Coherent polarization-multiplexed formats: receiver requirements and mitigation of fiber non-linear effects

Andrea Carena, Gabriella Bosco, Vittorio Curri
OPTCOM group
Dipartimento di Elettronica - Politecnico di Torino

Motivation

- Multi-level modulation with coherent detection are clearly becoming the enabling solution for future high capacity long-haul system
- A key component in such systems is the ADC: relaxing the requirements will be beneficial reducing costs, complexity and power consumption
- Fiber non-linear effects are limiting the maximum reach but coherent detection offers new opportunities for mitigating the impact

Outline

1. TX and RX set-up
2. Receiver requirements
3. Mitigation of fiber non-linear effects
4. Conclusions

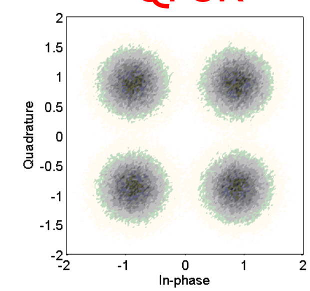
1. TX and RX set-up

Simulation parameters

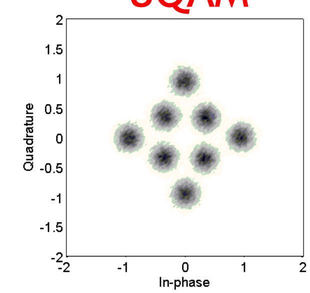
- Symbol rate
  - 25 Gbaud + 11% overhead: 27.75 Gbaud
- Three modulation formats:
  - PM-QPSK → 111.0 Gbps (100 Gbps)
  - PM-8QAM → 166.5 Gbps (150 Gbps)
  - PM-16QAM → 222.0 Gbps (200 Gbps)
- Channel spacing
  - Δf= 50 GHz

- <u>**Simulation details**</u>
  - Independent PRBSs for each tributary (degree 16)
  - BER evaluation based on error counting
  - Reference BER= $4 \cdot 10^{-3}$
  - Fiber propagation: full band split-step method

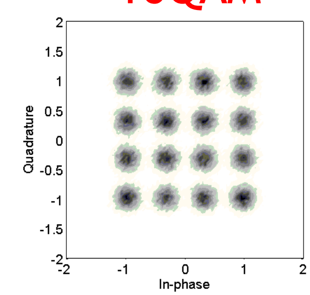
QPSK



8QAM

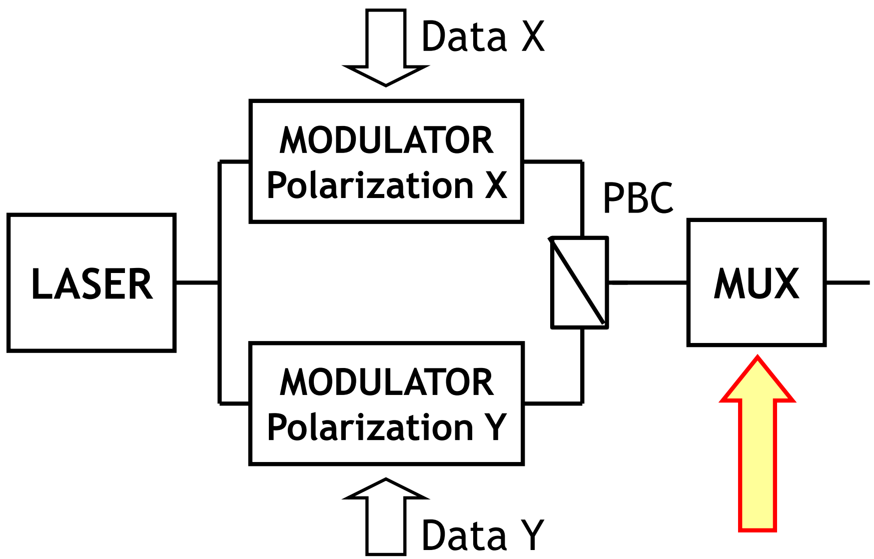


16QAM



Transmitter

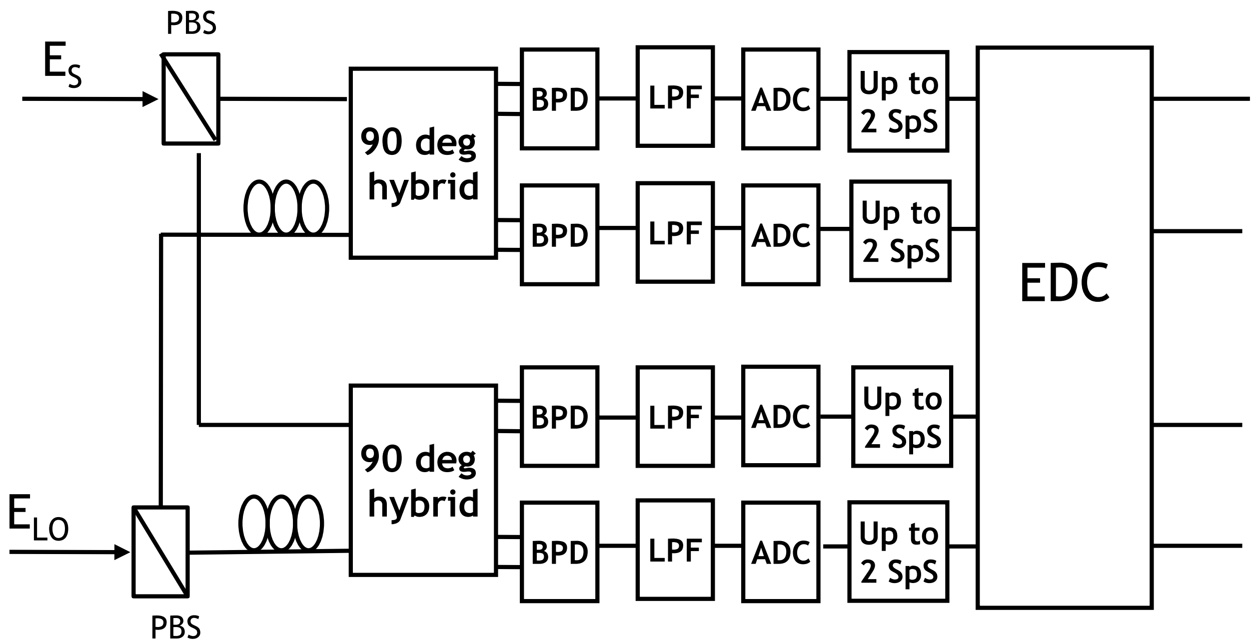
- Based on Nested Mach-Zehnder for QPSK and 16QAM
  - Binary driving for QPSK
  - Four level driving with pre-distortion for 16QAM
- Two cascaded Nested Mach-Zehnders for 8QAM



Optical Bandpass Filter
4th order Supergaussian

Opto-electronic front-end

- Common opto-electronic front-end for all formats
- When ADC speed is reduced below 2 SpS, then up-sampling is performed to run DSP at 2 SpS
- Ideal clock recovery
- Ideal EDC

