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FEC-assisted Perturbation-based Nonlinear Compensation for WDM Systems

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Abstract: A FEC-assisted iterative perturbation-based nonlinear post-compensation scheme is proposed and experimentally investigated. Improved compensation performance is observed for a 5×WDM-DP 32-GBd dispersion-uncompensated transmission over 3500 and 840 km for 16QAM and 64QAM, respectively.

OCIS codes: (060.1660) Coherent communications, (060.2360) Fiber optics links and subsystems

1. Introduction

Due to the availability of simplified one sample per symbol nonlinear fiber channel models, for which bounds on information rates can be derived, the performance investigation of digital receivers employing one sample per symbol nonlinearity compensation (NLC) algorithms is a topic of interest. Based on first-order perturbation analysis of the Manakov equation, methods to calculate and compensate intra-channel Kerr nonlinear interference (NLI) have been recently proposed and investigated [1]. Such methods have been mostly employed as transmitter-side pre-distortion techniques for NLC, since the calculation of the NLI waveform requires the knowledge of the symbols sent through the channel. However, the performance of pre-distortion techniques is bounded by hardware constraints, such as analog bandwidth and the effective number of bits of digital-to-analog converters [2, 3]. Alternatively, NLC can be achieved with a perturbation-based decision feedback equalizer (DFE) at the receiver side [4]. However, compared to the pre-compensation methods, the efficacy of the post-compensation is bounded by the incomplete knowledge of the receiver on the transmitted symbol sequences. Therefore, at high symbol error rates (SERs)/bit error rates (BERs), the performance of post-compensation can be severely degraded.

In this paper, we propose and investigate the performance of an iterative first-order perturbation-based NLC scheme assisted by feedback from a low-parity density check (LDPC) forward error correction (FEC) decoder. At each iteration, an updated estimation of the NLI is calculated based on a sequence of symbols regenerated from the output of the LDPC decoder. For comparison, we also evaluate the performance of an idealized genie-assisted perturbation NLC, where all the transmitted symbols are known a priori by the receiver. Additionally, we also investigate the receiver performance when a recursive least squares (RLS) fast-convergence linear adaptive equalizer is included within the iterative processing. This equalizer has the task of compensating for the time-varying intersymbol interference (ISI) caused by inter-channel NLI [6]. The performance of the iterative scheme is experimentally investigated for a 5×32 GBd DP-16QAM and DP-64QAM WDM system after 3500 km and 840 km, respectively, of dispersion uncompensated transmission.

2. Perturbation model and nonlinear compensation schemes

The proposed FEC-assisted iterative NLC scheme is depicted in Fig.1(b.1), and the schemes used for comparison are shown in Fig.1(b.2)-(b.3). The first-order perturbation calculation is performed according to the additive-multiplicative model (AM model) described in [5]. Assume $\hat{A}_x[k]$ to be the detected symbol of polarization-x at the instant $t = kT_s$, where T_s is the symbol period. After linear compensation of chromatic dispersion (CD) and matched filtering, $\hat{A}_x[k]$ can be expressed as

$$\hat{A}_x[k] = (A_x[k] + \Delta A_x[k])\exp(j\phi_x[k]) + n_x[k], \tag{1}$$

where A_x is the transmitted symbol, n_x is a complex additive white Gaussian noise, $(\Delta A_x, \phi_x)$ describe the intra-channel NLI distortion given by the AM model and are approximated by

$$\Delta A_x = P_0^{3/2}\left[\sum_{m\neq 0, n\neq 0}(A_x[n]A_x^*[m+n]A_x[m] + A_y[n]A_y^*[m+n]A_x[m])C[m,n] + \sum_{m\neq 0, n} A_y[n]A_y^*[m+n]A_x[m])C[m,n]\right], \tag{2}$$

$$\phi_x = P_0 \,\mathrm{Im}\left\{\sum_{m\neq 0}\left(2|A_x[m]|^2 + |A_y[m]|^2\right)C[m,0] + \left(2|A_x[0]|^2 + |A_y[0]|^2\right)C[0,0]\right\}, \tag{3}$$

where P_0 is the pulse peak power and C is a $(2L+1)\times(2L+1)$ matrix of coupling coefficients that depend on the physical parameters of the channel, the pulse shape and baud rate of the transmission [5]. The double summations in (m,n) are taken over the intervals $([-L,L],[-L,L])$. Same equations apply to the distortions in polarization-y, only exchanging the corresponding indexes. The matrix C is then a discrete model for the intra-channel NLI with a finite memory of $2L+1$ symbol periods. Note that the indexes in Eqs.(2)-(3) are relative delays to the symbol of interest, i.e., the symbol at $t = kT_s$.

