

Agenda

- Introduction of discussion leader Marco Secondini
- Errata
- Presentation by Christian Häger (30 min)
- Discussion (\approx 60 min)
- Questions and comments from the audience
- Final decision by examiner

On Signal Constellations and Coding for Long-Haul Fiber-Optical Systems

Christian Häger

Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden,
christian.haeger@chalmers.se



Licentiate Seminar, May 9, 2014



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Motivation and Outline

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- Higher-order signal constellations/modulation formats for optical communication to increase spectral efficiency

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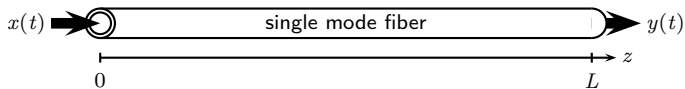
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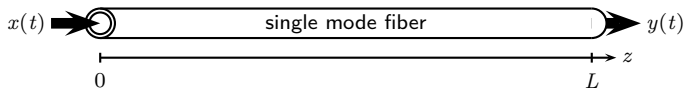
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4. Bit mapper optimization for protograph codes

Fiber-Optical Channel Modeling

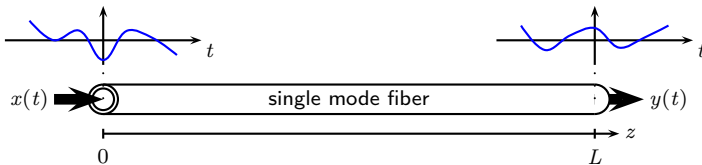


Fiber-Optical Channel Modeling



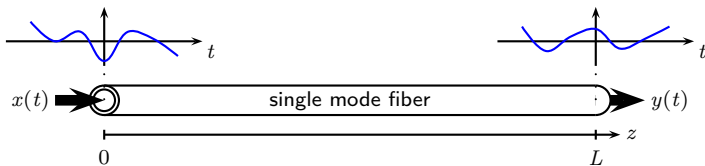
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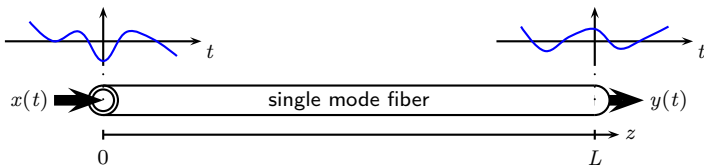
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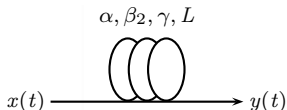


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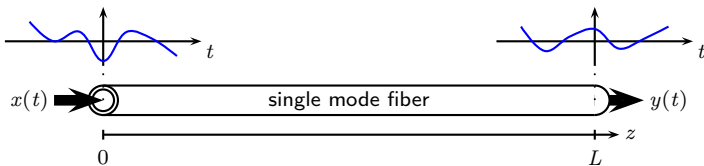
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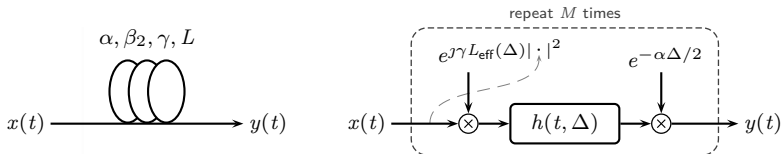
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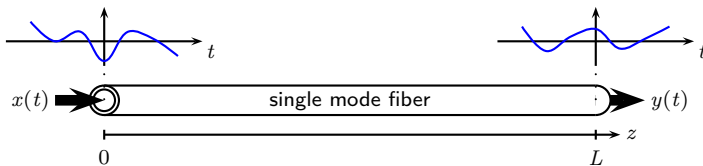
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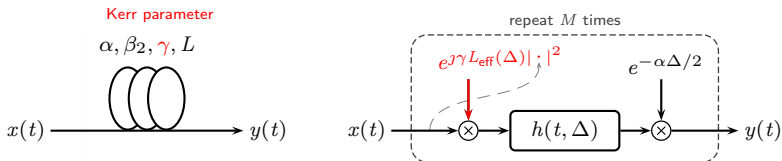
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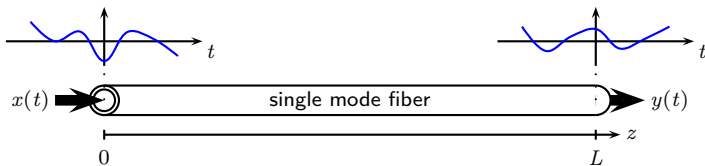


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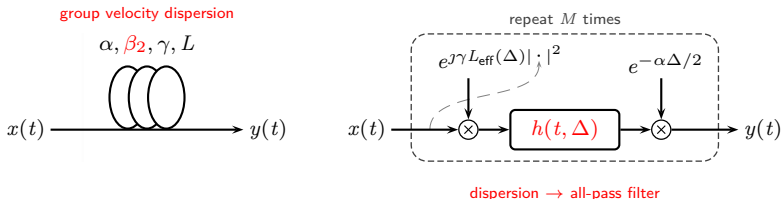


nonlinear Kerr effect \rightarrow phase rotation

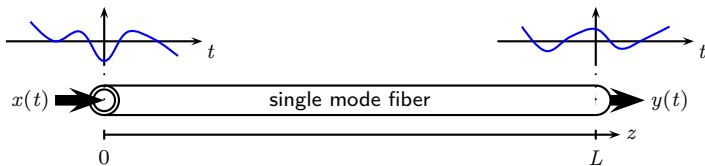
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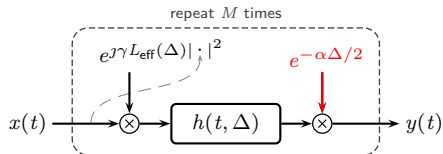
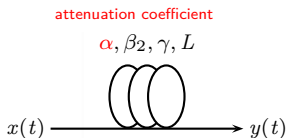
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attenuation \rightarrow decaying signal power

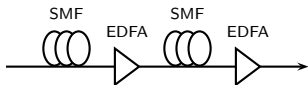
Optical Amplification and Noise

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- Periodic **signal amplification** along the transmission path **leads to noise**

