Performance Evaluation of Coherent PS-QPSK (HEXA) Modulation

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SPPCom 2011 - paper SPTuB2

Outline

- Four-dimensional constellations
- Transmitter and receiver architecture
- Back-to-back performance
- Long-haul transmission
- Experimental demonstrations
- Conclusions

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- **Four-dimensional constellations**
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Four-dimensional space

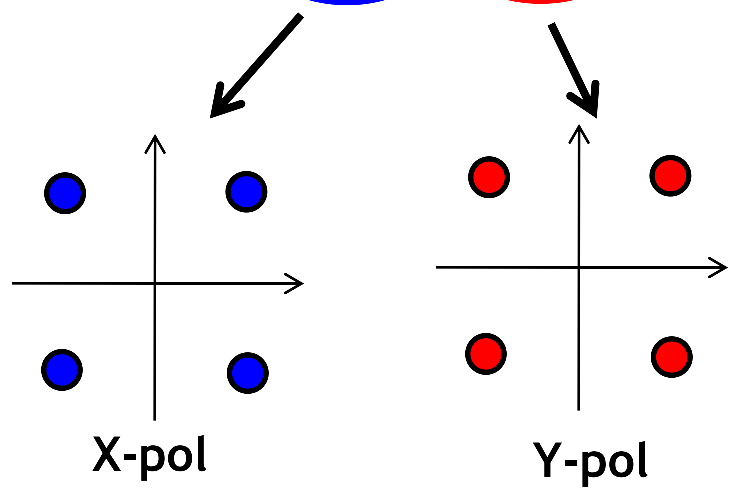
- Coherent detection permits to exploit the four-dimensional (4D) signal space consisting of the in-phase and quadrature components of the two polarizations of the electromagnetic field.
- Polarization-multiplexed QPSK (PM-QPSK) is an example of 4D constellation composed of 16 points.
- The constellation vectors are formed from real and imaginary parts of the electromagnetic field’s X and Y polarization components.

PM-QPSK coordinates in the 4D space

$$s_1 = (-1,-1,-1,-1) \qquad s_9 = (+1,-1,-1,-1)$$
$$s_2 = (-1,-1,-1,+1) \qquad s_{10} = (+1,-1,-1,+1)$$
$$s_3 = (-1,-1,+1,-1) \qquad s_{11} = (+1,-1,+1,-1)$$
$$s_4 = (-1,-1,+1,+1) \qquad s_{12} = (+1,-1,+1,+1)$$
$$s_5 = (-1,+1,-1,-1) \qquad s_{13} = (+1,+1,-1,-1)$$
$$s_6 = (-1,+1,-1,+1) \qquad s_{14} = (+1,+1,-1,+1)$$
$$s_7 = (-1,+1,+1,-1) \qquad s_{15} = (+1,+1,+1,-1)$$
$$s_8 = (-1,+1,+1,+1) \qquad s_{16} = (+1,+1,+1,+1)$$

- These coordinates correspond to the vertices of a 4D “hypercube”

$$s_i = (\pm 1, \pm 1, \pm 1, \pm 1)$$

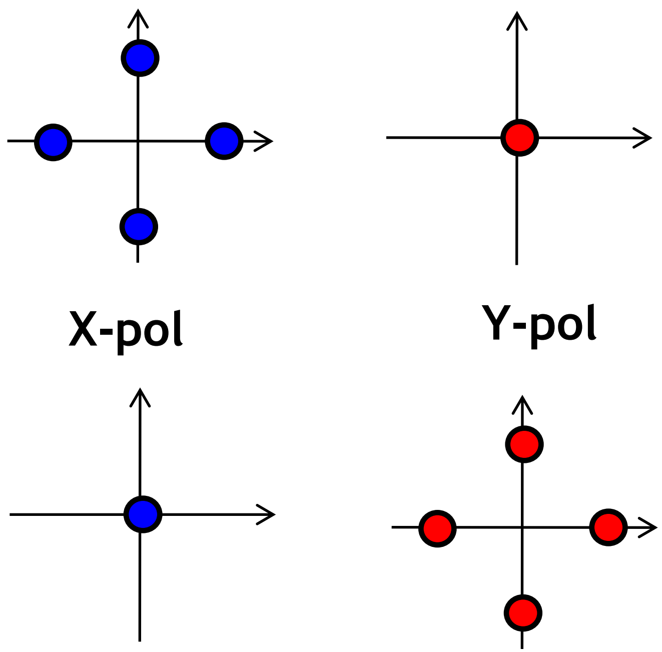


PS-QPSK coordinates in the 4D space

- PS-QPSK is 4D constellation composed of 8 points:

$$s_1 = (-2,0,0,0)$$
$$s_2 = (+2,0,0,0)$$
$$s_3 = (0,-2,0,0)$$
$$s_4 = (0,+2,0,0)$$
$$s_5 = (0,0,-2,0)$$
$$s_6 = (0,0,+2,0)$$
$$s_7 = (0,0,0,-2)$$
$$s_8 = (0,0,0,+2)$$

- Only one polarization at a time is transmitted
  → **polarization-switched QPSK**



- These coordinates correspond to the vertices of a 4D polychoron called "hexadecachoron" → **HEXA**

PS-QPSK coordinates in the 4D space

$$s_1 = (-2,0,0,0)$$
$$s_2 = (+2,0,0,0)$$
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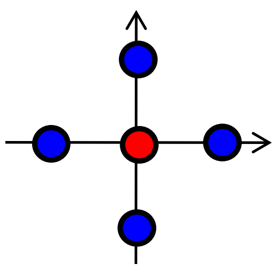
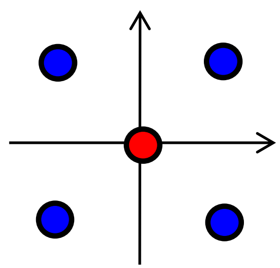


45° phase rotation

$$s_1 = \sqrt{2}(-1,-1,0,0)$$
$$s_2 = \sqrt{2}(-1,+1,0,0)$$
$$s_3 = \sqrt{2}(+1,-1,0,0)$$
$$s_4 = \sqrt{2}(+1,+1,0,0)$$
$$s_5 = \sqrt{2}(0,0,-1,-1)$$
$$s_6 = \sqrt{2}(0,0,-1,+1)$$
$$s_7 = \sqrt{2}(0,0,+1,-1)$$
$$s_8 = \sqrt{2}(0,0,+1,+1)$$



45° Polarization rotation

$$s_1 = (-1,-1,-1,-1)$$
$$s_2 = (-1,-1,+1,+1)$$
$$s_3 = (-1,+1,-1,+1)$$
$$s_4 = (-1,+1,+1,-1)$$
$$s_5 = (+1,+1,+1,+1)$$
$$s_6 = (+1,+1,-1,-1)$$
$$s_7 = (+1,-1,+1,-1)$$
$$s_8 = (+1,-1,-1,+1)$$

Sub-set of PM-QPSK points

The origin of PS-QPSK …

- PS-QPSK was firstly introduced in 1991:
  - *S. Betti et al., “A novel multilevel coherent optical system: 4-quadrature signaling,” J. Lightw. Tehcnol., vol. 9, no. 4, pp. 514-523, Apr. 1991.*

- However, only recently it was demonstrated that PS-QPSK is the most power efficient format for coherent uncoded optical systems, with an asymptotic gain of 1.76 dB w.r.t. PM-BPSK and PM-QPSK.
  - *M. Karlsson and E. Agrell, “Which is the most power efficient modulation format in optical links?”, Optics Express, vol. 17, no. 13, pp.10814-10819, Jun. 2009.*