In order to use Eqs.(2)-(3) for estimating $(\Delta A_{x/y}, \phi_{x/y})$ the receiver has to perform first an estimation on the transmitted sequence of symbols, which can be done by applying hard decisions (HD) on the received noisy symbols based on the

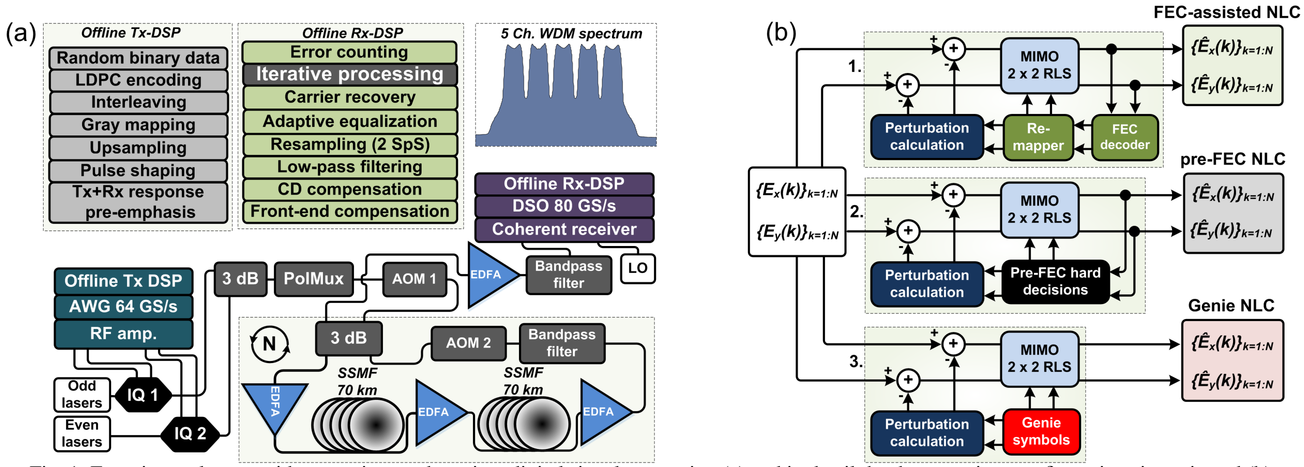

Fig. 1: Experimental setup with transmitter and receiver digital signal processing (a) and in detail the three receiver configurations investigated (b).

minimum Euclidean distance to a reference constellation. In this configuration, the perturbation NLC operates similarly to a DFE (Fig.1(b.2)). As a drawback, such equalizers are expected to have the performance degraded if a low SNR is available at the receiver leading to high SERs. Since the FEC in coherent wavelength division multiplexing (WDM) systems is designed to allow reliable communication even when the pre-FEC BERs are as high as 10^{-2}, DFE equalization will suffer performance degradation for SNR ranges close to the pre-FEC BER limits. Similar comments can be made about the performance of RLS filters used to compensate inter-channel NLI. Alternatively, to mitigate this problem the receiver may use a feedback from the FEC decoder attempting to improve the NLI estimation (Fig.1(b.1)) and, thereby, the NLC performance. Here we focus on comparing the schemes in Fig.1(b.1)-(b.2) with the ideal genie-assisted scheme (Fig.1(b.3)), where the NLI is estimated with full knowledge of the transmitted symbols.