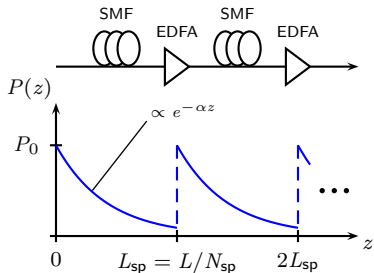
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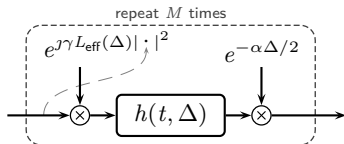
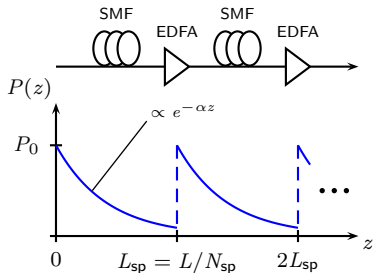
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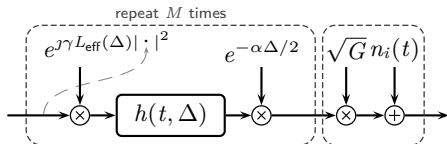
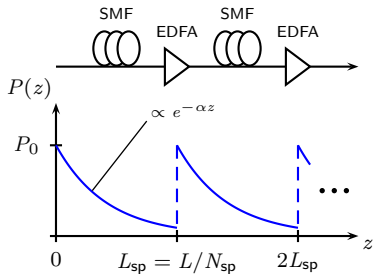
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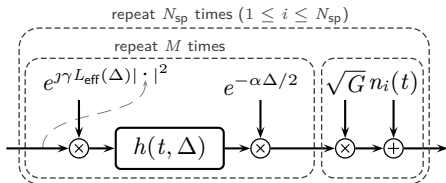
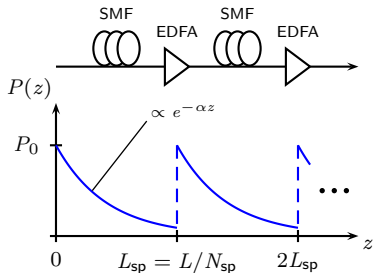
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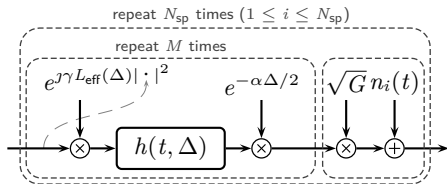
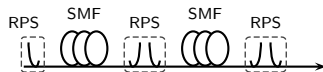
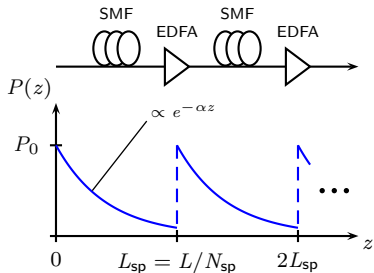
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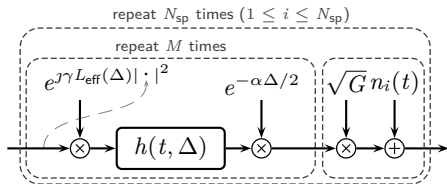
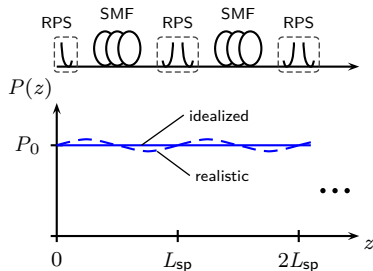
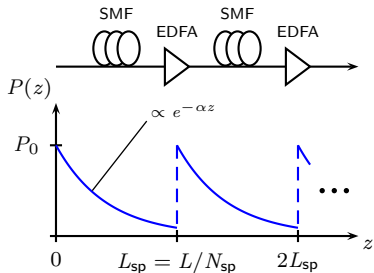
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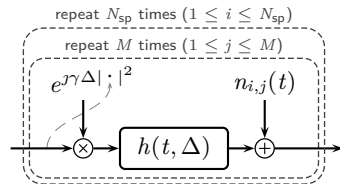
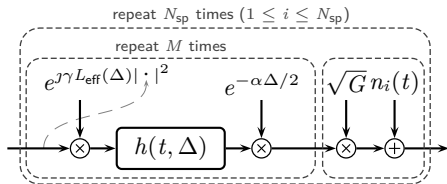
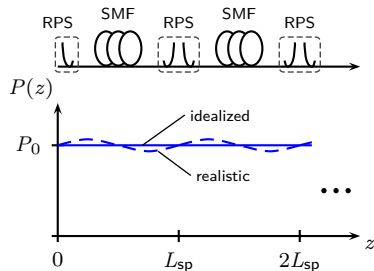
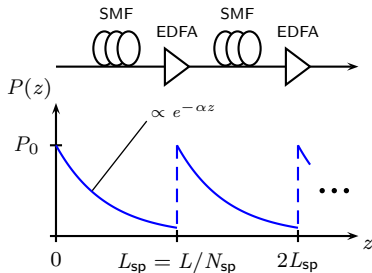
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Discrete-Time Channel Model for Zero-Dispersion Fiber

