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Low-Complexity Non-Linear Phase Noise Mitigation using a Modified Soft-Decoding Strategy

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Abstract: We propose a modified soft-decoding strategy that takes into account residual non-linear phase noise. We show the effectiveness of this method in a multi-span experiment with propagation over legacy fibers using uniform and probabilistic-shaped constellations.

OCIS codes: (060.4510) Optical communications; (060.4080) Modulation.

1. Introduction

The race towards high data-rates has led to several experimental demonstrations employing high-cardinality constellations, often combined with Constellation Shaping (CS) [1]. The use of CS and large constellations tries to mimic a Gaussian distribution of constellation points, which is capacity-achieving on an additive white Gaussian noise (AWGN) channel.

The long-haul coherent optical communications channel is approximately AWGN [2] and the use of CS as a means to improve performance was demonstrated to be effective in several experiments [3]. However, the optical channel is not strictly a Gaussian channel. In fact, it has been shown that the non-linear interference (NLI) can be decomposed, as a first approximation, into two contributions: a locally-white Gaussian-like disturbance and a correlated phase noise, called non-linear phase noise (NLPN) [4]. While long-correlated NLPN is removed by standard Carrier Phase Estimation (CPE) algorithms at the receiver, short-correlated NLPN cannot be compensated by the CPE and directly affects receiver performance. In addition, according to theory, large constellations and CS enhance the generation of NLPN [5]. This effect can be particularly detrimental in specific scenarios, such as systems using low symbol rates [6] or propagating over low-dispersion fiber [7]. Therefore, these systems need to be specifically designed to avoid or compensate for this additional NLPN. In this work, the receiver soft decoding metrics have been modified to take into account the presence of short-correlated NLPN, calling it NLPN-aware decoding. We experimentally show that this method, without significantly changing receiver complexity, can give a significant propagation advantage over legacy low-dispersion fibers (such as NZDSF), which are known to introduce strong NLPN [7]. These legacy fibers are still widely installed and deployed in several countries, such as Italy, Brasil, Japan and several others.

2. Channel model

The end-to-end channel, after adaptive equalization and phase recovery, can be modeled as

$$y_k = a_k e^{j\phi_k} + n_k \tag{1}$$

where y_k is the received signal sample in the k-th time interval, a_k is the transmitted symbol, n_k is an AWGN sample, combination of ASE noise and NLI, and ϕ_k is a short-correlated NLPN that has not been compensated for by the CPE, called *residual* NLPN. Modern multi-level receivers employ soft-decoding with Bit-Interleaved Coded Modulation (BICM) [8], which decouples symbol demapping and FEC decoding. These receivers first calculate bit-wise Log-Likelihood Ratios (LLRs), based on the knowledge of the received symbol y and channel statistics $p(y|a)$ using:

$$l_i = \log \frac{P(b_i = 1|y)}{P(b_i = 0|y)} = \log \frac{\sum_{a_1 \in \chi_i^1} p(y|a_1)P(a_1)}{\sum_{a_0 \in \chi_i^0} p(y|a_0)P(a_0)} \tag{2}$$

In this equation, $i = 1, \dots, m$ is the bit index, and χ_i^b is the set of constellation points whose i-th bit is equal to b. $P(a)$ is the a-priori probability to transmit symbol a. These LLRs are then fed to the bit-wise soft FEC decoder.

Most receivers assume that the channel is AWGN ($\phi_k = 0$ in (1)), so that $p(y|a)$ assumes the simple analytical form $p(y|a) = \exp\left(-|y-a|^2/\sigma_n^2\right)/(\pi\sigma_n)$, avoiding the need of large histogram-based look-up tables to evaluate the LLRs. However, in the presence of strong residual NLPN, channel statistics can be significantly different from a Gaussian distribution, thus impairing the receiver performance. Such performance loss can be partially mitigated by considering a more accurate distribution for the received noisy samples, as shown in the following.

