On the Influence of IQ-Imbalance on Carrier Recovery in WDM CO-OFDM Systems

Workshop der ITG-Fachgruppe 5.3.1

Simon Ohlendorf, Dennis Clausen und Werner Rosenkranz

Lehrstuhl für Nachrichten- und Übertragungstechnik
Christian-Albrechts-Universität zu Kiel (CAU)

18.02.2016

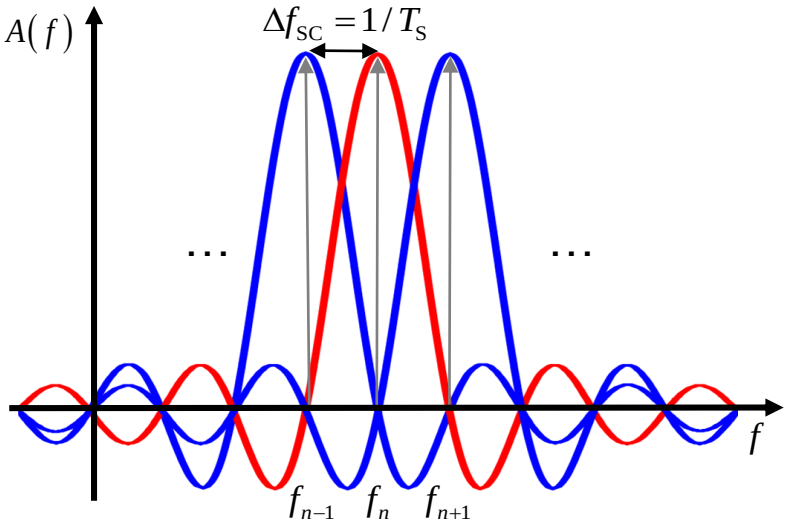
Outline

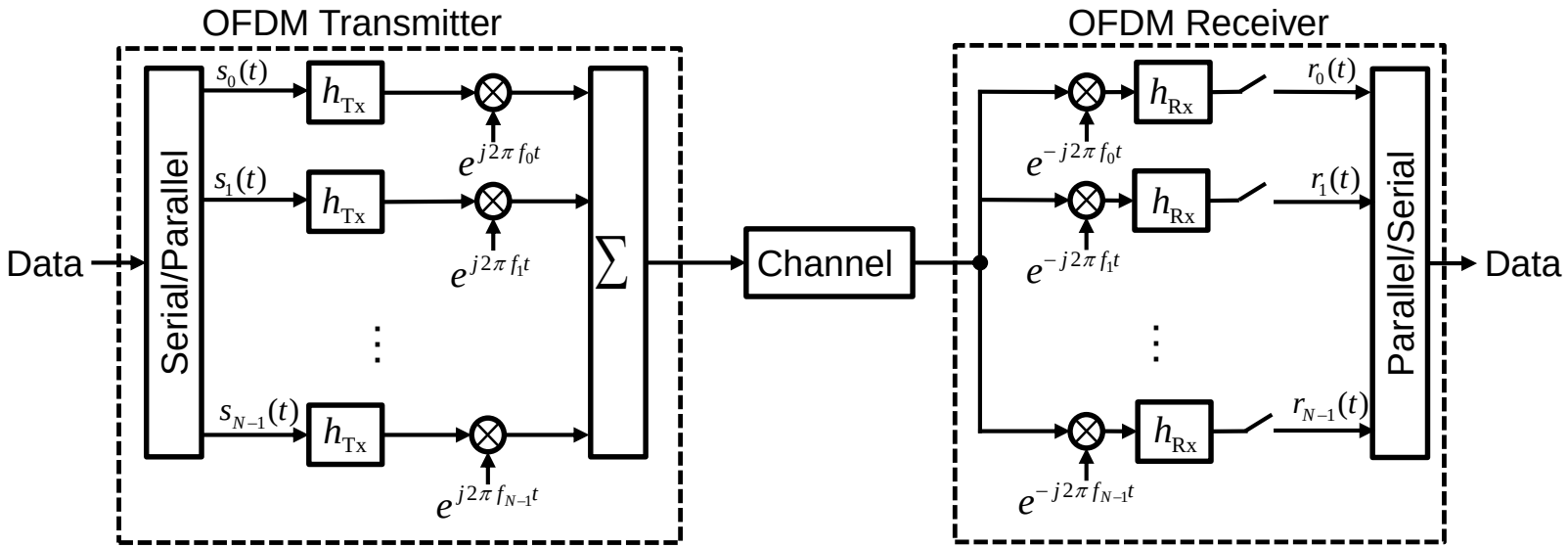
1. **CO-OFDM System**
2. **Influence of Carrier Frequency Offset**
3. **Methods for Carrier Recovery**
    a. **Pilot tone based**
    b. **TS based**
4. **Transmitter IQ-Imbalances**
    a. **Impact**
    b. **Compensation**
5. **Results**
6. **Summary and Conclusion**

OFDM Transmission System

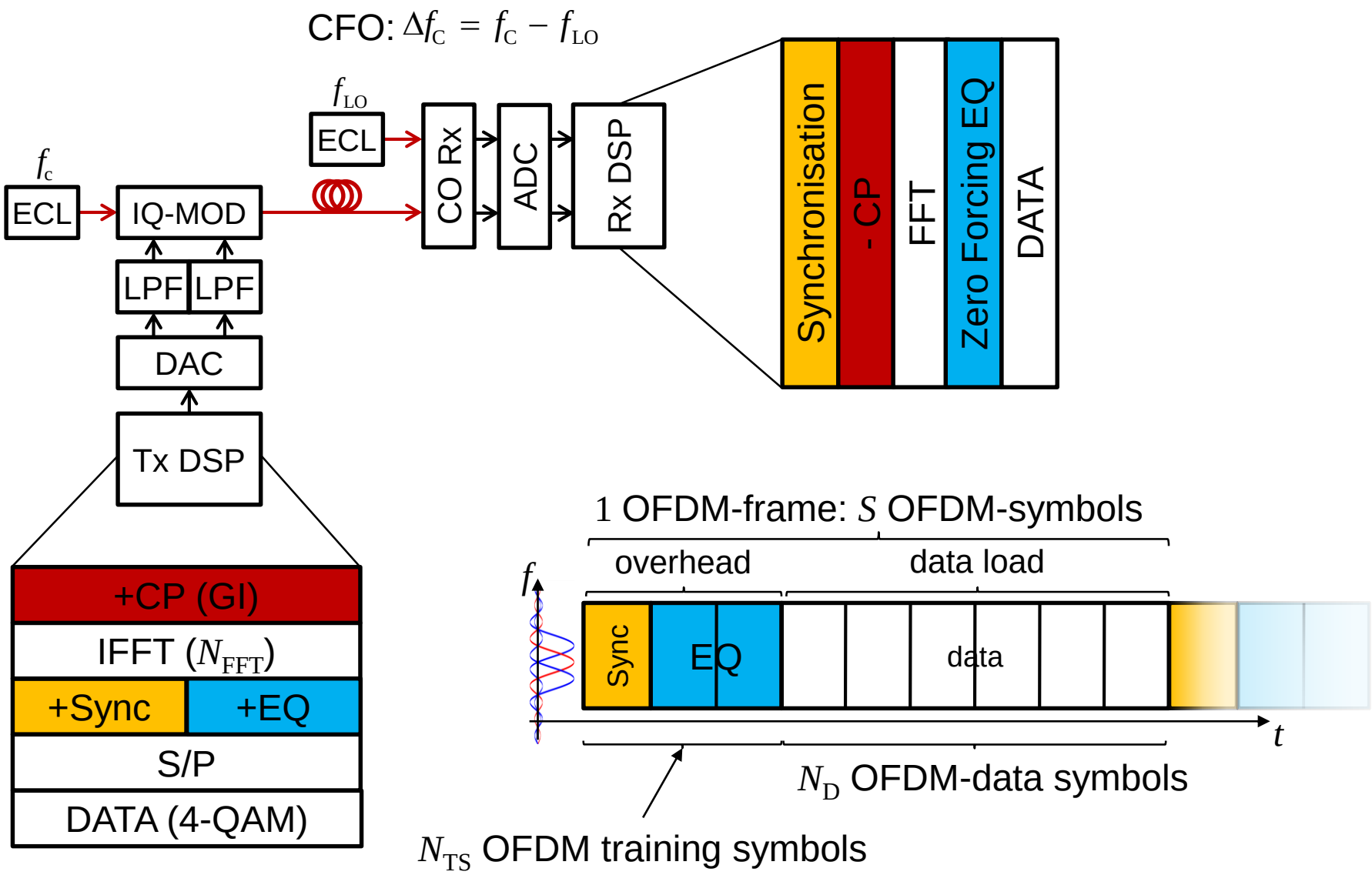
OFDM: Orthogonal Frequency Division Multiplexing