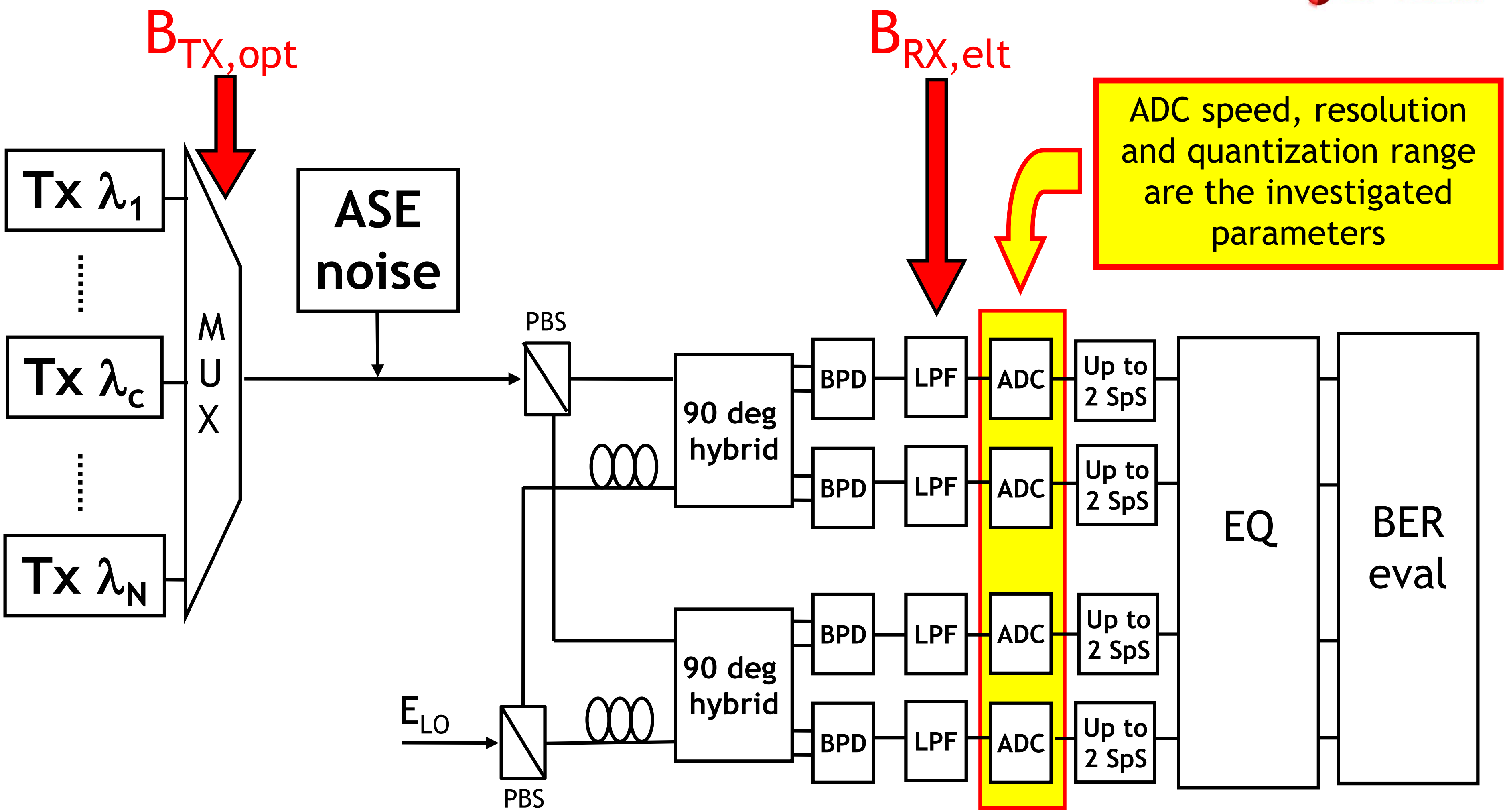


Equalizer updating and Symbol decision

- MIMO Equalizer
  - Ideal FIR with 15 taps
  - Updated through LMS
    - Training + Decision Driven
- Decision algorithms are specific for each format
  - PM-QPSK: single-threshold
  - PM-8QAM: maximum likelihood
  - PM-16QAM: multi-threshold

2. Receiver requirements

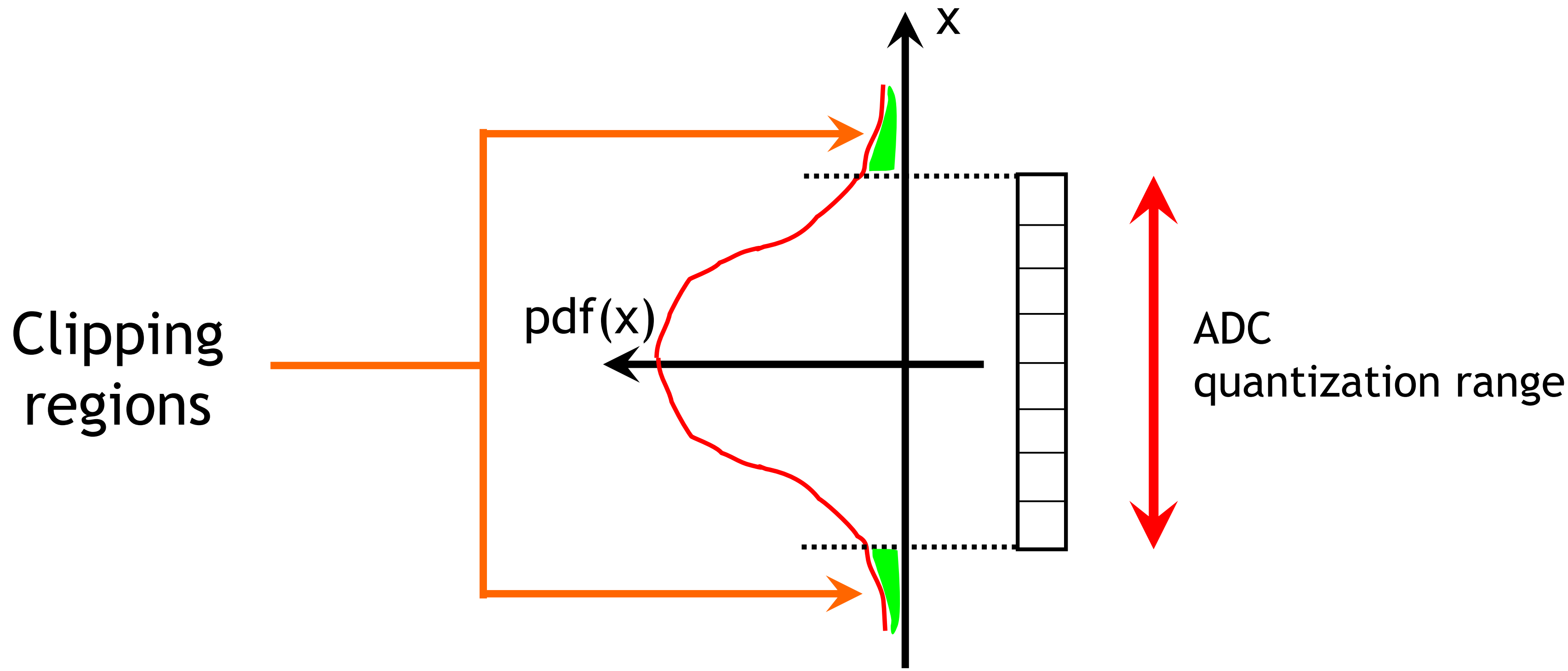
Optimization setup



Optimal bandwidths of
both Optical MUX and Electrical receiver filter
are dependent on ADC parameters

ADC quantization range

- After propagation, signal components have a gaussian-like distribution (see [A] P4.07 at ECOC 2010)



We define as clipping percentage the portion of samples left out of the ADC quantization range

[A] A. Carena, G. Bosco, V. Curri, P. Poggiolini, M. Tapia Taiba, F. Forghieri, “Statistical Characterization of PM-QPSK Signals after Propagation in Uncompensated Fiber Links”, in ECOC 2010 Proceedings, paper P4.07.

