Impact of Fiber Non-Linearities on Probabilistic Shaping in Long-Haul Optical Systems

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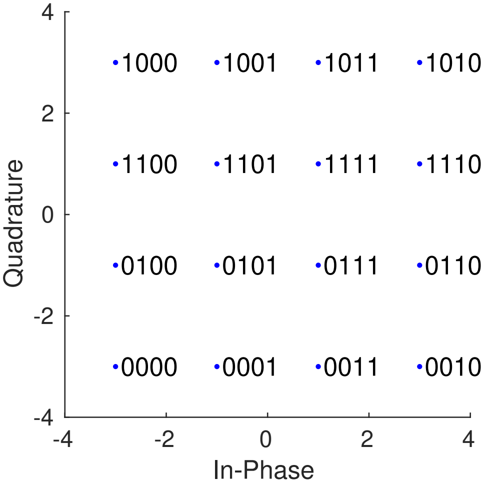
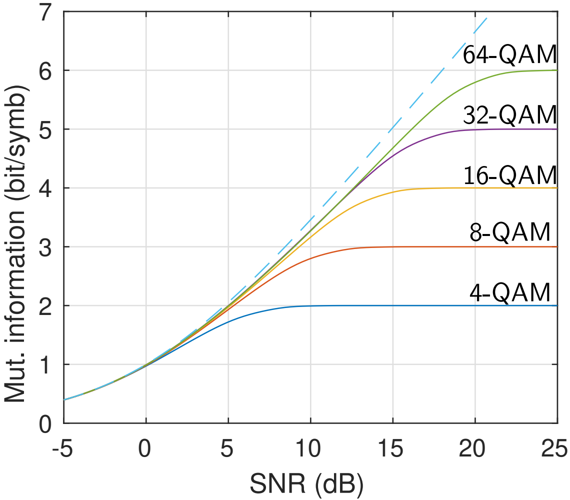
Outline

Quadrature Amplitude Modulation



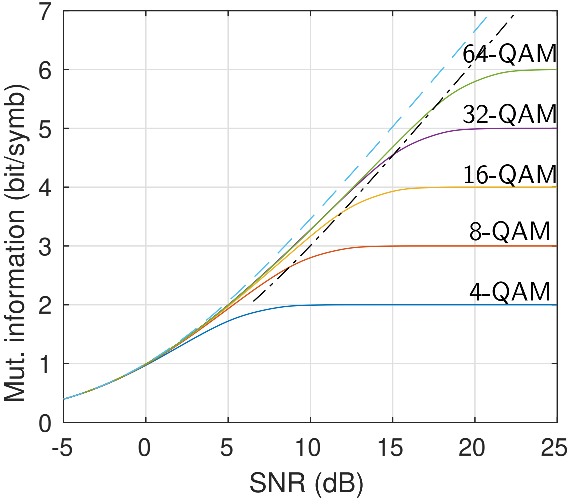
- Random bits are directly mapped to a constellation (e.g. 16-QAM)
- Gross data-rate is fixed (e.g. 4 bit/symbol for 16-QAM)
- Errors are corrected using FEC, which reduces the net data rate

Limits of QAM



- Maximum achievable data rate (Mutual Information) over an Additive White Gaussian Noise (AWGN) channel
- ~ 1.53 dB asymptotic gap to capacity

Limits of QAM



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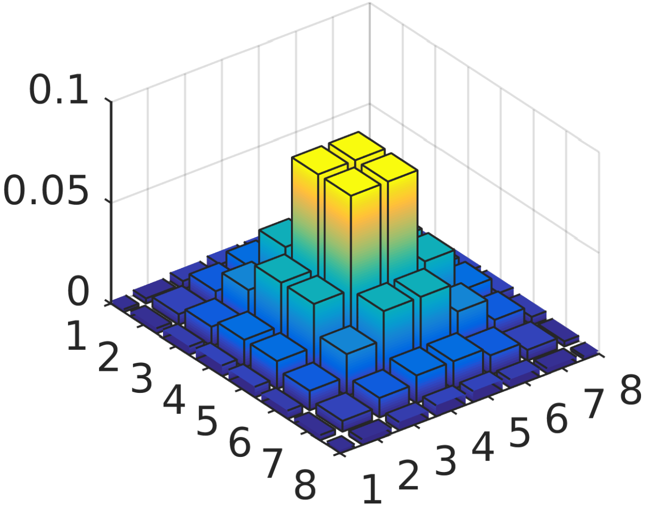
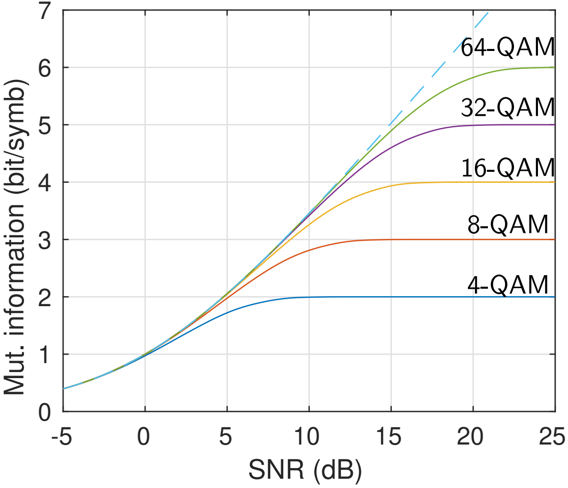
Probabilistic Constellation Shaping



