Compensation of XPM Interference by Blind Tracking of the Nonlinear Phase in WDM Systems with QAM Input

Tobias Fehenberger[(1)], Metodi P. Yankov[(2)], Luca Barletta[(1)], and Norbert Hanik[(1)]

[(1)] Institute for Communications Engineering, Technische Universität München, 80333 Munich, Germany
[(2)] Department of Photonics Engineering, Technical University of Denmark, Kgs. Lyngby 2800, Denmark
tobias.fehenberger@tum.de

Abstract *Exploiting temporal correlations in the phase, achievable rates are studied and a blind trellis-based receiver is presented. Gains of 0.5 bit per symbol are found in point-to-point links irrespective of the symbol rate. These gains disappear in network configurations.*

Introduction

Lower bounds on the capacity of optical fiber systems have been studied[1] by treating the fiber nonlinearities as additive and white, i.e., uncorrelated, Gaussian noise (AWGN). Recent studies consider the dependence on modulation format[2], and temporal[3] and additionally spectral[4] correlations due to cross-phase modulation (XPM). By exploiting the correlations of the phase noise, revised rates have been reported[3,4] that improve considerably on the previous bounds[1]. These increased achievable rates have been calculated for Gaussian input and point-to-point links. To our knowledge, only one implementation to obtain these rates has been presented[4], yet it uses knowledge of the sent symbols and is therefore not immediately applicable in practice.

In this paper, in place of Gaussian input, we consider uniformly distributed quadrature amplitude modulation (QAM) symbols to show achievable rates for a correlation-aware receiver that exploits the strong temporal correlations within a block of symbols. A blind trellis-based phase tracking algorithm is also presented. Point-to-point links and optical fiber networks are studied.

Phase Noise Receiver

We consider the transmission of a block of N symbols x^N over an optical fiber system and model the input-output relation at time k as

$$y_k = x_k \exp(j\phi_k) + n_k^{\mathrm{NLI}} + n_k^{\mathrm{ASE}}, \qquad (1)$$

where the complex Gaussian variates n_k^{NLI} and n_k^{ASE} denote the additive nonlinear interference noise (NLI) and the amplified spontaneous emission (ASE) noise from amplifiers, respectively. The phase noise term ϕ_k has temporal correlation between neighboring symbols mainly due to XPM, and is further assumed to be blockwise constant[3]. This assumption is justified by the auto-correlation function (ACF) shown in Fig. 2, which is discussed later in detail.

We exploit the intra-block correlation to calculate achievable rates as follows, without making explicit use of frequency correlation[4]. At the receiver, the angle between x_k and y_k is estimated for every k. This angle includes both the correlated phase noise ϕ_k as well as the additive noise terms n_k^{NLI} and n_k^{ASE}. Note that there might be correlations in n_k^{NLI}, but they are not considered in this work. The mean angle $\bar{\phi}_k$ of w past symbols is calculated as a moving-window average,

$$\bar{\phi}_k = \measuredangle \sum_{l=1}^{w} x_{k-l}^* y_{k-l}, \qquad (2)$$

where x^* is the complex conjugate of x. We are allowed to use all y_k but only past x_k to obtain an achievable rate, which becomes apparent by the chain rule of mutual information between input and output sequences[1]. If the phase noise samples $\measuredangle(x_k^* y_k)$ are not or are only weakly correlated, then $\bar{\phi}_k \approx 0$. The XPM-induced phase noise of the received symbol y_k is compensated by a phase rotation,

$$y_k' = y_k \cdot \exp(-j\bar{\phi}_k). \qquad (3)$$

Finally, an achievable rate is calculated from the symbols y_k' using circular Gaussian statistics on a symbol-by-symbol basis[6]. We call this correlation-aware processing a phase noise (PN) receiver, while we speak of an AWGN receiver when correlations are neglected and the rates are calculated directly from y_k with circular Gaussian statistics.

Blind Trellis-Based Phase Tracking

While the PN receiver produces an achievable rate, it requires knowledge of the past symbols, which makes it impractical. In order to build a practical receiver we model the phase noise as

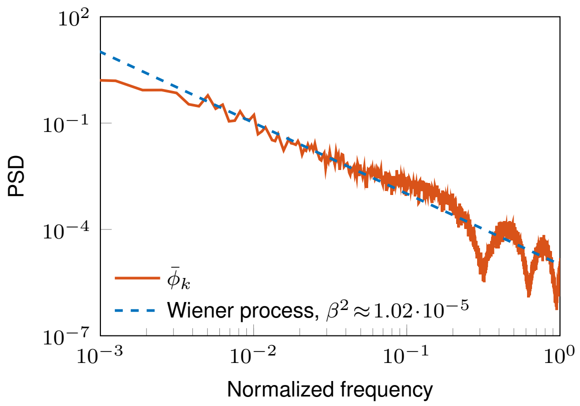

Fig. 1: Power spectral density (PSD) of the estimated phase noise $\bar{\phi}_k$, and a true Wiener process. The estimate is obtained from symbols after fiber transmission of 9 WDM channels.

