Spectral Shaping in Ultra-Dense WDM Systems: Optical vs. Electrical Approaches

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OFC 2012 - paper OM3H.1

Outline

- Nyquist-WDM
- Spectral shaping in the optical domain
  - System description
  - Simulation results
  - Experimental demonstrations
- Spectral shaping in the digital/electrical domain
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  - Simulation results
  - Experimental demonstrations
- Conclusions

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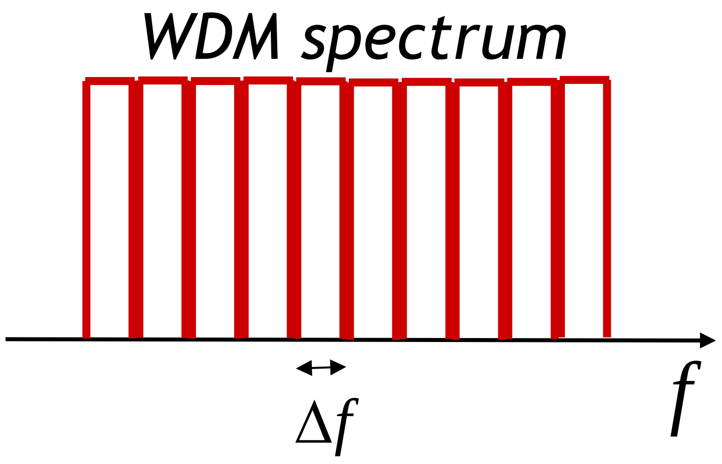
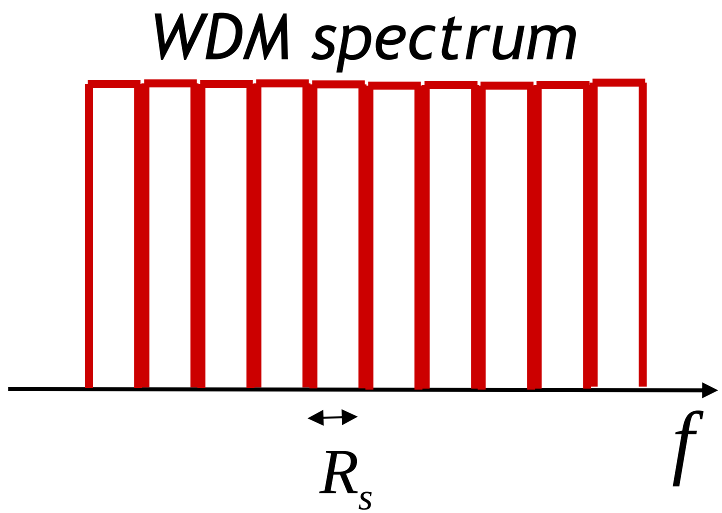
What is “Nyquist WDM”?

- "Nyquist WDM" is a technique used to generate high spectral efficiency optical signals.
- It is based on the idea of limiting the crosstalk between adjacent sub-channels by means of tight filtering at the transmitter:



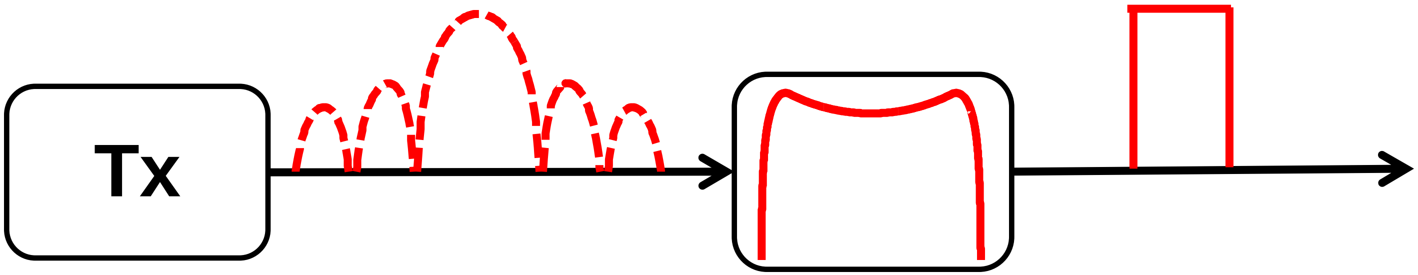
The "Nyquist" spectrum

- The ideal "Nyquist" spectrum is designed in order to satisfy the Nyquist criterion for the absence of ISI
  - Rectangular or raised-cosine are examples of spectra satisfying the Nyquist criterion
- The minimum channel spacing with potentially no penalty with respect to the ideal matched filter case is equal to the symbol-rate R_s:

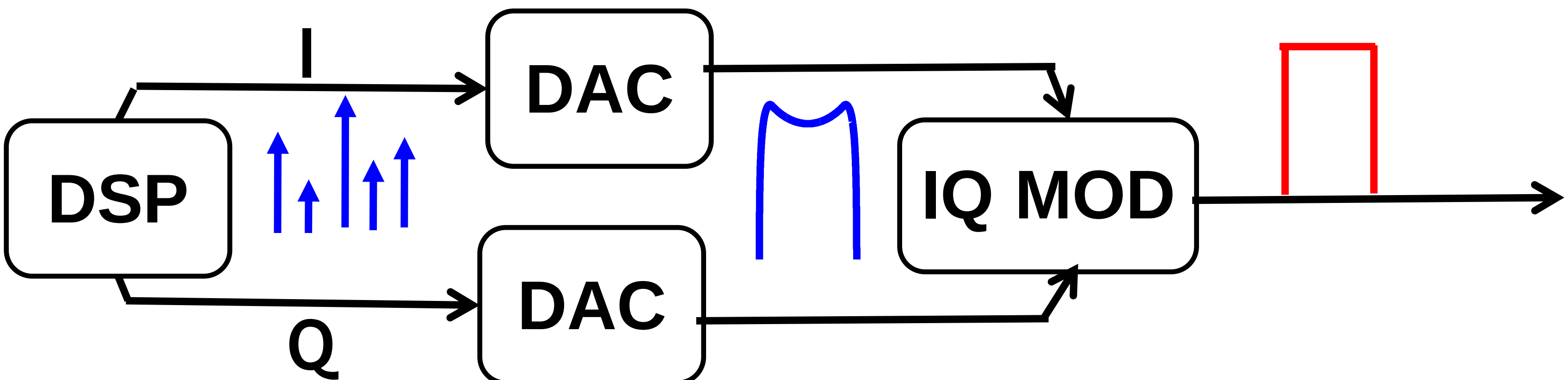


Spectral shaping: optical vs. digital

- Tight spectral shaping can be performed:
  - in the **optical domain**, through narrow transmitter (Tx) optical filtering



  - in the **digital/electrical domain**, combining digital signal processing (DSP) and digital-to-analog (D/A) conversion.



Same ultimate performance, but …

- Ideally, both techniques can achieve the same ultimate performance (with an optimum “matched filter” receiver).
- What limits the performance is the “practical” implementation of the transmitter, i.e. how well the spectral shaping can be performed [*].
- In the following, the characteristics of Nyquist-WDM generated in the optical and in the digital/electrical domain are reviewed, taking into account the implementation characteristics of realistic components.

[*] G. Bosco et al., “Investigation on the Robustness of a Nyquist-WDM Terabit Superchannel to Transmitter and Receiver Non-Idealities”, ”, ECOC 2010, paper Tu.3.A.4, Torino, Sep. 2010.

