Scalable modulation technology and the tradeoff of reach, spectral efficiency, and complexity

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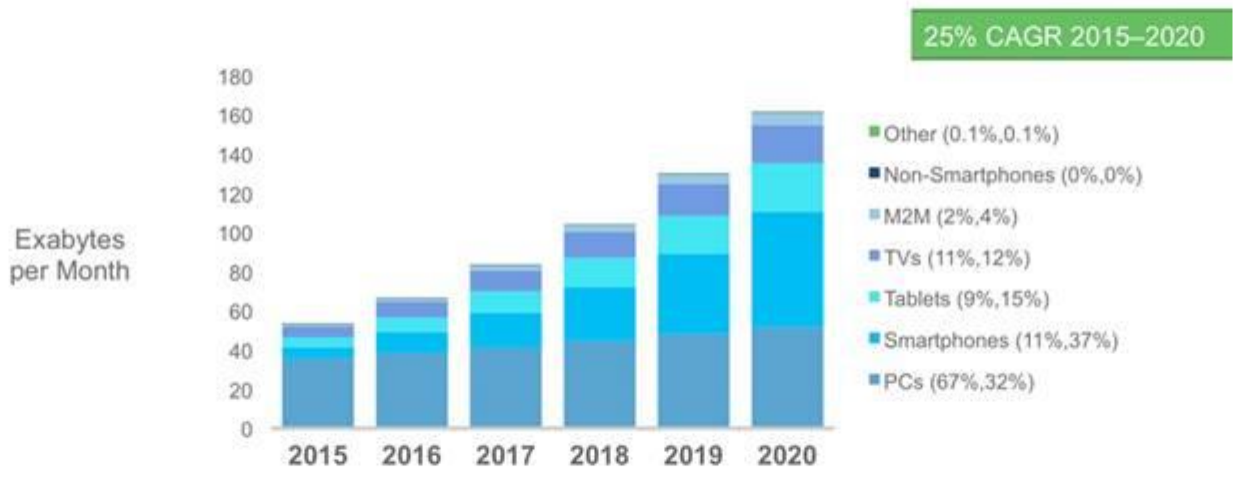
Introduction

- Huge bandwidth and capacity demand increase
  - driven by video streaming, cloud computing, social media and mobile applications

- Need to increase the transmission rate of currently deployed systems
  - 32-Gbaud PM-QPSK → 128 Gb/s per channel
  - 32-Gbaud PM-16QAM → 256 Gb/s per channel

Global IP Traffic by Devices



Source: "The Zettabyte Era - Trends and Analysis", Cisco, Jun 2016

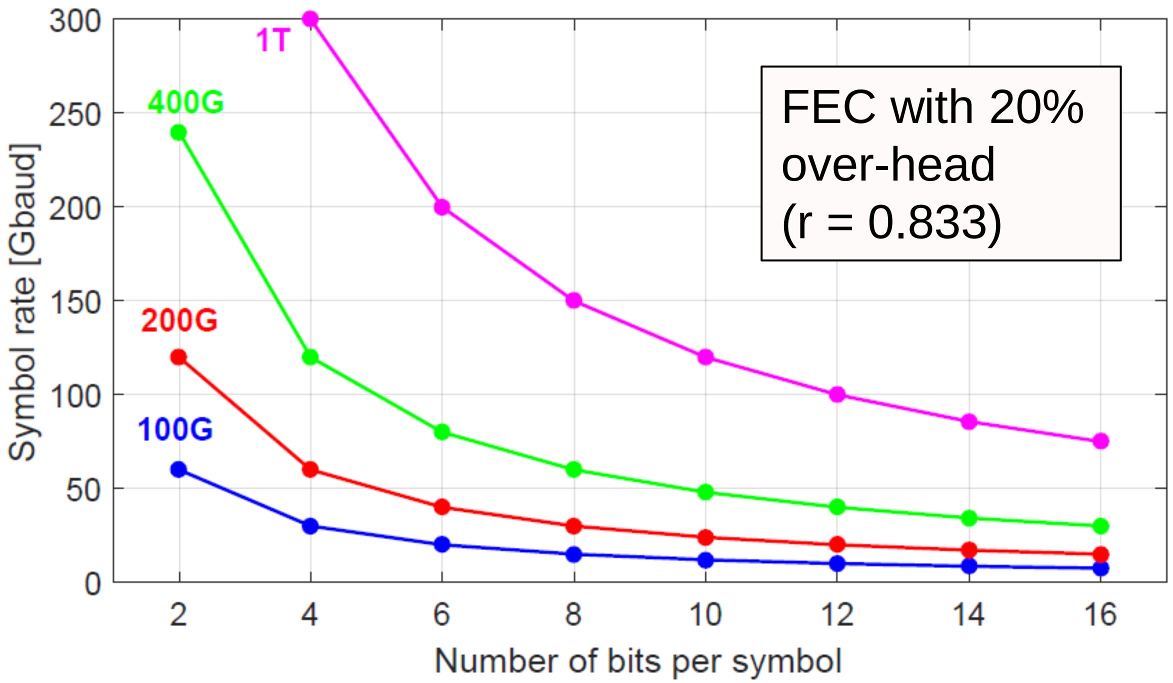
Raw bit-rate

$$R_b = R_s \cdot n_{bps}$$

Symbol rate (R_s) — **Number of bits per symbol** (n_{bps})

Introduction

- Goal: to scale the per-channel bit rate to 400 Gb/s and beyond



Raw bit-rate

$$R_b = R_s \cdot n_{bps}$$

Net bit-rate

$$R_b = R_s \cdot n_{bps} \cdot r$$

Symbol rate

FEC rate

Number of bits per symbol

- Two options:
  - Increase n_{bps} → high-order formats → Trade-off between spectral efficiency and reach
  - Increase R_s → Impact of symbol-rate on system reach

Outline

- Introduction
- Nyquist-WDM
- Trade-offs between spectral efficiency and reach
- Impact of symbol-rate on system reach
- Subcarrier multiplexing
- Probabilistic shaping
- Conclusions

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- **Nyquist-WDM**
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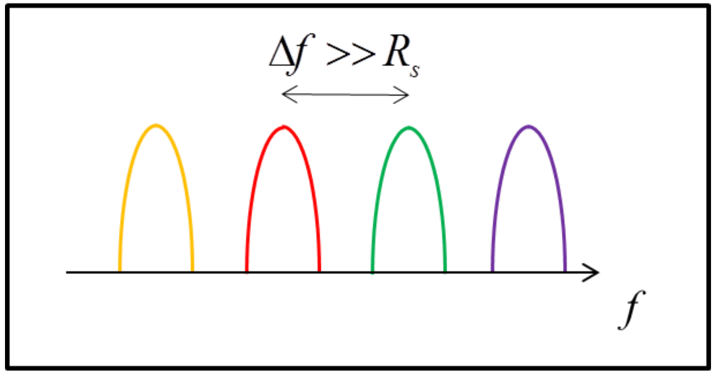
Nyquist-WDM

Standard WDM

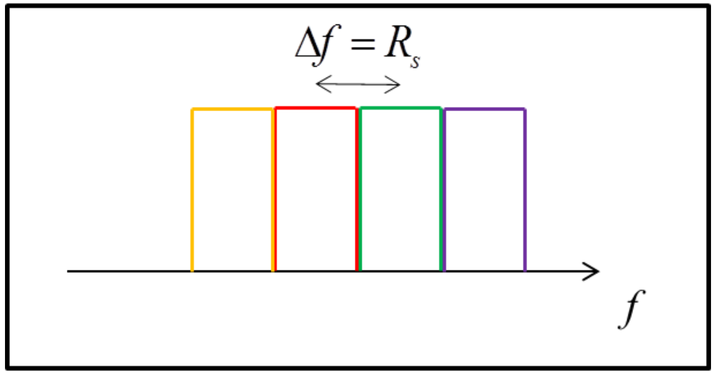


Raw spectral efficiency

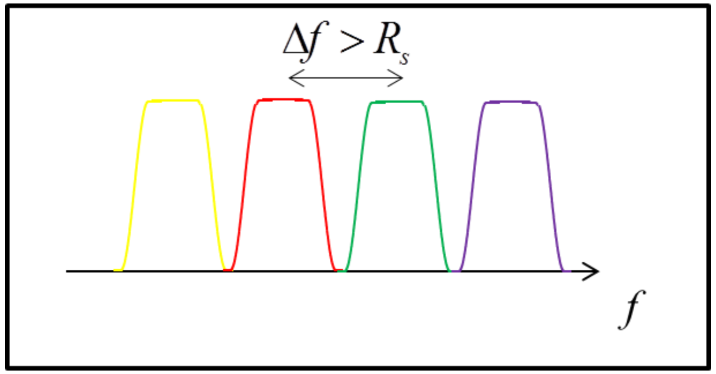
$$SE = n_{bps} \cdot \frac{R_s}{\Delta f}$$

- Maximum information that can be transmitted by the WDM comb:
  SE x available bandwidth

