A Post-Equalization Technique for PDL Compensation in Coherent Optical Systems

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Abstract: A practical post-equalization technique is proposed to compensate the loss due to polarization gain imbalance in an optical channel. The proposed scheme is implemented after legacy adaptive channel equalization and shown to provide significant performance gains.

1. Introduction

One of the limiting factors of polarization-division multiplexing (PDM) in coherent optical transmission is polarization-dependent loss (PDL), which can significantly reduce the system margin. For long-haul transmission, optical components can effectively result in several dBs of accumulated PDL and hence, there is an increasing interest in improving the system tolerance to PDL. Various mitigation methods had been proposed in the literature which can be classified into two main categories: transmitter PDL precoding and receiver post-processing.

Basically, in transmitter PDL precoding schemes [1–3], the goal is to improve the worst-case performance by applying the same principles of space-time coding. At the receiver side, along with channel equalization, PDL decoding is performed to restore the transmitted symbols. However, the resulting noise samples, after equalization and decoding, are spatially (polarization) and temporally correlated noise samples, leading to significant performance loss. Indeed, the second category for PDL mitigation schemes employs receiver post-processing techniques to deal with this polarization-time correlated noise [4,5].

In this paper, we propose a novel post-equalization scheme, capable of whitening the spatially-temporally correlated noise due to PDL. Further, we apply the transmitter precoding to demonstrate the joint pre- and post-equalization approach. Without loss of generality, precoding scheme in [3] is employed which does not require decoding at the receiver side as the adaptive channel equalizer can reverse the precoding operation. We show that the proposed PDL compensation scheme provides significant performance gains, e.g., more than 1dB gain for PDM-QPSK transmission at a target BER of %4 and 2.4dB at a target BER of %0.1.

2. Principles

Fig. 1 shows the block diagram of an optical communication system, including the proposed post-equalization stage. A simplified model (blocks shaded in gray in Fig.1) is assumed in the following analysis. At the transmitter side, the symbols are precoded and then sent through the PDL channel $\mathbf{H}_{\mathrm{PDL}}$. The frequency-domain representation of the received signal can be described by:

$$\mathbf{R}(f)=\begin{bmatrix} r_X(f) \\ r_Y(f) \end{bmatrix}=\mathbf{H}_{\mathrm{PDL}}\begin{bmatrix} \acute{S}_X(f) \\ \acute{S}_Y(f) \end{bmatrix}+\begin{bmatrix} n_X(f) \\ n_Y(f) \end{bmatrix}=\begin{bmatrix} \sqrt{1-\gamma} & 0 \\ 0 & \sqrt{1+\gamma} \end{bmatrix}\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} \acute{S}_X(f) \\ \acute{S}_Y(f) \end{bmatrix}+\begin{bmatrix} n_X(f) \\ n_Y(f) \end{bmatrix}, \quad (1)$$

where γ determines the amount of PDL according to $\Gamma_{\mathrm{dB}}=10\log_{10}\frac{(1-\gamma)}{(1+\gamma)}$, θ determines the state of polarization (SOP) rotation, $\acute{S}_X$ and $\acute{S}_Y$ are the precoded transmitted symbols, r_X and r_Y are the received symbols, n_X and n_Y are the AWGN noise added to the X and Y polarization respectively.

Assuming adaptive Least Mean Square (LMS) equalization, the equalized signal can be written as:

$$\hat{\mathbf{R}}(f)=\mathbf{W}_{\mathrm{LMS}}(f)\mathbf{R}(f)=\begin{bmatrix} \hat{r}_X(f) \\ \hat{r}_Y(f) \end{bmatrix}=\begin{bmatrix} \hat{S}_X(f) \\ \hat{S}_Y(f) \end{bmatrix}+\begin{bmatrix} \hat{n}_X(f) \\ \hat{n}_Y(f) \end{bmatrix}, \quad (2)$$

where $\mathbf{W}_{\mathrm{LMS}}$ is the adaptive LMS filter taps matrix, $\hat{S}_X$ and $\hat{S}_Y$ are the equalized symbols and $\hat{n}_X$ and $\hat{n}_Y$ are the noise samples after equalizations. Accordingly, we find that $\begin{bmatrix} \hat{n}_X(f) \\ \hat{n}_Y(f) \end{bmatrix}=\mathbf{W}_{\mathrm{LMS}}(f)\begin{bmatrix} n_X(f) \\ n_Y(f) \end{bmatrix}$. Unless $\mathbf{W}_{\mathrm{LMS}}$ is a unitary matrix, the noise samples exhibit temporal and spatial (polarization) correlation that leads to performance loss due to the adaptive equalization process in presence of PDL [2].

