MODELLING OF NONLINEAR FIBER EFFECTS IN SYSTEMS USING CODIRECTIONAL RAMAN AMPLIFICATION

Nelson Costa (Coriant Portugal), Lutz Rapp (Coriant R&D GmbH)
Email: nelson.costa@coriant.com

Coriant Portugal, R. Irmãos Siemens 1-1A, 2720-093 Amadora, Portugal

Abstract: This paper proposes a new technique for determining the impact of nonlinear fiber effects on signal propagation in unrepeatered transmission systems when using codirectional Raman amplification. The proposed concept is based on pre-calculated nonlinear penalties for a set of power profiles by making use of accurate but computation-intensive techniques. Once the performance of a specific link needs to be determined, an accurate estimate of the nonlinear penalty is derived from the entries of the generated database almost instantly. The composition of the database and the method to derive the nonlinear penalties from the entries are explained.

1. INTRODUCTION

Accurate planning tools are essential means to provide a quick response to customer requests and to offer the best suited solution. In order to be competitive, the lowest cost configuration guaranteeing the required performance needs to be selected.

Characterizing signal distortions arising from nonlinear fiber effects is one of the most time consuming steps in performance calculation. In particular, accurate solutions can be obtained by solving coupled differential equations such as the nonlinear Schrödinger [1] or the Manakov equation [2]. However, these approaches are not suitable for providing fast responses to customer requests due to the large simulation time.

Simplified methods providing faster estimates of the nonlinear penalties at the expense of lower accuracy have been proposed in literature. An example of such a method is the Gaussian noise (GN) approach applicable to coherent modulation formats [3, 4]. While the most simplified versions of the GN approach are simple and very fast, the most accurate ones are more complex and may still lead to considerable simulation time [5]. The fast and accurate performance estimation for transmission systems is even more challenging in unrepeatered long single-span systems due to the high launch powers.

Moreover, with the trend to higher data rates more and more systems have been equipped with codirectional Raman amplifiers leading to power profiles in the fiber that make accurate performance modeling even more difficult. Additionally, phase modulated signals detected coherently experience nonlinear crosstalk from a larger number of neighboring channels, which further enhances the difficulty to obtain a fast but still accurate performance estimate.

In this paper, a new technique for determining the performance of unrepeatered transmission systems using codirectional Raman amplification is proposed. The impact of nonlinear fiber effects for a link is derived from entries of a database generated before considering a specific project. In particular, the database contains information about nonlinear penalties for several power profiles in the transmission fiber, wherein the penalties have been calculated beforehand with high accuracy. The power profiles are chosen to represent all kind of relevant power profiles. Thus, the database can be used to estimate the performance of a large variation of transmission systems in a fast but still accurate manner. The main advantage of this approach is that link performance can be determined almost instantly with small computational power, since required complex computations have already been done by a high-performance computer beforehand. Moreover, since similar transmission systems should lead to similar impact of nonlinear fiber transmission effects, the database needs to comprise a small number of power profiles, only.

2. MAPPING PROCEDURE

The key problem to be solved is mapping a given power profile to an appropriate power profile for which the penalty has already been calculated and deriving the actual penalty. Therefore, a mapping rule has been developed. The set of pre-calculated scenarios will be referred to as baselines in the remaining of this paper. Various power profiles in the transmission fiber covering a wide range of possible applications need to be considered.

Figure 1 shows several different shapes of power profiles in the transmission fiber obtained when using codirectional Raman amplification. The power profiles representing different gain values and pumping configurations have been normalized to a launch power of 0 dBm. However, the nonlinear penalty needs to be estimated for different launch powers for each of the curves. A good characterization in the range of small nonlinear penalties is of major importance since maximum performance is typically achieved in this range. Moreover, the impact of dispersion precompensation should also be taken into account. Therefore, in general, each baseline consists of several entries containing the nonlinear penalty for different pairs of launch power and dispersion precompensation values. Please note that only the nonlinear penalty is provided by the baselines, since determining the available optical-to-signal noise ratio (OSNR) does not require significant computational power.

