Experimental Disaggregation of Propagation Effects in Optical Links

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Abstract: We introduce a protocol to evaluate experimentally the fiber nonlinear coefficients for intra- and inter-channel effects. We characterized a three-span transmission using highly dispersed QPSK signals, observing good agreement with the eGN model. © 2024 The Author(s)

1. Introduction

Accurate quality of transmission (QoT) estimation has become essential for optical networks to reduce margins during network design. For a decade, the enhanced Gaussian noise (eGN) model [1] has become the reference in the optical network community for nonlinearity modeling. eGN model allows evaluating separately intra-channel nonlinear effects, or self-phase modulation (SPM), and inter-channel nonlinear effects, or cross-phase modulation (XPM). However, the experimental validation of these models is complex as it targets nonlinear noise accumulation, which is, in practice, difficult to evaluate for real systems in transmission operation. In literature, the eGN model has been experimentally validated and also refuted by different research groups, as described in [2]. Usually, for model validations, the aggregation of all the propagation effects is measured in transmission and compared to the model prediction. Thus, the noise targeted can be hidden by other noises. Indeed, it is difficult to evaluate each effect for long haul systems as spectral haul burning (SHB) smooths the power profile, and thus, it is complex to control the stimulation of XPM and SPM.

Thus, this paper aims to present a methodology to isolate the different propagation effects, such as the SPM and XPM noises, as well as an additional source of noise characterized by a signal-to-noise ratio (SNR) term independent of power. We experimentally isolated each effect in a few-span transmission link that could be representative of a long-haul system. Having only three spans allows us to avoid amplifiers SHB, and we could vary the input power in different single- and multi-channel configurations, over wide ranges of power. All modulated channels were pre-dispersed with 10ns/nm to operate in a dispersive regime typical of long-haul propagations. The measured SPM and XPM noise variances are compared with the eGN model predictions, showing good agreement, and the additional source of noise could correspond, according to the calibration done in [5,6], to the Guided Acoustic Wave Brillouin Scattering (GAWBS) penalty and the equalization enhanced phase noise (EEPN).

2. Experimental investigations setup

The experimental setup is presented in Fig. 1. The transmission line consists of three spans of SMF of 100 km each, an attenuation of 0.21 dB/km, 80- µm2 effective area, and a chromatic dispersion of 16.7 ps/nm/km. We used dual-stage erbium-doped fiber amplifiers (EDFAs) with an output power per channel ranging between -5 and 10 dBm. Fifteen dual-polarization (DP) QPSK channels were modulated at 32 GBd with a spacing of 50 GHz using three different offline transponders properly decorrelated to avoid non-desirable correlation effects. QPSK channels were shaped by a root-raised-cosine filter with a 0.01 roll-off factor, and the central channel, the channel of interest (COI), was inserted at 1545.4 nm. At emission, we applied a digital chromatic dispersion pre-distortion of 10 ns/nm to the signal. The pre-distortion was to ensure we had a constellation with Gaussian statistics at reception. The SNR was not computed from the measured bit error rate (BER) (too few errors after the propagation to measure a BER in a reasonable time) but with the error vector magnitude (EVM) method. EVM is the root-mean-square value of the difference between the collection of measured symbols and ideal symbols. However, the EVM method is rigorously valid only for a constellation with Gaussian statistics at reception [3]. At the reception, we estimated the SNR with ten oscilloscope acquisitions after the coherent mixer. We also measured the COI's optical SNR (OSNR), which accounts for the amplified spontaneous emission (ASE) noise. The OSNR was measured with an optical spectrum analyzer and by replacing the COI with a depolarized laser to access the actual ASE noise floor, as presented in [4].

Additionally, the power spectrum was measured at the output of each EDFA. The transceiver penalty was characterized through back-to-back transmissions as described in [4], where the SNR was measured for different levels of ASE noise. The SNR_{TRx} was estimated at 21.3 dB. It permitted isolating SNR_{EXT} using the formula in [4]. SNR_{EXT} is like the GSNR but also includes the noise caused by the transceiver due to propagation specific effects such as EEPN. In the following, we call variance the inverse of the SNR.

