Reduced Complexity Adaptive Background Compensation of Electro-Optic Tx Impairments in Coherent Optical Transceivers

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Abstract: We propose a novel background compensation of electro-optic Tx impairments for coherent optical transmitters based on the backpropagation algorithm and a direct detection low bandwidth feedback channel. Its excellent effectiveness is demonstrated by computer simulations.

1. Introduction

Next generation communications demand coherent optical transceivers (COT) with data rates in the 1.6 Terabit-per-second range and beyond [1]. Achieving these high speeds may require high-order modulation formats and/or high baud rates. In these scenarios, severe performance degradation may be experienced in the presence of impairments introduced by the transmitter (Tx). Among them, we can mention the amplitude and phase imbalances between the in-phase (I) and quadrature (Q) components (i.e., Tx I/Q imbalance), Tx I/Q time skew, and bandwidth (BW) mismatches in the frequency responses of the electrical paths between the digital-to-analog converters (DACs) and the Mach-Zehnder modulator (MZM). In this paper, we will refer to these Tx impairments as *Tx I/Q mixing effects*.

The compensation of the Tx I/Q mixing effects has been extensively addressed in the literature. Techniques of (pre) compensation used in the transmitter are preferred over schemes implemented in the receiver side [2–5]. In these approaches, a feedback channel (FC) is used at the transmitter to estimate the different parameters of the Tx channel. In general, existing compensation techniques suffer from the following drawbacks: *(i)* they are performed in foreground mode, and therefore are not applicable to coherent transceivers, and/or *(ii)* they require photodetectors (PDs) and a feedback channel with a bandwidth large enough to process the full bandwidth of the transmitted signal, which increases significantly the complexity and power consumption. Adaptive background operation instead of foreground is important in coherent optical transmitters to ensure automatic compensation of the errors caused by process, voltage, and temperature variations, and therefore achieve high manufacturing yield of the integrated circuit implementations. On the other hand, having a low-bandwidth feedback channel would allow the use of low-cost PD, transimpedance amplifiers (TIAs), and analog-to-digital converters (ADCs), which is essential for its adoption in commercial COT.

In this work, we propose an all-digital adaptive background compensation of Tx I/Q mixing effects based on a low complexity and low bandwidth feedback channel. The key ingredients of the proposed technique are (*i*) a novel channel estimation algorithm introduced recently in [6], and (*ii*) the backpropagation algorithm used to adapt the coefficients of the compensation equalizer [7]. The complexity reduction of the feedback channel comes from the fact that the Tx electro-optical (EO) response in a given polarization, can be accurately estimated at the transmitter by using a single PD followed by a low bandwidth observation channel (see [6] for more details). Thus, to implement the feedback channel at the Tx, it is possible to use not only low-cost PDs and TIAs but also low speed ADCs. Computer simulations demonstrate that accurate mitigation of the EO Tx impairments can be achieved with the proposed reduced complexity compensation scheme.

2. Background Compensation based on a Single Photodetector and Low BW Feedback Channel

Without loss of generality, a coherent optical transmitter with one polarization is considered in this work (see Fig. 1.a). Let $\hat{a}[k] = a_I[k] + ja_Q[k]$ be the complex quadrature amplitude modulation (QAM) transmit symbol. We also define T and $1/T_s$ as the symbol duration and the sampling rate of the DACs, respectively. For simplicity, we assume that the oversampling factor $M = T/T_s$ is an integer number greater than unity (e.g., $M = 2$). Then, the digital complex signal results

$$\hat{s}[n] = s_I[n] + js_Q[n] = \sum_k \hat{a}[k]g[n-kM], \tag{1}$$

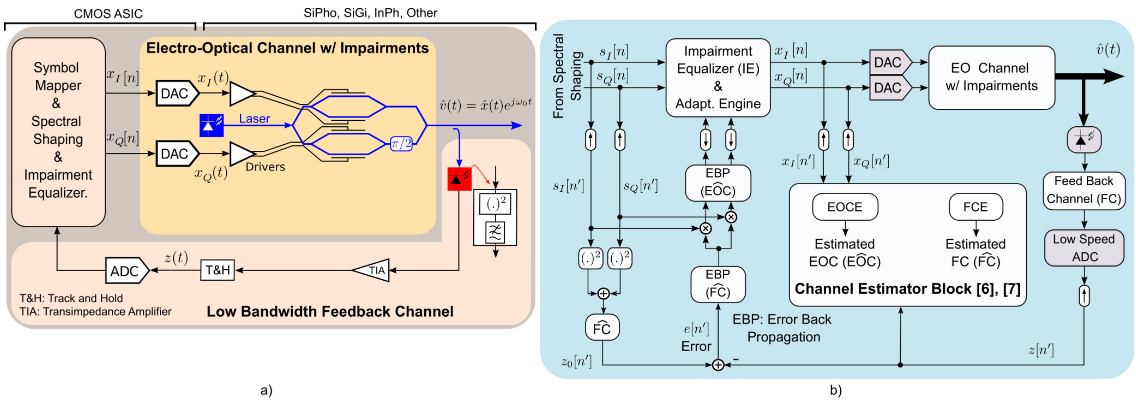

Fig. 1: Coherent optical transmitter with an all-digital adaptive background compensation system based on a low bandwidth feedback channel. a) Top view of the proposed architecture. b) Block diagram of the compensation system for one polarization. Ideal PD, DACs, and ADC stages are assumed (bandwidth limitations and impairments are included in both EO channel (EOC) and feedback channel (FC) blocks).