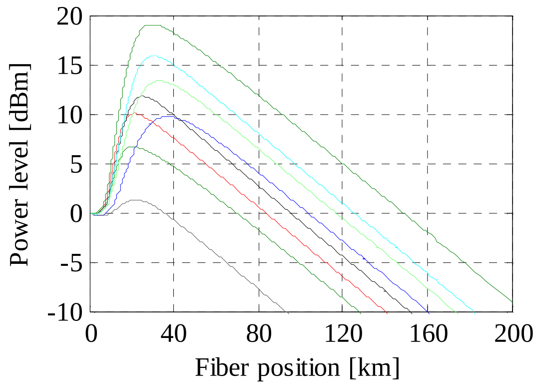

Figure 1. Example of power profiles along optical fiber when using codirectional Raman amplification

Saving the difference in penalty with respect to an exponential power decay for the same launch power is convenient, since it allows to align the simulation results with experimental data obtained for a configuration with a high power booster. In fact, simulations provide a good estimate of the relative reach improvement achieved by codirectional Raman amplification over a configuration with a booster amplifier. In contrast, the absolute transponder performance depends on many parameters and larger deviations between simulation results and experimental data are possible. Thus, accurate results can be obtained by measuring transponder performance versus channel power for a configuration with high power booster and using these results for the further calculations, whereas the effect of the codirectional Raman amplifier is taken into account by the simulation results. Hence, only few experimental data are required for the calculations.

The concept of the mapping procedure can be summarized as follows:

1. First, the power evolution of the channel to be evaluated is calculated, leading to a power profile similar to the ones shown in Fig. 1. The calculation of the OSNR available at the receiver side can also be done in this step.

2. In the second step, an appropriate baseline is selected for the actual power profile. This can be achieved by assessing which baseline has the shape with the highest similarity to the actual normalized power evolution of the considered channel. The similarity between the power profiles can be evaluated using a root mean square (RMS) deviation as criteria. After this step, a baseline having a shape that is very similar to the actual power profile has been selected, but the relevant launch power is still not known.

3. Next, the "equivalent launch power" has to be determined. For this purpose, the integral of the power profile calculated according to

$$I = \int_0^L P(z)dz \qquad \text{eq. 1}$$

for the channel of interest, where z is the position along the fiber, L is the length of the fiber, and $P(z)$ is the power of the channel at position z is used. In this equation, the power is expressed in linear units. Then, two approaches can be used to determine the "equivalent launch power":

a) Data estimated for several launch powers are available for the selected baseline and eq. 1 can be used to calculate I for each power level of the baseline. Thus, the relation between the integral I and the launch power is known for the selected baseline. Since the integral of the actual power profile has already been determined, the "equivalent launch power" can be determined by applying interpolation.

b) Alternatively, as the shape $p_b(z)$ of the power evolution is determined by the selected baseline only and is independent of the launch power, we can write:

$$P_b(z) = P_{launch} * p_b(z) \qquad \text{eq. 2}$$

where the index b refers to the selected baseline. Using eq. 1 to calculate I for the selected baseline we get:

$$I_b = P_{launch} * \int_0^L p_b(z)dz \qquad \text{eq. 3}$$

Then, by noticing that P_{launch} is the "equivalent launch power" when I=I_b, we get

$$p_{equiv} = I \Big/ \int_0^L p_b(z)dz \qquad \text{eq. 4}$$

4. In a fourth step, the required OSNR (ROSNR) is calculated for the "equivalent launch power" using the relative nonlinear penalty provided by the corresponding baseline (again determined by means of interpolation) and by adding the measured ROSNR for the case without codirectional Raman amplification. The margin of the transmission system under evaluation is the difference between the calculated OSNR and the ROSNR. The series of steps forming the mapping rule is illustrated in Fig. 2.