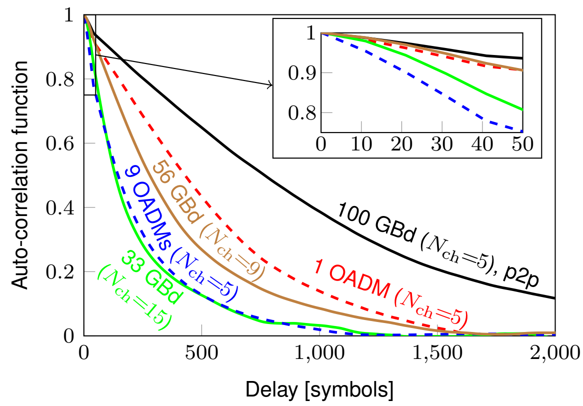

Fig. 2: ACF of point-to-point (p2p) WDM systems at different symbol rates (solid), and different network configurations at 100 GBd (dashed). Inset: Zoomed ACF for up to 50 symbols.

a Wiener process,

$$\phi_k = \phi_{k-1} + \beta v_k, \tag{4}$$

where the samples v_k's are i.i.d. and drawn from a standard Gaussian distribution. The scalar β^2 is obtained offline from the PN receiver:

$$\beta^2 = \mathrm{E}_k[(\bar{\phi}_k - \bar{\phi}_{k-1})^2]. \tag{5}$$

Figure 1 shows a good match between the power spectral density (PSD) of the phase noise process $\bar{\phi}_k$ obtained from simulation data, and the theoretical PSD of a Wiener process with $\beta^2 \approx 1.02 \cdot 10^{-5}$, thus justifying the Wiener phase noise model. Based on it, we implement a trellis-based receiver[5] where each state represents the distribution of the phase noise given the channel output samples, $p(\phi_k|y_1^N)$. The phase is discretized into a finite number of bins within a limited range that is obtained offline from the PN receiver. A large number of bins improves the phase estimate ϕ_k but increases the complexity. The model (4) allows for the factorization of $p(\phi_k|y_1^N)$ into $p(\phi_k, y_1^k)p(y_{k+1}^N|\phi_k)$, which can be efficiently calculated by the BCJR algorithm. The posterior distribution of the input is then

$$p(x_k|y_1^N) = \sum_{\phi_k} p(\phi_k|y_1^N)p(x_k|\phi_k, y_k). \tag{6}$$

The second term in Eq. (6) is calculated using Bayes' theorem, where the likelihood $p(y_k|\phi_k, x_k)$ is circular Gaussian with zero mean and variance estimated offline. The posterior shown in Eq. (6) is used in the achievable rate calculation and in the demodulation process[5]. The PN receiver and this trellis algorithm work for any input distribution.

Numerical Analysis

We investigate a single-polarization wavelength division multiplexing (WDM) system where each WDM channel uses 1024-QAM and a sinc pulse shape. The guard band between neighboring channels is 2% of their bandwidth and the overall spectral width is constant at 510 GHz. We study N_{ch}=5, 9, 15 WDM channels, with a symbol rate of 100, 56, and 33 GBd, respectively.

The signal propagates over 1000 km of standard single-mode fiber with γ=1.3 (W·km)$^{-1}$ and D=17 ps/nm/km. Ideal distributed amplification is employed to compensate for the fiber loss of α=0.2 dB/km. Fiber propagation is simulated using the split-step Fourier method with 32 samples per symbol and 0.1 km step size. Optical add-drop multiplexers (OADMs) are inserted into the link when a network setup is studied. An OADM is modeled by ideal band-pass filtering of the center WDM channel, creating new WDM neighbors and combining the old center channel and the new neighbors. We consider point-to-point (p2p) links, links with one OADM at 500 km, and with an OADM every 100 km, i.e., 9 OADMs in total.

At the receiver, the center WDM channel is ideally band-pass filtered, digitally back-propagated (DBP) to remove self-phase modulation, and down-sampled. The received symbols are either not processed further (AWGN receiver), processed with the PN receiver, or with the blind trellis phase tracking, and achievable rates are calculated on a symbol-by-symbol basis using circular Gaussian noise statistics. We also tested conditional bivariate Gaussian statistics and found no significant difference in achievable rates. The parameter w of Eq. (2) is set to 40 for the considered optical system parameters. Simulations show that w in the range between 30 and 80 is not critical for calculating $\bar{\phi}_k$.