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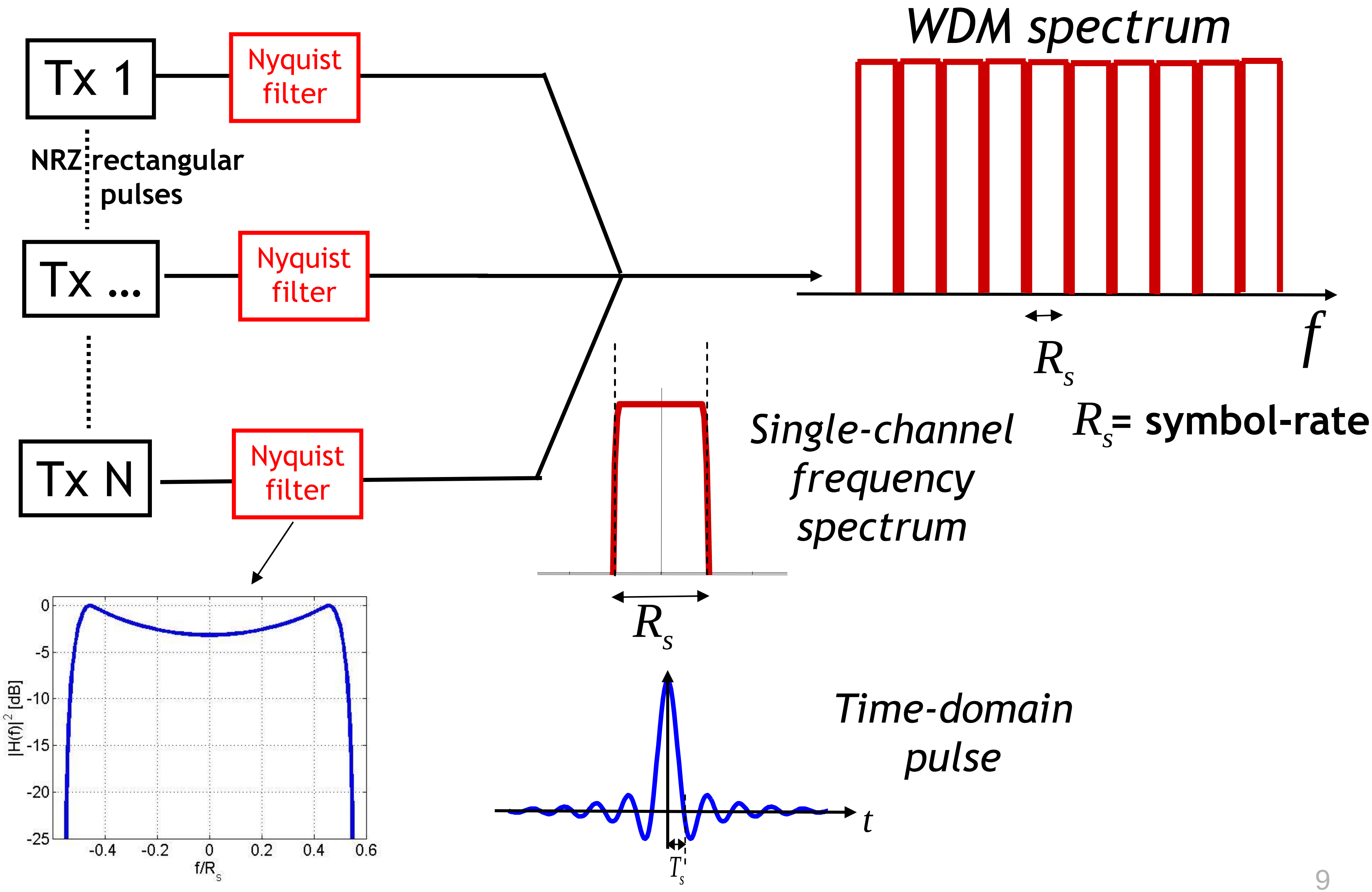
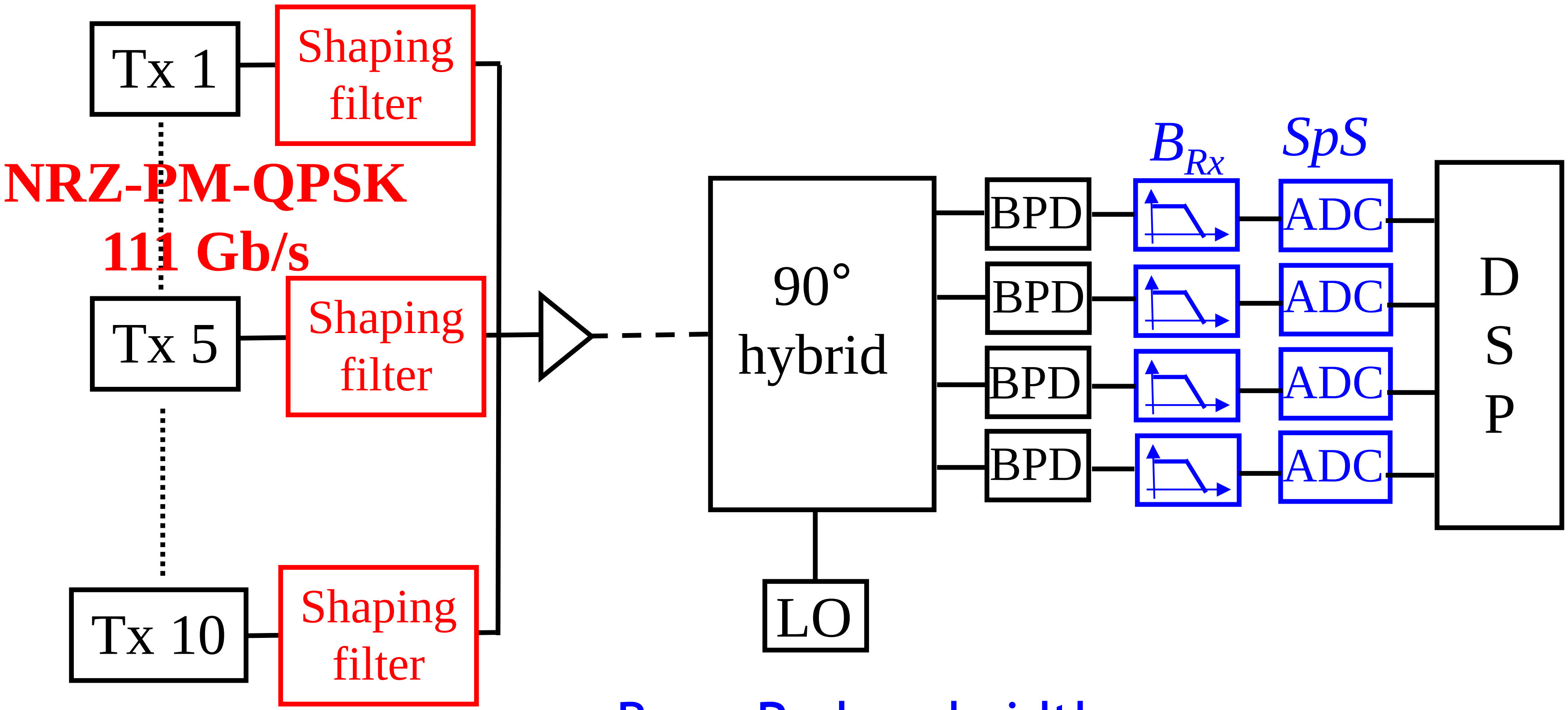
Ideal Nyquist-WDM transmitter



