Experimental characterization of Gaussian-distributed nonlinear distortions

F. Vacondio[1], C. Simonneau[1], L. Lorcy[1], J.C.Antona[1], A. Bononi[2] and S. Bigo[1]
[1]*Alcatel-Lucent Bell Labs, Centre de Villarceaux, Route de Villejust, 91620, Nozay, France*
[2]*Università degli Studi di Parma, v.le G. Usberti 181/A, 43100, Parma (Italy)*
francesco.vacondio@alcatel-lucent.com

Abstract: We show that in dispersion-uncompensated 100G systems Kerr nonlinearity is akin to additive Gaussian noise. Its variance grows as a power of propagation distance, and represents 1/3 of total noise variance at optimal channel power.
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1. Nonlinear distortions as Gaussian noise

Recently, it has been suggested that nonlinear distortions induced by propagation over links without optical dispersion management (NDM) on polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) have a Gaussian distribution [1]. Shortly after, simple models for predicting the performance of such systems have been proposed, exploiting the Gaussian nature of the noise [2-4]. In these models, the distortions from propagation are modeled as additive Gaussian noise. The signal to noise ratio at the decision gate can be written as $SNR_{tot} = P/(N_A+N_{NL})$, where N_A is the noise variance due to amplified spontaneous emission (ASE), P is the channel power and N_{NL} is the variance of the noise from fiber nonlinearities. From a first-order perturbation expansion of the χ^3 nonlinear Kerr distortion, we approximate the nonlinear noise power as $N_{NL} = a_{NL}P^3$, where a_{NL} is a suitable constant, which depends on the system parameters and can be obtained analytically or by simple measurements [3,4]. The quality parameter of interest is then

$$SNR_{tot} = \frac{P}{N_A + a_{NL}P^3} \qquad (1)$$

In this paper, we focus on the noise characteristics in PDM-QPSK systems over standard single mode fiber (SSMF) without optical dispersion compensation. We experimentally show that after fiber propagation the noise is indeed Gaussian both in the linear and nonlinear regime. We experimentally demonstrate that, for a channel power P_{NLT} that optimizes the performance of a given link, the nonlinear noise power is half the linear noise power, and we finally report that, over the investigated range, the nonlinear noise variance grows as $N_s^{1.4}$, where N_s is the number of spans.

2. Experimental Setup and back to back characterization

Fig. 1(a) depicts the experimental setup for our transmitter. Eighty lasers are divided in odd and even 100 GHz combs before passing through a wavelength multiplexer (MUX). Each wavelength division multiplexed (WDM) signal is then modulated with an I/Q modulator driven by four 28 Gbaud independent pseudo-random bit sequences (PRBSs) of length 2^{15}-1. Polarization division multiplexing (PDM) is emulated by splitting the signal, delaying one branch and recombining the signal through a polarization beam combiner. The two combs are then multiplexed through an interleaver to achieve one WDM PDM-QPSK comb with a spacing of 50 GHz.

The recirculating loop is depicted in Fig. 2(b). Inside the loop we have 300 km of standard single mode fiber (SSMF) separated by erbium doped fiber amplifiers (EDFAs), a polarization scrambler and a wavelength selective switch (WSS) that we use for equalizing the power profile of the WDM comb. At the loop output, we have the possibility of loading additional noise through a noise source. The output of a local oscillator (LO) is mixed with the channel selected by an optical filter before photodetection. Data are stored on a 50 Gsamples/s scope and processed

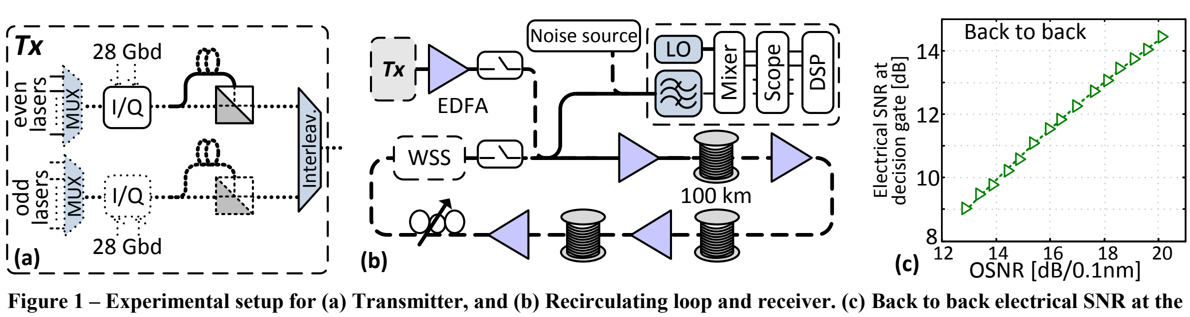

Figure 1 – Experimental setup for (a) Transmitter, and (b) Recirculating loop and receiver. (c) Back to back electrical SNR at the decision gate versus optical signal to noise ratio (OSNR) measured in 0.1 nm.

