Impact of the Transmitter IQ-Skew in Multi-Subcarrier Coherent Optical Systems

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Abstract: We show that the impact of non-ideal time synchronization between in-phase and quadrature electrical signals can be critical in multi-subcarrier systems. We propose the use of an 8x8 real-valued butterfly equalizer structure to mitigate it.
OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications; (060.4080) Modulation

1. Introduction

Recently, it has been shown that multi-subcarrier (SC) systems show a higher tolerance to fiber non-linear effects than single-subcarrier ones [1–3]. Maximum reach gains of 10%-20% appear to be possible. However this advantage can be significantly reduced by transmitter (Tx) or receiver (Rx) non-idealities, among which possible unbalances between the electrical and/or optical paths for the four quadratures of a polarization-multiplexed (PM) system with coherent detection [4–6]. In particular, the "IQ-skew", i.e. the time delay between the in-phase and quadrature signals, seems to be particularly critical in multi-SC systems: in a single-SC system the penalty for a certain amount of absolute IQ-skew increases with the symbol rate, whilst in a multi-SC system, even though the symbol rate of each SC is significantly lower than the corresponding single-SC case (when keeping the aggregate bit-rate fixed), the impact of the IQ-skew not only is not reduced, but in fact becomes more critical.

Whilst time skews between the four sampling channels of a coherent detector can be calibrated out in the first stage of Rx DSP, IQ-skews inserted at the Tx cannot be compensated for before polarization de-multiplexing, which is typically performed through an adaptive butterfly equalizer. In single-SC systems, polarization recovery and IQ-skew compensation can be jointly performed through a 4x4 real-valued adaptive equalizer, able to treat separately the real and imaginary part of the incoming signal samples: this is not the case for multi-SC systems, in which this approach would introduce a signal distortion which will in turn induce a substantial back-to-back performance degradation. In this work we analytically show the presence of such a distortion and propose the use of an 8x8 real-valued equalizer, jointly processing pairs of SCs, which is able to compensate for the Tx IQ-skew while performing polarization recovery and residual ISI mitigation without introducing additional signal distortion.

2. Multi-SC system setup

The Tx schematics is shown in Fig.1. Each WDM channel consists of N SCs based on quadrature-phase shift-keying (QPSK) modulation. They are generated in the digital domain, as follows. A set of baseband signals $s_n(t)$, with n=1, … , N, each of symbol rate R_{SC}, is created. Each SC is then Nyquist filtered in order to obtain pulses with a square-root raised cosine (SRRC) Fourier transform, with roll-off 0.05. They are digitally up-shifted to their respective center frequency: $f_n=(n-(N+1)/2)\cdot\Delta f$, where $\Delta f = 1.05\cdot R_{SC}$ is the spacing between the SCs. Note that the aggregate channel symbol rate is equal to $R_s=N\cdot R_{SC}$. The SCs are then multiplexed and their samples fed to a digital-to-analog converter (DAC), which generates the electrical signals $x_I(t)$ and $x_Q(t)$, corresponding to the in-phase and quadrature components of the transmitted electrical signal. The two components are then input to a standard IQ modulator.

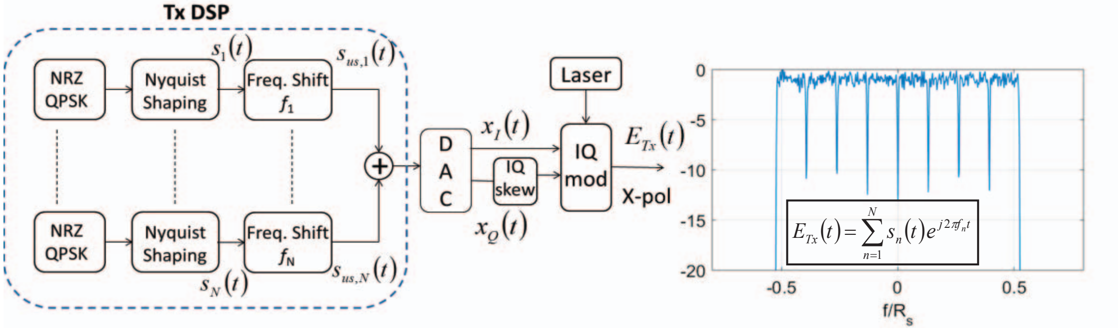
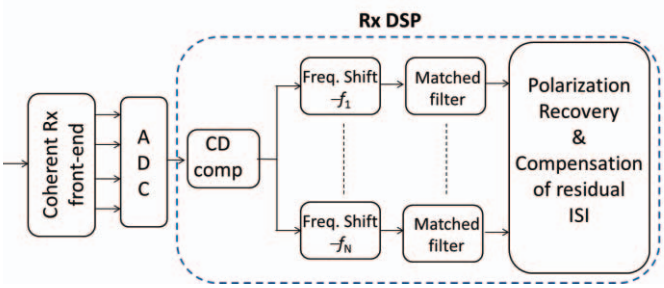


