Experimental Study of Nonlinear Phase Noise and its Impact on WDM Systems with DP-256QAM

Metodi P. Yankov[1], Francesco Da Ros[1], Edson P. da Silva[1], Tobias Fehenberger[2], Luca Barletta[3], Darko Zibar[1], Leif K. Oxenløwe[1], Michael Galili[1], Søren Forchhammer[1]

[1] Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads 343, 2800 Kgs. Lyngby, Denmark meya@fotonik.dtu.dk
[2] Institute for Communications Engineering, Technische Universität München, 80333 Munich, Germany
[3] Department of Electronics Information and Bioengineering, Politecnico di Milano, 20133 Milan, Italy

Abstract *A probabilistic method for mitigating the phase noise component of the non-linear interference in WDM systems with Raman amplification is experimentally demonstrated. The achieved gains increase with distance and are comparable to the gains of single-channel digital back-propagation.*

Introduction

As both short and long range wavelength division multiplexing (WDM) optical fiber channels are pushed to operate at high spectral efficiency (SE), larger modulation formats, such as 64- and 256-quadrature amplitude modulation (QAM), are a hot topic for coherent fiber systems. The nonlinear interference noise (NLIN) is currently a major limitation to the maximum reach and SE of such systems[1], as it limits the effective signal-to-noise ratio (SNR) at the receiver for high launch powers. The properties of the NLIN have been studied for WDM systems and it was shown that it exhibits strong temporal and spectral correlations, highly dependent on the modulation format[2]. Particularly, the phase noise (PN) component of the NLIN has been of interest, as standard PN tracking algorithms can be used to cancel some of the NLIN effects[3–5]. As also shown recently[6], the NLIN can be modeled as a time-varying, data-dependent inter-symbol interference (ISI), which is separated in two parts - polarization and phase rotation noise (PPRN) and circularly symmetric Gaussian noise. Tracking the PPRN provides significant gains when increasing the modulation format size[4,6]. However, at longer distances, the PPRN no longer represents a significant part on the NLIN, and the gains from tracking it diminish if only the correlation properties of the PPRN are exploited[5,6], and the higher-order ISI terms are neglected.

In this work, it is experimentally demonstrated that exploiting not only the correlations, but also the *distribution* of the PN component is beneficial, which suggests that the PN component of higher order ISI terms can also be successfully tracked and mitigated.

Experimental setup

The experimental setup is shown in Fig. 1. At the transmitter, 256QAM data symbols X are interleaved with QPSK pilots at pilot rate 10%. The QAM sequence is K symbols long in time, and is denoted by x_1^K. A square root raised cosine pulse shaping is then applied with roll-off factor of 0.5. Five channels on a 25 GHz grid are modulated at 10 GBaud by this signal with two IQ modulators driven by a 64 GSa/s arbitrary waveform generator (AWG).

The central channel, which is the channel under test uses a sub-kHz linewidth fiber laser (Koheras BasiK C-15) while the four co-propagating channels use standard external cavity lasers (ECL, 100 kHz linewidth). The 5 channels are decorrelated by a wavelength selective switch (WSS) and a delay-and-add polarization emulator provides the dual-polarization signal.

The recirculating loop consists of 100 km of standard, single mode fiber (SSMF) using distributed Raman amplification (DRA) with backward pumping every 50 km. In order to compensate for the power losses of the acusto-opto modulators (AOM), used as switches, an EDFA is inserted in the loop.

