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

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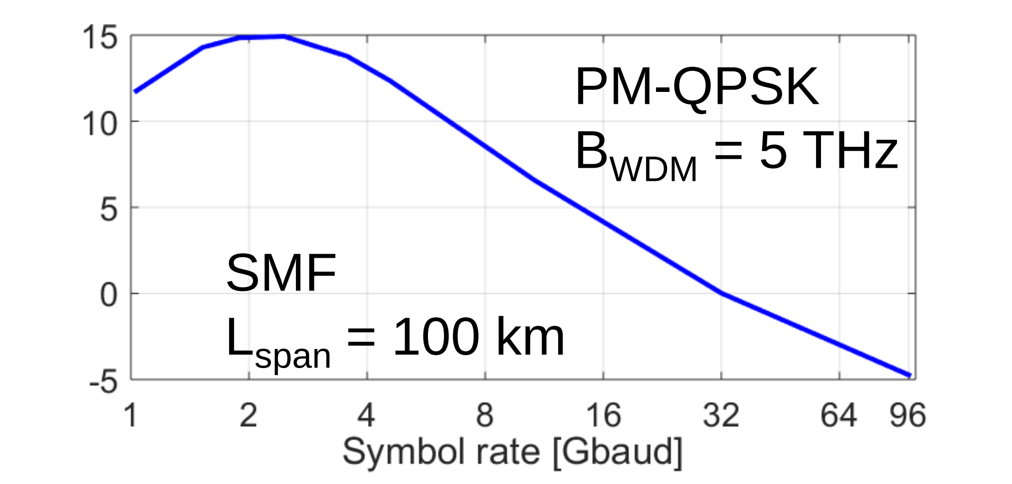
Background

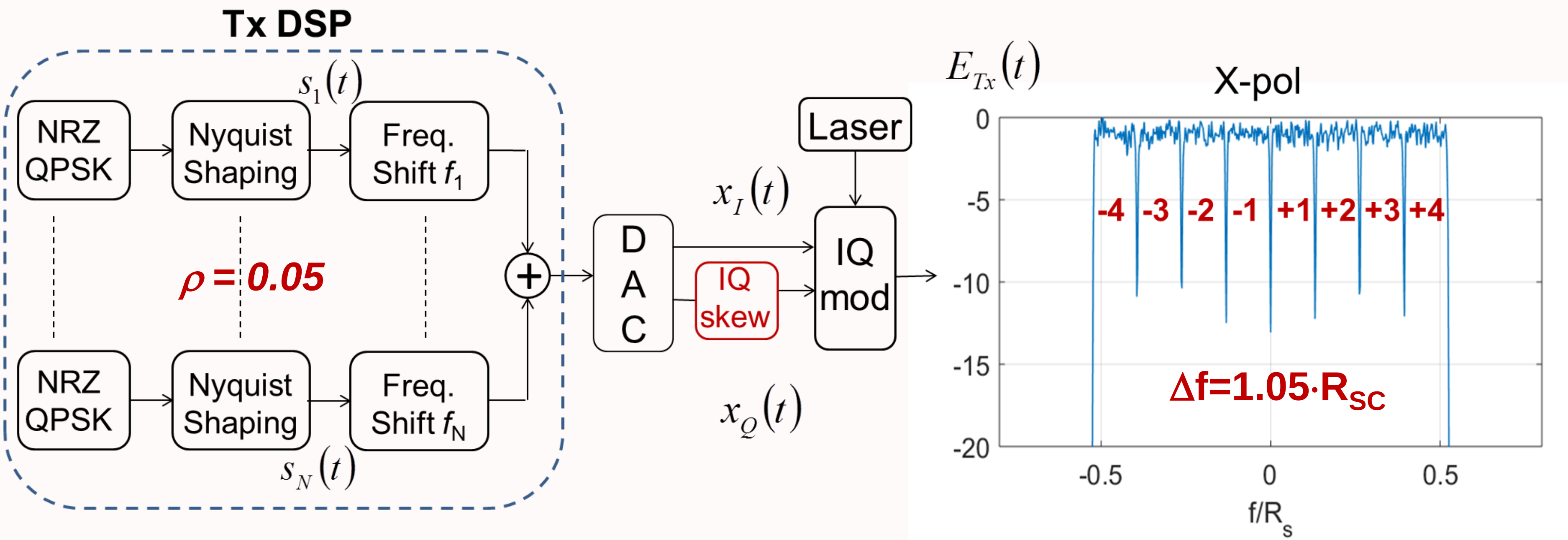
- Multi-subcarrier systems have a potential advantage over single-subcarrier ones due to a higher tolerance to non-linear propagation effects
  - W. Shieh, Y. Tang, IEEE Phot. J., Vol. 2, n. 3, p.276 (2010)
  - A. Bononi et al., ECOC 2013, paper Th.1.D.5, London (2013)
  - M. Qiu et al., OFC 2014, Tu3J.2, San Francisco (2014).
  - A. Nespola et al., ECOC 2015 , Mo.3.6.3, Valencia (2015)

% of maximum reach increase w.r.t. 32 Gbaud



- This advantage can be significantly reduced by transceiver practical implementation issues.

