Spectrally Efficient Transmission: a Comparison between Nyquist-WDM and CO-OFDM Approaches

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Motivations

- High-spectral efficiency
  - High-order modulation formats
  - Tighter channel spacing
- Two complementary approaches to achieve symbol-rate (or near symbol-rate) spacing:
  - Nyquist-WDM (or Quasi-Nyquist-WDM)
  - CO-OFDM
- Which technique is the best choice (in terms of performance/complexity) for a “superchannel” transmission?

Outline

- Nyquist-WDM and CO-OFDM
- Defining the test set-up
- Back-to-back performance
  - Single super-channel
  - 3 super-channels
- Offset-QAM
- Conclusions

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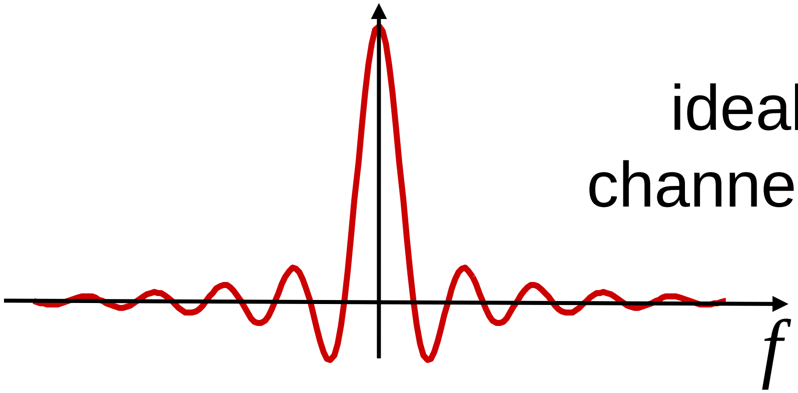
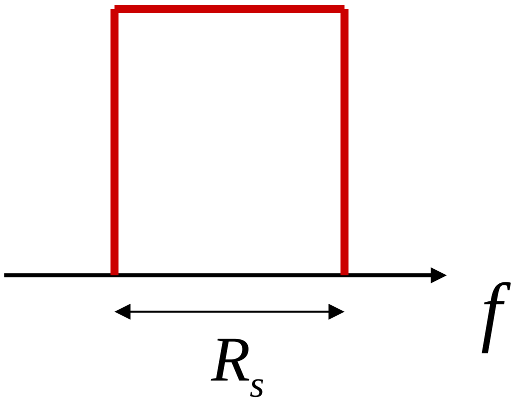
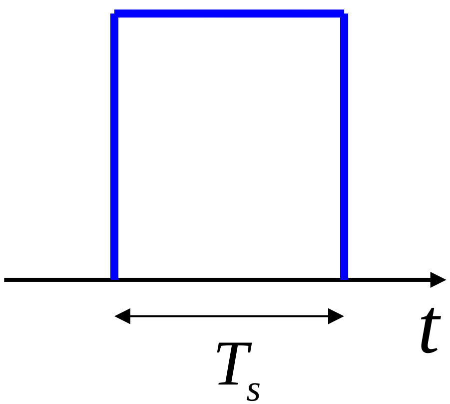
Ideal single-channel pulses

- CO-OFDM
- Nyquist WDM

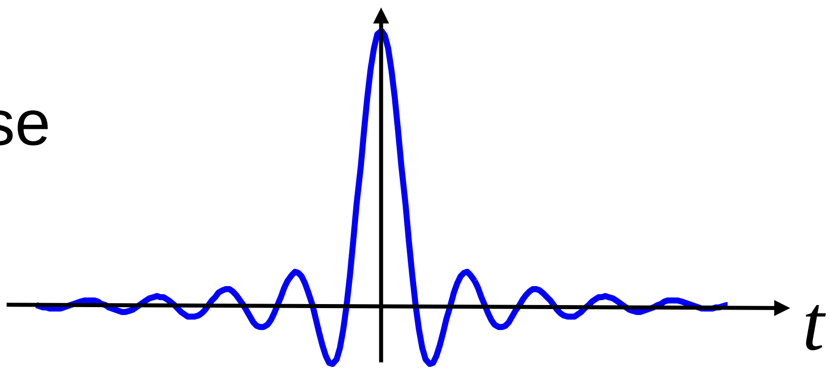


ideal single channel spectrum





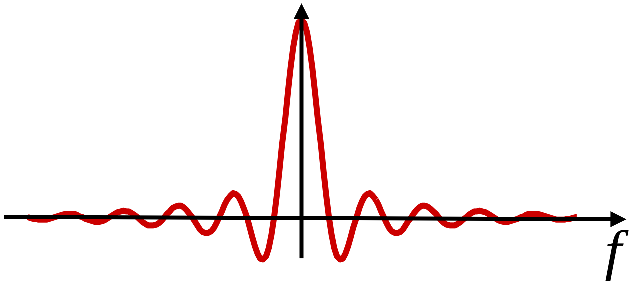
ideal pulse shape



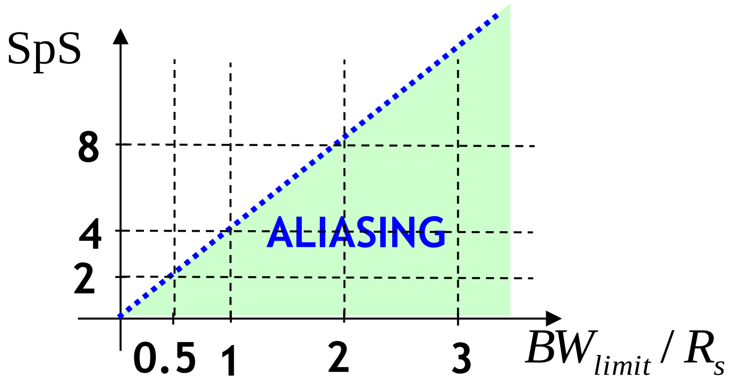
- For both systems, the performance reaches the quantum limit if the overall Rx transfer function (optical filter + PD filter + equalizer) is “matched” to the transmitted pulses

Requirements for CO-OFDM

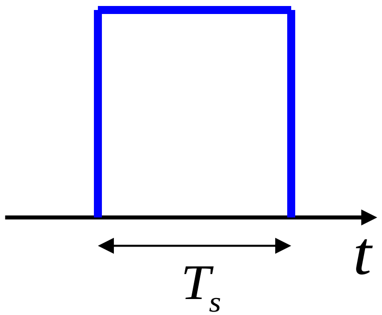
- A large RX bandwidth is required to properly approximate the sinc function in the frequency domain



- A large number of samples per symbol (SpS) is required by DSP in order to avoid aliasing

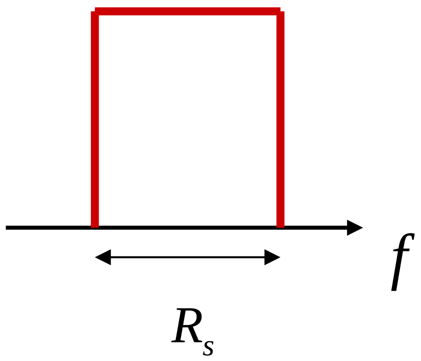


- Since the time domain pulse is limited in one symbol slot, a very small number of FIR taps is required in the absence of other sources of ISI

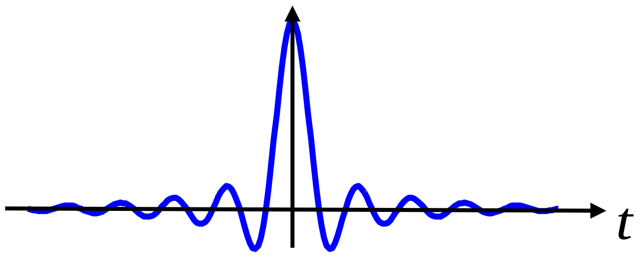


Requirements for Nyquist WDM

- Very "steep" (optical or electrical) analog filtering is required



- If the analog filtering is not present (or not enough steep), a FIR with a very large number of taps is necessary to properly approximate the sinc function in the time domain



- Since the frequency spectrum is limited to R_s, 2 SpS are sufficient to avoid aliasing

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Superchannel

- We compare the performance of CO-OFDM and Nyquist-WDM approaches for the generation of **400 Gb/s** superchannels, based on the **PM-16QAM** modulation format.