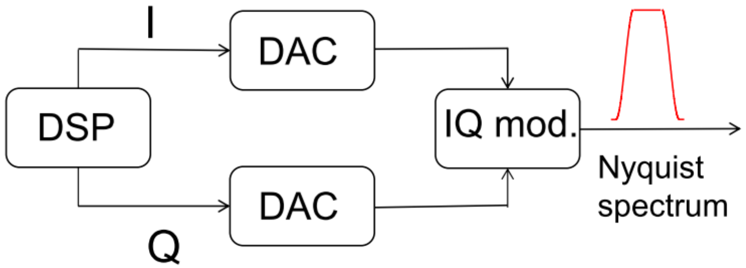
Ideal Nyquist-WDM

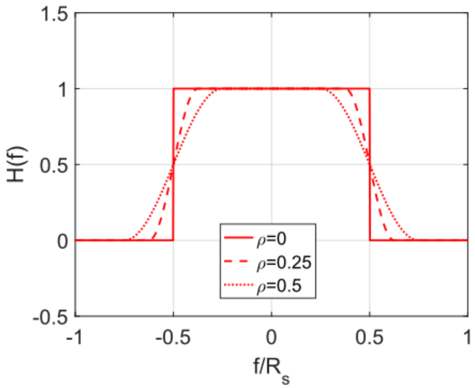


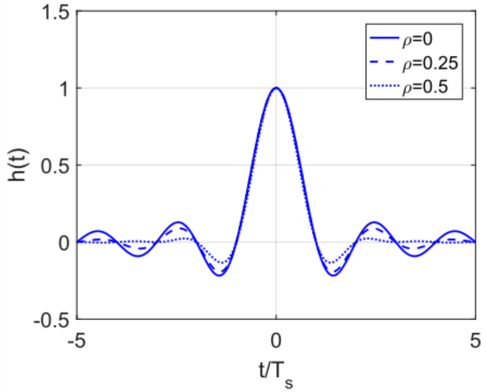
Quasi Nyquist-WDM



Generation of a Nyquist-WDM signal



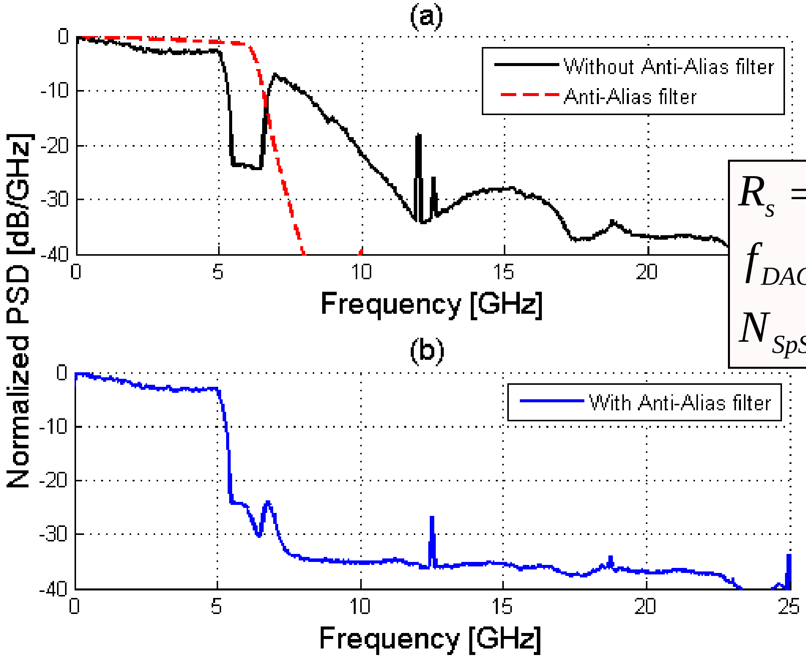




$$R_s = \frac{f_{DAC}}{N_{SpS}}$$

DAC sampling speed (samp/s)

Number of samples per symbol



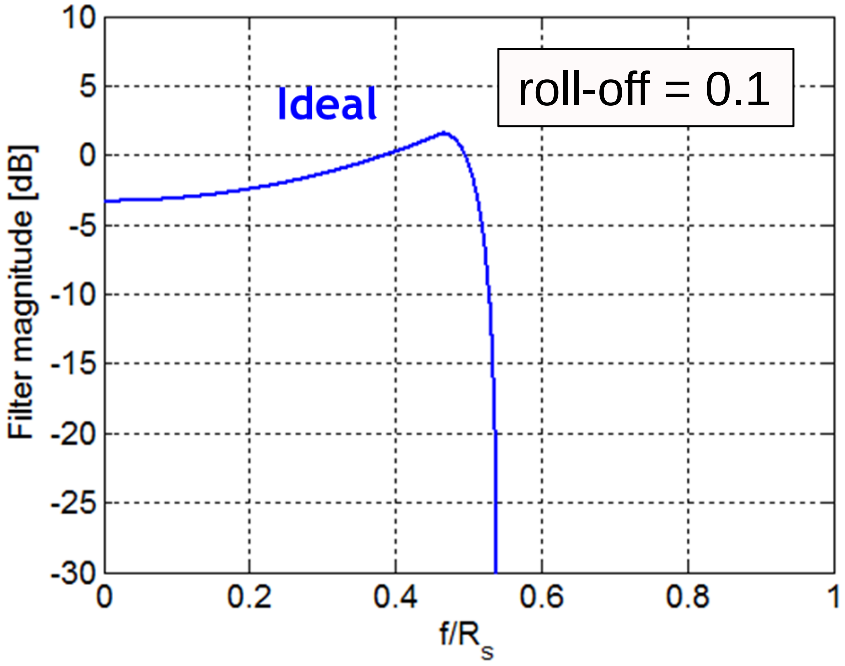
$$R_s = 10.4\,\text{Gbaud}$$
$$f_{DAC} = 11.96\,\text{Gsamp/s}$$
$$N_{SpS} = 1.15\,\text{samp/symb}$$

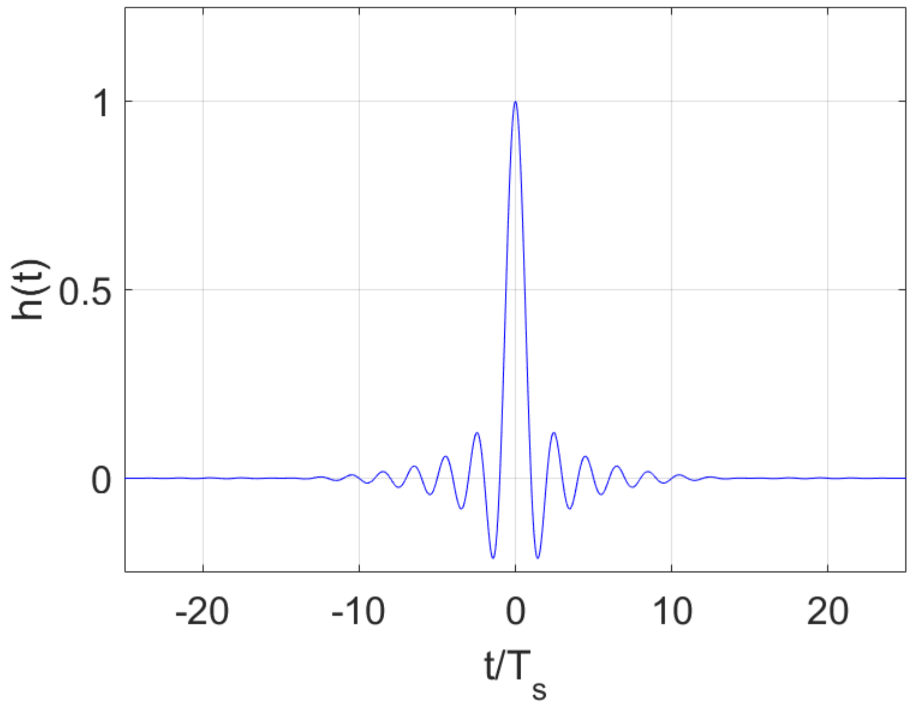
- R_s can be increased by reducing the "oversampling factor" N_{SpS} → interference between spectral replica → need to use a proper anti-alias filter

A. Nespola et al., "1306-km 20x124.8-Gb/s PM-64QAM Transmission over PSCF with Net SEDP 11,300 (b·km)/s/Hz using 1.15 samp/symb DAC," *Opt. Exp.* (**22**), 2014.

Nyquist pulse shaping

- Nyquist pulse shaping is performed in the digital domain using FIR filters





Generation of a Nyquist-WDM signal

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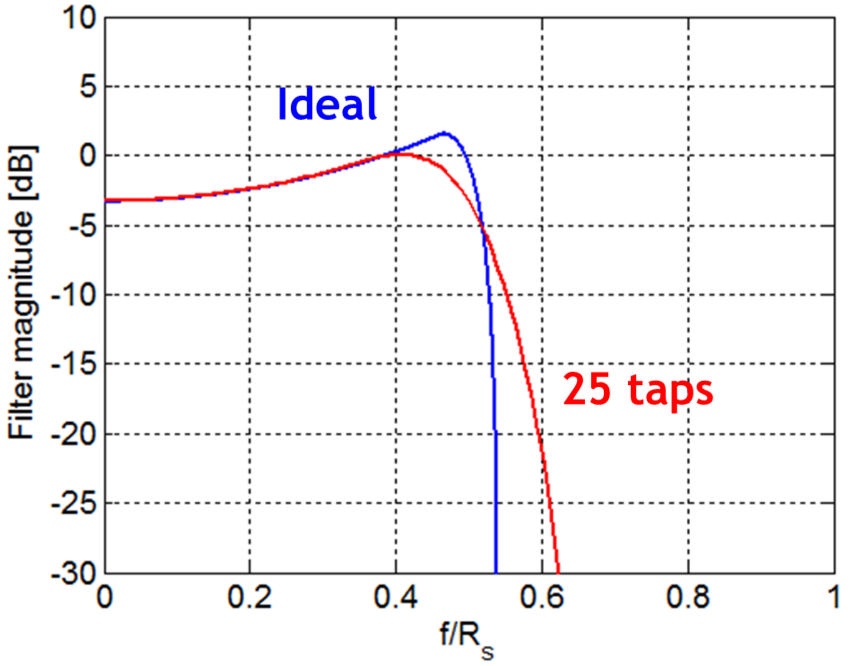