The temporal ACF of the phase noise is shown in Fig. 2. We use simulation data and the blockwise phase noise model[3] for computing the ACF. We observe that temporal correlations are re-

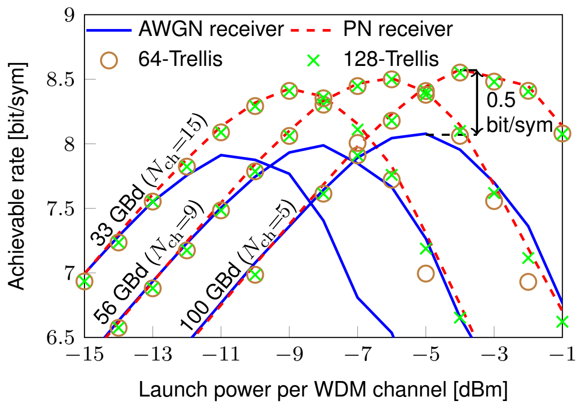

Fig. 3: Achievable rates for three WDM systems. The gain from the PN receiver (dashed) and the trellis processing (markers) over the AWGN receiver (solid) is 0.5 bit/sym at the optimum power for every WDM configuration.

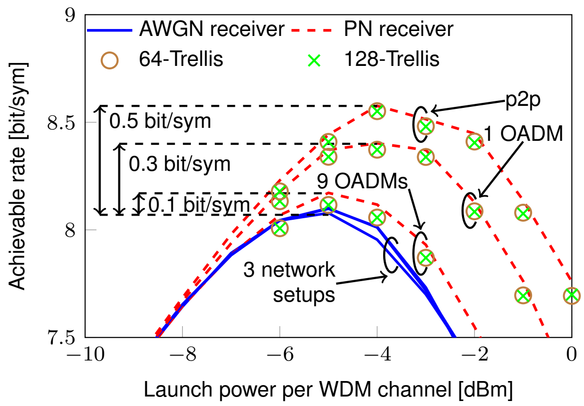

Fig. 4: Achievable rates for N_{ch}=5 WDM channels and three link configurations: point-to-point (p2p), one OADM after 500 km, and one OADM every 100 km (9 OADMs in total). The fiber length is always 1000 km.

duced when the symbol rate per channel is decreased (recall that the total WDM bandwidth is kept constant), and also when network elements are inserted in the fiber. We will next analyze whether the correlations that are apparent from the ACF translate into rate gains.

Achievable rates for the three different WDM setups are compared in Fig. 3. For the AWGN receiver, the maximum rate for 15 channels is 7.9 bits per symbol (bit/sym) and increases to 8.1 bit/sym for 5 channels. This is because for fewer WDM channels, single-channel (SC) DBP is able to cancel a larger amount of nonlinearities. Exploiting the block-wise correlations in the receiver improves the achievable rate by 0.5 bit/sym, which is comparable to simulations with Gaussian input[3]. The gain from the PN receiver is found to be constant for all three WDM setups, despite the dependence of the ACF on the per-channel symbol rate shown in Fig. 2.

The rates obtained with blind phase tracking (markers in Fig. 3) closely approach the rates of the PN receiver for all considered configurations. We also observe that 64 trellis states are sufficient to get full gains at relevant powers.

Achievable rates for N_{ch}=5 channels and three different network setups are shown in Fig. 4. For the AWGN receiver, the maximum rates are about 8.1 bit/sym, independent of the network configuration. When one OADM is inserted in the center of the link, the rate of the PN receiver is reduced from 8.6 bit/sym to 8.4 bit/sym, which is a decrease in gain by 0.2 bit/sym in comparison to the 0.5 bit/sym for the p2p case without OADMs. This is because the coherent build-up of correlations is effectively terminated half-way during propagation. Further simulations show that the center of the link is the worst among all potential locations of one OADM with respect to achievable rates. In a network with 9 OADMs, the gain is reduced to less than 0.1 bit/sym due to repeated filtering of the co-propagating WDM channels and the addition of new, uncorrelated channels. For all network setups, the trellis processing gives rates very close to the PN receiver.

For a long-haul p2p fiber system[6] with dual-polarization 16-QAM at 28 GBd, 60 spans of 100 km each, lumped amplification and SC DBP, we found that the gain by applying the PN receiver was 0.1 bit/sym. This limited gain is mainly attributed to lumped amplification leading to less temporal correlation of the XPM phase noise[4].

Conclusions

We show gains in achievable rate of up to 0.5 bit/sym by exploiting correlation in the nonlinear phase noise. These gains are also obtained by trellis-based processing without knowledge of input symbols. Larger gains are expected by using models that resemble the XPM-induced correlations better than a block-wise constant phase. Especially correlations in the additive NLI noise term could be investigated.

References

[1] R.-J. Essiambre *et al.*, “Capacity limits of optical fiber networks,” JLT **28**(4), 2010.

[2] A. Mecozzi and R.-J. Essiambre, “Nonlinear shannon limit in pseudolinear coherent systems,” JLT **30**(12), 2012.

[3] R. Dar *et al.*, “Properties of nonlinear noise in long, dispersion-uncompensated fiber links,” Opt. Exp. **21**(22), 2013.

[4] M. Secondini and E. Forestieri, “On XPM mitigation in WDM fiber-optic systems,” PTL **26**(22), 2014.

[5] L. Barletta *et al.*, “Pilot-aided trellis-based demodulation,” PTL **25**(13), 2013.

[6] T. Fehenberger *et al.*, “On achievable rates for long-haul fiber-optic communications,” Opt. Exp. **23**(7), 2015.