where $g[n]$ is the oversampled impulse response of the transmit filter (e.g., square root raised cosine filter). As we will explain later, the complex signal $\hat{s}[n]$ is processed by the *Impairment Equalizer* (IE) in order to compensate the Tx mixing effects. The DACs produce two continuous-time signals, $x_I(t)$ and $x_Q(t)$ from the discrete-time real signals provided by the IE, $x_I[n]$ and $x_Q[n]$, respectively. The signals $x_I(t)$ and $x_Q(t)$ are amplified by two modulator drivers and then used to control the MZM.

Some of the most important impairments in the analog Tx EO paths are the following. *(a) I/Q Time Skew* (τ_{skew}): this is mainly caused by mismatches between the I/Q electrical paths from the Tx DACs upto the MZM. *(b) Bandwidth Mismatches*: DACs, drivers, and MZM should have an ideal flat low pass filter response with a nominal bandwidth of $B_0 \approx \frac{1}{2T}$. In reality, the frequency responses of the Tx I/Q EO paths are not well controlled: their bandwidths may be larger or smaller than B_0 and not flat in the signal band. *(c) Gain and Phase Errors (Tx I/Q Imbalance)*: the complex optical carrier with Tx I/Q imbalance can be written as $p(t) = (1-\varepsilon_g)\cos[\omega_0 t + \phi_e/2 + \theta(t)] + j(1+\varepsilon_g)\sin[\omega_0 t - \phi_e/2 + \theta(t)]$, where ε_g and ϕ_e are the gain and phase imbalance, respectively, $\theta(t)$ is the carrier phase error, while $\omega_0 = 2\pi f_0$ with f_0 being the carrier frequency. As a result of the high symbol rates (e.g., 128 Giga-baud (GBd)) and/or high-order modulation formats (e.g., 64-QAM), all these Tx impairments would introduce large distortions and severely degrade the system performance.

The proposed technique for the adaptive compensation of Tx I/Q mixing effects consists in the *backpropagation* algorithm [7], allowing for the optimal digital and background compensation of the Tx EO channel impairments. In addition, we propose a novel *channel estimator* algorithm to allow the system identification of the Tx EO channel[1] and thus providing the model used in the backpropagation algorithm [7]. Since the latter requires to feedback the modulated optical signal to the Tx, we propose this measuring to be performed with a conventional PD and a low speed ADC, in order to reduce drastically the cost of the device. The feasibility of using a single PD followed by a low-bandwidth FC[2] to accurately estimate the Tx EO channel has been suggested in [6]. It was mathematically demonstrated, and verified by computer simulations, that it is possible to identify a certain system (e.g., Tx EO channel) using a feedback channel based on an *uncoupling nonlinear block* (e.g., single photodetector) followed by an *observation linear channel* (e.g, FC) with a bandwidth much lower than that of the system of interest (see [6] for more details).

Figure 1.b depicts a block diagram of the proposed compensation system. The *Channel Estimator* (CE) block is used to estimate the channel responses needed to achieve the error backpropagation for adapting the IE. The Tx EO channel and the observation channel are estimated by the *EO channel estimator* (EOCE) and the *feedback channel estimator* (FCE), respectively. These blocks use the DAC inputs ($x_{I,Q}[n']$), the upsampled feedback signal $z[n']$, and the least mean squares (LMS) algorithm [6] [7]. Notice that quadratic blocks are used to emulate the nonlinear response of the photodetector. On the other hand, since the quadratic operation duplicates the bandwidth of the input sequence, upsampling stages are used to avoid aliasing.

Once the Tx EO and feedback (observation) channel responses are estimated, we can evaluate the error signal $e[n'] = z_0[n'] - z[n']$, where $z[n']$ is the feedback sample while $z_0[n']$ is the real signal obtained by filtering $|\hat{s}[n']|^2$ with the estimated FC response (see Fig. 1.b). Then, the IE is adapted to minimize the mean squared error (i.e., $E\{|e[n']|^2\}$ with $E\{.\}$ being the expectation operator) by using the LMS algorithm. It is important to observe that, although $e[n']$ is the error that must be driven towards zero to achieve the compensation of the Tx EO channel mismatches, it is not the proper error to adapt the IE since it is not computed directly at the output of the latter. Therefore $e[n']$ must be *backpropagated* before it can be applied to the adaptation of the IE (see Fig. 1.b). The estimated EOC and FC responses are used to perform the error backpropagation as explained in [7].

