Digital Signal Processing for Optical Phase Conjugation Assisted Coherent Systems

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ABSTRACT

We review our recent progress in the development of digital signal processing techniques to mitigate the impact of the phase modulation of the pump source on coherent optical systems deploying fibre-based optical phase conjugation devices.

Keywords: digital signal processing, optical phase conjugation, pump dithering, phase-modulated signals, phase and phase-to-amplitude distortion.

1. INTRODUCTION

Optical phase conjugation (OPC) is a promising technology for the simultaneous compensation of the accumulated chromatic dispersion and distortion due to fibre Kerr nonlinearities in coherent optical systems [1],[2]. In fibre-based OPC devices relying on FWM, a widely used approach to overcome the limitation on the launched pump power imposed by stimulated Brillouin scattering consists in imparting a phase modulation to the pump source so as to broaden the laser linewidth, hence minimise the power spectral density integrated over the Brillouin bandwidth [3]. However, the pump phase modulation introduces phase distortions on the conjugated signal (idler) can severely and directly degrade the performance signal formats carrying information in the phase, and subsequent dispersion may induce phase to amplitude distortion conversion. In a dual-pump OPC system, the phase modulation transfer from the pump to the idler can, in principle, be fully suppressed by modulating the two pumps with the opposite phase modulation (push-pull) [4]. However, this approach involves adjustment of the delays and amplitudes of the electrical signals driving the phase modulators, which is difficult to perform exactly. Therefore, some residual dithering commonly exists in practice, even under carefully adjusted dithering settings [5], and appeals for the use of advanced digital signal processing (DSP) to counteract its side effects. Conventional DSP carrier phase recovery algorithms developed to estimate and compensate the effective phase noise (PN) due to non-zero laser linewidth in phase-modulated signal transmission, are not sufficient to track high levels of dithering PN because of their decision-directed operation [6] or the requirement of a relatively constant PN evolution over a long time-window [7].

In this paper, we review our recent work on the development of advanced DSP schemes for mitigating the phase distortion induced by imperfect counter-phasing of the pumps in the OPC of quadrature-amplitude modulation (QAM) signals [8],[9] and the phase-to-amplitude noise transfer resulting from the interaction of the residual pump dithering with the dispersive fibre channel in OPC-assisted QAM transmission [10].

2. DITHERING-INDUCED PHASE DISTORTION COMPENSATION

Figure 1(a) shows the experimental setup of the OPC-assisted dual-polarisation 28-Gbaud M-QAM system that was used to validate our PN compensation methods. The transmitted optical signal was conjugated through a polarisation insensitive OPC with orthogonally polarised pumps spectrally located at 1540.4nm and 1560.1nm, and with laser linewidth ~30kHz [2]. Two signals consisting of two sinusoidal radiofrequency (RF) tones at frequencies f_1 = 60MHz and f_2 = 600MHz were used to independently modulate the phases of the pump lasers after non-ideal RF amplification and lowpass filtering (700-MHz cut-off). The amplitude and phase parameters of the dithering tones were first adjusted to minimise the phase modulation transfer to the idler. The RF spectrum of the photo-detected conjugated copy of a continuous-wave laser after the OPC shown in the inset of Fig. 1(a) features 37.5 dB suppression of the phase-modulation sidebands transferred from the pumps. Then, we intentionally increased the counter-dithering phase mismatch $\delta\theta$ by tuning the phase offset of the RF tones. A standard DSP procedure for data recovery [11] was implemented offline at the receiver. Assuming perfect timing recovery, ideal synchronisation and zero frequency-offset, the phase-distorted signal at the input to the PN compensation module, sampled at 1 sample per symbol, can be written in the form $y[k] = x[k]\exp[i(\delta\phi[k] + \phi_m[k])] + \varepsilon[k]$, where $x[k]$ are the transmitted symbols and $\varepsilon[k]$ is the additive white Gaussian noise in the system (Fig. 1(b)). The first phase term represents the Wiener random laser PN: $\delta\phi[k] = \delta\phi[k-1] + W[k]$, where $W[k] \sim \mathcal{N}(0,2\pi\delta\nu T_s)$, $\delta\nu$ is the combined spectral linewidth of the system (total linewidth of transmit, receive, and pump lasers), and T_s is the symbol period. The second phase term $\phi_m[k] = \phi_{m1}[k] + \phi_{m2}[k] \sim (m + \delta m)[\cos(2\pi f_1 t_k + \delta\theta) + \cos(2\pi f_2 t_k + \delta\theta)] + m[-\cos(2\pi f_1 t_k) - \cos(2\pi f_2 t_k)]$ represents the deterministic phase distortion generated by imperfect pump counter-phasing which we aim to estimate and remove, where m is the modulation index and the modulation-index mismatch δm represents possibly different modulation indices.