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off-line. We use the typical digital signal processing (DSP) for PDM-QPSK signals: 1) Normalization and resampling to 2 samples/symbol, 2) Chromatic dispersion compensation 3) Adaptive blind equalization with the constant modulus algorithm [5], 4) Phase and frequency estimation and correction [5], 5) Symbol decision and 6) Electrical signal to noise ratio (SNR) and bit error rate (BER) evaluation. Figure 1(c) shows the measured back to back SNR at the decision gate versus the optical signal to noise ratio (OSNR), which is expressed in the typical 0.1nm bandwidth. The SNR is defined throughout the paper as the average signal power divided by the noise variance over the receiver bandwidth, and it is calculated from the recovered signal constellation before decision gate (after digital signal processing). As it can be seen, in practice the relationship between SNR and OSNR is not linear in dB/dB, due to transmitter/receiver imperfections. Nevertheless, we can use the curves of Fig. 1(c) to numerically link OSNR and electrical SNR.

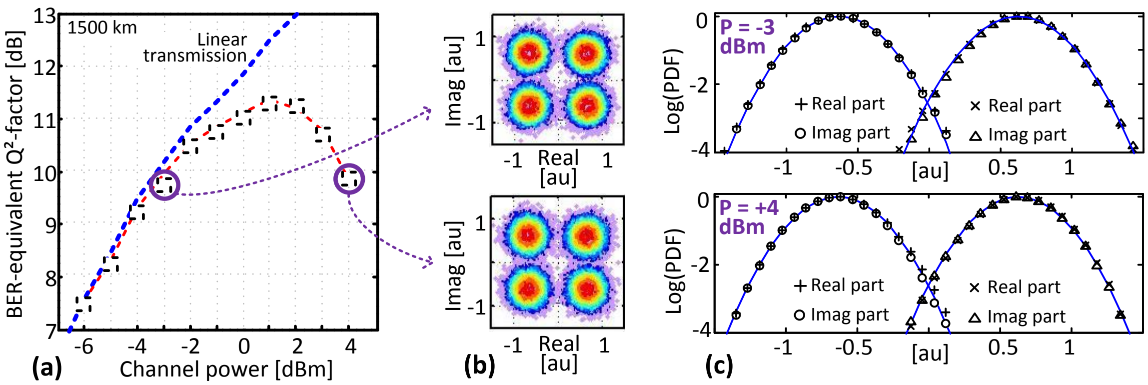

Figure 2 – (a) Measured Q²-factor vs channel power after 15x100km. Dashed line represents the OSNR-limited performance. (b) Signal constellations and, (c) corresponding PDFs (markers) and Gaussian fit (lines) for a signal power of -3 dBm (top) and +4 dBm (bottom).

3. Signal-to-Noise characterization after 15x100 km

First, we investigate the noise statistics after fiber propagation; Fig. 2a represents the Q²-factor versus channel power at each fiber input. It can be seen that the best performance is obtained at the optimum value of $P_{NLT} \approx +1$dBm. We focus next on two channel power levels apart from the optimum, at -3dBm (top row of Fig. 2) and +4dBm (bottom row of Fig. 2), where the system performance is roughly the same: SNR_{tot}~10.9 dB, and BER ~10^{-3}. At -3dBm, we assume that the system operates primarily in the linear regime, mainly limited by amplifiers' ASE, whereas at 4dBm, it is mainly impaired by fiber nonlinearities. At these power levels. Fig. 2(b) shows the measured constellations after 15x100 km of SSMF propagation, and in Fig. 2(c) the corresponding normalized probability density functions (PDF) for the real and imaginary parts of the optical field before the decision gate. Only one polarization is shown, as the other is similar. The continuous lines in Fig. 3(c) are analytical Gaussian distributions with mean and variance calculated from the recovered constellation. A very good agreement between the measured PDFs and the Gaussian distributions is found in both cases, confirming that the signal statistics are well approximated by Gaussian distributions also after propagation and realistic digital signal processing.

Equation (1) lends itself to many useful manipulations. Since the inverse of SNRs are additive, we can write

$$\frac{1}{SNR_{tot}} = \frac{1}{SNR_{lin}} + \frac{1}{SNR_{NL}} \qquad (2),$$

where SNR_{lin} is the signal to noise ratio due to ASE and measured on the same bandwidth as N_A. SNR_{tot} is the total signal to noise ratio, which we can measure from the received constellation. From the measurement of the OSNR after propagation, together with the characterization of Fig. 1(c), we can infer its linear part SNR_{lin}. We can therefore obtain the signal to noise ratio due to nonlinearities SNR_{NL} from (2) and doing so, we have a method for separating the impact of linear noise due to ASE from that of nonlinear noise coming from propagation distortions.

