Experimental Study of Nonlinear Interference with Modulated Signals vs. ASE Noise in Single-Span Transmission

H. Bissessur, A. Busson, D. Kravchenko, F. Hedaraly

Alcatel Submarine Neworks, Paris Saclay, 91620 Nozay, France, hans.bissessur@asn.com

Abstract *We assess different bandwidth loading strategies in an unrepeatered system and measure the non-linear noise contribution of ASE-based or modulated interferers vs their spacing to the channel under test. We then compare our results to the AWGN theory. ©2023 The Author(s)*

Introduction

The system performance of Wavelength-Division Multiplexed (WDM) optical transmission systems without inline dispersion compensation is usually assessed with the help of transmission experiments where the channel of interest carries the modulation of interest and the WDM spectrum is emulated with loading channels, made of Amplified Spontaneous Emission (ASE) noise and/or modulated channels.

Previous studies have shown that the Non-Linear Interference (NLI) noise depends on the characteristics of the loading channels, spectrally shaped ASE channels providing a worst-case estimate of the system performance. It is thus shown in [1] that the nonlinear SNR degrades as the modulation order is increased. From [2] and [3], it can be concluded that ASE channels provide a good emulation of modulated channels over multiple spans of high dispersion fibre such as SMF. In contradiction to these, [1] and [4] show significant dependence of the NLI noise on the interferer type in a multi-span link with high dispersion. On the other hand, significant difference for different bandwidth loading strategies is expected over low-dispersion fibre [2],[5].

In this paper, we experimentally assess the influence of the neighbour channels (consisting of either ASE noise or modulated channels) on the non-linear noise in a single-span system. We confirm that even over high dispersion fibre, ASE loading the immediate neighbours is pessimistic vs modulated channels, but also show that the difference reduces when the interferer is affected by chromatic dispersion. We then carefully measure the individual non-linear noise contribution of the neighbour channels in different configurations. We clarify the noise contribution from different modulation types versus the channel separation and find some discrepancy with the predictions by the AWGN model. Using our measured non-linear noise results, we finally simulate several system configurations to estimate how precisely ASE channels can emulate the system performance.

Experimental set-up

The experimental setup is illustrated in Fig.1. The Channel Under Test (CUT) is at a centre of a 9-channel multiplex. It is modulated at 69 GBd with either QPSK or 16-QAM and shaped with a root-raised cosine filter with a roll-off of 0.1; it is surrounded by either 2 modulated channels from independent transmitters or ASE channels, both with 75 GHz channel spacing. The remaining channels are represented by broadband ASE which is channelised by a Wavelength Selective Switch (WSS).

The WDM spectrum is boosted to 30 dBm by an Erbium Doped Fibre Amplifier and followed by an attenuator (VOA1) to carefully adjust the optical power injected into 129 km of Enhanced Pure Silica Core Fibre (EPSCF) span. The spectral tilt at the booster output is kept at zero. The EPSCF fibre has a Chromatic Dispersion (CD) of 21 ps/nm/km and an effective area of 110 µm^2 at 1550 nm. It is followed by a second attenuator (VOA2) which adjusts the total link loss (budget). At the receiver end, the channel under test is selected by a tuneable filter and amplified to operate at the optimum optical power of the real-time coherent receiver.

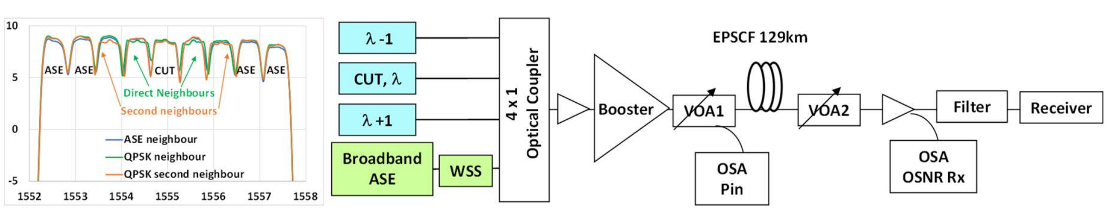

Fig. 1: Experimental set-up for 9 channels; the neighbour channels λ_{-1} and λ_{+1} are modulated or consist of shaped ASE.