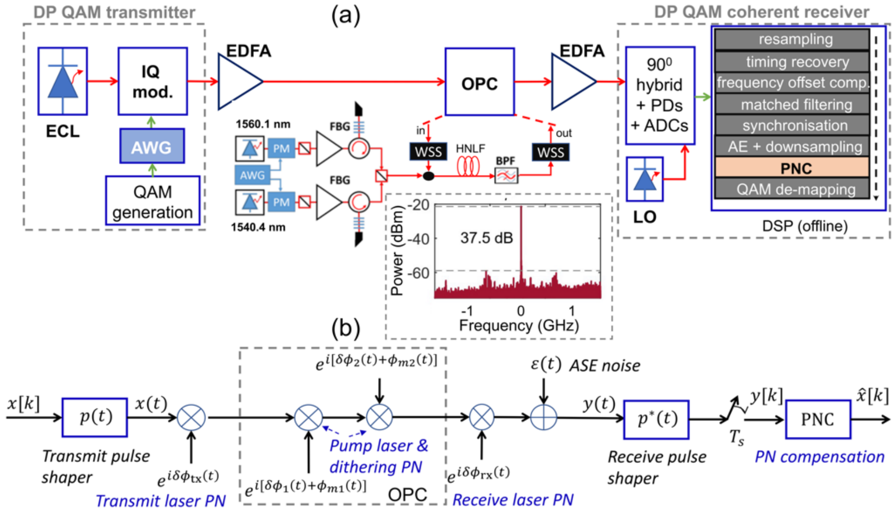

Figure 1. (a) Experimental setup showing the dual-polarisation 28-Gbaud M-QAM transmitter, the dual-pump OPC device, the coherent receiver, and the offline DSP. Inset: RF spectrum of coherently received conjugated continuous-wave signal after the OPC with optimised pump dithering. (b) Conceptual model of the various sources of noise in the OPC transceiver.

In [8], we developed a new dual-stage PN compensation scheme for high-order signal modulation formats, where the first stage was a conventional blind phase search (BPS; for 16-QAM) or pilot-aided (for 64- and 256-QAM) phase estimation algorithm. After the first stage, the phase distortion arising from the residual pump dithering is partly removed from the input signal. Therefore, in the second PN compensation block we focussed on the dominant residual dithering components, which occur at the original dithering drive frequencies, and we performed a least-squares (LS) error fit to the required amplitudes and phases of the tone signals. We demonstrated experimentally and numerically that the proposed approach achieves large effective signal-to-noise (SNR) improvement relative to conventional PN compensation when it is used with 16/64/256-QAM signals in the presence of severe imperfections in the pump-modulation scheme. Therefore, our results indicate that a slight increase in the complexity of the offline DSP in coherent optical systems deploying OPC may be considered as an alternative to the precise calibration of the pump dithering scheme. The technique may firstly allow the applied pump dithering to be increased, improving the OPC conversion efficiency and secondly, reduce residual dithering penalties for OPC systems with lower optical SNR penalties.

