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Time Skew Estimator for Dual-Polarization QAM Transmitters

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Abstract *A simple method for joint estimation of transmitter's in-phase/quadrature and inter-polarization time skew is proposed and experimentally demonstrated. The method is based on clock tone extraction of a photodetected signal and genetic algorithm. The maximum estimation error was 0.5 ps.*

Introduction

To meet the upcoming data rate demands, optical communication systems are moving towards baud-rates and modulation formats exceeding 64 GBd and 64-QAM, respectively[1]. Such baud-rates and modulation formats are highly sensitive to timing misalignment (time skew) between electrical signal components, both at the transmitter and the receiver[2]. This is especially valid for multi-subcarrier transmission systems[3].

To address the problem of time misalignment, some approaches based on adaptive multiple-input-multiple-output (MIMO) equalizers robust to time skews between components were proposed[4–6]. However, these algorithms significantly increase the already stressed receiver complexity by at least a factor of two[4]. An alternative approach would be to estimate and compensate the time skews statically. In order to do it, transmitter and receiver time skews should be estimated separately. Recently, a joint chromatic dispersion and time skew estimator was proposed for a coherent receiver[7]. For the transmitter time skew estimation, a method based on reconfigurable interference was proposed[8]. This method, however, needs an special apparatus based on integrated photonics.

In this paper, we propose and experimentally demonstrate a low-complexity method for estimating and compensating mutual timing misalignment between the four electrical drive signals that are employed for generation of dual-polarization modulation formats in an optical transmitter. The method is based on clock tone amplitude (CTA) extraction from a directly-detected optical signal and an iterative optimization procedure based on a genetic algorithm. As a proof-of-principle, the method is experimentally investigated on an optical transmitter operating at 32 GBd and employing dual-polarization QPSK modulation.

Proposed method

The proposed method is illustrated in Fig. 1. The main principles are as following: a dual-polarization optical signal is detected by employing direct detection, and the output current is sampled in an analog-to-digital-converter (ADC) with a sampling frequency greater than twice the baud rate. Next, the CTA is extracted from the sampled signal and employed as a fitness function for the genetic algorithm that will iteratively control a bank of interpolators[9] and estimate the time skew values that align in time all the modulator electrical inputs.

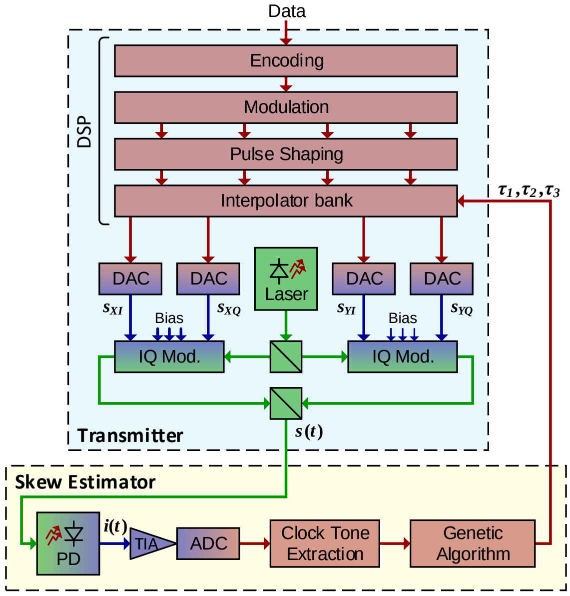

Fig. 1: Proposed algorithm scheme.

Theoretical framework

Dual-polarization signal with time skew

Assuming that the in-phase (I) and quadrature (Q) components of a dual-polarization optical signal are time-skewed, the optical signal, $s(t)$, can be written as

$$s(t) = e^{j\phi(t)}((s_{XI}(t) + js_{XQ}(t - \tau_X))\,\vec{X} + (s_{YI}(t - \tau_{XY}) + js_{YQ}(t - \tau_{XY} - \tau_Y))\,\vec{Y}), \quad (1)$$

where $\phi(t)$ is the phase of the transmitter laser, $\vec{X}$ and $\vec{Y}$ are the orthogonal polarization direction vectors, s_{XI}, s_{XQ}, s_{YI}, and s_{YQ} are the in-phase and quadrature components of polarizations X and Y. τ_X is the IQ time skew in polarization X, τ_Y is the IQ time skew in polarization Y, and τ_{XY} is the time skew between polarizations.