The signal is detected by an 80 GSa/s coherent receiver with a sub-kHz linewidth fiber laser (Koheras BasiK E-15) as local oscillator (LO). Offline processing is performed consisting of (in order) low-pass filtering, down sampling, chromatic dispersion (CD) compensation, frequency offset estimation based on the pilots, time-domain equalization and carrier phase recovery. The constant modulus algorithm (CMA) equalizer with 101 taps is used on the QPSK pilots. The equalizer taps are then linearly interpolated and applied on the
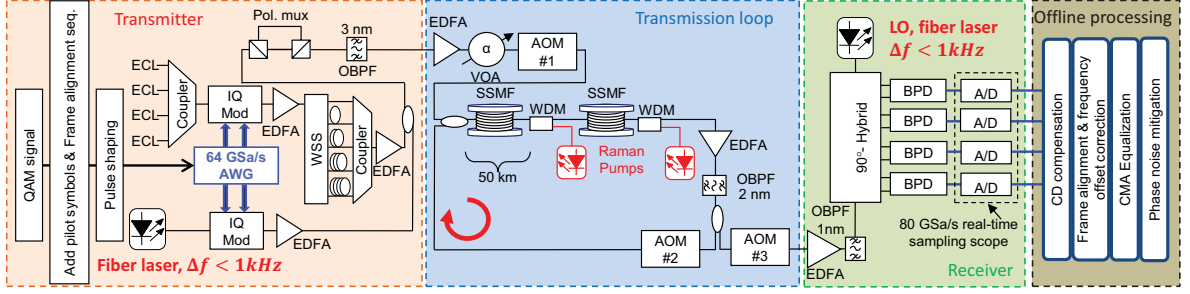
Fig. 1: Experimental setup. The waveform of one polarization is generated offline, then fed to the AWG. WDM signal is then generated, and sent to the recirculating loop. After 80 GSa/s coherent reception, the received samples are processed offline.

entire received sequence. The sequence after equalization *in each polarization* is denoted y_1^K.

The performance metric used in this paper is the bit-wise mutual information (MI), also known as generalized MI (GMI)[7]. The GMI is preferred to other metrics such as the pre-FEC BER or the Q-factor, as it was shown to provide a more accurate prediction for the performance of soft-decision FEC codes[7]. The GMI is measured in bits / symbol / polarization, and the two polarizations after equalization are processed separately.

Phase noise mitigation

Three receivers are studied in this work. The first is an AWGN receiver, assuming a circularly symmetric Gaussian noise with mean μ and variance σ^2, estimated for each constellation symbol separately. This receiver assumes no phase noise in the system. As previously demonstrated, carrier phase estimation and recovery in the presence of local-oscillator phase noise prevents the experimental study of NLPN[8]. However, the fiber lasers employed at the transmitter and receiver result in virtually non-existent laser phase noise, allowing this receiver to be directly used without carrier phase noise mitigation.

The second receiver uses a genie phase noise removal (GPNR) technique. It assumes knowledge of the transmitted symbols and employs a rectangular sliding window of a certain length L to estimate the phase noise sample at time k as $\hat{\theta}_k = \angle \sum_{l=k-L/2}^{k+L/2} y_l x_l^*$. Even though this data-aided approach is not practical, it serves the purpose of characterizing the PN, and furthermore provides an upper-bound to the performance of standard, blind phase search PN tracking algorithms, such as the one used in[5]. Several values of L were investigated between 50 and 200, and an optimized value of 100 is found. We note that the performance difference of different window sizes was negligible (less than 0.02 bits/symbol). After canceling the phase noise, the back-rotated sequence $\hat{y}_k = y_k \cdot e^{-i\hat{\theta}_k}$ is used for es-
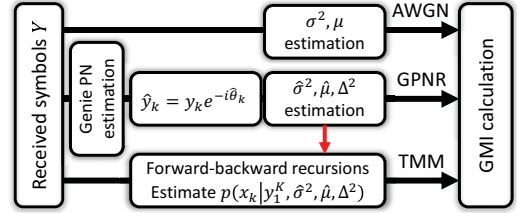

Fig. 2: Overview of the receivers studied in this work.

timation of new Gaussian parameters $\hat{\mu}$ and $\hat{\sigma}^2$, and then the AWGN receiver is used for GMI calculation.

The last receiver is the Tikhonov mixture model (TMM) based algorithm[3], which assumes that the phase noise process $\{\theta\}$ is generated by a first-order Wiener model, $\theta_k = \theta_{k-1} + \Delta \cdot v_k$. The process noise variance is given by $\Delta^2 = \mathrm{E}_k\left[(\hat{\theta}_k - \hat{\theta}_{k-1})^2\right]$, and the samples v_k come from a standard Gaussian distribution. The Wiener process was previously shown to be a good model for NLPN[3]. Instead of simply canceling the estimated PN value $\hat{\theta}_k$, this receiver models the posteriors of the PN at each time $p(\theta_k|y_1^K)$ as mixtures of Tikhonov distributions and calculates them via forward and backward recursions and the *belief propagation algorithm*. This in turn allows for computing the posterior probabilities of the input symbols $p(x_k|y_1^K, \Delta^2, \hat{\sigma}^2, \hat{\mu})$, which are then used for GMI calculation. We note that the TMM takes significant advantage of the QPSK pilots which were already used for equalization.