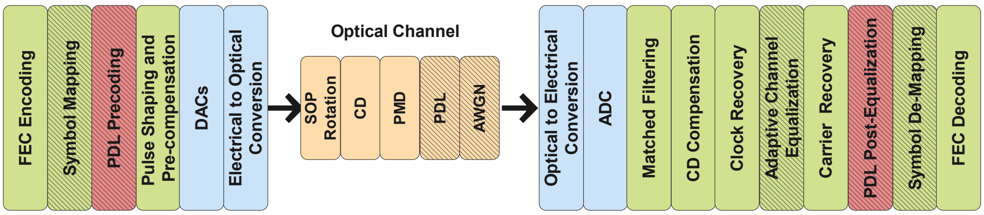

Fig. 1. End-to-End Optical System Model.

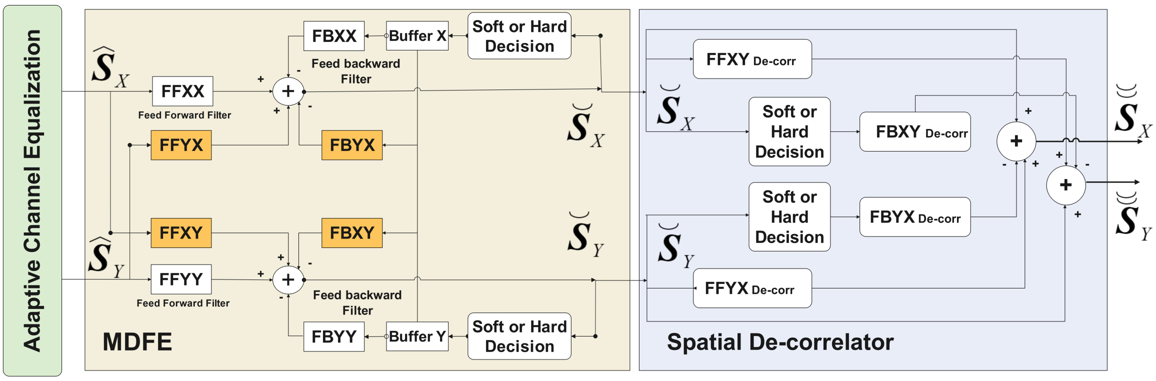

Fig. 2. Proposed Post-Equalization Architecture.

3. Proposed Post-Equalization Approach

In order to whiten the spatially-temporally correlated noise, we propose the post equalization architecture shown in Fig. 2. The equalized symbols $\hat{S}_X$ and $\hat{S}_Y$, output of the adaptive channel equalizer, are fed into a modified Decision Feedback Equalizer (MDFE), followed by a spatial de-correlator stage. It is known that DFE is a non-linear equalizer that improves the quality of the current estimate based on previous decisions. In optical systems, it has been implemented for compensating the impact of wavelength selective switch (WSS) or narrow-band filtering effects as a stand-alone post-equalizer [6]. As discussed in [6], filtering results in the noise samples to become temporally correlated. However, PDL adds additional spatial correlation to the noise samples. Accordingly, as shown in Fig. 2, we modify the DFE structure by adding additional filtering branches (shaded in orange) that takes into account the spatial-temporal nature of the noise correlation. Therefore, MDFE output can be expressed as:

$$\check{S}_X[n] = \sum_{k=0}^{L_F-1} FFXX[k]\hat{S}_X[n-k] - \sum_{k=0}^{L_B-1} FBXX[k]\bar{S}_X[n-k-d_0] + \sum_{k=0}^{L_F-1} FFYX[k]\hat{S}_Y[n-k] - \sum_{k=0}^{L_B-1} FBYX[k]\bar{S}_Y[n-k-d_0] \quad (3)$$

$$\check{S}_Y[n] = \sum_{k=0}^{L_F-1} FFYY[k]\hat{S}_Y[n-k] - \sum_{k=0}^{L_B-1} FBYY[k]\bar{S}_Y[n-k-d_0] + \sum_{k=0}^{L_F-1} FFXY[k]\hat{S}_X[n-k] - \sum_{k=0}^{L_B-1} FBXY[k]\bar{S}_X[n-k-d_0] \quad (4)$$

where L_F is the number of taps of the feed-forward filters $FFXX, FFYY, FFYX$ and $FFXY$, and L_B is the number of taps of the feed-backward filters $FBXX, FBYY, FBYX$ and $FBXY$, $\bar{S}_X[n]$ and $\bar{S}_Y[n]$ are the decided symbols at time n and d_0 is the decision delay. All the filters are updated adaptively using an LMS update equation.