- Possible solution: transmit *standard* QAM symbols with different probabilities!

PCS QAM Sensitivity Gain



- At low SNR, gap to capacity is significantly reduced

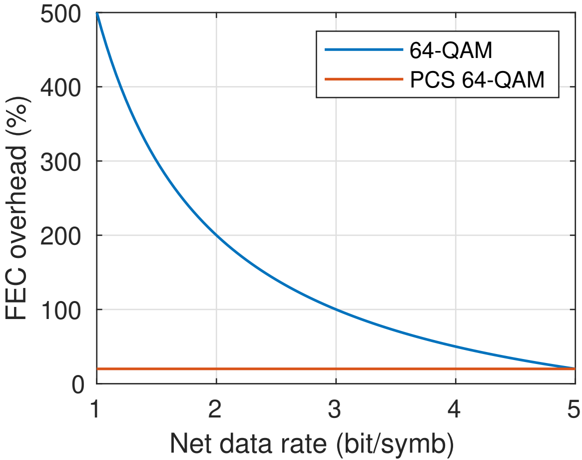
Probability Amplitude Shaping (PAS)

- Practical realization of PCS is still an open research question
- In research, most common algorithm is Probabilistic Amplitude Shaping (PAS)
- It exploits PCS to obtain data-rate flexibility with a fixed FEC rate

$$R_{\text{PAS}} = \mathbb{H}(C) - (1 - R_{\text{FEC}}) \log_2(M)$$

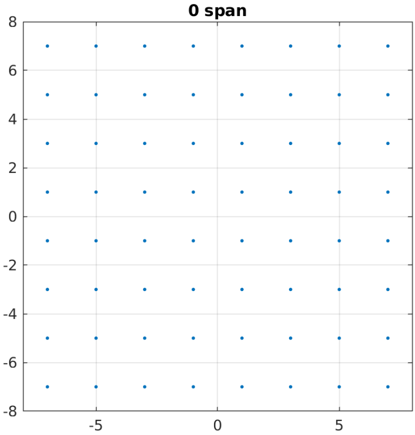
  - $R_{\text{FEC}} = 1/(1 + \text{OH})$: FEC rate
  - M: QAM cardinality
  - $\mathbb{H}(C) \leq \log_2(M)$: entropy of constellation

Example: PCS 64-QAM using PAS

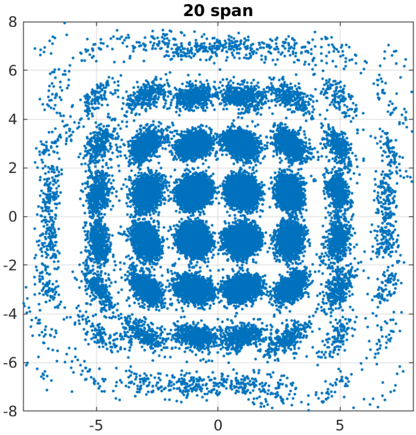


- A wide range of net data rates can be obtained with a single FEC overhead
- This example uses a 20% FEC overhead for PAS

Is the Channel AWGN?



After 20 Spans...



- Channel is definitely not AWGN
- Strong phase-noise component

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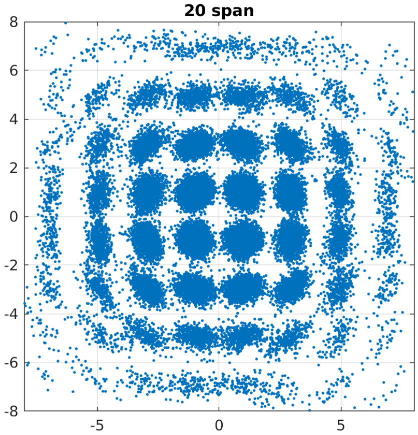
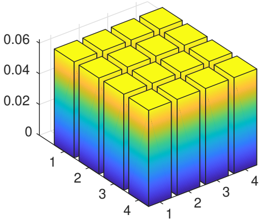
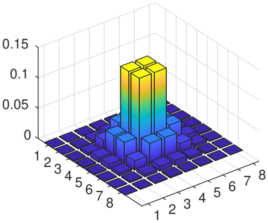


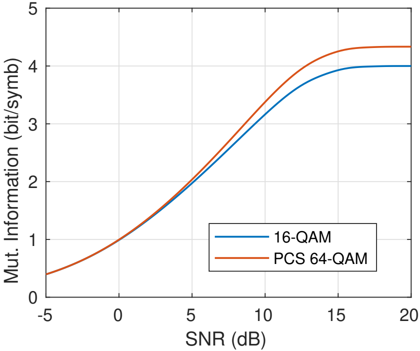
- Channel is definitely not AWGN
- Strong phase-noise component
- Can be compensated by the CPE!