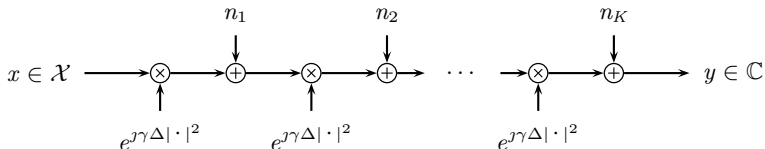
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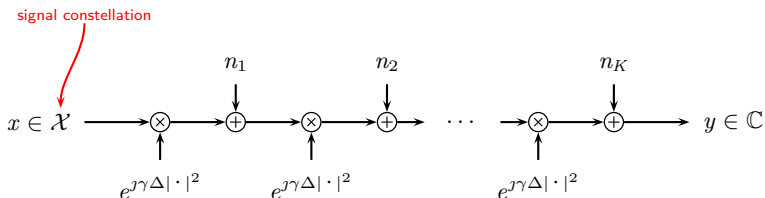
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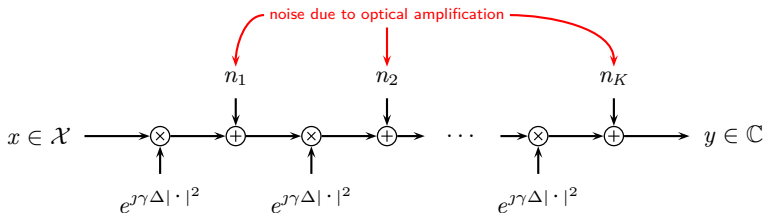
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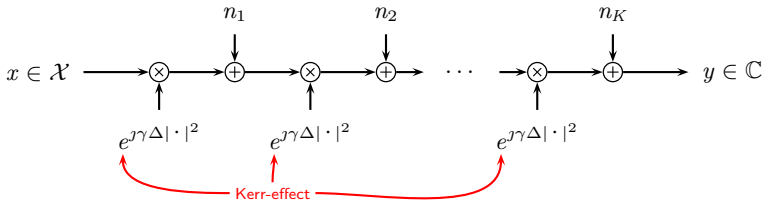
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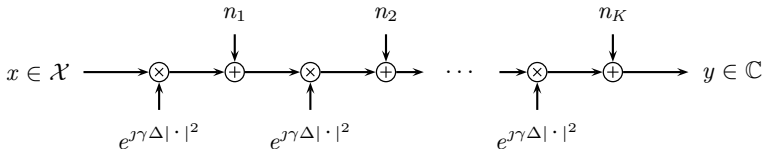
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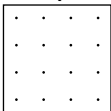


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- Extensive work on this model, e.g., [Mecozzi, 1994], [Turitsyn et al., 2003], [Ho, 2005], [Yousefi and Kschischang, 2011]

Power Dependent Phase Noise

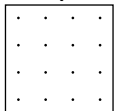
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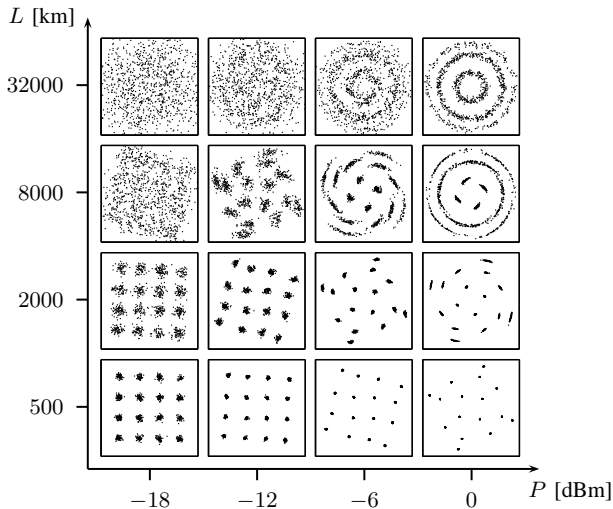
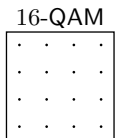


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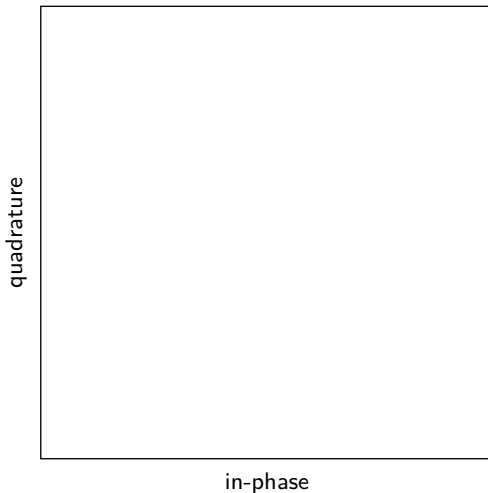
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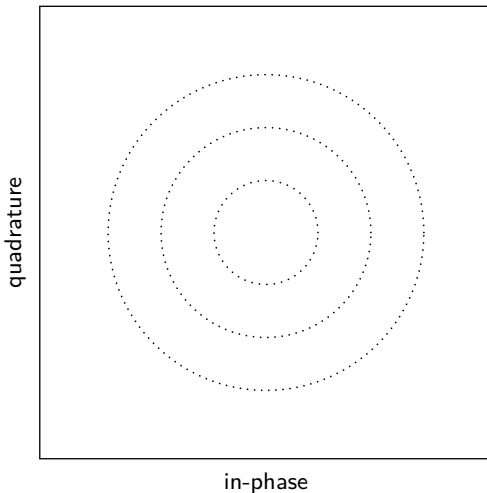
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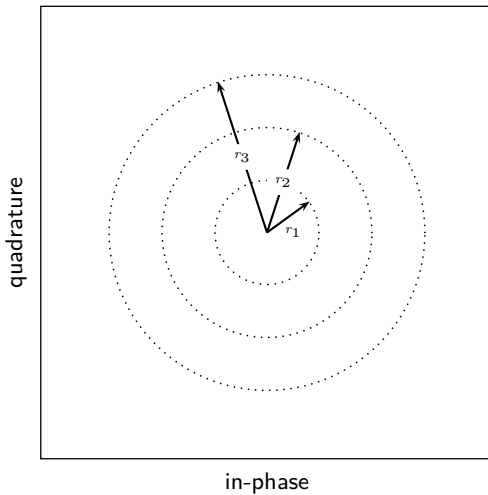
Amplitude Phase-Shift Keying (APSK), Example



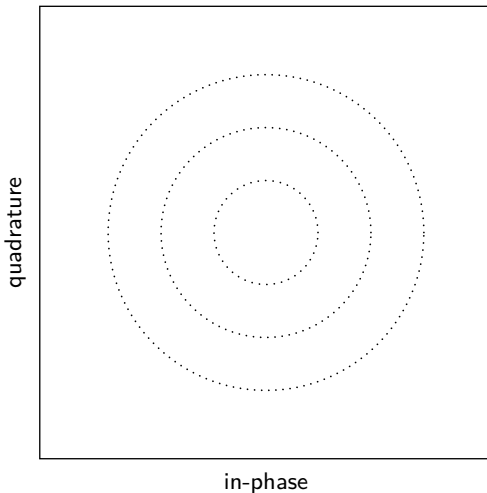
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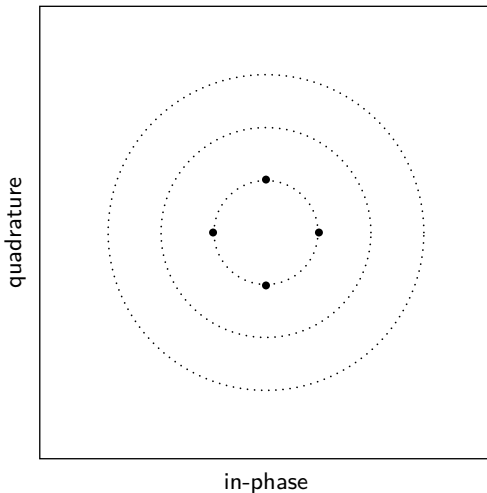