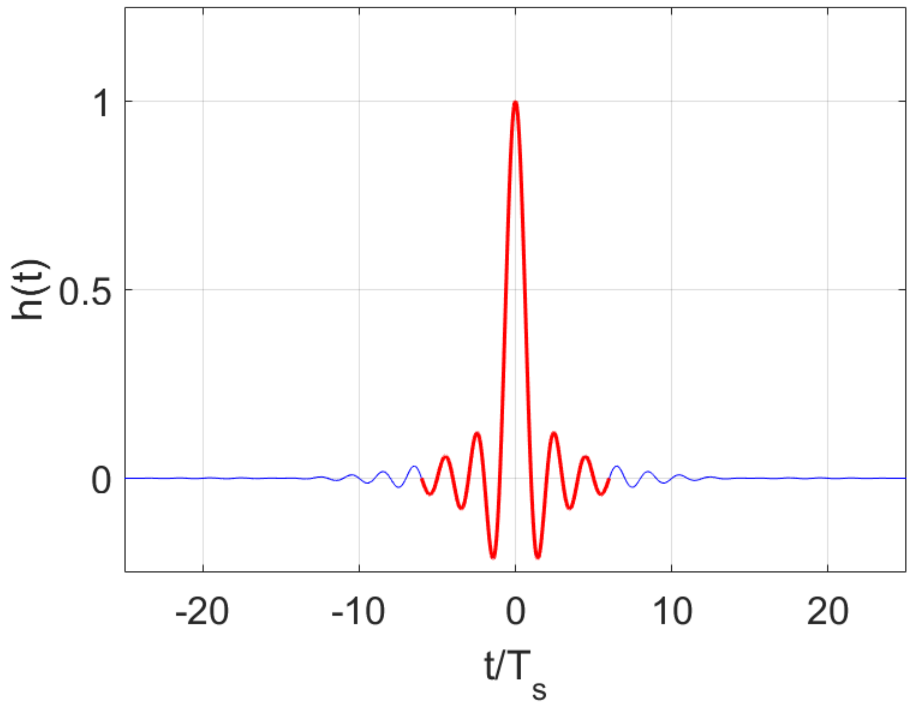

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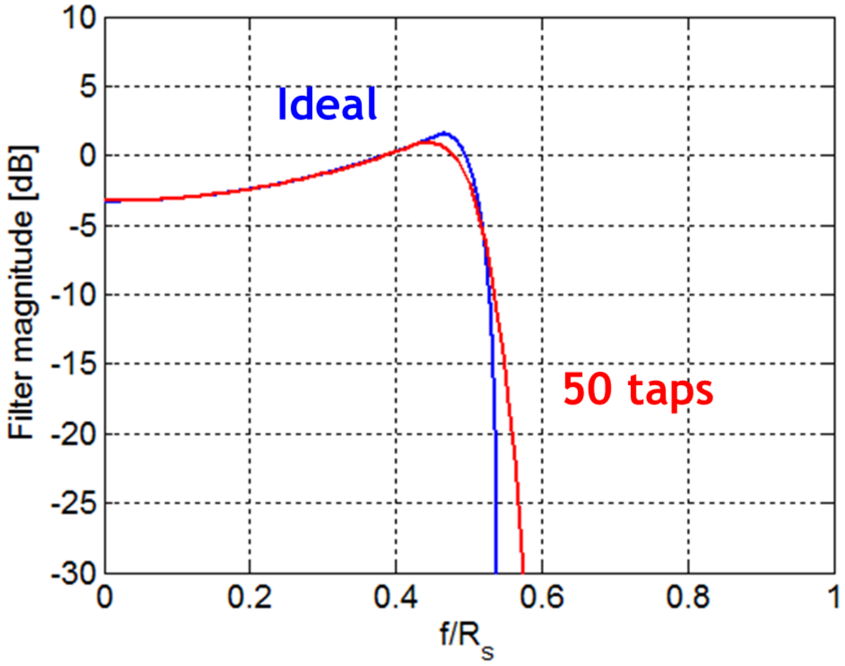

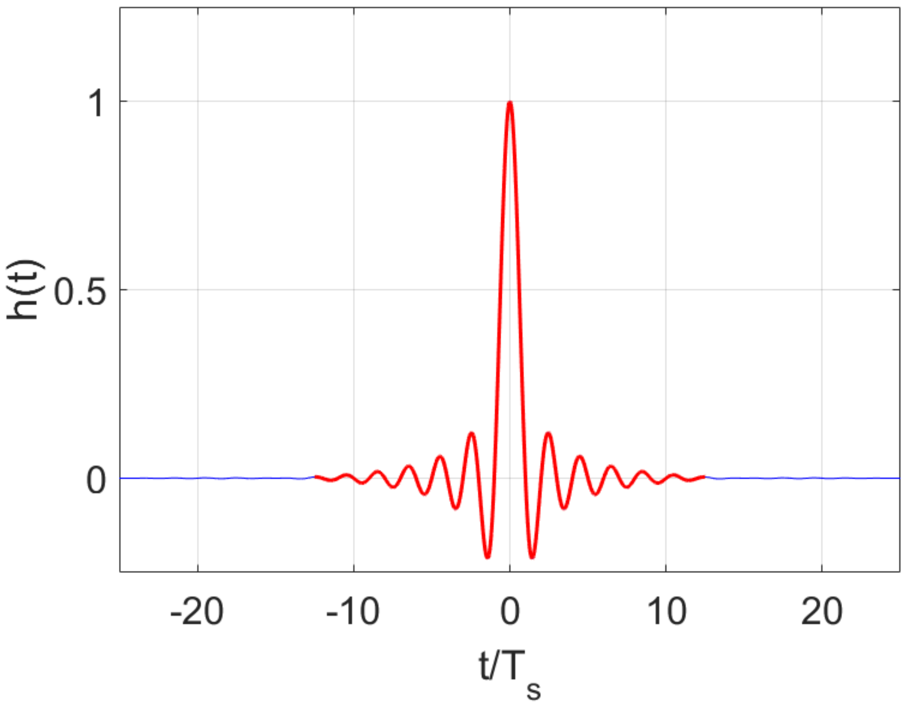

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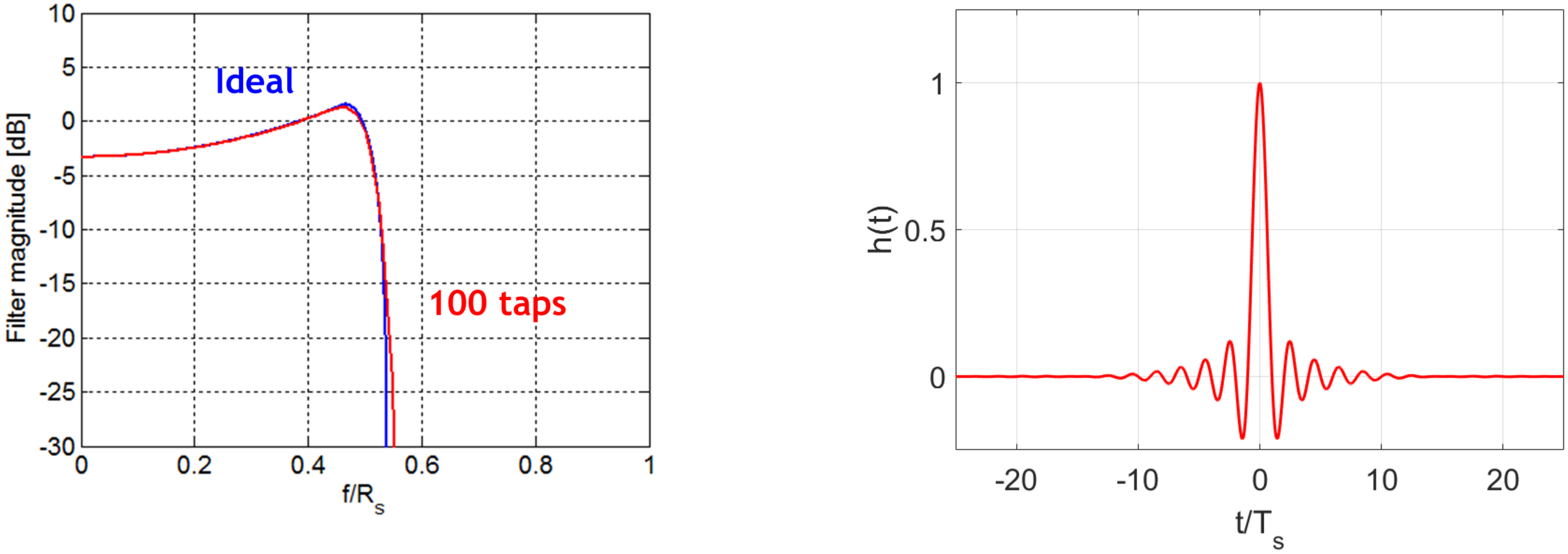

- Trade-off between complexity and achievable spectral efficiency

Outline

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- **Trade-offs between spectral efficiency and reach**
- Impact of symbol-rate on system reach
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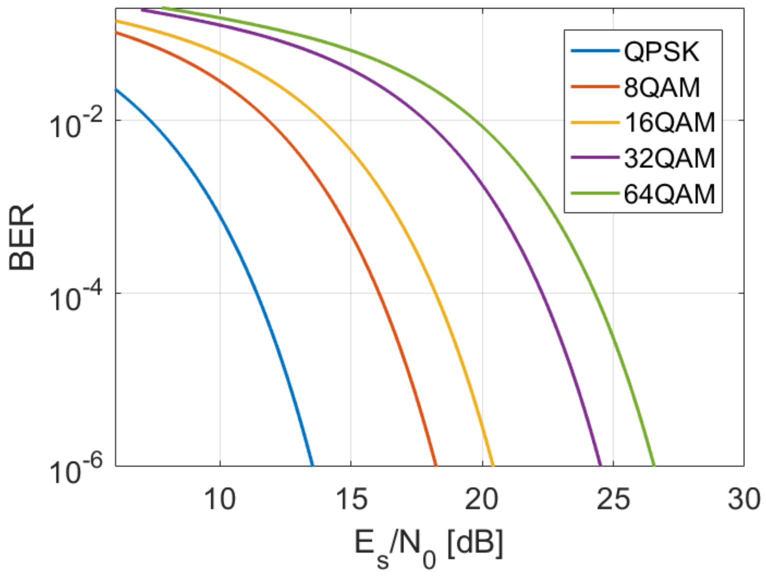
Trade-offs between spectral efficiency and reach

Net spectral efficiency

$$SE = n_{bps} \cdot \frac{R_s}{\Delta f} \cdot r$$

- If n_{bps} increases, SE increases but the back-to-back performance gets worse → reduction in reach