3. Experimental setup

The experimental setup is shown in Fig.1 (a). The WDM system is composed of five carriers modulated at 32 GBd and disposed in a grid spacing of 50 GHz. The transmitted symbols are generated by encoding an pseudo random bit sequences with LDPC code rates $R = 5/6$ (20% overhead) for DP-16QAM and $R = 3/4$ (33% overhead) for DP-64QAM (DVB-S.2 standardized FEC). The encoded bits are interleaved and Gray mapped into QAM symbols. Two decorrelated sequences of eight LDPC blocks (64800 encoded bits per block) are loaded in the arbitrary waveform generator (AWG). The signal is pulse shaped with a root-raised cosine (RRC) filter with 401 taps and roll-off factor of 0.5. A linear pre-emphasis is applied in order to compensate for the combined frequency response of transmitter and receiver. After amplification, each baseband signal drives one of two in-phase/quadrature (IQ) modulators. The even-odd five carrier WDM system is obtained after further combination in a polarization multiplexing stage. All optical carriers in the experiment are external cavity lasers with 10 kHz linewidth. In back-to-back configuration, the maximum received SNR of the central WDM channel saturates at 20.5 dB. The WDM channels propagate in a recirculating loop composed of two 70 km spans of standard single mode fiber (SSMF), with all the losses compensated by Erbium-doped fiber amplifiers (EDFAs). After coherent detection, the signal passes through a front-end compensation stage, resampling, CD compensation, low-pass filtering, decimation, $T_s/2$-fractionally spaced adaptive equalization (85 taps, trained blindly and with 5% pilot-symbols for 16QAM and 64QAM, respectively), and carrier recovery with a digital direct-decision phase-locked loop. The estimated symbols are then sent to the iterative stage where the first order perturbation model and the RLS filter are used to perform intra- and inter-channel NLC, respectively. The matrix of coefficients C is numerically calculated assuming the analytical models presented in [1,5], and a fixed memory length L of 80 symbols. In order to reduce the number of calculations, here a cutoff threshold of -16 dB is chosen to discard coefficients much smaller than $C[0,0]$. The RLS adaptive equalizer is configured as a complex-valued 2×2 finite impulse response (FIR) with 3 taps, and forgetting factor ranging within the interval [0.98,1]. The LDPC decoder is configured to perform a fixed number of 10 iterations per block.

4. Experimental results

The experimental results are shown in Figure 2. For each launch power, the BER values shown correspond to the average BER of the central WDM channel over 96 code blocks. The performance without NLC is included for comparison. Figures 2 (a.1)-(b.1) show the average received SNR per polarization for the three receivers depicted in Fig.1 (b). Therein, we refer to the received SNR results of DP-64QAM followed by the results of DP-16QAM in parenthesis. Without the RLS filter, for the pre-FEC NLC scheme, the maximum received SNR is increased by 0.20 dB (1.0 dB), whereas for the FEC-assisted NLC scheme an additional gain of ≈ 0.20 dB (1.0 dB) is obtained. With the RLS filter, the FEC-assisted scheme exhibits a further improvement of 0.6 dB (0.5 dB), whereas the gain of the pre-FEC NLC scheme is unaltered. Therefore, in both cases the performance of the RLS filter is enhanced by the FEC-assisted scheme. Interestingly, the per-