Multi-Subcarrier Transmitter

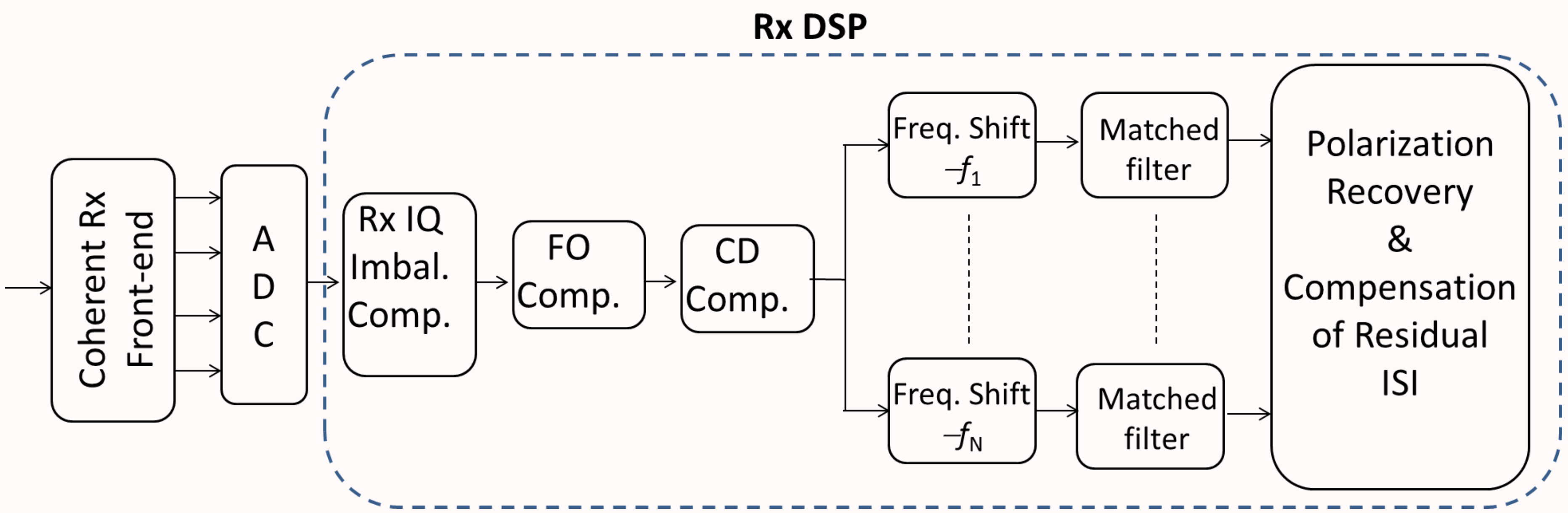


- SC = subcarrier
- N = number of SCs
- R_{SC} = symbol rate per SC

- Aggregate symbol rate:
  $R_s = R_{SC} \cdot N = 32$ Gbaud

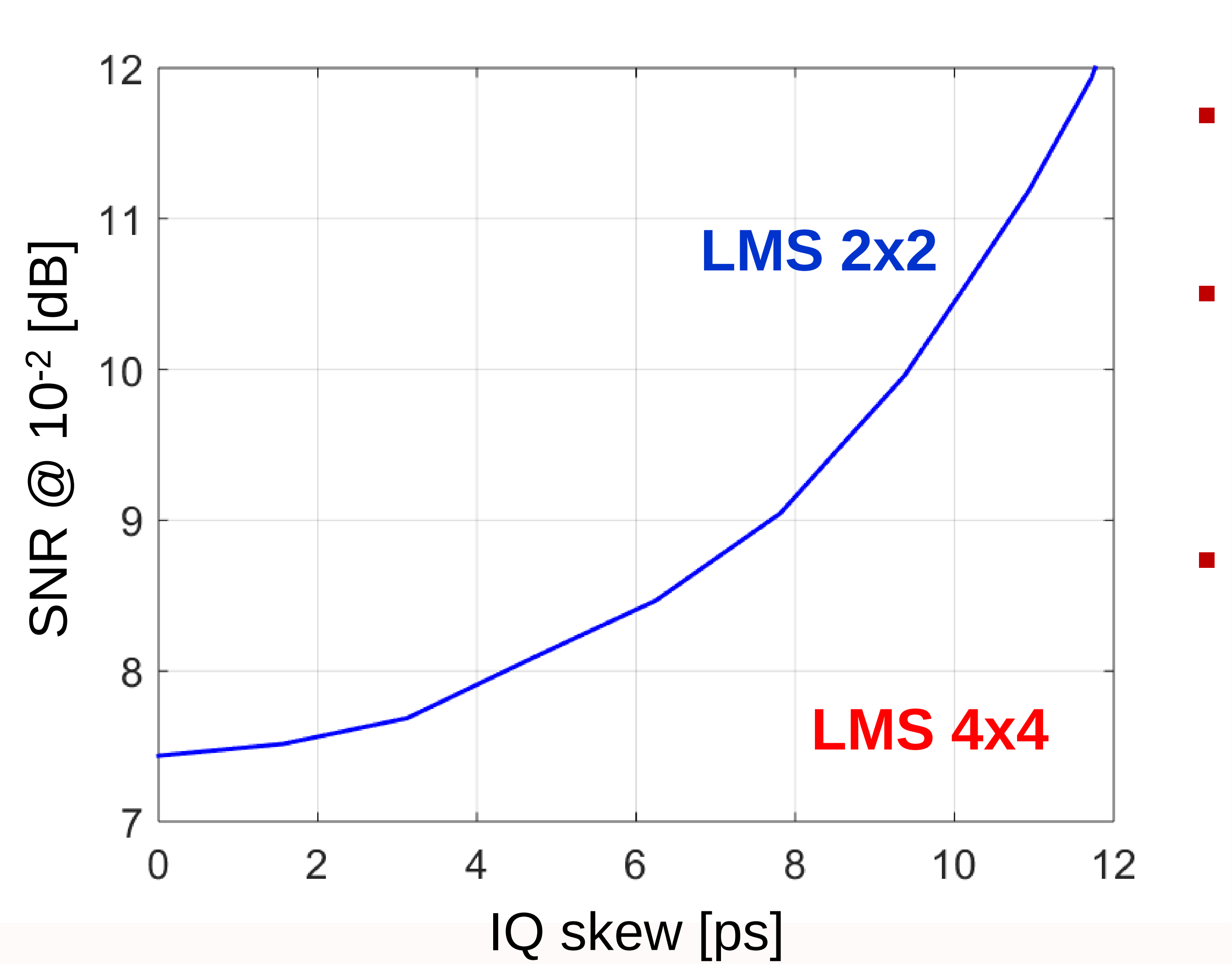
- **A time delay between the I and Q components at the Tx side can strongly affect the performance in the multi-SC scenario**