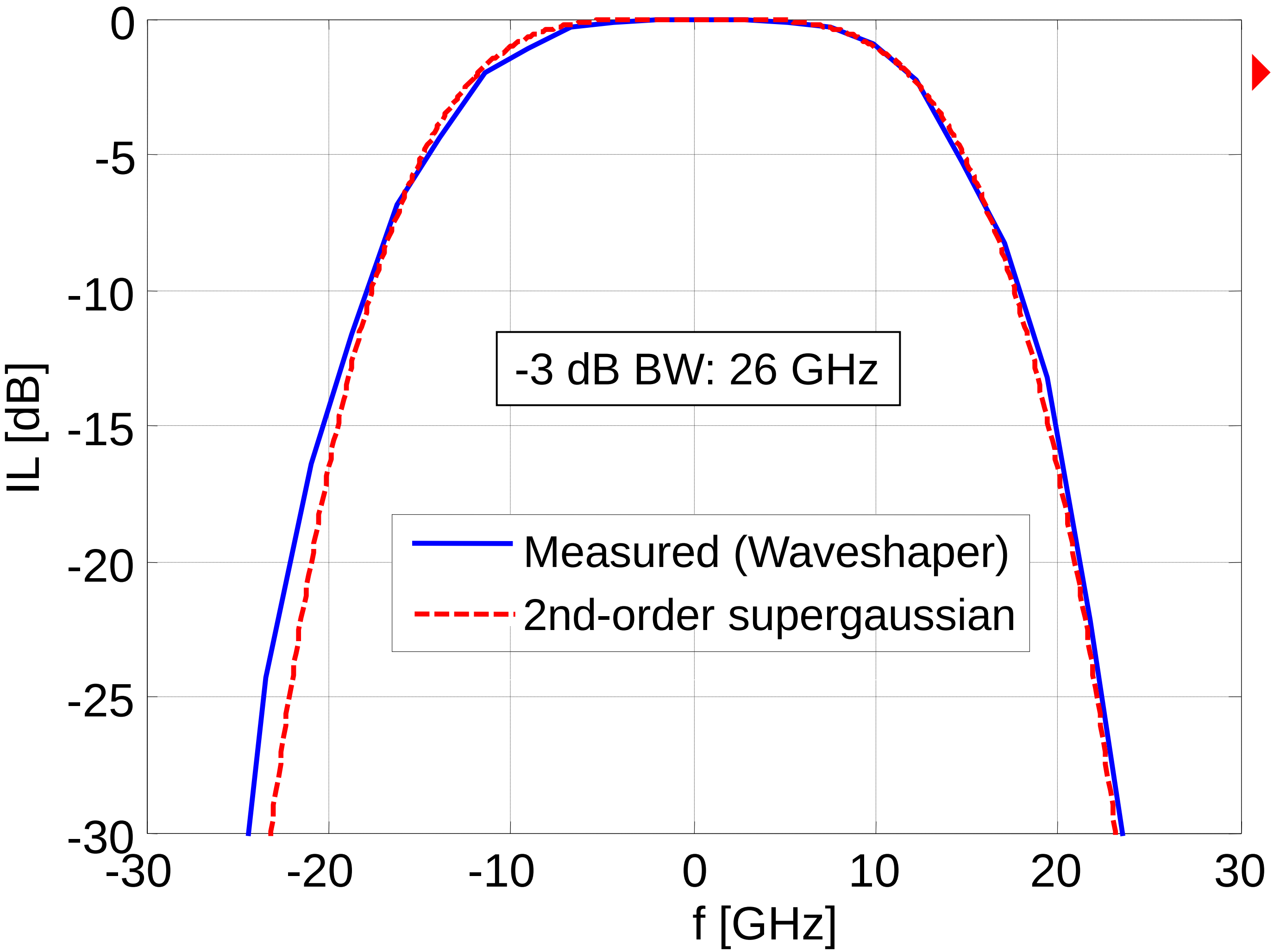
Layout of the simulated system



B_{rx}: Rx bandwidth

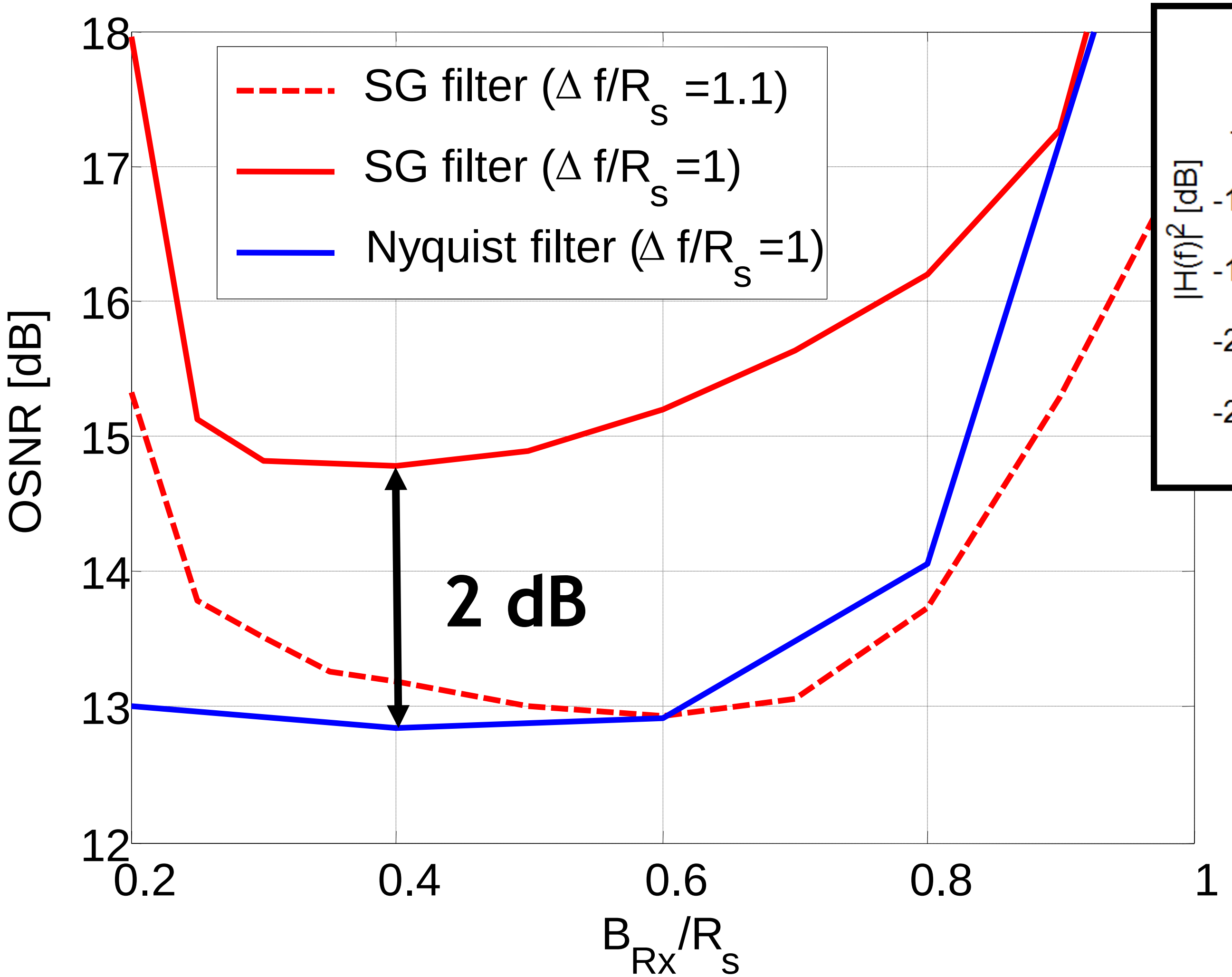
SpS: Number of samples per symbol

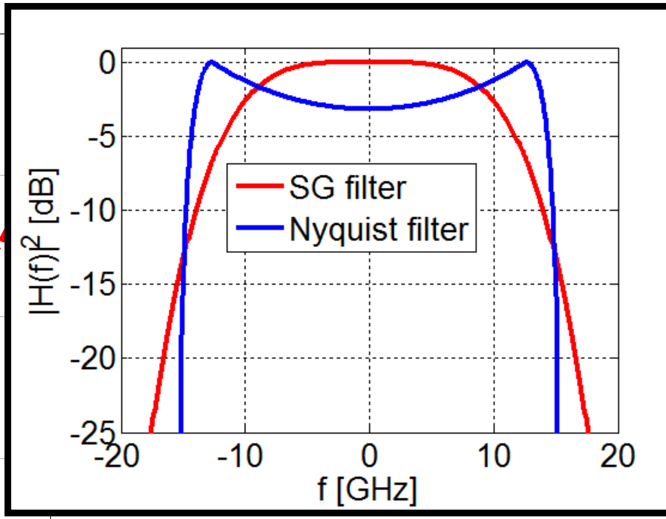
Fitting of Finisar Waveshaper™ with analytical function



- Note that this a sort of "worst case" since state-of-the-art AWGs and interleavers have steeper transfer functions (up to 4th order Supergaussian)

Ideal vs. realistic optical filter in btb



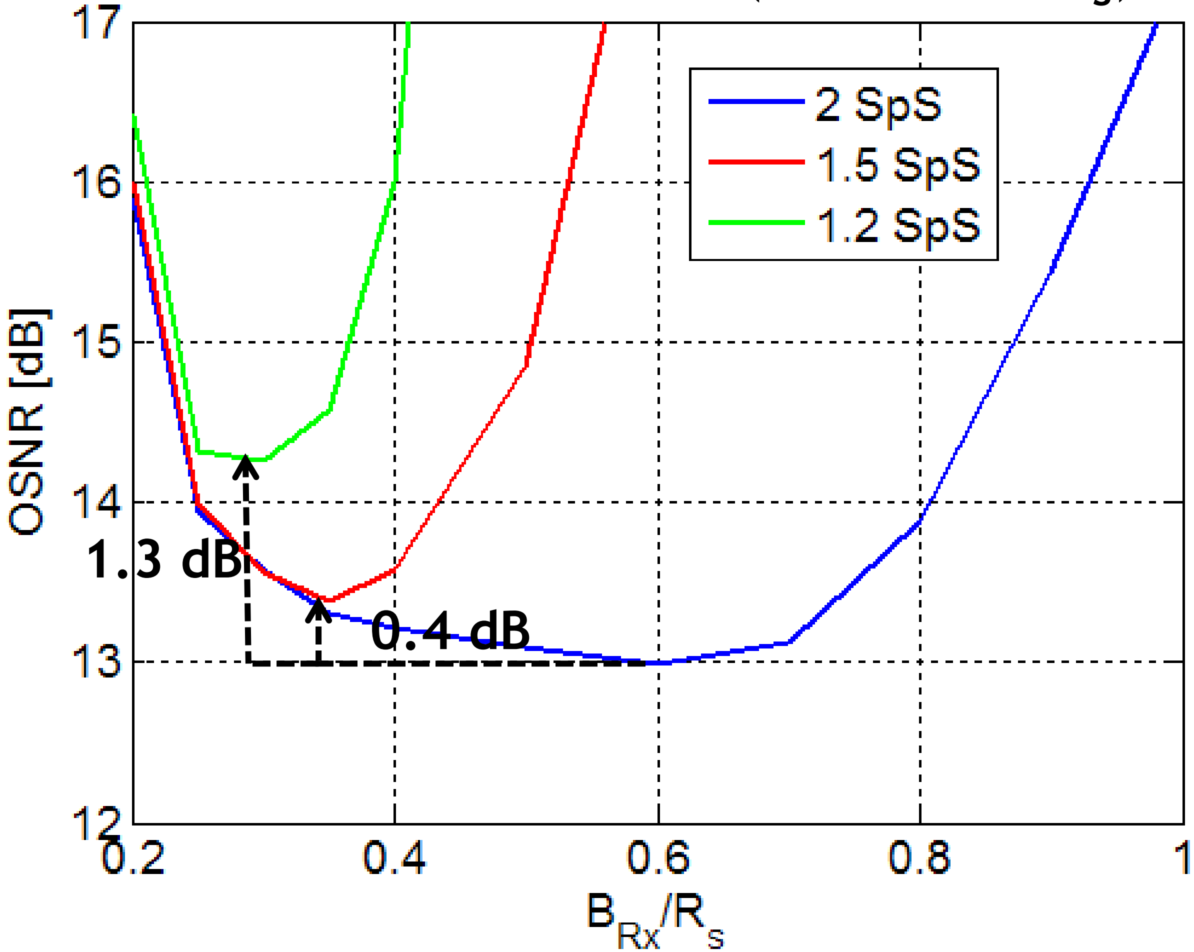


- Increasing the spacing to 1.1 R_s this penalty is almost canceled

- ADC with ideal resolution and 2 SpS
- Target BER: $4 \cdot 10^{-3}$, OSNR defined over 0.1 nm

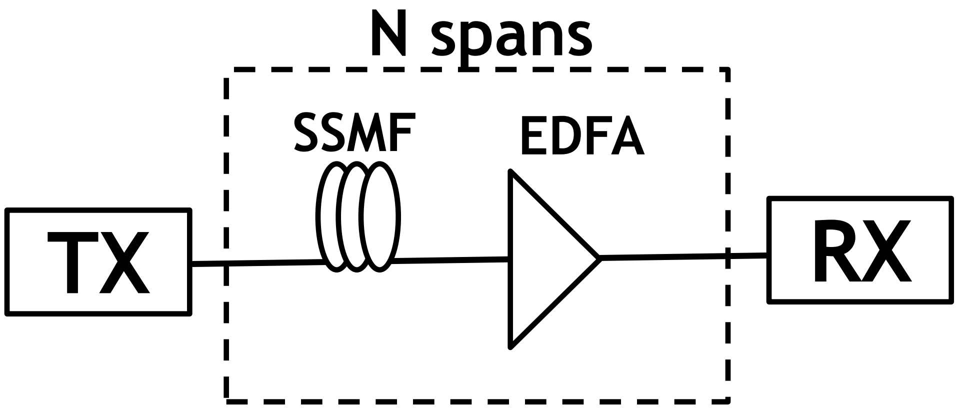
ADC sampling speed

Finisar-like filter ($\Delta f = 1.1\ R_s$)



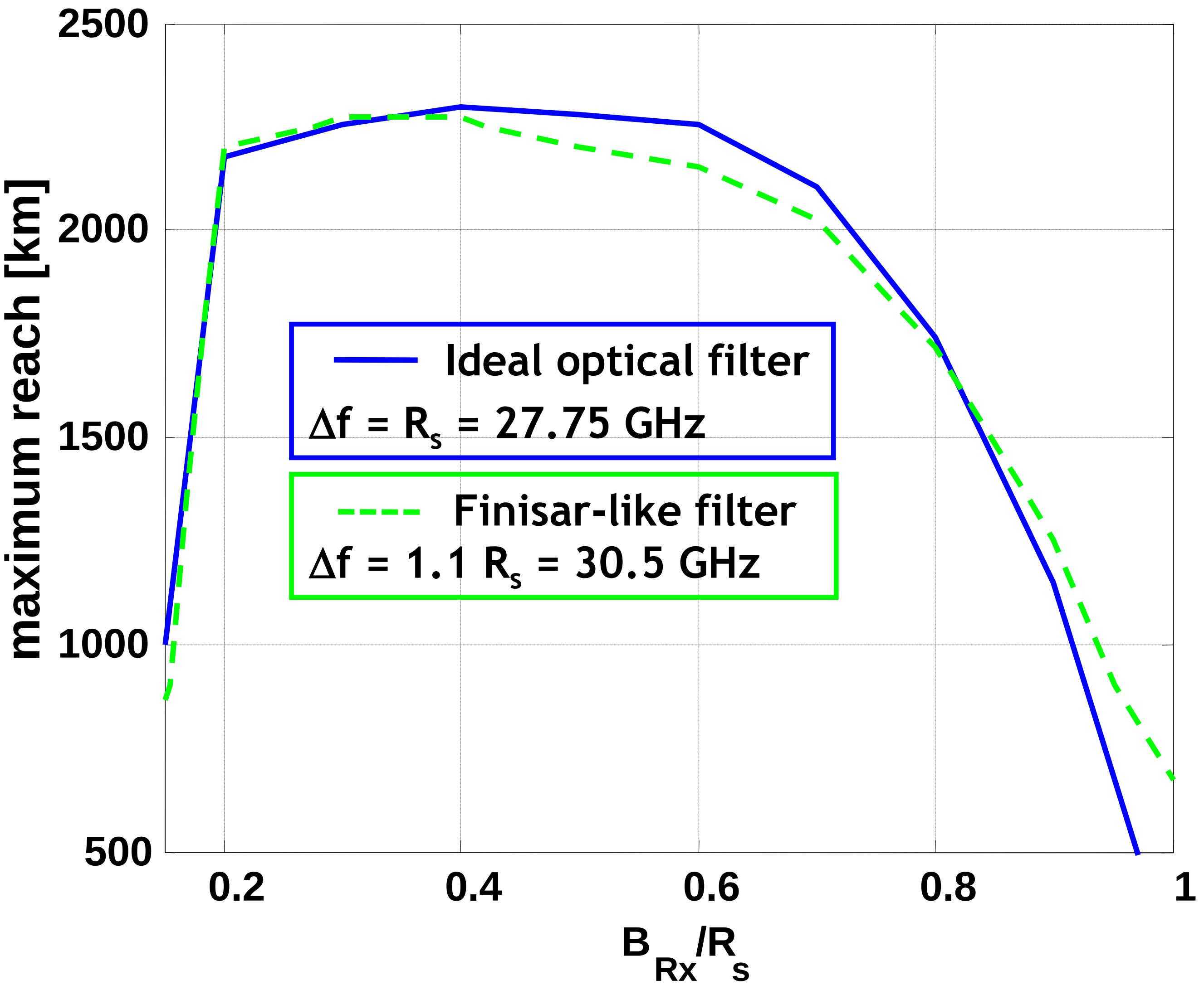
- ADC with 5-bits resolution
- Target BER: $4 \cdot 10^{-3}$
- OSNR defined over 0.1 nm