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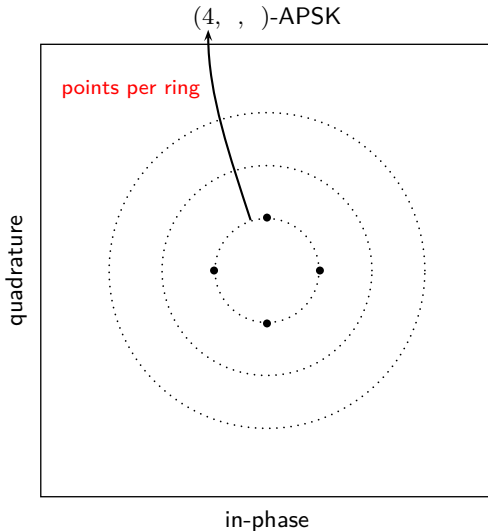


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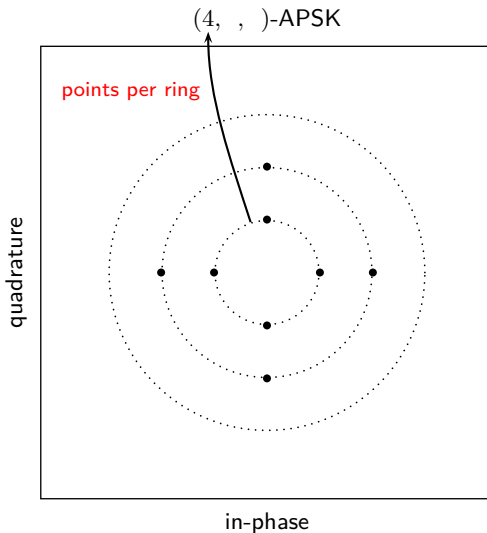
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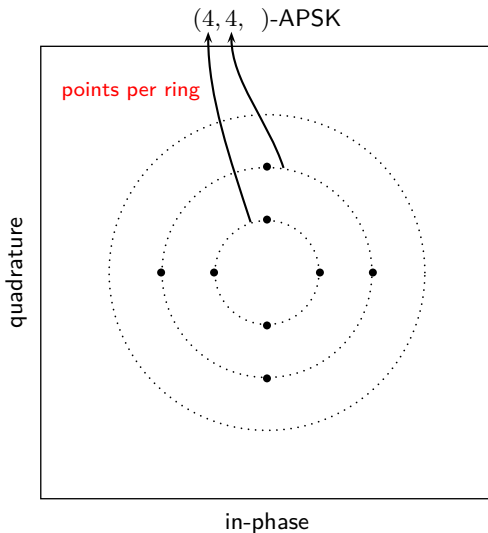
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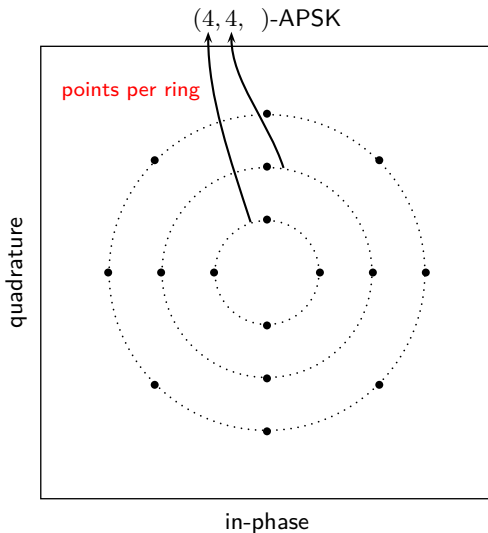
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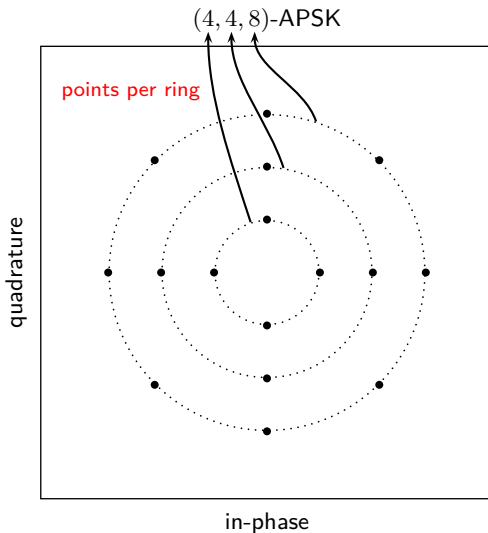
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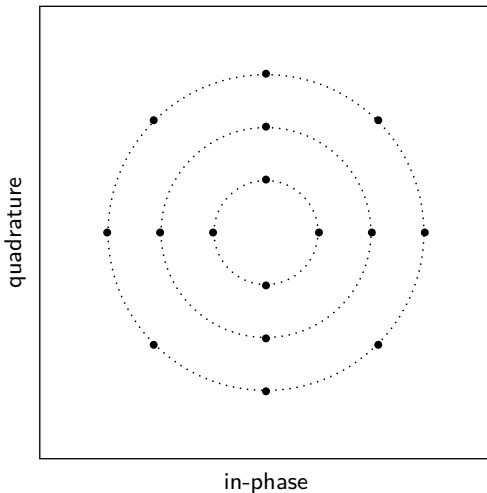


