PDL Impact on Linearly Coded Digital Phase Conjugation Techniques in CO-OFDM Systems

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Abstract

We investigate the impact of polarization-dependent loss (PDL) on the linearly coded digital phase conjugation (DPC) techniques in coherent optical orthogonal frequency division multiplexing (CO-OFDM) superchannel systems. We consider two DPC approaches: one uses orthogonal polarizations to transmit the linearly coded signal and its phase conjugate, while the other uses two orthogonal time slots of the same polarization. We compare the performances of these DPC approaches by considering both aligned- and statistical-PDL models. The investigation with aligned-PDL model indicates that the latter approach is more tolerant to PDL-induced distortions when compared to the former. Furthermore, the study using statistical-PDL model shows that the outage probability of the latter approach tends to zero at a root mean square PDL value of 3.6 dB. On the other hand, the former shows an outage probability of 0.63 for the same PDL value.

Index Terms

Digital phase conjugation (DPC), fiber Kerr nonlinearity, polarization-dependent loss (PDL).

I. INTRODUCTION

The fiber Kerr nonlinearity and its interplay with the random polarization effects limit the achievable capacity of the polarization division multiplexed (PDM) coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems [1]. Over the last decade, there have been extensive efforts to surpass the Kerr nonlinearity limit through the development of several digital signal processing techniques [2]. The most investigated digital nonlinear compensation (NLC) techniques are digital back propagation, Volterra series-based nonlinear equalization, and perturbation-based methods. However, the large computational complexity limits the practical implementation of such techniques in coherent optical systems [2]. In [3], a digital phase conjugation (DPC) based technique, referred to as the phase conjugated twin wave (PCTW), is proposed for the mitigation of the first-order nonlinear distortions in PDM optical transmission systems. The PCTW technique can be implemented with minimal additional digital signal processing, providing a simple and effective solution for optical fiber nonlinearity mitigation [4]. However, this gain comes with halving the spectral efficiency of the PDM coherent optical system [5]. Recently, in [6], we proposed a linear polarization-coded phase conjugated twin signals (LPC-PCTS) technique to solve the spectral efficiency issue of the PCTW technique. In this scheme, the data symbols on the adjacent subcarriers of the OFDM symbol are linearly coded and transmitted as phase conjugate pairs on the two orthogonal polarizations. At the receiver, the signals on the two polarizations are coherently superimposed to cancel the first-order nonlinear distortions.

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Only a few studies consider the effects of the random polarization impairment, such as polarization-dependent loss (PDL), on the performance of the digital NLC techniques. In [7], an investigation of the impact of polarization effects on the performance of digital back propagation and perturbation-based NLC is performed. However, to the best of our knowledge, no investigation of the PDL impact on the DPC technique is considered in the literature.

In this letter, we investigate the impact of the PDL on the performance of the recently proposed LPC-PCTS technique. The PDL-induced signal power imbalance between the two polarizations disrupts the cross-correlation property of the nonlinear impairments, which can affect the distortion cancellation through the coherent superposition of the LPC-PCTS technique. Therefore, we introduce a modified procedure, referred to as the linear time-coded (LTC)-PCTS technique, where we transmit linearly coded phase conjugate pairs on adjacent time slots of the same polarization, and compare its PDL tolerance with that of the LPC-PCTS technique. We carry out the investigation with both aligned- and statistical-PDL models. We present results to demonstrate that the LTC-PCTS shows a superior PDL tolerance when compared to the LPC-PCTS, regardless of the PDL model.

The remainder of this letter is organized as follows: Section II describes the aligned- and statistical-PDL models, and Section III explains the simulation setup. In Sections IV and V, the impact of PDL on the two DPC approaches is compared, by considering the aligned- and statistical-PDL models, respectively. Section VI draws the conclusions.

