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Experimental Investigation of Non-Linear Interference Accumulation in Uncompensated Links

G. Bosco, R. Cigliutti, A. Nespoli, A. Carena, V. Curri, F. Forghieri, Y. Yamamoto, T. Sasaki, P. Poggiolini

Abstract—Noise due to non-linear effects in uncompensated links has recently been shown to be Gaussian and additive. We experimentally investigate the law governing its accumulation. Our results suggest a mild super-linear accumulation vs. number of spans, compatible with coherent accumulation models.

Index Terms—non-linear effects, NLI, uncompensated systems, fiber propagation

I. INTRODUCTION

RECENTLY it has been suggested that non-linear propagation effects in uncompensated links may give rise to an overall disturbance that can be approximated as additive Gaussian noise (AGN). In [1], computer simulations were shown in support. Convincing experimental proof was then provided in [2]. According to the AGN assumption, system performance is governed by a modified OSNR which includes both ASE and non-linear noise contributions as follows:

\[
\text{OSNR}_{\text{tot}} = \frac{P_{\text{ch}}}{P_{\text{ASE}} + P_{\text{NLI}}} \quad (1)
\]

where NLI stands for ‘non-linear interference’ and \( P_{\text{ch}} \) is the launched power per channel.

Various analytical approximated propagation models have been proposed, which provide formulas expressing \( P_{\text{NLI}} \) as a function of system parameters. Some of them resort to truncated Volterra series, others to a FWM-like approach applied to the WDM signal spectrum decomposed into small spectral slices, still others to different perturbative approaches. For a comprehensive bibliography see [3]. Notably, the equations predicting \( P_{\text{NLI}} \) bear substantial similarities across models. A key common feature of the models, and one that appears to have gained firm experimental and experimental validation, is that \( P_{\text{NLI}} \) is proportional to the launched power as \( P_{\text{ch}}^3 \). Yet, no consensus has been reached on the key aspect of the growth of \( P_{\text{NLI}} \) vs. the number of spans.

Regarding this aspect, one hypothesis is that the NLI produced in one span is incoherent, and hence independent, of that produced in all other spans. If so, \( P_{\text{NLI}} \) would simply scale linearly as the number of spans \( N_{\text{span}} \).

Another hypothesis assumes some form of coherent interaction of the NLI generated in different spans. Closed-form expressions of coherent accumulation are not available but approximations or numerical solutions based on such models predict that \( P_{\text{NLI}} \) should accumulate super-linearly, that is:

\[
P_{\text{NLI}} \approx P_{\text{NLI}}^{(1)} \cdot N_{\text{span}}^{1+\epsilon} \quad (2)
\]

with \( \epsilon > 0 \). However, the currently available estimations of \( \epsilon \) provide rather different values. In [1] and [4] \( \epsilon \) was predicted to be about 0.25 for standard single-mode fiber (SMF). Numerical integration of the coherent model in [3] resulted in \( \epsilon \approx 0.125 \) for non-zero dispersion shifted fiber (at 50 GHz channel spacing) and lower than 0.1 for SMF. Experimental evidence from [2] found \( \epsilon \) to be 0.37 for SMF. In [5], incoherent accumulation was measured for 28 Gb/d transmission (\( \epsilon = \pm 0.05 \)), independent of channel spacing, whereas strong superlinear accumulation was found at 11.56 Gbaud: \( \epsilon = 0.2 \) to 0.6, depending on channel spacing.

In summary, at present there are quite diverging hypotheses and results regarding the actual law of NLI noise accumulation along uncompensated links. In this paper we provide further experimental evidence, gathered from an ultra-long-haul 16-channel quasi-Nyquist-WDM polarization-multiplexed 16QAM system at 112 Gb/s per channel (14 Gbaud), separately reported on in [6]. We then compare our results with those predicted by various laws. We find that the coherent model described in [3] might be a good candidate to describe NLI accumulation in this experiment. Further evidence is however needed to ascertain whether such model has a more general validity.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The transmitter (Tx) used a source consisting of 16 continuous-wave (CW) distributed feedback (DFB) lasers, spaced 14.7 GHz. The odd and even wavelengths were separately fed to two nested Mach-Zehnder modulators (NMZM). The NMZMs were driven by four electrical signals, each carrying one 14 GBaud 4-level amplitude-shift-keying (ASK) signal, with \( 2^{15} - 1 \) pseudo-random binary sequences (PRBSs). The four signals were generated using a single 23.8 GS/s digital-to-analog converter (DAC), whose output was suitably decorrelated through electrical delays (EDLs=76 and EDLs=120 symbols). Digital pre-filtering was used to obtain a square-root-raised-cosine spectrum, with bandwidth 7 GHz and roll-off 0.05. The NMZMs peak modulation depth was 30% on both I and Q modulator arms. Polarization-multiplexing (PM) was emulated...
outside the recirculating loop and to ASE noise accumulation along the link. The measured values deviate from the expected $N_{\text{span}}^{-1}$ dependence, which would be a straight downward line. This is due to ASE noise produced by the EDFA outside the loop, which resulted in a measured OSNR of 30.3 dB (over 0.1 nm) at zero recirculations. When this additional ASE noise is calibrated out of the linear OSNR, a downward straight line is indeed found, shown as a dashed-dotted line in Fig. 2a. The corresponding noise figure of loop EDFA is 5.7 dB, in good agreement with the one found through a stand-alone characterization of the EDFA at the same operating point.