Measurements at fixed Budget

We start by assessing a QPSK CUT in a 9-channel system at a constant budget (constant VOA2). As seen in Fig.2, the performance at low power is identical whatever its neighbour since NL noise is negligible; however, the optimum Q^2 and channel power depend on the modulation of the two direct neighbours, the best results being obtained with QPSK neighbours. A similar result is found when the channel is modulated in 16-QAM (see Fig.3). We confirm that shaped ASE is pessimistic compared to modulated channels. Altogether we find that even on a high-dispersion fibre such as EPSCF, the neighbour channels have an influence on the measured performance (up to 0.3 dB between QPSK and shaped ASE neighbours). However, when the neighbour channels are pre-compensated by -2000 ps/nm (triangles in Figs 2 and 3), we find that their behaviour is close to that of ASE channels, as can be expected by the fact that chromatic dispersion turns the modulated channels into gaussian-like noise [6].

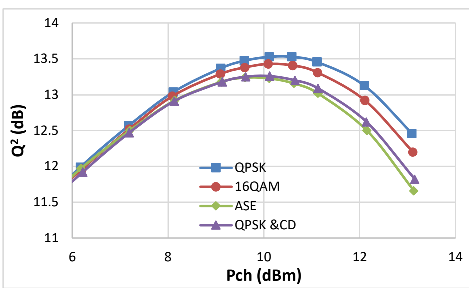

Fig. 2: Variation of Q^2 with different direct neighbour channels as given in the legend when the CUT is modulated with QPSK.

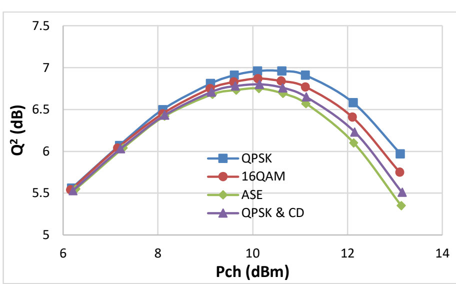

Fig. 3: Variation of Q^2 with different direct neighbour channels when the CUT is modulated with 16-QAM.

On the other hand, less than 0.1 dB variation is measured when the second neighbours (at 150 GHz from the CUT) are changed, as seen in Fig. 4. Therefore, it appears that representative results can be obtained when only the direct neighbours are modulated, and the remaining channels are emulated with ASE.

Non-Linear Noise measurement

In order to understand these results, we now

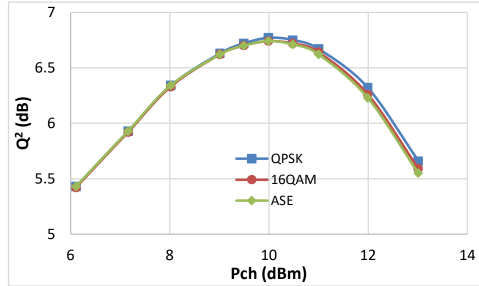

Fig. 4: Variation of Q^2 with different second neighbours (at 150 GHz) when the CUT is modulated with 16-QAM.

proceed to estimate the contribution of the individual channels of the WDM spectrum. We therefore modify the transmitter configuration vs that of Fig.1 and reduce it to 3 channels (CUT and 2 neighbours). We apply a procedure similar to [7], varying the channel power and adjusting VOA2 to reach a fixed BER/Q^2 and deduce the NLI noise contribution by assuming an NLI contribution $\sigma_{NLI}=A_{nl}*P_{ch}^3$ (P_{ch} being the channel power). We then calculate the non-linear WDM contribution by subtracting the single-channel non-linear noise contribution from the noise contribution as measured with the 3 channels:

$$\sigma_{NLI,\ WDM}=\sigma_{NLI,\ 3\ channels}-\sigma_{NLI,\ 1\ channel}$$

We vary the spacing Δf between the CUT and the two interferers from 75 to 300 GHz and compare the results in different configurations in Fig.5. From our measurements, the non-linear noise follows the same trend for all the interferers vs Δf, with a slope around -2 indicating a variation close to $1/\Delta f^2$. The lowest NL noise is found with QPSK, followed by 16-QAM. The same ASE NL noise is obtained whether measured with a QPSK or a 16-QAM CUT. Once -2000 ps/nm dispersion is applied to the interferer (16QAM&CD results in Fig.5), the NL noise approaches that of shaped ASE.