Nonlinear propagation



- Span length: 90 km
- SSMF fiber
  - D = 16.7 ps/nm/km
  - α = 0.22 dB/km
  - γ = 1.3 1/w/km
- EDFAs noise figure: 5 dB
- No in-line dispersion compensation
- Total span loss (fiber attenuation + extra-losses + margin) = 25 dB
- Reference BER: $4 \cdot 10^{-3}$

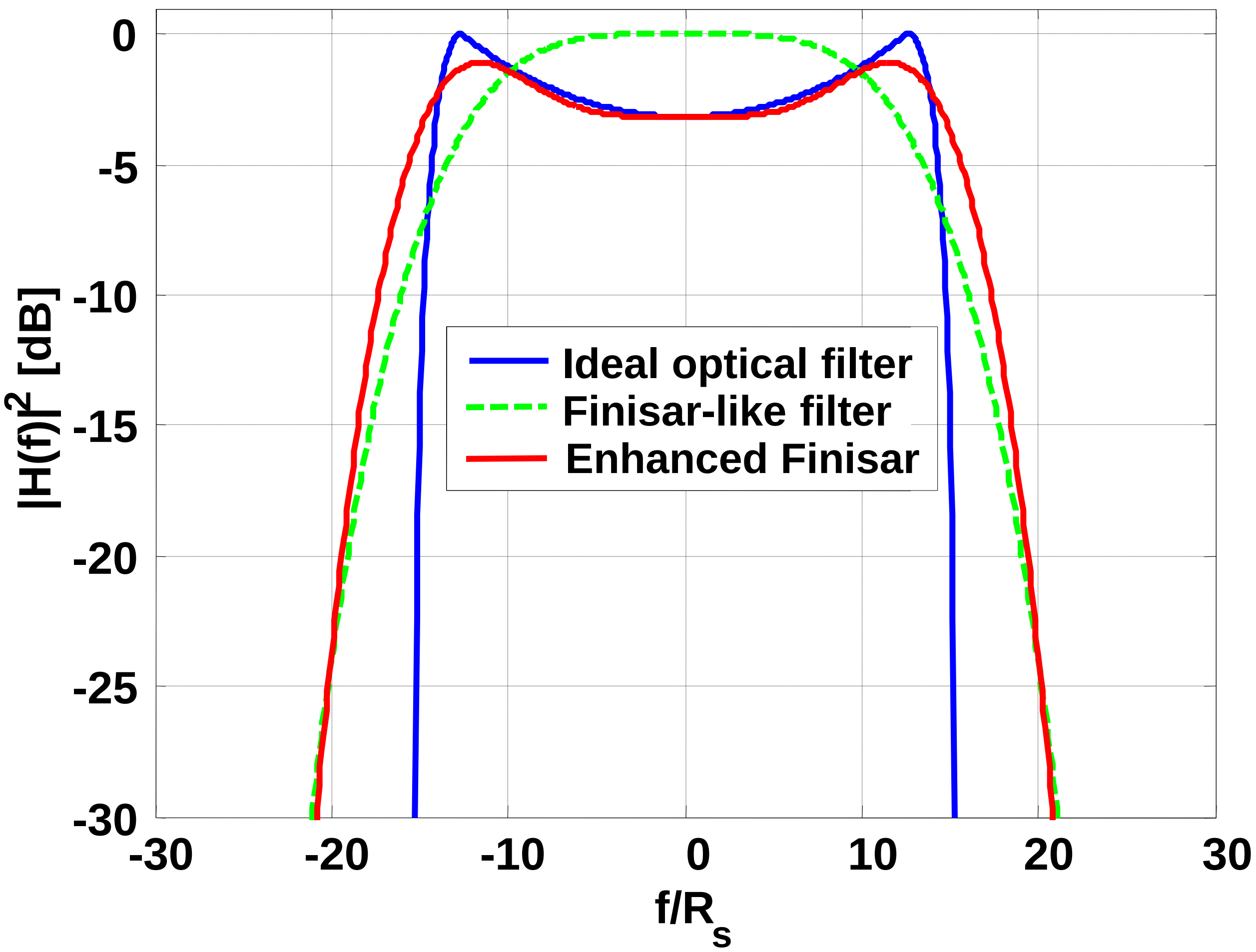
Maximum reach



- The same maximum distance of 2300 km can be achieved with both
  - Nyquist filter at $\Delta f = R_s$
  - SG filter at $\Delta f = 1.1\ R_s$

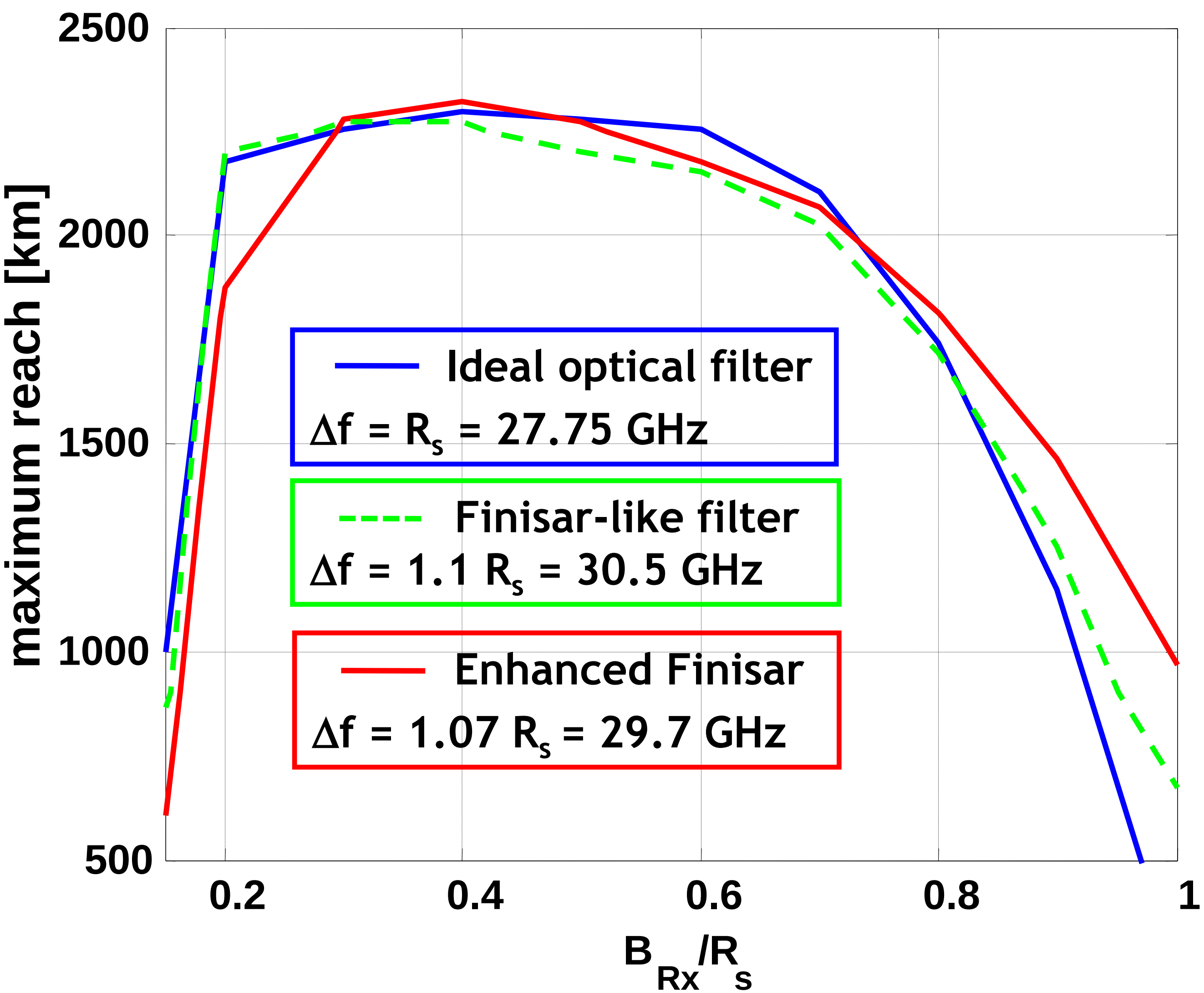
when using 2 SpS and 5 bits of ADC resolution.

Pre-enhanced filter



- A tighter channel spacing can be achieved by applying a pre-enhancement to the shaping filter to better approximate the ideal Nyquist-filter shape

Maximum reach



- The channel spacing was reduced from 1.1 R_s to 1.07 R_s

Experimental demonstrations

- *Cai, J.-X. et al., OFC 2010, San Diego, paper PDPB10.*
  - *28 Gbaud PM-QPSK*
  - *Channel spacing: 1.18 R_s Reach: 10,608 km of ULAF*
- *E. Torrengo et al., ECOC 2010, Torino, paper We.7.C.2*
  - *30 Gbaud PM-QPSK*
  - *Channel spacing: R_s Reach: 9,000 km of PSCF*
- *Y. Cai et al., ECOC 2010, Torino, paper We.7.C.4*
  - *28 Gbaud PM-QPSK*
  - *Channel spacing: 0.9 R_s (MAP detection) Reach: 8,000 km of ULAF*
- *J. Renaudier et al., ECOC 2010, Torino, paper Mo.2.C.3*
  - *28 Gbaud PM-QPSK*
  - *Channel spacing: 1.18 R_s Reach: 2,400 km of SSMF*

Main drawback

- Steep and highly tuned optical filter required at the TX
- Not enough steep optical filter → inter-channel crosstalk
- Not suitable for high-order modulation formats
- Solution: spectral shaping in the digital/electrical domain