- Bandwidth is divided into subbands
- Parallel data streams
- $h_{\mathrm{Tx}} = \mathrm{rect}\left(t / T_{\mathrm{S}}\right)$
- N orthogonal subcarriers with frequencies $f_0, \ldots, f_{(N-1)}$
- Modulation: IDFT (IFFT), Demodulation: DFT (FFT)





CO-OFDM Transmission System

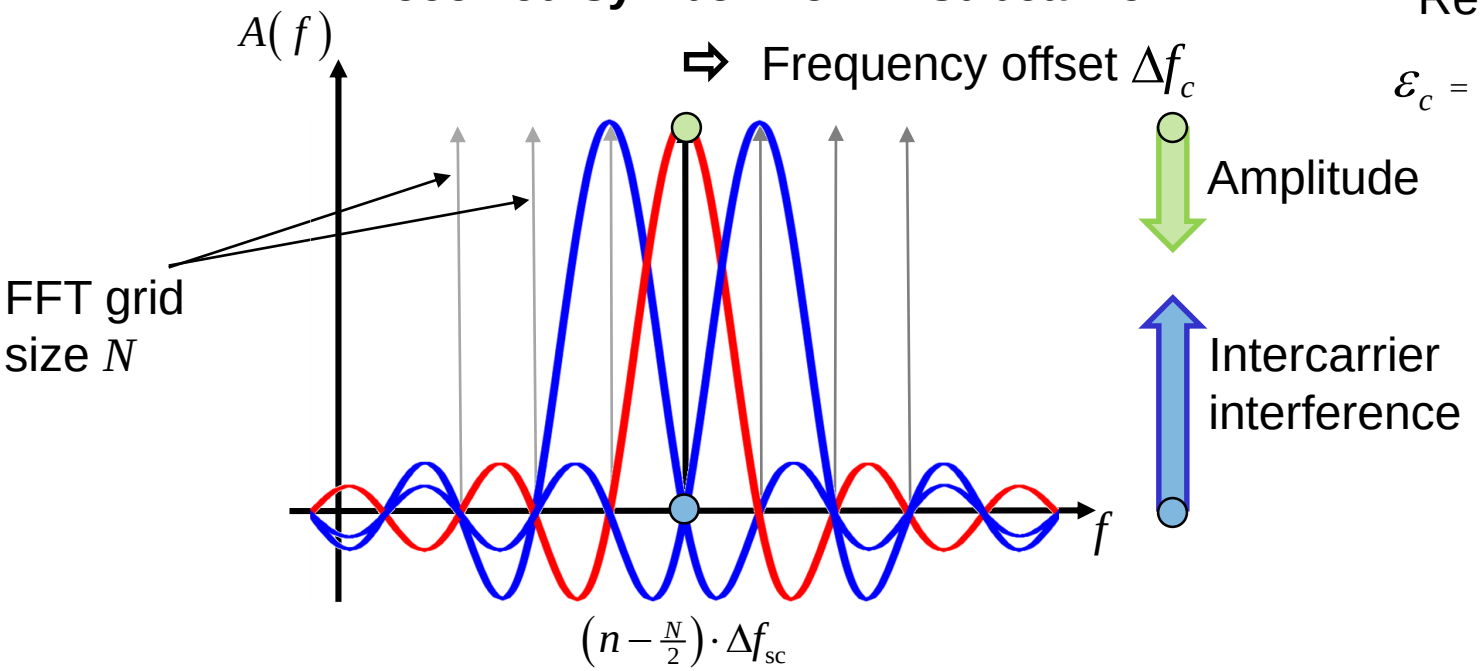


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Effects of Carrier Frequency Offset on CO-OFDM

Received symbol k of n^{th} subcarrier



Relative freq. offset

$$\varepsilon_c = \frac{\Delta f_c}{\Delta f_{SC}} \triangleq \frac{\text{carrier freq. offset}}{\text{subcarrier spacing}}$$

Symbol k of n^{th} subcarrier after FFT (Rx):

$$r_n[k] = e^{j2\pi k\varepsilon_c \frac{N+N_{CP}}{N}} \left[s_n[k] \frac{\sin(\pi\varepsilon_c)}{N\sin\left(\frac{\pi\varepsilon_c}{N}\right)} e^{j\pi\varepsilon_c \frac{N-1}{N}} + \sum_{\substack{m=0 \\ n\neq m}}^{N-1} s_m[k] \frac{\sin(\pi(\varepsilon_c+m-n))}{N\sin\left(\frac{\pi}{N}(\varepsilon_c+m-n)\right)} e^{j\pi(\varepsilon_c+m-n)\frac{N-1}{N}} \right]$$

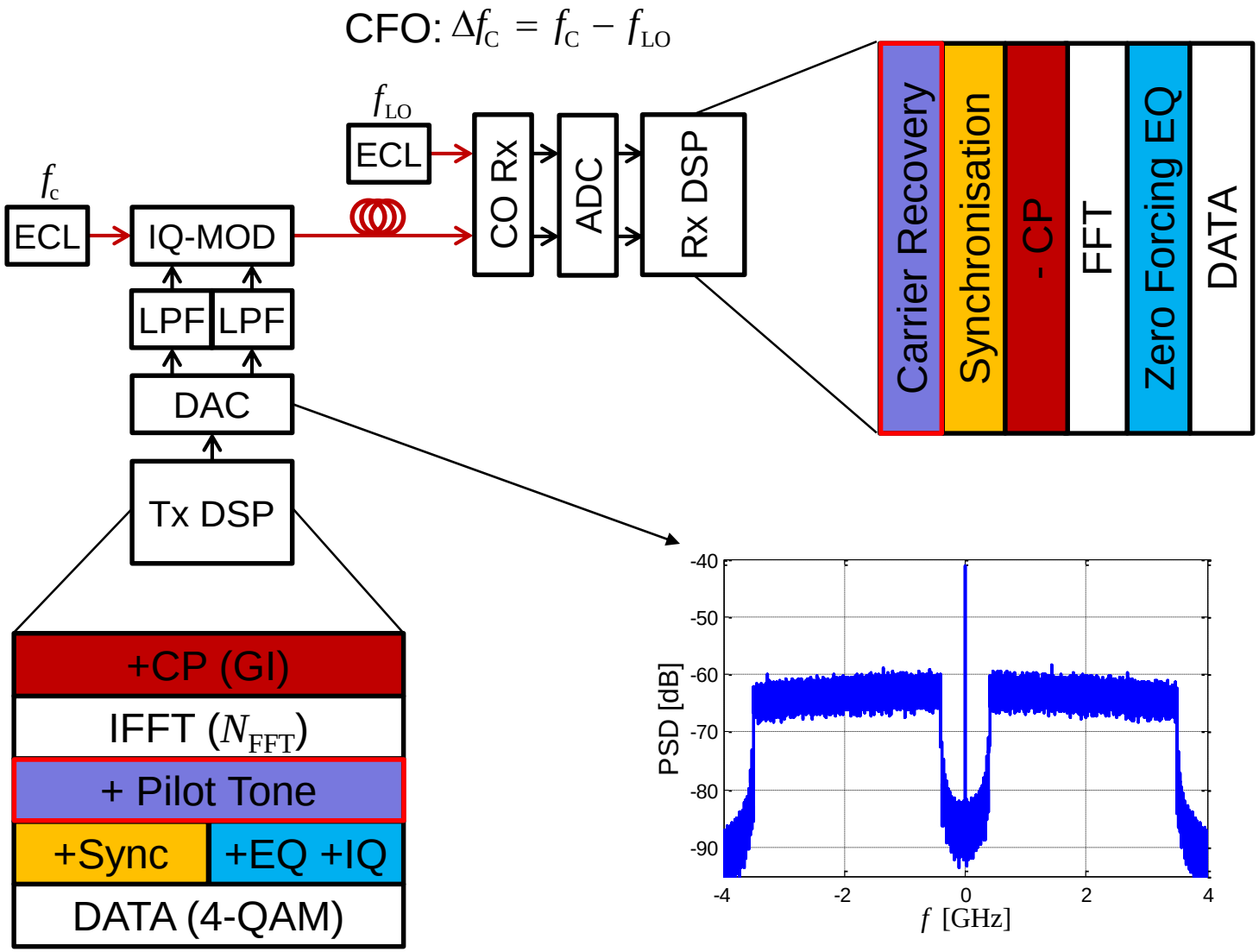
Phase rotation | Attenuation | Phase rotation | Intercarrier interference