Multi-Subcarrier Receiver



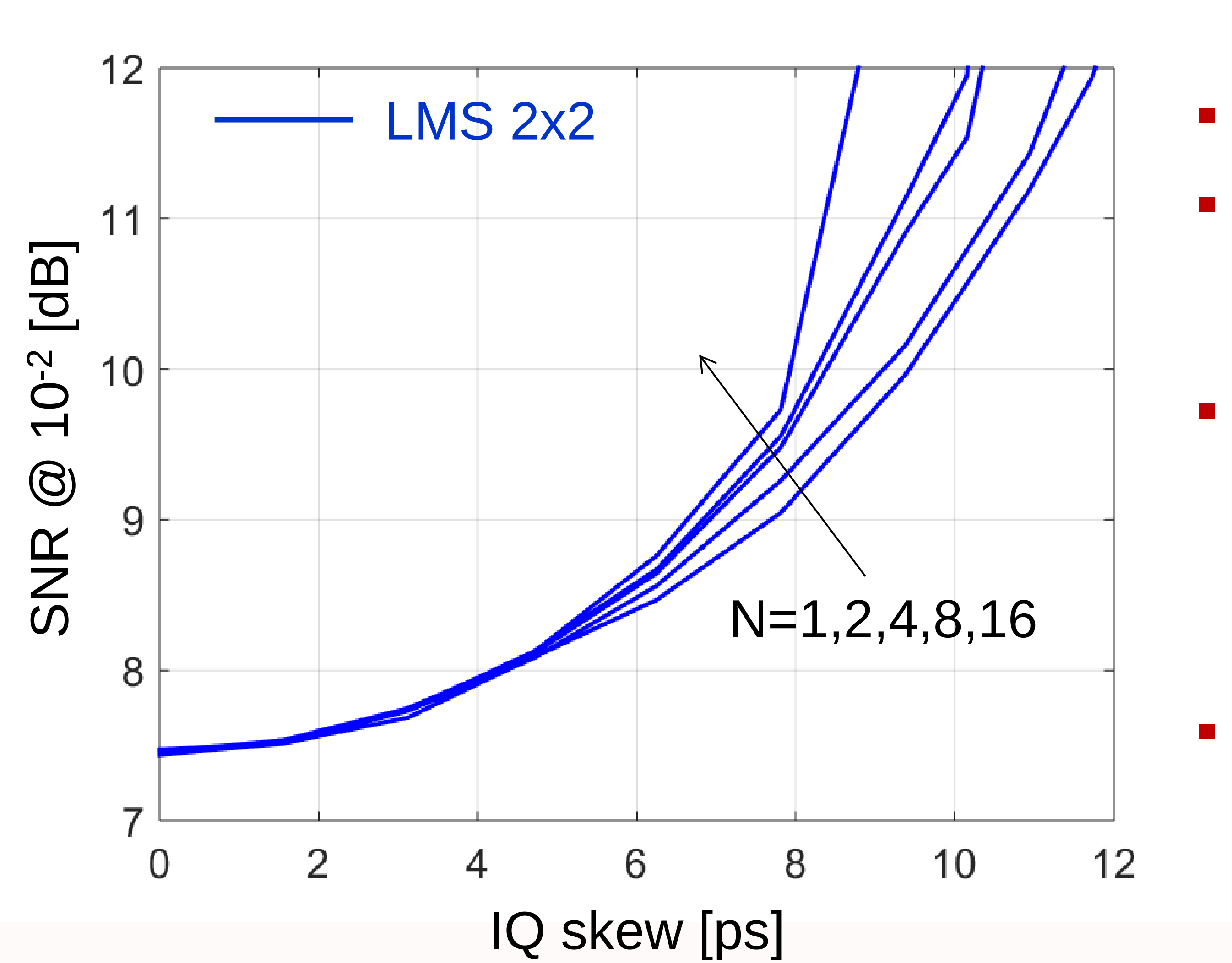
- Adaptive equalizer update algorithms:
  - 2x2 LMS (complex values)
  - 4x4 LMS (real values)