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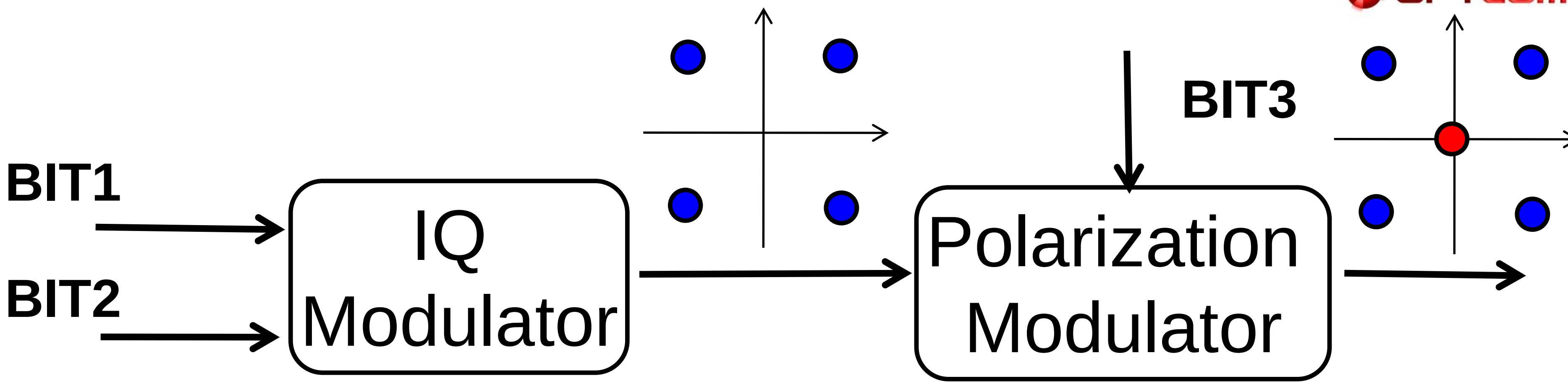
Transmitter architecture



Sub-set of PM-QPSK points

$$s_1 = (-1,-1,-1,-1)$$
$$s_2 = (-1,-1,+1,+1)$$
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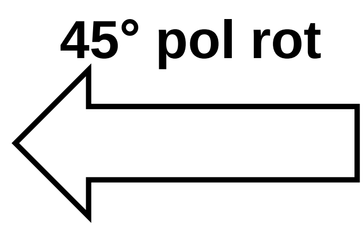
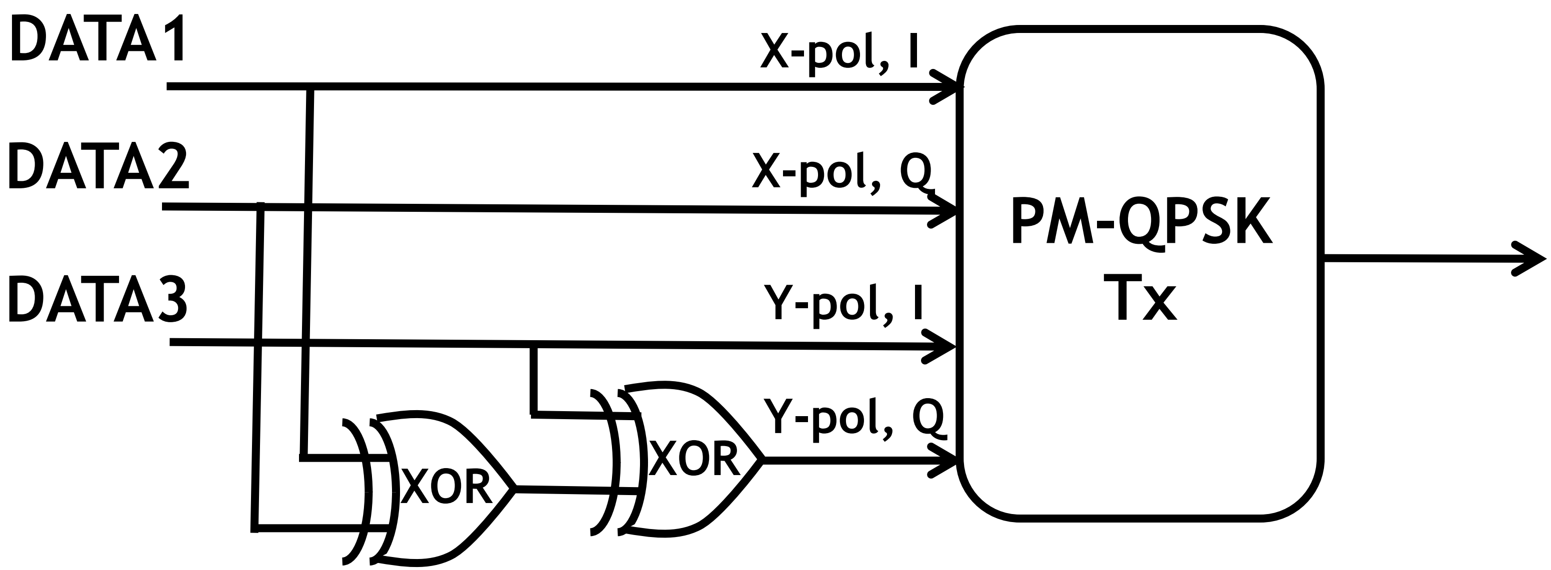


$$s_1 = \sqrt{2}(-1,-1,0,0)$$
$$s_2 = \sqrt{2}(-1,+1,0,0)$$
$$s_3 = \sqrt{2}(+1,-1,0,0)$$
$$s_4 = \sqrt{2}(+1,+1,0,0)$$
$$s_5 = \sqrt{2}(0,0,-1,-1)$$
$$s_6 = \sqrt{2}(0,0,-1,+1)$$
$$s_7 = \sqrt{2}(0,0,+1,-1)$$
$$s_8 = \sqrt{2}(0,0,+1,+1)$$

Alternative Tx architecture

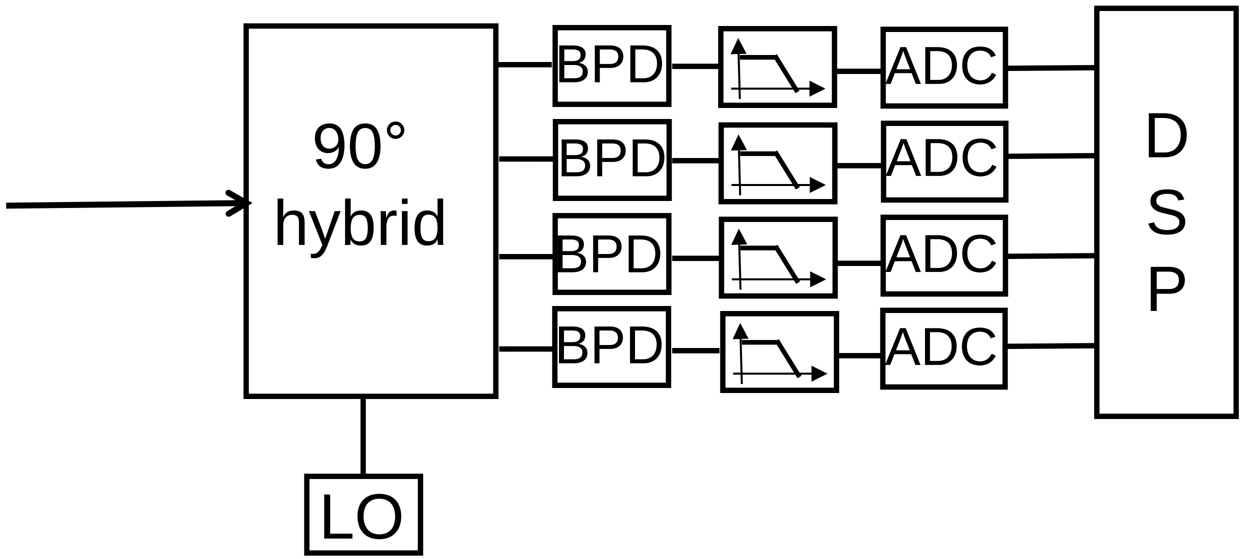


Same complexity as PM-QPSK Tx (+ 2 logical gates)

- *M. Karlsson and E. Agrell, “Which is the most power efficient modulation format in optical links?”, Optics Express, vol. 17, no. 13, pp.10814-10819, 22 Jun. 2009.*

Receiver architecture

- A standard coherent Rx is used to extract the four components of the electrical field.



- The only difference w.r.t. a PM-QPSK receiver is in the DSP section.