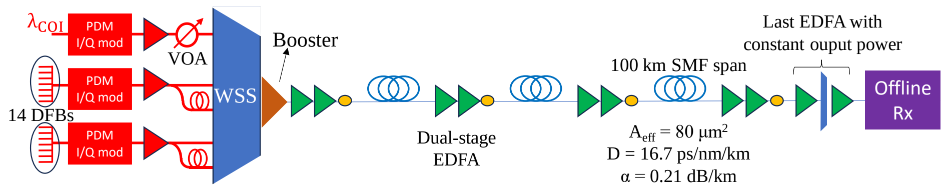

Fig. 1. Experimental setup for the propagation of 15 channels on the 300-km line.

We studied the transmission of different power profile configurations with 15 channels shown in Fig. 2. There are:
1) P_{FLAT}: a flat power profile and each channel power varies from -5 to 10 dBm; its nonlinear threshold is P(NLT)
2) P_{CUT}: the COI varies from -5 to 10 dBm while the 14 adjacent channels remain at P(NLT),
3) P_{ADJ}: the adjacent channels vary from -5 to 10 dBm while the COI remains at P(NLT),
4) P_{1CH}: a pseudo-single channel transmission where the COI varies from -5 to 10 dBm. The adjacent channels are on the edge of the amplifier's bandwidth, 1.5 THz away from the COI to emulate a single channel transmission.

3. Protocol to obtain the nonlinear coefficients

The optical transmission total variance is the sum of three contributions: $var_{TOT} = var_{ASE}+var_{NLI}+var_{res}$ $(=1/SNR_{EXT})$. var_{ASE} accounts for the ASE noise, var_{res} accounts for the residual noise whose variance is independent of power, (like GAWBS and EEPN penalties), and var_{NLI} accounts for the nonlinear noise, which variance scales like the square of the power: $var_{NLI} = \alpha_{SPM} * P_{COI}^2 + \beta_{XPM} * P_{WDM}^2$, with α_{SPM} and β_{XPM} the coefficients for SPM and XPM, respectively, and P_{COI} the power on the COI and P_{WDM} the averaged power on the 14 adjacent channels.
We aim to estimate α_{SPM} and β_{XPM} experimentally, assess their reproductivity by testing different configurations, and compare them to the predictions of the eGN model. Additionally, we estimate var_{res} and compare it to the simulation tool's prediction for EEPN and GAWBS.
The first step is to remove the ASE noise contribution that we obtained through the OSNR measurements to the total noise, and we do so for each configuration: $var_{TOT\text{-}ASE} = var_{TOT} - var_{ASE}$. We obtain for the four configurations:
P_{FLAT}: $var_{TOT\text{-}ASE} = var_{res} + \alpha_{SPM}*P_{COI}{}^2 + \beta_{XPM}*P_{WDM}^2$ P_{ADJ}: $var_{TOT\text{-}ASE} = var_{res} + \alpha_{SPM}*P(NLT)^2 + \beta_{XPM}*P_{WDM}^2$
P_{CUT}: $var_{TOT\text{-}ASE} = var_{res} + \alpha_{SPM}*P_{COI}^2 + \beta_{XPM}*P(NLT)^2$ P_{1CH}: $var_{TOT\text{-}ASE} = var_{res} + \alpha_{SPM}*P_{COI}^2 + XPM_{edge\_channels}$
We obtain α_{SPM} with P_{1CH} and P_{CUT} as these are the transmissions for which P_{COI} varies, and thus, SPM dominates at high power. We use a linear function fit to determine α_{SPM} from P_{CUT} and P_{1CH}. Similarly, we use P_{ADJ} to obtain β_{XPM} as it is a configuration for which P_{WDM} varies and, at high power, the XPM is predominant. Then, using α_{SPM} and β_{XPM}, we remove the estimated SPM plateau, $\alpha_{SPM}*P(NLT)^2$, from P_{ADJ} and the XPM plateau, $\beta_{XPM}*P(NLT)^2$, from P_{CUT}. We also remove the plateau due to the XPM from the amplifier's bandwidth edge channels, $XPM_{edge\_channels}$ (estimated with the eGN model at -42.5 dB), from P_{1CH}. Lastly, we search for the remaining var_{res} that minimizes the overall distance to the experiments $var_{TOT\text{-}ASE}$ of P_{1CH}, P_{CUT}, P_{ADJ}, and P_{FLAT}.