Single-SC case



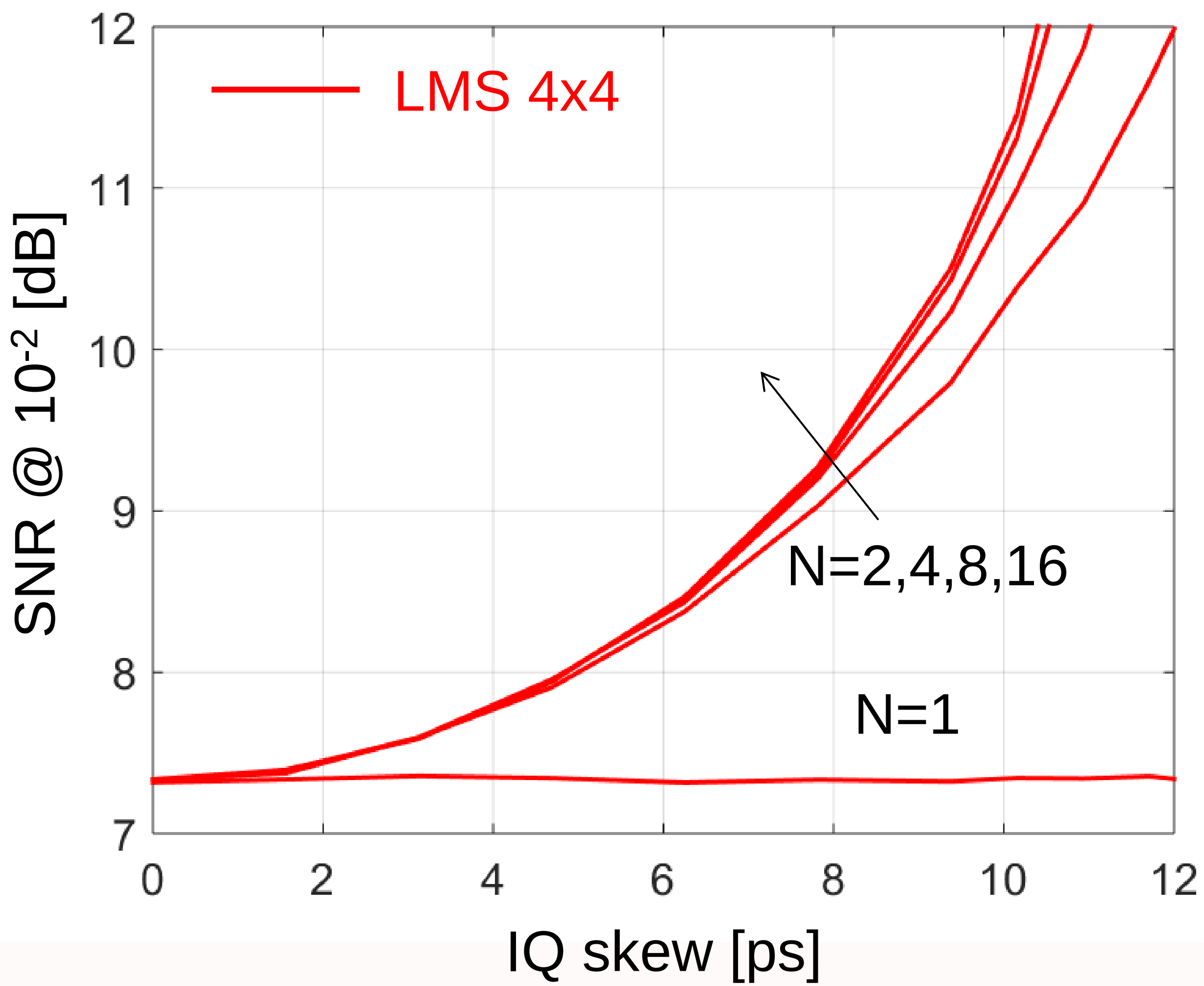
- R_s = 32 Gbaud
- Symbol length: 31.25 ps
- The penalty is completely cancelled