Receiver DSP

- Standard LMS algorithm
  - Initialized using a training sequence

- Modified CMA algorithm
  - Blind equalization

  - *P. Johannison et al., "Modified constant-modulus algorithm for polarization-switched QPSK", Optics Express, vol. 19, no.8, pp. 7734-7741, 11 Apr. 2011.*
  - *D.S. Millar, S.J. Savory, "Blind adaptive equalization of polarization-switched QPSK modulation", Optics Express, vol. 19, no.9, pp.8533-8538, 25 Apr. 2011.*
  - *P.Johannison, M. Sjödin, M. Karlsson, "A Modified CMA for PS-QPSK", SPPCom 2011, paper SPTuB3, Jun. 2011.*

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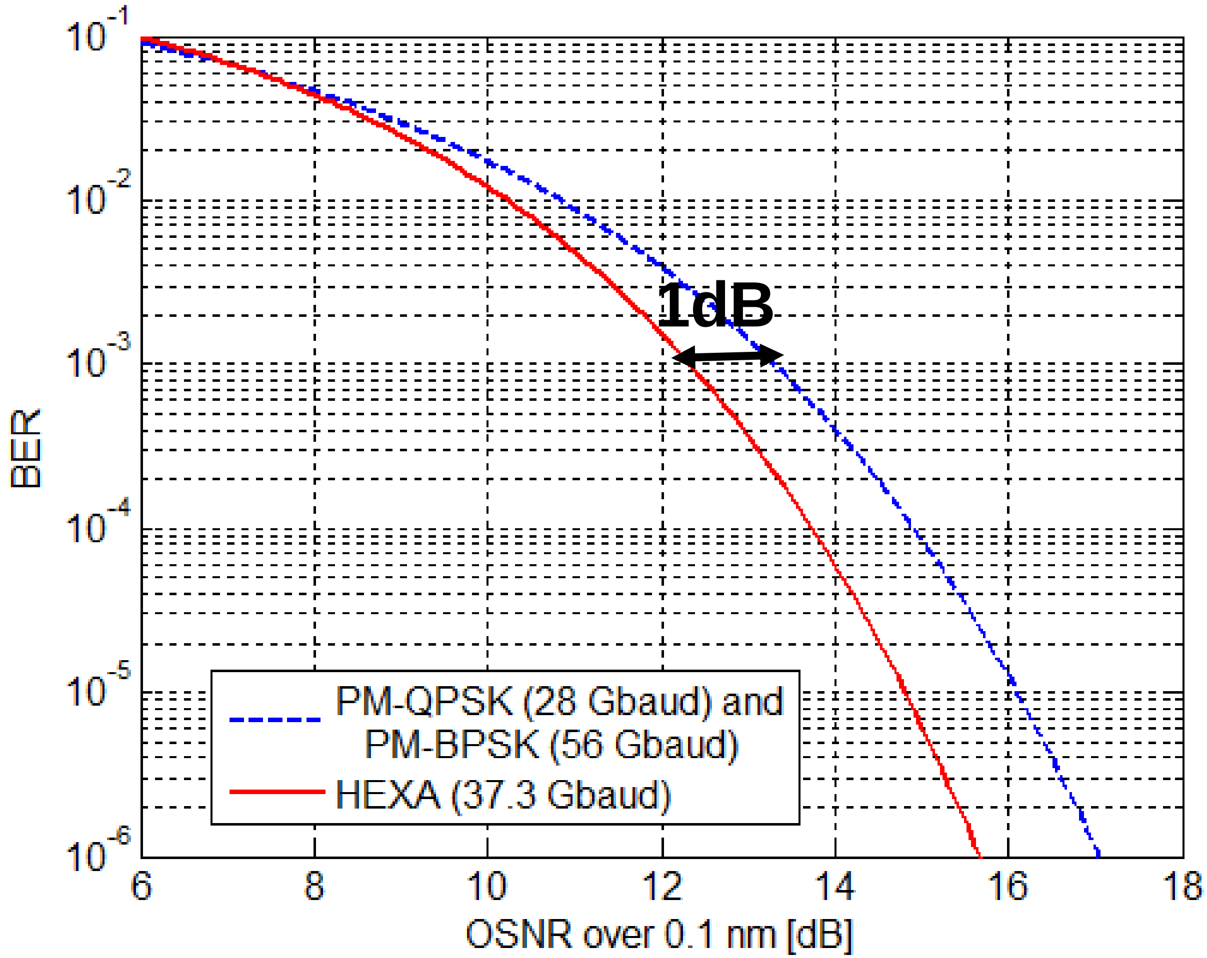
Comparison at fixed bit-rate

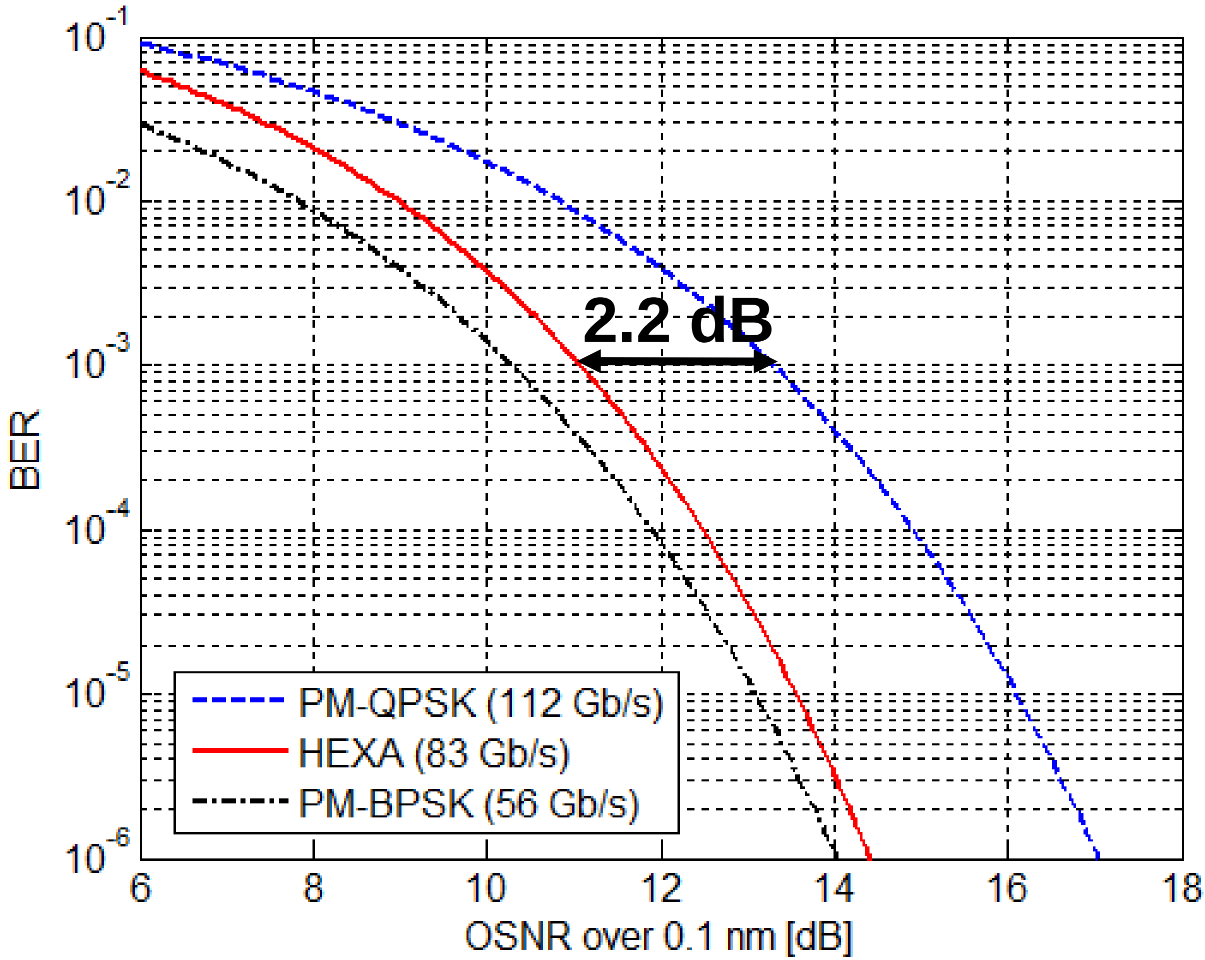
- R_b = 112 Gb/s



1.76-dB asymptotic gain of PS-QPSK (HEXA)over PM-QPSK

Comparison at fixed symbol-rate

- R_s = 28 Gbaud



Flexible transceiver which can switch "on-the-fly" from PM-QPSK to HEXA when channel conditions degrade.