- Each superchannel is composed of a number of optical sub-channels and is routed optically through the network as a single entity.

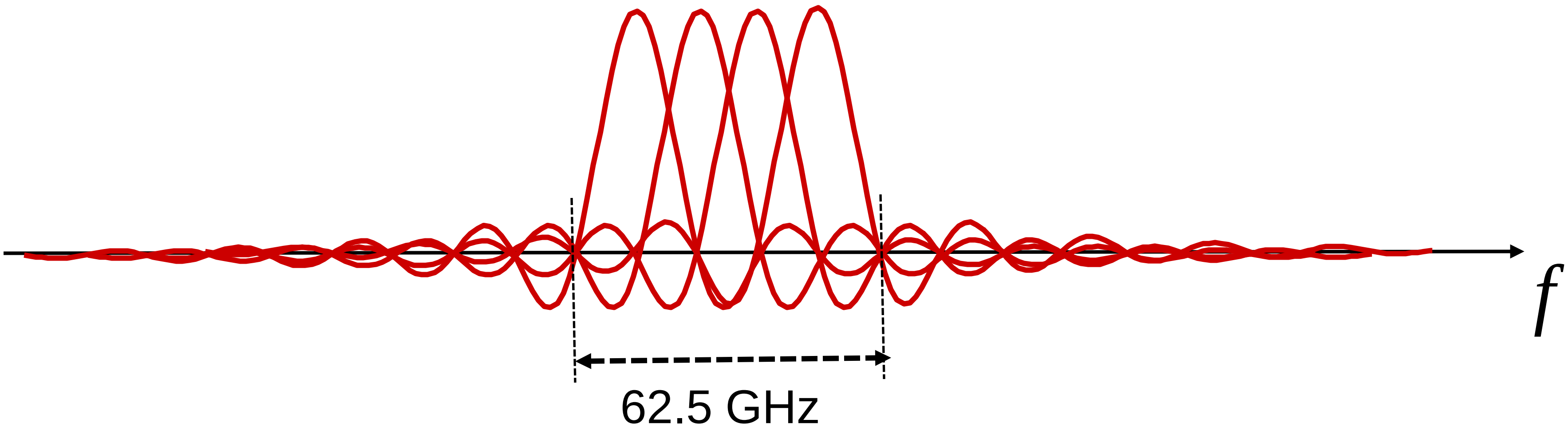
- We analyze by simulation the robustness to:
  - optical filtering due to ROADMs present in the optical network
  - crosstalk induced by adjacent superchannels

Receiver

- At the Rx side, we assume the availability of the same component technology for implementation of either CO-OFDM or Nyquist-WDM:
  - **ADC with 50 Gsamp/s and BW~12.5 GHz**
  - CO-OFDM needs a DSP with at least 4 samp/symbol
    → symbol rate: R_s=50/4=12.5 Gbaud
  - For Nyquist-WDM, 2 samp/symbol are sufficient to achieve almost ideal performance
    → symbol rate: R_s=50/2=25 Gbaud

CO-OFDM

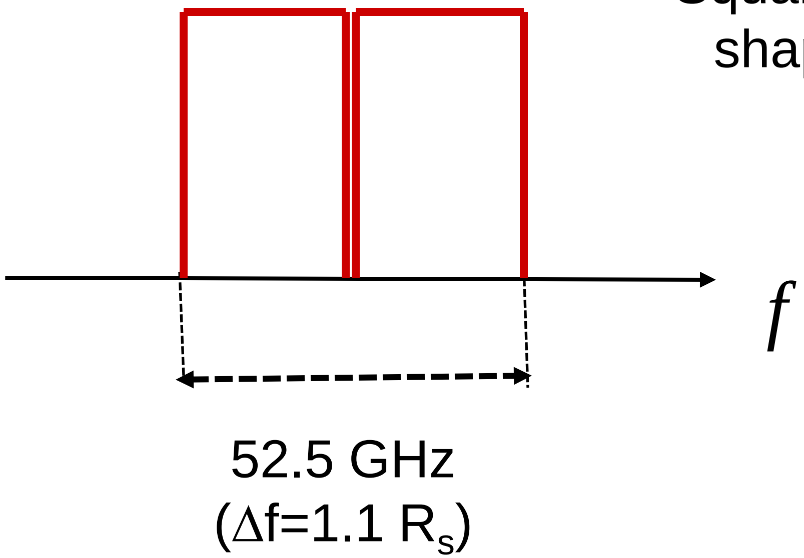
- 12.5 Gbaud PM-16QAM → 100 Gb/s
- ADC speed: 50 Gsamp/s → 4 SpS
- A 400G superchannel is composed of 4 PM-16QAM sub-channels:



Nyquist-WDM

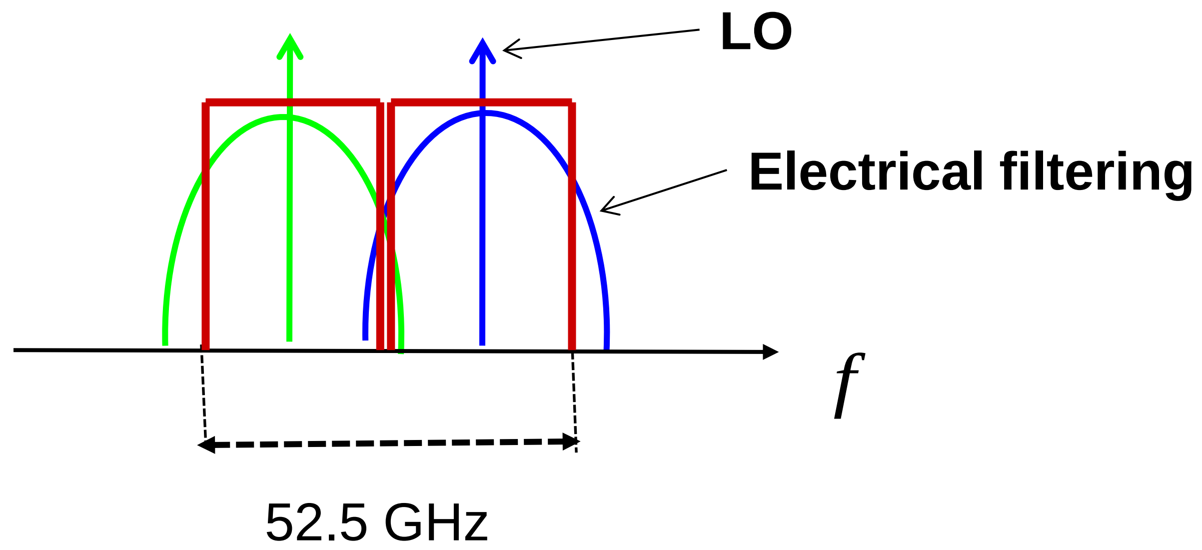
- 25 Gbaud PM-16QAM → 200 Gb/s
- ADC speed: 50 Gsamp/s → 2 SpS
- A 400G superchannel is composed of 2 PM-16QAM sub-channels:

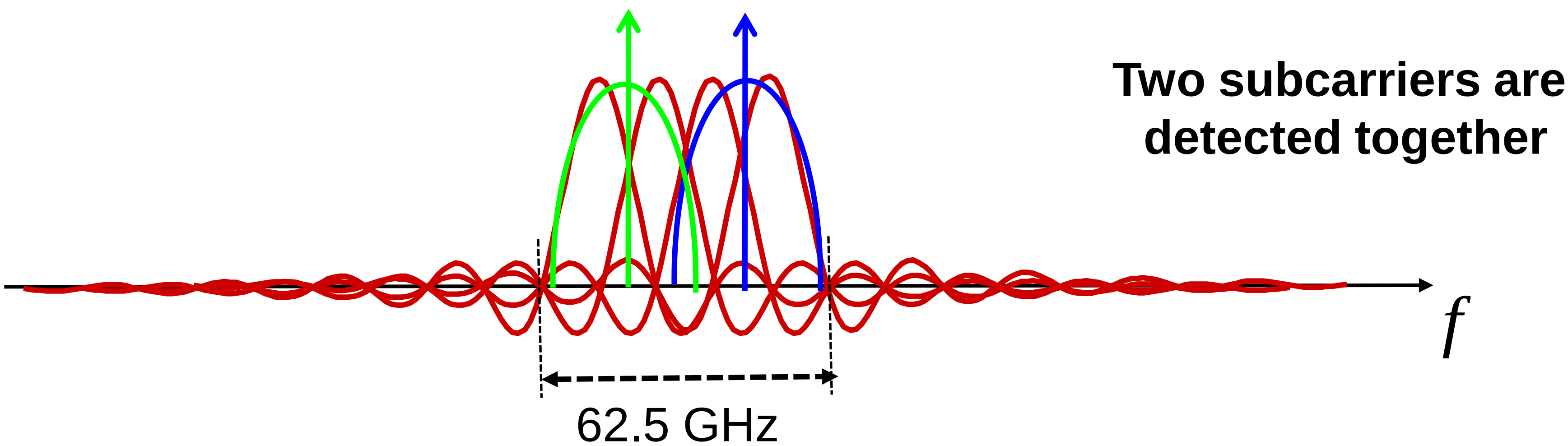
Square-root raised-cosine shape with roll-off 0.03



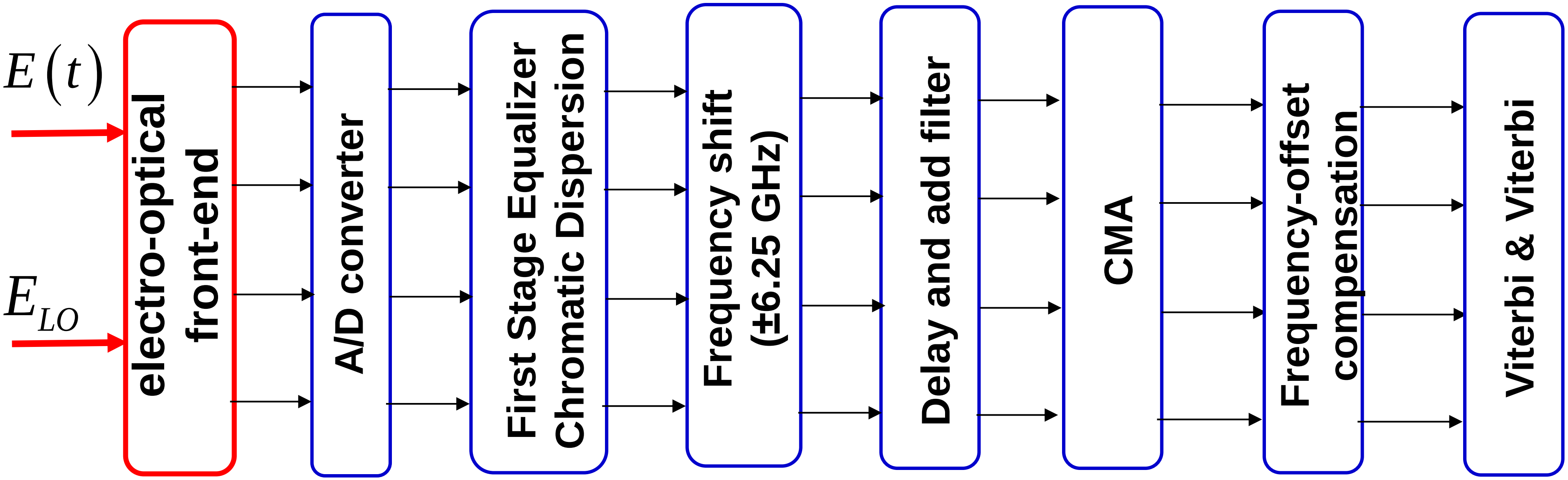
Nyquist-WDM and CO-OFDM Receivers

- In both cases, two Rx's are sufficient to receive all the WDM comb:





CO-OFDM receiver schematic



- The LO frequency f_{LO} is in the middle of the two sub-carriers (spaced 12.5 GHz)
- Carrier separation is performed by shifting each carrier to the baseband and passing each shifted carrier through a T/2 delay-and-add filter.