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

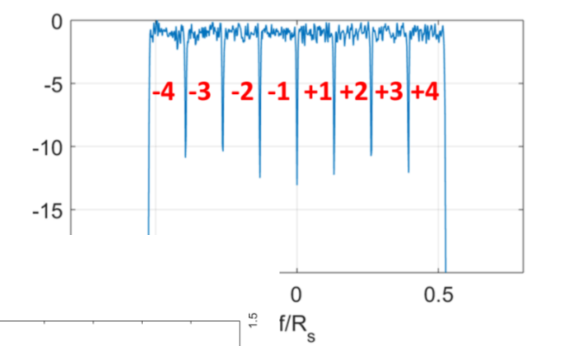
SNR vs. IQ skew for LMS 4x4

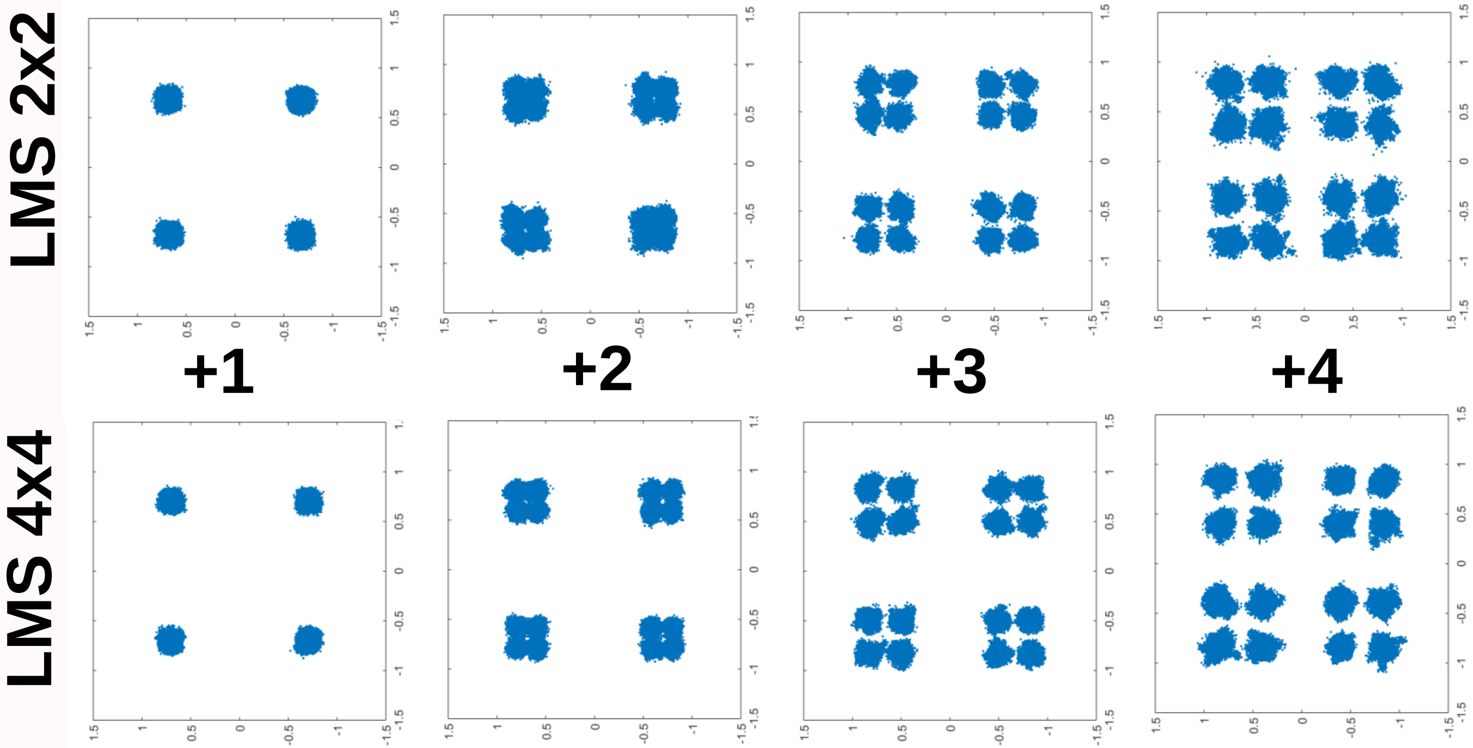


- R_s = 32 Gbaud
- N = number of SCs
- In the multi-SC cases, almost no difference is observed w.r.t. LMS 2x2

Outer SCs are more distorted …

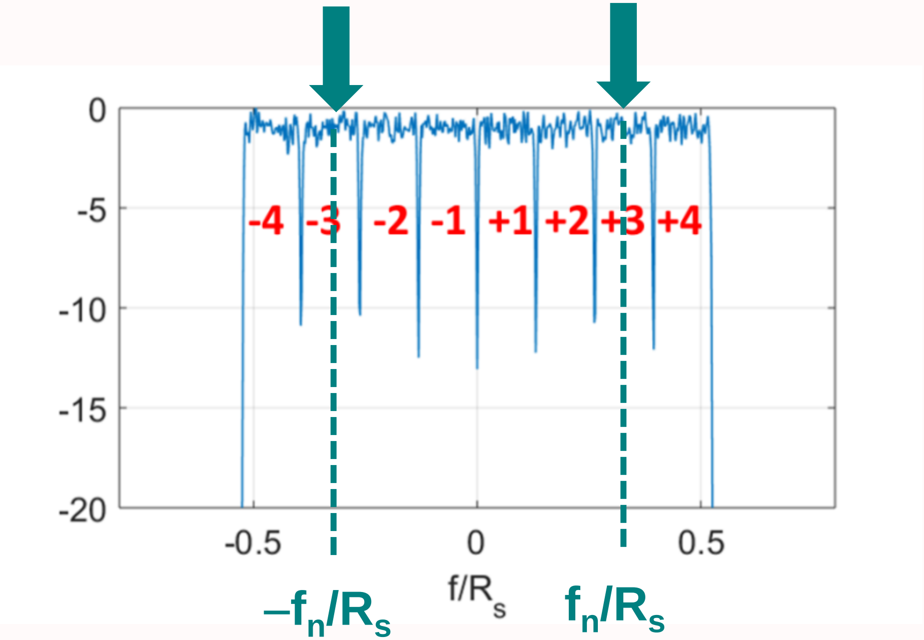
- IQ skew: τ = 7.8 ps
- Symbol time in each SC: 250 ps





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:

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

Ideal case

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

- 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:

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

Time skew effect on the “positive” SC

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- A time skew equal to τ is present: $s^{\pm}(t) = s_I^{\pm}(t) + j s_Q^{\pm}(t+\tau)$

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

$$
\begin{aligned}
r_I^{+}(t) = {} & \frac{1}{2}x_I^{+}(t) + \frac{1}{2}x_I^{+}(t+\tau)\cos(\varphi) - \frac{1}{2}x_Q^{+}(t+\tau)\sin(\varphi) + \\
& + \frac{1}{2}x_I^{-}(t) - \frac{1}{2}x_I^{-}(t+\tau)\cos(\varphi) - \frac{1}{2}x_Q^{-}(t+\tau)\sin(\varphi) \\
r_Q^{+}(t) = {} & \frac{1}{2}x_Q^{+}(t) + \frac{1}{2}x_Q^{+}(t+\tau)\cos(\varphi) + \frac{1}{2}x_I^{+}(t+\tau)\sin(\varphi) + \\
& - \frac{1}{2}x_Q^{-}(t) + \frac{1}{2}x_Q^{-}(t+\tau)\cos(\varphi) - \frac{1}{2}x_I^{-}(t+\tau)\sin(\varphi)
\end{aligned}
$$

