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Abstract

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Cross Polarization Modulation (XPolM) Compensation for Submarine Upgrade Links using DP-8QAM

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Abstract *We propose a method of XPolM compensation suitable for submarine upgrade systems, and experimentally validate performance for a 70×192 Gb/s DP-8QAM system. The method improves the Q-factor by 0.16dB and outperforms the conventional NPCC by 0.12dB.*

Introduction

Cross-polarization modulation (XPolM) is one of non-linear impairments accompanying the transmission of optical signal through a fiber. The XPolM causes rotations of the state of polarization around an axis which itself exhibits random walk on a sphere[1]. The XPolM becomes prominent in systems with DWDM waveforms transmitted over long, dispersion managed (DM) links.

To compensate the XPolM, the Nonlinear Polarization Cross-talk Canceler (NPCC)[2] first makes hard-decisions on symbols, then obtains instantaneous estimates of the cross-talk coefficients and processes them through the moving average filter in the final stage. The XPolM compensator based on the generalized maximum likelihood (GML)[3] assumes that the cross-talk coefficients are constant over a certain number of symbol intervals. Building upon the NPCC, an XPolM compensator based on multi-stage phase recovery of the state of polarization is proposed[4]. However, in submarine upgrade systems, we need to ensure the gain over dispersion maps which have been designed to provide significant dispersion per span while maintaining near zero dispersion over the entire link[5]. While these dispersion maps minimized nonlinearity for their original signals, their impact on XPolM in upgrade systems is significant.

In this paper, we propose a novel XPolM compensation method, suitable for submarine upgrade systems, which recovers a symbol by jointly considering a certain number of samples following and preceding that symbol, and iteratively updating the maximum likelihood estimates of the cross-talk coefficients. The proposed method has moderate computational complexity and is amenable to parallel implementation in hardware. Our algorithm was experimentally validated with 70×192 Gb/s DP-8QAM transmission over a 1260 km dispersion managed link with significant accumulated CD at the EDFAs, typical of a legacy submarine cable[5]. We demonstrate an improvement in Q-factor of 0.16 dB at the optimal launch power, outperforming the fully optimized NPCC method by 0.12 dB.

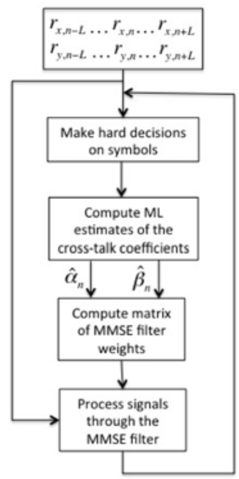

Fig. 1: Estimation of cross-talk coefficients at discrete time n using $2L+1$ samples in both polarizations.

XPolM Compensation Algorithm

We assume that all impairments other than XPolM are compensated and the samples $r_{x,n}$ and $r_{y,n}$ of the resulting signal at signaling time n corresponding to x- and y-polarization, are given by[2,3]

$$\begin{bmatrix} r_{x,n} \\ r_{y,n} \end{bmatrix} = \begin{bmatrix} 1 & \alpha_n \\ \beta_n & 1 \end{bmatrix} \begin{bmatrix} s_{x,n} \\ s_{y,n} \end{bmatrix} + \begin{bmatrix} v_{x,n} \\ v_{y,n} \end{bmatrix}, \quad (1)$$

where α_n and β_n are the cross-talk coefficients, $s_{x,n}$ and $s_{y,n}$ are the transmitted symbols at signaling time n, and $v_{x,n}$ and $v_{y,n}$ are samples of circularly symmetric zero-mean white Gaussian noise of variance σ_v^2.

The proposed XPolM compensation method is iterative and its block diagram is shown in Fig. 1. The estimation of the cross-talk coefficients and transmitted symbols at symbol time n is carried out by considering L samples preceding and L samples following the considered symbol. In first iteration, we make hard decisions corresponding to $r_{x,k}$ and $r_{y,k}$, denoted with $\hat{s}_{x,k}^{(1)}$ and $\hat{s}_{y,k}^{(1)}$, where $k = n - L, \ldots, n + L$.