Fig. 1 Multi-subcarrier Tx schematics for polarization X. The same architecture is used to generate the signal for polarization Y. The power spectrum of $E_{Tx}(t)$ is shown for the case N=8. The block "IQ skew" represents a possible delay mismatch τ between $x_I(t)$ and $x_Q(t)$.



LMS 8x8

Samples at the equalizer output at time n:

$$E_i^{eq}(n) = \sum_{k=1}^{8} \underline{h}_{ik}^{(n)} \cdot \underline{E}_k^{(n)} \quad i = 1,\ldots,8$$

with $\underline{E}_i^{(n)} = \left[E_i(n)\ E_i(n-1)\ldots E_i(n-N+1)\right]^T$

Update equations for the 64 filters $\underline{h}_{ik}$:

$$\underline{h}_{ik}^{(n+1)} = \underline{h}_{ik}^{(n)} - \mu\,\varepsilon_i(n)\underline{E}_k^{(n)} \qquad i,k = 1,\ldots,8$$

with $\varepsilon_i(n) = E_i^{eq}(n) - E_i^{tx}(n) \quad i = 1,\ldots,8$

Fig. 2 Multi-subcarrier Rx schematics (left) and LMS update algorithm for the 8x8 butterfly equalizer (right).

The signal at the output of the transmitter is then polarization-multiplexed with a similar signal generated for the Y polarization, forming a complete channel which could then be wavelength-multiplexed with others and transmitted through an optical link. The Rx (see Fig. 2) is a standard polarization-diversity coherent receiver with an analog-to-digital converter (ADC) which samples the incoming signals at a speed equal to $2 \cdot R_s$. DSP blocks follow, including a static filter for chromatic dispersion (CD) compensation, frequency down-shift to translate to baseband all subcarriers for demodulation, a static matched filter with SRRC transfer function and an adaptive butterfly equalizer for polarization recovery and residual ISI removal.

3. Joint impact of IQ skew and frequency-shift

In this section we analytically evaluate the effect of an IQ-skew in a multi-SC scenario, where each single SC goes through both frequency up-shift and down-shift operations. In the following, we will focus on two generic frequency-symmetric SCs. Specifically, we focus on $s_n(t)$ and $s_m(t)$, chosen such that $f_n = -f_m$, with $f_n > 0$. We consider for simplicity a single polarization, but an identical analysis could be performed on the other polarization. For notational convenience, we rename these two SCs as $s^+(t)$ and $s^-(t)$, respectively. Their upshifted versions $s_{us}^+(t)$ and $s_{us}^-(t)$ can be written in terms of the baseband in-phase and quadrature components as:

$$s_{us}^+(t) = \left[s_I^+(t) + j s_Q^+(t)\right] e^{+j2\pi f_n t} \qquad\qquad s_{us}^-(t) = \left[s_I^-(t) + j s_Q^-(t)\right] e^{-j2\pi f_n t} \tag{1}$$