We assume that the memory of the residual NLPN is short and therefore we consider it as an approximately memoryless phenomenon. As a result, ϕ_k is statistically independent from ϕ_i if $k \neq i$. Under this assumption, a commonly adopted probability density function (PDF) for for phase noise is the Tikhonov (or Von Mises) distribution [9]:

$$p(\phi) = \frac{e^{\kappa_\phi \cos\phi}}{2\pi I_0(\kappa_\phi)} \qquad \phi \in (-\pi, \pi] \tag{3}$$

where the parameter κ_ϕ is called concentration, and $I_0(.)$ is the modified Bessel function of the first kind. Considering also the effect of phase noise, the channel statistics can be expressed as [10]:

$$p(y|a) \approx \sqrt{\frac{\kappa_\phi}{8\pi^3}} \frac{e^{-\kappa_\phi}}{\sigma_n^2} \exp\left(-\frac{|y|^2 + |a|^2}{2\sigma_n^2} + \left|\frac{ya^*}{\sigma_n^2} + \kappa_\phi\right|\right) \tag{4}$$

where the modified Bessel function of the first kind has been approximated as $I_0(x) \approx e^x/\sqrt{2\pi x}$. This expression can be substituted into (2) to obtain a scalar and fully-analytical expression of the LLRs. This allows NLPN-aware decoding without substantially increasing the complexity of the DSP.

3. Experimental setup and results

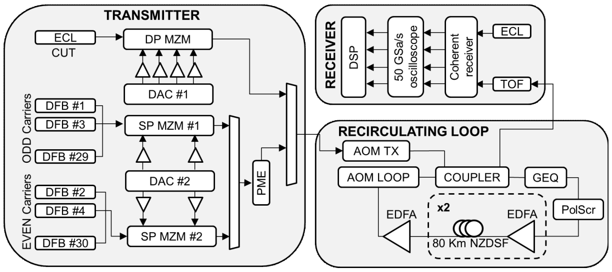

Fig. 1. Experimental setup.

The experimental setup is shown in Fig. 1. Two four-channel DACs were used to generate the channel-under-test (CUT) and 31 interfering WDM channels at 16 GBaud around 1558 nm. As modulation format, four different Polarization-Multiplexed (PM) constellations were tested: 16QAM, 32QAM and two different Probabilistic-Shaped (PS) 64QAM, with entropy equal to $13/3 \approx 4.33$ bit/symbol (PS64QAM-1) and $31/6 \approx 5.17$ bit/symbol (PS64QAM-2). Using these parameters, the same net data rate was achieved by uniform and PS constellations, assuming 20% FEC and 2% pilot overhead [7]. An integrated coherent receiver, connected to a four-channel 50 Gs/s real-time oscilloscope, was used to detect the CUT. The receiver DSP, performed offline, included a 24-tap LMS adaptive equalizer, followed by a pilot-aided Blind Phase Search (BPS) phase recovery. The LLRs were calculated by the decoder using (2) and the Generalized Mutual Information (GMI) was evaluated from the LLRs using Monte-Carlo integration [8].

The performance of the four constellations in optical back-to-back is shown in Fig. 2, in terms of GMI as a function of the OSNR (normalized to the symbol rate). Solid lines are obtained using a standard (AWGN) decoder, whilst markers have been calculated with the NLPN-aware decoding (PN). The only phase noise sources in back-to-back are the transmit and local oscillator lasers, which are almost totally compensated for by the CPE. As a consequence, the proposed algorithm gives no improvement. Assuming a NGMI threshold of 0.9 [11], shown as a dashed-dotted line in Fig. 2, back-to-back penalties with respect to theoretical performance are approximately 0.9 dB for 16QAM and PS64QAM-1 and 1.4 dB for 32QAM and PS64QAM-2.