Ideal back-to-back performance

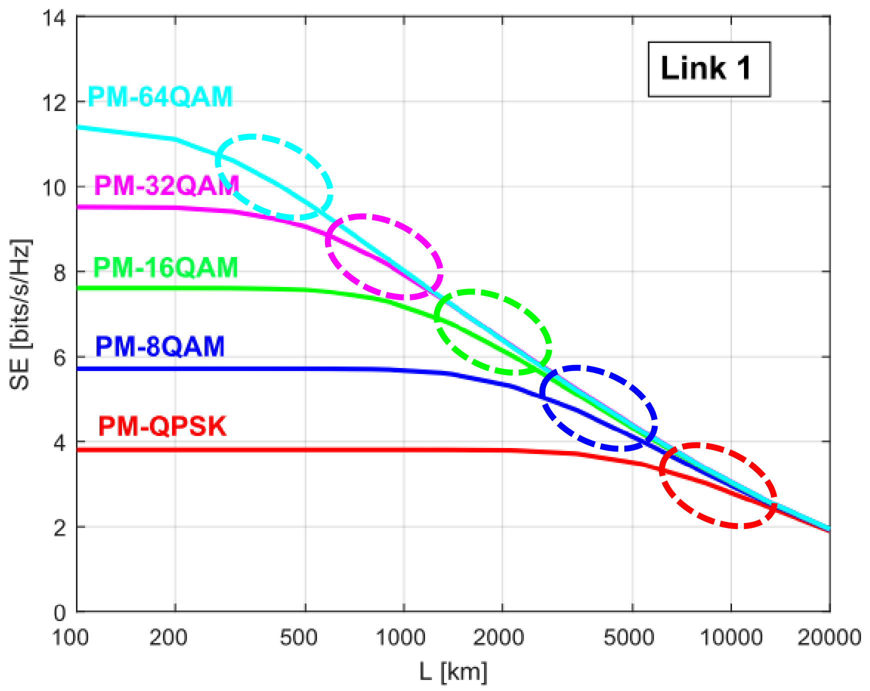


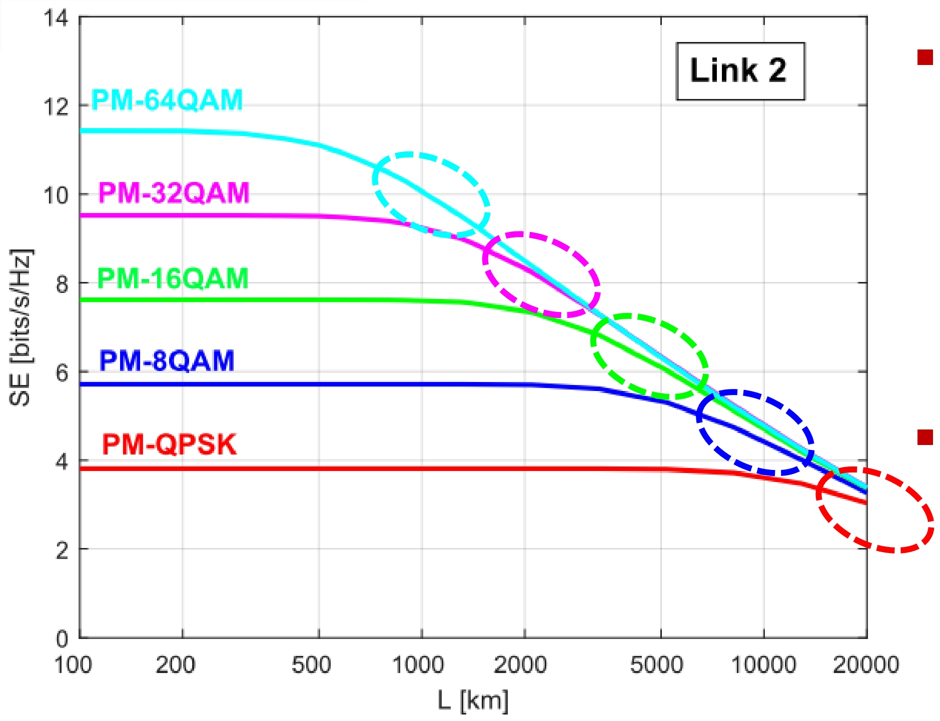
- Analysed setup:
  - Nyquist-WDM transmission at R_s = 32 Gbaud, with spacing Δf=1.05 R_s (roll-off 0.05)
  - Bandwidth of the WDM comb: 5 THz
  - EDFA only amplification with F = 5 dB
  - PSCF or SSMF with 100-km span length
  - SNR margin of 3 dB w.r.t. the ideal back-to-back performance

SE vs. total link length (100-km span length)

Link #	Fiber type	Dispersion [ps/nm/km]	Loss [dB/km]	Non-linearity coeff. $[W^{-1}km^{-1}]$	Span length [km]
Link 1	SSMF	16.7	0.2	1.3	100
Link 2	PSCF	20.5	0.165	0.75	100

Results obtained using the EGN model:
Poggiolini and Y. Jiang, "Recent Advances in the Modeling of the Impact of Non-Linear Fiber Propagation Effects on Uncompensated Coherent Transmission Systems", JLT, Early Access





- Distance between operating point and asymptotic performance → FEC overhead
- Complexity increases with modulation format order and FEC overhead

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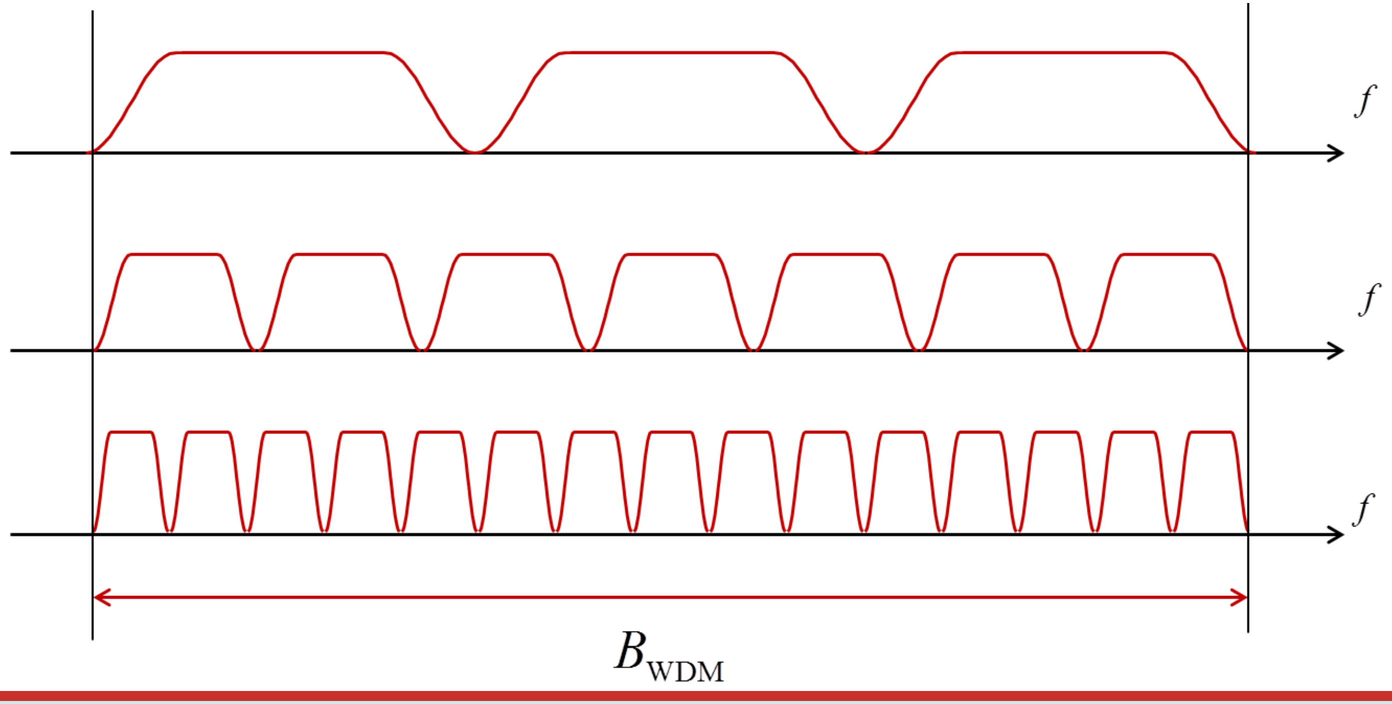
Impact of symbol rate on system reach

- Over the last few years, various simulative and theoretical papers have presented evidence of a **dependence of system performance on the transmission symbol rate**:
  - *W. Shieh and Y. Tang, 'Ultrahigh-speed signal transmission over nonlinear and dispersive fiber optic channel: the multicarrier advantage,' IEEE Photonics J., vol. 2, no. 3, pp. 276-283, Jun. 2010.*
  - *C. Behrens et al., 'Nonlinear transmission performance of higher-order modulation formats,' PTL (**23**), Mar. 2011.*
  - *L. B. Du and A. J. Lowery, 'Optimizing the subcarrier granularity of coherent optical communications systems,' Optics Expr (**19**) Apr. 2011.*
  - *M. Qiu et al., "Subcarrier multiplexing using DACs for fiber nonlinearity mitigation in coherent optical communication systems," OFC 2014, paper Tu3J.2.*
  - *A. Bononi et al., 'Performance dependence on channel baud-rate of coherent single-carrier WDM systems,' ECOC 2013, paper Th.1.D.5, Sept. 2013.*
  - *N. Rossi, P. Serena, A. Bononi, 'Symbol-rate dependence of dominant nonlinearity and reach in coherent WDM links, JLT (**33**), Jul. 2015.*
- **What is the symbol rate which minimizes the non-linear interference (NLI) ?**

The analyzed set-up

- ***What is the symbol rate which minimizes NLI ?...***
  …having fixed:
  - the total WDM bandwidth (B_{WDM}=504 GHz, 1.5 THz, 2.5 THz, 5 THz)
  - the modulation format and roll-off (PM-QPSK, ρ=0.05)
  - the relative frequency spacing (Δf=1.05 R_s)



- SSMF fiber (100-km span length)
  EDFA-only amplification (F=5 dB)