Clipping percentage

- We performed preliminary simulation in order to optimize the clipping percentage
- For all formats, in the range between 0.1% and 2%, performances does not change substantially at reference BER ($4 \cdot 10^{-3}$)

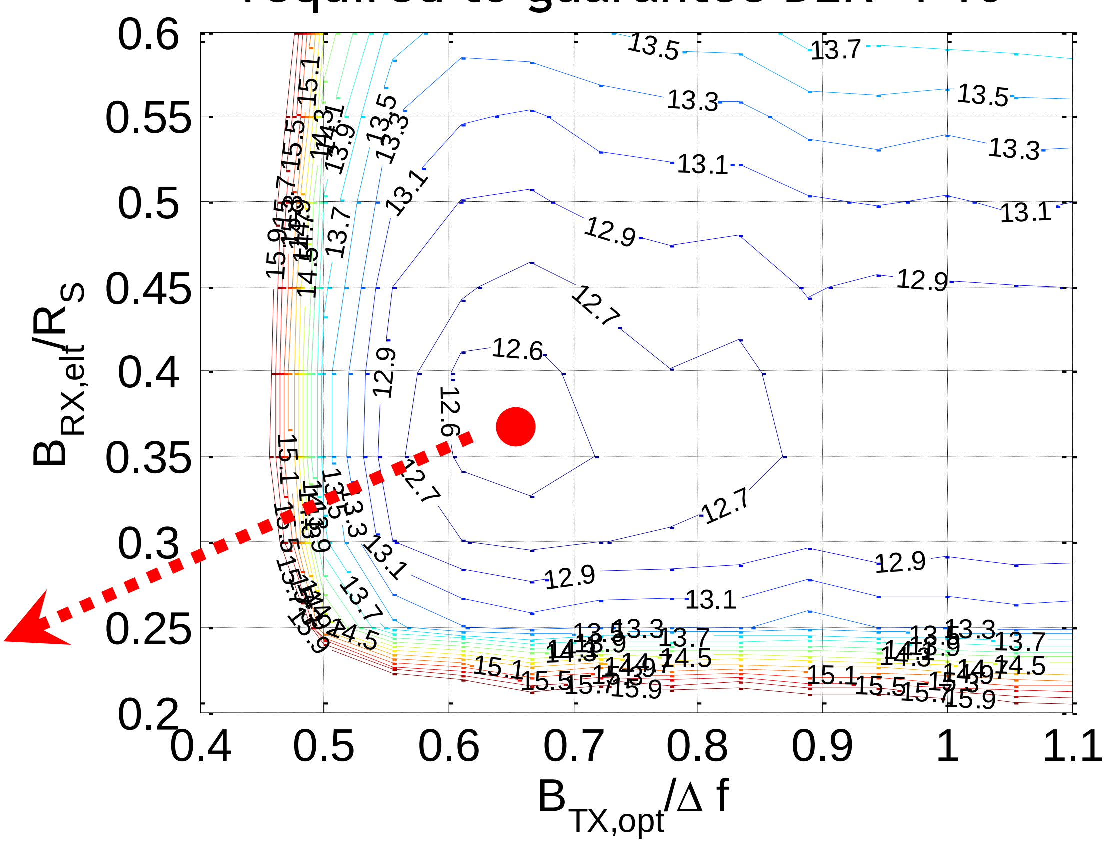
- For bandwidth optimization and non-linear analysis we have used the following clipping percentages:
  - 0.5% for PM-QPSK
  - 0.2% for both PM-8QAM and PM-16QAM

Optimization map

- For each modulation format
- ADC Speed ➔ SpS=[2.00 1.67 1.43 1.25 1.11]
- ADC Resolution ➔ N_{bit}=[4 5 6 7]

PM-QPSK
SpS=1.25
N_{bit}=4

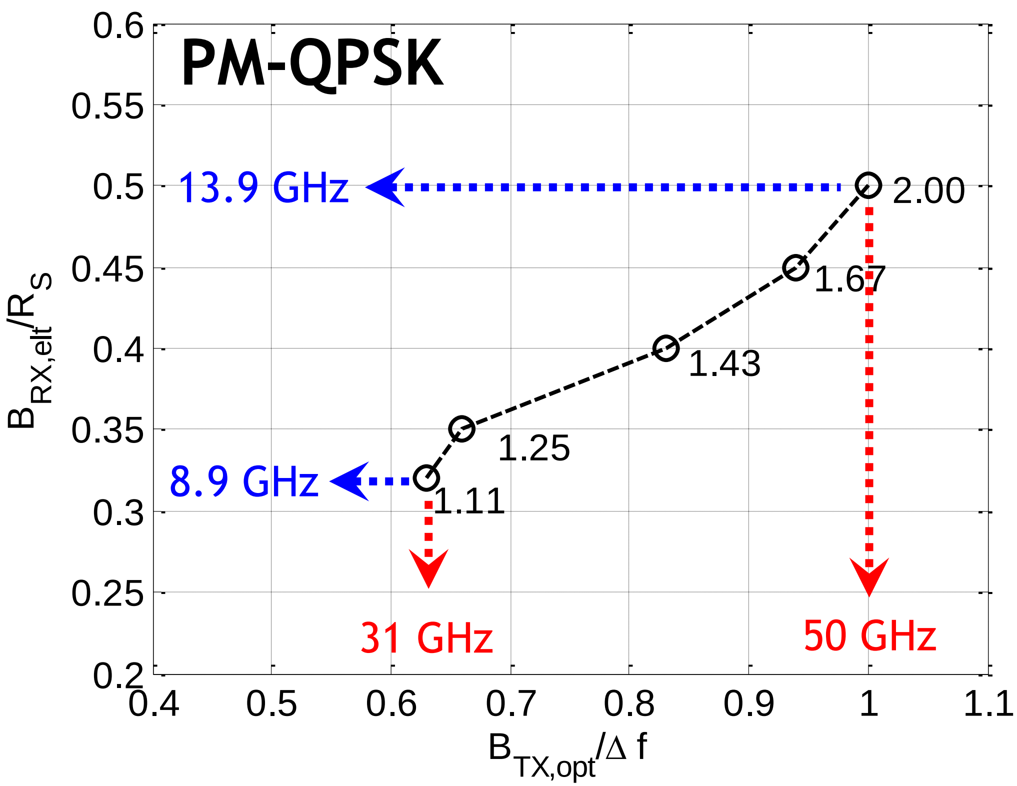
Contour plot of OSNR (in 0.1 nm) required to guarantee BER=$4 \cdot 10^{-3}$