At an iteration l, we assume the cross-talk coefficients α_n and β_n are the same across all samples within the considered block, such that their maximum likelihood (ML) estimates are given by

$$\hat{\alpha}_n^{(l)} = \frac{\sum_{k=n-L}^{n+1} \hat{s}_{k,y}^{(l)*}(r_{k,x} - \hat{s}_{k,x}^{(l)})}{\sum_{k=n-L}^{n+L} \hat{s}_{k,y}^{(l)*} \hat{s}_{k,y}^{(l)}} \quad (2)$$

$$\hat{\beta}_n^{(l)} = \frac{\sum_{k=n-L}^{n+1} \hat{s}_{k,x}^{(l)*}(r_{k,y} - \hat{s}_{k,y}^{(l)})}{\sum_{k=n-L}^{n+L} \hat{s}_{k,x}^{(l)*} \hat{s}_{k,x}^{(l)}} \quad (3)$$

The cross-talk coefficient estimates are then used to process the samples $r_{k,x}$, $r_{k,y}$, $k = n - L, \ldots, n + L$ in order to estimate the transmitted symbols. This could be done by means of zero forcing (ZF) equalization, minimum mean square error (MMSE) equalization, or jointly to obtain the MAP symbol estimates. To keep complexity relatively low, especially with denser modulation formats, we employ the MMSE processor whose output is given by

$$\begin{bmatrix} \hat{s}_{x,k}^{(l)} \\ \hat{s}_{y,k}^{(l)} \end{bmatrix} = \left(\mathbf{G}\mathbf{G}^H + \sigma_v^2 \mathbf{I}\right)^{-1} \mathbf{G} \begin{bmatrix} r_{x,k} \\ r_{y,k} \end{bmatrix}, \quad (4)$$

where $\mathbf{G} = \begin{bmatrix} 1 & \hat{\alpha}_n^{(l)} \\ \hat{\beta}_n^{(l)} & 1 \end{bmatrix}$. We note that the matrix inverse in (4) is relatively easy to compute since the matrix is of order two and its inverse can be obtained directly from corresponding formulas.

The soft symbol estimates from (4) are mapped to hard-decisions and feed back to re-estimate the cross-talk coefficients in (2) and (3). The described process is repeated a certain number of iterations I, which yields the estimates $\hat{\alpha}_n^{(I)}$ and $\hat{\beta}_n^{(I)}$, $n = 1, \ldots, N$. The variations in these estimates are smoothen by applying a moving average filter of appropriate length, whose output is the sequence of final cross-talk estimates.

Experimental Setup

We have conducted transmission experiment by using the setup shown in Fig. 2. The modulation format was DP-8QAM. The symbol rate was 32 Gbaud and the roll-off factor of root-raised-cosine (RRC) filtering was 0.15. The digital-to-analog converter was operated at 64 GS/s. The WDM signal was generated with a bulk modulation of 70 optical carriers spaced at 50 GHz, and de-correlated them afterward via 4 signal paths having different delays. The transmission distance was 1,260 km, consisting of 19 spans, and EDFA noise figure of 5 dB. The spans were mostly non-zero dispersion shifted fiber (NZ-DSF), with span numbers 4, 10 and 16 being standard single mode fiber (SSMF) for chromatic dispersion (CD) management. The default received optical signal-to-noise ratio (OSNR) was 19.9 dB in 0.1 nm resolution at -2.9 dBm/ch launched power. Half of the total accumulated CD was compensated at the transmitter. The received signal was coherently detected after wavelength demultiplexing via bandpass filter (OBPF). Each laser linewidth including local oscillator was $<$500 kHz and the measured wavelength was 1548.5 nm. The signal was quantized with 64 GS/s analogue-to-digital converters (ADCs), and processed offline.

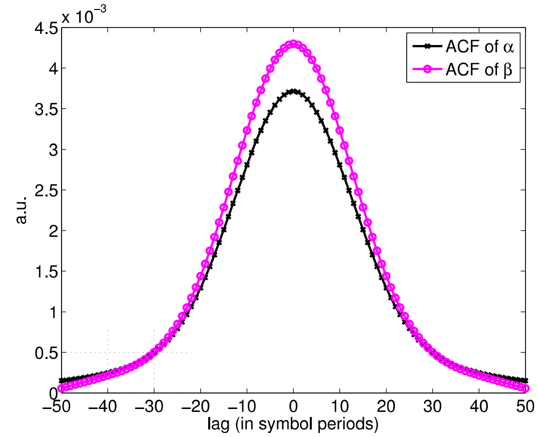

Fig. 3: Autocorrelation function of the estimated cross-talk coefficients

The offline DSP included CD compensation, adaptive equalization with constant modulus algorithm for initial convergence and radius directed equalization afterward, carrier recovery with multi-pilot aided algorithm[6] and pilot-aided cyclic phase-slip recovery. The signal at the CPE output was then processed to compensate the cross-talk impairment using the proposed method with the ML window length 21 (i.e., $L = 10$) and the number of iterations was limited to 2. The averaging window length in the final stage was optimized to yield the lowest BER.