Example: 16-QAM vs PCS 64-QAM

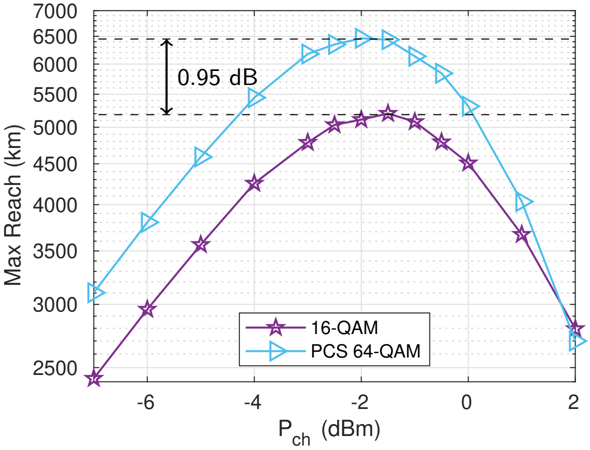




- FEC overhead: 20%
- 16-QAM and PCS 64-QAM: same *net* data rate with $\mathbb{H}(C) = 4.33$ bit/symb
- Theoretical gain @3.6 bit/symb: 1.24 dB

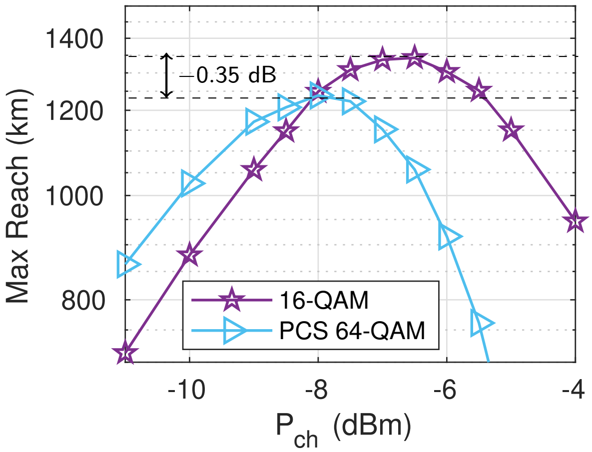


PSCF Propagation



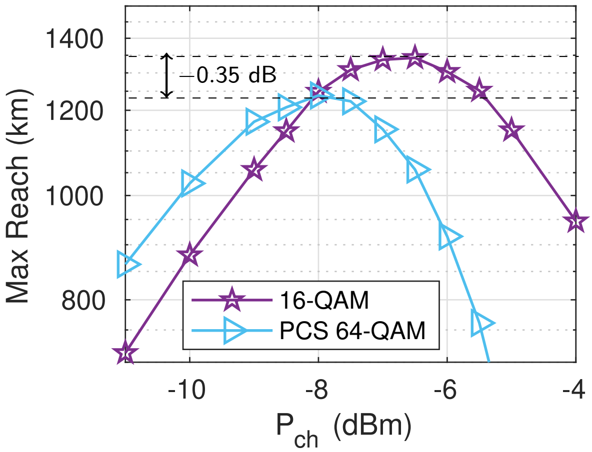
- 31 × 16 GBaud transmission over 108-km spans of PSCF
- PCS 64-QAM additional back-to-back penalty: 0.2 dB

NZDSF Propagation



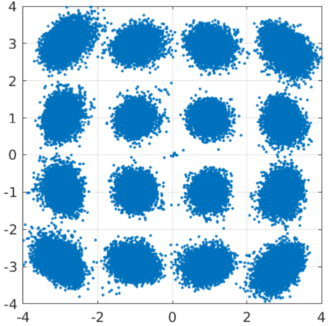
- 31 × 16 GBaud transmission over 80-km spans of NZDSF

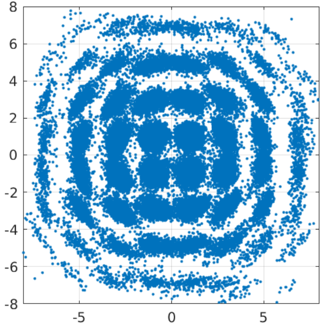
NZDSF Propagation



- 31 × 16 GBaud transmission over 80-km spans of NZDSF
- Negative PCS gain?