$B_{TX,opt}$=33 GHz
$B_{RX,elt}$=9.8 GHz

Optimum bandwidths

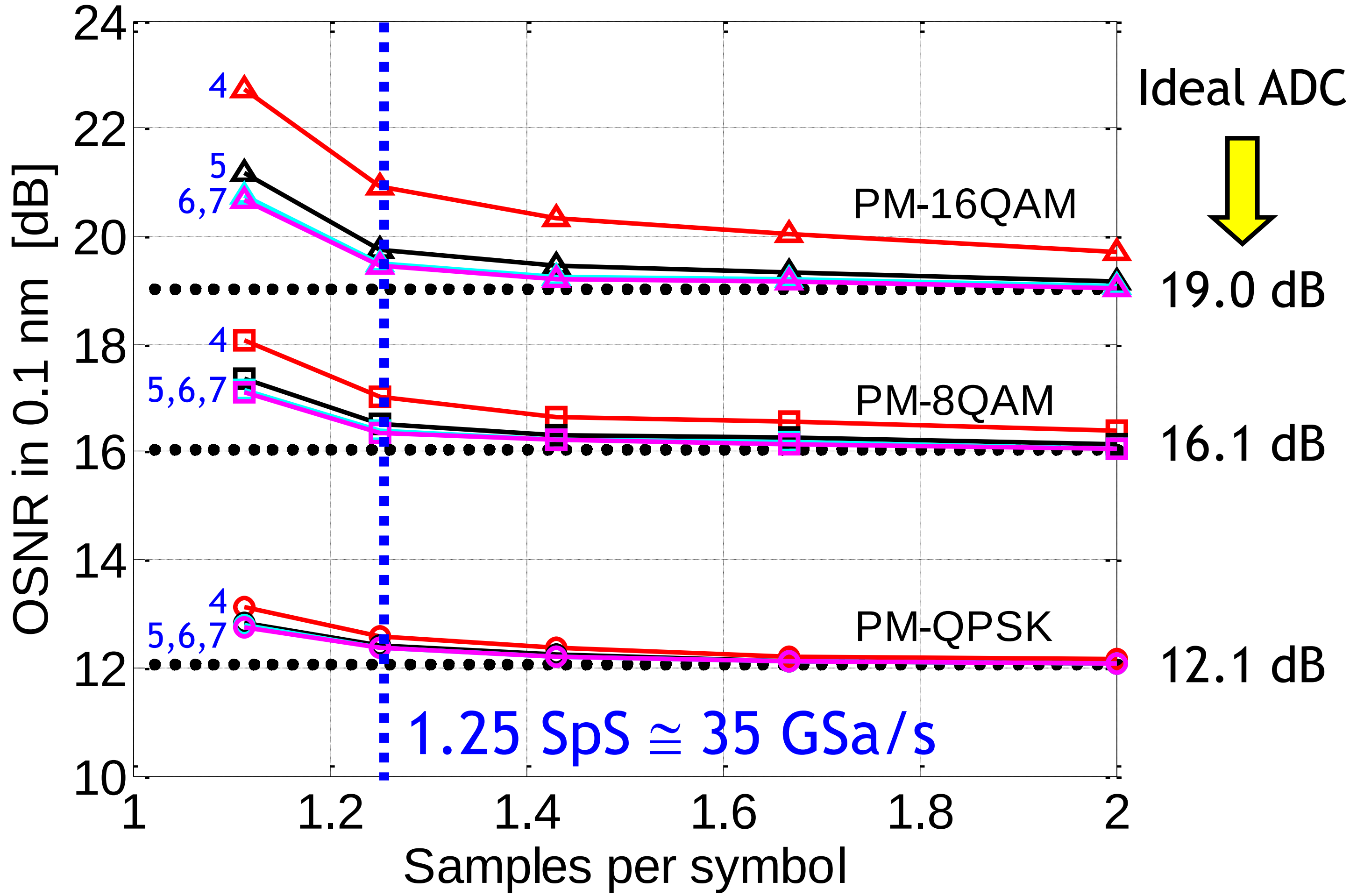
- Bandwidths optimization results did not show any dependence on ADC resolution



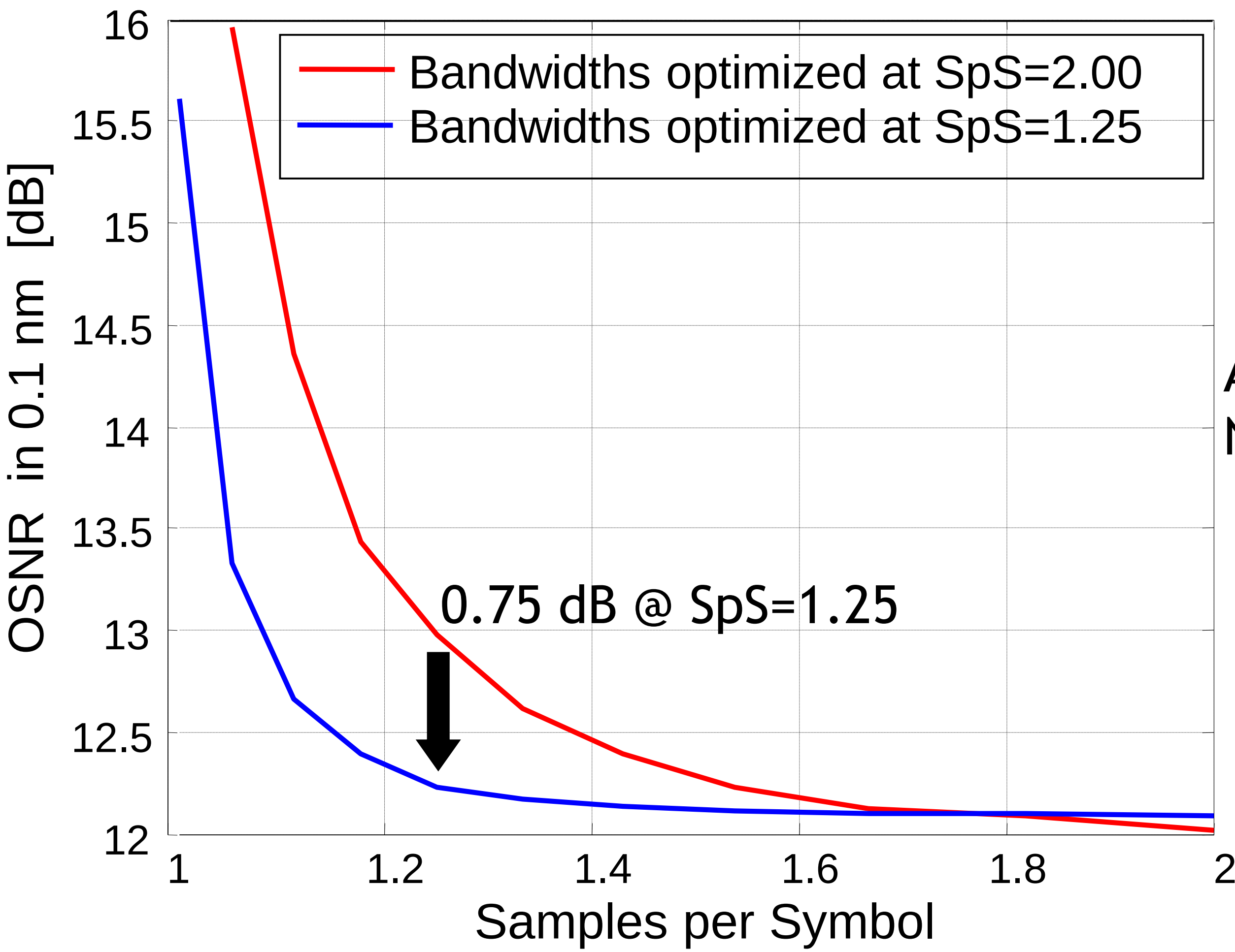
- Reducing ADC speed introduces aliasing in the system, that can be neutralized with tighter filtering

Back-to-Back performance

- We measured the OSNR (in 0.1 nm) required to guarantee BER=$4 \cdot 10^{-3}$



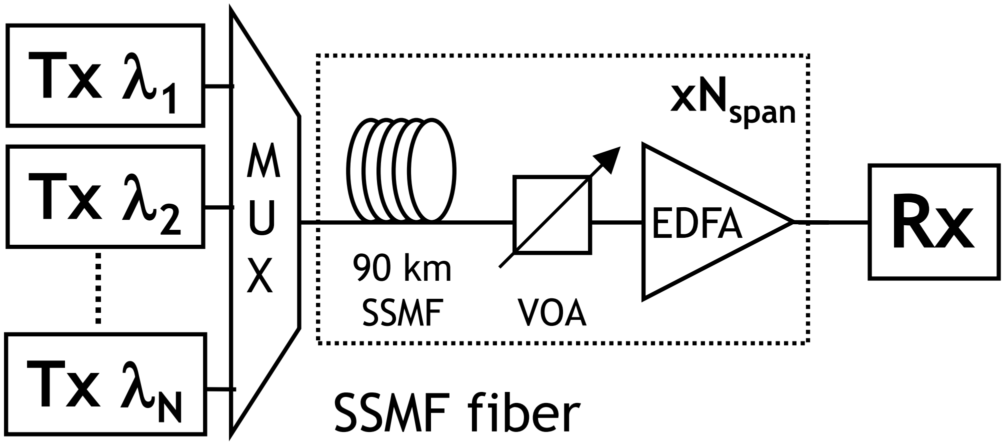
What if you do not properly optimize?