An overview of the different receivers is given in Fig. 2. In our experiment, $K = 72000$ symbols in each polarization, which is long enough to capture the stationary distribution of the received signal. We can therefore safely assume that using the same symbols for estimating the parameters ($\sigma^2, \mu, \hat{\sigma}^2, \hat{\mu}$, and Δ^2) and testing (estimating the GMI) provides a valid comparison between the receivers. We note that the GMI of the AWGN and TMM receivers represents an achievable rate, in contrast to the GPNR, which assumes knowledge of all symbols for phase estimation.
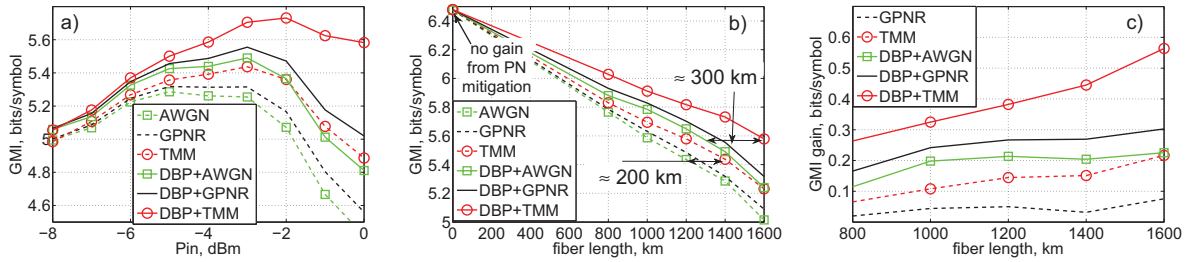
Fig. 3: Experimental results for 5x10-GBaud, DP-256QAM WDM setup. a) GMI at 1400 km; b) GMI at optimal launch power; c) GMI gain w.r.t. basic AWGN receiver. Sophisticated PN tracking achieves near-single-channel-DBP gains (200 km), which increase with distance at least up to the studied distances of 1600 km.

Results

The GMI results are given in Fig. 3. We studied 256QAM input in optical back-to-back and distances between 800 km and 1600 km. The solid lines are obtained with additional single-channel digital back-propagation (DBP). As we see in Fig. 3(a), in the linear region of transmission, PN tracking is not beneficial, which allows us to argue that all the PN in the system is nonlinear. This can also be seen from the back-to-back results in Fig. 3(b), where the GMI is given at the optimal launch power for each distance (highest OSNR in back-to-back). At 1400 km, see Fig. 3(a), the genie PN estimation and direct cancellation provides very little gain, which was also suggested previously [4–6]. However, exploiting the distribution of the PN allows for increased optimal launch power and gains around 0.15 bits/symbol, which translates to around 200 km at this distance. This is comparable to the gain achieved with single-channel DBP and standard AWGN receiver. The gains are even higher with PN mitigation and DBP combined - more than 0.2 bits/ symbol, which translates to around 300 km at 1300 km base distance. In Fig. 3(c), a summary of the achieved gains from PN tracking with and without DBP is given w.r.t. a standard, AWGN receiver. We see that the gains with genie PN estimation are below 0.1 bits/symbol and relatively stable with distance. However, the more sophisticated, probabilistic TMM provides gains that increase with distance, both with and without DBP.

The results suggest that exploiting higher-order statistics of the NLPN is highly beneficial w.r.t. simply exploiting the correlations in the PN. In this work, a first-order Wiener process was assumed for the PN component of the NLIN. More complex models may provide even higher gains.

Conclusions

In this paper, the nonlinear phase noise (NLPN) was studied experimentally in a Raman ampli-fied WDM system. Extremely narrow linewidth lasers allowed for capturing the NLPN, and it was demonstrated that significant gains can be achieved by tracking it. In contrast to previous results, where only the correlation properties of the PN were exploited, we employed a probabilistic model for PN tracking, which allowed for gains, increasing with distance. The result is particularly important for metro range WDM systems with high-order QAM, as the 256QAM considered in this work.

Acknowledgements

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