3-dB asymptotic gain of PS-QPSK (HEXA) over PM-QPSK

Comments

- At a reference BER of 10^{-3}, the gain of PS-QPSK w.r.t. PM-QPSK is 1 dB when working at the same bit-rate and 2.2 dB when working at the same symbol-rate.

- **Is the potential gain over PM-QPSK maintained also after long-haul non-linear propagation?**

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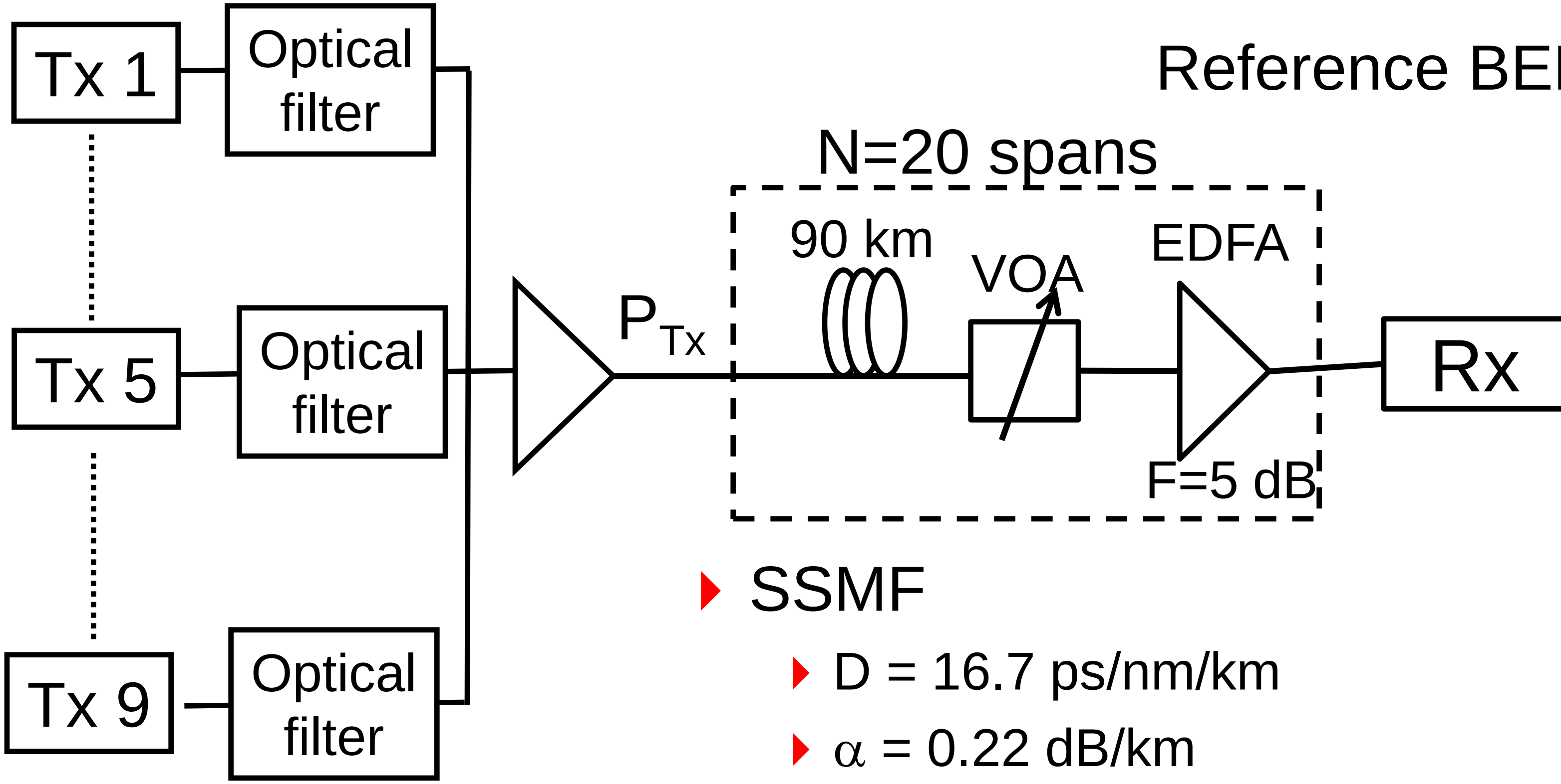
Analyzed system setup

Reference BER: 10^{-3}

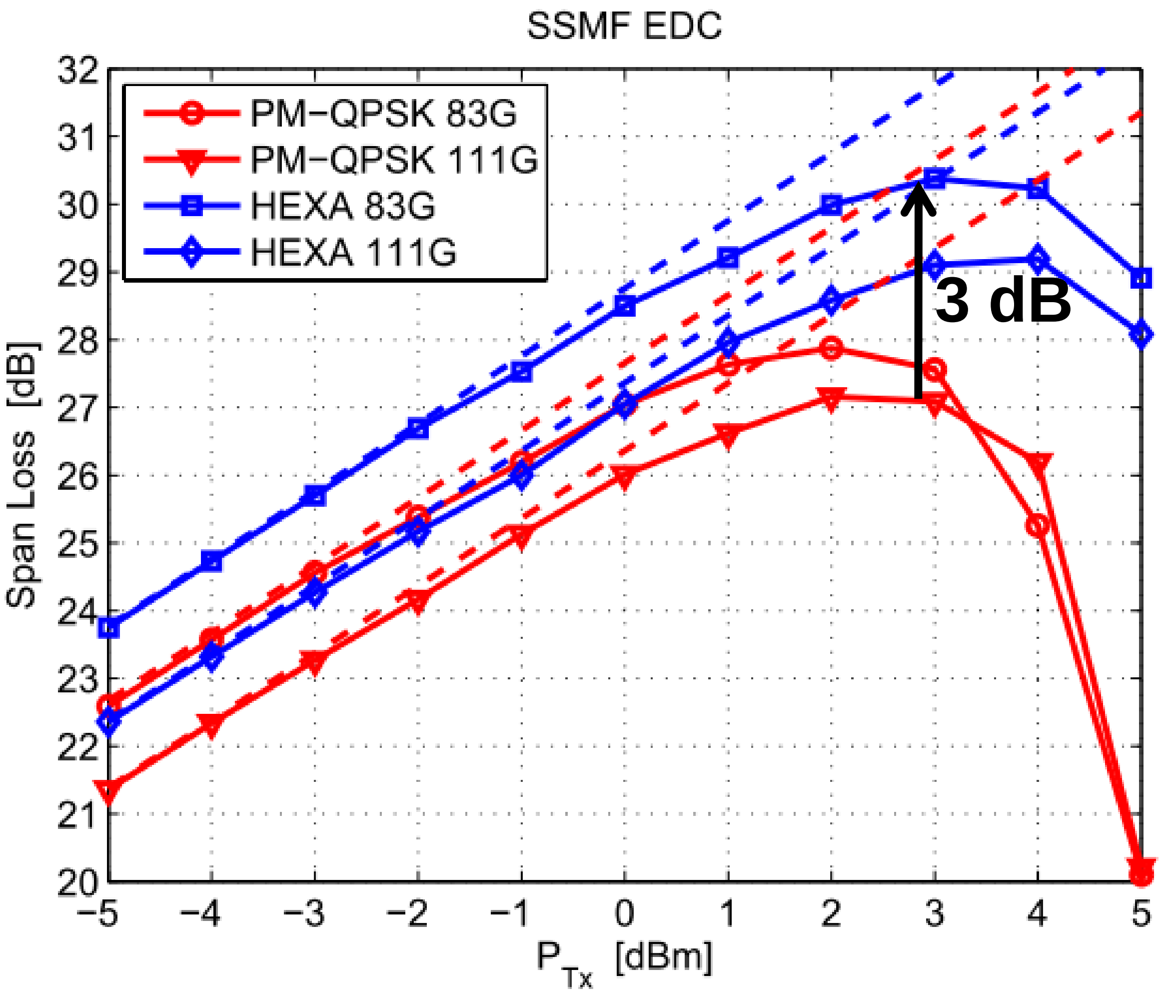


Δf=50 GHz

2nd order Supergaussian with 40-GHz bandwidth

- SSMF
  - D = 16.7 ps/nm/km
  - α = 0.22 dB/km
  - γ = 1.3 1/w/km
- NZDSF
  - D = 3.8 ps/nm/km
  - α = 0.22 dB/km
  - γ = 1.5 1/w/km