II. THE ALIGNED- AND STATISTICAL-PDL MODELS

PDL is caused by the polarization dependence on the transmission properties of optical components, where one polarization component of the signal suffers more loss than the other. The input/output field relation of a PDL element, rotated with respect to the signal state-of-polarization (SOP) by an angle $\theta$, can be expressed using the Jones matrix representation as [9]:

$$
\begin{bmatrix}
    u_x(t) \\
    u_y(t)
\end{bmatrix}
= \begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    1 & 0 \\
    0 & \alpha
\end{bmatrix}
\begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    v_x(t) \\
    v_y(t)
\end{bmatrix},
\tag{1}
$$

where $[v_x(t) \ v_y(t)]^\dagger$ and $[u_x(t) \ u_y(t)]^\dagger$ represent the input and output optical fields, respectively, with the superscript $^\dagger$ as the transpose. The parameter $0 < \alpha < 1$ is the PDL coefficient defined as the ratio between the minimum and maximum transmission intensities; this is related to the PDL measured in decibels (dB) as $\rho = -20 \log \alpha$ [10].
The PDL impact has been studied in coherent optical systems using two different models: the aligned- and statistical-PDL models [7,11]. In the aligned-PDL model, the signal SOP and the PDL axes of the optical components are aligned with the same rotation angle $\theta$. Fig. 1 (a)-(b) shows two cases for the aligned-PDL model with $\theta = 0^\circ$ and $45^0$, respectively. At the rotation angle $\theta = 0^\circ$, the optical signal-to-noise ratio (OSNR) of one of the polarizations is degraded when compared to the other. On the other hand, for $\theta = 45^0$, the PDL causes same OSNR degradation for both polarization components along with the signal cross-talk due to the loss of orthogonality. In [11], it has been shown that pathological cases of the aligned-PDL elements, such as $\theta = 0^\circ$ and $45^0$, are the worst cases of PDL in linear and nonlinear regimes, respectively.

In the statistical-PDL model, the rotation angle $\theta$ varies uniformly within $[0, 2\pi)$, as shown in Fig. 1 (c). This induces the random signal power and OSNR fluctuations between the two polarizations. In this case, the total cumulated PDL has a Maxwellian distribution with the root mean square (rms) value $\rho_{rms} = \rho \sqrt{N}$, where $N$ is the number of spans [1].

III. Simulation Setup

The simulation setup used to study the PDL impact on the DPC approaches is shown in Fig. 2. We consider a 5-section PDL emulator, which closely approximates a real system [7]. In this setup, the signal interacts with the PDL element after propagating through eight spans of standard single mode fiber (SSMF). Five such loops realize a 5-section PDL emulator. The PDL along the transmission link mainly comes from the lumped optical elements. In a realistic transmission link, such optical elements are placed after several fiber spans. Therefore, placing a PDL element after eight spans of fiber is sufficient enough to study its impact on the performances of the DPC approaches [7]. A polarization controller is placed before the PDL element to control the signal SOP after each round trip. Insets (a) and (b) show the encoder and decoder, respectively, for both LPC/LTC-PCTS techniques. The encoder linearly combines the data symbols on the adjacent subcarriers of the OFDM symbol,
one at full amplitude and the other at half amplitude. This linear coding provides an equal distance between the constellation points and reduces the average probability of symbol error [6]. The linearly combined symbols are then transmitted as phase conjugate pairs on the orthogonal polarizations/time slots. At the receiver, after coherent superposition, maximum-likelihood detection of the recovered symbol is carried out on a symbol-by-symbol basis and a look-up table decoder is applied to obtain the transmitted data symbols [6].

The transmission system consists of a wavelength division multiplexed (WDM) CO-OFDM superchannel employing the LPC/LTC-PCTS techniques. The superchannel comprises four OFDM sub-bands with a frequency spacing of 37.5 GHz. The baud rate is 32 Gbaud. The OFDM symbol consists of 3300 data subcarriers, and the inverse fast Fourier transform size is 4096 [6]. In each OFDM symbol, four pilot subcarriers are inserted for the common phase error compensation and a cyclic prefix of 3% is added. The modulation format is quadrature phase-shift-keying (QPSK). Therefore, the net data rate is 401.33 Gb/s. The long-haul fiber link consists of 40 spans of SSMF, each having a length of 80 km, an attenuation coefficient of 0.2 dB/km, a nonlinear parameter of 1.22/(W.km), and a dispersion parameter of 16 ps/nm/km. The optical power loss for each span is compensated by an erbium doped fiber amplifier with 16 dB gain and 5.5 dB noise figure. The transmitter and receiver lasers have the same linewidth of 100 kHz. At the receiver, after the polarization diversity detector, the dispersion compensation is carried out using the overlapped frequency domain equalizer with the overlap-and-save algorithm [12]. The channel equalization and carrier phase recovery are carried out as in [13].