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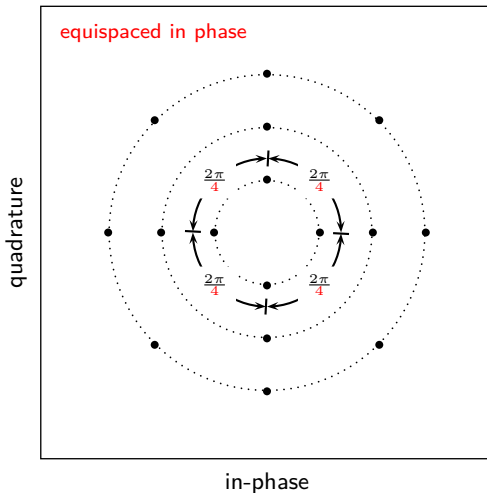
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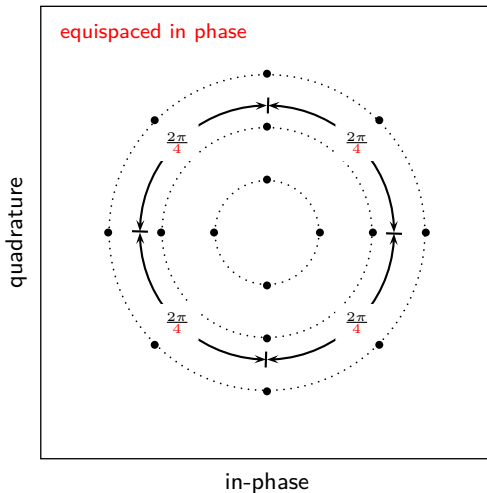
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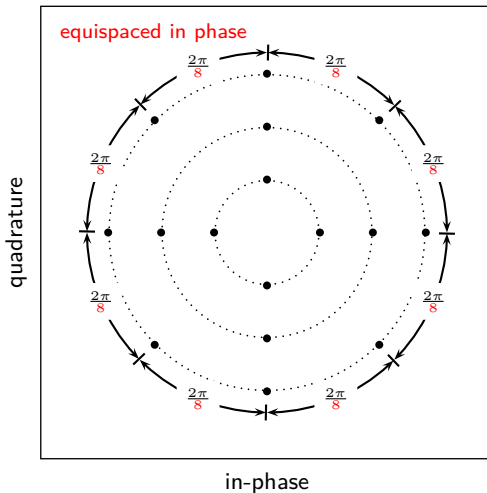
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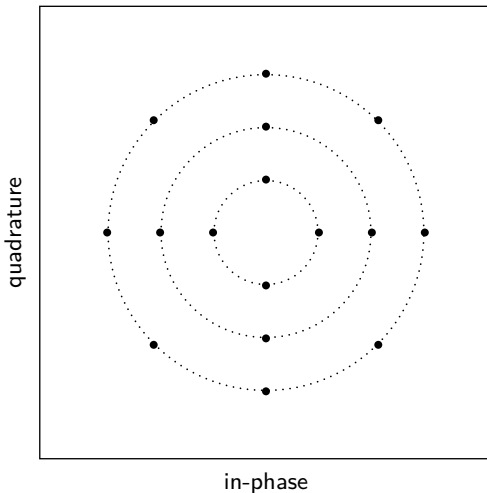
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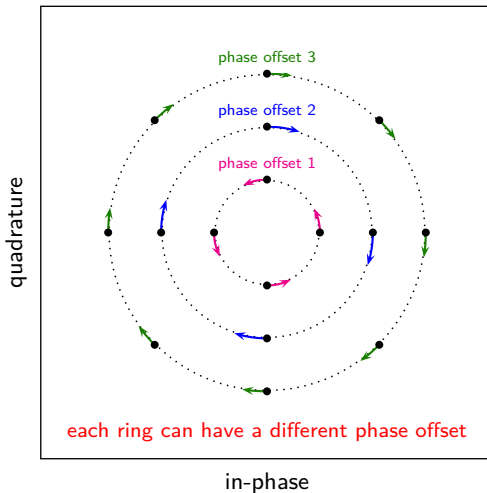
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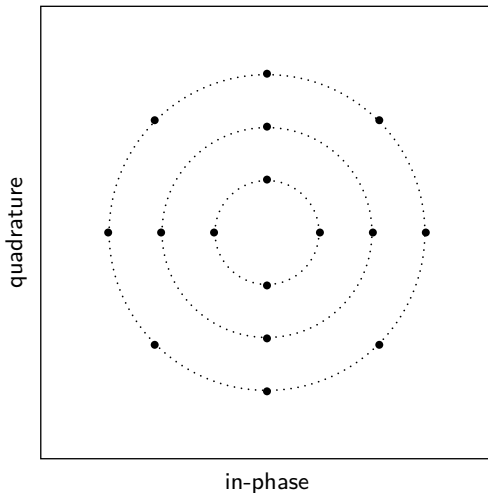
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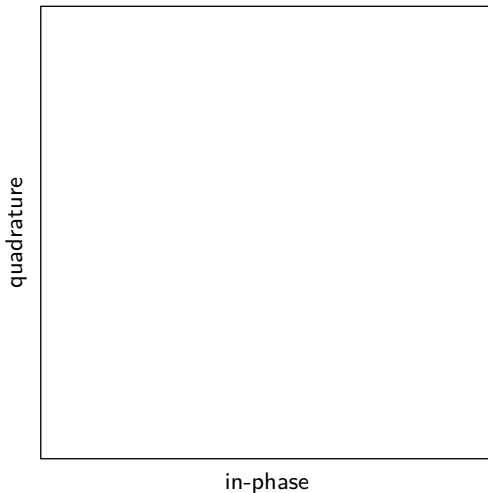


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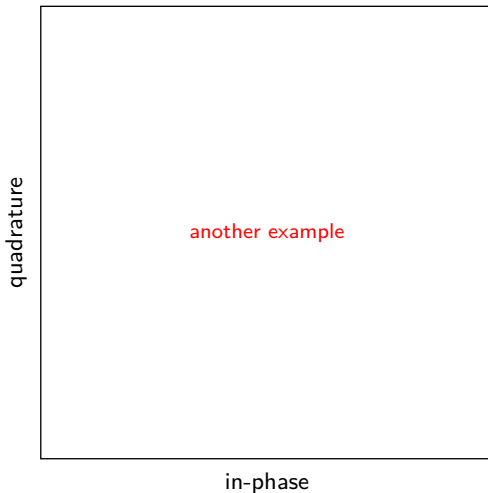
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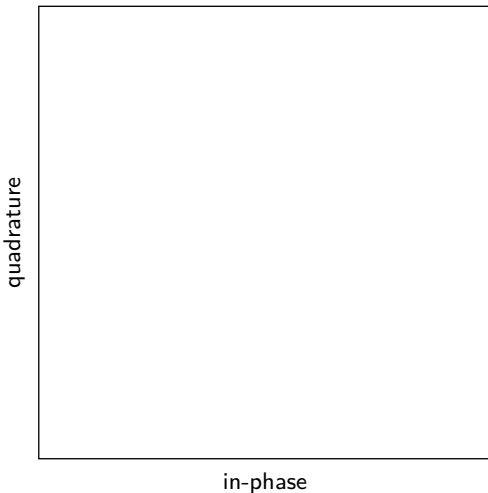