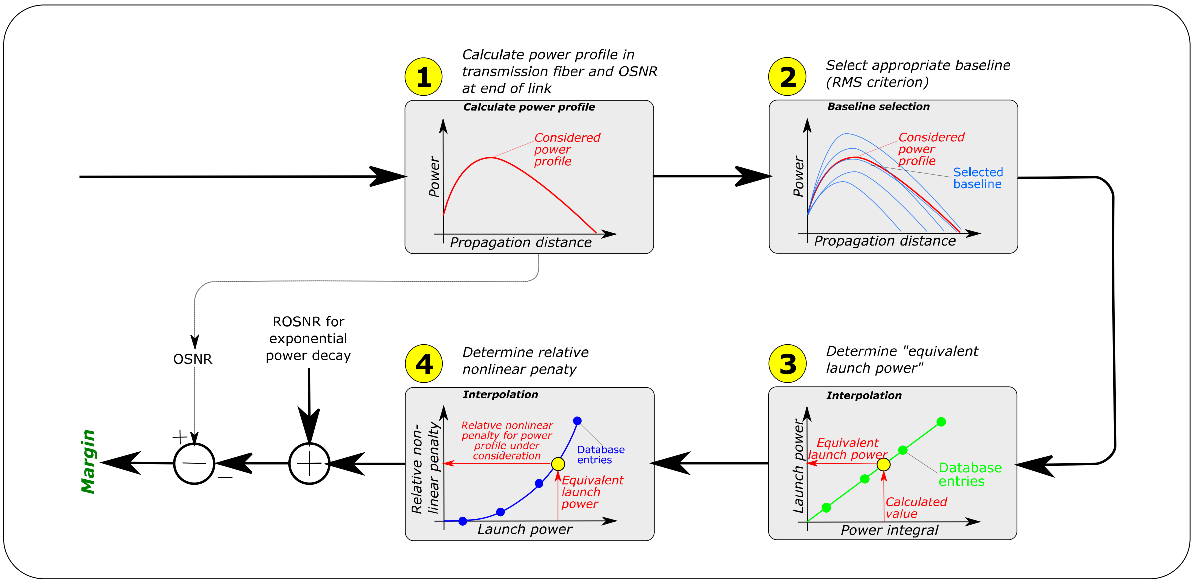

Figure 2. Illustration of steps performed to calculated the relative nonlinear penalty, the required OSNR, and the link margin

Another parameter that has not been considered so far and that may impair the accuracy of the performance estimate is the channel count. When considering intensity modulated channels, only next-neighbor channels influence the channel under consideration and the baseline penalties can be calculated taking into account the nonlinear distortions induced by these channels. In contrast, it has been shown that the performance of phase modulated channels using coherent detection can be significantly affected by channels having a quite large frequency spacing to the considered channel [3, 6]. In order to mitigate the impact of this limitation, several approaches can be followed:

a) The nonlinear penalty and measured ROSNR without codirectional Raman amplification can be obtained for several channel counts. This approach should lead to very accurate results. However, the simulation time required to generate the baselines — the baselines also have to be calculated for various channel counts — and also the size of the database that needs to be generated will increase considerably. Moreover, it is difficult to take into account the different launch power levels used to compensate for stimulated Raman scattering (SRS) among the channels.

b) A worst case scenario can be considered by calculating the nonlinear penalty and by measuring the ROSNR without codirectional Raman amplification with the maximum channel count. However, too conservative transmission system performance estimates may be obtained for reduced channel counts.

c) The nonlinear penalty and the measured ROSNR without codirectional Raman amplification can be obtained only for a single channel count that is not too high (e.g. 16 channels). Evaluating the performance of the transmission system for any number of channels considering only the information obtained when 16 channels are transmitted is not very accurate, but should lead to acceptable results for a large range of transmission systems. If a smaller number of channels is deployed, the performance estimate will be conservative. But the impact of possibly larger channel counts in the future is already being taken

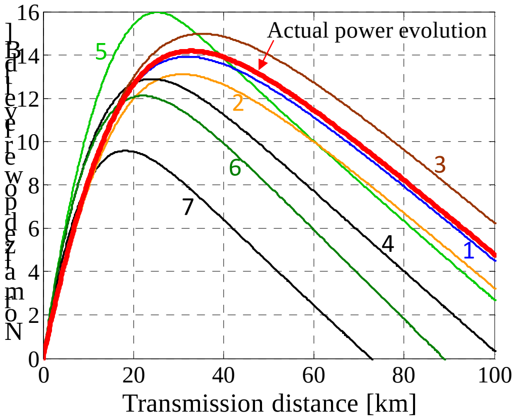

Figure 3. Actual power profile of transmitted channel (red) and of baselines

into account. If a channel count higher than 16 is deployed, the performance estimate will be optimistic. However, the impact of multi-channel transmission is already captured to a large extent when the transmission of 16 channels is considered and, therefore, only small inaccuracy should arise from such an approach.

d) A rule that takes into account the impact of channel count can be used. This is the approach that leads to the best compromise between accuracy and simulation time/database size. The derivation of such a rule can be done by exploring the exponential dependence of the OSNR penalty on the number of channels [6, 7]. Moreover, the dependence of channel count on fiber type can be taken into account by using the strategy presented in [8].

3. RESULTS AND DISCUSSION

The accuracy of the performance estimates obtained using the technique proposed in this paper is discussed in this section.

The red line shown in figure 3 represents the power profile of one of the data channels under analysis when the transmission of 7 channels in a pure silica core fiber (PSCF) characterized by an attenuation

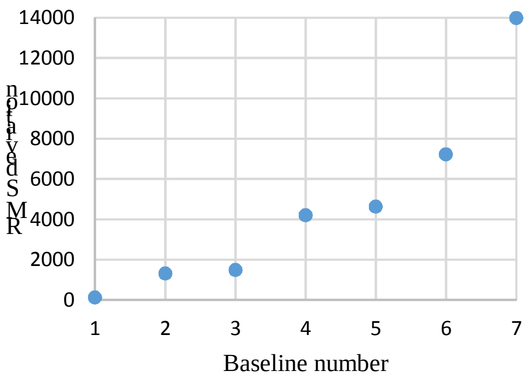

Figure 4. Mean RMS deviation between the power profile of data channels and of each baseline

parameter of 0.177 dB/km at 1550 nm is considered. Only the power profile of one of the data channel is shown because the power evolutions of the 7 channels are similar. The power profiles of baselines that can be used to estimate the nonlinear penalty are also shown in Fig. 3.