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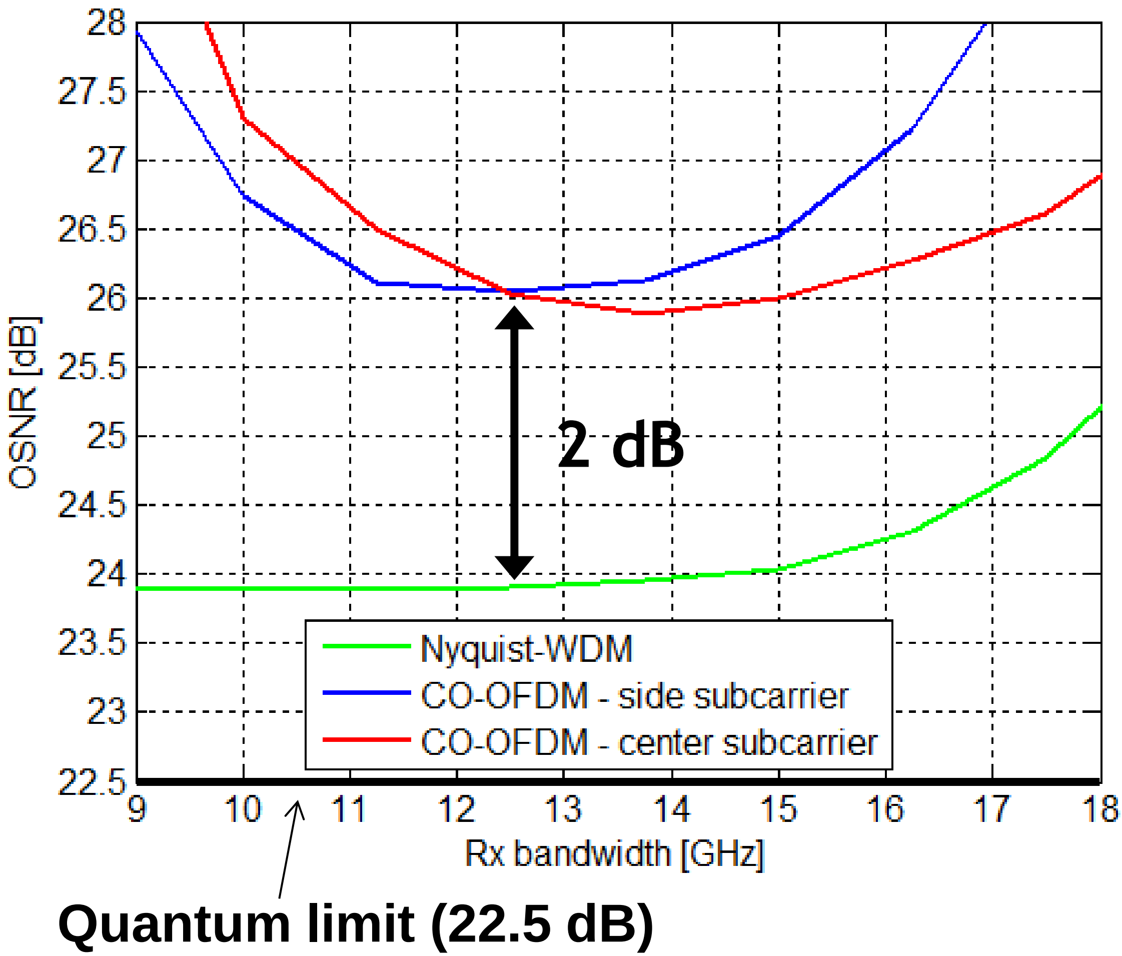
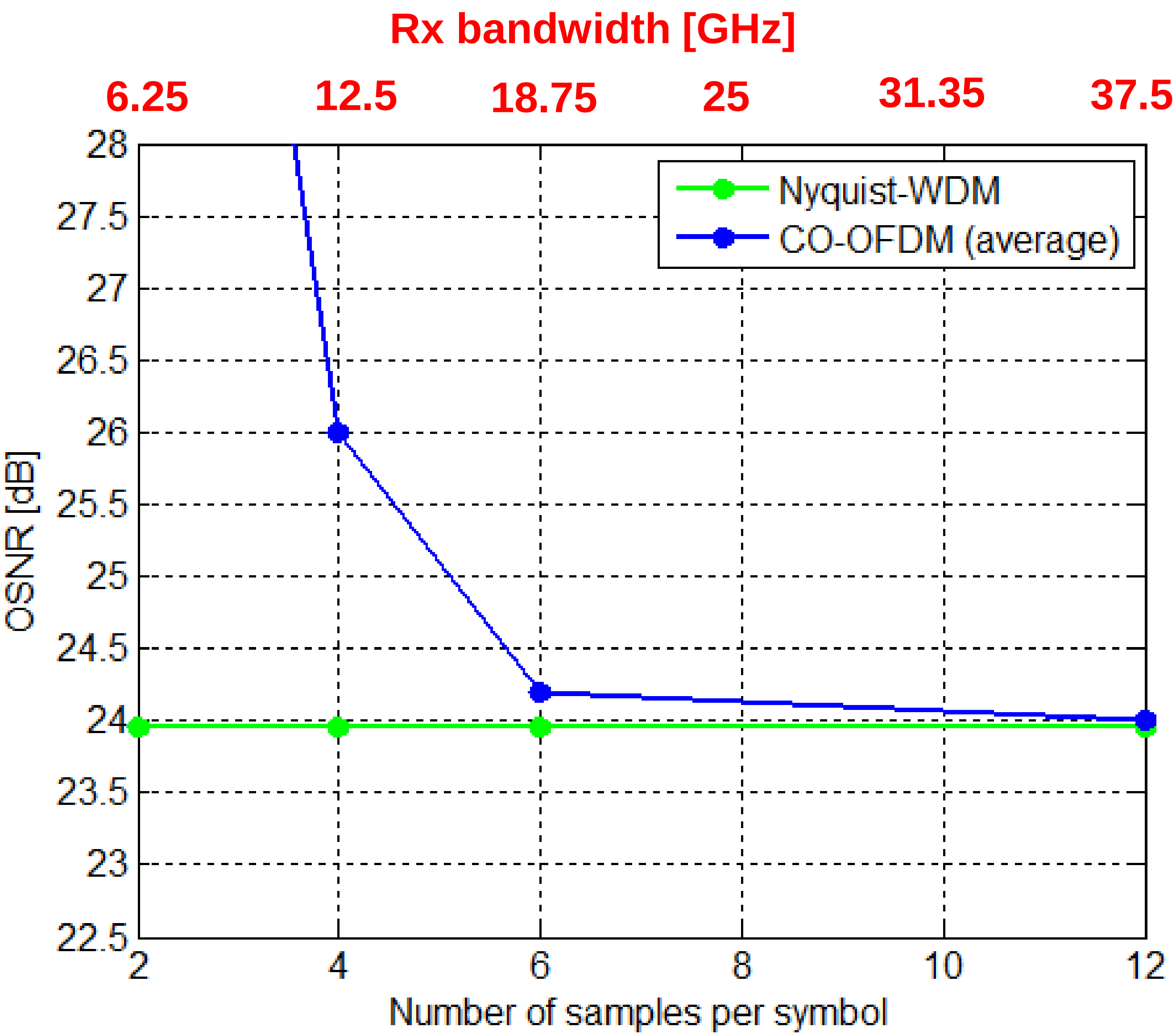
OSNR vs. Rx bandwidth



- Target BER: 10^{-3}
- OSNR evaluated over a 0.1 nm bandwidth and is referred to the whole super-channel.
- Number of taps:
  - 41 for Nyquist-WDM
  - 25 for CO-OFDM
- 2SpS for Nyquist-WDM
- 4SpS for CO-OFDM