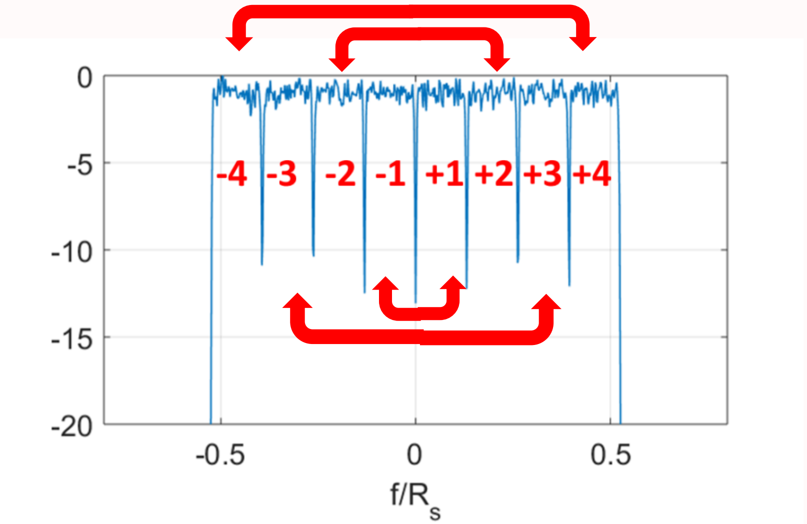
$$\varphi = 2\pi f_n \tau$$

Time skew effect on the "negative" SC

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

$$\varphi = 2\pi f_n \tau$$

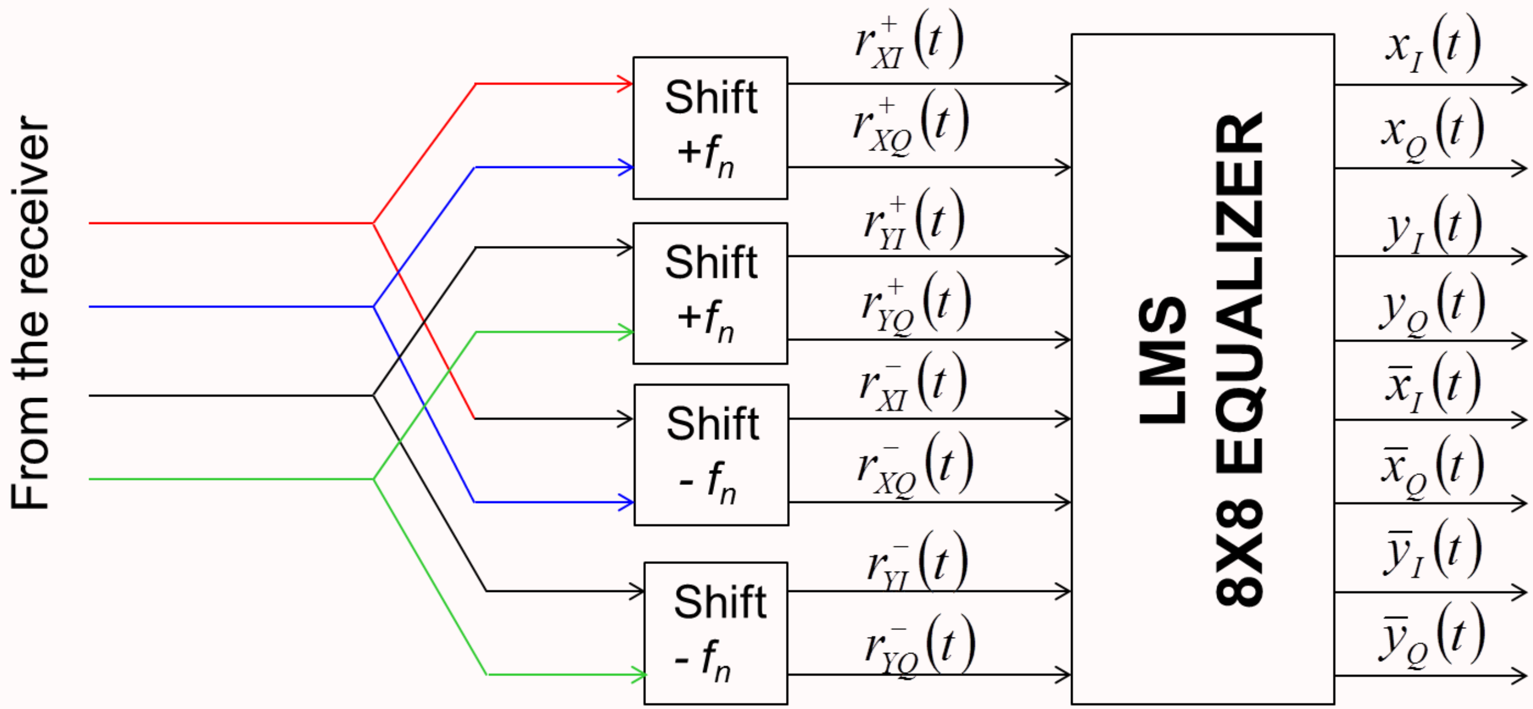
$$r_I^-(t) = \frac{1}{2}x_I^-(t) + \frac{1}{2}x_I^-(t+\tau)\cos(\varphi) + \frac{1}{2}x_Q^-(t+\tau)\sin(\varphi) +$$
$$+\frac{1}{2}x_I^+(t) - \frac{1}{2}x^+(t+\tau)\cos(\varphi) + \frac{1}{2}x_Q^+(t+\tau)\sin(\varphi)$$
$$r_Q^-(t) = \frac{1}{2}x_Q^-(t) + \frac{1}{2}x_Q^-(t+\tau)\cos(\varphi) - \frac{1}{2}x_I^-(t+\tau)\sin(\varphi)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