IV. PERFORMANCE EVALUATION WITH ALIGNED-PDL

The DPC is a generalized technique in which one can use orthogonal polarization states or time slots to transmit the phase conjugate pairs [5]. The motivation behind the recently proposed LPC-PCTS technique is to solve the issue of halving the spectral efficiency associated with the PCTW technique [6]. Its effectiveness strongly depends on the cross-correlation between the nonlinear distortions added onto the transmitted phase conjugate pairs on the two polarizations. However, the polarization cross-talk induced signal power imbalance between the two polarizations may disrupt this cross-correlation property and significantly degrade the performance of the LPC-PCTS technique. For this reason, we consider the LTC-PCTS approach, in which we transmit the linearly coded phase conjugate pairs on adjacent time slots of the same polarization.

In Fig. 3, we consider two simulation scenarios to investigate the performances of the DPC approaches: one is with PDL alone and the other is with the polarization mode dispersion (PMD) and PDL. In both cases, the performances are showed for the two worst case aligned-PDL scenarios with the rotation angles $\theta = 0^\circ$ and $45^\circ$, respectively. The optical launch power is set at the optimum value of $-3$ dBm per channel. When considering only the PDL, the performance of the LPC-PCTS technique with $\theta = 45^\circ$ monotonically decreases as the PDL value increases. The LTC-PCTS technique shows an improved performance, above the soft-decision forward error correction (SD-FEC) limit for the two considered worst case scenarios of the aligned-PDL. The PMD effect is included in the transmission fiber by choosing a typical mean differential group delay of 20 ps, as in [14]. It is observed that the performances of the DPC approaches are significantly affected for the case considering both PMD and PDL. The interplay between PMD and PDL distorts a communication system more than either effects alone. A
separate study is required to understand the interaction between PMD and PDL in the optical transmission link. Henceforth, we focus only on the impact of PDL on the performances of the DPC approaches.

Fig. 3: Q-factor as a function of PMD and PDL with rotation angles $\theta = 0^0$ and $45^0$ at the optimum launch power of $-3$ dBm. SD-FEC: soft-decision forward error correction.