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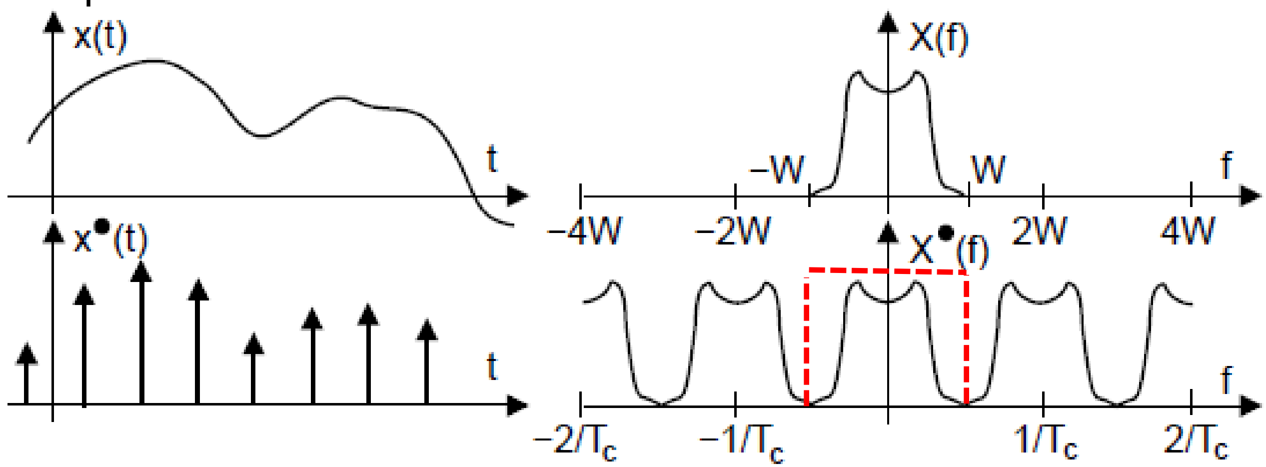
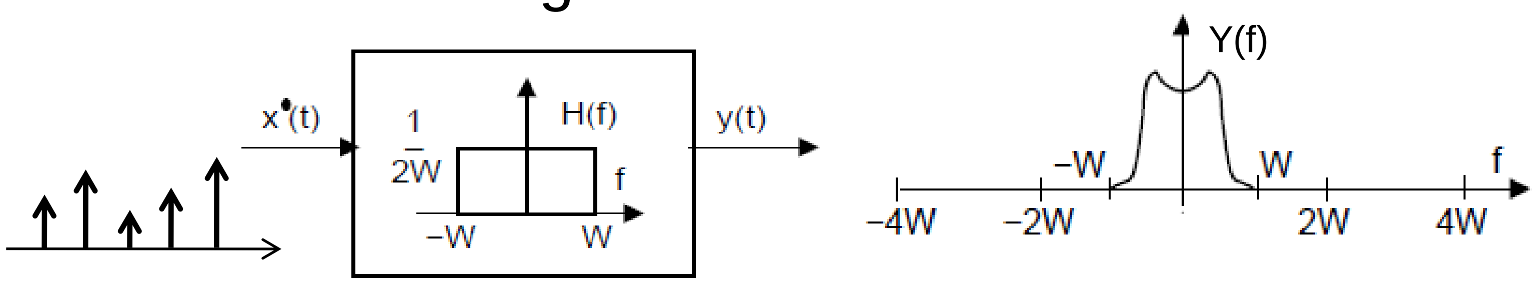
Ideal D/A conversion

- The “Nyquist sampling theorem” states that any analog signal x(t), band-limited in [−W,W], can be perfectly reconstructed from its samples provided that the sampling frequency f_{samp} is greater than 2·W.

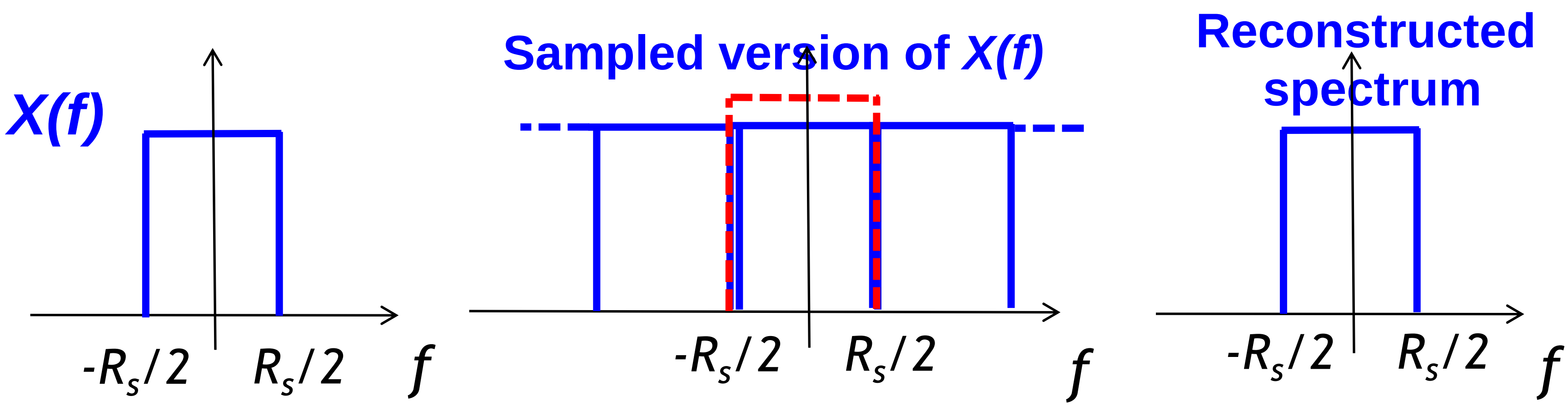


- Reconstruction of the signal:



From ideal to realistic …

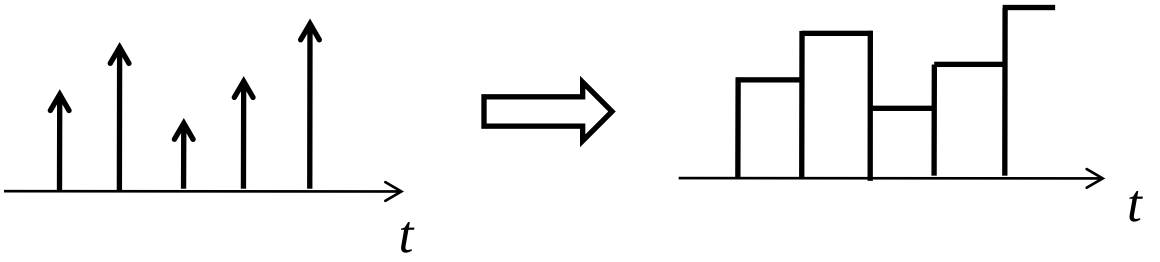
- To generate a perfectly rectangular Nyquist spectrum a DAC is needed operating at a speed equal to R_s samples/s (i.e. 1 sample/symbol) and with a perfectly rectangular transfer function with bandwidth $B_{DAC}=0.5 \cdot R_s$



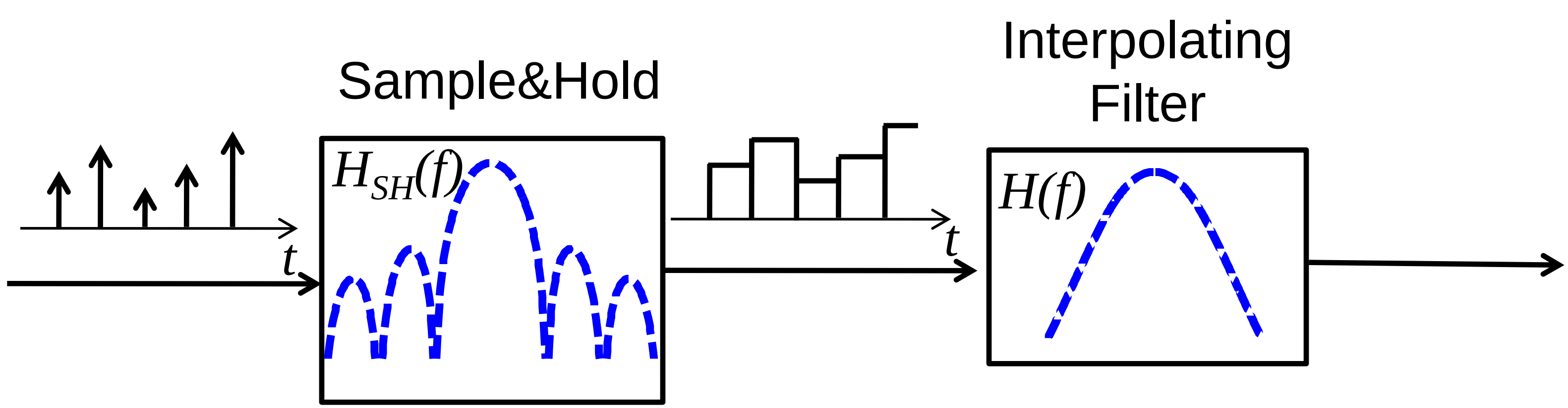
- Today commercial DACs are characterized by a maximum sampling speed f_{samp} around 24-30 Gsamples/s and a transfer function which is far from rectangular.

Realistic D/A conversion

- In "real" DACs, the "sampled" version of the signal is not composed of a sequence delta functions, but it is generated by "sample&hold" circuits

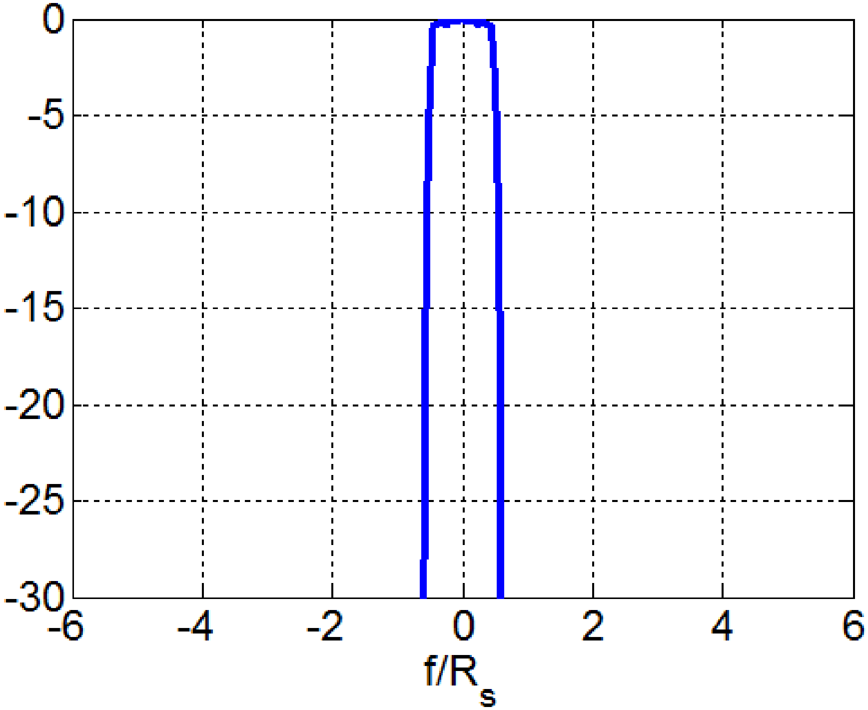


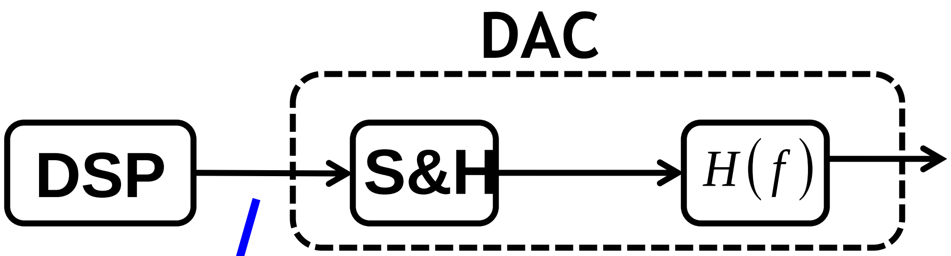
- Moreover, the interpolating filter is not an ideal low-pass filter, but a realistic one