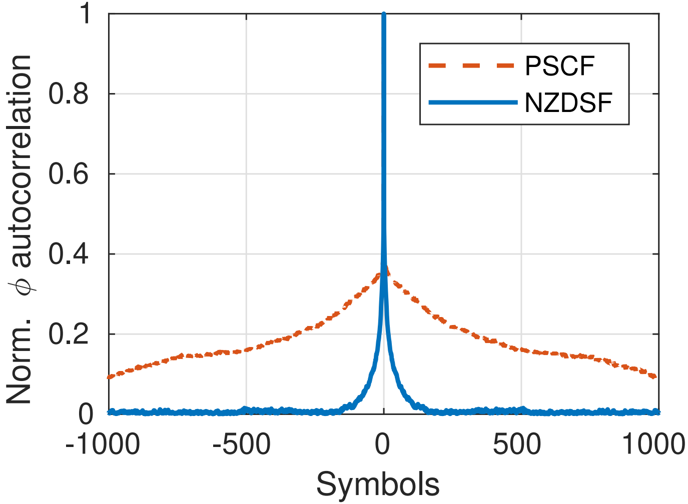
After 24 Spans of NZDSF...



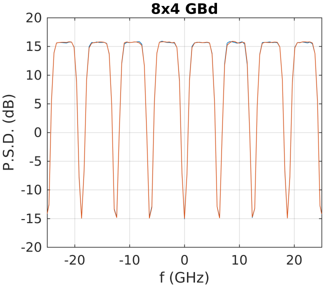


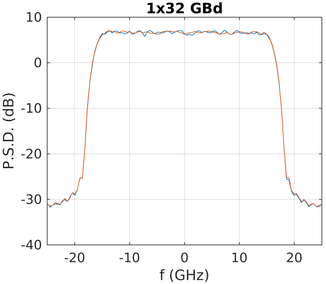
- Split-step simulations without ASE noise

What About CPE?



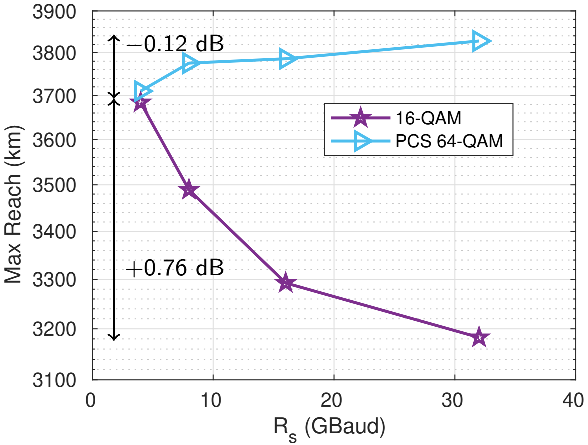
Different Symbol Rates





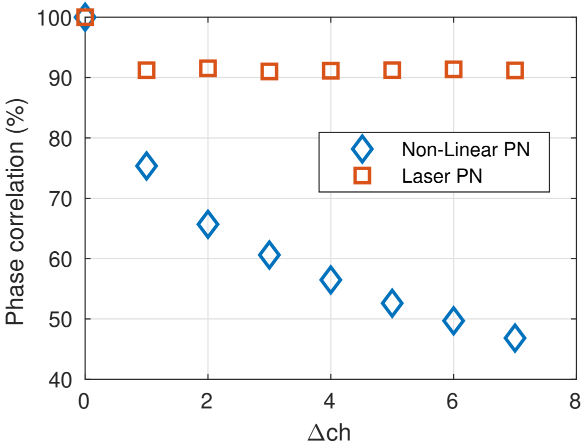
- Signals at different symbol rates are compared at the same *optical* bandwidth
- Optimal symbol rate is $\sim$ 5.5 GBaud after 35 $\times$ 100 km of SMF

Propagation over SMF



Split-step simulations of 15 × 32 GBaud and 120 × 4 GBaud signals over 100-km spans of SMF

Joint CPE?



Phase correlation (%)
100
90
80
70
60
50
40
0
2
4
6
8
Δch
Non-Linear PN
Laser PN

Summary and Conclusion

- The optical channel for PCS constellations is not AWGN, since it adds non-linear phase noise
- If its memory is large enough, it is compensated by the CPE, and channel becomes AWGN
- For low values of chromatic dispersion, memory is too short and PCS has a penalty

Summary and Conclusion

- The optical channel for PCS constellations is not AWGN, since it adds non-linear phase noise
- If its memory is large enough, it is compensated by the CPE, and channel becomes AWGN
- For low values of chromatic dispersion, memory is too short and PCS has a penalty
- Phase recovery algorithms are the key elements to improve PCS in those scenarios

Thank You

References

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