Morelli, M., et al.(2007): *Proceedings of the IEEE 95, Nr.7*

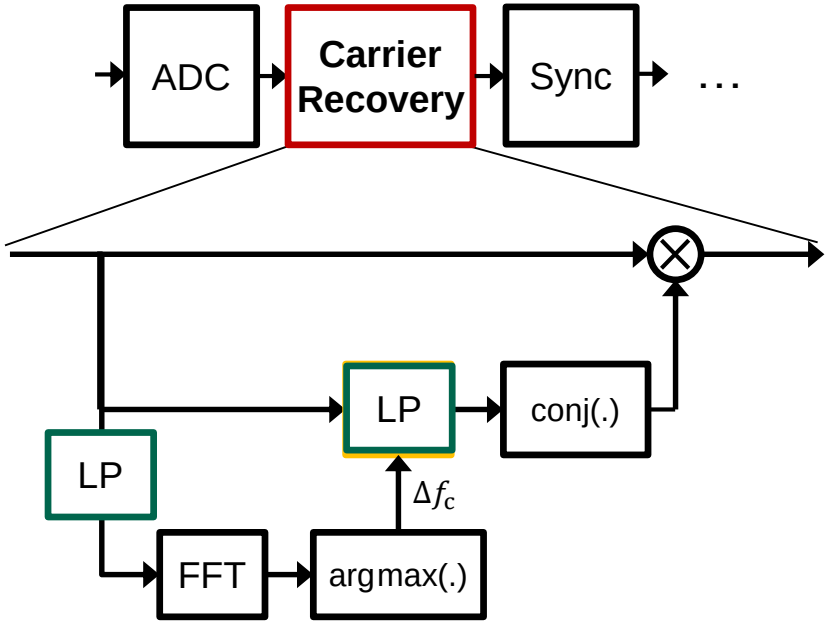
Outline

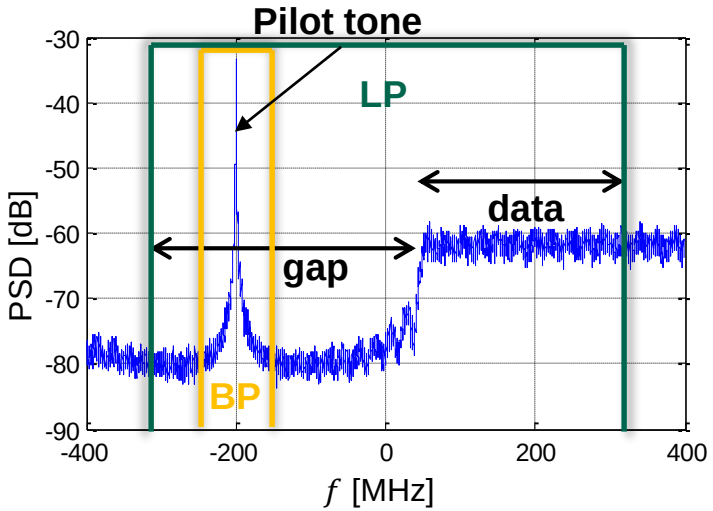
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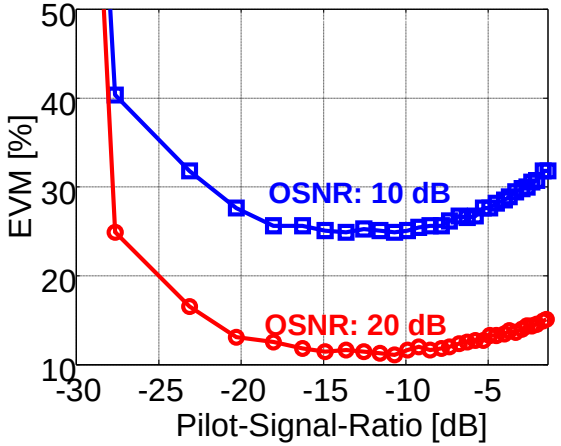
CO-OFDM Transmission System – Pilot Tone CR

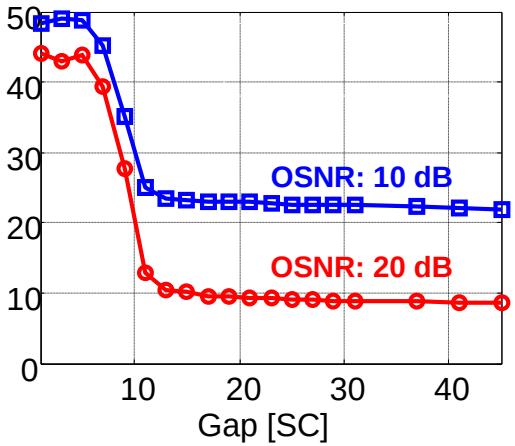


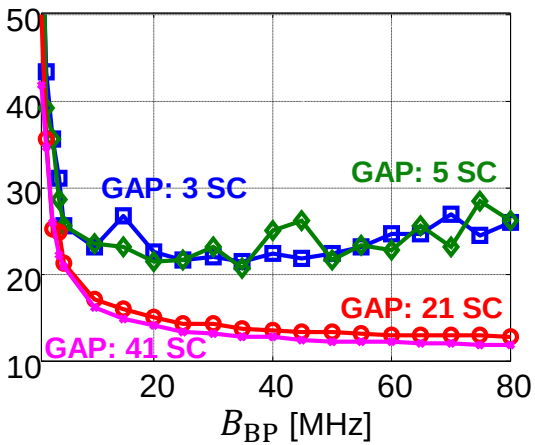
Pilot Tone Based CFO and PN Compensation