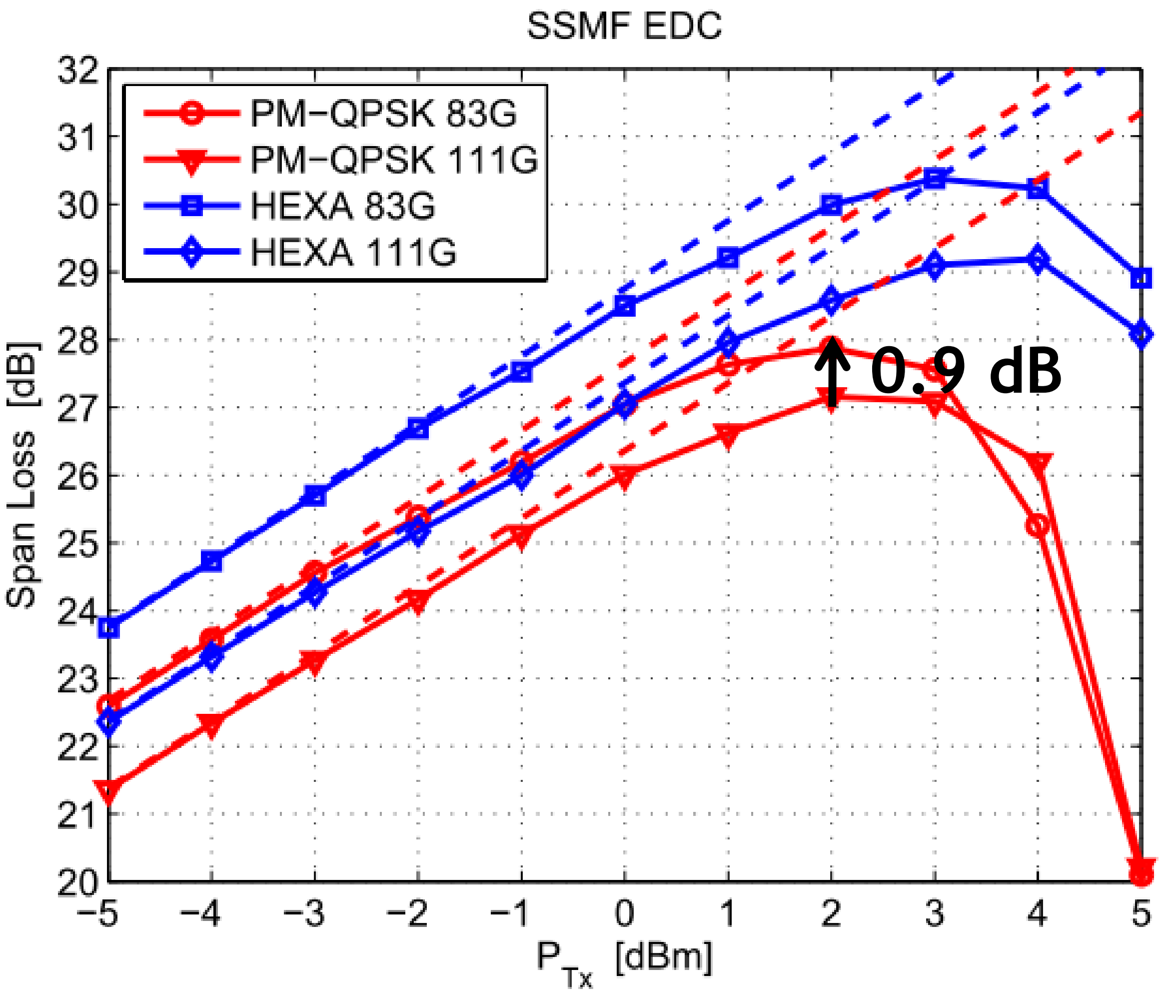
SSMF fiber



- Switching on-the-fly from 111 Gb/s PM-QPSK to 83 Gb/s PS-QPSK (HEXA) at a constant 27.75 Gbaud provides a very substantial increase in loss margin (3 dB or higher).

- *P. Poggiolini et al., "Performance evaluation of coherent WDM PS-QPSK (HEXA) accounting for non-linear fiber propagation effects", Optics Express, vol.18, no.11, May 2010, p. 11360.*

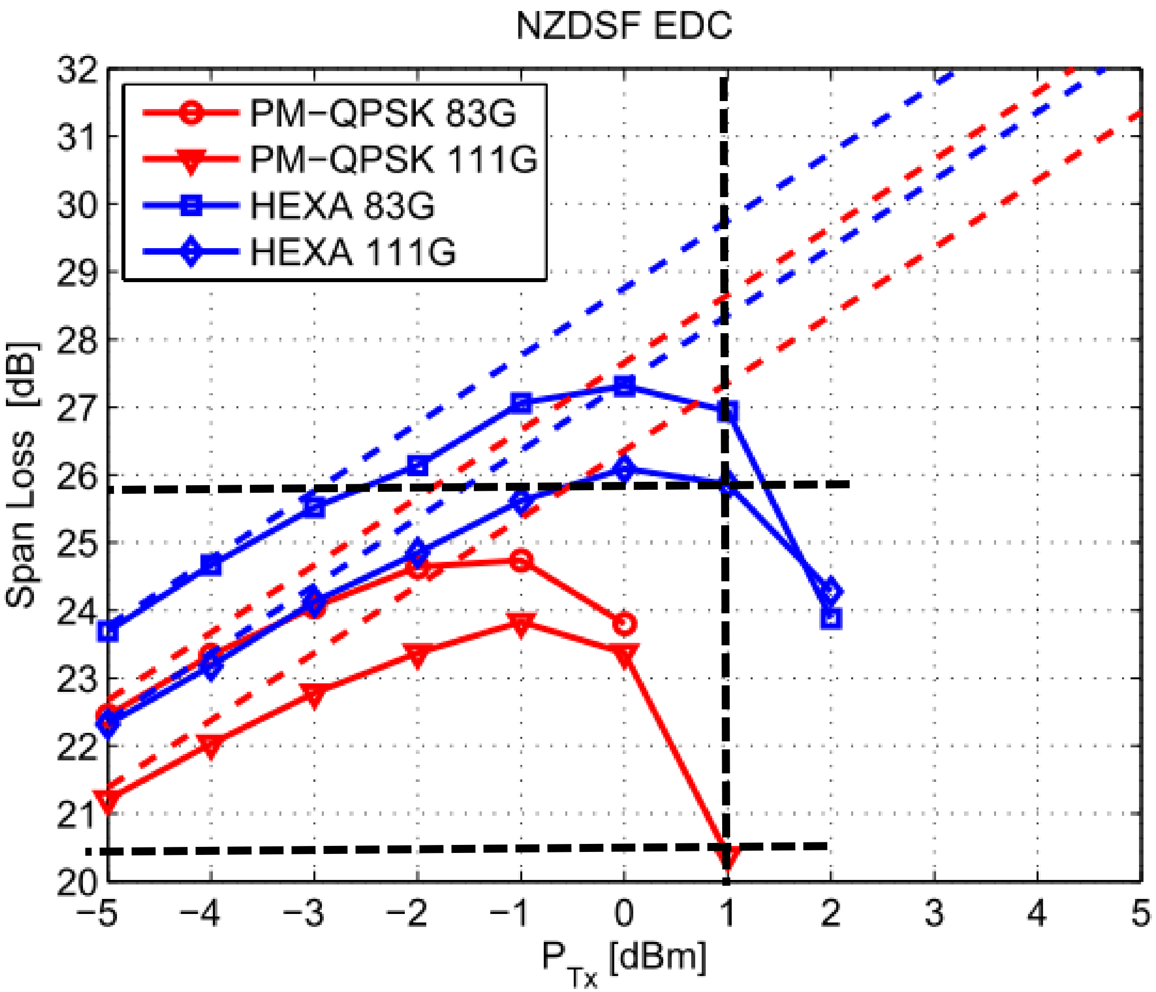
SSMF fiber



- Simply reducing the PM-QPSK bit-rate down to the same 83 Gb/s does not nearly yield the same margin increase (1 dB or less is gained, only).