Normalized NLI power spectral density

- The total NLI power (P_{NLI}) at the output of the transmission link is estimated either with the EGN model [*] or by numerical simulations based on the split-step Fourier method.
- Systems at different symbol rate are compared in terms of the **normalized NLI power spectral density (PSD)**

$$\tilde{G}_{NLI} = \frac{P_{NLI}}{R_s G_{ch}^3}$$

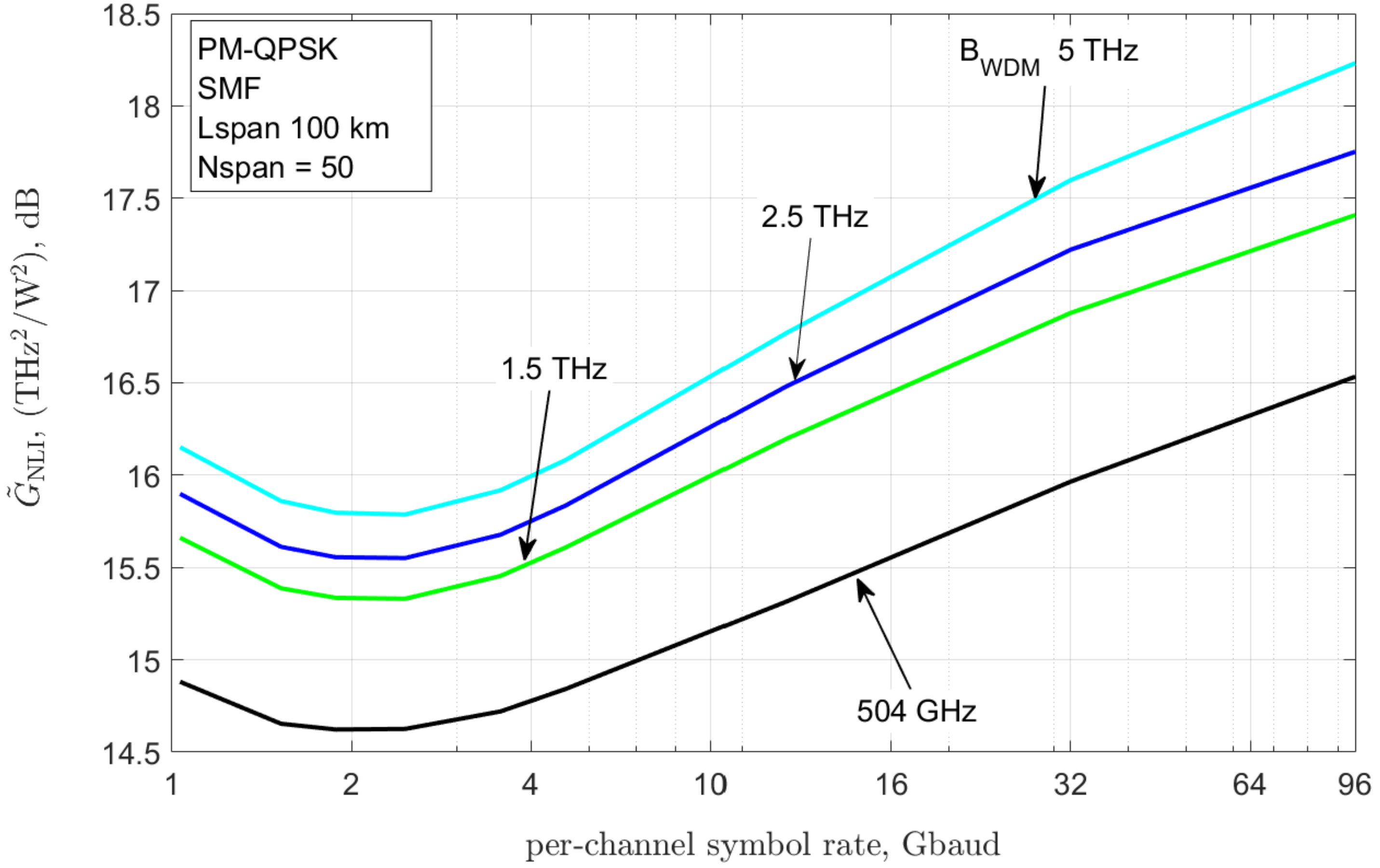
Transmitted signal PSD

which is independent of the transmitted power per channel.

- Same value of $\tilde{G}_{NLI}$ means same maximum reach.

*[*] A. Carena et al., "EGN model of non-linear fiber propagation," Opt. Exp (**22**), 2014.*

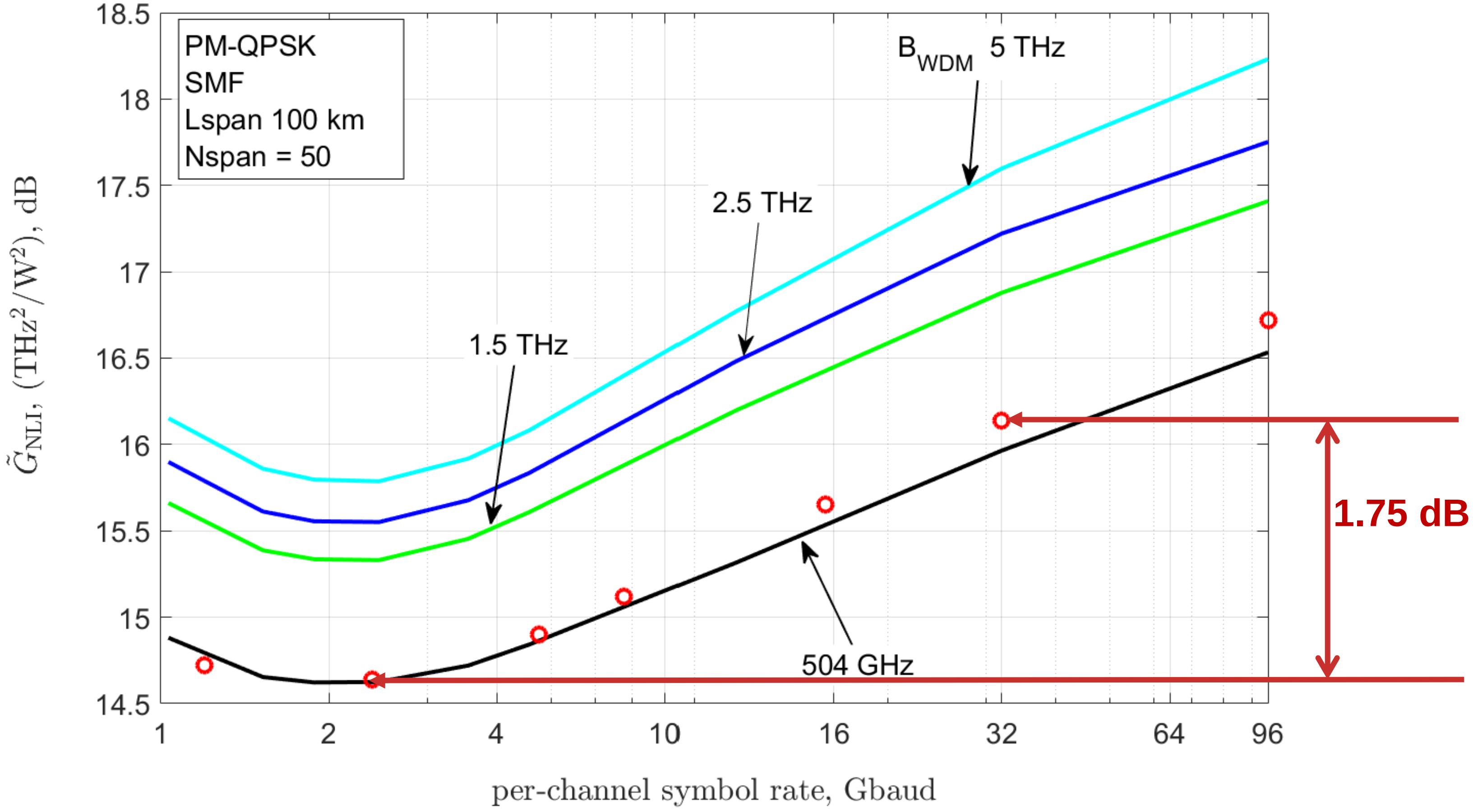
Normalized G_{NLI} – PM-QPSK over SMF



- Solid lines: EGN model

- *P. Poggiolini et al., "Analytical and experimental results on system maximum reach increase through symbol rate optimization," J. Lightw. Technol., vol. 34, no. 8, pp. 1872–1885, Apr. 2016.*

Normalized G_{NLI} – PM-QPSK over SMF



- Solid lines: EGN model
- Markers: numerical simulations
- Maximum reach gain:

$$\left(\Delta MR\right)_{dB} \approx \frac{1}{3}\left(\Delta\tilde{G}_{NLI}\right)_{dB}$$

~ 0.6 dB or 15%

- *P. Poggiolini et al., "Analytical and experimental results on system maximum reach increase through symbol rate optimization," J. Lightw. Technol., vol. 34, no. 8, pp. 1872–1885, Apr. 2016.*

How to exploit symbol-rate optimization gain?

- Optimum symbol rate values in the range 2-4 Gbaud
- It would be extremely inefficient to use a separate transceiver for each low-symbol-rate signal
  - To reach the transmission speed of commercially available 32-Gbaud systems, 16× more transceivers (including laser sources) at 2 Gbaud would be required

⬇

Sub-carrier multiplexing

- A high symbol-rate signal is electrically decomposed into a given number of subcarriers, each of which operating at a lower symbol-rate (multiplexing in the digital domain)