Results

The proposed compensation method is compared with the NPCC[2]. The length of the moving average filter in the NPCC is fully optimized to yield the smallest BER. The performance was evalu-

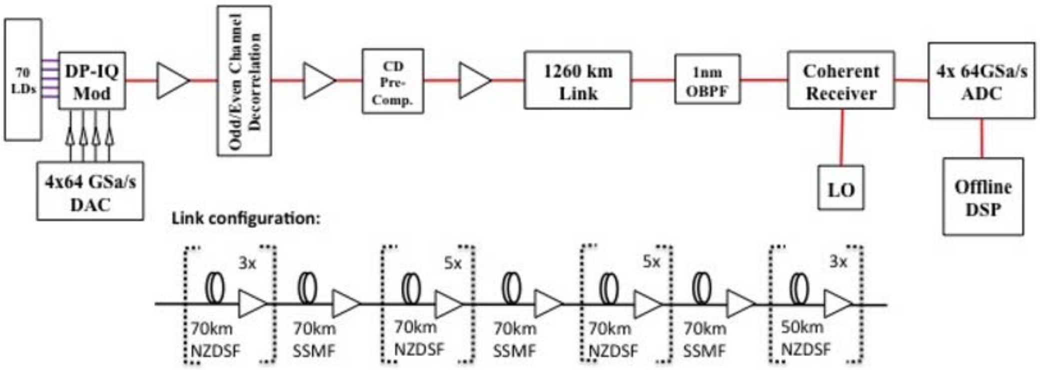

Fig. 2: Experimental setup with 1260 km link configuration inset.

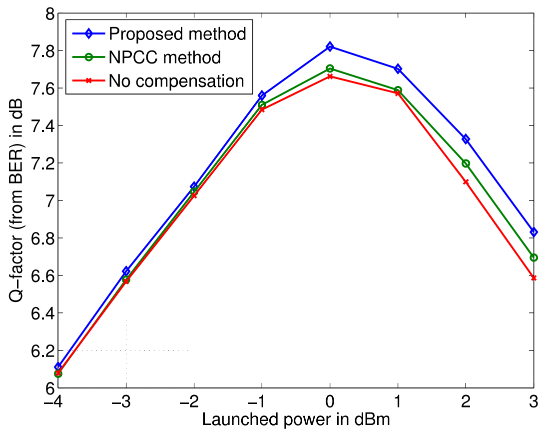

Fig. 4: Experimental BER Q-factor versus launched power

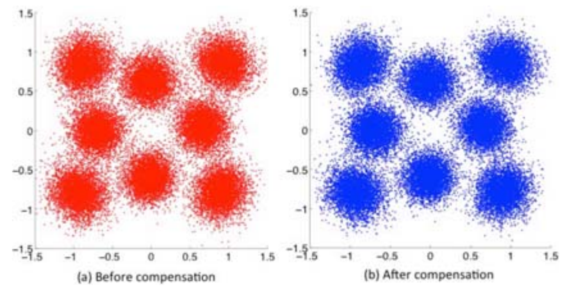

Fig. 5: Signal constellation before (left) and after (right) the XPolM compensation with the proposed method.

ated with hard-decision BER Q-factor, defined as $Q = \sqrt{2}\text{erfc}^{-1}(2\text{BER})$, which represents the SNR required to achieve the obtained BER in binary-symmetric additive white Gaussian noise channel. The performance comparison between the proposed method and NPCC is shown in Fig. 4. Notably, comparing the Q-factors achieved at optimal launch powers, the proposed method provides 0.16 dB gain with respect to the case when XPolM compensation is not employed, and improves the performance of the fully optimized NPCC method by 0.12 dB.

While this improvement is much smaller than the gain that might be expected from previously reported results[2], we note that in this optical link, the amplifiers occur at distances where accumulated dispersion is relatively high, leading to lower levels of XPolM. While a reference system with SSMF spans and 105% inline compensation has 56 ps/nm residual CD per span, an NZ-DSF only system exhibits a residual dispersion of 210 ps/nm. While it is known that XPolM decreases in systems with significant accumulated CD[7], we speculate that in a low-XPolM environment, equalizer parameterization becomes a critical task, and provides the source of our gain compared with the conventional NPCC.

The constellation plot of symbols in both polarizations before and after the proposed cross-talk compensation are shown in Fig. 5. The corresponding launch power of the considered waveform was 0 dBm.

Conclusions

We have proposed a novel XPolM compensation method suitable for use in submarine upgrade systems. We have tested the proposed method using 70×192 Gb/s DP-8QAM transmission over a 1260 km dispersion managed link with significant accumulated dispersion at the EDFAs, which is typical of a legacy submarine cable. We demonstrated an improvement in Q-factor of 0.16 dB, outperforming the conventional fully optimized NPCC method by 0.12 dB.

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