ADC resolution

N_{bit}=7

Maximum reach evaluation



WDM
Δf=50 GHz

SSMF fiber

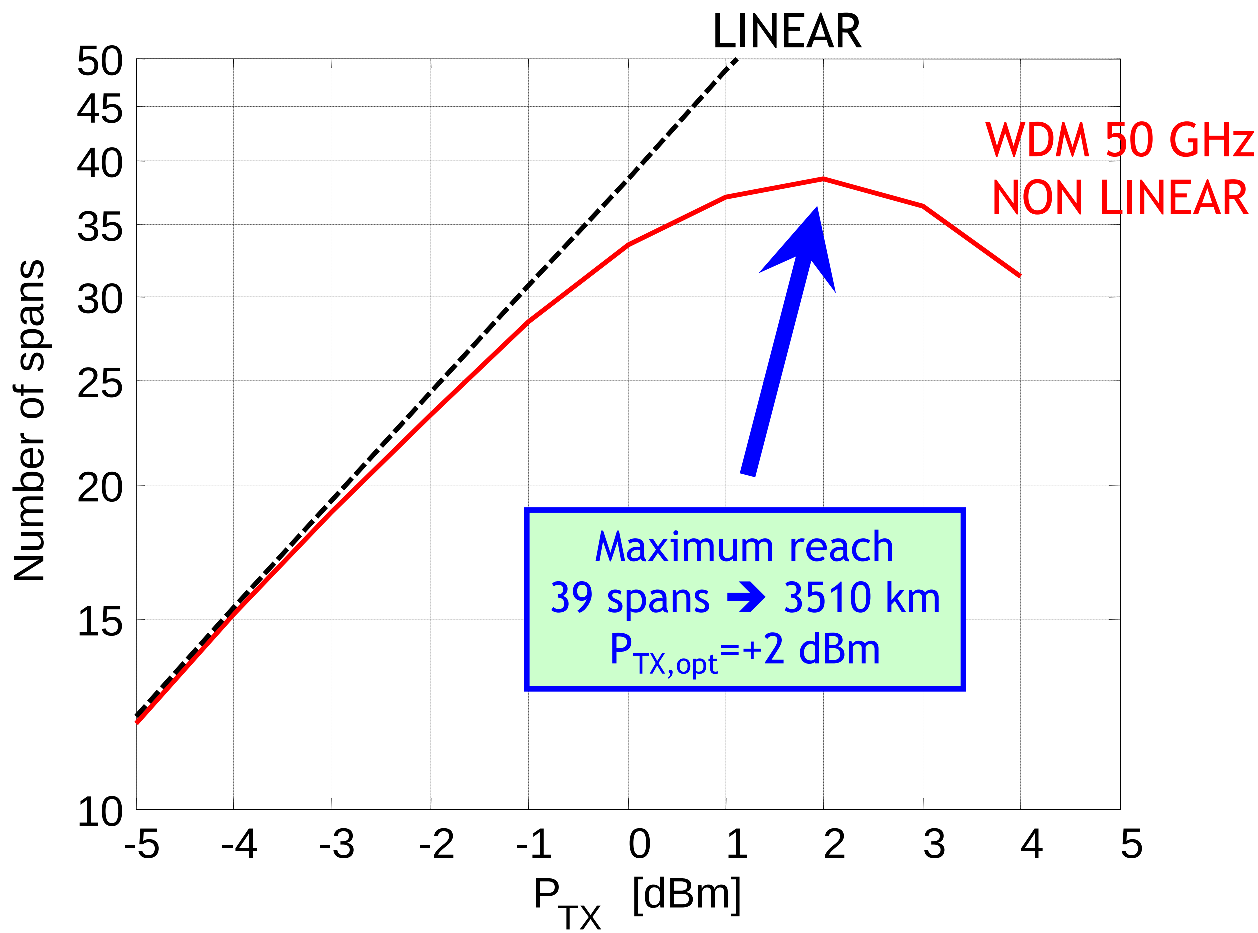
- D=16.7 ps/nm/km
- α=0.22 dB/km
- γ=1.3 1/W/km

EDFA
F=6 dB

- Uncompensated link
- Span budget: 25 dB
- Optimal filter bandwidths
- We look for maximum reach at BER target, optimizing the launch power