In Fig. 3(a) we report SNR_{tot} and its two components as a function of signal power in the case of 1500 km of SSMF propagation without noise loading (empty markers). Filled markers are the result of a measurement where we load noise at the receiver, to degrade the OSNR by roughly 2 dB. SNR_{tot} has a maximum at P_{NLT}. SNR_{lin} increases as the signal power (and therefore the OSNR) grows. The nonlinear signal to noise ratio SNR_{NL}, on the other hand, decreases as the signal power triggers the nonlinear effects. The decrease rate of SNR_{NL} (in dB) is roughly twice the growth rate of SNR_{lin}, which would suggest that the former depends on the signal power, while the latter on the signal power squared. The solid line shows the results of the model, where eq. (1) has been used along with the back-to-back characterization of Fig. 1(c). The value of a_{NL} has been fixed to have a P_{NLT} of roughly 1 dBm in the case without noise loading, and is used also in the second series of measurements. The model in both cases fits very well the measured values.

Fig. 3(b) shows $1/SNR_{lin}$ and $1/SNR_{NL}$ as fraction of $1/SNR_{tot}$, in the case without noise loading. We demonstrate that around P_{NLT} (~ +1dBm) the nonlinear noise power is half the linear noise power as predicted in [2-4], as $1/SNR_{NL}$ accounts for ~1/3 and $1/SNR_{lin}$ for ~2/3 of it of the total noise-to-signal ratio.

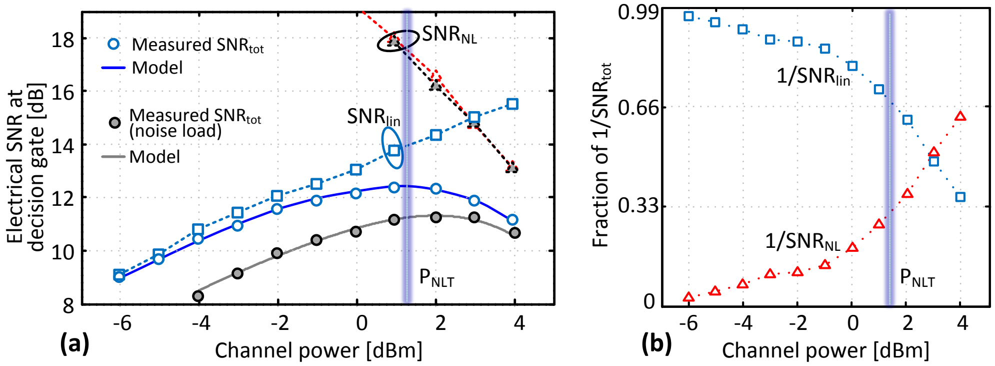

Figure 3 – (a) The total SNR as well as its linear and nonlinear components are shown as function of the power per channel with and without noise loading. (b) The linear and nonlinear components of the NSR are shown as fraction of the total NSR (no noise loading).

4. Evolution of nonlinear noise with distance

In a previous report [6], we observed that nonlinearities accumulate differently in NDM systems with respect to traditional dispersion managed (DM) systems, and we showed that the product $N_s P_{NLT}$ is not a constant in NDM systems. With the same technique used for the results obtained in the last section, we now want to understand how the nonlinear noise accumulates as a function of distance. We measured $1/SNR_{NL}$ (which is proportional to the nonlinear noise variance) for a fixed signal power in the nonlinear regime versus the number of spans. We repeated the experiment for four different channel powers and the results are depicted in Fig. 5. The measured values show a slope of ~1.4 dB/dB for the four tested powers. Therefore, independently of power, the nonlinear noise, and thus the term a_{NL} in (1), depends on $N_s^{1.4}$ rather than simply on N_s. Analytic results supporting our findings will be the object of a companion publication.

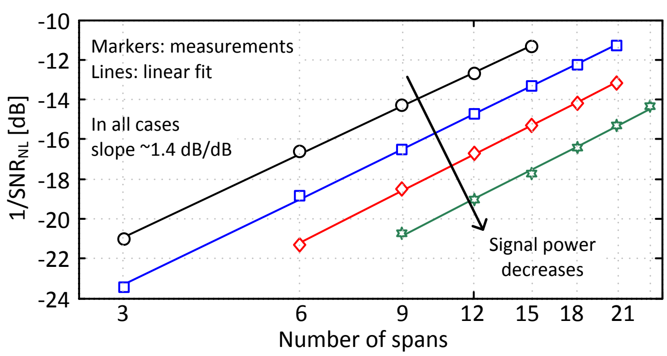

Figure 4 – Nonlinear noise-to-signal ratio as function of the number of spans for different signal powers.

5. Conclusion

We have experimentally investigated the characteristic of nonlinearity-induced distortions in PDM-QPSK systems over SSMF without optical dispersion compensation. We have found that the noise statistics are well approximated by a Gaussian distribution both in the linear and nonlinear regime. The variance of the noise due to nonlinear distortions has been investigated as a function of channel power (it is found to be half the variance of the linear noise for an optimal power), and as a function of the number of propagation distance, where it is found to increase as $N_s^{1.4}$ over the investigated span range.

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