4. Experiments results and comparison with the model

For the transmissions, the COI's power was always within less than 0.1 dB of the target power. On the other hand, the input power profile tilt was optimized such that, on average, on the three spans, the power on each channel was within less than 0.2 dB of the target. We also consider the connector losses at the output of the amplifiers which were equivalent to -0.96 dB at each span. Using the experimental calibrations obtained from [5] we obtained var_{GAWBS} = -33.6 dB and EEPN will be adjusted with the residual noise obtained.
Fig. 3 shows the OSNR measured after propagation for all configurations versus the varying power (P_{COI} for P_{1CH}, P_{CUT}, and P_{FLAT}, and P_{WDM} for P_{ADJ}). We observe that from -5 to 2.2 dBm, as expected, P_{1CH}, P_{CUT}, and P_{FLAT} superpose, and P_{ADJ} stays constant as power of the adjacent channels is moving. For the nonlinear coefficients' estimation, we permanently remove var_{ASE} $(=1/SNR_{ASE})$ from var_{TOT}.
Fig. 4 shows the COI's averaged SNR_{EXT} on all acquisitions versus the power. We observe that the curves for P_{1CH},

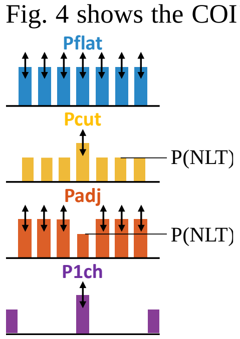

Fig. 2. Power profiles

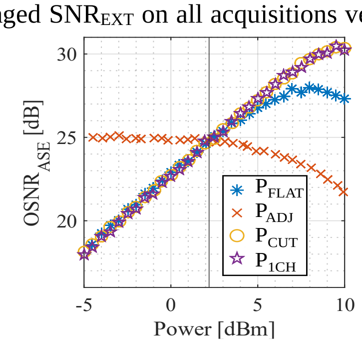

Fig. 3. Measured COI OSNRs

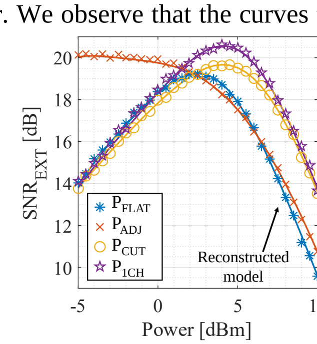

Fig. 4. COI SNR_{EXT} and the reconstructed model

P_{CUT}, and P_{FLAT} superpose for low powers as ASE noise predominates. When reaching the regime where nonlinear effects have a higher impact (around 0dBm), the first configuration degraded is P_{CUT} because of the adjacent high-power channels' strong XPM. Meanwhile, at low power, P_{ADJ} is limited by the ASE noise of the COI, then degrades as the power of the adjacent channels increases and thus exhibits stronger XPM. P_{FLAT}'s NLT is at 2.2 dBm. At this point, P_{CUT}, P_{ADJ}, and P_{FLAT} have the same power profile; thus, the three curves superpose. After this point, P_{FLAT} is slightly above P_{ADJ} as the ASE noise is still predominating. However, they switch for higher power as they have equal XPM, but P_{FLAT} has a higher SPM. After 2.2 dBm, P_{CUT} and P_{1CH} have similar behaviors. Around P_{FLAT}'s NLT, P_{1CH} is above as it does not have XPM, but they converge towards 10 dBm as SPM becomes predominant.
Regarding the nonlinear coefficients; with the fit on P_{1CH} and P_{CUT}, we estimate the same α_{SPM}^{P1CH} value, reported in Table 1. We also report β_{XPM}^{EXP} obtained with P_{ADJ}, and the eGN model predictions. We note that the estimated coefficients are within +/-0.1 dB of the eGN model predictions. var_{res} is then found at -33.4 dB, corresponding to 3.6% of the total noise contribution at P_{FLAT}'s NLT. This residual noise could correspond to the estimated GAWBS and an estimated EEPN of -46.3 dB if an effective laser linewidth in the local oscillator of 7 kHz is considered, which is inline with the prediction in [6] using a similar offline transponder (var_{GAWBS}+var_{EEPN}(7kHz) = var_{res}).