In Fig. 4, the $Q$-factor performance of the DPC approaches is shown for different values of the fiber launch power at a fixed aligned-PDL. In this case, we select a PDL value of 3.6 dB. This corresponds to the rms value of the cumulated PDL in the evaluation with statistical-PDL model, as it will be discussed in Section V. We start analyzing the linear regime, i.e., the initial increasing part of the $Q$-factor curves. For both DPC approaches, the performance in the presence of PDL when $\theta = 0^0$ is lower when compared to the absence of PDL. This degradation in performance can be explained by the impact of the PDL-induced OSNR imbalance between the two polarizations. For $\theta = 45^0$, the performance of the LPC-PCTS is significantly reduced when compared to the LTC-PCTS. This is due to the signal cross-talk induced power fluctuations on the two polarizations along with the OSNR degradation. At high input powers, where the performance is limited by the nonlinear distortions, the DPC approaches with $\theta = 0^0$ perform slightly better than the case without PDL. This can be explained by the decrease of the higher-order nonlinear distortions. In fact, in the presence of PDL, the signal in one polarization is attenuated more than in the other. This leads to the reduction of higher-order nonlinear distortions after the coherent superposition. Note that the higher-order nonlinear distortions are not canceled by the DPC approaches [5]. It is observed that the performance of the LPC-PCTS technique with $\theta = 45^0$ degrades when compared to the LTC-PCTS technique in both linear and nonlinear regimes. This is because the polarization cross-talk, due to the loss of orthogonality, causes signal power fluctuations on the two polarizations [8].
In Fig. 5, the performance of both DPC approaches is presented as a function of the rotation angle \( \theta \) in terms of the \( Q \)-factor penalty. The \( Q \)-factor penalty is defined as: \( \Delta Q = Q_{opt} - Q \), where \( Q_{opt} \) is the \( Q \)-factor at the optimum launch power when PDL is not considered. It is seen that the \( Q \)-factor penalty is maximum at the rotation angle \( \theta = 45^0 \) and minimum at \( \theta = 0^0 \). We also observe that the cross-talk induced \( Q \)-factor penalty at \( \theta = 45^0 \) for the LPC-PCTS technique is 1.84 dB, while it is only about 0.35 dB for the LTC-PCTS technique. It should be noted that further increasing the angle from \( \theta = 45^0 \) to \( 90^0 \)
would result in the mirror image of the plot with a minimum $Q$-factor penalty at $\theta = 90^\circ$ because of the lower cross-talk induced power fluctuations. Therefore, we provide results for angles ranging from $\theta = 0^\circ$ to $45^\circ$ only.

V. PERFORMANCE EVALUATION WITH STATISTICAL-PDL

The $Q$-factor distribution presents a more realistic impact of the PDL on the performances of DPC approaches. Fig. 6 shows the estimated probability density function (PDF) of the $Q$-factor in the presence and absence of PDL for both LPC/LTC-PCTS techniques. We carried out Monte Carlo simulation to estimate the $Q$-factor PDF by using 500 random seeds of the signal SOP and the PDL orientation angle $\theta$ in the limit $[0, 2\pi)$. We select a typical PDL value of $\rho = 1.6$ dB [7]. This gives an rms cumulated PDL value for a 5-section PDL emulator of 3.6 dB (i.e., $1.6 \times \sqrt{5}$). The fiber launch power is fixed at the optimum value of $-3$ dBm.

![PDF of Q-factor for LPC-PCTS and LTC-PCTS at $\rho_{rms} = 3.6$ dB and optical launch power $= -3$ dBm.](image)

The results indicate that without PDL, the $Q$-factor distributions for both DPC approaches are very narrow. On the other hand, in the presence of PDL, the $Q$-factor distribution of LPC-PCTS significantly enlarges, which leads to an increased outage probability. We define the outage probability as the probability that the random $Q$-factor is less than a certain threshold value, i.e., $Pr[Q < Q_t]$, where $Q_t$ is the threshold. For instance, assuming a $Q_t$ value of 5.7 dB corresponding to the SD-FEC limit [15], the outage probability for LPC-PCTS in the presence of PDL is 0.63. However, it is observed that the outage probability for LTC-PCTS approaches zero in the presence of PDL. This indicates that the approach which uses the orthogonal time slots of the same polarization is only slightly affected by the PDL-induced distortions.

VI. CONCLUSION

We investigated the performance penalties induced by the PDL on the LPC/LTC-PCTS techniques, in a CO-OFDM superchannel system. We carried out a comprehensive numerical study using aligned- and statistical-PDL models. In the
investigation with the aligned-PDL, LTC-PCTS shows a superior PDL tolerance when compared to LPC-PCTS. The $Q$-factor performance of the former is above the SD-FEC limit for the pathological cases of all aligned-PDL with $\theta = 0^\circ$ and $45^\circ$.

The investigation with the statistical-PDL model also indicates that LTC-PCTS outperforms the LPC-PCTS technique, with the former providing an outage probability approaching zero for an rms PDL value of 3.6 dB. We concluded that while LPC-PCTS is severely affected by the PDL-induced distortions, LTC-PCTS still provides a good performance under such conditions. In future, this work can be extended to consider the impact of the interplay between PMD and PDL on the performance of the LPC/LTC-PCTS techniques.

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