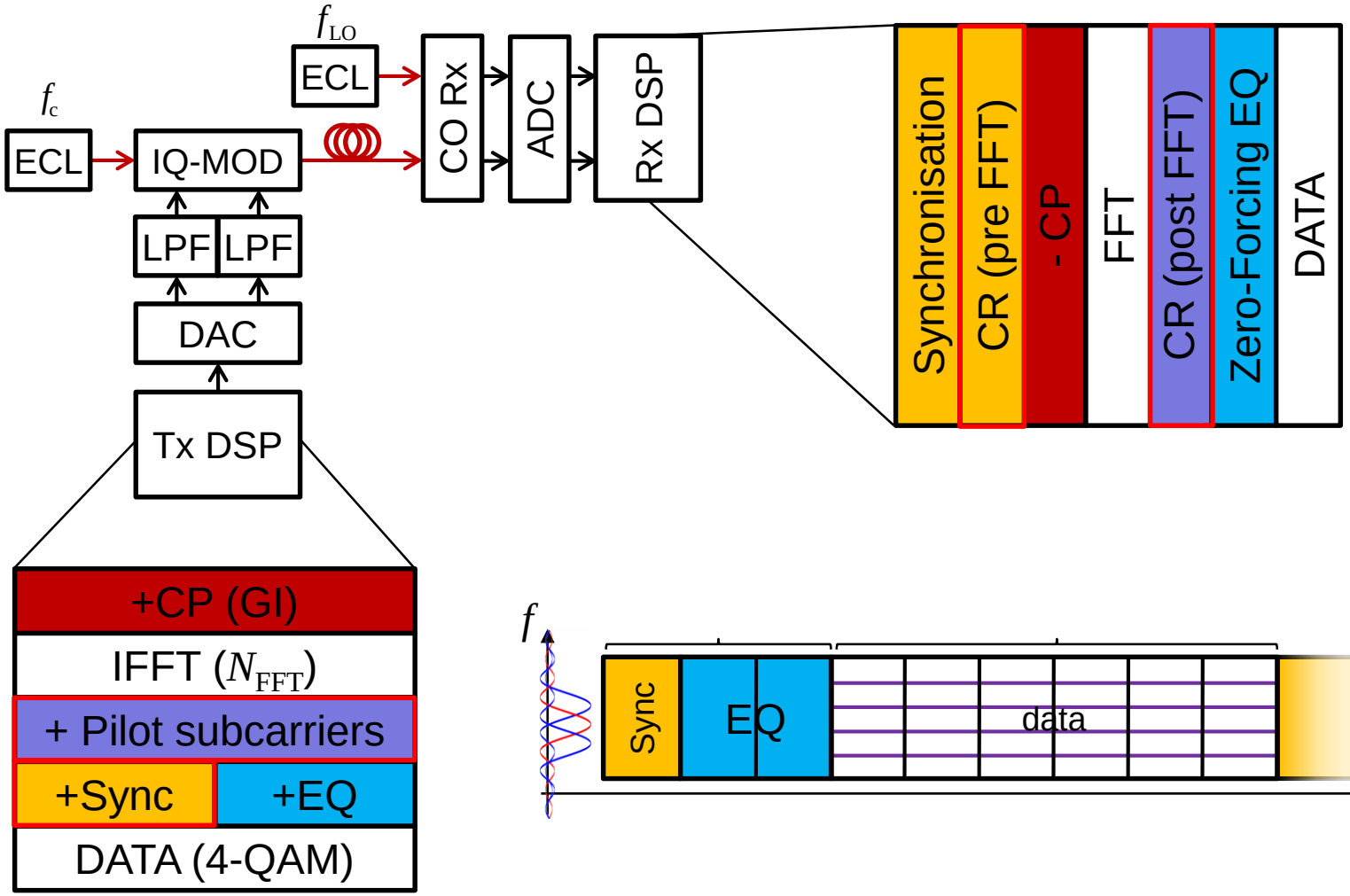




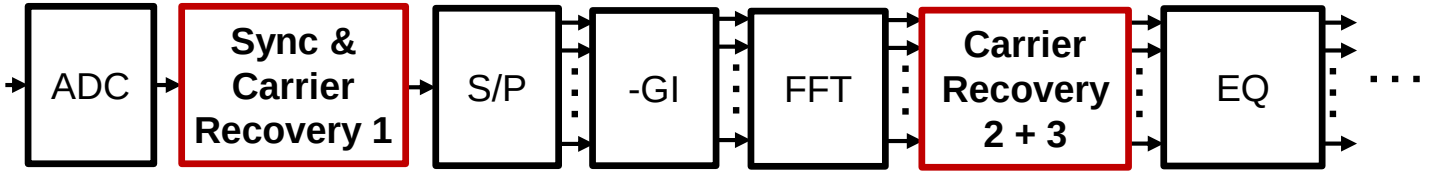


Jansen, S. L., et. al (2008). *Journal of Lightw, Techn.*.

CFO: $\Delta f_C = f_C - f_{LO}$



TS Based CFO and PN Compensation



1. S&C TS with identical halves → CFO causes phase rotation Φ

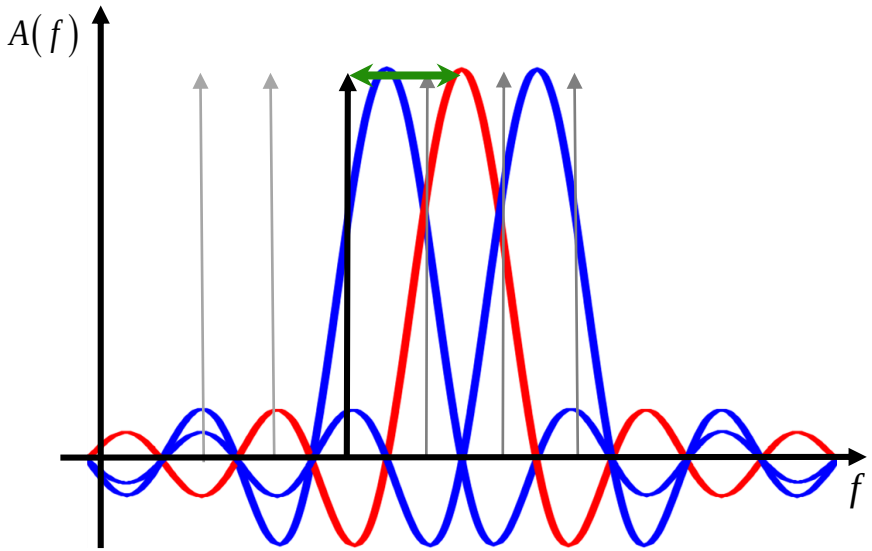
Timing metric (γ) for synchronisation

→ phase offset $\hat{\Phi} = \arg\left(\gamma(k=0)\right)$

→ Max. CFO: Subcarrier spacing

⇨ fractional CFO $\frac{\Phi}{\pi T}$

$$\Delta f_c = \frac{\Phi}{\pi T} + \frac{2z}{T}$$



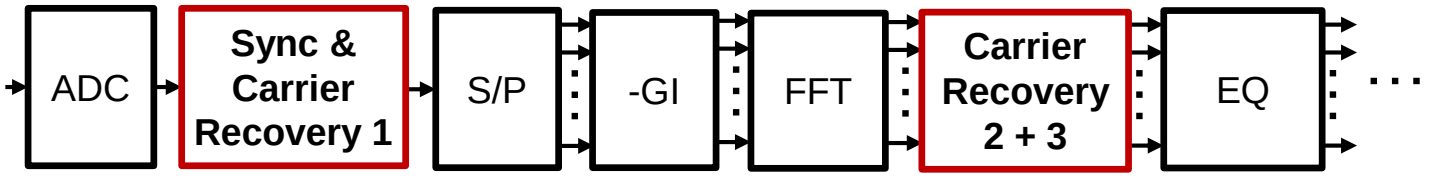
2. 2. TS with differential data on even SC

Estimation of integer CFO after FFT

⇨ $\frac{2z}{T}$

Schmidl, T., & Cox, D. (1997). , *IEEE Transactions on Communications*

TS Based CFO and PN Compensation



Phase Noise → Track along complete signal

3. Pilot subcarriers

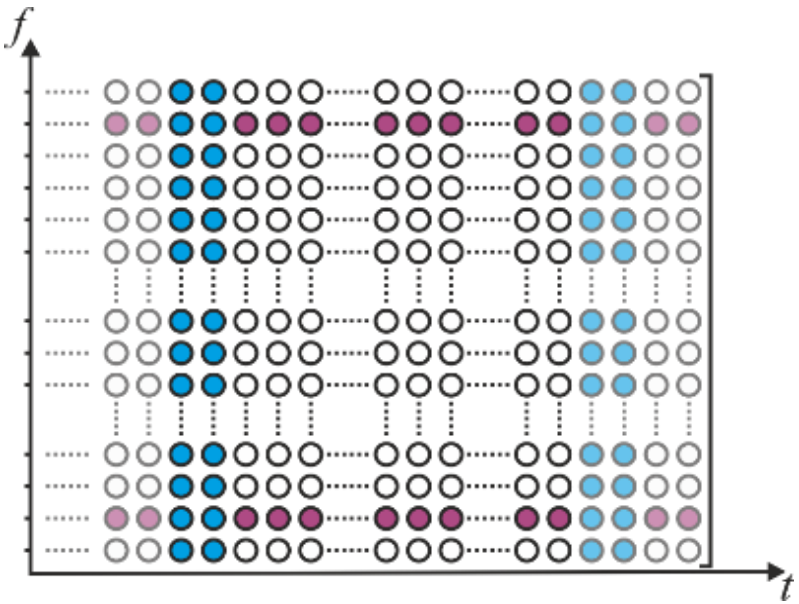
Extract N_p pilot subcarriers

Phase rotation for every OFDM-symbol

$$\hat{\Phi}(k) = \frac{1}{N_\mathrm{p}} \sum_{n=1}^{N_p} \arg\left(r_n(k)\right) - \arg\left(s_n(k)\right)$$