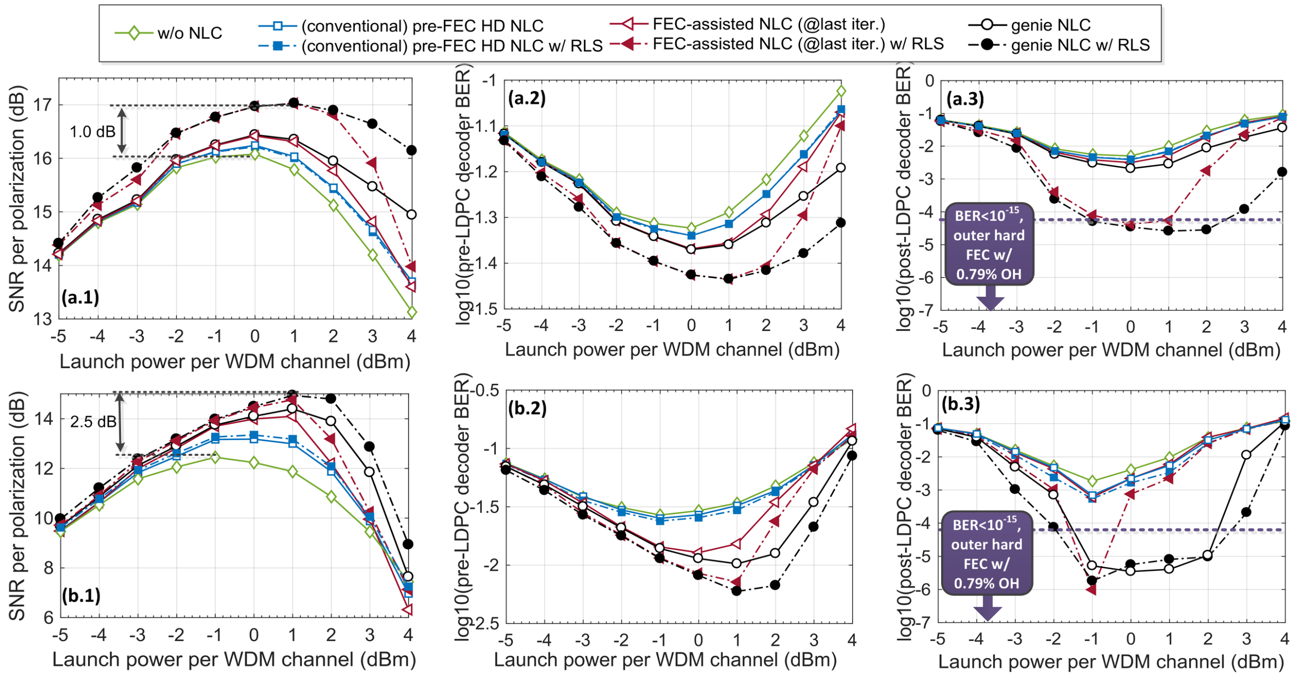

Fig. 2: Experimental results for the central channel performance as a function of launched power for dispersion uncompensated WDM transmission of (a) 5×32 GBd DP-64QAM after 840 km and (b) 5×32 GBd DP-16QAM after 3500 km.

formance of the FEC-assisted NLC scheme is similar to the performance of the genie-assisted NLC scheme for a number of points,including the optimal launch power. Figures 2 (a.2-.3)-(b.2-.3) show the translation from SNR into pre-FEC and post-FEC BER performance, respectively. It is noticed that, even though pre-FEC BER follow a similar pattern observed in the SNR, the post-FEC performance of the FEC-assisted NLC scheme deviates from the genie-assisted NLC curve. A possible reason for this behavior can be related to difference on the noise statistics of the symbols produced after FEC-assisted NLC and genie-assisted NLC. It was observed that around the optimal launch power, the receiver required around three iterations between FEC decoder and NLC to achieve the minimum BER, whereas in the nonlinear regime the number of iterations increases. All the results displayed here correspond to a fixed number of five iterations between LDPC decoder and the NLC. Overall, an improvement of ≈ 1.0 dB (2.5 dB) of received SNR per polarization is obtained by the proposed scheme with respect to the performance without NLC, reducing the post-LDPC decoder BER from $10^{-2}/10^{-3}$ to less than 5×10^{-5}. Assuming that an outer linear hard FEC code is used to bring the BER down to below 10^{-15}, error-free performance can be achieved with an extra overhead of 0.79%, i.e. assuming a pre-hard-FEC limit BER of 5×10^{-5} [7]. It should be noticed that the increment in SNR required to decrease the BER below the hard FEC limit considered is mostly due to implementation penalties that lead to sub-optimality of the LDPC decoder.

5. Conclusion

FEC-assisted perturbation-based nonlinearity compensation (NLC) is demonstrated by using an iterative NLC scheme assisted by the output of an LDPC decoder. Experimental results show that FEC-assisted NLC outperforms pre-FEC NLC, improving the bit error rate performance of the central channel in a 5×32 GBd WDM dispersion uncompensated transmission of DP-16QAM and DP-64QAM after 3500 km and 840 km, respectively.

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References

[1] Tao, Z.*et al*, "Multiplier-free intrachannel nonlinearity compensating algorithm operating at symbol rate," *J. Light. Technol.*, 29(17), pp. 2570-2576, 2011.

[2] Oyama, T.*et al*, "Impact of Pulse Shaping and Transceiver Electrical Bandwidths on Nonlinear Compensated Transmission," *Proc. of the Optical Fiber Communication Conference (OFC)*, paper OTh3C.2, 2013.

[3] Ghazisaeidi, A.*et al*, "Perturbative Nonlinear Pre-Compensation in Presence of Optical Filtering," *Proc. of the Optical Fiber Communication Conference (OFC)*, paper ThD3.3, 2015.

[4] Oyama, T.*et al*, "Robust and efficient receiver-side compensation method for intra-channel nonlinear effects," *Proc. of the Optical Fiber Communication Conference (OFC)*, paper Tu3A.3, 2014.

[5] Tao, Z. *et al*, "Analytical Intra-channel Nonlinear Models to Predict the Nonlinear Noise Waveform," *J. Light. Technol.*, 33(10), pp. 2111-2119, 2014.

[6] Dar, R.*et al*, "Inter-channel nonlinear interference noise in WDM systems: Modeling and mitigation," *J. Light. Technol.*, 33(5), pp. 1044-1053, 2015.

[7] Millar, D. S.*et al*, "Design of a 1 Tb/s superchannel coherent receiver," *J. Light. Technol.*, 34(6), 1453-1463, 2016.