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Design of APSK Constellations for Coherent Optical Channels with Nonlinear Phase Noise

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Abstract

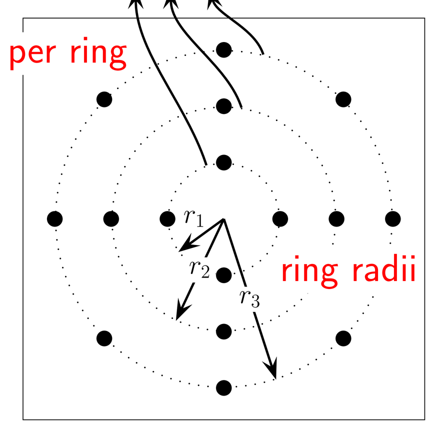
We study the design of amplitude phase-shift keying (APSK) constellations for a coherent fiber-optical communication system where nonlinear phase noise is the main system impairment. A practical two-stage detection scheme is analyzed and we optimize APSK constellations in terms of symbol error probability (SEP) under two-stage detection. Performance gains of 3.2 dB can be achieved at a SEP of 10^{-2} compared to 16-QAM. We also demonstrate that in the presence of severe nonlinear distortions, it may become beneficial to sacrifice a constellation point or an entire constellation ring to reduce the average SEP.

Motivation

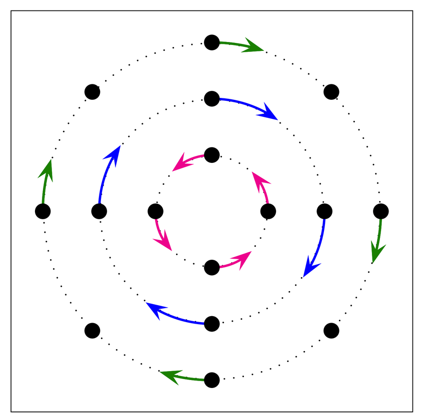
- Higher order modulation formats are crucial to increase spectral efficiency of optical transmission systems.
- The optical channel suffers from distortions that are absent for example in wireless channels, in particular nonlinear phase noise.
- Practical question: How much can we gain by optimizing the constellation compared to standard QAM?
- Theoretical question: How do optimal constellations look like for very strong nonlinearities?

APSK

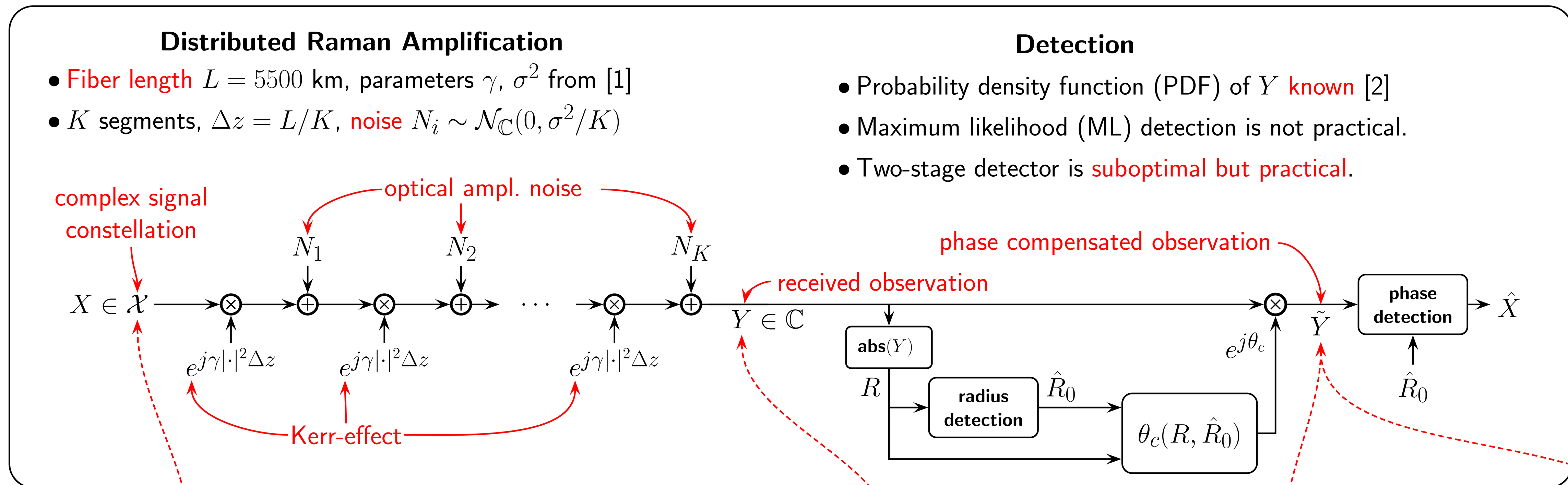
APSK constellations can be regarded as a union of phase-shift keying (PSK) signal sets with different amplitude levels. Example:

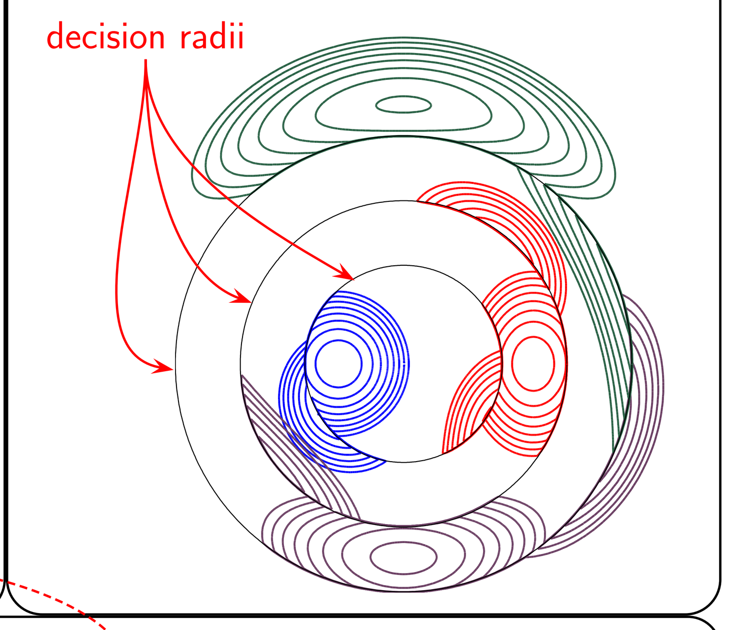


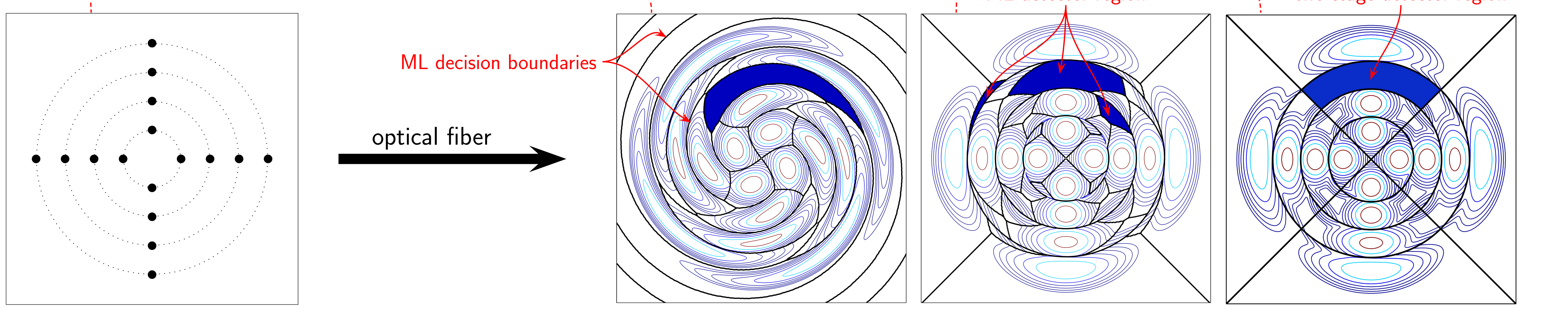
The radii are uniform if neighboring rings are equidistant. Further, a phase offset may be applied to rotate each ring:



Channel Model and Detection







Problem Statement

Definitions:

- $P = \mathbb{E}[|X|^2]$, input power (in [dBm])
- SNR, signal-to-additive-noise ratio