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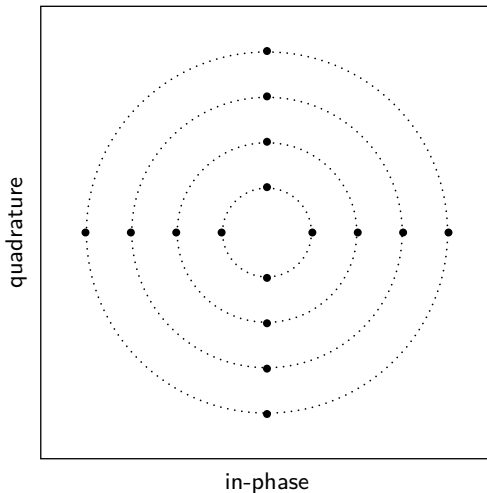
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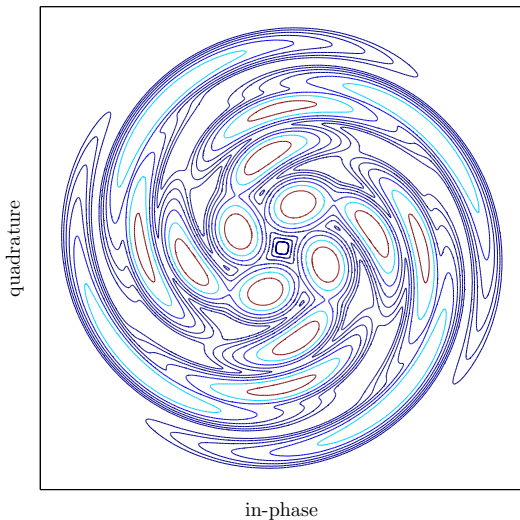
Amplitude Phase-Shift Keying (APSK), Example

(4, 4, 4, 4)-APSK

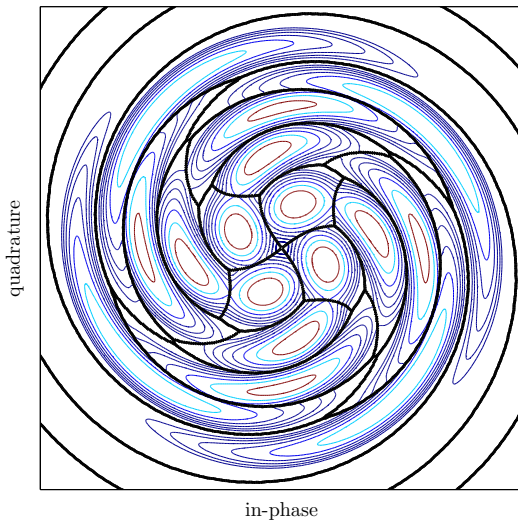


PDF for (4,4,4,4)-APSK at $P = -4$ dBm, $L = 5500$ km

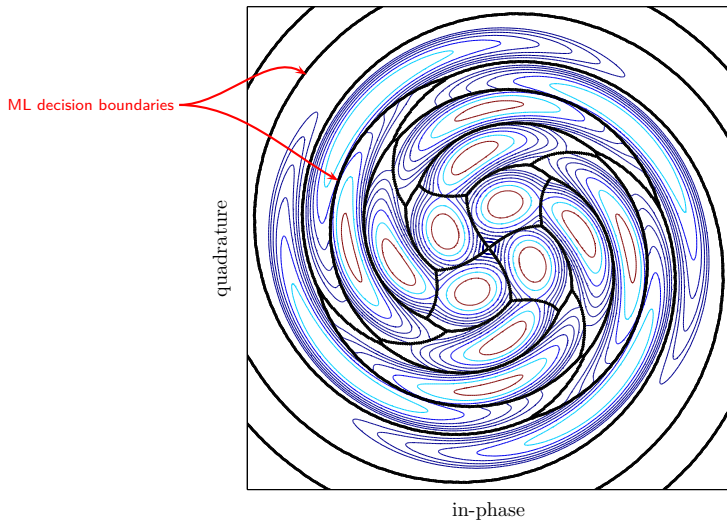
PDF for (4,4,4,4)-APSK at $P = -4$ dBm, $L = 5500$ km



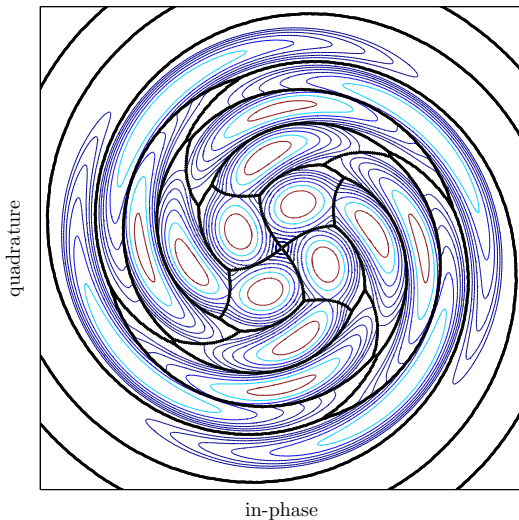
PDF for (4,4,4,4)-APSK at $P = -4$ dBm, $L = 5500$ km



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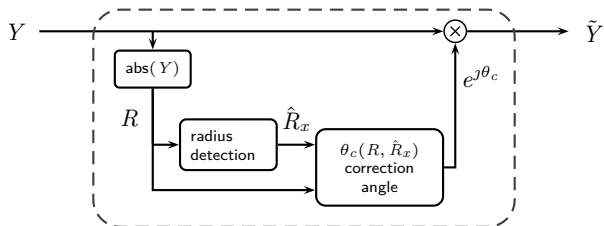
PDF for (4,4,4,4)-APSK at $P = -4$ dBm, $L = 5500$ km



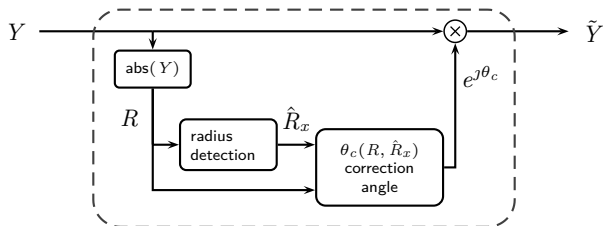
ML detection possible,
but not practical.