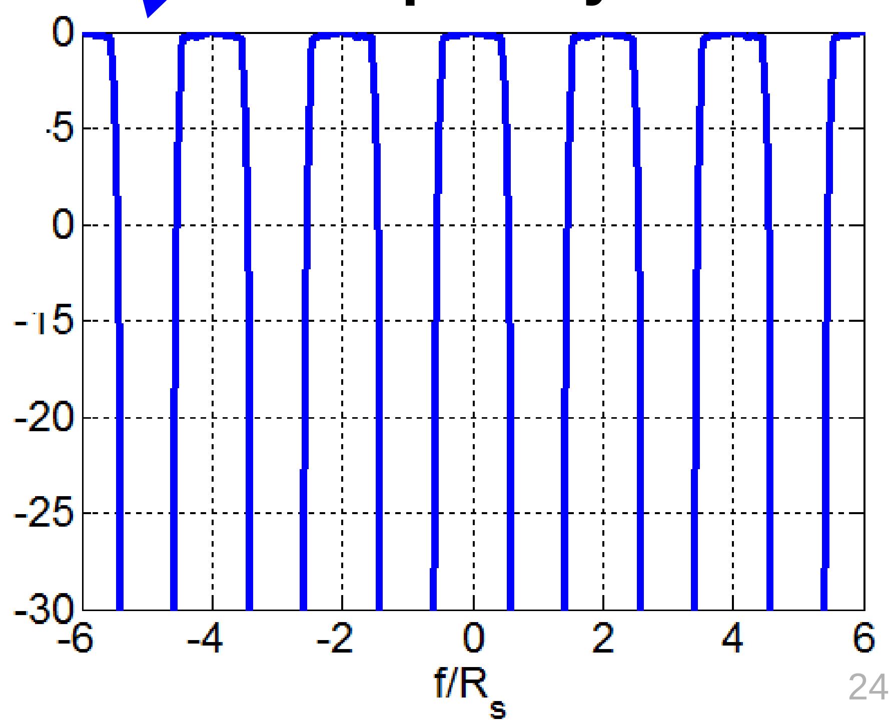
Spectra evolution in the D/A process

Ideal spectrum

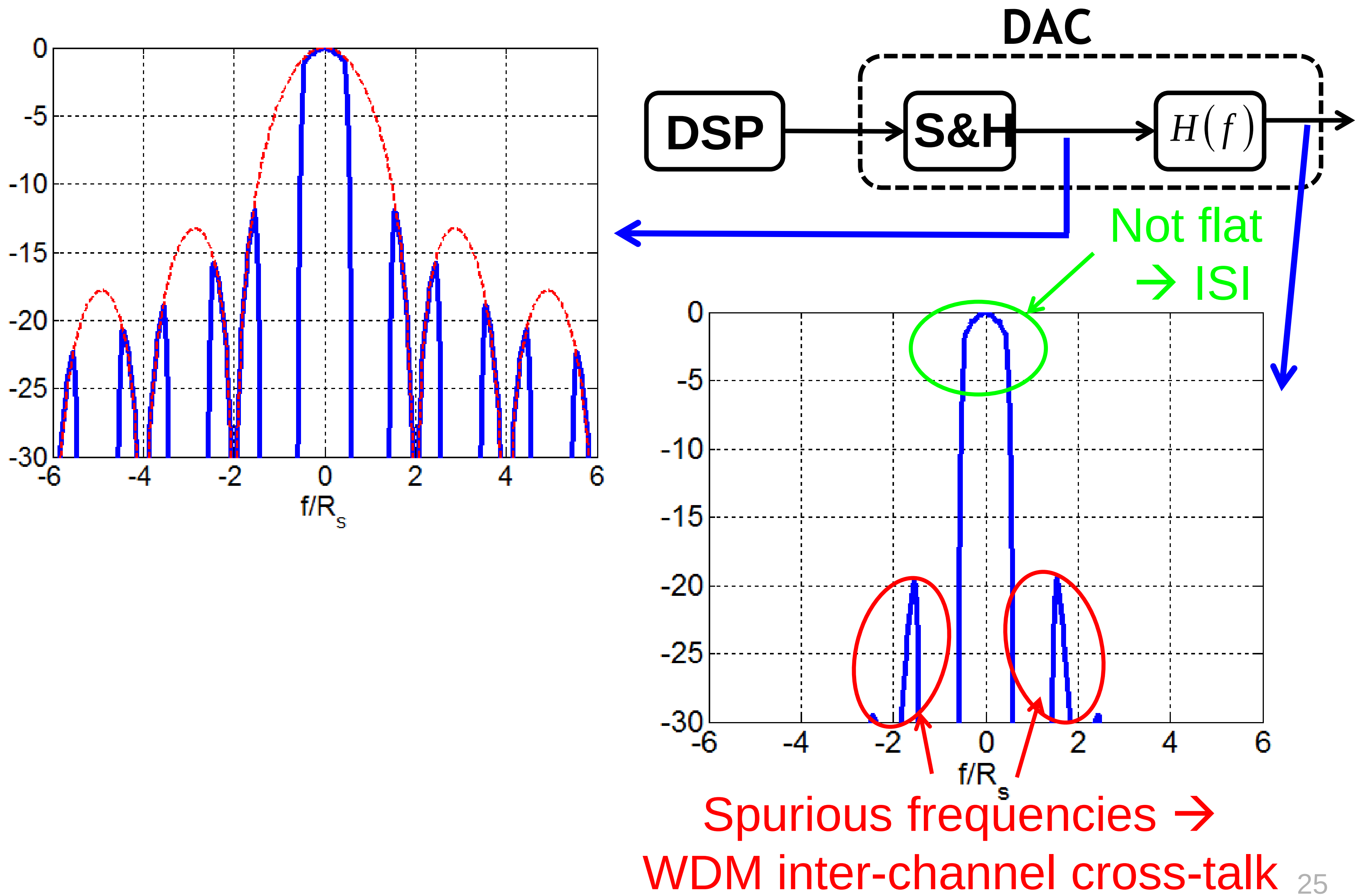




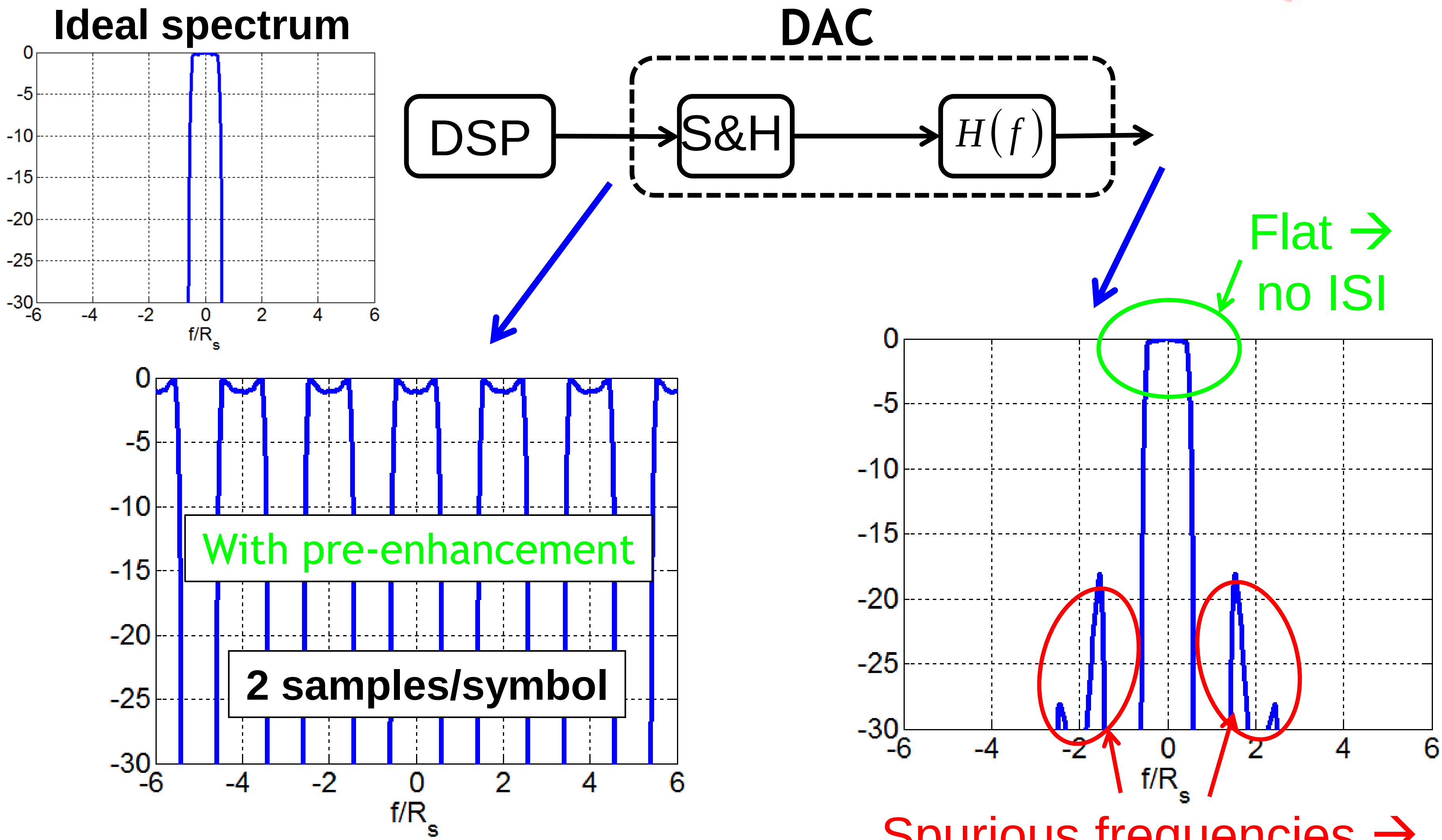
After sampling at 2 samples/symbol



Spectra evolution in the D/A process

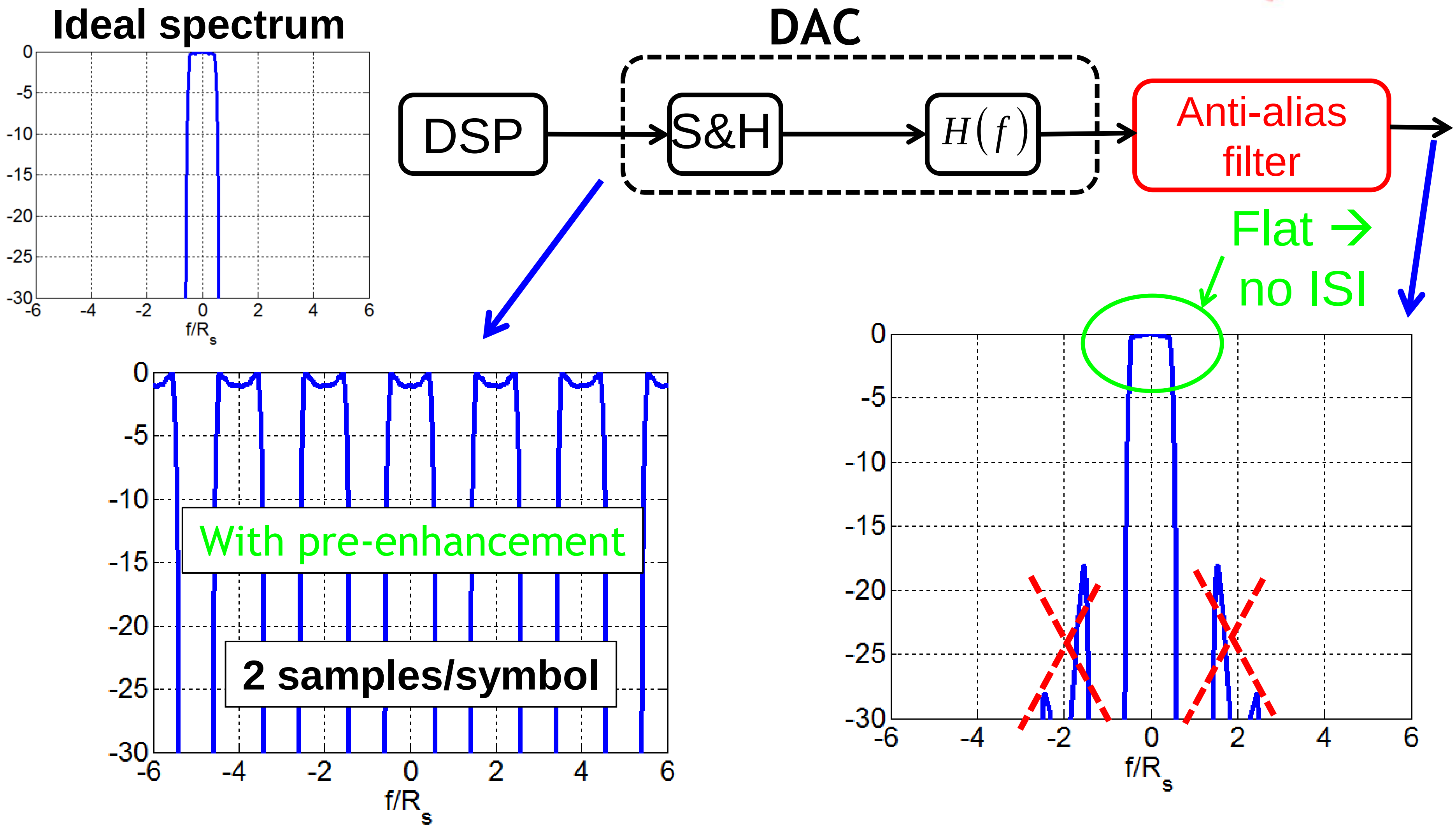


Pre-enhancement

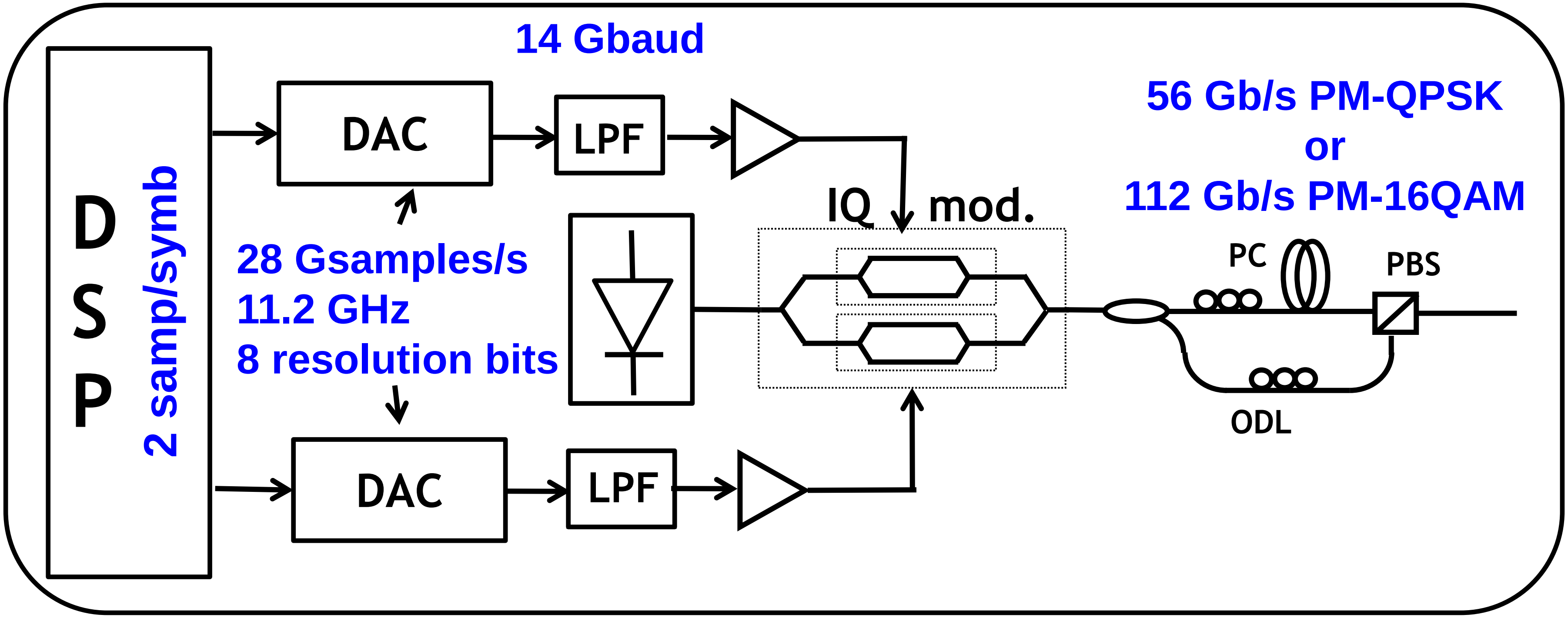


Spurious frequencies → WDM inter-channel cross-talk

Anti-alias filtering

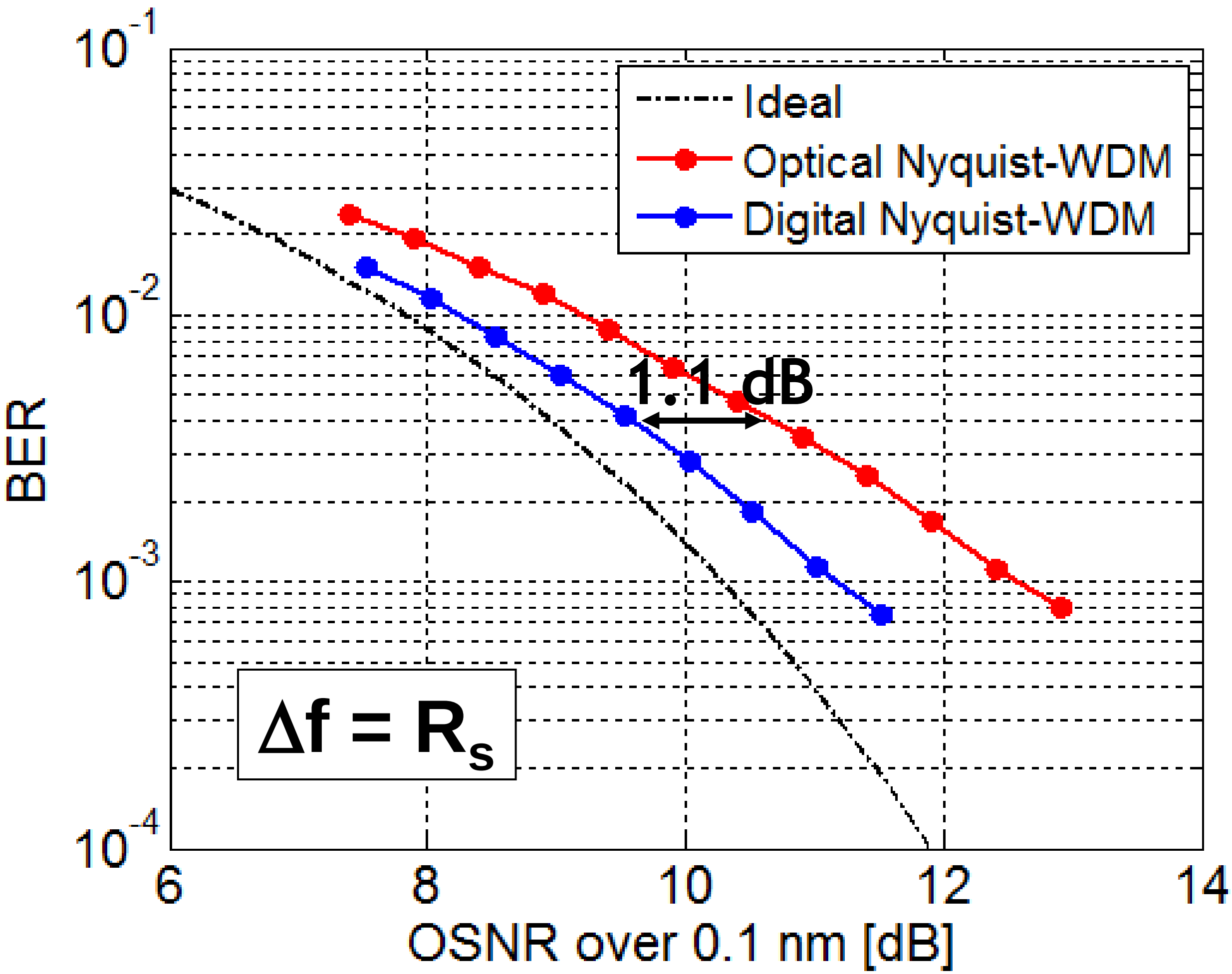


Layout of the simulated system



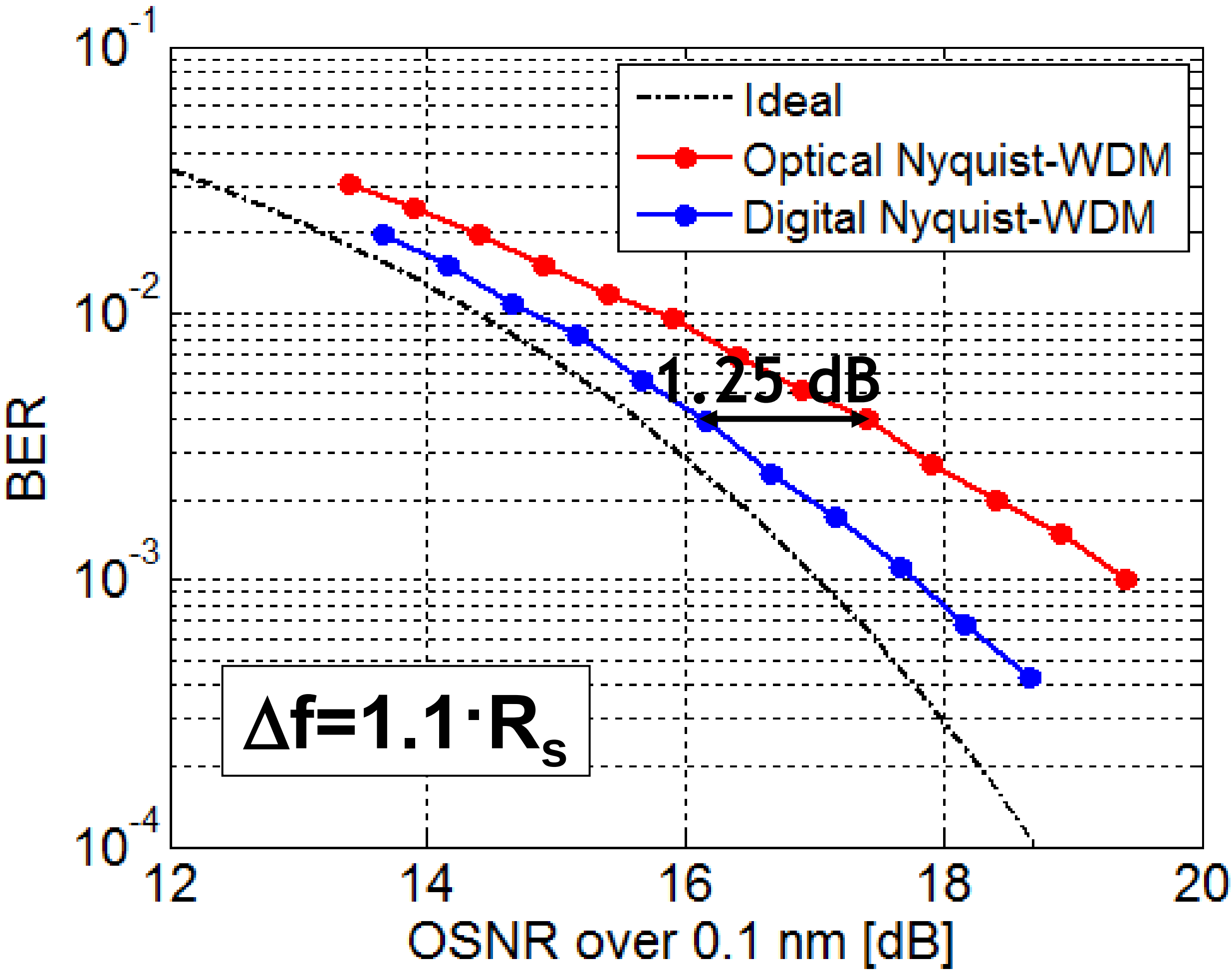
- The IQ modulator was biased in order to work in a quasi-linear regime and a proper pre-enhancement was applied to the digital samples.
- WDM signals with spacing from R_s to 1.1 R_s

14-Gbaud PM-QPSK



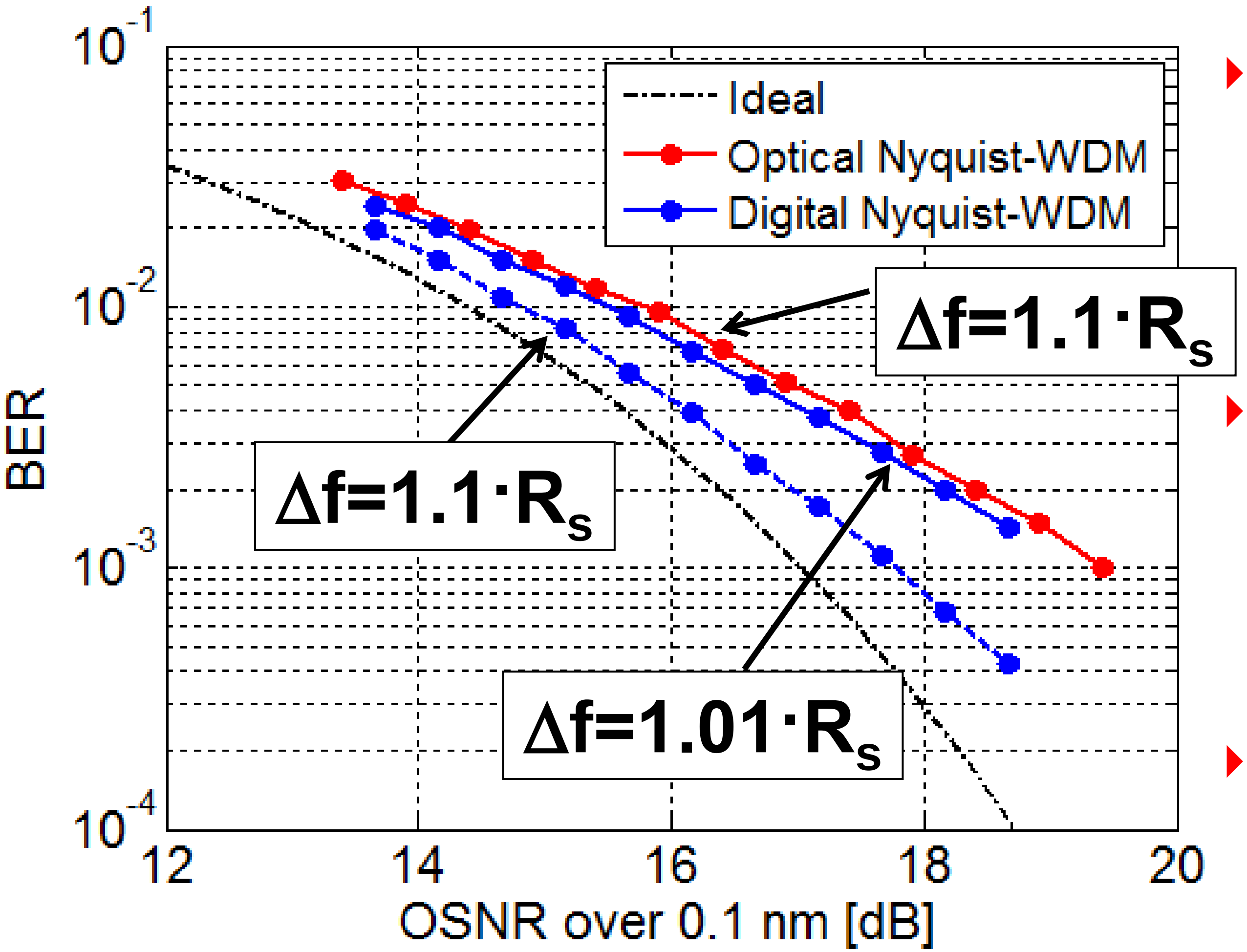
- Optical filter:
  4th order Supergaussian
  with optimized
  bandwidth (14 GHz)
- Digital spectra:
  square-root
  raised-cosine
  with roll-off 0.05

14-Gbaud PM-16QAM



- Optical filter: 4th order Supergaussian with optimized bandwidth (14 GHz)
- Digital spectra: square-root raised-cosine with roll-off 0.05