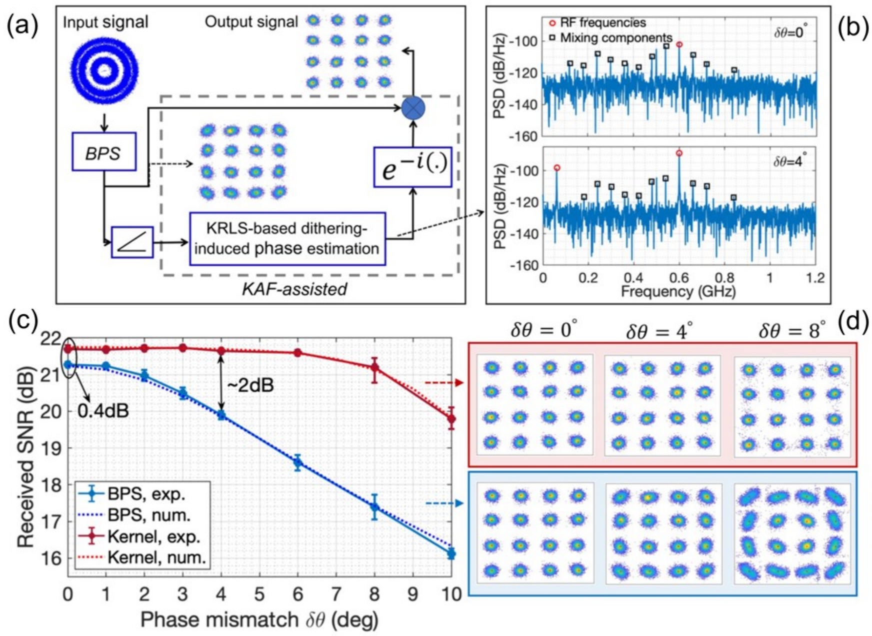

Figure 2. (a) Block diagram of the KRLS-based PN compensation scheme. (b) Spectral representation of the estimated PN after the KAF unit for 16-QAM. (c) Received SNR versus pump-phase mismatch $\delta\theta$ for 16-QAM

system after BPS and KRLS-based PN compensation (blue and red curves, respectively). The experimental and numerical results are represented by solid and dotted curves, respectively. (d) Constellation diagrams at $\delta\theta = 0°, 4°,$ and $8°$ for the BPS and KRLS-based schemes.

In [9], we have proposed for the first time the aid of machine learning (ML) to conventional DSP phase recovery by deploying the sliding-window kernel-based recursive LS (KRLS) algorithm presented in [12] to correct the residual dithering phase distortion of pilot-free QAM signals. In this approach, the phase of the signal after conventional PN compensation is regarded as the result of a time-varying process. The algorithm then tracks these time variations by considering data in windows of fixed size and calculating the updated solution for each window. Within the proposed scheme (Fig. 2(a)), the phase of the signal after BPS compensation, $\widehat{\boldsymbol{Y}}_1$, was stripped off and fed into the kernel adaptive filtering (KAF) unit. Slightly differently from [12], our implementation of the KRLS algorithm sought the optimal model vector $\boldsymbol{h}$ that solved the LS problem: $\min_{\boldsymbol{h}}\left\|\angle\{|\widehat{\boldsymbol{Y}}_1\boldsymbol{h}|_{\mathrm{D}}\} - \angle\{\widehat{\boldsymbol{Y}}_1\boldsymbol{h}\}\right\|^2$, where $\angle\{\cdot\}$ and $|\cdot|_{\mathrm{D}}$ are the angle and direct-decision operators, respectively. The phase evolution estimated in this way was then used to compensate for the remaining phase distortion after the BPS block. Remarkably, the scheme can detect the several frequency components transferred from the RF tones and their linear and nonlinear mixing to the idler that are still present in the optimum pump counter-phasing configuration ($\delta\theta \sim 0°$; Fig. 2(b)). Figure 2(c) shows the experimentally and numerically calculated performance of the KRLS-enhanced scheme in terms of effective SNR for varying pump-phase mismatch $\delta\theta$ when used with a 16-QAM signal. We can see that the proposed approach achieves SNR gain over conventional BPS-based PN compensation under fully optimised dithering settings ($\delta\theta \sim 0°$) and shows negligible performance penalty relative to the optimum case in the region of small to moderate residual dithering. These results evidence that the KRLS-based approach is highly sensitive to the residual pump dithering, which sets it apart from the dithering compensation method demonstrated in [8] by making it particularly suitable for offsetting small imperfections in the pump-phase modulation scheme of the OPC. Furthermore, owing to its non-parametric nature, the KRLS algorithm deployed requires no prior knowledge of the dithering frequencies and is indifferent to the number of frequencies used.