Launch power optimization

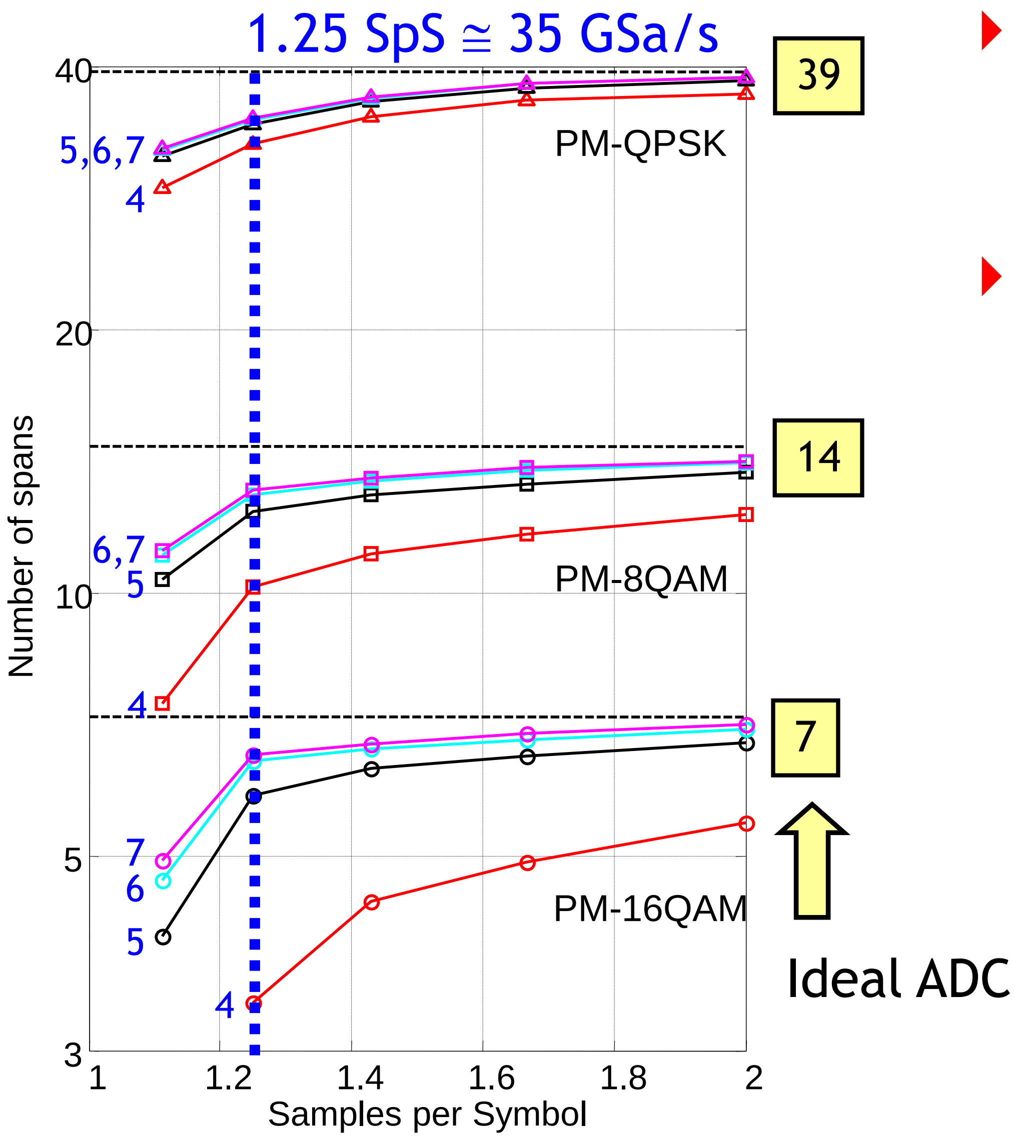
PM-QPSK
SpS=2.00
N_{bit}=7



Maximum reach
39 spans ➔ 3510 km
$P_{TX,opt}$=+2 dBm

Optimum launch power is not dependent on ADC speed and resolution

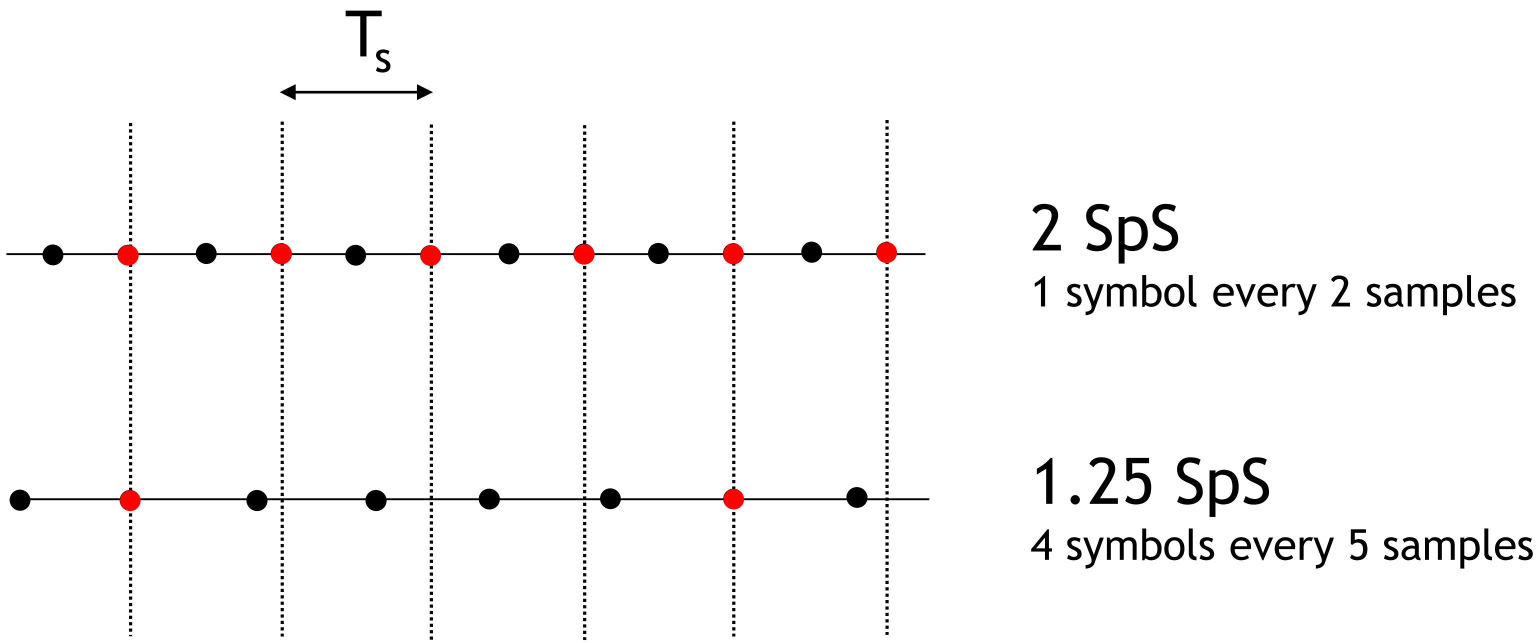
Maximum reach comparison



- Reach reduction is only due to poorer back-to-back performance
- Assuming to work with SpS=1.25 and using N_{bit}=5 we get:

	Capacity in C band [Tbps]	Reach	
		Span	Length [km]
PM-QPSK	8	35	3150
PM-8QAM	12	12	1080
PM-16QAM	16	6	540

DSP running at 1.25 SpS



Equalizer update performed only on RED points:

- at 2 SpS EQ is updated every 2 samples
- at 1.25 SpS EQ is updated every 5 samples

DSP running at 1.25 SpS: penalty?

- Back-to-Back performance
  - Sampling at 1.25 SpS
    - with DSP running at 2.00 SpS → 12.25 dB
    - with DSP running at 1.25 SpS → 12.40 dB

      0.15 dB penalty

- Maximum Reach with 7 bit ADC resolution is 35 spans in both cases

3. Mitigation of non-linear effects

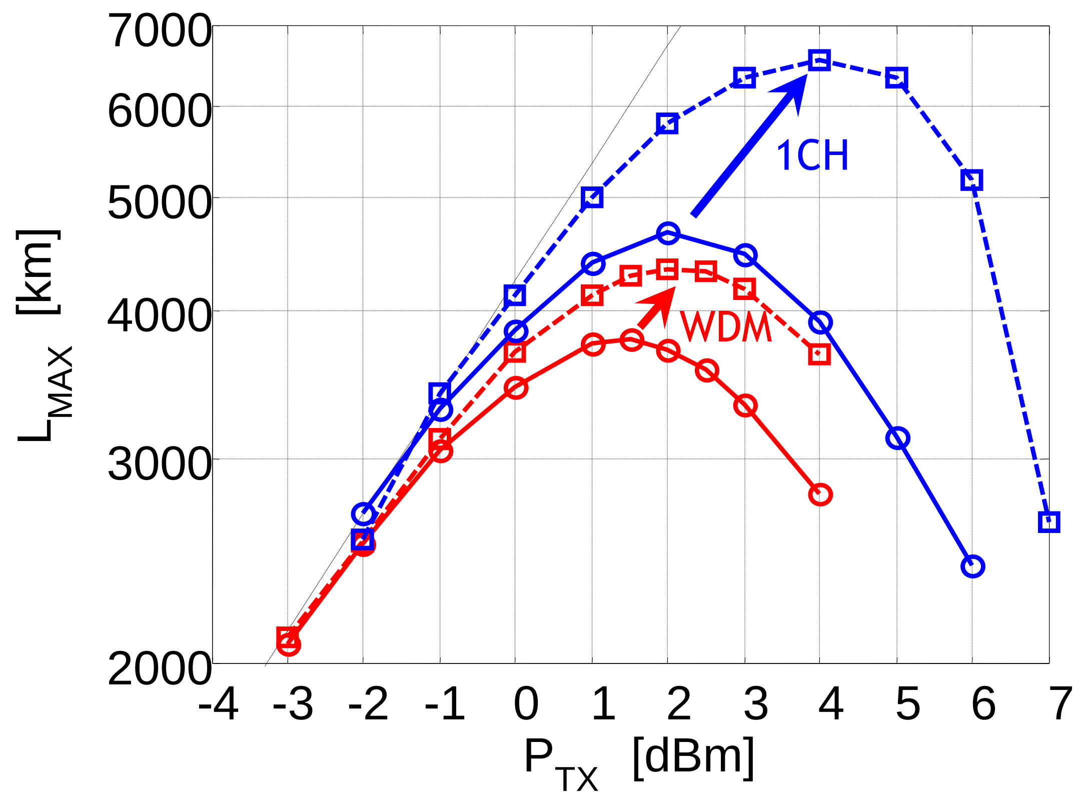
A digital approach

- Coherent receiver can take advantage of DSP also to compensate for non-linear effects
- Several approaches: all very effective on single channel
- **Complexity is a major issue…**