Nonlinear Phase Postcompensation

Nonlinear Phase Postcompensation

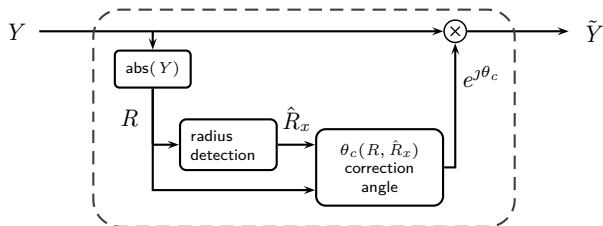


Nonlinear Phase Postcompensation



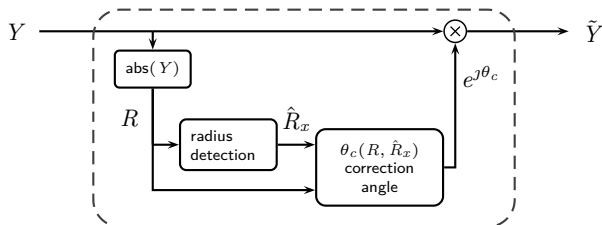
- Building block for suboptimal (but practical) **two-stage detector**

Nonlinear Phase Postcompensation



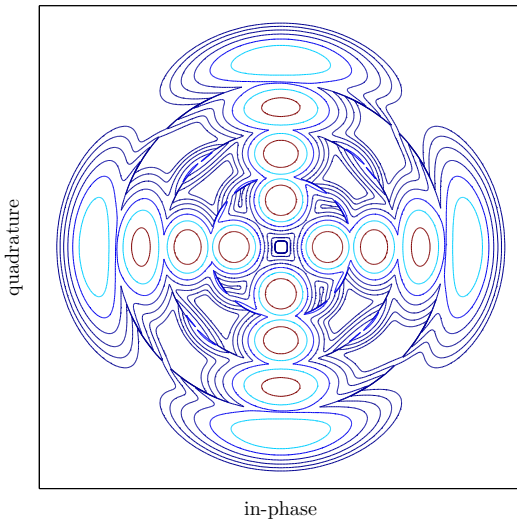
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Nonlinear Phase Postcompensation

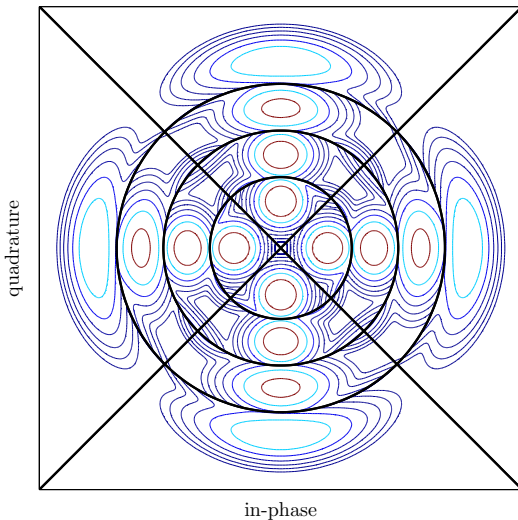


- Building block for suboptimal (but practical) **two-stage detector**
- Characterization of the PDF of \tilde{Y}
- Necessary to compute, e.g., bit error probability