Figure 4 shows the mean RMS deviation between the power profile of the transmitted channels and the power profile of the different baselines. The analysis of Fig. 4 shows that baselines 1, 2 and 3 should lead to very accurate performance estimates while estimates based on the remaining baselines may be more inaccurate.

Figure 5 shows the error of the estimation of the transmission system margin when the different baselines are employed to

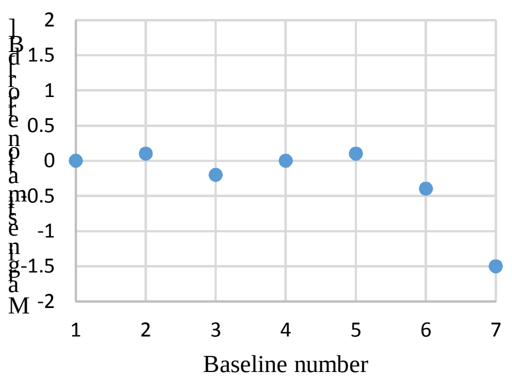

Figure 5. Margin estimation error when using the different baselines

estimate the nonlinear degradation arising from using codirectional Raman amplification. In order to stress the effect of the baseline, it is assumed that the channels are launched at high optical power level into the optical fiber which leads to quite large penalties. Indeed, a total nonlinear penalty of about 3 dB has been estimated for the transmission system under evaluation.

The analysis of Fig. 5 shows that accurate performance estimates have been obtained when using 5 of the 7 different baselines. Only selecting baselines with power profiles very different from the actual one leads to higher inaccuracy. Additional results have shown that this result holds for a quite wide range of transmission system parameters. This observation leads to the conclusion that the proposed method can be applied to a large number of transmission systems using only a small database size. The high accuracy of this approach can be attributed, in part, to only having to estimate the increase of nonlinear penalty originating from the codirectional Raman amplification with respect to the case without codirectional Raman amplification instead of having to estimate the total nonlinear penalty.

4. CONCLUSIONS

A new technique to estimate the impact of nonlinear fiber transmission effects in unrepeatered transmission systems using codirectional Raman amplification has been proposed. The presented strategy consists in preparing a database containing information about the impact of codirectional Raman amplification on nonlinear penalty for a small set of reference scenarios. Afterwards, the information contained in the database will be used to estimate the performance of any unrepeatered transmission system employing codirectional Raman amplification in a very fast and, as has been shown, accurate manner.

5. References

[1] G. Agrawal, "Nonlinear fiber optics", 3rd ed., Academic Press, 2001.

[2] I. Kaminow, T. Li, and A. Willner, "Optical fiber telecommunications A: Components and Subsystems", 5th ed., Elsevier, 2008.

[3] P. Poggiolini, "The GN model of non-linear propagation in uncompensated coherent optical system", IEEE J. of Lightwave Technology, vol. 30, no. 24, pp. 3857-3879, Dec. 2012.

[4] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, "The GN-model of fiber non-linear propagation and its applications," IEEE J. of Lightwave Technology, vol. 32, no. 4, pp. 694-721, Feb. 2014.

[5] A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini and F. Forghieri, "EGN model of non-linear fiber propagation", OSA Optics Express, vol. 22, no. 13, pp. 16335-16362, Jun. 2014.

[6] C. Xia, W. Schairer, A. Striegler, L. Rapp, M. Kuschnerov, J. Pina, and D. van den Borne, "Impact of channel count and PMD on polarization-multiplexed QPSK transmission", IEEE J. of Lightwave Technology, vol. 29, no. 21, pp. 3223-3229, Aug. 2011.

[7] R. Pastorelli, G. Bosco, A. Carena, P. Poggiolini, V. Curri, S. Piciaccia, and F. Forghieri, "Investigation of the dependence on non-linear interference on the number of WDM channels in coherent optical networks", in Proc. ECOC 2012, Amsterdam, Netherlands, paper We.2.C.2.

[8] A. Carena, V. Curri, G. Bosco, R. Cigliutti, E. Torrengo, P. Poggiolini, A. Nespola, D. Zeolla, and F. Forghieri, "Novel figure of merit to compare fibers in coherent detection systems with uncompensated links", OSA Optics Express, vol. 20, no. 1, pp. 339-346, Jan. 2012.