Performance vs. number of SpS

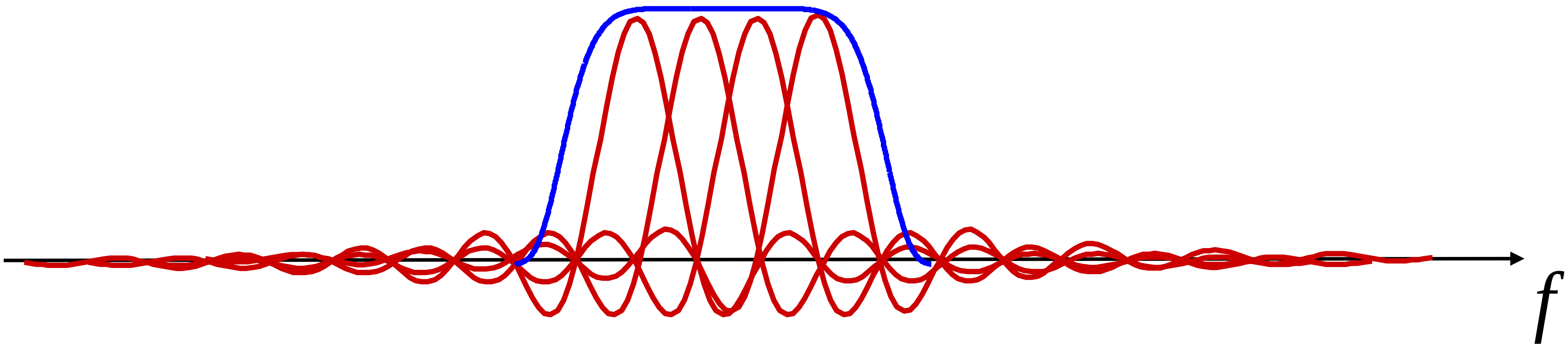


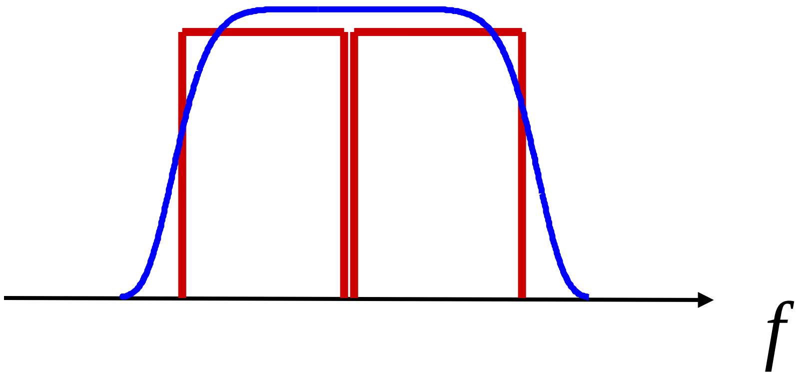
CO-OFDM

# SpS	Optimum Rx BW
2	$\sim 0.5 \cdot R_s$
4	$\sim R_s$
6	$\sim 1.5 \cdot R_s$
12	$\sim 3 \cdot R_s$

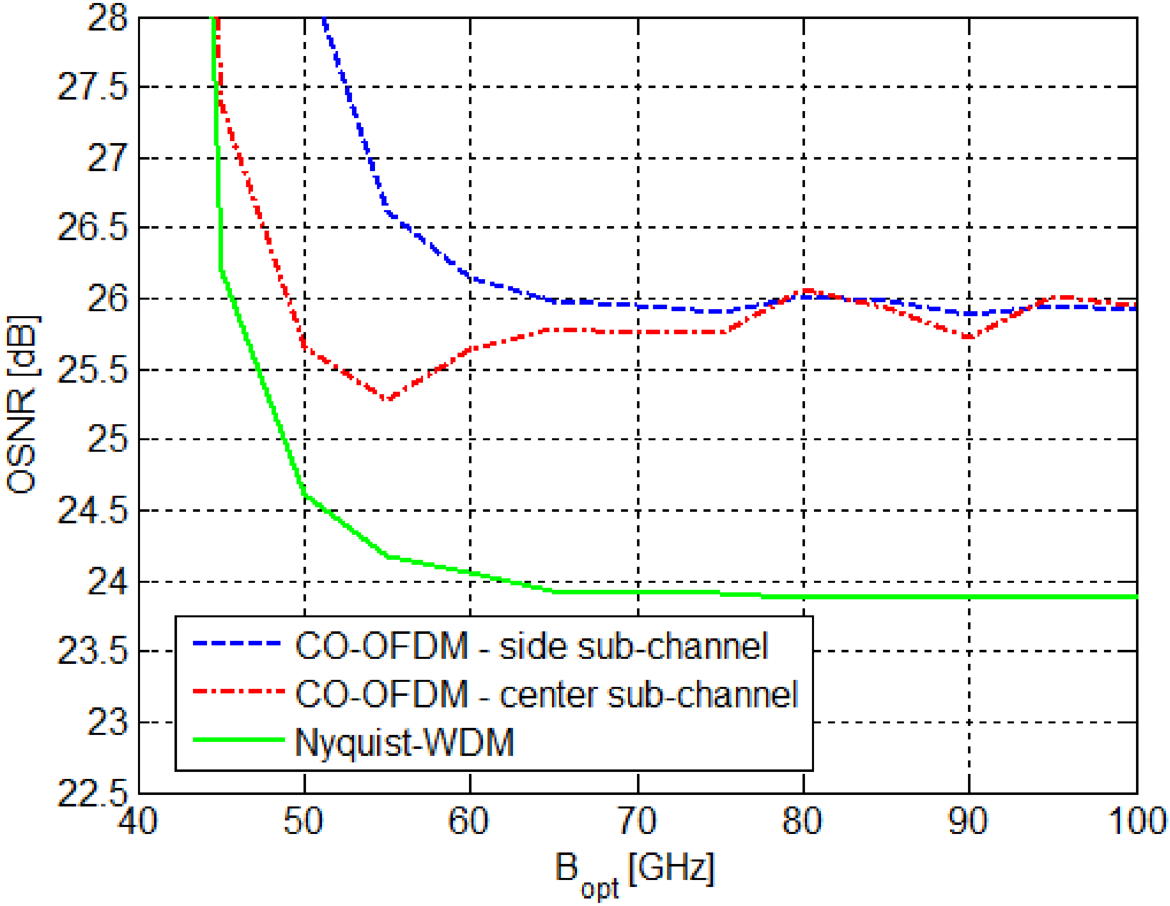
With optical filtering

- 4^{th} order Supergaussian optical filter with bandwidth B_{opt} which filters the whole super-channel



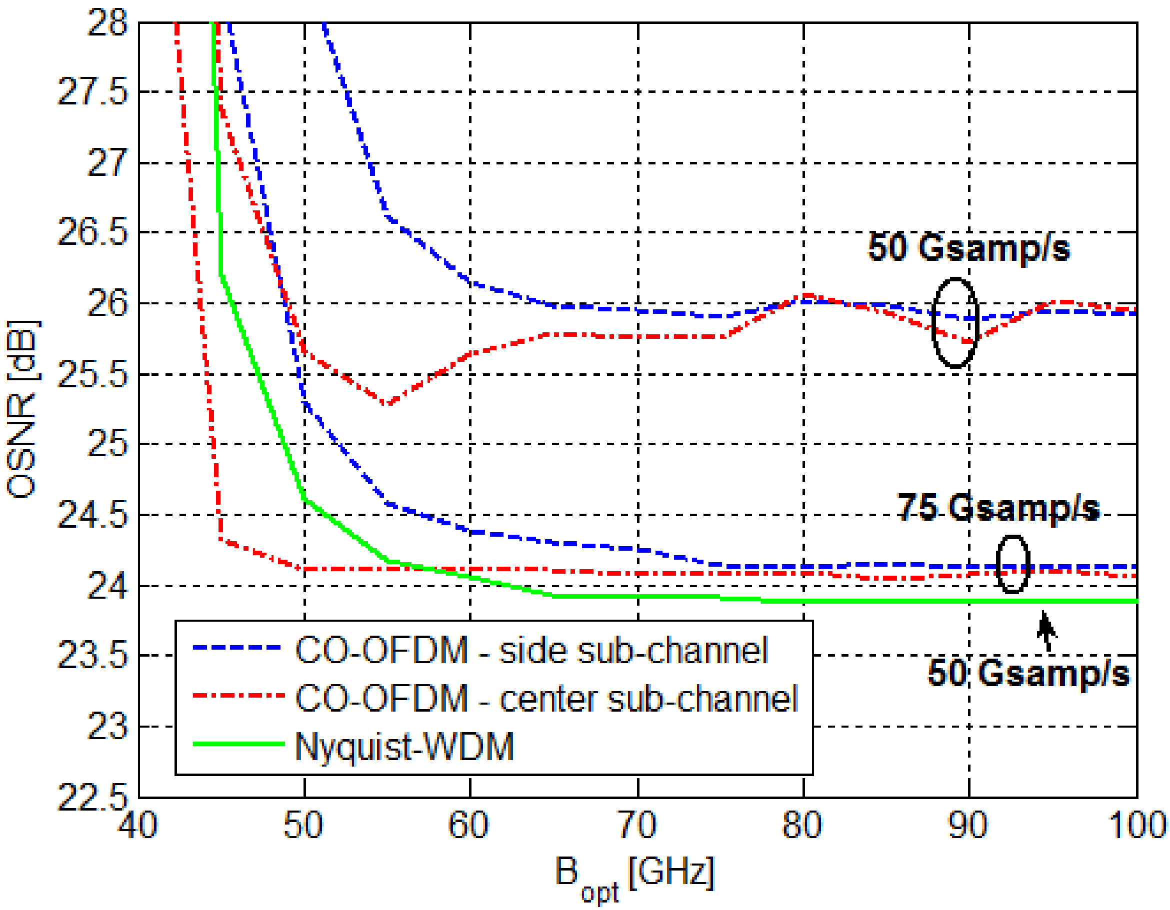


OSNR vs. optical filter BW



- Target BER: 10^{-3}
- 2SpS for Nyquist-WDM and 4 SpS for CO-OFDM:
  - ADC: 50 Gsamp/s
  - Rx BW: 12.5 GHz

