Inverse Hyperbolic-Tangent Pre-distortion for OOFDM Systems

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***Abstract*—We propose an inverse hyperbolic-tangent-based digital pre-distorter that can suppress the Mach-Zehnder modulator-induced harmonic distortions by about 13 dB for single-tone signals, while maintaining the peak-to-average power ratio in optical orthogonal frequency division multiplexed signals.**

***Index Terms*—Digital pre-distortion, harmonic distortion, Mach–Zehnder modulator, optical orthogonal frequency division multiplexing, peak-to-average power ratio.**

I. Introduction

Optical orthogonal frequency division multiplexing (OOFDM) has been widely adopted in intensity modulation-direct detection (IM-DD)-based radio-over-fiber (RoF) communications due to its multiple advantages, particularly, its high spectral efficiency. However, one of its inherited limitations is its sensitivity to the electro-optic (E-O) conversion nonlinearities, especially when the OFDM signal possesses a high peak-to-average power ratio (PAPR). This limitation requires the E-O modulators, such as the Mach–Zehnder modulator (MZM), to be highly linear over a wide dynamic range. Several approaches have been proposed to linearize the MZM characteristics over its full range and/or reduce the PAPR of the driving OFDM signal. For instance, in [1], the inverse-sine transfer function (IST) has been proposed as a digital pre-distortion (DPD) technique that can fully compensate the MZM transfer function and hence, reduce the sensitivity of high PAPR OFDM signals to its nonlinearities. In [2], a memory polynomial model is used to mitigate the MZM nonlinearities and, at the same time, improve the optical signal modulation index (MI). Furthermore, the use of signal pre-distortion, together with PAPR reduction techniques, such as IST combined with selective mapping [3] or with companding [4], has also been considered for the same reason. To this end, here, we propose an inverse hyperbolic-tangent (IHT)-based DPD technique and evaluate its impact on single-tone radio frequency (RF) signals in terms of the total harmonic distortion (THD). Additionally, the impact of this technique on the PAPR of typical OFDM signals is also evaluated. The IHT-DPD is compared with DPD-free and the IST-DPD cases as upper and lower performance bounds.

II. IM-DD OOFDM System Model with the Proposed digital pre-distorter

Fig. 1 illustrates a block diagram for the digital signal processing (DSP) stages in a typical IM-DD OOFDM transmitter, including the DPD stage. As this figure shows, an M constellation points quadrature amplitude modulation (M-QAM) signal is distributed over N sub-carriers with a uniform sub-carrier spacing of Δf. Then, the modulated sub-carriers are transformed into a time domain OFDM symbol via an N-points inverse fast Fourier transform (IFFT) module before being cyclically prefixed (CP) by the last N_{CP} samples of the same OFDM symbol. After that, the IHT transform is applied to the CP-OFDM complex symbol in-phase (I) and quadrature (Q) components separately. The pre-distorted symbol is then forwarded to the DAC, which is followed by an RF up-converter for IQ mixing. The resulting RF signal is applied to the single-drive MZM, which is biased at its negative quadrature ($-$Q) point, for E-O conversion. The optical intensity at the MZM output, denoted by $P_o(t)$, can be expressed as follows [5]:

$$P_o(t) = P_i\left[1+\cos\left(\pi\frac{v_{\mathrm{RF}}(t)+V_B}{V_\pi}\right)\right] , \quad (1)$$

where P_i is the un-modulated input optical power, $v_{\mathrm{RF}}(t)$ is the RF input voltage, V_B is the MZM DC bias voltage, and V_π is the voltage required by the MZM to introduce a phase shift of π to the input light-wave carrier. In this paper, the IST transform refers to the inverse of the E-O conversion function in (1). The proposed IHT transform can be mathematically expressed as follows:

$$v_{\mathrm{out}} = \frac{2V_\pi}{\pi}\tanh^{-1}\left(\frac{-v_{\mathrm{in}}}{2\max\{|v_{\mathrm{in}}|\}}\right) , \quad (2)$$

where v_{in} and v_{out} are the IHT input and output voltages, respectively, and v_{in} voltage is amplitude-normalized for both the IHT and IST signals.

III. Results and Discussion

The simulations start by examining the impact of the MZM nonlinearity on a single-tone RF signal with and without IHT

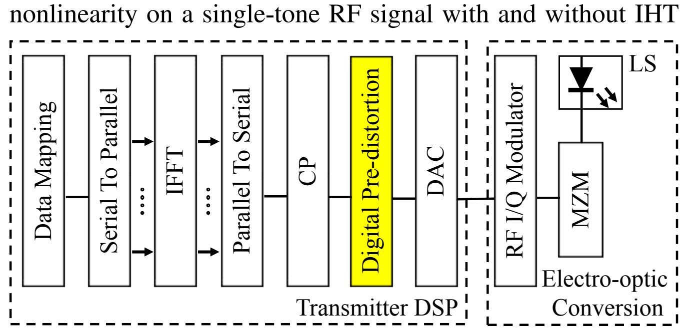

Fig. 1. Block diagram of a typical IM-DD OOFDM transmitter. DSP: Digital signal processing. IFFT: Inverse fast Fourier transform. CP: Cyclic prefix. DAC: Digital-to-analog converter. MZM: Mach–Zehnder modulator. LS: Laser source.