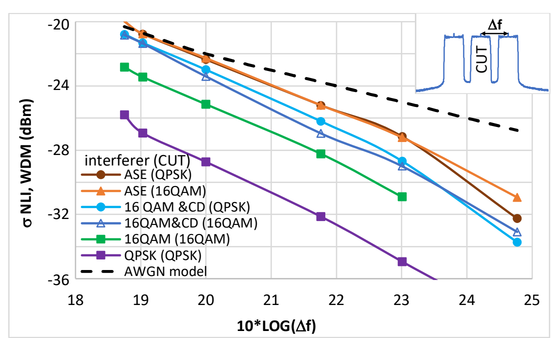

Fig. 5: Non-linear WDM noise contribution of two interferers as a function of the channel spacing. The interferer type is given in the legend (with the CUT in brackets). The insert shows the spectrum for QPSK (QPSK) and Δf=100 GHz

We also plot the NL noise of the interferer as calculated from the Additive White Gaussian Noise (AWGN) theory (using e.g. formula (39) in

[8]) in a dotted line. We could expect agreement of this theory with our results with ASE noise. Indeed, reasonable agreement is found when the interferer spacing is below 100 GHz. However, it is no longer the case for larger spacing; a dependence of the non-linear WDM noise in 1/Δf is expected from the AWGN theory, which does not agree with our results.

These results enable to simulate the situation with all channels modulated, which is not easy to realize experimentally since it would involve many independent transponders.

System simulations

Using our measured values of the NL WDM noise and assuming that the noise contribution of different channels or over different spans adds up incoherently, any non-dispersion-managed QPSK or 16-QAM system can be simulated. We first simulate the centre channel of a 3-span system with 120km SMF spans (30 dB loss) with 16-QAM channels and 16-QAM or ASE neighbours. The difference in system performance is small, since the signal reaches spans 2 and 3 with accumulated CD. With 2 modulated neighbours, the Q^2 is within 0.1 dB of the actual system where all the channels are modulated. With only ASE loading, the Q^2 is within 0.2 dB of the actual system. This holds for 16-QAM (shown in Fig.7) as well as QPSK (not shown).

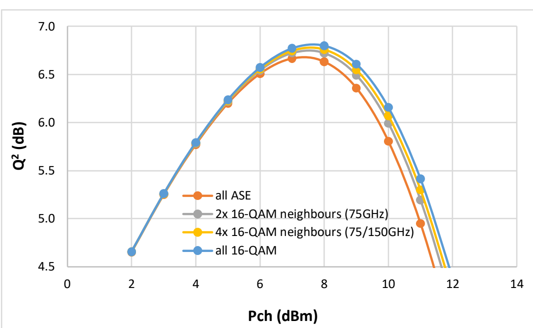

Fig. 7: 3-span simulation for the centre channel of a 9 x 16-QAM system, where the channel is surrounded with ASE and a variable number of 16-QAM neighbours.

We then simulate a single-span 9 x QPSK system with 75 GHz spacing and a variable number of QPSK neighbours, the remaining channels consisting of shaped ASE. As seen in Fig. 7, all-ASE neighbours should not be applied for system assessment, since they underestimate the peak Q^2 by 0.75 dB. However, with 2 QPSK neighbours, the peak Q^2 results are only 0.3 dB lower than with all-QPSK channels. In an unrepeatered system with high dispersion fibre, 2 modulated neighbours should therefore provide reasonable system assessment, while in a multi-span system, all-ASE neighbours should

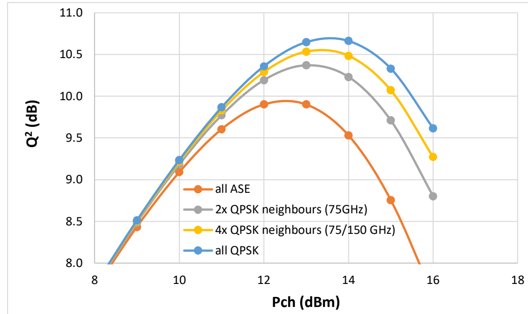

Fig. 6: Single-span simulation for the centre channel of a 9 x QPSK system, where the channel is surrounded with ASE and a variable number of QPSK neighbours.

give a good estimate of the system performance.