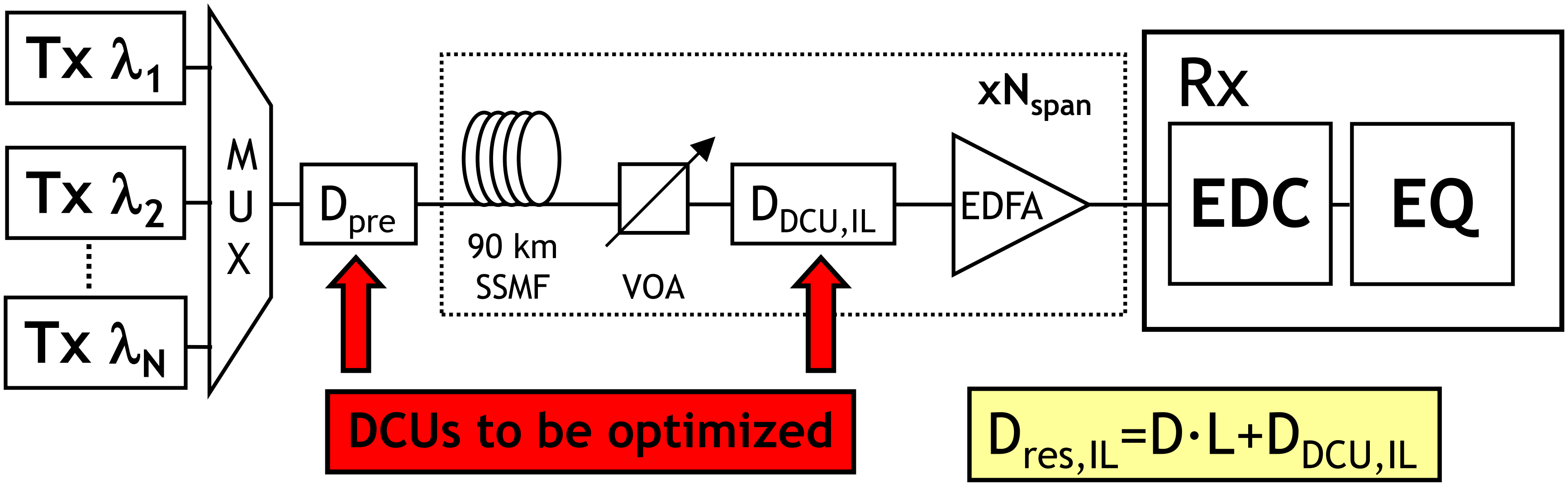
PM-QPSK
Backward Propagation
(1 step per span)

1CH
Improve from 52 to 72 spans ➔ 1.4 dB

WDM
Improve from 39 to 47 spans ➔ 0.8 dB



Dispersion management

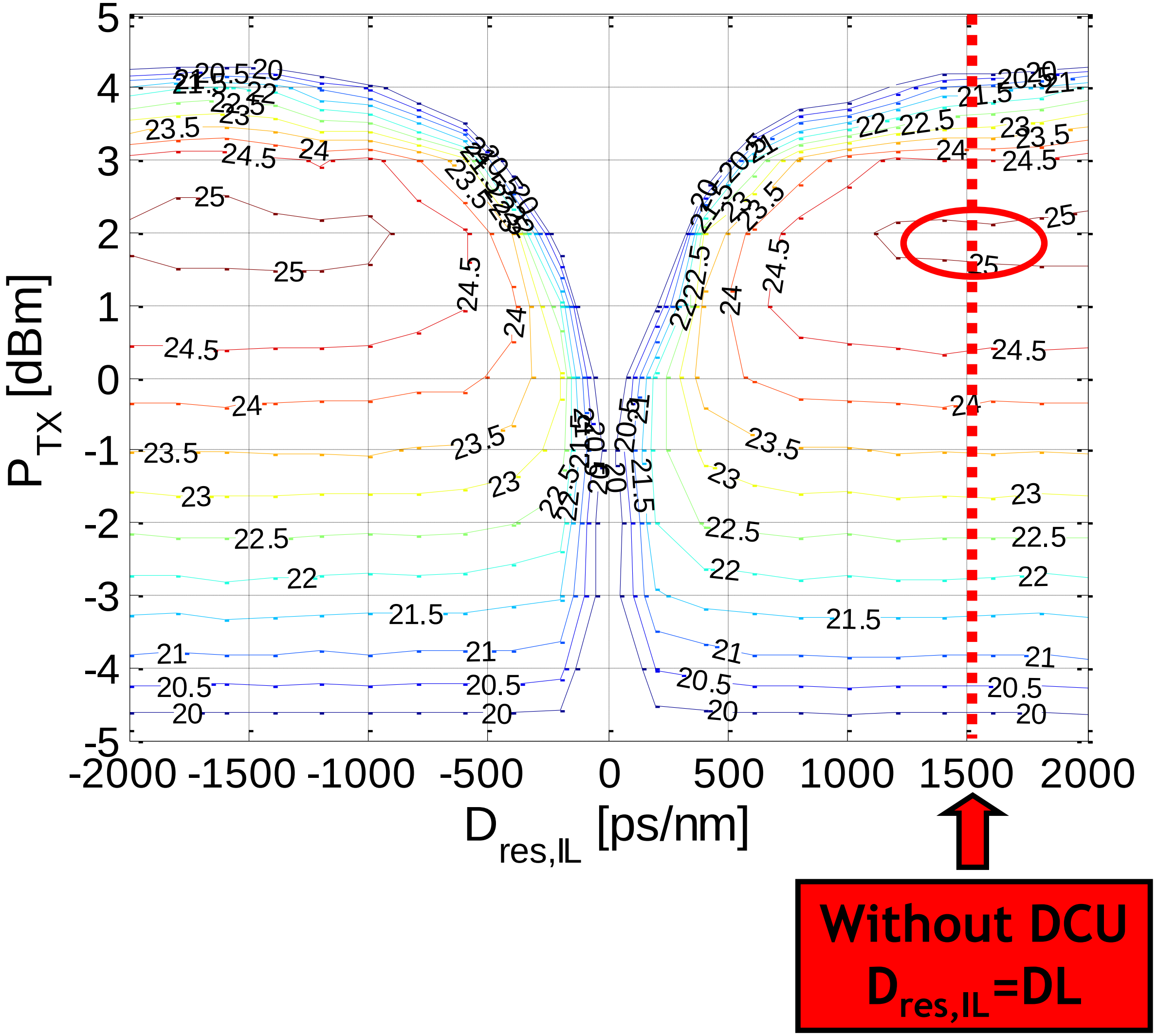


- EDC is set to fully compensate total residue
- Pre-compensation does not give any substantial advantage (see [B]) ➔ D_{pre}=0 ps/nm
- We carried out joint launch power and in-line residue ($D_{res,IL}$) optimization, looking for maximum Span Budget

[B] V. Curri, P. Poggiolini, A. Carena, and F. Forghieri, "Performance analysis of coherent 222 Gb/s NRZ PM-16QAM WDM systems over long-haul links," IEEE Photonics Technology Letters, vol. 22, no. 5, pp. 266–268, Mar. 1, 2010.