- *P. Poggiolini et al., “Performance evaluation of coherent WDM PS-QPSK (HEXA) accounting for non-linear fiber propagation effects”, Optics Express, vol.18, no.11, May 2010, p. 11360.*

NZDSF fiber



- 111 Gb/s HEXA can handle up to 1 dBm of P_{TX}, with a tolerated span loss of almost 26 dB
- 111 Gb/s PM-QPSK, at the same launch power, is heavily impacted by non-linearity and its tolerated span loss is only about 20.5 dB.

- *P. Poggiolini et al., “Performance evaluation of coherent WDM PS-QPSK (HEXA) accounting for non-linear fiber propagation effects”, Optics Express, vol.18, no.11, May 2010, p. 11360.*

Non-linear propagation analytical models

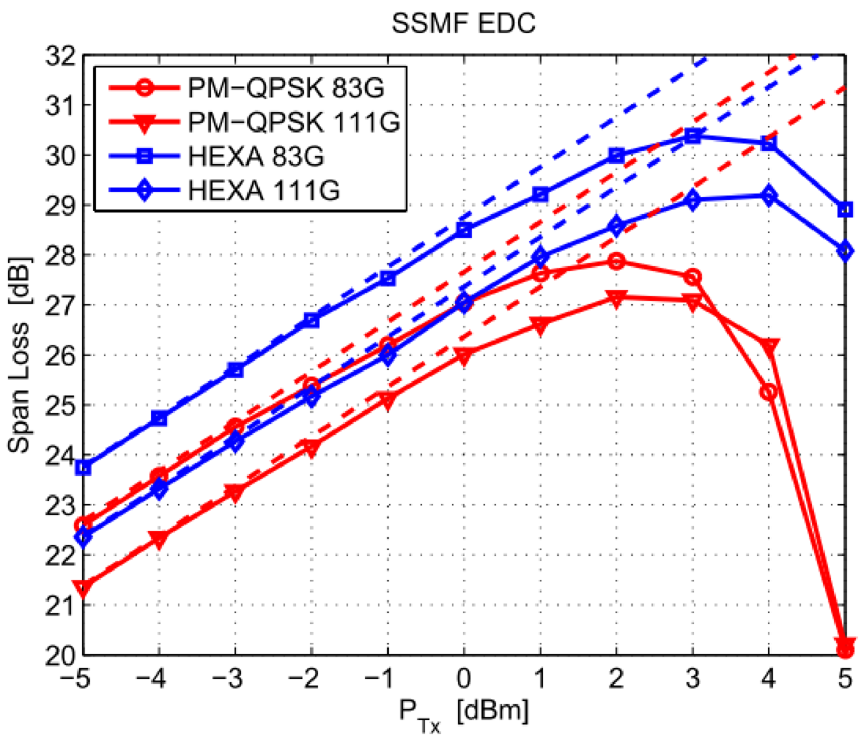
- The simulations required to obtain the results shown in previous slides took the equivalent of several months of single high-performance CPU time.

- In order to further investigate the performance of PS-QPSK, we resorted to an analytical model which has been proven to accurately predict the performance of uncompensated coherent optical systems.

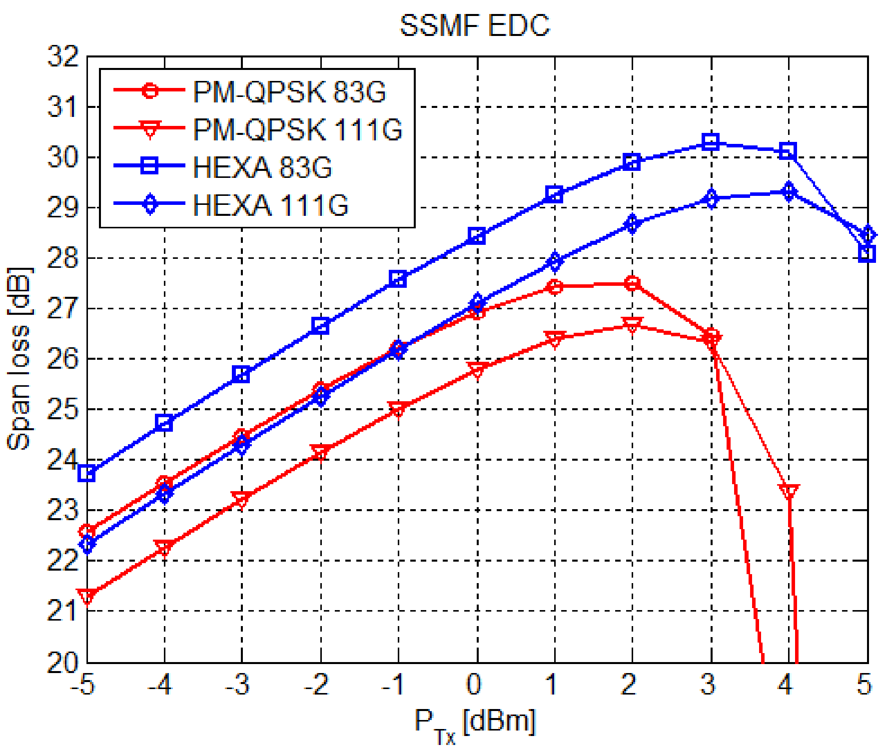
- *P. Poggiolini et al., "A simple and accurate model for non-linear propagation effects in uncompensated coherent transmission links", ICTON 2011, paper We.B1.3, Stockholm, 26-29 June 2011.*