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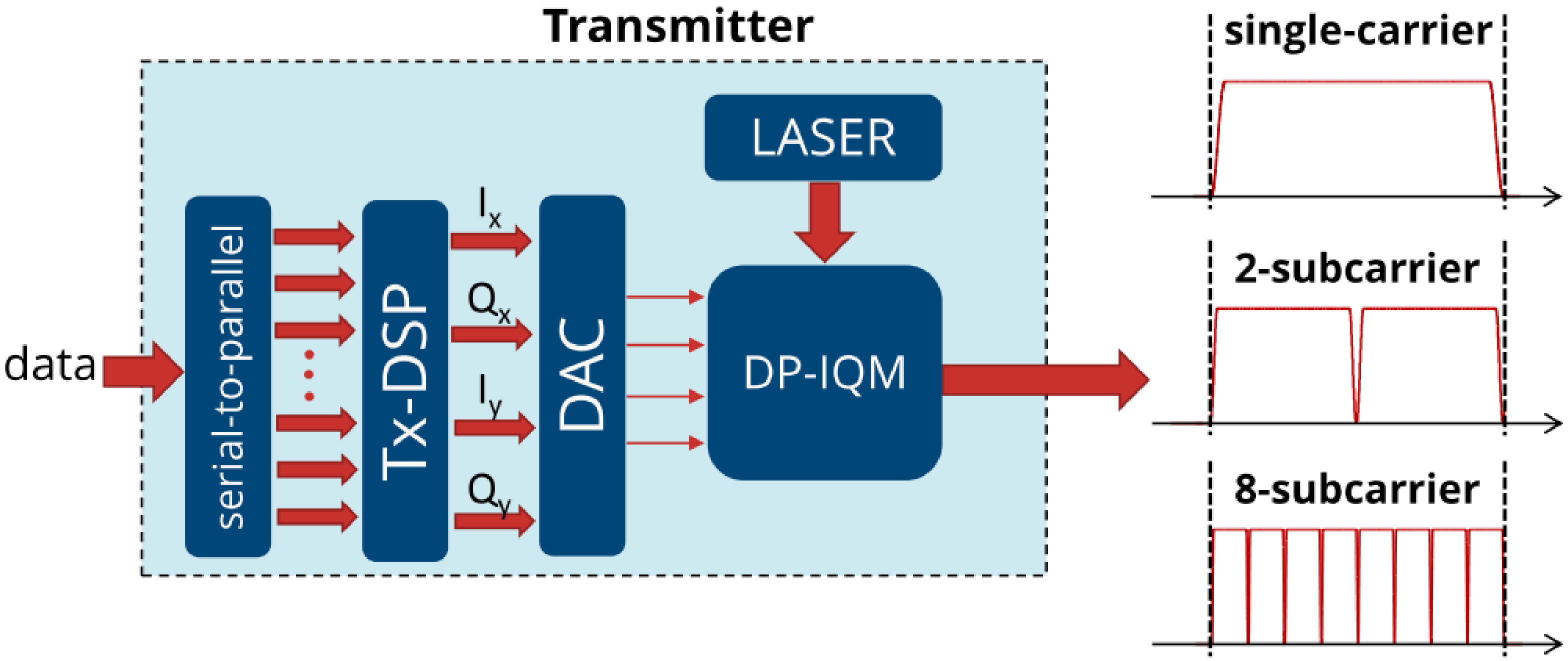
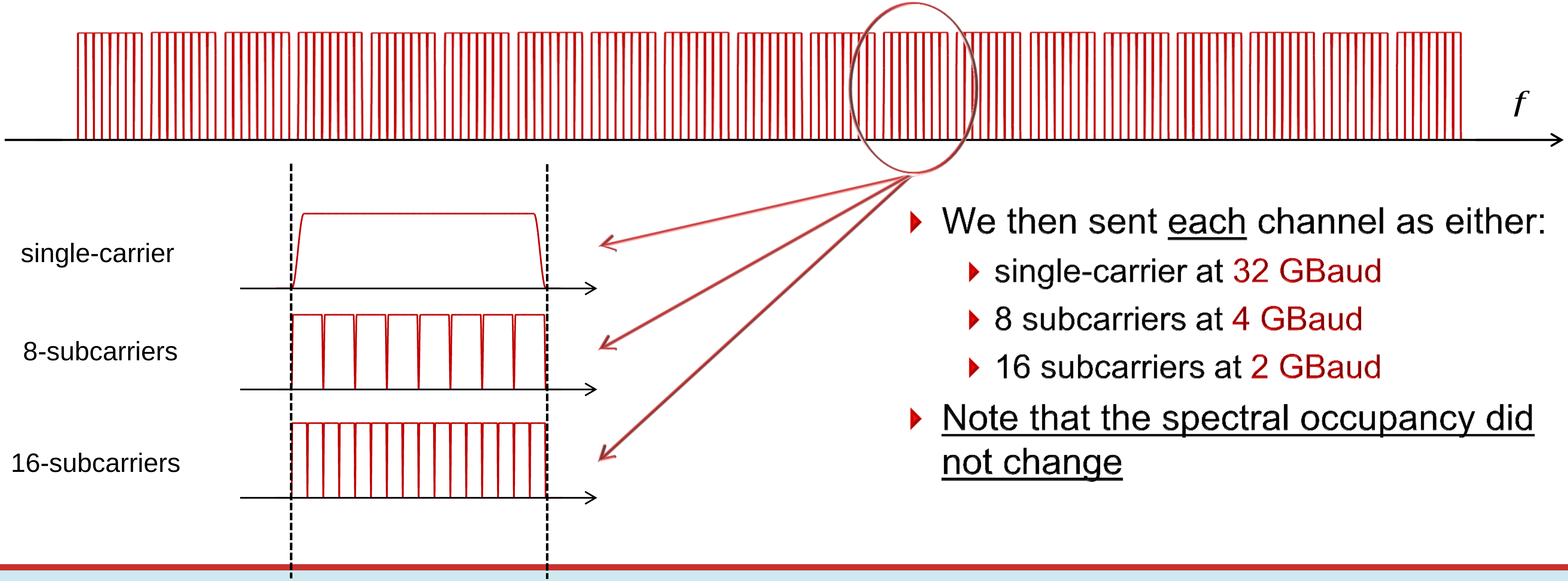


- A. Nespola et al., *"Experimental demonstration of fiber nonlinearity mitigation in a WDM multi-subcarrier coherent optical system,"* ECOC 2015, Sep. 2015.

The experiment

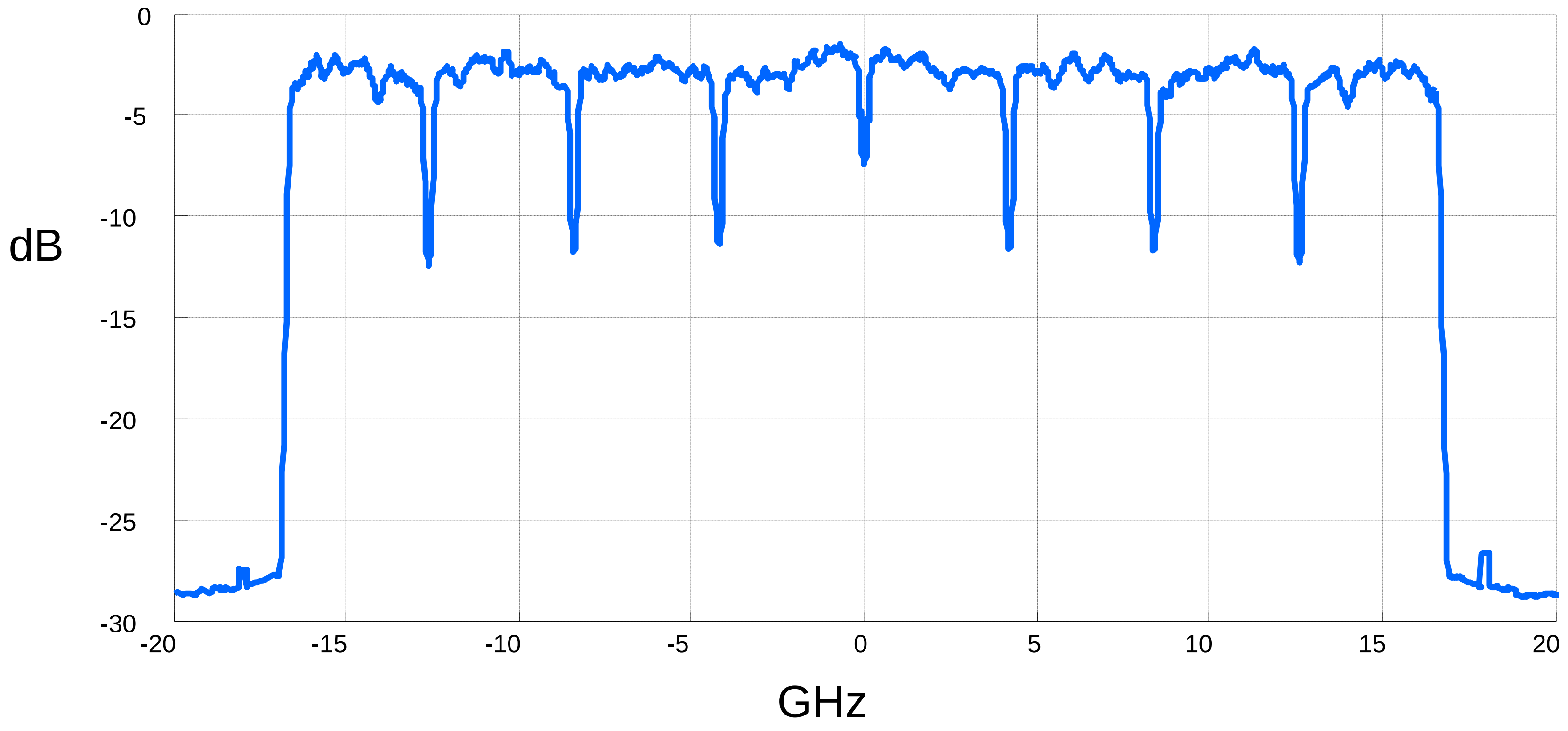
- We started out with a **19 channel** WDM comb, with channel **spacing 37.5 GHz**, for a total WDM bandwidth of **710 GHz**



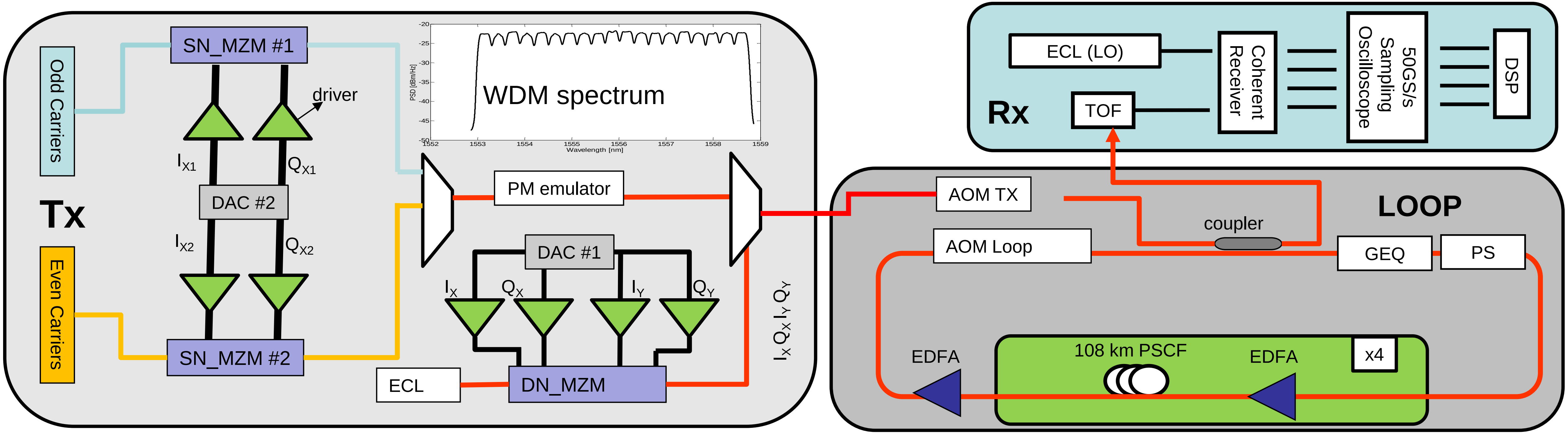
- We then sent each channel as either:
  - single-carrier at 32 GBaud
  - 8 subcarriers at 4 GBaud
  - 16 subcarriers at 2 GBaud
- Note that the spectral occupancy did not change