14-Gbaud PM-16QAM



- Optical filter:
  4th order Supergaussian
  with optimized bandwidth (14 GHz)
- Digital spectra:
  square-root raised-cosine with roll-off 0.05
- The spacing of Digital Nyquist-WDM can be further reduced …

Experimental demonstrations

- *Shogo Yamanaka et al., ECOC 2010, paper We.8.C.1*
  - *21.375-Gbaud PM-16QAM*
  - *Channel spacing: 1.25 R_s* *Reach: 1440 km of PSCF*
- *X. Zhou et al., ECOC 2011, paper We.8.B.2.*
  - *9-Gbaud PM-32QAM*
  - *Channel spacing: 1.022 R_s* *Reach: 800 km of ULAF*
- *T. Kobayashi et al., ECOC 2011, PDP Th.13.C.6.*
  - *5.6-Gbaud PM-64QAM*
  - *Channel spacing: 1.12 R_s* *Reach: 240 km of PSCF*
- *R. Cigliutti et al., OFC 2012, paper OTh3A.3*
  - *14-Gbaud PM-16QAM*
  - *Channel spacing: 1.05 R_s* *Reach: 3700 km of PSCF*

Experimental demonstrations

OPTCOM

OFC 2012 – OM2A – Higher-order QAM

- ***OM2A.2***
  X. Zhou et al., "1200km Transmission of 50GHz spaced, 5x504-Gb/s PDM-32-64 hybrid QAM using Electrical and Optical Spectral Shaping"
- ***OM2A.3***
  T. Kobayashi et al. "High-Order QAM Transmission for Spectrally-efficient and High-capacity Transport"
- ***OM2A.4***
  Jianjun Yu et al. "30-Tb/s (3×12.84-Tb/s) Signal Transmission over 320km Using PDM 64-QAM Modulation", OFC 2012, paper OM2A.4
- ***OM2A.5***
  T. Kobayashi et al., "Nonlinear tolerant long-haul WDM transmission over 1200km using 538Gb/s/ch PDM-64QAM SC-FDM signals with pilot tone"
- ***OM2A.6***
  R. Schmogrow et al. "150 Gbit/s Real-Time Nyquist Pulse Transmission Over 150 km SSMF Enhanced by DSP with Dynamic Precision"

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Conclusions

- With both optical or electrical spectral shaping, WDM channel spacing equal or close to the symbol rate has been achieved
- Main drawback in optical spectral shaping:
  - need of optical filters with very steep profile
- Digital/electrical shaping through DSP and DACs is more flexible
  - Same Tx hardware can be used to generate different modulation formats (keeping the symbol-rate fixed).
- Main limitation of digital/electrical shaping:
  - finite sampling speed of state-of the-art DACs

Acknowledgments

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