In Fig.8, we finally compare simulations of the achievable VOA2 at a fixed BER/Q^2 in a 16-QAM unrepeatered system, with three 16-QAM modulated channels (CUT and 2 direct neighbours) and a variable number of shaped ASE interferers. We can see that the contribution of the neighbours decreases as their distance to the centre channel increases. We find reasonable agreement between our simulations (assuming that the NLI of the different channels adds up incoherently) and the experimental results; simulations applying the AWGN theory to the ASE interferers (and the measured NLIs for the 16-QAM direct neighbour channels) show that the AWGN theory is pessimistic.

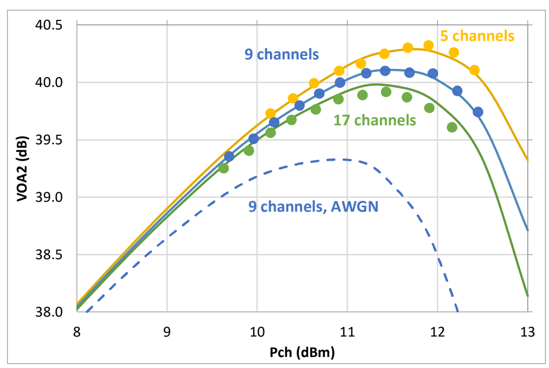

Fig. 8: Single-span 16-QAM system, with two 16-QAM neighbours surrounded by a variable number of ASE interferers. The dots show measurements; the lines show simulation with the previous parameters. The dotted line represents the simulation with AWGN ASE interferers.

Conclusions

We analyse different bandwidth-loading strategies in a single -span system over high dispersion fibre. We measure the NL noise brought by different interferers and find a variation close to $1/\Delta f^2$. We show that shaped ASE is pessimistic vs modulated channels and that at least two modulated neighbours are required when assessing an unrepeatered system.

References

[1] L. Galdino, G. Liga, G. Saavedra, D. Ives, R. Maher, A. Alvarado, S. Savory, R. Killey, and P. Bayvel, "Experimental Demonstration of Modulation-Dependent Nonlinear Interference in Optical Fibre Communication," *European Conference on Optical Communications*, pp 950-951, 2016.

[2] S. Searcy, T. Richter, and S. Tibuleac, " Experimental Study of Bandwidth Loading with Modulated Signals vs. ASE Noise in 400ZR Single-Span Transmission," O*ptical Fiber Communications Conference (OFC)*, W1G.6, 2022, DOI https://doi.org/10.1364/OFC.2022.W1G.6

[3] A. Carbó Meseguer, P. Plantady, A. Calsat, S. Dubost, J.C. Antona, V. Letellier, " Automated Full C-Band Technique for Fast Characterization of Subsea Open Cable G-SNR," *Asia Communications and Photonics Conference (ACP)*, S4B.5, 2019 DOI: 10.1364/ACPC.2019.S4B.5.

[4] D. Elson, et al, "Investigation of bandwidth loading in optical fibre transmission using amplified spontaneous emission noise," *Optics Express*, 25(16), pp. 19529-19537, 2017, DOI https://doi.org/10.1364/OE.25.019529

[5] T. Richter, J. Pan, S. Tibuleac, "Comparison of WDM Bandwidth Loading Using Individual Transponders, Shaped, and Flat ASE Noise", O*ptical Fiber Communications Conference (OFC),* W1B.2, 2018, DOI http://dx.doi.org/10.1364/OFC.2018.W1B.2

[6] P. Poggiolini and Y. Jiang, "Recent advances in the modeling of the impact of nonlinear fiber propagation effects on uncompensated coherent transmission systems", in *Journal Lightwave Technology* 35(3), pp. 458-480, 2017, DOI https://doi.org/10.1109/JLT.2016.2613893

[7] H. Bissessur, "Optical Nonlinear Distortions of Probabilistically Shaped and Uniform Constellations in Unrepeatered systems", *OptoElectronics and Communications Conference (OECC)*, WA3-1, 2022, DOI https://doi.org/10.23919/OECC/PSC53152.2022.9850041

[8] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang and F. Forghieri, "The GN-Model of Fiber Non-Linear Propagation and its Applications", in *Journal Lightwave Technology* 32(4), pp. 694-721, 2014 DOI https://doi.org/10.1109/JLT.2013.2295208