[1]Tx EO channel (EOC) includes the frequency responses of DACs, drivers, and MZM, as well as the modulator phase and gain errors [7].
[2]The feedback channel (FC) includes the combined frequency responses of PD, TIA, and track-and-hold (T&H).

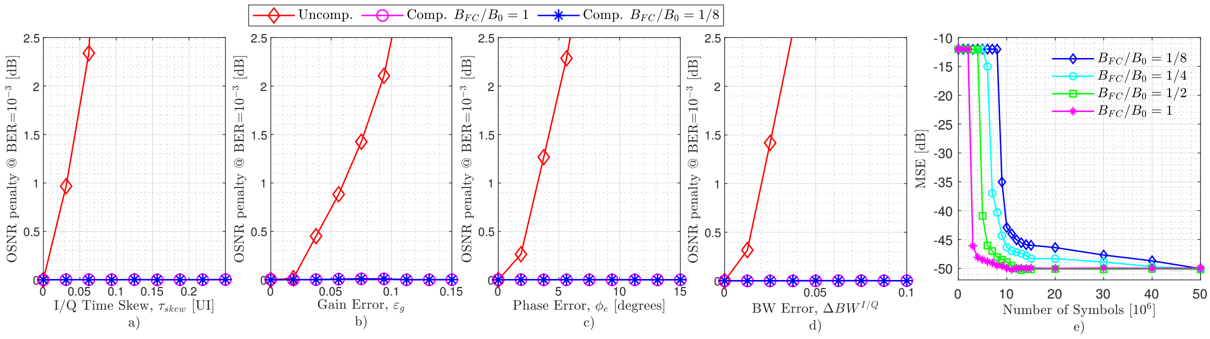

Fig. 2: OSNR penalty versus (a) Tx I/Q time skew, (b) gain error, (c) phase error, and (d) bandwidth error, at BER= 10^{-3} for a feedback channel with $B_{FC} = B_0$ and $B_{FC} = B_0/8$. (e) MSE vs different feedback bandwidths, B_{FC}.

3. Simulation Results and Conclusions

We investigate the performance of the proposed adaptive compensation scheme in the presence of Tx I/Q mixing effects. We consider 64-QAM with a baud rate of $1/T = 128$ GBd in a back-to-back optical channel. We assume 8-bit resolution DACs with $1/T_s = 192$ GS/s sampling rate and $B_0 = 64$ GHz nominal BW. Pulse shaping with raised cosine filters and rolloff factor of 0.10 is applied. The numbers of taps in the different digital filters were properly adjusted to avoid any performance degradation (optimization of DSP blocks will be discussed in a future work). The electrical analog path responses between DACs and MZM are modeled by sixth-order Butterworth lowpass filters (LPFs) with BWs $B_0 \pm \frac{\Delta BW}{2}$ where ΔBW is the BW mismatch. In the feedback channel, PD is modeled as a current generator proportional to the optical power, followed by a LPF in charge of the modeling of the PD frequency response. This LPF, combined with the responses of the TIA and T&H, is also modeled by a sixth-order Butterworth LPF with a bandwidth B_{FC} ($B_{FC}/B_0 \in \{1, \frac{1}{2}, \frac{1}{4}, \frac{1}{8}\}$). We focus on the optical signal-to-noise ratio (OSNR) penalty at a bit-error-rate (BER) of 10^{-3}, which is computed using an ideal software receiver. For details of the traditional DSP blocks of a coherent optical transceiver see [1].

Figures 2.a to 2.d show the OSNR penalty as a function of the I/Q time skew, gain, quadrature, and BW mismatches, respectively. To emphasize the mismatch effects, only one effect is applied at a time. We present results with and without the proposed background compensation technique for two BWs of the feedback channel ($B_{FC} = B_0$ and $B_0/8$). The effectiveness of the IE to compensate the Tx I/Q mixing effects is verified in all cases.

Figure 2.e shows the temporal evolution of the averaged quadratic error between the Tx baseband signal and the ideal sequence (1) for several values of B_{FC} when combined Tx impairments are applied simultaneously ($\tau_{skew} = 0.125T$, $\varepsilon_g = 0.075$, $\phi_e = 7.5^o$, $\Delta BW/B_0 = 0.05$). The different starts of convergence are due to the longer time required to estimate the Tx EO and FC responses when B_{FC} is reduced. In all cases, notice that the use of a low BW observation channel practically does not impact on the resulting error level, enabling a drastic reduction in the implementation complexity of the feedback channel (i.e., PD, TIA, ADC). Furthermore, considering that Tx I/Q mixing effects change very slowly over time in multi-gigabit COT, adaptations of the IE, EOCE, and FCE coefficients do not need to operate at full rate. Thus, further complexity reduction can be enabled by: *(i)* strobing the adaptation algorithms once they have converged, and/or *(ii)* implementing them in firmware in an embedded processor, typically available in COT. As the technique runs in background, the calibration can track parameter variations caused by temperature, voltage, aging, etc., without operational interruptions. All these features make the proposed scheme very attractive for its application in commercial coherent optical transceivers.

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