Analytical model validation over SSMF

Monte-Carlo simulations

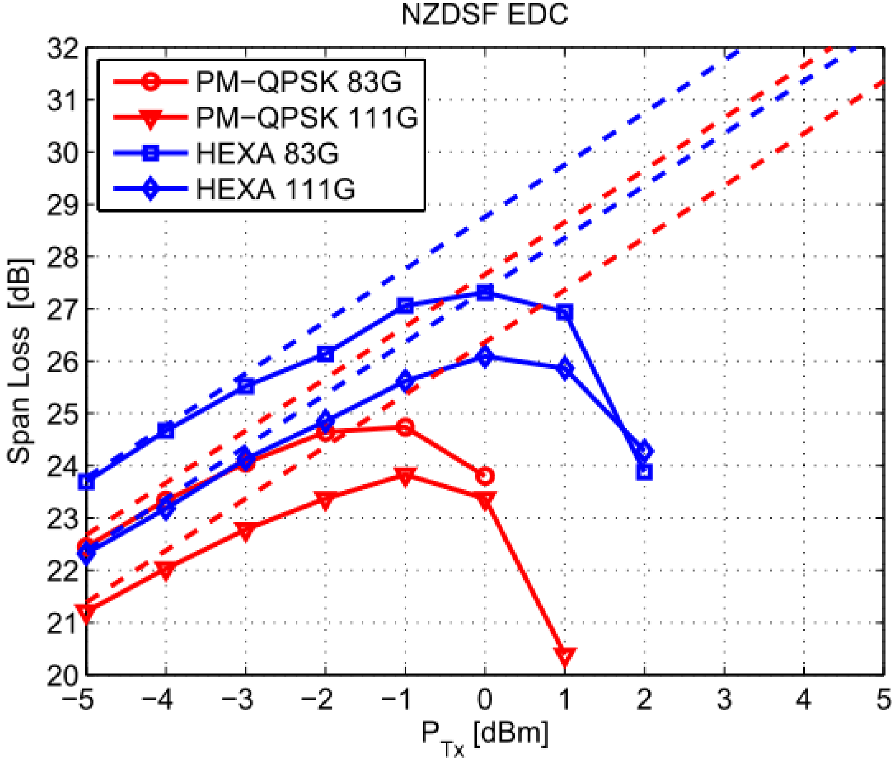


Analytical model

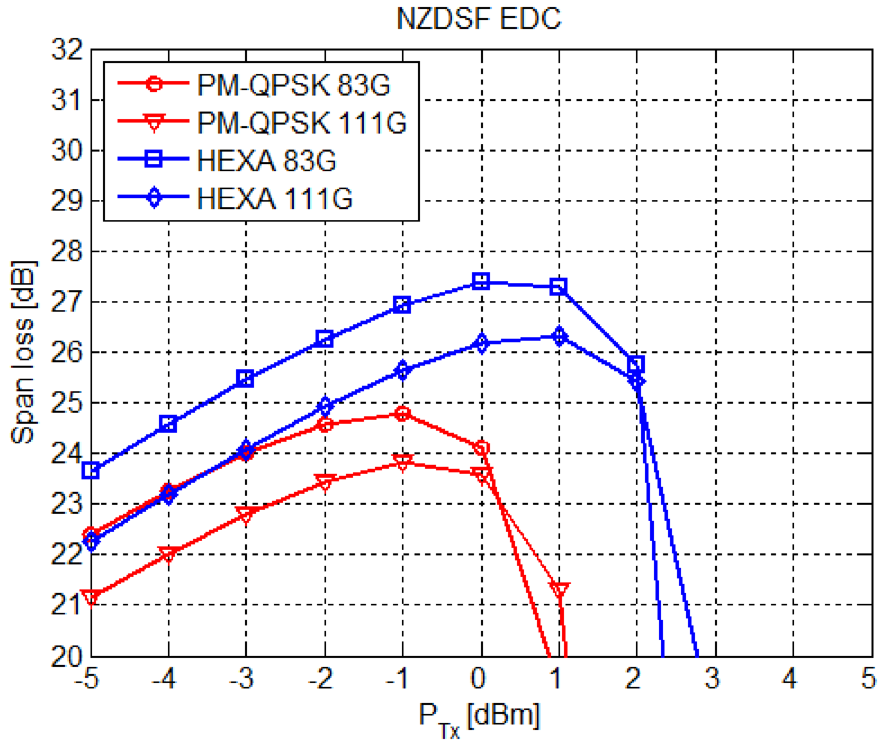


Analytical model validation over NZDSF

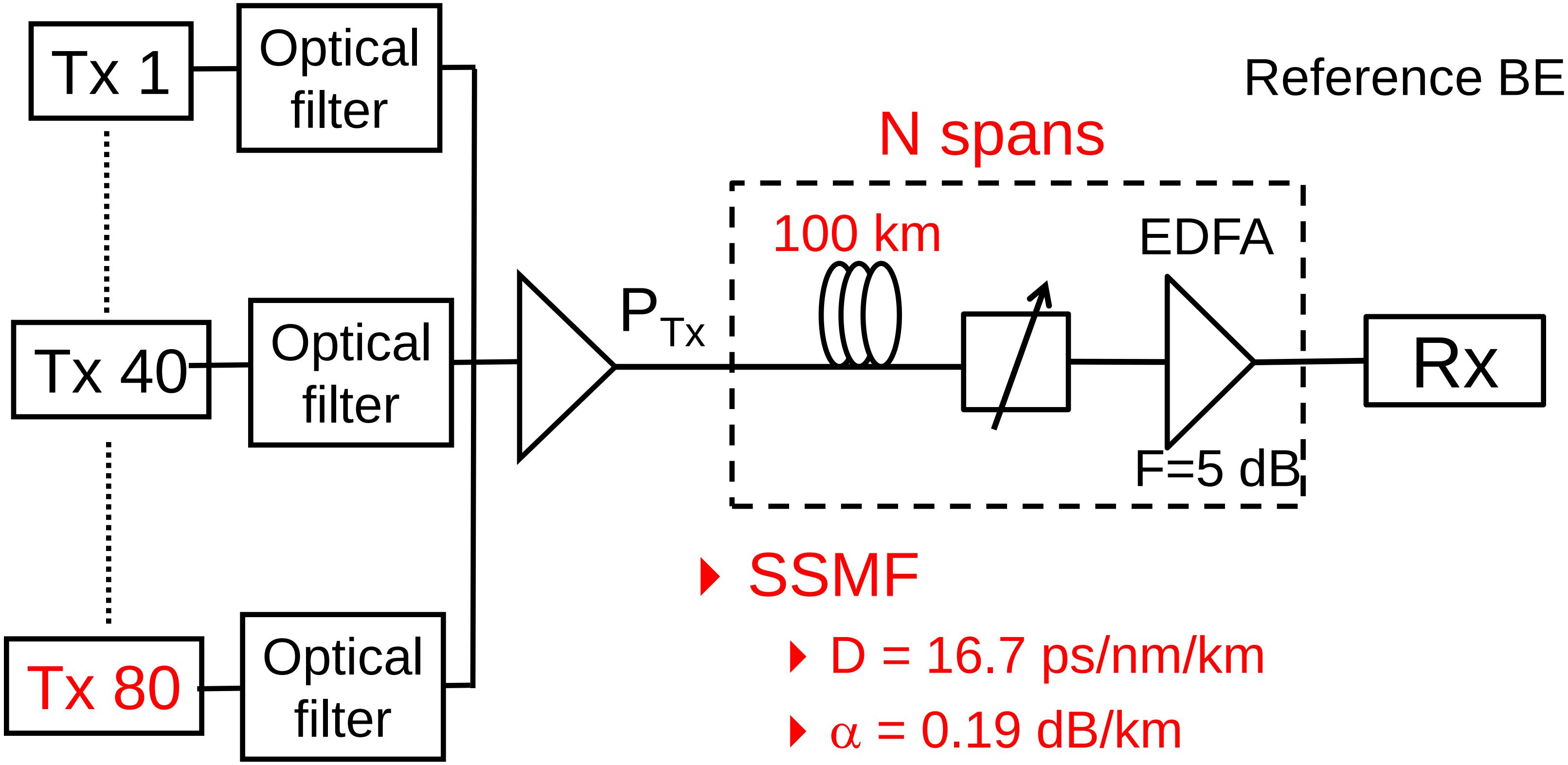
Monte-Carlo simulations



Analytical model



System set-up



Reference BER: 10^{-3}

Δf=50 GHz ⇩ C-band

2nd order Supergaussian with 40-GHz bandwidth

- SSMF
  - D = 16.7 ps/nm/km
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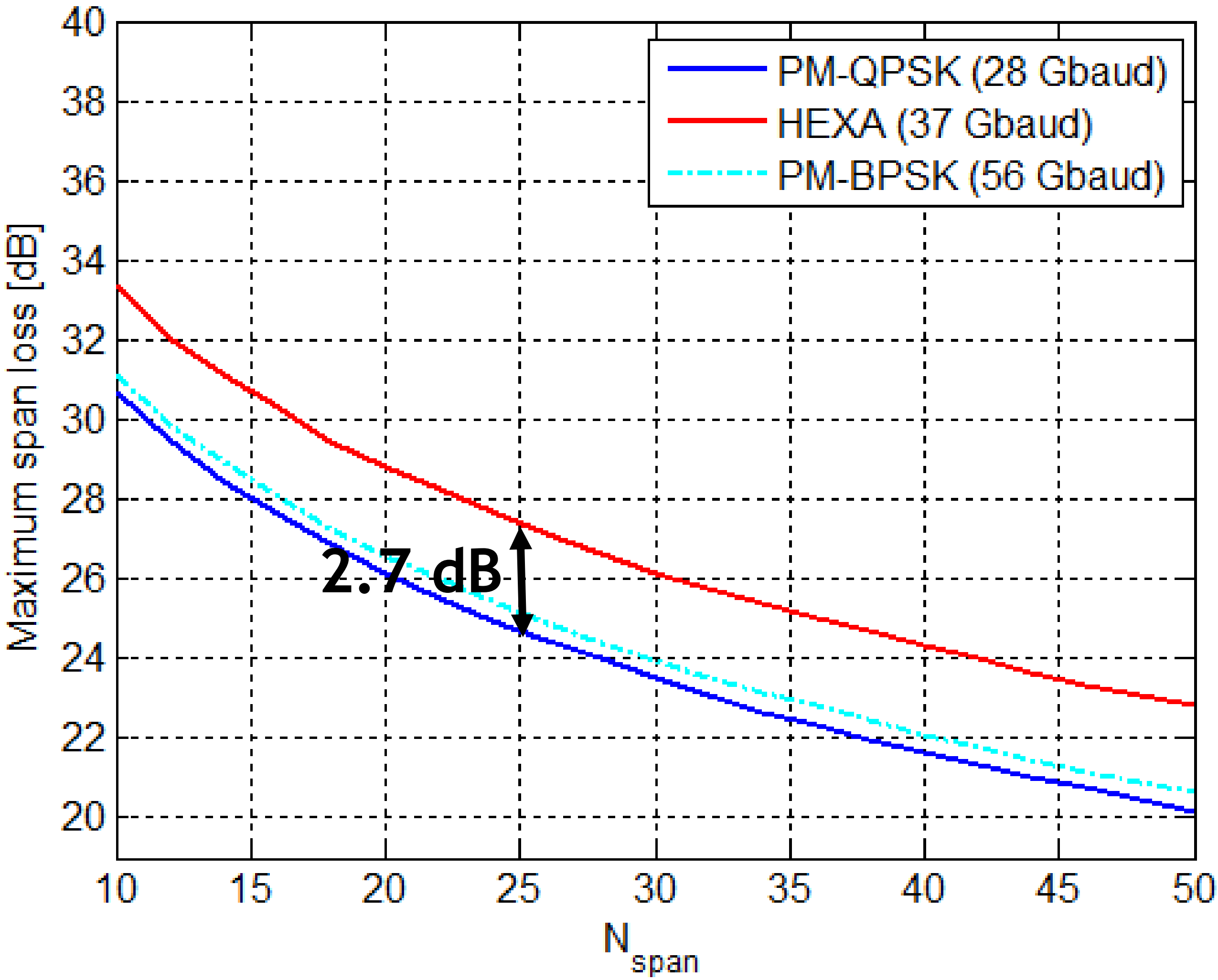
Comparison at fixed bit-rate

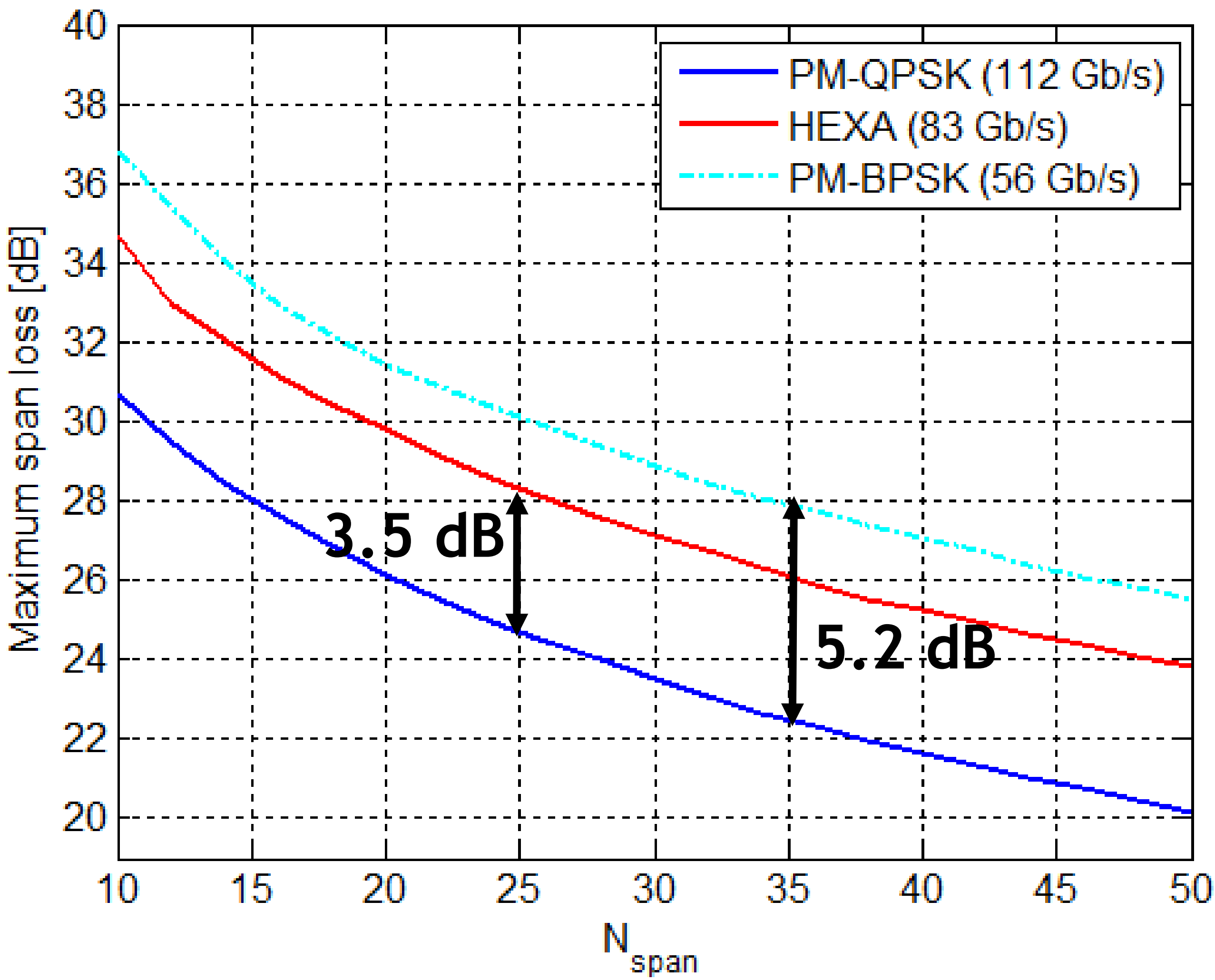
- 112 Gb/s



- The gain of PS-QPSK (HEXA) over PM-QPSK is independent of the transmission distance
- The gain has increased from 1 dB in back-to-back to 2.7 dB.

Comparison at fixed symbol-rate

- 28 Gbaud



- The gain of PS-QPSK (HEXA) over PM-QPSK is independent of the transmission distance
- The gain has increased from 2.2 dB in back-to-back to 3.5 dB.

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- Long-haul non-linear transmission
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Experimental demonstrations

- Recently, experimental demonstrations of generation and transmission of PS-QPSK has started to appear, confirming analytical/simulation predictions.

- *M.Sjödin et al., "Comparison of polarization-switched QPSK and polarization-multiplexed QPSK at 30 Gbit/s", Optics Express, vol.19, no.8, pp.7839-7846, 11 Apr. 2011.*