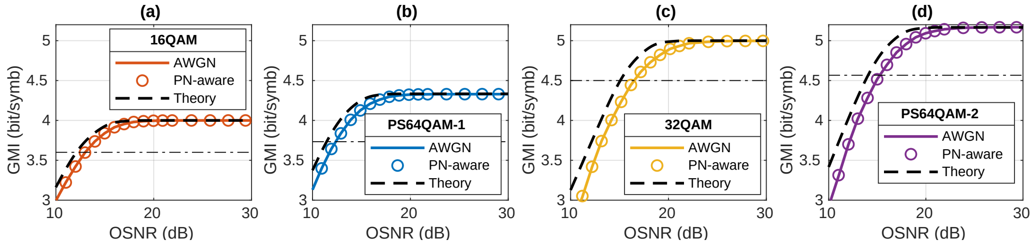

Fig. 2. Optical back-to-back results for the four considered constellations, along with the GMI thresholds corresponding to a normalized GMI of 0.9.

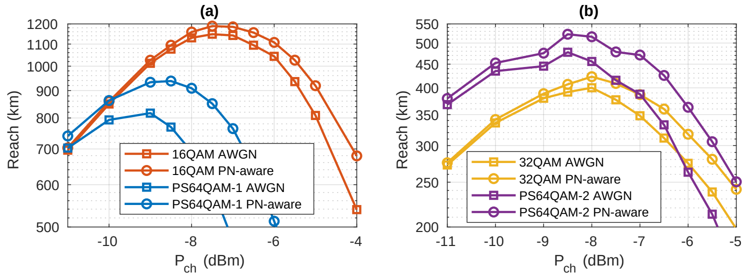

Fig. 3. System maximum reach over NZDSF for the center channel. 31 channels at 16 GBaud, with span length 80 km. The target normalized GMI is 0.9 for all formats.

The WDM spectrum was then transmitted over a recirculating loop, depicted in Fig. 1, made of two 80-km spans of NZDSF ($D = 2.65$ ps/(nm km)) with EDFA amplification. Performance results are shown in Fig. 3 as maximum reach (at an NGMI threshold of 0.9) for different per-channel launch power values. Notice from Fig. 3a that the PS constellation has a worse max reach than 16QAM [7]. This is because NLPN is so strong that the theoretical gain of PS is overcome, even using PN-aware decision. Nevertheless, NLPN-aware decoding is able to substantially increase its reach by 14.1%, while the reach increase with 16QAM is only 4%. In (b), the difference between 32QAM and PS64QAM-2 is smaller, and the reach increase due to NLPN-aware decoding is equal to 5.6% and 9.9%, respectively.

4. Conclusions

In this work, we have proposed a modified soft-decoding strategy that takes into account residual non-linear phase noise, experimentally demonstrating maximum reach gains up to 14.1% with PS constellations over NZDSF.

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References

1. S. Olsson et al., “Record-High 17.3-bit/s/Hz Spectral Efficiency…”, *proc. OFC 2018*, Th4C.5.
2. P. Poggiolini et al., “The GN-model of Fiber Non-linear…”, *J. Lightw. Technol.* 32.4, 694-721 (2014).
3. F. Buchali et al., “Rate Adaptation and Reach Increase…”, *J. Lightw. Technol.* 34.7, 1599-1609 (2016).
4. R. Dar et al., “Properties of Non-Linear Noise…”, *Opt. Express* 21.22, 25685-25699 (2013).
5. A. Carena et al., “EGN model of Non-linear Fiber Propagation” ,*Opt. Express* 22.13, 16335-16362 (2014).
6. D. Pilori et al, “Residual Non-linear Phase Noise…”, *proc. OFC 2018*, M3C.6.
7. D. Pilori et al., “Comparison of Probabilistically Shaped…”, *J. Lightw. Technol.* 36.2, 501-509 (2018).
8. A. Alvarado et al., “Achievable Information Rates for Fiber…”, *J. Lightw. Technol.* 36.2, 424-439 (2018).
9. G. Foschini et al., “On the Selection of a Two-dimensional…”, *Bell Sys. Tech. J.* 52.6, 927-965 (1973).
10. F. Kayhan and G. Montorsi, “Constellation Design…”, *IEEE Trans. Wireless Commun.* 13.5, 2874-2883 (2014).
11. J. Cho et al., “Normalized Generalized Mutual Information…”, *proc. ECOC 2017*, M.2.D.2.