3. DITHERING-INDUCED PHASE-TO-AMPLITUDE DISTORTION COMPENSATION

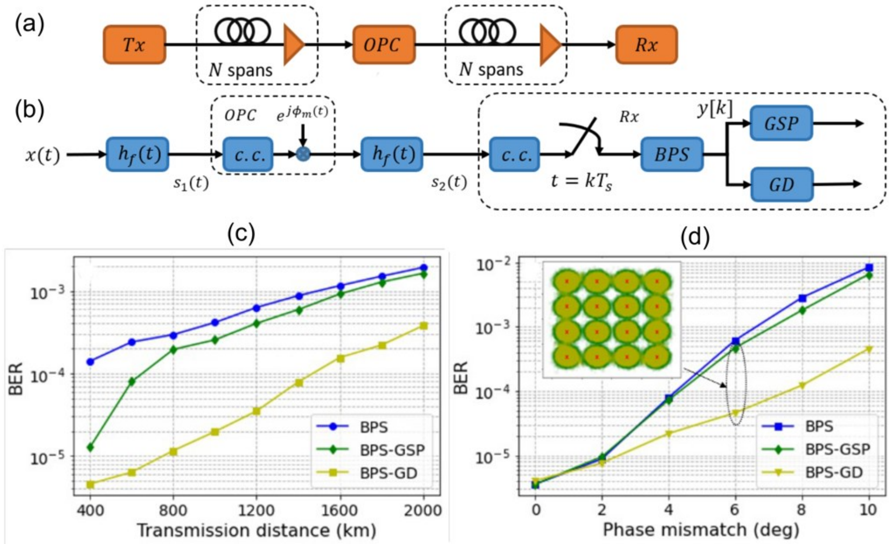

Figure 3. (a) Schematic of mid-link OPC transmission system. (b) Baseband channel model. (c) BER after BPS, BPS-GSP and BPS-GD PN compensation versus transmission distance in the link at a pump-phase mismatch of $\delta\theta = 6°$. (d) BER versus pump phase mismatch after 1200-km transmission. The inset shows the signal constellation diagrams for $\delta\theta = 6°$.

Both the compensation methods discussed in the previous section can deal only with the residual phase distortion of the signal. Therefore, their effectiveness in transmission is diminished by the accumulation of phase-to-amplitude noise transfer that results from the interaction of the PN induced by the pumps in the OPC with the chromatic dispersion of the fibre channel. In [10], we have proposed for the first time a ML-enabled DSP scheme that is able to extrapolate and remove the amplitude impact from the dither-induced phase distortion of the received signal. It consists of two blocks: a BPS stage followed by noise compensation using gradient descent (BPS-GD). The BPS mitigates the linewidth induced slow varying PN from the laser components [6]. Considering a linear baseband model equivalent to a fibre channel with mid-link OPC (Fig. 3(b)), the complex received signal or post-BPS signal (if non-zero laser linewidths present) can be approximated as $y[k] = x[k] + n[k]$, where $n[k] = [s_1[k] i\phi_m[k]] * h_f^*[k]$ represents the dithering-induced complex noise, $s_1(t)$ is the signal after the first fibre link, and $h_f(t)$ is the finite impulse response filter representing the fibre channel. The second compensation block focuses on creating an estimate of the complex noise $n[k]$ in the received signal, assuming full knowledge of the chromatic dispersion in the fibre channel. It does that by assuming that the dithering frequencies can be extracted from the spectral representation of the residual phase distortion after the BPS compensation. Therefore, we can form a feature vector $X = [\sin(2\pi f_i k), \cos(2\pi f_i k), \ldots]^T$, $i = \overline{1, L}$, where L is the number of RF tones and apply linear regression. The model was trained through a batch GD algorithm with an error signal obtained from the complex difference of the received symbols and post-BPS symbols.

Our numerical model was implemented for the transmission of a 28-Gbaud 16-QAM signal over a channel containing N standard single-mode fibre spans of 100-km length (Fig. 3(a)) [5],[8]. Figures 3(c) and 3(d) show examples of the direct-count BER performance of the proposed BPS-GD scheme compared with those of the scheme demonstrated in [8] using grid search on the signal phase after BPS (BPS-GSP), as well as with single-block BPS compensation. We observe in Fig. 3(c) that the BPS-GSP method gives significant BER improvement over single-stage BPS compensation at short transmission lengths where the impact of phase-to-amplitude noise transformations is small, but then it quickly fails to cope with the accumulation of this effect over transmission. Conversely, the proposed BPS-GD algorithm shows consistent performance benefit across a wide range of transmission lengths. Figure 3(d) highlights significant reduction of the rate of BER growth by the BPS-GD method when the effects of the residual dithering PN start becoming important.

4. CONCLUSIONS

We have discussed various recently introduced DSP methods for compensating the phase and phase-to-amplitude signal distortions caused by the pump phase modulation in OPC-assisted coherent systems. Current work includes the development of more advanced ML-based schemes able to simultaneously remove the dithering-induced phase and amplitude distortions from the received signal within a single stage, in coherent transmission systems with cascaded fibre-optical parametric devices.

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