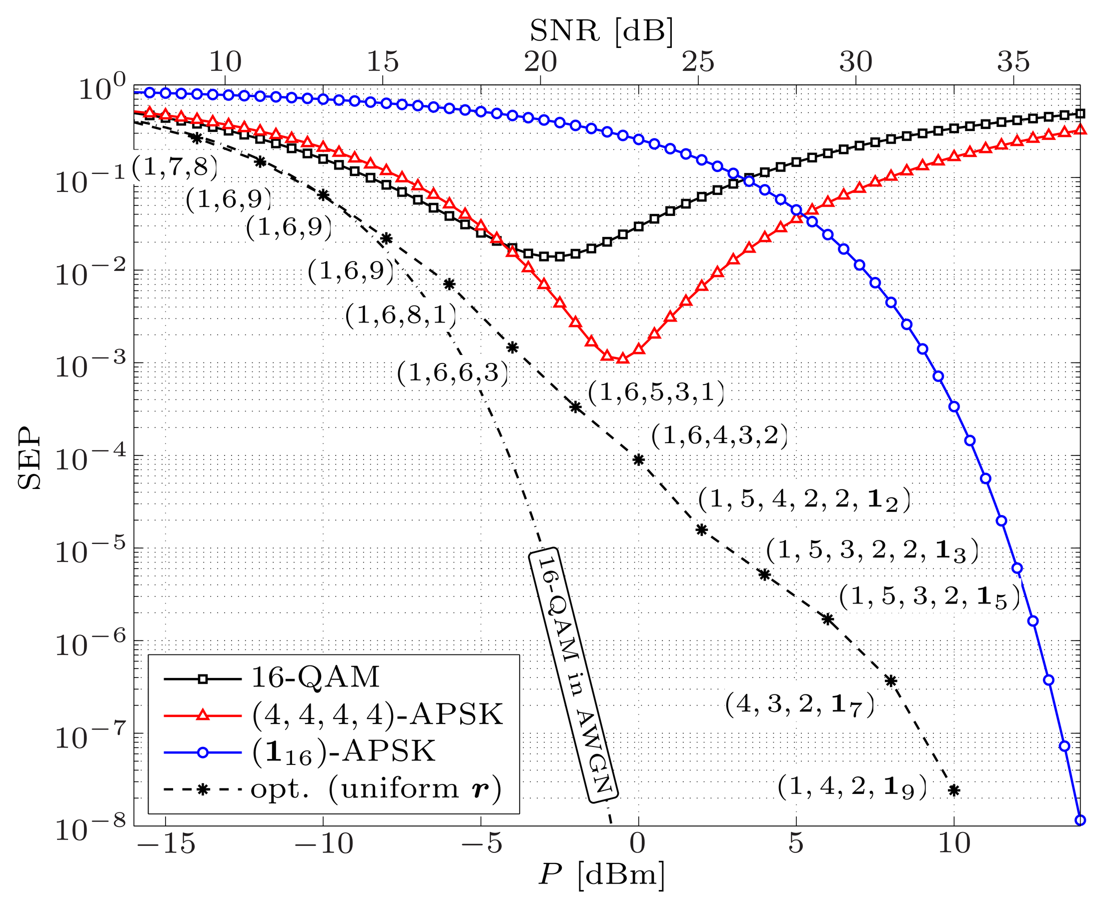
Goal: Which APSK constellation minimizes the SEP under two-stage detection for a given input power P?

- How many rings?
- How many points per ring?
- How to choose the radii?
- What phase offset?

Remark 1: For the two-stage detector, it can be shown that any phase-offset in the rings has no effect on the SEP. Thus, we set all phase offsets to zero.