If no time delay is present between the in-phase and quadrature components of the signals $s_{us}^{\pm}(t)$, after down-conversion of an amount equal to $-f_n$ (i.e. a multiplication by $e^{-j2\pi f_n t}$) and low-pass filtering, the signals $s^+(t) = s_I^+(t) + j s_Q^+(t)$ and $s^-(t) = s_I^-(t) + j s_Q^-(t)$ are perfectly recovered, and no interference is generated from the other subcarrier. On the contrary, if a time skew equal to τ is present, i.e. $s^{\pm}(t) = s_I^{\pm}(t) + j s_Q^{\pm}(t+\tau)$, it can be shown that the real and imaginary parts of the generated signal are a combination of the upper and lower subcarriers:

$$\begin{aligned}
r_I^+(t) &= \tfrac{1}{2}s_I^+(t) + \tfrac{1}{2}s_I^+(t+\tau)\cos(\varphi) - \tfrac{1}{2}s_Q^+(t+\tau)\sin(\varphi) + \\
&\quad + \tfrac{1}{2}s_I^-(t) - \tfrac{1}{2}s_I^-(t+\tau)\cos(\varphi) - \tfrac{1}{2}s_Q^-(t+\tau)\sin(\varphi) \\
r_Q^+(t) &= \tfrac{1}{2}s_Q^+(t) + \tfrac{1}{2}s_Q^+(t+\tau)\cos(\varphi) + \tfrac{1}{2}s_I^+(t+\tau)\sin(\varphi) + \\
&\quad - \tfrac{1}{2}s_Q^-(t) + \tfrac{1}{2}s_Q^-(t+\tau)\cos(\varphi) - \tfrac{1}{2}s_I^-(t+\tau)\sin(\varphi)
\end{aligned}
\qquad
\begin{aligned}
r_I^-(t) &= \tfrac{1}{2}s_I^-(t) + \tfrac{1}{2}s_I^-(t+\tau)\cos(\varphi) + \tfrac{1}{2}s_Q^-(t+\tau)\sin(\varphi) + \\
&\quad + \tfrac{1}{2}s_I^+(t) - \tfrac{1}{2}s_I^+(t+\tau)\cos(\varphi) + \tfrac{1}{2}s_Q^+(t+\tau)\sin(\varphi) \\
r_Q^-(t) &= \tfrac{1}{2}s_Q^-(t) + \tfrac{1}{2}s_Q^-(t+\tau)\cos(\varphi) - \tfrac{1}{2}s_I^-(t+\tau)\sin(\varphi) + \\
&\quad - \tfrac{1}{2}s_Q^+(t) + \tfrac{1}{2}s_Q^+(t+\tau)\cos(\varphi) + \tfrac{1}{2}s_I^+(t+\tau)\sin(\varphi)
\end{aligned} \tag{2}$$

with $\varphi = 2\pi f_n \tau$. Eq. (2) shows that the received signals after down-conversion are a linear combination of the in-phase and quadrature components of both the useful signal and of the "symmetric" subcarrier. Note that, if no IQ skew is present (i.e. $\tau = 0$), then $\varphi = 0$ and a perfect cancelation of the image frequency is achieved: e.g. from Eq. (2) we get $r_I^+(t) = s_I^+(t)$, $r_Q^+(t) = s_Q^+(t)$. It can also be shown that no interference on the SCs centered at frequency $\pm f_i$ is generated by the SCs centered at frequencies different from $\pm f_i$, that is the spurious terms due to the IQ skew are produced by the symmetric SC only. These spurious terms induce a performance degradation which cannot be compensated for by standard Rx DSP algorithms: a complex-valued 2x2 equalizer (operating on the complex signal samples in the two polarizations) is not able to compensate for any delay or amplitude mismatch between the I and Q components and a 4x4 real-valued butterfly equalizer, operating on the I and Q components of the two polarizations of a single SC, cannot compensate for the interference produced by the symmetric SC. In fact, eq. (2) indicates that the signals coming from the symmetric SC at frequency $-f_n$ have to be jointly processed with the components of the SC at frequency $+f_n$ in order to get a complete cancelation of the interference. For this reason, we propose the use of a real-valued 8x8 butterfly equalizer, updated through a standard LMS algorithm [7], jointly processing pairs of "symmetric" SCs (i.e. two quadratures for each polarization of each carrier, for a total of 8 real signals). The corresponding update equations are shown in the right part of Fig. 2.

4. Simulation results

We compare in this section the back-to-back performance of three different structures for the butterfly equalizer, i.e. complex-valued 2x2, real-valued 4x4 and real-valued 8x8 for both single-SC and multi-SC transceivers, all updated through the LMS algorithm [7]. The PM-QPSK multi-SC signals are generated following the scheme of Fig. 1. The aggregate symbol rate is R_s=32 Gbaud. Four different PRBS's of degree 15 are used for each SC. In all cases, the number of taps of the butterfly equalizer is equal to 31. Ideal frequency offset compensation is assumed.

