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

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Multi-subcarrier systems have a potential advantage over single-subcarrier ones due to a higher tolerance to non-linear propagation effects

- M. Qiu et al., OFC 2014, Tu3J.2, San Francisco (2014).
- A. Nespola et al., ECOC 2015, Mo.3.6.3, Valencia (2015)

This advantage can be significantly reduced by transceiver practical implementation issues.
- SC = subcarrier
- N = number of SCs
- \( R_{sc} = \) symbol rate per SC

- A time delay between the I and Q components at the Tx side can strongly affect the performance in the multi-SC scenario

Aggregate symbol rate:
\[ R_s = R_{sc} \cdot N = 32 \text{ Gbaud} \]
Multi-Subcarrier Receiver

Adaptive equalizer update algorithms:
- 2x2 LMS (complex values)
- 4x4 LMS (real values)
Single-SC case

- $R_s = 32$ Gbaud
- Symbol length: 31.25 ps
- The penalty is completely cancelled

Graph showing SNR @ $10^{-2}$ [dB] vs. IQ skew [ps] with data points for LMS 2x2 and LMS 4x4.
SNR vs. IQ skew for LMS 2x2

- $R_s = 32$ Gbaud
- $N$ = number of SCs
- Symbol length:
  - $N=1$: 31.25 ps
  - $N=8$: 250 ps
- The penalty increases with the number of SCs
SNR vs. IQ skew for LMS 4x4

- $R_s = 32$ Gbaud
- $N =$ number of SCs
- In the multi-SC cases, almost no difference is observed w.r.t. LMS 2x2
Outer SCs are more distorted ...

- IQ skew: $\tau = 7.8$ ps
- Symbol time in each SC: 250 ps
Analysis of the problem

- We focus on two symmetric SCs centered around frequencies $+f_n$ and $-f_n$, considering a single polarization for simplicity.

- $s^+(t)$ and $s^-(t)$ are the signals transmitted on the two SCs:

  $s^+(t) = [x_I^+(t) + jx_Q^+(t)]e^{+j2\pi f_n t}$
  $s^-(t) = [x_I^-(t) + jx_Q^-(t)]e^{-j2\pi f_n t}$
Ideal case

- No time delay is present between I and Q components of the signals $s^{±}(t)$.

- After down-conversion and low-pass filtering, both signals are perfectly recovered, and no interference is generated between the two subcarriers.

- $s^{+}(t)$ and $s^{-}(t)$ are the signals transmitted on the two SCs:
  
  $$ s^{+}(t) = [x^{+}_I(t) + jx^{+}_Q(t)]e^{+j2\pi f_n t} \cdot e^{-j2\pi f_n t} = x^{+}_I(t) + jx^{+}_Q(t) $$
  
  $$ s^{-}(t) = [x^{-}_I(t) + jx^{-}_Q(t)]e^{-j2\pi f_n t} \cdot e^{+j2\pi f_n t} = x^{-}_I(t) + jx^{-}_Q(t) $$
Time skew effect on the “positive” SC

- A time skew equal to $\tau$ is present: $s^\pm(t) = s^\pm_I(t) + js^\pm_Q(t + \tau)$

- It can be shown that the real and imaginary part of the generated signal are a combination of the upper and lower subcarriers:

$$
\begin{align*}
r_I^+(t) &= \frac{1}{2} x_I^+(t) + \frac{1}{2} x_I^+(t + \tau) \cos(\varphi) - \frac{1}{2} x_Q^+(t + \tau) \sin(\varphi) + \\
&\quad + \frac{1}{2} x_I^-(t) - \frac{1}{2} x_I^-(t + \tau) \cos(\varphi) - \frac{1}{2} x_Q^-(t + \tau) \sin(\varphi) \\
\varphi &= 2\pi f_n \tau
\end{align*}
$$

$$
\begin{align*}
r_Q^+(t) &= \frac{1}{2} x_Q^+(t) + \frac{1}{2} x_Q^+(t + \tau) \cos(\varphi) + \frac{1}{2} x_I^+(t + \tau) \sin(\varphi) + \\
&\quad - \frac{1}{2} x_Q^-(t) + \frac{1}{2} x_Q^-(t + \tau) \cos(\varphi) - \frac{1}{2} x_I^-(t + \tau) \sin(\varphi)
\end{align*}
$$
Time skew effect on the “negative” SC

- Similar expressions are obtained when performing down-conversion of an amount equal to $+f_n$:

$$r_i^{-}(t) = \frac{1}{2} x_i^{-}(t) + \frac{1}{2} x_i^{-}(t + \tau) \cos(\varphi) + \frac{1}{2} x_Q^{-}(t + \tau) \sin(\varphi) + \frac{1}{2} x_i^{-}(t) - \frac{1}{2} x_i^{+}(t + \tau) \cos(\varphi) + \frac{1}{2} x_Q^{+}(t + \tau) \sin(\varphi)$$

$$r_Q^{-}(t) = \frac{1}{2} x_Q^{-}(t) + \frac{1}{2} x_Q^{-}(t + \tau) \cos(\varphi) - \frac{1}{2} x_Q^{-}(t + \tau) \sin(\varphi) + \frac{1}{2} x_Q^{+}(t + \tau) \cos(\varphi) + \frac{1}{2} x_i^{+}(t + \tau) \sin(\varphi)$$

- It can be shown that no interference is generated by the SCs centered at frequencies different from $\pm f_n$. 

$$\varphi = 2\pi f_n \tau$$
Taking also polarization into account, an 8x8 equalizer, jointly processing two symmetric sub-carriers, is able to recover the original signals.
SNR vs. IQ skew LMS 4x4/8x8

- $R_s = 32$ Gbaud
- $N =$ number of SCs
- Using LMS 8x8, the penalty is completely cancelled in the multi-SC case

$\text{SNR} @ 10^{-2}$ [dB]

IQ skew [ps]

LMS 4X4

N=2,4,8,16
LMS 4x4 vs. LMS 8x8

- $\tau = 7.8$ ps
- symbol time in each SC: 250 ps
Conclusions

- **Multi-SC modulation**
  The impact of the **delay between the I and Q components** of an IQ-modulation is higher than in the single-SC scenario.

- **Main source of penalty**
  Interference generated by the symmetric SC

- **Countermeasure**
  **8x8 real-value MIMO equalizer** jointly processing a SC and its symmetric-frequency counterpart
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