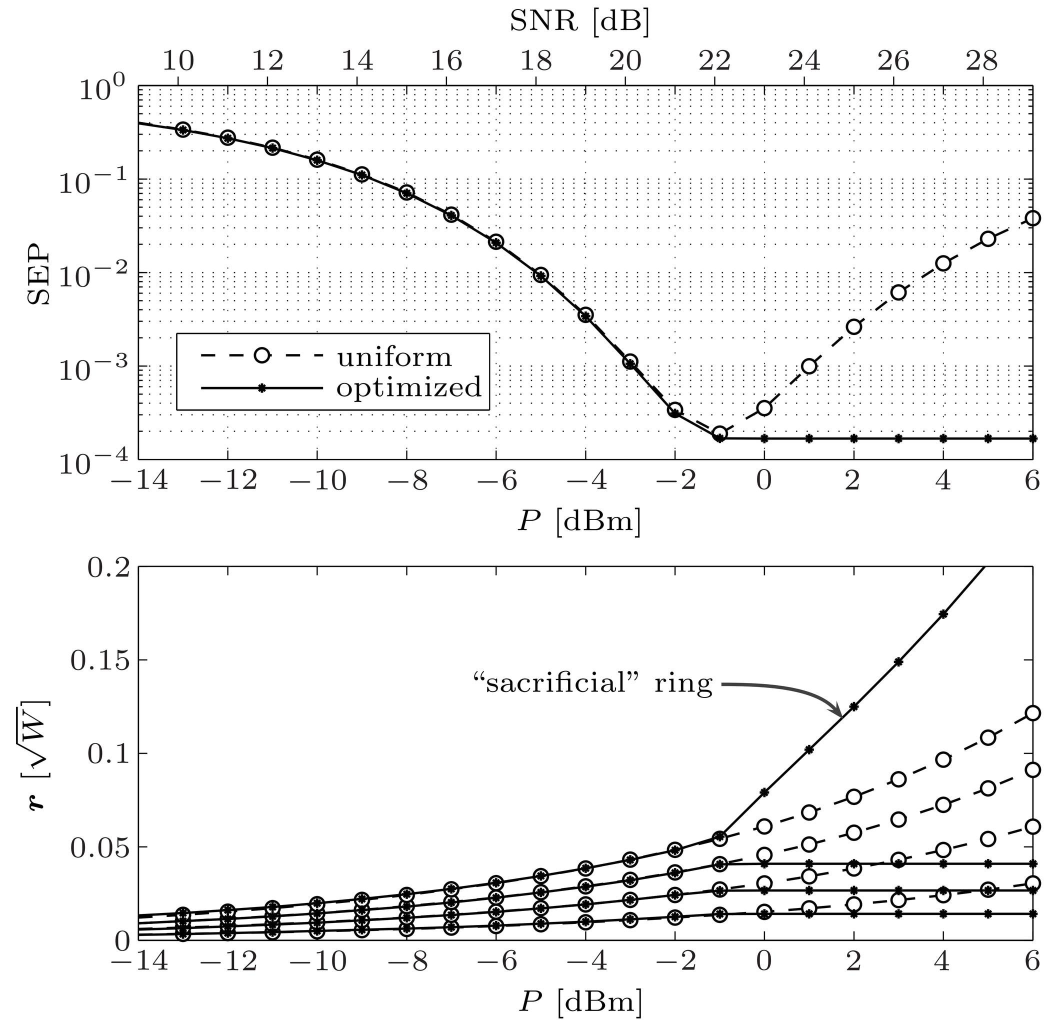
Remark 2: We use the convention that, if there is only one point in the first ring, then this point is placed at the origin.

Points-per-Ring Optimization



- We optimize the number of rings and points per ring for P between -14 and 10 dBm in steps of 2 dBm assuming uniform radii.
- More rings are optimal for increasing input power due to high nonlinear phase noise (see markers in the above figure).
- The optimized constellations for low input power are almost as good as 16-QAM in a Gaussian channel.

Radius Optimization



- For (1,6,5,3,1)-APSK, we optimize the radii of the rings.
- For high input power, it is optimal to move the point in the last ring far away from the remaining constellation points.

Conclusion

1. Significant gains can be obtained by choosing an optimized APSK constellations compared to regular 16-QAM.
2. High nonlinearities and an average power constraint may lead to counterintuitive optimization results.

References

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[2] A. Mecozzi, "Limits to long-haul coherent transmission set by the Kerr nonlinearity and noise of the in-line amplifiers," *J. Lightw. Technol.*, vol. 12, no. 11, pp. 1993–2000, Nov. 1994.

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Research conducted at the Fiber-Optic Communications Research Center. More infos can be found at www.chalmers.se/mc2/force-en.
This work was partially funded by the Swedish Agency for Innovation Systems (VINNOVA) under the P36604-1 MAGIC project, Sweden, and by the European Community's Seventh's Framework Programme (FP7/2007- 2013) under grant agreement No. 271986.