Fig. 3a shows the results in terms of signal to noise ratio (SNR), defined over a bandwidth equal to R_s, required to achieve a target BER (averaged over all SCs) equal to 10^{-2}, as a function of the amount of IQ-skew, when a complex-valued 2x2 equalizer is used. Even though the symbol length is longer than in the single-SC case (e.g. 250 ps when N=8 vs. 31.25 ps for N=1), the impact of the IQ-skew is larger in the multi-SC cases w.r.t. the single-SC one. This is due to the interference produced by the "symmetric" SC, which induces a distortion on the signal which is higher for higher f_i values. This behavior can be explained by the increase with f_i of the phase φ in Eq. (2).

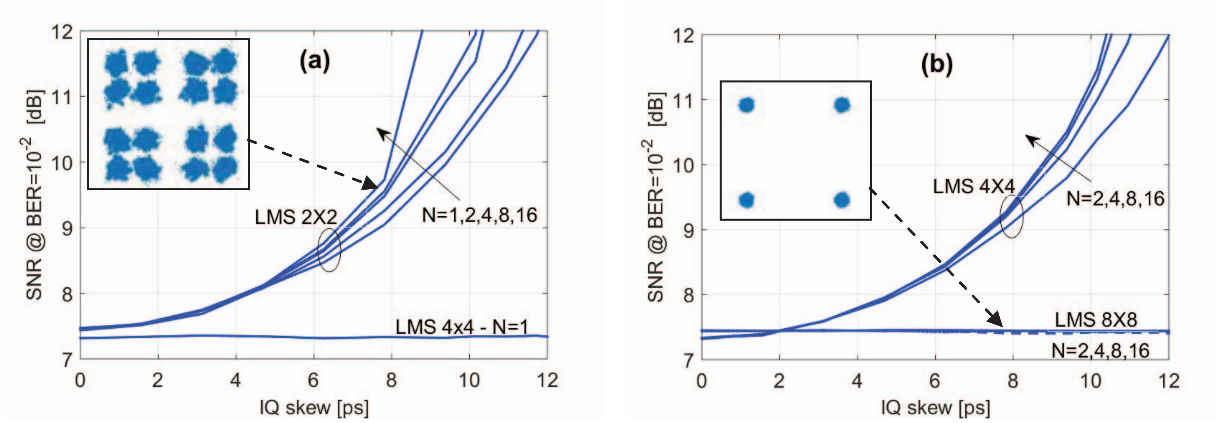


Fig.3 SNR required to obtain a target BER (averaged over all SCs) equal to 10^{-2} vs. IQ skew for 2x2, 4x4 and 8x8 equalizers. The symbol rate is 32 Gbaud (corresponding to a symbol time equal to 31.25 ps). Insets: scattering diagrams of x-pol of 8th SC for N=8 and τ=0.25 R_S.

In Fig. 3a the performance of the real-valued 4x4 equalizer in the single-SC case is shown as well, highlighting a full compensation of the IQ-skew. Fig. 3b shows the performance of the real-valued 4x4 and 8x8 equalizers for the multi-SC scenarios, indicating that the 8x8 equalizer is able to completely compensate for the IQ-skew, whilst the 4x4 equalizer yields almost the same performance as 2x2. Note that the presence of residual chromatic dispersion and differential group delay does not alter the performance of the equalizer, which is able to compensate for them as in the 2x2 and 4x4 cases.

5. Conclusions

We showed that the impact of the delay between the I and Q components of an IQ-modulation, due to a non-perfect matching between the electrical paths of the two signals, is critical in a multi-SC scenario. As a possible countermeasure, we proposed the use of a real-valued 8x8 equalizer and successfully tested its performance through numerical simulations. Our results show that, thanks to the simultaneous processing of a SC and of its symmetric-frequency counterpart, their mutual interference due to imperfect I-Q component delay can be efficiently mitigated.

This work was supported by CISCO Systems within a SRA contract.

4. References

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