and IST pre-distortion. The peak voltage of this signal is varied from 10 mV to $V_\pi/2$, with a step of 25 mV, around the MZM's $-$Q point, i.e., $V_B = V_\pi/2$. Accordingly, the MI, defined as $\mathrm{MI} = 2V_{\mathrm{in,RMS}}/V_\pi$ [2], changes from 0.0028 to $1/\sqrt{2}$, where $V_{\mathrm{in,RMS}}$ is the RMS value of v_{in}. The MZM switching voltage, V_π, is 5 V and its optical input power P_i is 1 W. Fig. 2(a) and (b) illustrate the fundamental component power and the THD contained in the resulting signals, respectively, versus the MI. Both power components are evaluated using Fourier-based harmonic analysis [6]. Fig. 2(a) shows that, for all values of MI, the proposed IHT pre-distorter can produce approximately the same fundamental component power as the ideal IST pre-distorter. Both pre-distortion techniques, however, result in a power loss in the fundamental component, which can be as high as 3.9 dB relative to the DPD-free signal. In terms of the THD performance, Fig. 2(b) indicates that the IST technique outperforms the proposed IHT technique as the former can invert the MZM nonlinear characteristics with a residual THD as low as -120 dB. However, compared to the DPD-free signal, still the proposed IHT technique can suppress the THD by about 13 dB at an MI of 0.35.

The OFDM input signal is formed by distributing 64-QAM symbols over $N = 512$ and 64 sub-carriers with a sub-carrier spacing of $\Delta f = 0.3125$ MHz and a CP length of $N_{\mathrm{CP}} = N/4$. Fig. 3 shows the complementary cumulative distribution function (CCDF) versus the PAPR for the three considered OFDM signals. As can be seen in this figure, for CCDF < 1, both pre-distortion techniques increase the PAPR of the OFDM signal above the DPD-free levels. Nevertheless, the CCDF-PAPR performance of the proposed IHT technique is closer to the DPD-free levels than the IST technique. To put into perspective, considering a reference CCDF as low as 10^{-3}, the IHT technique increases the PAPR of an undistorted 64 sub-carriers OFDM signal by about 0.4 dB, whereas the IST technique increases the PAPR of the same signal by about 2 dB. When the number of sub-carriers increases to 512, the PAPR increases by 2.6 dB compared to the DPD-free level as a result of applying the IST transform, whereas the IHT technique maintains its PAPR relatively close to the DPD-free level by about 0.6 dB.

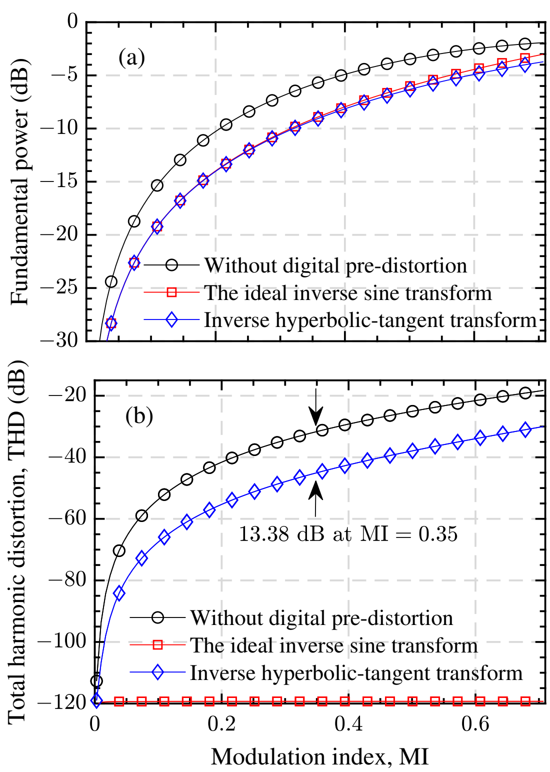

Fig. 2. Output optical power components of the Mach-Zehnder modulator in response to pre-distorted and distortion-free single-tone electrical signals. (a) Fundamental component power. (b) Total harmonic distortion.

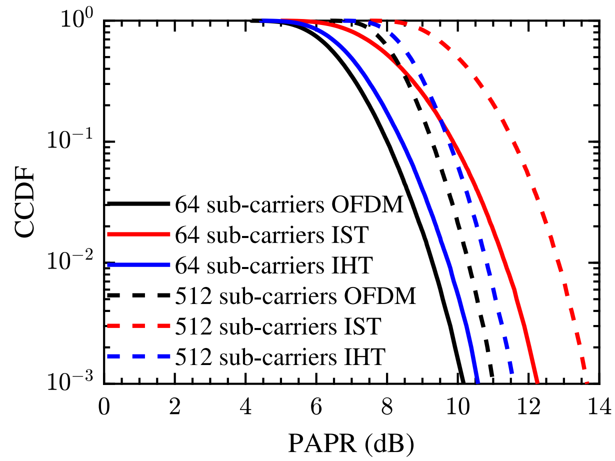

Fig. 3. Complementary cumulative distribution function (CCDF) versus the peak-to-average power ratio (PAPR) for the 64-QAM pre-distorted and distortion-free OFDM input signal. IST: inverse sine transform. IHT: inverse hyperbolic-tangent transform.

IV. Conclusion

We propose an inverse hyperbolic-tangent pre-distortion technique for OOFDM IM-DD systems. Simulation results show that the proposed technique can reduce the harmonic distortions caused by the MZM nonlinearity by about 13 dB when applied to un-modulated single-tone signals and introduces a negligible impact on the PAPR of 64-QAM-modulated OFDM signals.

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