A remaining challenge with MDFE is that it cannot improve the signal quality in presence of spatial correlation at the current time instant n. In order to solve this issue, the output of MDFE is passed to a simple spatial de-correlator as shown in Fig. 2. Specifically, the output of the spatial de-correlator can be expressed as:

$$\breve{\check{S}}_X[n] = \check{S}_X[n] + FFYX_{Decorr}\check{S}_Y - FBYX_{Decorr}D(\check{S}_Y), \quad \breve{\check{S}}_Y[n] = \check{S}_Y[n] + FFXY_{Decorr}\check{S}_X - FBXY_{Decorr}D(\check{S}_X) \quad (5)$$

where $\breve{\check{S}}_X[n]$ and $\breve{\check{S}}_Y[n]$ are the spatial de-correlator outputs, all filters $FFYX_{Decorr}, FFXY_{Decorr}, FBYX_{Decorr}$ and $FBXY_{Decorr}$ are single tap filters and updated by LMS update equations. $D(.)$ is a decision device of its argument which can be soft or hard decision.

4. Results and Discussion

In order to examine the performance of the proposed solution, we carried out two different simulation scenarios. In the first one, the simplified model (blocks shaded in gray in Fig.1) is used in which the PDL is set to $\Gamma_{\text{dB}} = 6dB$ with varying SOP angle θ. At the receiver side, an LMS equalizer is used for channel equalization followed by the proposed post-equalization approach. Fig. 3 shows the required signal-to-noise-ratio (RSNR) for PDM-QPSK

Table 1. RSNR (in dB) for PDM-QPSK versus SOP θ at 6dB PDL to achieve different target BERs.

Target BER	Worst-Case LMS without Precoding	Worst-Case LMS with Precoding	Worst-Case PDLC (Post-Equalization and Precoding)	Precoding Gain	PDLC Gain to LMS with precoding	PDLC Gain to LMS without Precoding
4.00E-02	7.14	6.47	6.01	0.67	0.46	1.13
2.00E-02	8.94	7.95	7.27	1.00	0.67	1.67
1.00E-02	10.29	9.08	8.28	1.21	0.8	2.01
1.00E-03	13.21	11.66	10.73	1.57	0.90	2.47

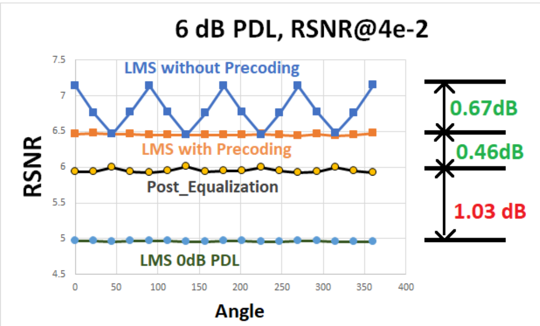

Fig. 3. RSNR (in dB) for PDM-QPSK at BER of %4 for 6dB PDL.

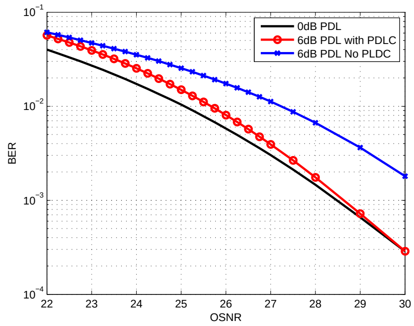

Fig. 4. BER vs OSNR.

signaling against the angle θ to achieve a target BER of %4. In Table 1, we summarized the worst-case RSNR at different target BER at 6 dB PDL. These results confirm more than 1dB performance gain for PDM-QPSK transmission at a target BER of $4e-2$ and 2.4dB at a target BER of $1e-3$.

In the second scenario, we simulate an end-to-end optical communication system as shown in Fig. 1. The system operates at 140 Gbaud using probabilistic constellation shaped 16QAM with entropy rate of 3.8 bits/symbol. PDL value is set to 6dB and an adaptive LMS equalizer, along with other DSP modules, are used to compensate for the channel and devices impairments. Finally, the bit-error-rate (BER) of the equalized symbols versus the optical signal-to-noise ratio (OSNR) assuming no PDL and with 6dB PDL are depicted in Fig. 4. It shows that the proposed architecture provides significant performance gains and reduces the gap to the case of no PDL. As one example, at a practical BER of $1e-2$, the proposed architecture provided 1.6dB gain compared to the case without PDL compensation. Another important observation is that the proposed scheme reduces the gap to 0dB PDL case asymptotically by increasing OSNR or reducing the target BER (e.g., at $1e-3$).

5. Conclusions

We proposed a novel PDL mitigation scheme based on combination of precoding and post-processing which is compatible with high speed coherent optical systems. The practical noise whitening scheme can be implemented following the adaptive equalization scheme and provides significant gains at practical target values of BER.

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