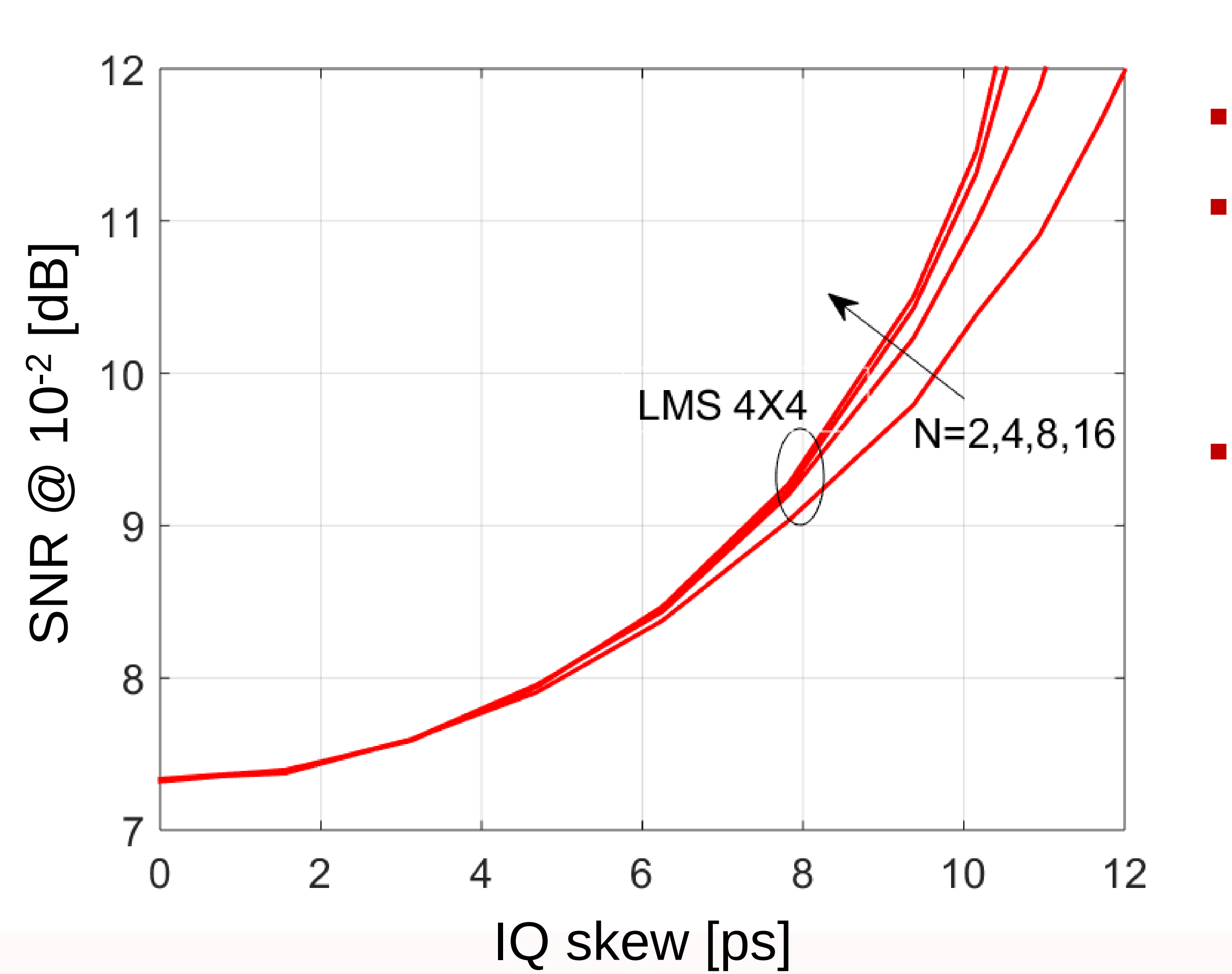
- It can be shown that no interference is generated by the SCs centered at frequencies different from $\pm f_n$.

8x8 butterfly equalizer

- Taking also polarization into account, an 8x8 equalizer, jointly processing two symetric sub-carriers, is able to recover the original signals.