OSNR vs. optical filter BW



- Target BER: 10^{-3}
- 2SpS for Nyquist-WDM and 4 SpS for CO-OFDM:
  - ADC: 50 Gsamp/s
  - Rx BW: 12.5 GHz
- 6SpS for CO-OFDM:
  - ADC: 75 Gsamp/s
  - Rx BW: 17.5 GHz

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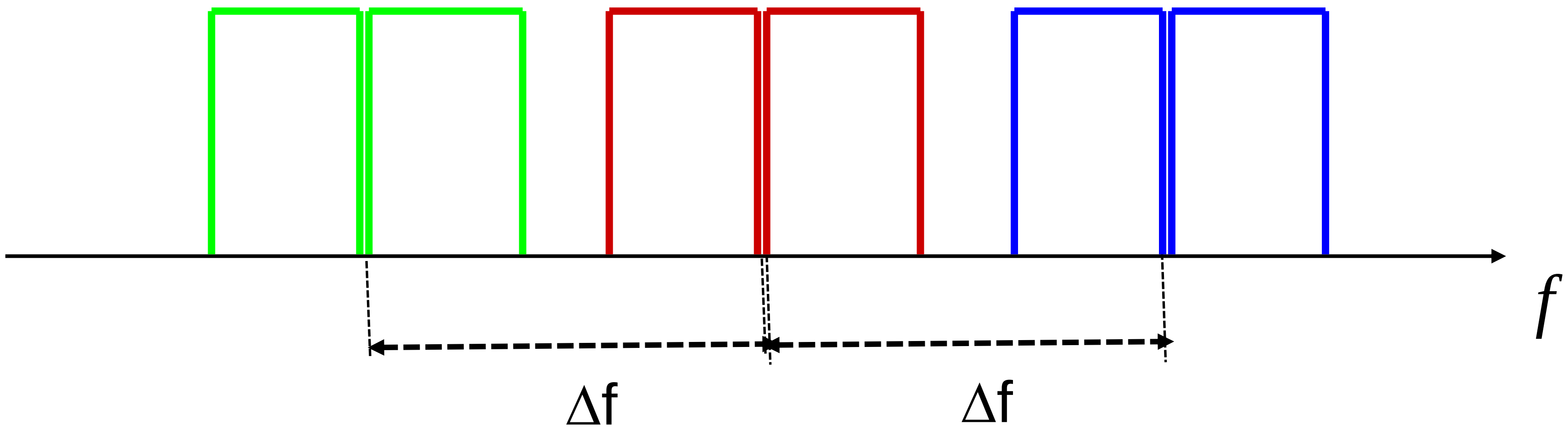
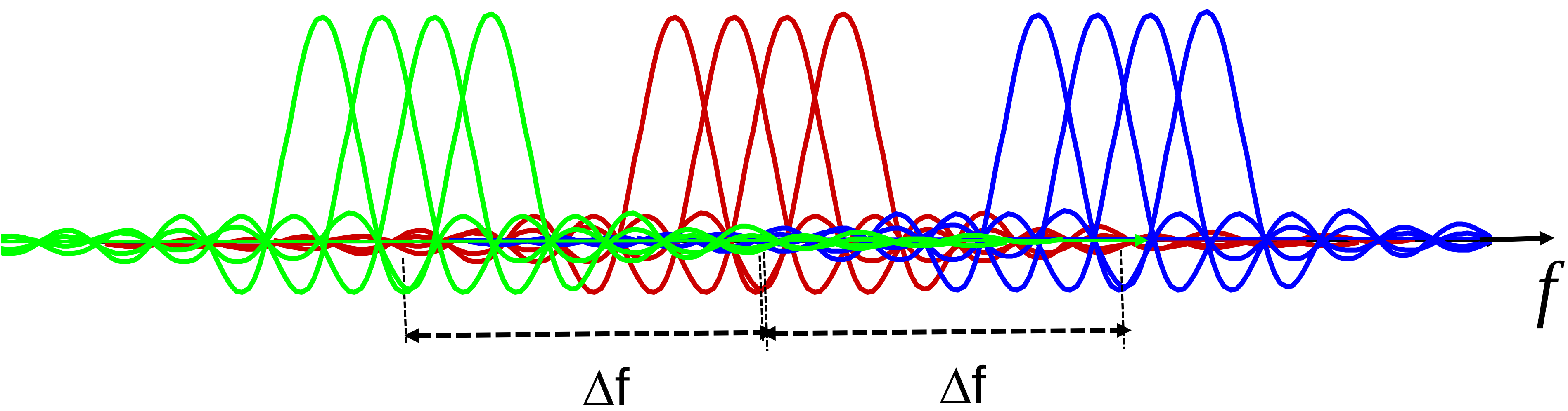
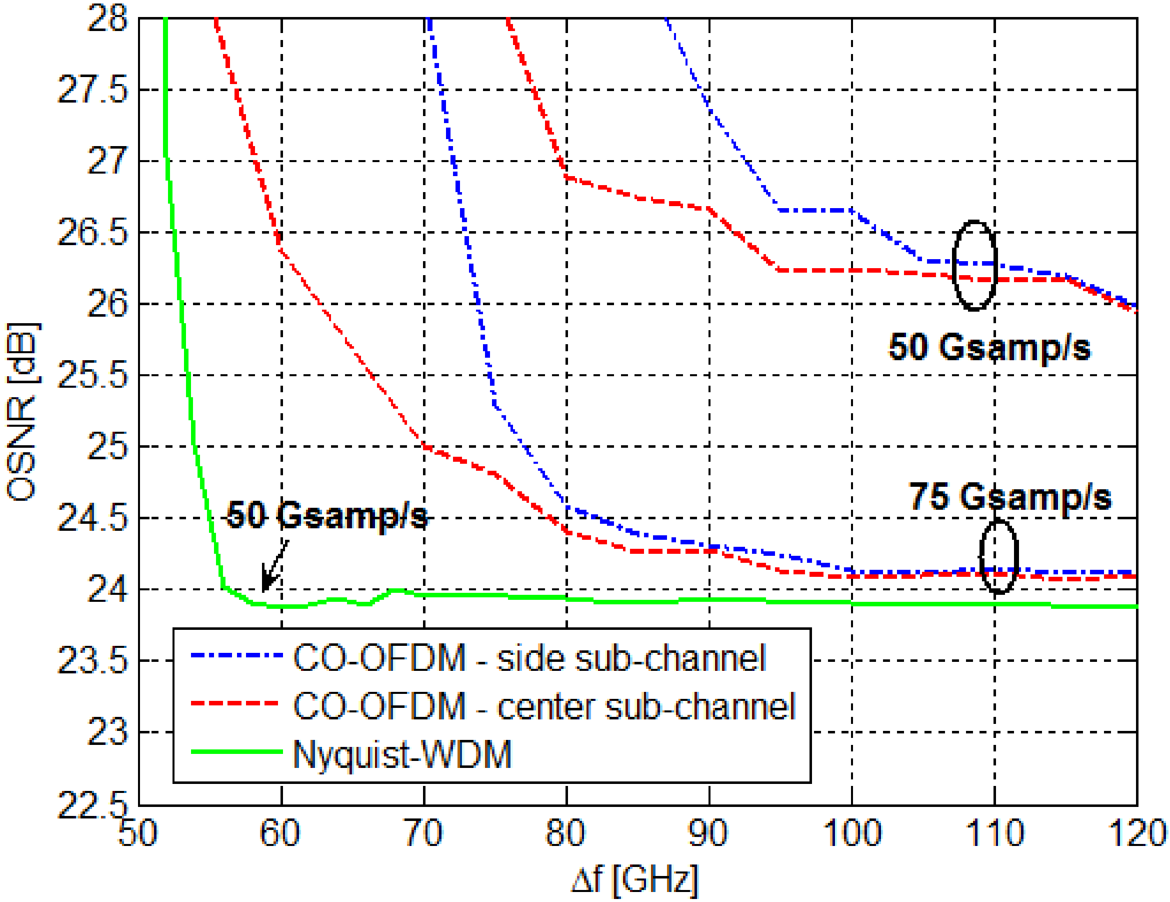
3 super-channels