  - 30 Gb/s, single channel, 4x75 km SSMF
  - 0.7 dB OSNR gain over PM-QPSK at same bit-rate
  - 2.2 dB OSNR gain over PM-QPSK at same baud-rate

Experimental demonstrations

- *D.S.Millar et al., "Generation and long-haul transmission of polarization-switched QPSK at 42.9 Gbit/s", Optics Express, vol.19, no.10, pp.9296-9302, 9 May 2011.*
  - 42.9 Gb/s, WDM (50 GHz grid), 170x80 km SSMF (13,640 km, record length at 40 Gb/s)

- *L.E.Nelson et al., "Experimental comparison of coherent polarization-switched QPSK to polarization-multiplexed QPSK for 10x100 km WDM transmission", Optics Express, vol.19, no.11, pp.10849-10856, 25 May 2011.*
  - 40.5 Gb/s, WDM (50 GHz grid), 10x100 km SSMF
  - 0.9 dB OSNR gain over PM-QPSK at same bit-rate
  - 1.6 dB higher launch power

Conclusions

- The obtained results indicate that PS-QPSK, besides having a better back-to-back sensitivity than PM-QPSK, is also more tolerant to non-linear propagation effects.

- Consequently, PS-QPSK emerges as an interesting option for dual-format transceivers (with fixed symbol-rate but variable bit-rate) capable to switch on-the-fly between PM-QPSK and PS-QPSK when channel propagation degrades.

- The price to pay is a 25% rate reduction, but with a gain of 2.2 dB in sensitivity and an increased tolerance to non-linear propagation effects.

Thank you!

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