Direct detection of a dual-polarization signal

Rewriting the time skews as $\tau_1 = \tau_X$, $\tau_2 = \tau_{XY}$, and $\tau_3 = \tau_{XY} + \tau_Y$, the photocurrent $i(t)$ generated after passing the signal $s(t)$ through a photodetector is

$$i(t) = R(|s_{XI}(t)|^2 + |s_{XQ}(t-\tau_1)|^2 + |s_{YI}(t-\tau_2)|^2 + |s_{YQ}(t-\tau_3)|^2), \quad (2)$$

with R being the responsivity of the photodetector. The directly-detected signal in Eq. (2) is a combination of the power of each of the components of the optical signal.

Clock tone extraction

The CTA is the maximum value of the timing error detector characteristics and it can be extracted by the following equation[10],

$$W = \left| \left\langle \sum_{k=1}^{L/S} I(k) I^* \left(k + \frac{(S-1)L}{S} \right) \right\rangle \right|, \quad (3)$$

where $I(k)$ is the L-sized discrete Fourier transform of the received photocurrent at $S \geq 2$ samples per symbol.

It is known that the clock tone characteristics are maintained in a directly-detected high-order QAM signal[11], so the CTA of the photodetected current will be proportional to the sum of the clock tones from each of the four components (s_{XI}, s_{XQ}, s_{YI}, and s_{YQ}) of the optical signal. When the there is no time skew between the electrical signals, the CTA will have its maximum value. For non-zero value of the time skew, the CTA value will decrease as illustrated in Fig. 2. More specifically, the figure shows the theoretical results for the CTA as a function of time skew for the single-polarization (Fig. 2(a)) and dual-polarization (Fig. 2(b)) cases.

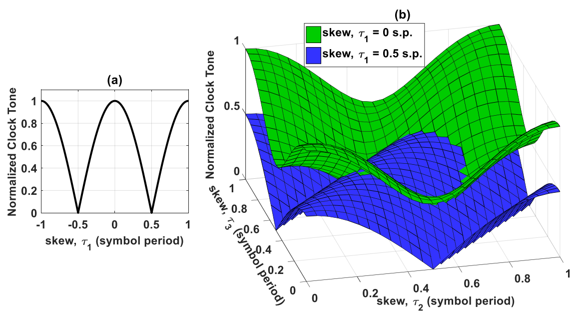

Fig. 2: Theoretical curves for CTA relative to transmitter time skew for **(a)** single-polarization signal; **(b)** dual-pol. signal.

Genetic algorithm for time skew optimization

Common gradient ascent search algorithms could converge to a local maxima, e.g., the region where the blue surface overlap the green surface in Fig. 2(b). Also, due to the noise present in the CTA extraction process they could have a slow and imprecise convergence. In order to avoid these problems, a search algorithm based on a genetic algorithm (GA) can be implemented[12]. The GA is based on the idea of natural selection to evolve towards solutions that maximize a fitness function. It starts by randomly creating individuals of a population and evaluating the fitness function for each of the individuals. The individuals associated to the highest values of the fitness function are selected as elite individuals and they are copied into the next generation. The remaining individuals are, then, recombined through a crossover process or they are mutated based on the elite individuals. Then, the generations progress until a stopping criteria is met. In our case, the fitness function is the CTA and the individuals are sets of time skew values, (τ_1, τ_2, τ_3). The CTA value for each time skew set is evaluated by adjusting the pre-compensation time skew of the generated optical signal and then extracting the CTA value from the directly-detected signal. Fig. 3 depicts a block diagram of the GA.

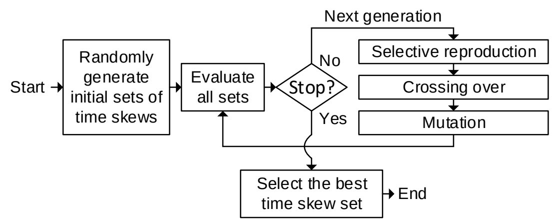

Fig. 3: Genetic algorithm block diagram.

Results

In order to validate the proposed method an experimental validation is reported. The experimental setup is presented in Fig. 4. Four output channels of a 64-GSa/s arbitrary waveform generator (AWG) drove two Mach-Zehnder-based IQ modulators in dual-polarization configuration. The generated optical signal was amplified by an erbium doped fiber amplifier (EDFA), directly-detected in a 45-GHz photodetector and then sampled on a real-time oscilloscope at 160 GSa/s. The clock tone was calculated on a personal computer (PC) that was also used to automatically control the time skew pre-compensation values in the AWG. The time skew values of this setup were previously found as $\tau_X \approx$ -6 ps and $\tau_Y \approx$ -10 ps through extensive optimization of BER.