PM-QPSK – N_{span}=39

Contour plot of Span Budget
giving BER=$4 \cdot 10^{-3}$



Contour plot of Span Budget

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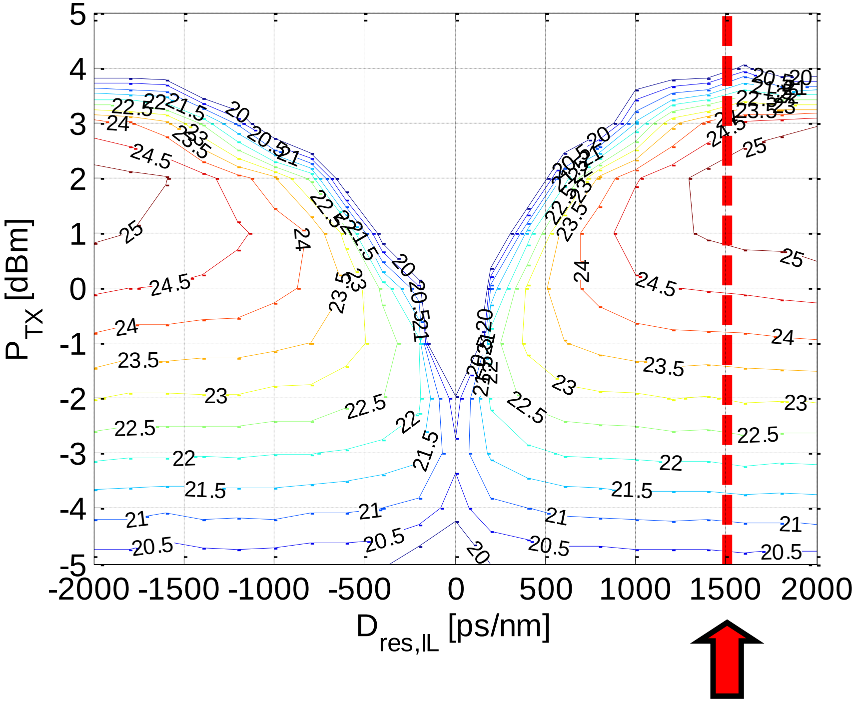
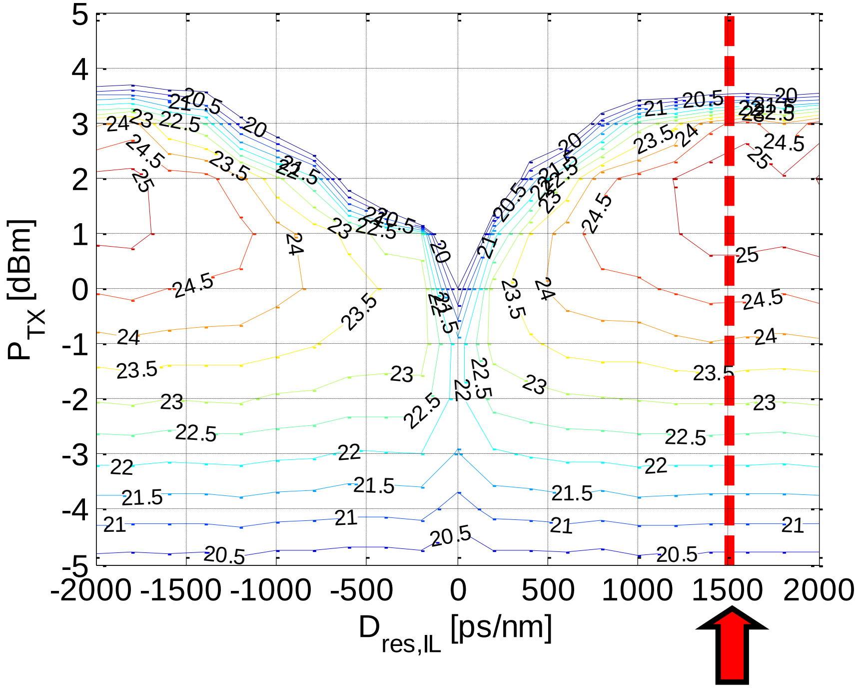
PM-8QAM - N_{span}=14



Without DCU
$D_{res,IL}$=DL

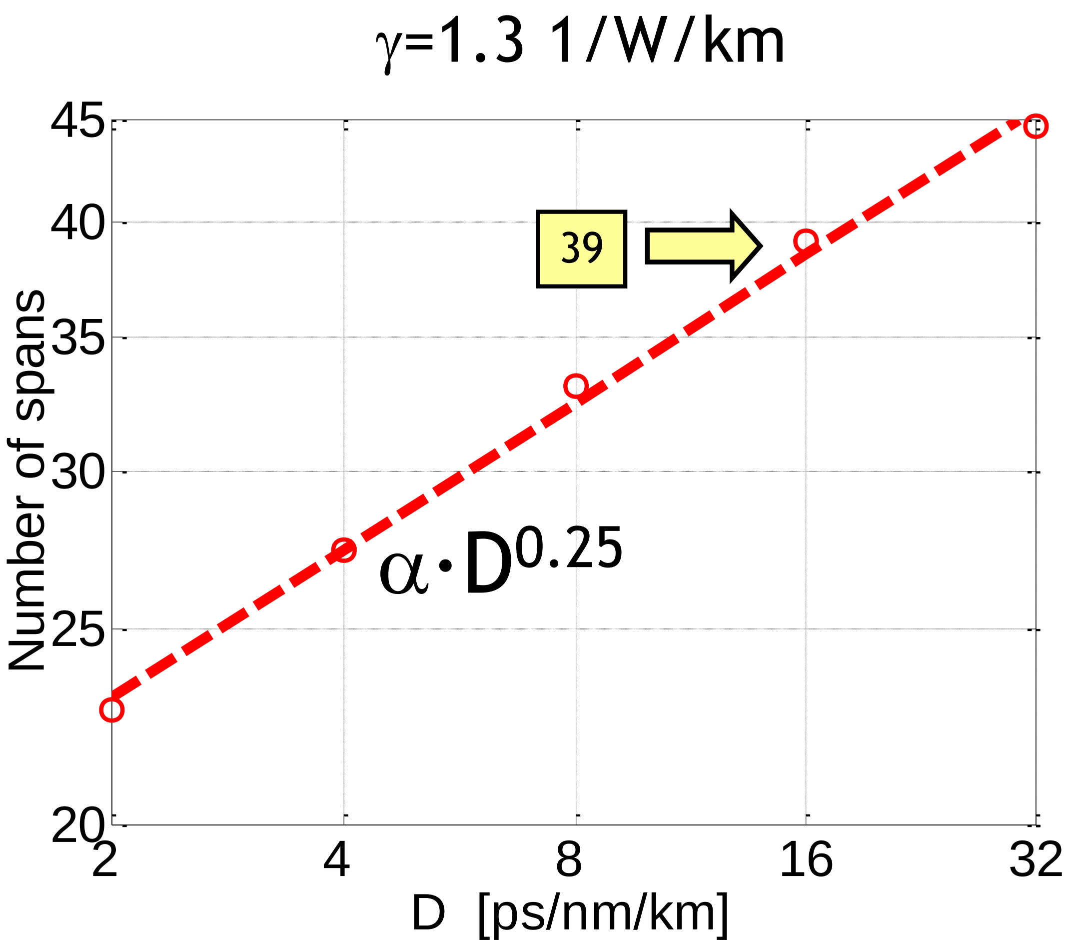
PM-16QAM - N_{span}=7



Without DCU
$D_{res,IL}$=DL

New fibers

- New fibers, PSCF in particular, show lower γ, lower α and typically higher dispersion
- Reducing γ obviously improves the performance
- Which is the merit of the dispersion itself? For details see [C].



[C] V. Curri, P. Poggiolini, G.Bosco, A. Carena, and F. Forghieri, "Performance Evaluation of Long-Haul 111 Gb/s PM-QPSK Transmission Over Different Fiber Types," IEEE Photonics Technology Letters, vol. 22, no. 19, pp. 1446-14488, Oct.1, 2010.

4. Conclusions

- RECEIVER REQUIREMENTS
  - ADC speed: using only 1.25 SpS (35 GSa/s) does not cause a substantial penalty
  - ADC resolution: 5 bits are enough
    - 6 bits is better for PM-16QAM
  - Electrical bandwidth: 10 GHz are enough

- NON-LINEAR MITIGATION
  - Ready
    - Avoid in-line compensation
    - New fibers with high dispersion (and low non-linearity)
  - To come
    - Digital approaches

Acknowledgments

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The simulator OptSim was supplied by RSoft Design Group Inc.