Table 1. Nonlinear coefficients obtained in experiments and with the eGN model and the deviation between them

	Exp	eGN	Deviation (dB)
α_{SPM}	3.9*1e-04	4.0*1e-04	0.1 dB
β_{XPM}	6.5*1e-04	6.4*1e-04	-0.1 dB

Fig. 5 shows $var_{TOT\text{-}ASE}$ versus the power on the COI for P_{CUT}. We additionally plot the estimated XPM contribution with β_{XPM}^{EXP}, the estimated SPM contribution with α_{SPM}^{EXP}, the estimated var_{res}, and the prediction of SPM from the eGN model. Similarly, Fig. 6 shows $var_{TOT\text{-}ASE}$ for P_{ADJ}, the estimated XPM, SPM, var_{res} contributions and the eGN prediction of XPM. On Fig. 4, we show for the four configurations the reconstructed model. The reconstructed model is the sum of the experimental ASE noise measurements, the estimated var_{res}, and the estimated nonlinear effects with β_{XPM} and α_{SPM} estimated with P_{1CH}, P_{CUT}, and P_{ADJ}. We observe on Fig. 4 that the predicted SNR_{EXT} for P_{FLAT} is very accurate while α_{SPM} and β_{XPM} were obtained with only P_{1CH}, P_{CUT}, and P_{ADJ}. Fig. 7 shows the deviation between the experiments SNR_{EXT}, and the ones obtained with the reconstructed model versus the power for the four configurations. For all configurations, the mean error is below 0.1 dB, and the maximum error is within +/- 0.4 dB.

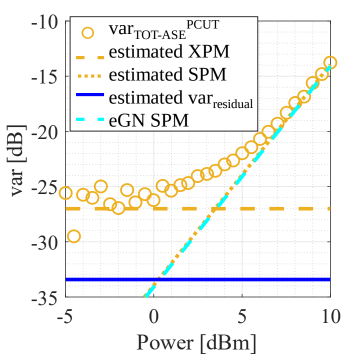

Fig. 5. $Var_{TOT\text{-}ASE}$ of P_{CUT}, the estimated SPM, XPM and var_{res} obtained with the fits and SPM predicted by the eGN model

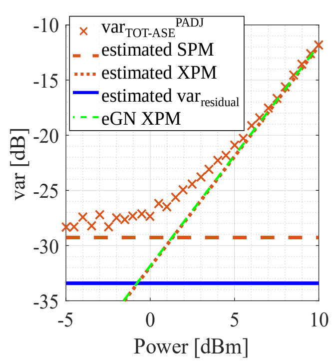

Fig. 6. $Var_{TOT\text{-}ASE}$ of P_{ADJ}, the estimated SPM, XPM and var_{res} obtained with the fits and XPM predicted by the eGN model

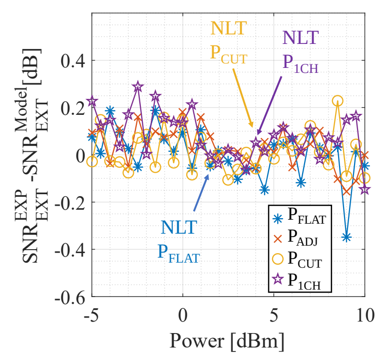

Fig. 7. Deviation between the experimental SNR_{EXT} and the ones obtained with the estimated nonlinear coefficients and residual noise

5. Conclusions

We have experimentally measured the SPM and XPM fiber nonlinear coefficients in a highly dispersed QPSK transmission scenario. We tested the estimated values on different configurations to assess their reproductivity. We also compared them with the ones predicted by the eGN model. Both estimations are within +/-0.1 dB, showing a good agreement. On the other hand, we have isolated a residual noise that could correspond to GAWBS and EEPN.

6. References

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