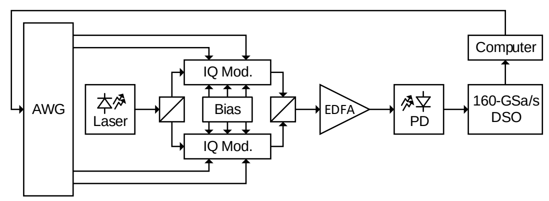

Fig. 4: Experimental setup.

To evaluate the CTA behavior, we first tested the modulators separately, by performing the experiment in single-polarization. We generated a single-polarization NRZ-QPSK signal at 32 GBd and we swept the pre-compensation time skew from -24 to 24 ps with steps of 0.1 ps. For each time skew value we acquired ten different traces of 131072 samples and plotted the average of the CTA values for both modulators (Fig. 5).

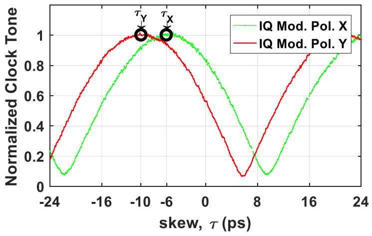

Fig. 5: Experimental curves for clock tone relative to transmitter time skew in a single-polarization signal.

As expected, the maximum CTA values were at time skew values of $\tau_X \approx$ -6 ps and $\tau_Y \approx$ -10 ps.

Then, we generated a dual-polarization NRZ-QPSK signal at 32 GBd. We swept the time skew values from -25 to 25 ps with steps of 1.25 ps. A subset of the 10-trace average CTA values are shown in Fig. 6.

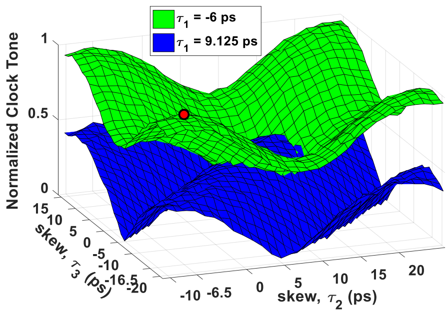

Fig. 6: Experimental curves for clock tone relative to transmitter time skew in a dual-polarization signal.

In this case, the time skew values that maximized CTA were $\tau_1 \approx$ -6 ps, $\tau_2 \approx$ -6.5 ps, and $\tau_3 \approx$ -16.5 ps, leading to the same τ_X and τ_Y found previously, and an inter-polarization time skew of $\tau_{XY} \approx$ -6.5 ps.

To evaluate the performance of the GA as searching method for the time skew estimator we created a random population of 50 three-dimensional individuals (τ_1, τ_2, τ_3). After each generation the GA selected the 10 individuals associated with the highest CTA values as elite individuals and performed cross-over and mutation on the other individuals based on them. We ran the GA through 35 generations and the evolution of CTA values are shown in Fig. 7.

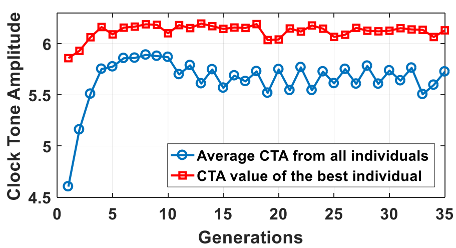

Fig. 7: Experimental CTA evolution for the proposed GA-based time skew estimator.

After the last generation, the best individual found was τ_1 = -6.33 ps, τ_2 = -6.53 ps, and τ_3 = -16.46 ps, which was, once again, consistent with the time skew values previously found. We can see in Fig. 7 that after the 10th generation the averate CTA of all individuals stopped to rise indicating convergence. So only 500 CTA calculations were needed to converge to the final skew values. We then repeated the GA procedure 5 times and all the resulting time skew values found were inside a small deviance of ±0.5 ps.

Conclusions

We proposed a novel and simple time skew estimation method based on clock tone extraction of a directly-detected signal. The method was experimentally demonstrated and correctly estimated and mitigated the transmitter time misalignments. The results also show the potential of the genetic algorithm as a fast optimization method to fine tune the time skews.

Acknowledgements

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