OSNR vs. super-channel spacing



- Target BER: 10^{-3}
- 2SpS for Nyquist-WDM and 4 SpS for CO-OFDM:
  - ADC: 50 Gsamp/s
  - Rx BW: 12.5 GHz
- 6SpS for CO-OFDM:
  - ADC: 75 Gsamp/s
  - Rx BW: 17.5 GHz

Conclusions

- The results of this analysis indicate that:
  - Nyquist-WDM super-channels can be spaced 55-60 GHz without the need of any optical filter, obtaining a raw spectral efficiency (SE) around 7 b/s/Hz
  - If no optical filter is used, the spectral efficiency of CO-OFDM is very poor (80 GHz spacing for 400 Gb/s super-channels → SE=5 b/s/Hz)
  - In order to place the CO-OFDM super-channels very close, optical filtering is mandatory
    - Alternative solution:
      R. Schmogrow, "Raised-Cosine OFDM for Enhanced Out-of-Band Suppression at Low Subcarrier Counts", SPPCom 2012, paper SpTu2A.2

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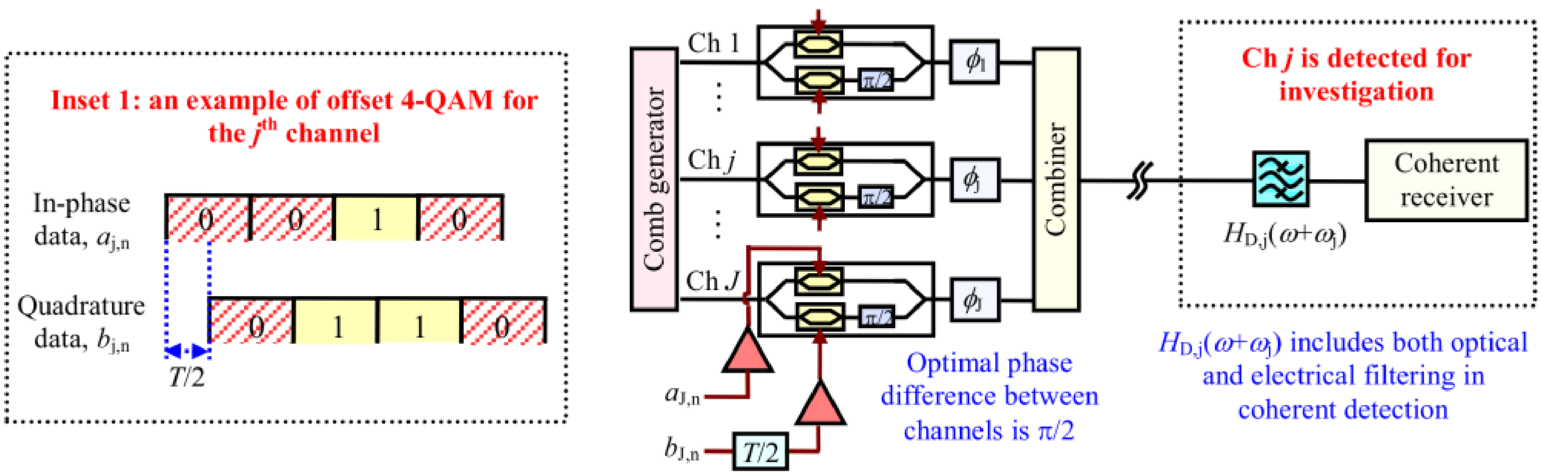
Basic idea

- The basic idea is that, by offsetting the in-phase and quadrature tributaries by half symbol period in time, the crosstalk and ISI can be eliminated even using practical signal spectral profile or pulse shape → limited bandwidth both at Tx and Rx side w/o performance loss



- *J. Zhao and A. D. Ellis, "Offset-QAM based coherent WDM for spectral efficiency enhancement", Optics Express, vol.19, no.15, pp. 14617-14631, Jul 2011.*

References

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- J. Zhao, A.D. Ellis, “Spectral Efficiency Enhancement Using Coherent WDM with Multi-Level Offset-QAM”, ECOC 2011, Sep. 2011, Geneve, paper We.10.P1.71.
- S. Randel, A. Sierra, X. Liu, S. Chandrasekhar, P.J. Winzer, “Study of Multicarrier Offset-QAM for Spectrally Efficient Coherent Optical Communications”, ECOC 2011, Sep. 2011, Geneve, paper Th.11.A.1.
- S. Randel et al., “Generation of 224-Gb/s Multicarrier Offset-QAM Using a Real-Time Transmitter”, OFC 2012, Mar. 2012, Los Angeles, paper OM2H.

Requirements

- In summary, crosstalk and ISI free operation in offset-QAM CoWDM can be achieved provided that:
  - The spectral profile of the demultiplexing filter is matched to that of the signal.
  - The overall baseband system response before demultiplexing is properly designed in order that:
    - It satisfies Nyquist ISI criterion for ISI free operation.
    - It is an even function.
    - No spectral overlapping is present between the targeted channel (e.g. the j-th channel) and channels more than one channel distant (e.g. the (j-2)-th and (j+2)-th channels)
  - The transmitter is coherent with optimal phase difference between channels of $\pi/2$.

Simulation set-up

- 25 Gbaud per carrier with 25-GHz spacing
- 50 Gsamp/s ADCs (2 samples per symbol)

- Nyquist-WDM
  - Raised-cosine pulse shape (in frequency) with roll-off 0.1
  - Rx FIR filter taps: 12