Channel spectrum

- The 8-subcarrier DAC-generated electrical spectrum for one channel



System schematic

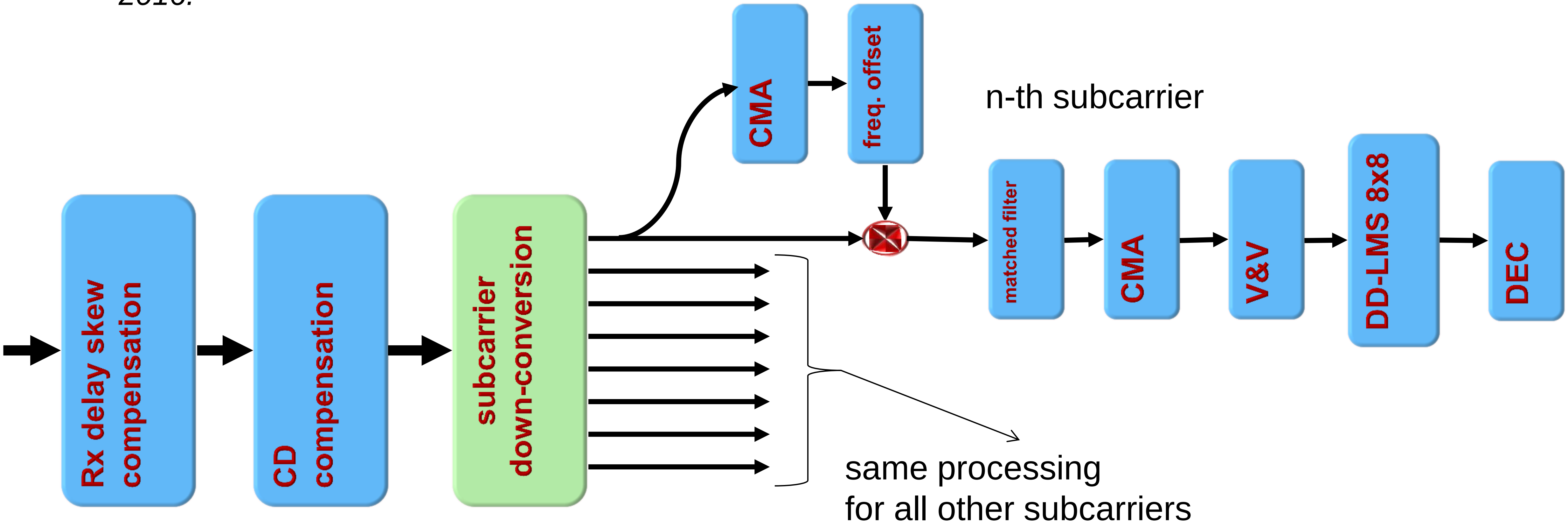


SN_MZM: single-nested Mach-Zehnder mod.
DN_MZM: double-nested Mach-Zehnder mod.

GEQ: Gain EQualizing programmable filter
PS: synchronous Polarization Scrambler
AOM: Acousto-Optic Modulator (used as switch)
TOF: Tunable Optical Filter

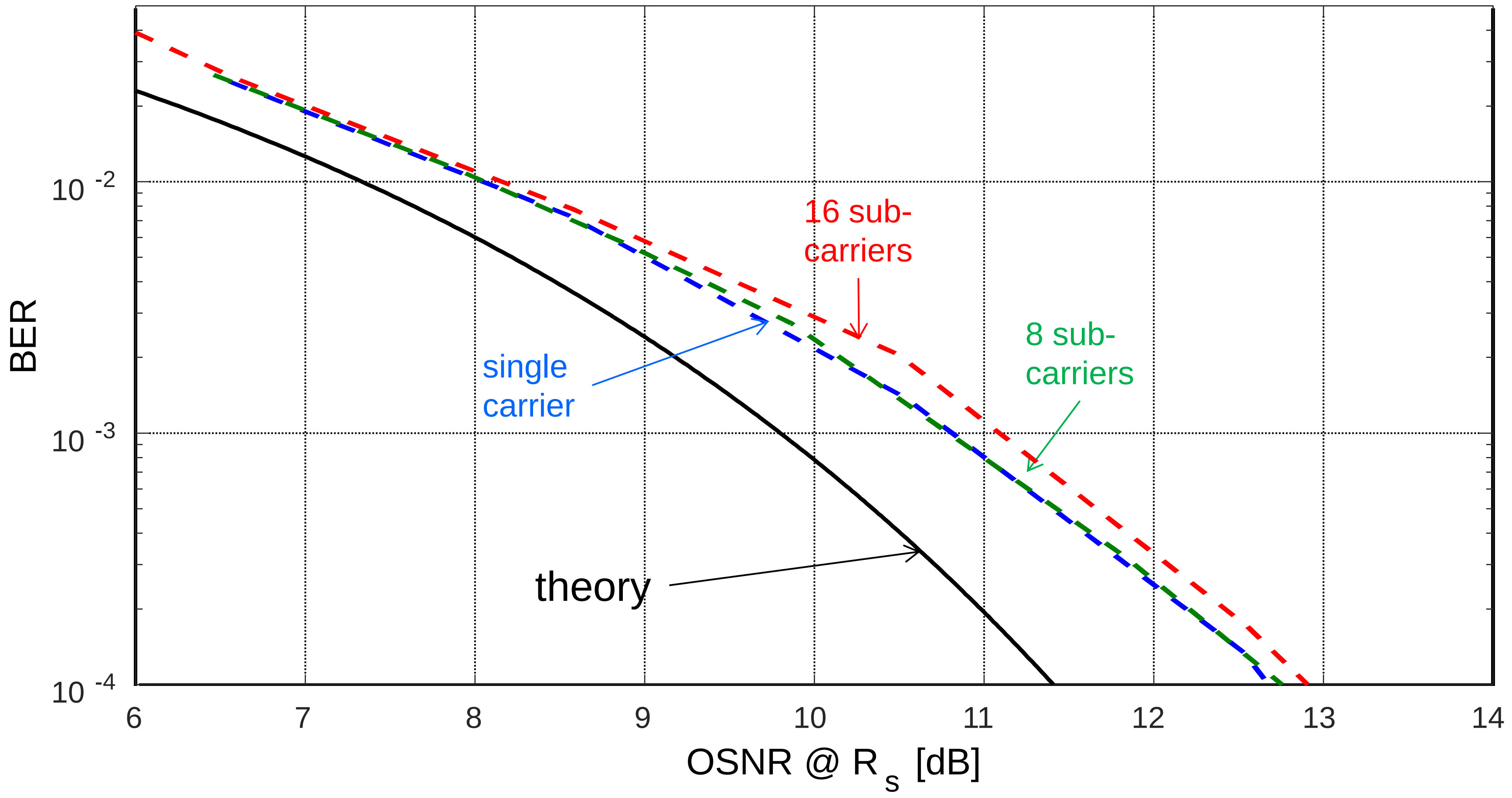
The Rx DSP

- The 8x8 (real) LMS is necessary to correct for I/Q delay skew at the transmitter modulator (otherwise 4x4 is enough)
  - *G. Bosco et al. "Impact of the transmitter IQ-skew in multi-subcarrier coherent optical systems," OFC 2016.*



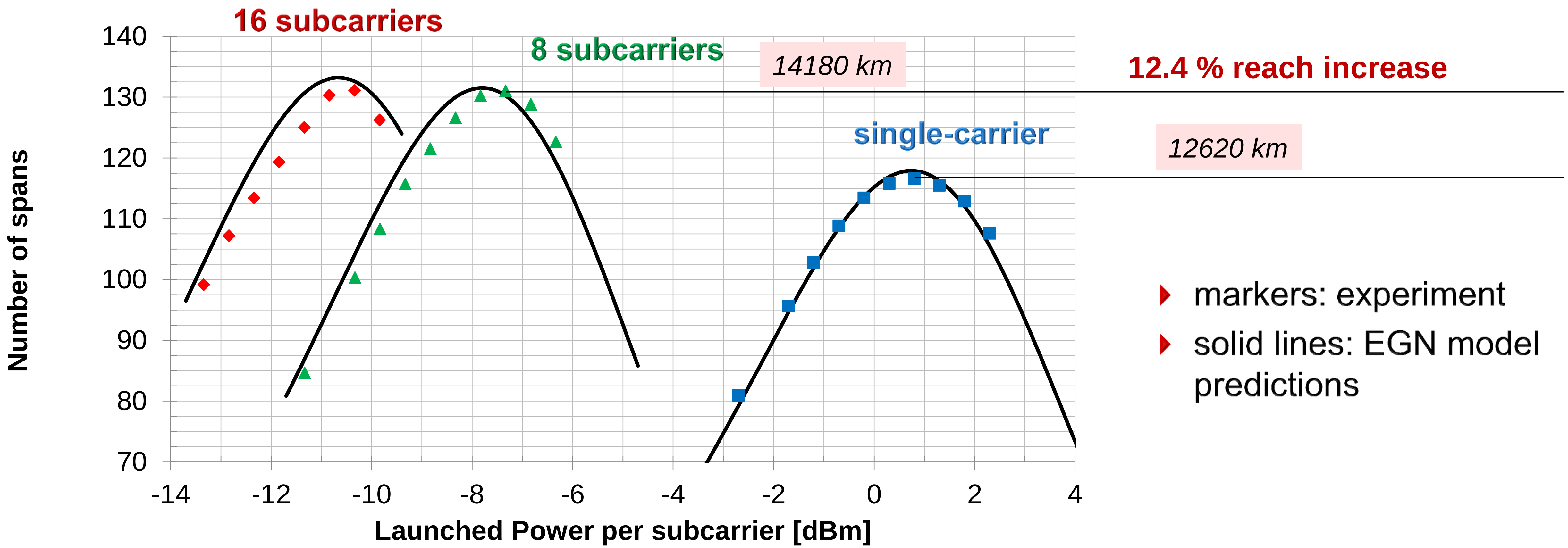
Back-to-back characterization

- To perform a meaningful comparative test over the long-haul, it is important that the btb is the same



- At the reference BER=10^{-2}:
  - No penalty from single SC to 8 SCs
  - 0.1-dB penalty from single SC to 16 SCs

Reach curves at BER 10^{-2}



- markers: experiment
- solid lines: EGN model predictions

Pros and cons of SCM transmission

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PROS

- Exploitation of the nonlinear propagation benefits associated with SRO (symbol rate optimization)
- Increase of system flexibility, by adjusting the number of subcarriers, modulation formats and spectral occupation to the current load of the network.