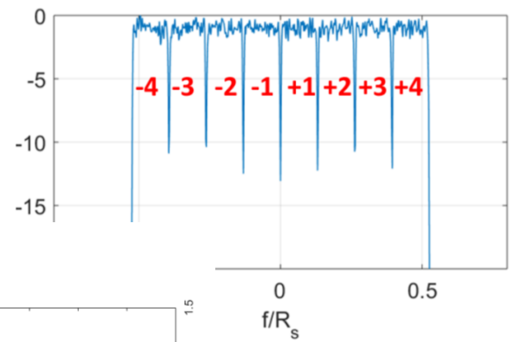
SNR vs. IQ skew LMS 4x4/8x8

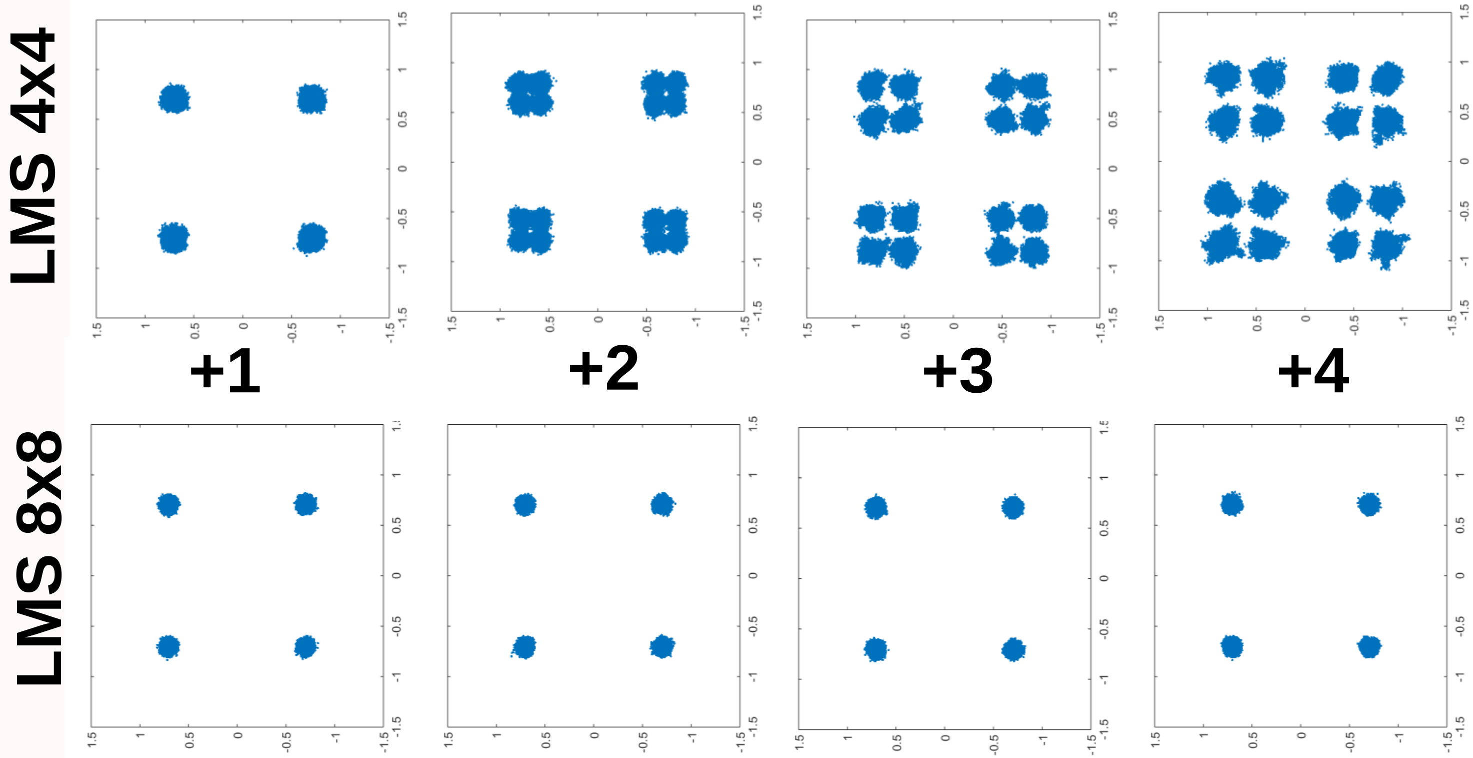


- R_s = 32 Gbaud
- N = number of SCs
- Using LMS 8x8, the penalty is completely cancelled in the multi-SC case

LMS 4x4 vs. LMS 8x8

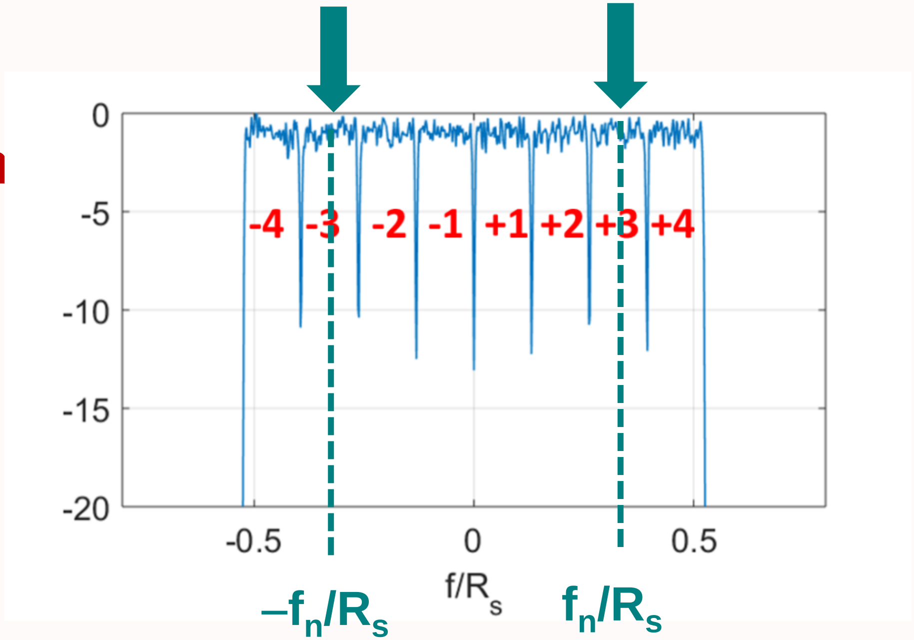
- τ = 7.8 ps
- symbol time in each SC: 250 ps





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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