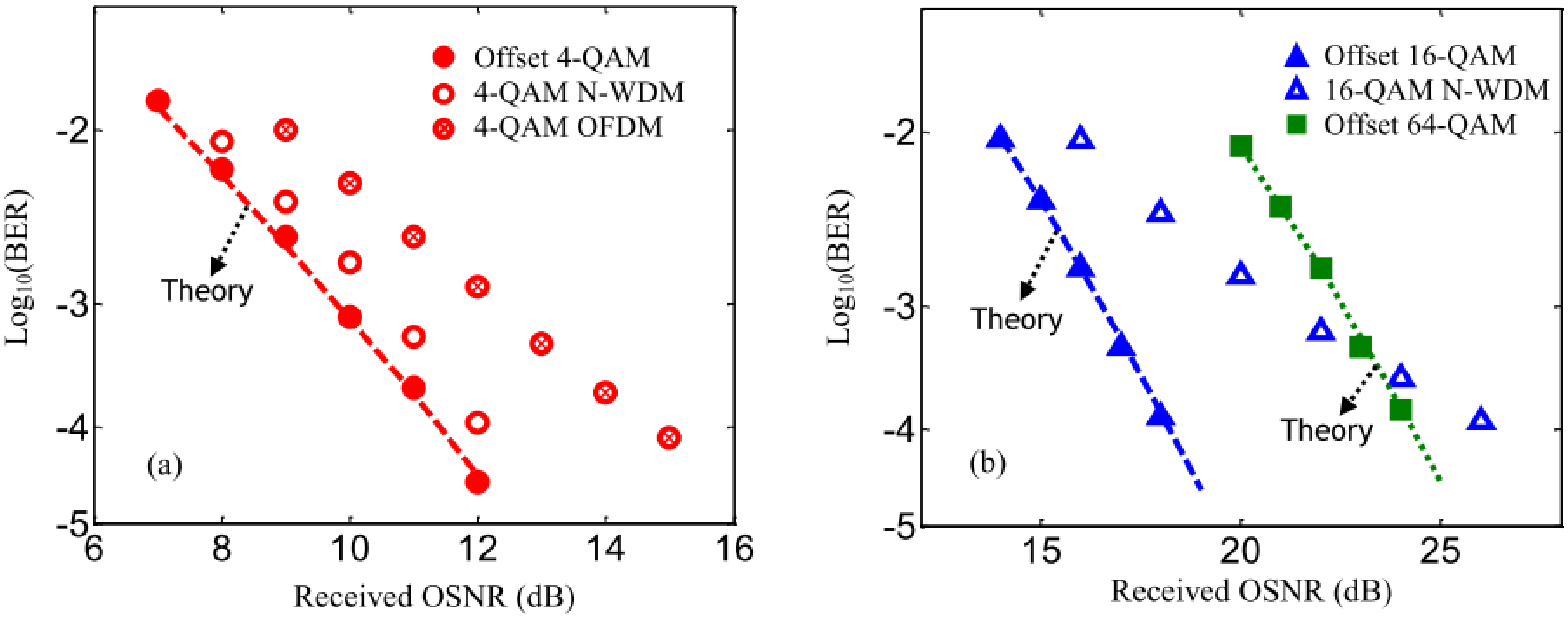
- Offset -QAM
  - Raised-cosine pulse shape (in time) with roll-off 0.4.
  - Quadrature signal delayed by T/2 w.r.t. in-phase signal.
  - The modulated optical signals were phase controlled by adding an additional phase $\phi_k = (k-1)\pi/2$, k = 1…5 before they were combined.
  - Rx FIR filter taps: 6

- *J. Zhao and A. D. Ellis, Optics Express, vol.19, no. 15, pp. 14617-14631, Jul 2011.*

Simulation results

- The performance was evaluated by direct error counting in terms of the BER versus the normalized OSNR for the central channel :

$$Normalized\ \ OSNR = \frac{Total\ Signal\ Power}{5 \times Noise\ Power\ in\ 0.1nm}$$



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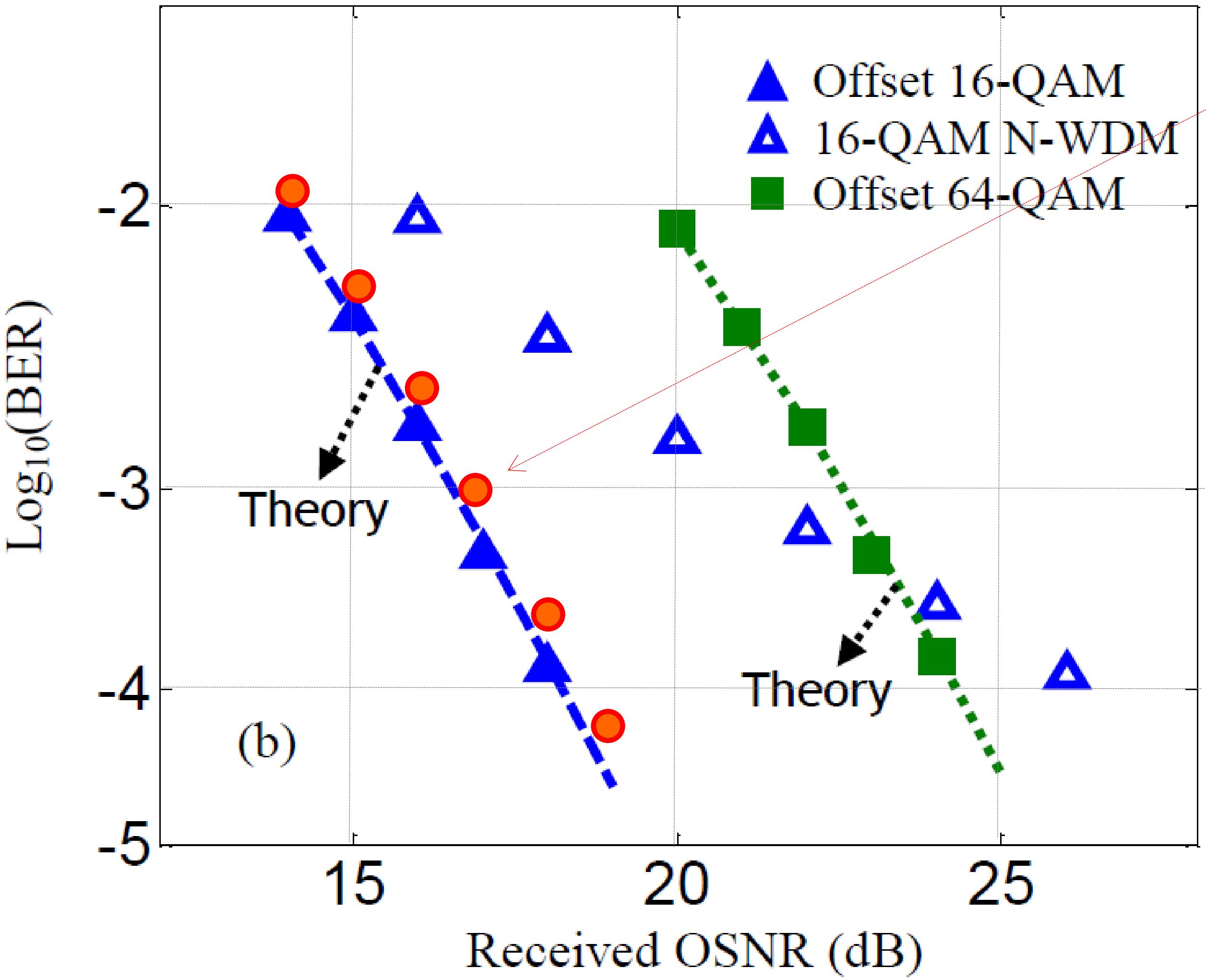
Simulation results



- Quasi-Nyquist-WDM
  - Raised-cosine pulses with 0.03 roll-off
  - Channel spacing = 1.1 R_s
  - Rx FIR filter taps: 41

Conclusions

- Advantages of offset-QAM over standard CO-OFDM:
  - A receiver with limited bandwidth and 2 samples per symbol DSP can be used without substantial penalty
  - Tx bandwidth requirements are relaxed as well
- Advantages of offset-QAM over Nyquist-WDM:
  - Low number of FIR filter taps can be used at both the Tx and the Rx
- Advantages of Nyquist-WDM over offset-QAM :
  - No phase control needed at the Tx
  - Standard DSP algorithm (2x2 CMA or LMS) can be used

Thank you!

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