff\text{-}dB}(N)$ to the transponder OSNR threshold and solve for N.

Example #1: Max 100G Reach in SMF

For SMF, η is about 450 (1/W^2) with 93 channels and 120-km, 0.23-dB/km spans. An EDFA with NF 5.0 dB has a NF_{dB} of 33.4 dB (at 1528 nm) resulting in an effective OSNR of 24.7 dB. A coherent PM-QPSK 100 Gb/s transponder has an effective OSNR threshold of about 13.5 dB so that the maximum reach of this example is about 13 spans, or 1,560 km. [Note that the maximum reach is (24.8 dB – 13.5 dB) converted to linear # spans: 11.3 dB = 13.] The same example with Xtera's 10-dB backward Raman module has a NF_{dB} of 28.0 dB and a maximum reach of 30 spans, or 3,600 km.

Example #2: Max 200G Reach in SMF

Assuming twice the spectral efficiency for 200G (PM-16QAM) and the same channel bandwidth, η is about the same as last example. For 93 channels and 100-km, 0.23 dB/km spans, the $OSNR_{eff}$ is about 27.8 dB for an EDFA-only line system and 31.4 dB with a 10-dB Raman module on each span. A coherent PM-16QAM 200 Gb/s transponder has an effective OSNR threshold of about 19.5 dB. The maximum reach without Raman is 600 km and with Raman is 1500 km.

Note that these maximum reach values do not include the effect of ROADMs, PMD, or PDL which can be accounted for separately. Also, see reference [4] for some slight differences between modulation formats that were not included in the above analysis.

Relative Scaling Rules

We saw in the last section that the ASE power is proportional to ($\propto$) the NF, the optimal signal power $\propto$ NF$^{1/3}$, the nonlinear power $\propto$ NF, the linear effective OSNR $\propto$ NF$^{-2/3}$, and the effective OSNR in dB $\propto$ -2/3$\cdot NF_{dB}$. The ratio of $OSNR_{eff}$ of an EDFA-only span to a backward Raman amplified span is equal to $NF_{ratio}^{-2/3}$. Because the linear ratio of NF's do not depend on span loss, one can see that the general scaling of the last example is that a 10-dB backward Raman amplifier has a maximum reach that is (3.5)$^{2/3}$ =2.3 X the distance of an EDFA-only line system for any coherent transponder in any SMF line system. Xtera's 24-dB Raman gain module (SE24) has a NF ratio of 5.0 resulting in (5.0)$^{2/3}$ =2.9 X the maximum reach compared to an EOA-only solution (the SE24 has a higher NF ratio at longer wavelengths as shown in Fig. 1).

Different fiber types have different NF ratios. The relative reach factor depends only on this NF ratio. The table below shows the reach factors for different fiber types. (In some fiber types, the SE24 gain must be reduced to keep the multi-path interference below a certain value and, therefore, does not scale the same as the SE10C.)

Fiber	SE10C NF ratio	SE24 NF ratio	SE10C Reach Ratio	SE24 Reach Ratio
SMF	3.5	5.0	2.3	2.9
PSC	3.9	5.0	2.5	2.9
LEAF	4.2	5.0	2.6	2.9
TW-C	4.7	5.1	2.8	3.0
TW-RS	4.7	5.1	2.8	3.0
DSF	5.2	5.4	3.0	3.1
LS	5.2	5.4	3.0	3.1

Table 1. NF ratios (NF_{ratio}) and maximum reach ratios for different fiber types using Xtera's SE10C or SE24 Raman gain module.

These scaling rules apply to the case of using Raman amplification on each span, but typically Raman amplification is more cost effective in being applied only to the longer spans. This will be discussed in more detail in the following section.

Non-equivalent Spans

The scaling results of the previous section apply only to the case of equivalent spans which is not typical of terrestrial applications. The total effective OSNR can be calculated by summing up the $OSNR_{eff}$ of each span calculated from equation (8) for N spans:

$$\frac{1}{OSNR_{eff}(total)} = \sum_{i=1}^{N} \frac{1}{OSNR_{eff}(i)}. \qquad (11)$$

It is helpful to take out the common factors and rewrite the equation in terms of NF ratio and span loss per span as

$$\frac{1}{OSNR_{eff}(total)} = k \cdot \sum_{i=1}^{N} \left(\frac{L_{span}(i)}{NF_{ratio}(i)} \right)^{2/3} \qquad (12)$$
$$k = 3\eta^{1/3} (h\nu\, \Delta\nu / 2)^{2/3} (NF_{EDFA})^{2/3}$$

In equation (12), NF_{ratio} is either 1.0 for an EDFA, or one of the ratios in the first two columns of Table 1 for Raman and L_{span} might range from 20 (13 dB span) to 2000 (33 dB span) with an average of maybe 200 (23 dB span). We want to minimize the sum as that maximizes $OSNR_{eff}(total)$. Clearly, the most effective way to do this is to use a larger NF_{ratio} (Raman amplification) on the large spans which contribute the most to the summation. In this case, one may only need several spans of Raman amplification to avoid a regeneration site. Thus, one does not need to add Raman to every span equally to significantly improve the performance, just the larger spans.

Conclusion

This white paper has developed a simple formula for the effective OSNR which is the main performance metric of a fiber optic transmission system. The relative scaling laws for Raman amplification (used in each span) apply over all span losses and coherent transponder types. However, most of the benefit of Raman amplification can be achieved by employing Raman on the longest spans.

The maximum reach in any fiber type is proportional to $NF^{-2/3}$ and Xtera's Raman line system increases the reach by 2.3 to 3.1X

The cost advantage of Raman is the reduction or elimination of transponder regeneration by improving the performance to meet a reach threshold. The reach multipliers in Table 1 show whether the deployment of Raman is capable or eliminating regeneration points that would result if using an EDFA-only line system. The cost of a Raman-enhanced line system may be equivalent to just several regeneration channel cards. Thus, at higher channel capacity the savings of regeneration cards will dominate the network costs resulting in a considerable reduction in total cost.

References

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