Following, we accurately measured the Tx-Rx pair BER vs. the noise-loaded back-to-back OSNR (Fig. 2b), with all channels turned on. From this characterization we derived the best-fit BER-vs.-OSNR law of the Tx-Rx pair shown in Fig. 2b, called $\Phi$. Then, in linearity, the system BER along the link would ideally be: $\text{BER} = \Phi(\text{OSNR}_{\text{lin}})$. However, when non-linearity is present, according to Eq. (1) the OSNR accumulated along the link is due not only to $P_{\text{ASE}}$ but also to $P_{\text{NLI}}$ and the BER is therefore given by:

$$\text{BER} = \Phi(\text{OSNR}_{\text{tot}})$$

(3)

Defining: $\text{OSNR}_{\text{NLI}} = P_{\text{ch}}/P_{\text{NLI}}$, from Eq. (1) we can write:

$$\text{OSNR}_{\text{tot}}^{-1} = \text{OSNR}_{\text{lin}}^{-1} + \text{OSNR}_{\text{NLI}}^{-1}$$

(4)

Then, inserting Eq. (4) into Eq. (3), taking $\Phi^{-1}$ of both sides and performing straightforward manipulations, we can finally write:

$$P_{\text{NLI}} = \left[\frac{1}{\Phi^{-1}(\text{BER})} - \frac{1}{\text{OSNR}_{\text{lin}}}\right] \cdot P_{\text{ch}}$$

(5)

Therefore, if BER is measured experimentally, and using $\text{OSNR}_{\text{lin}}$ from Fig. 2a, then an estimate of $P_{\text{NLI}}$ can be found through Eq. (5).

We measured the system BER on channel #8 (one of the two center ones) vs. $N_{\text{span}}$, at the optimum launch power of $-6$ dBm per channel. The results are shown as markers in Fig. 2c, together with the best-fit curve (dashed line). We then extrapolated the $P_{\text{NLI}}$ values through Eq. (5), using the best-fit curves in the three plots of Fig. 2. The resulting plot of $P_{\text{NLI}}$ vs. $N_{\text{span}}$ is shown in Fig. 3 as markers.

We then compared the results with those predicted by the models reported in [3]. Note that, according to the nonlinear model, the scaling factor $\epsilon$ is independent of the launch power. The curve labeled ‘coherent’ was found using the coherent accumulation model of Eq. (18) in [3]. All other curves were plotted according to Eq. (2), as follows: first, $P_{\text{ch}}^{(1)}$ was calculated using Eq. (15) in [3], yielding 16.06 [nW]. Then, the bottom curve was drawn assuming $\epsilon=0$ (incoherent accumulation), while the top three curves were drawn assuming $\epsilon = 0.2, 0.3$ and 0.4. In addition, we found that the coherent accumulation curve too can almost perfectly be expressed through Eq. (2), with the same $P_{\text{ch}}^{(1)}=16.06$ [nW] and $\epsilon=1.116$.

Note that Eqs. (15) and (18) in [3] require parameters that are found experimentally but are completely independent of the BER and OSNR measurements used to estimate the $P_{\text{NLI}}$ markers in Fig. 3. Specifically, they are: fiber dispersion, non-linearity and loss coefficients, span length, channel spacing and number of channels.
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dependent on specific set-ups. Many models, including [3],
note that NLI accumulation does depend on various system
parameters (e.g. symbol rate, number of channels, frequency
spacing fiber type) although in a non-straightforward way.

In summary we believe that our results contribute to the
experimental evidence regarding NLI noise accumulation in
the sense of suggesting that mild super-linear accumulation,
similar to the coherent accumulation model proposed in [3],
could take place in actual systems. However, the problem of
NLI accumulation is complex and further investigation, both
theoretical and experimental, is needed to settle it.

The experimental markers and the coherent accumulation
curve in Fig. 3 appear very close. This is remarkable, as they
are derived in a completely different way, based on parameters
found through independent measurements. This correspond-
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possible analytical candidate to describe NLI accumulation.

On the other hand, we must point out that the measurement
of $P_{\text{NLI}}$ accumulation is rather delicate and sensitive to errors.
Assuming a possible independent error of $\pm 0.5 \, \text{dB}$ on all
three of the key measured quantities OSNR, OSNR_{90%} and
$P_{\text{th}}$, the wide 90% confidence intervals shown in Fig. 3 are
found. We strived to carry out accurate measurements, but
errors of this extent are possible. According to the error bars,
although at the extremes, both incoherent accumulation on the
low end or super-linear accumulation with $\varepsilon=0.2$ would still
be compatible, though less likely, with our results.

Instead, we believe that our results are incompatible with
strong non-linear accumulation; bringing the markers close to
the top two curves of Fig. 3 would require assuming unrealis-
tically large systematic measurement errors of several dB’s
on the listed quantities. Therefore, at least in the context of
our set-up, we believe we can rule out these larger exponents.

This does not mean that, in general, large exponents such
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IV. COMMENTS AND CONCLUSION

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