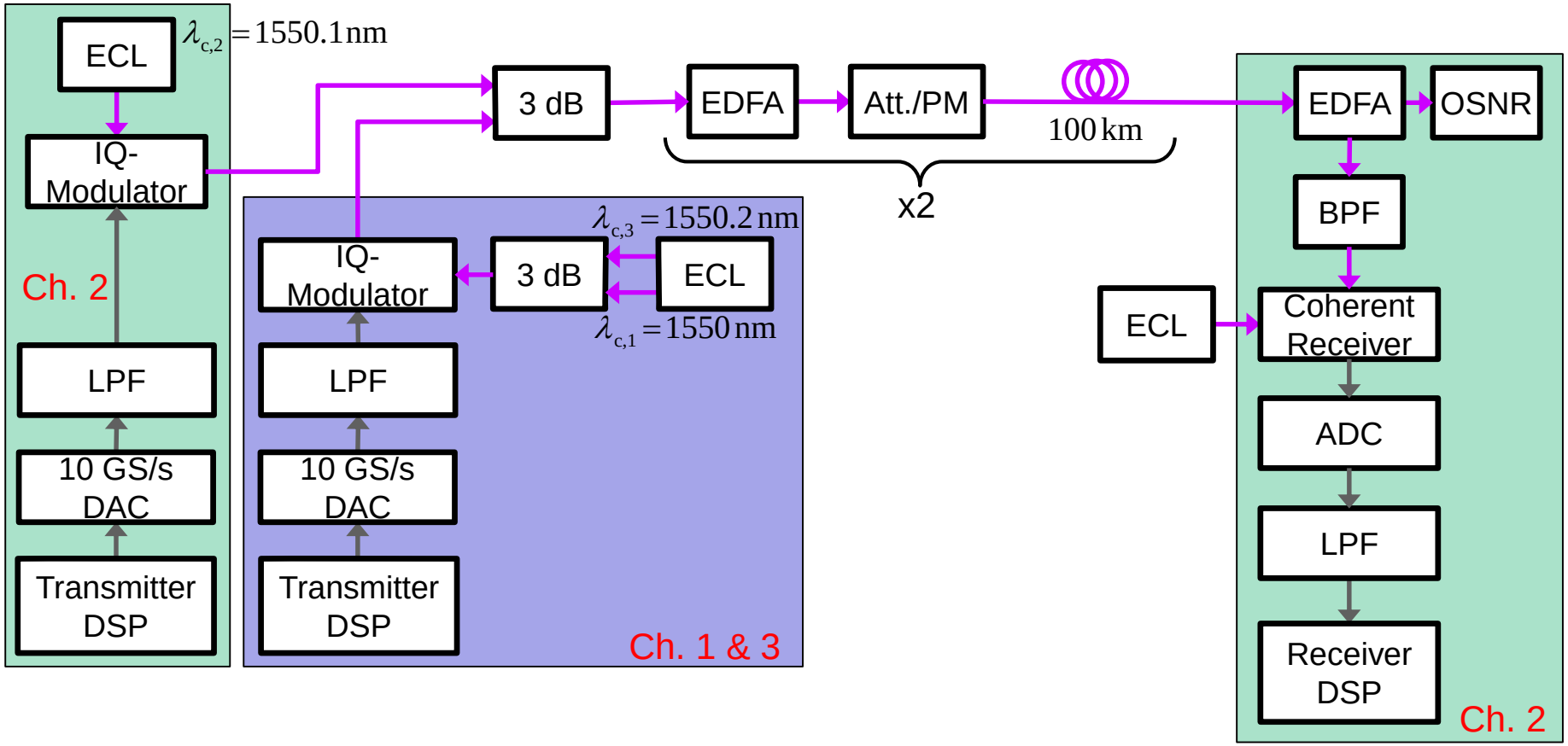
Compensation

$$\hat{s}_n(k) = r_n(k) \exp\left[-j2\pi\,\hat{\Phi}(k)\right]$$



Yi, X. (2007), *Australian Conference on Optical Fibre Technology*, *19*(12).

CO-OFDM WDM Simulation Model

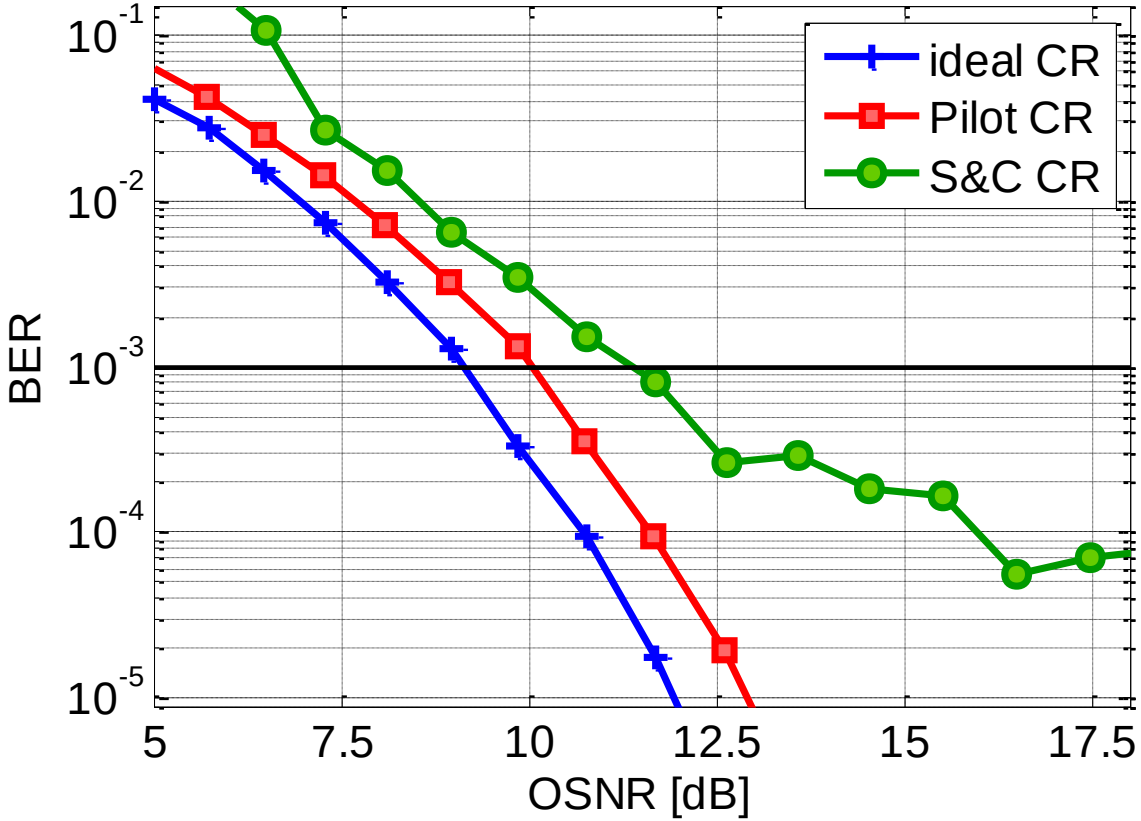


Preamble: 1 Sync-TS, 2 EQ-TS
Load: 50 Data-Symbols

N_{FFT} = 512 N = 354 (70%)
N_{CP} = 24 Gap = 41 subcarriers

⇨ 5.6 Gbaud/ch
11.2 Gbit/s/ch

Carrier Recovery Simulation Results



Δf_c = 200 MHz

linewidth = 100 kHz

l = 200 km

OSNR @ BER = 10^{-3}:

Ideal: 9,1 dB
Pilot tone: 10 dB
S&C: 11,4 dB

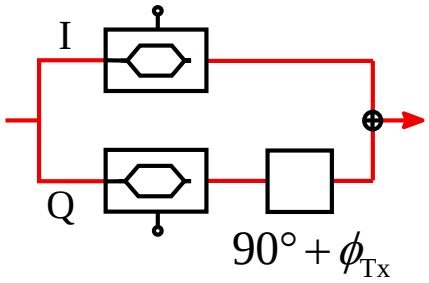
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Transmitter IQ-Imbalance Impairments

Tx IQ-Imbalance:

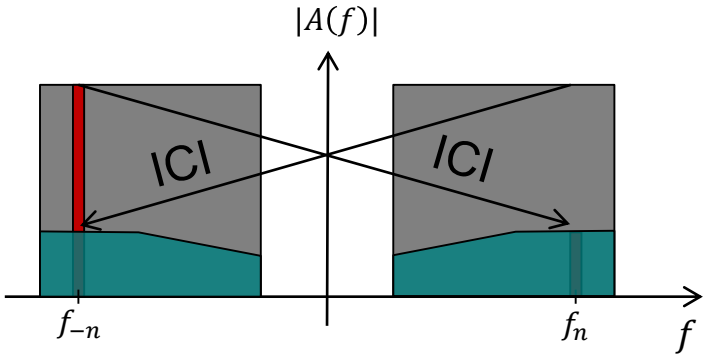
- Loss of power balance between I- & Q-branch → amplitude imbalance g_{Tx}
- Loss of orthogonality between I- & Q-branch → phase imbalance ϕ_{Tx}

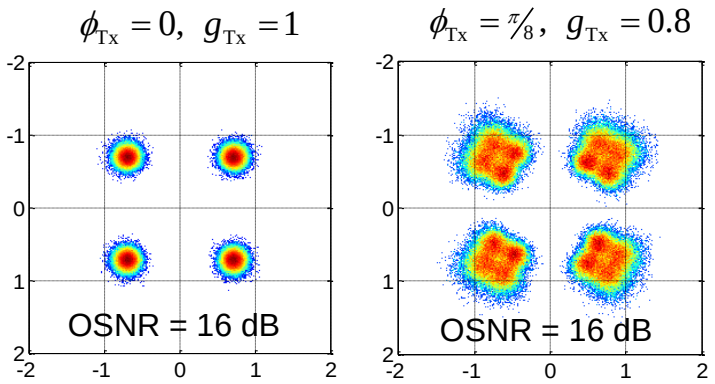


Data symbols of n^{th} SC:

$$r_n(k) = \underbrace{h_n G_{1,n} s_n(k)}_{\text{Imbalance}} + \underbrace{h_n G_{2,n} s^*_{-n}(k)}_{\text{ICI}}$$

$$G_{1,n} = \frac{1 + g_{\mathrm{Tx},n} \cdot e^{j\phi_{\mathrm{Tx},n}}}{2}, \qquad G_{2,n} = \frac{1 - g_{\mathrm{Tx},n} \cdot e^{-j\phi_{\mathrm{Tx},n}}}{2}.$$



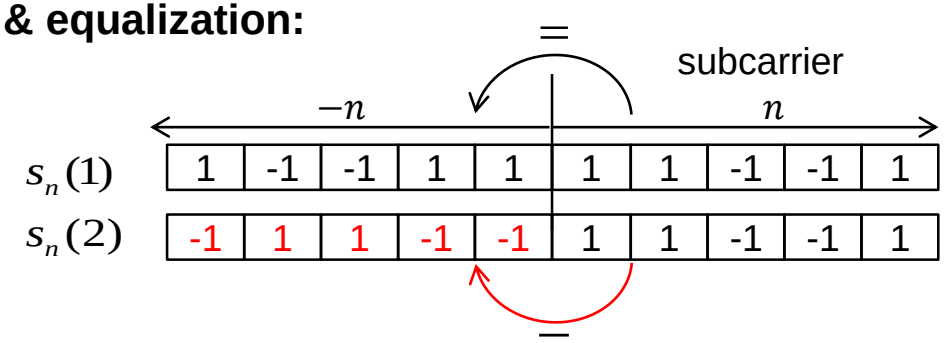


Schenk, T. (2008), *RF-Imperfections in high-rate wireless systems: impact and digital compensation*.

Transmitter IQ-Imbalance Compensation

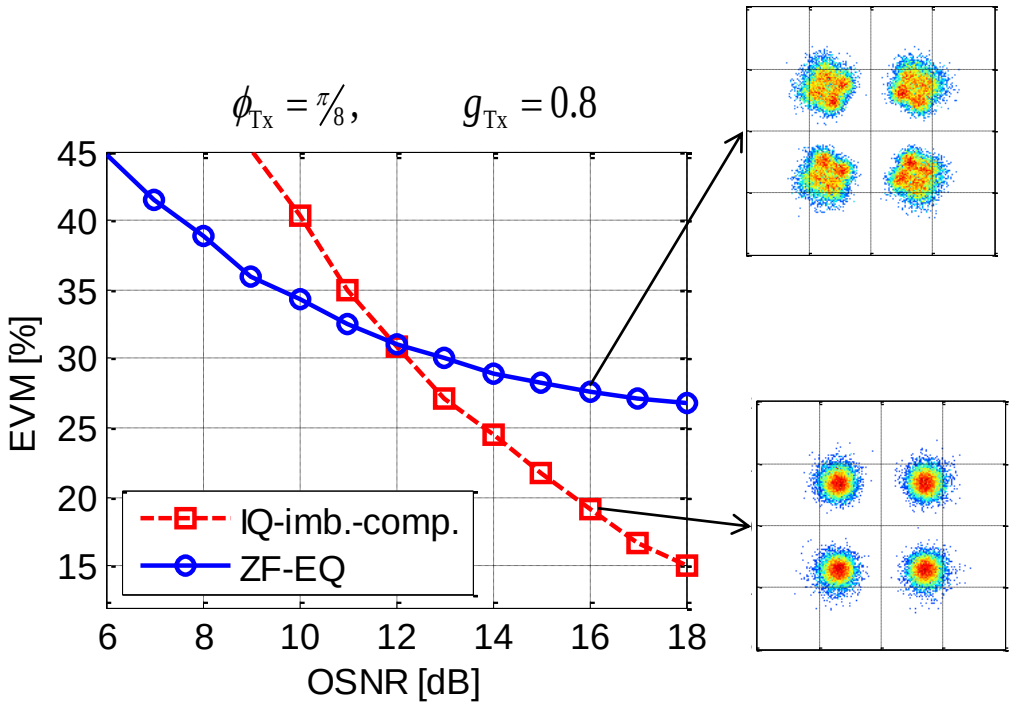
Training symbols for compensation & equalization:

1st Channel estimation
2nd IQ-Imbalance estimation

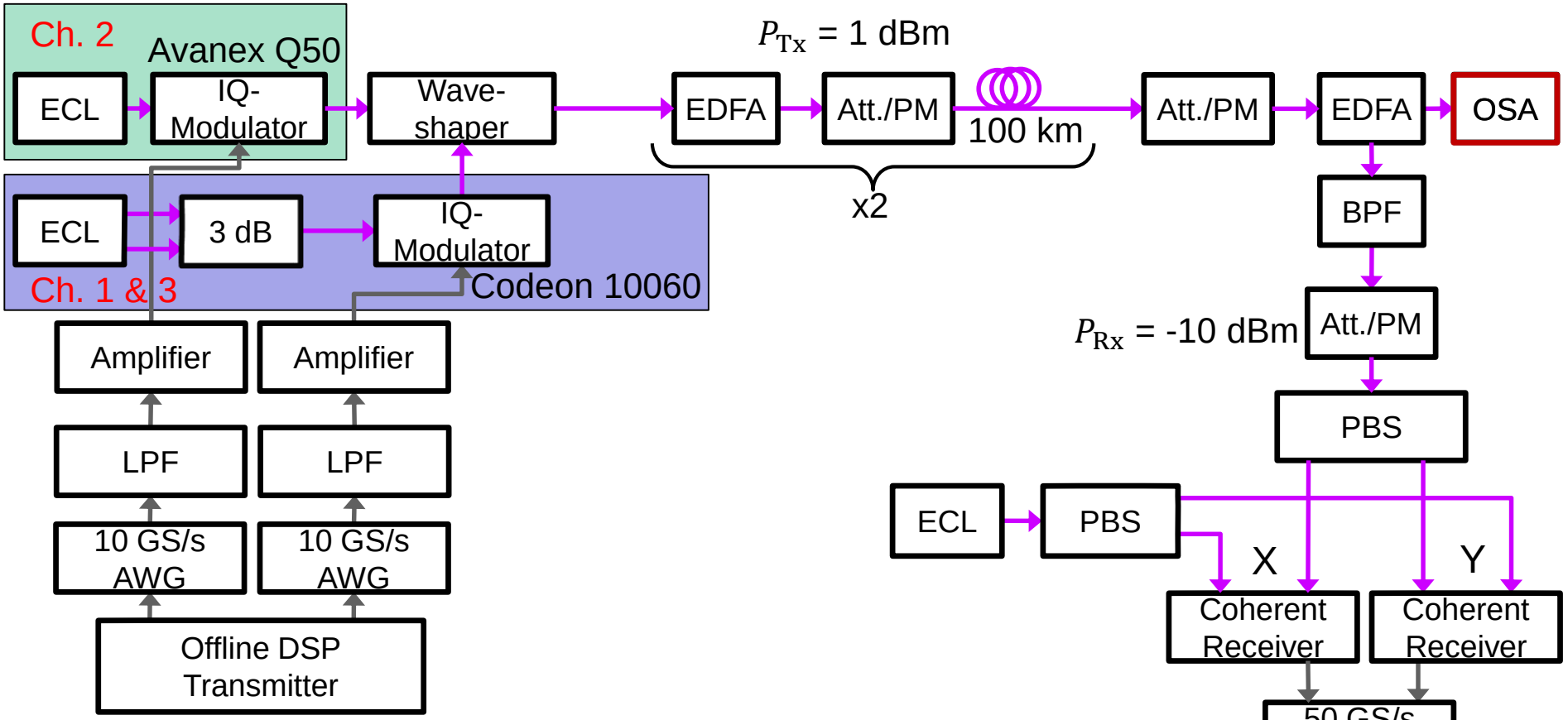


Compensation & EQ

$$\begin{bmatrix} \hat{s}_n(k) \\ \hat{s}_{-n}(k) \end{bmatrix} = \begin{bmatrix} \hat{h}_n(k)\hat{G}_{1,n} & \hat{h}_n(k)\hat{G}^*_{2,n} \\ \hat{h}^*_{-n}(k)\hat{G}_{2,n} & \hat{h}^*_{-n}(k)\hat{G}^*_{1,n} \end{bmatrix}^+ \cdot \begin{bmatrix} r_n(k) \\ r_{-n}(k) \end{bmatrix}$$



CO-OFDM WDM Experimental Setup



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N_{CP} = 24 Gap = 41 subcarriers

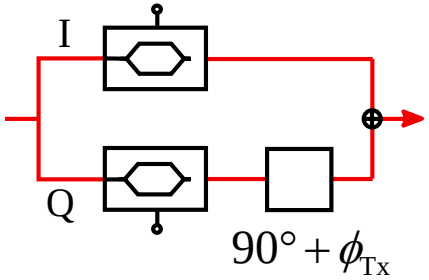
5.6 Gbaud/ch
11.2 Gbit/s/ch

Phase Imbalance Variation (B2B)

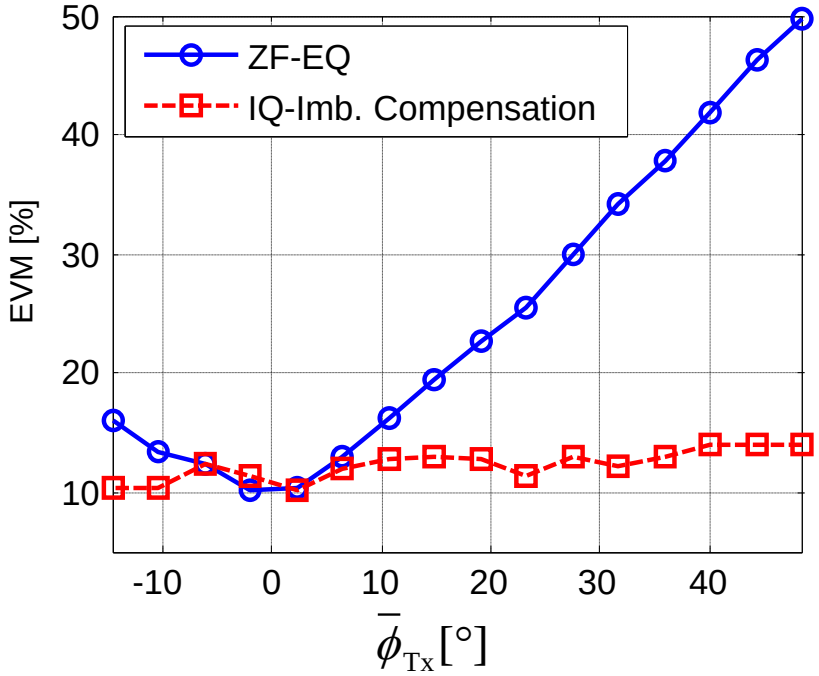
B2B, OSNR = 40 dB

Variation of bias voltage from phase modulator

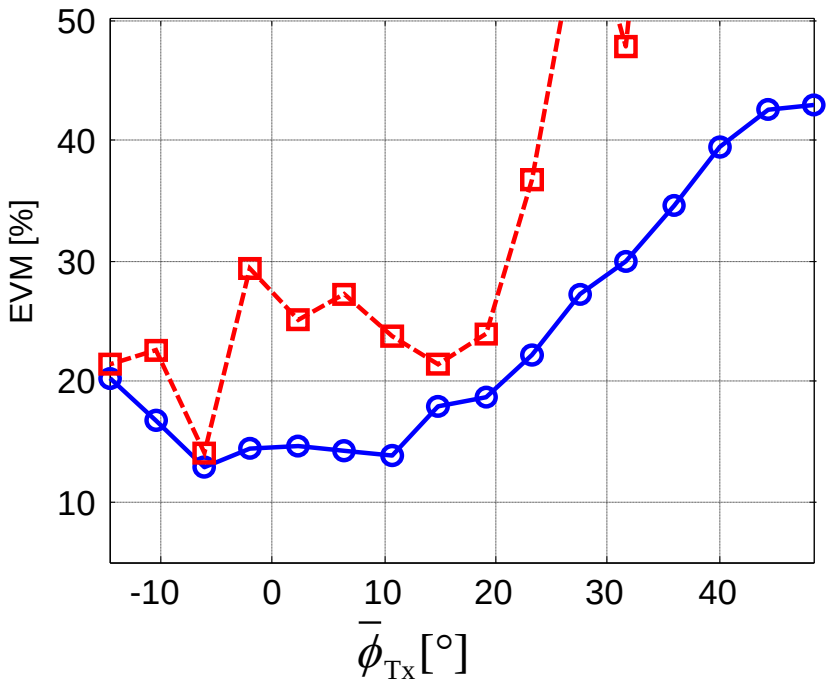
Comparison between ZF-Equalizer and IQ-imbalance compensation



Pilot tone approach:

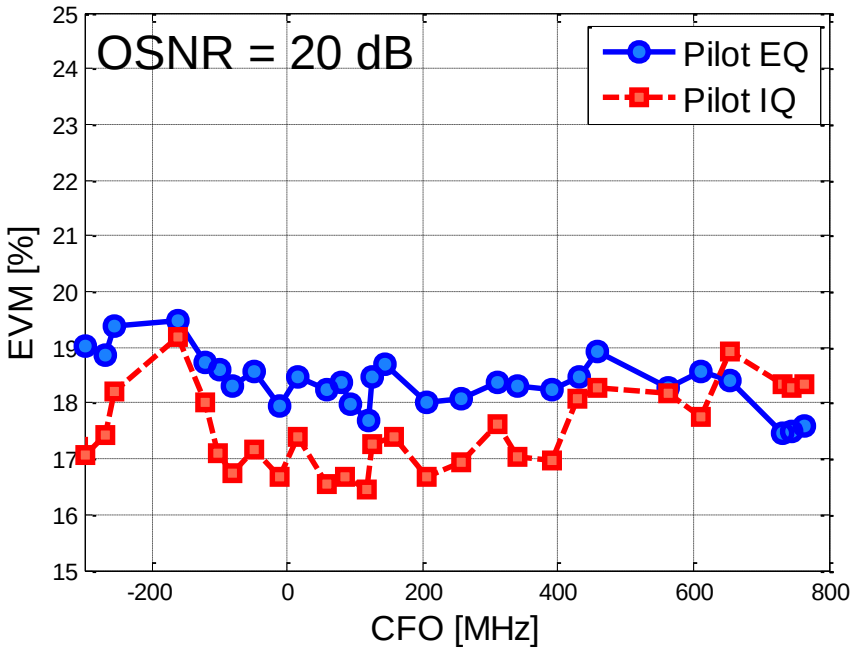


S&C TS approach:

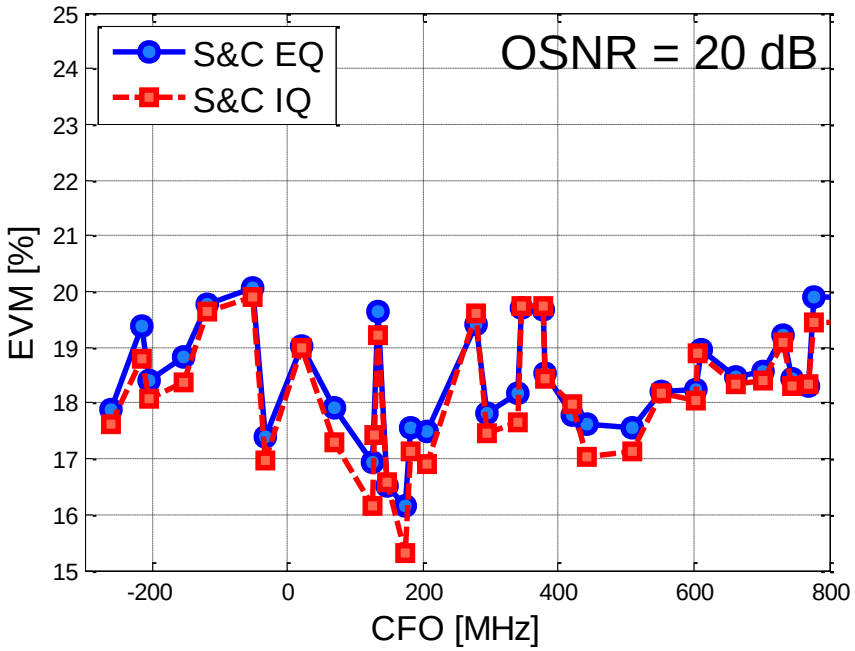


CFO Variation (200km)

Pilot tone approach



S&C TS approach

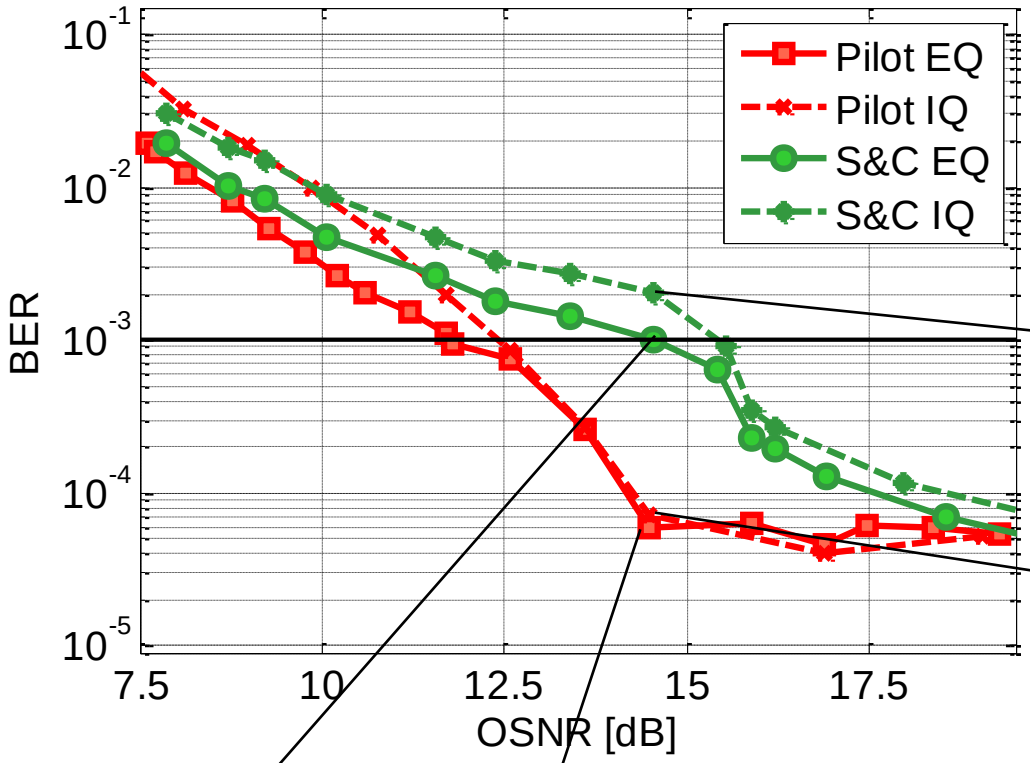


$$\bar{\phi}_{\mathrm{Tx}} = 2.4^{\circ}, \quad \bar{g}_{\mathrm{Tx}} = 1.06$$

Mean EVM:

Only ZF-EQ:	**18.4%**	**Only ZF-EQ:**	**18.4%**
w IQ-Imb. Comp.:	**17.5%**	**w IQ-Imb. Comp.:**	**18.2%**

OSNR Variation (200km)

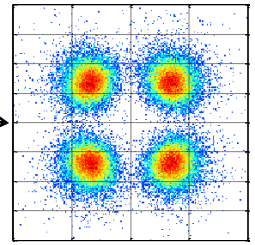


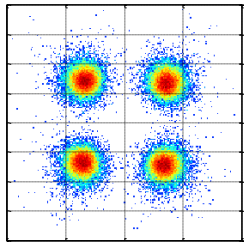
$$\Delta f_c \approx 150\,\text{MHz}$$

$$\bar{\phi}_{\text{Tx}} = 2.65°$$

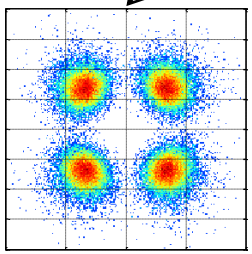
$$\bar{g}_{\text{Tx}} = 1.16$$

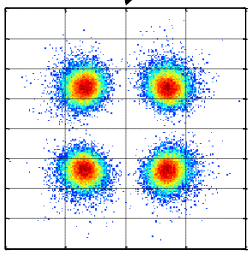
IQ-Imb. Comp.





ZF:





OSNR @ BER = 10^{-3}:

Ideal EQ (Simulation): 9,1 dB

Pilot EQ: 11,75 dB

S&C EQ: 14,6 dB

Summary + Conclusion

Summary

- Experimental verification for CFO + PN compensation methods
- Experimental evaluation of an IQ-imbalance compensation method

Conclusion

- Pilot tone based CFO + PN compensation:
  - Robust, IQ-imbalances can be compensated
- TS based CFO + PN compensation (pilot subcarriers):
  - Degraded performance with IQ-imbalances

Thank you for your attention!