CONS

  - Higher sensitivity to transceiver impairments (like IQ-skew) and phase noise → requires more complex DSP algorithms

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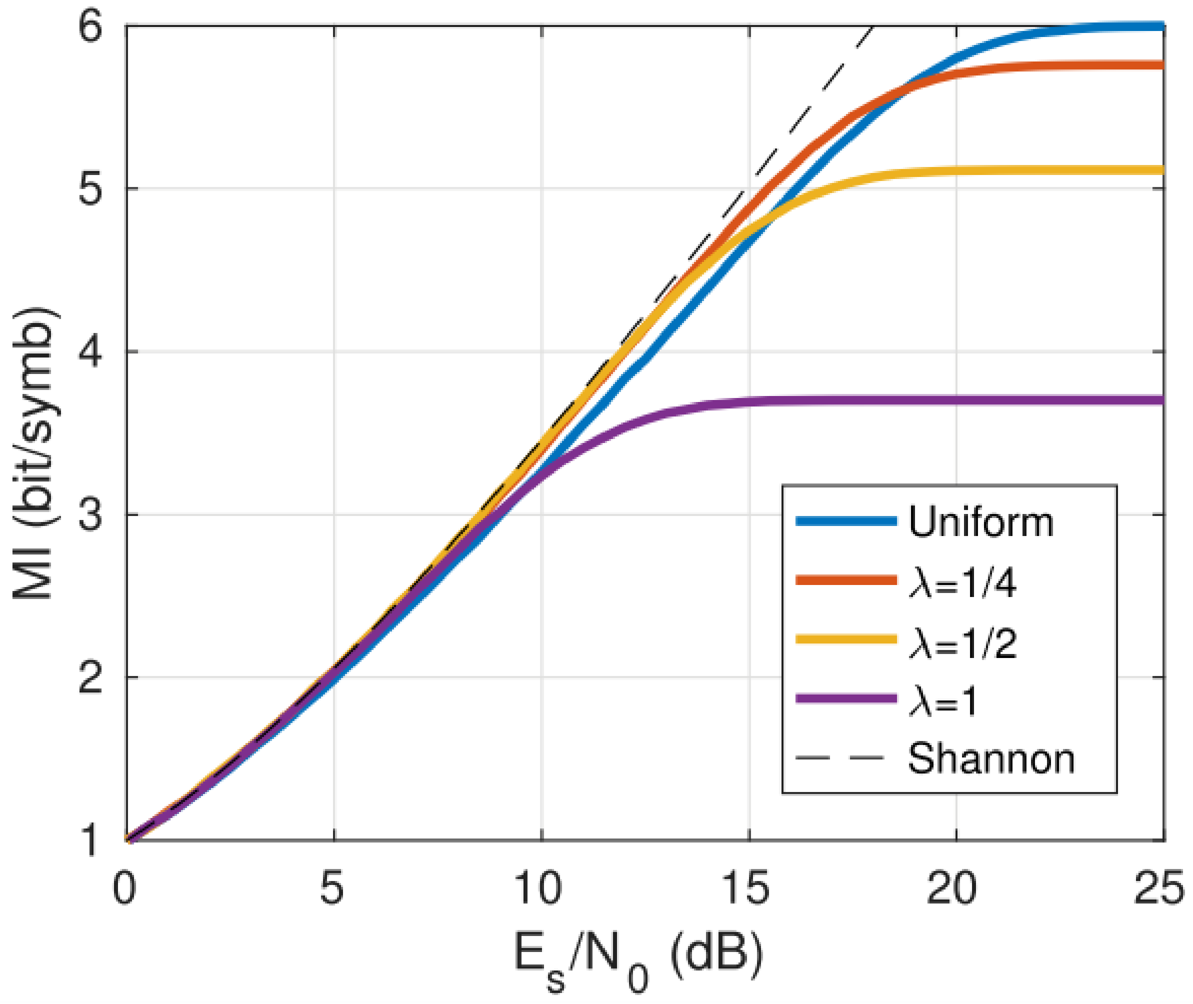
Mutual Information vs. SNR

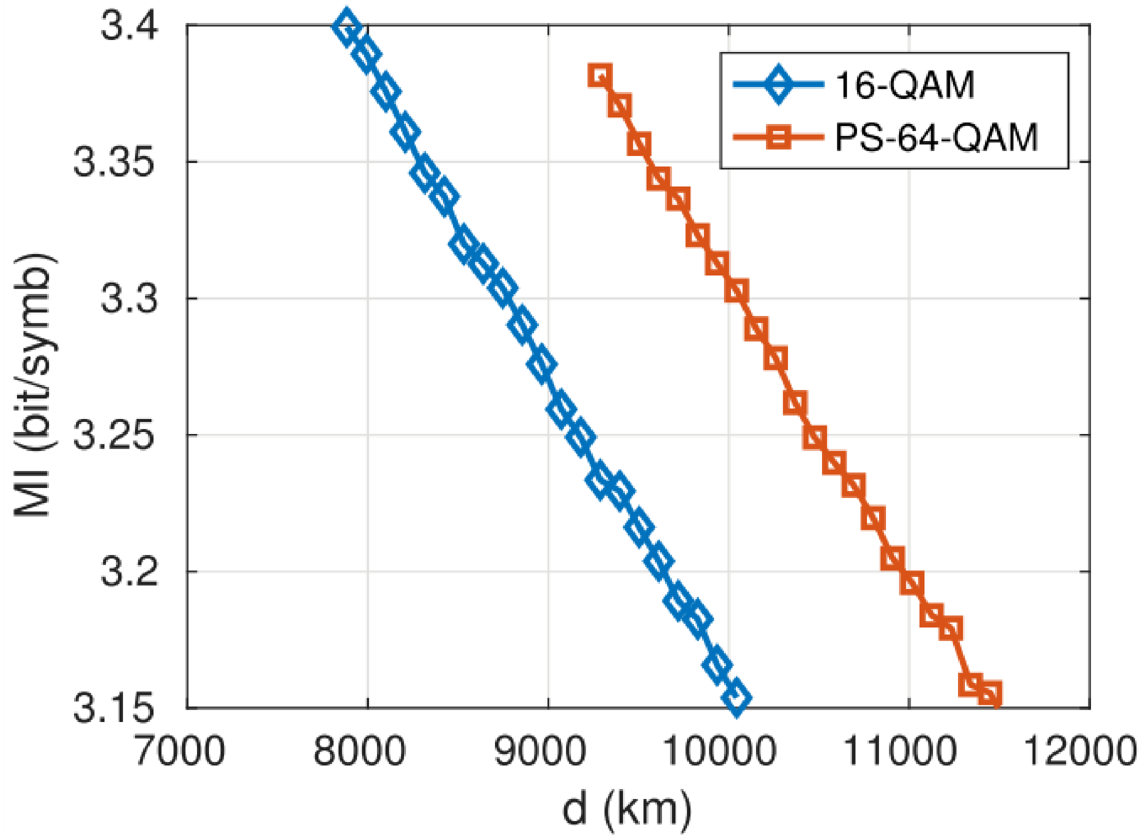


- Shaping reduces the maximum achievable mutual information (or, equivalently, transmit rate), represented by the MI floor for high values of SNR.
- This value corresponds to the constellation entropy:

$$\mathcal{H}(C) = -\sum_i \mathcal{P}(a_i)\log_2 \mathcal{P}(a_i)$$

- For low values of SNR, PS constellations perform slightly better than uniform 64-QAM.

MI vs. Propagation distance



- PS-64QAM with the same entropy as the uniform 16-QAM constellation
- PSCF fiber (108-km span length)
- 11 WDM channels at 32 Gbaud (frequency spacing = 50 GHz)
- The maximum reach gain at the same mutual information is 13.75%, which corresponds approximately to the SNR gain in back-to-back.

Pros & Cons

- PROS
  - Enhanced system reach
  - High flexibility of the transponder (transmission speed can be tuned by changing the shaping of the constellation)
- CONS
  - The highest SNR gains of probabilistic shaping are achieved for low values of MI, which corresponds to very high pre-FEC Symbol Error Rates (SERs)
    → High values of SER represent a big challenge for blind DSP algorithms, such as adaptive equalizer and phase recovery.

[1] F. Buchali et al., "Rate adaptation and reach increase by probabilistically shaped 64-QAM …," JLT (34), Apr. 2016.
[2] M.P. Yankov et al., "Constellation shaping for fiber-optic channels with QAM and high spectral effciency," PTL (26), Dec. 2014.
*[3] F.R. Kschischang et al., "Probabilistic 16-QAM Shaping in WDM Systems," JLT (**34**), Sep. 2016.*
[4]S. Chandrasekhar et al., "High-spectral-efficiency transmission of PDM 256-QAM with Parallel Probabilistic Shaping at Record Rate-Reach Trade-offs", ECOC 2016, paper. Th.3.C.1 (2016).

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Conclusions

- Two main strategies to increase the transmission speed:
  - Increase the order of the modulation format
    → SNR penalty, increase of DSP complexity
  - Increase the symbol rate
- There is an optimum value of symbol-rate that minimizes the impact of nonlinearities (around 2-4 Gbaud) → subcarrier modulation
  - more impacted by transceiver impairments (like IQ-skew) and phase noise
  - requires more complex DSP algorithms
  - increases flexibility
- Other ways to increase flexibility
  - Constellation shaping
  - Hybrid formats