Performance Evaluation of Coherent PS-QPSK (HEXA) Modulation

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Outline

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

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

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

\[
\begin{align*}
  s_1 &= (-2, 0, 0, 0) \\
  s_2 &= (+2, 0, 0, 0) \\
  s_3 &= (0, -2, 0, 0) \\
  s_4 &= (0, +2, 0, 0) \\
  s_5 &= (0, 0, -2, 0) \\
  s_6 &= (0, 0, +2, 0) \\
  s_7 &= (0, 0, 0, -2) \\
  s_8 &= (0, 0, 0, +2)
\end{align*}
\]

- These coordinates correspond to the vertices of a 4D polychoron called “hexadecachoron”
  → HEXA
PS-QPSK coordinates in the 4D space

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

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:

- 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.
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Transmitter architecture

BIT1
BIT2
IQ Modulator
Polarization Modulator

Sub-set of PM-QPSK points

\[ s_1 = (-1, -1, -1, -1) \]
\[ s_2 = (-1, -1, +1, +1) \]
\[ s_3 = (-1, +1, -1, +1) \]
\[ s_4 = (-1, +1, +1, -1) \]
\[ s_5 = (+1, +1, +1, +1) \]
\[ s_6 = (+1, +1, -1, -1) \]
\[ s_7 = (+1, -1, +1, -1) \]
\[ s_8 = (+1, -1, -1, +1) \]

45° pol rot

\[ s_1 = \sqrt{2}(-1, -1, 0, 0) \]
\[ s_2 = \sqrt{2}(-1, +1, 0, 0) \]
\[ s_3 = \sqrt{2}(+1, -1, 0, 0) \]
\[ s_4 = \sqrt{2}(+1, +1, 0, 0) \]
\[ s_5 = \sqrt{2}(0, 0, -1, -1) \]
\[ s_6 = \sqrt{2}(0, 0, -1, +1) \]
\[ s_7 = \sqrt{2}(0, 0, +1, -1) \]
\[ s_8 = \sqrt{2}(0, 0, +1, +1) \]
Alternative Tx architecture

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

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.
Standard LMS algorithm
  - Initialized using a training sequence

Modified CMA algorithm
  - Blind equalization

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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

- $R_s = 28 \text{ Gbaud}$

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
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

**SSMF**
- $D = 16.7 \text{ ps/nm/km}$
- $\alpha = 0.22 \text{ dB/km}$
- $\gamma = 1.3 \text{ 1/w/km}$

**NZDSF**
- $D = 3.8 \text{ ps/nm/km}$
- $\alpha = 0.22 \text{ dB/km}$
- $\gamma = 1.5 \text{ 1/w/km}$

Reference BER: $10^{-3}$

Diagram:
- Tx 1, Tx 5, Tx 9
- Optical filters
- 90 km fiber
- EDFA (F=5 dB)
- VOA
- Rx
- $\Delta f=50 \text{ GHz}$
- Supergaussian with 40-GHz bandwidth
- 2nd order
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).

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).

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.

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.

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: $10^{-3}$

- **SSMF**
  - $D = 16.7$ ps/nm/km
  - $\alpha = 0.19$ dB/km
  - $\gamma = 1.3$ 1/w/km

Tx 1

Tx 40

Tx 80

Optical filter

Optical filter

Optical filter

$\Delta f=50$ GHz

2nd order Supergaussian with 40-GHz bandwidth

C-band

N spans

100 km

EDFA

$P_{Tx}$

F=5 dB

Rx

P_{Rx}
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.
Four-dimensional constellations

Transmitter and receiver architecture

Back-to-back performance

Long-haul non-linear transmission

Experimental demonstrations

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


- 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

- 42.9 Gb/s, WDM (50 GHz grid), 170x80 km SSMF (13,640 km, record length at 40 Gb/s)


- 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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