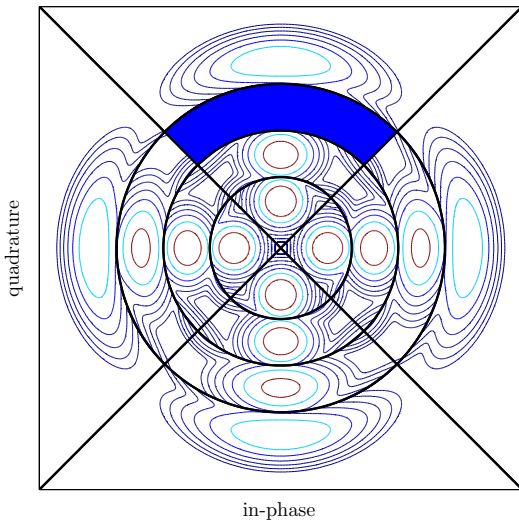
Two-Stage Detection



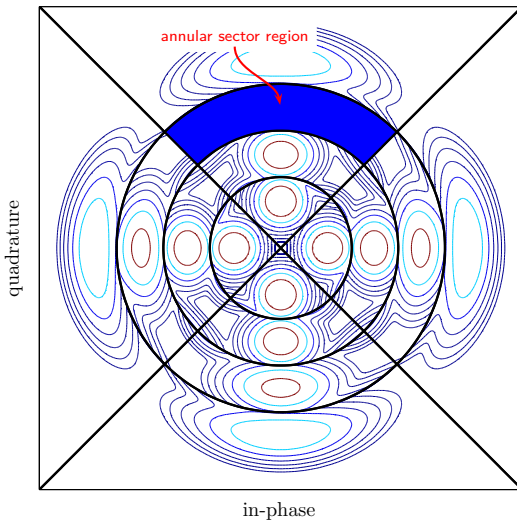
Two-Stage Detection



Two-Stage Detection

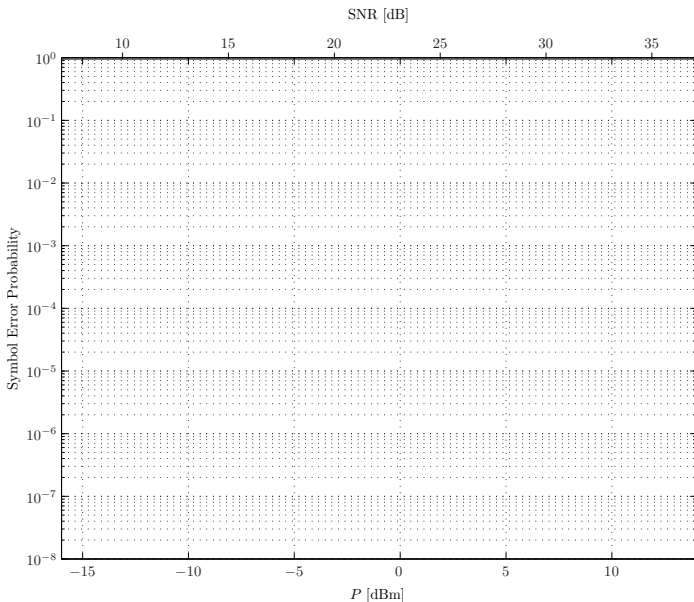


Two-Stage Detection

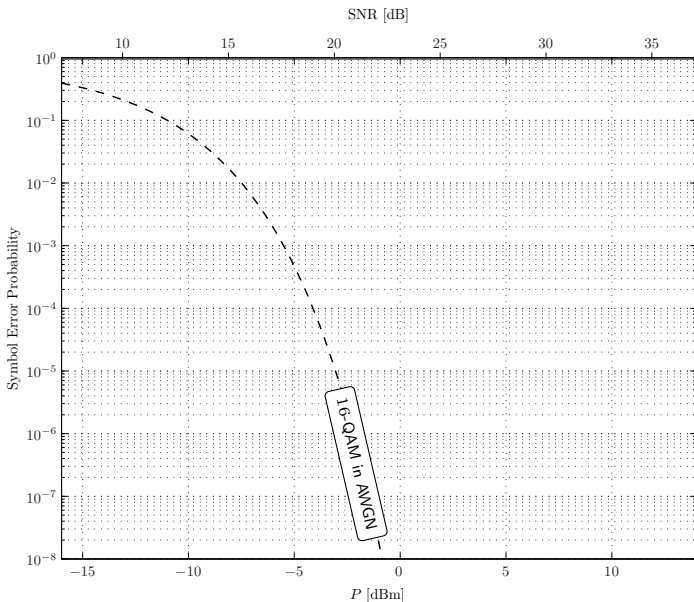


Optimizing the Number of Rings and Points per Ring

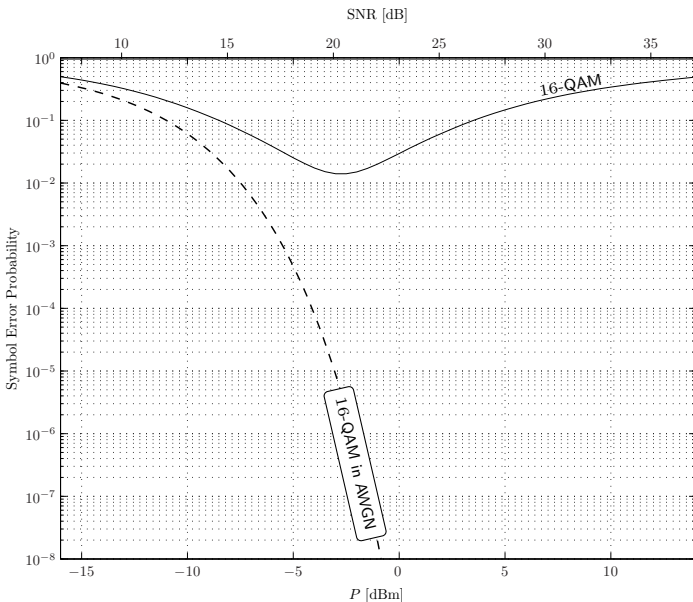
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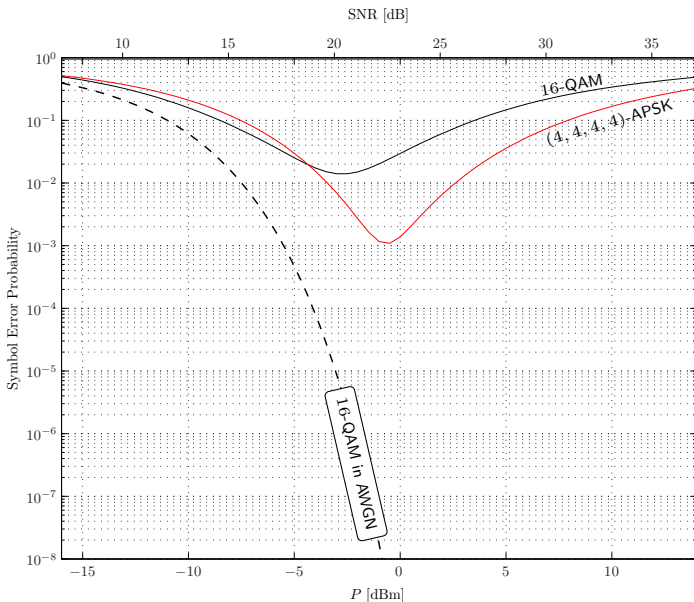
Optimizing the Number of Rings and Points per Ring



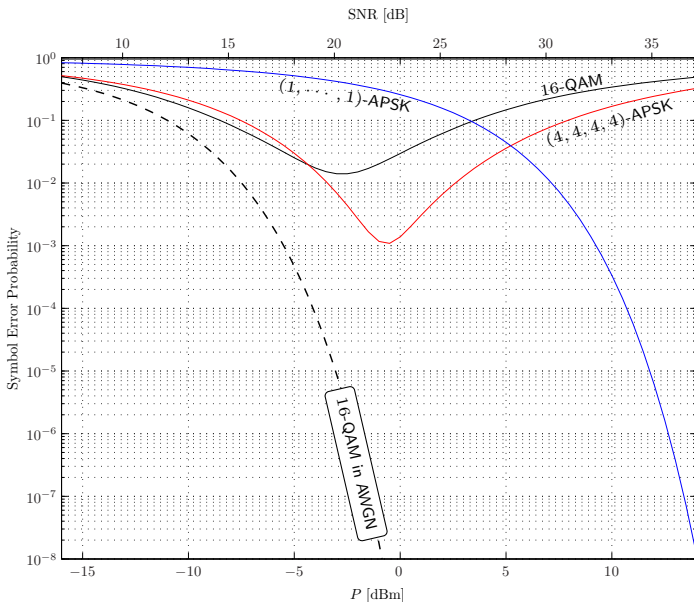
Optimizing the Number of Rings and Points per Ring



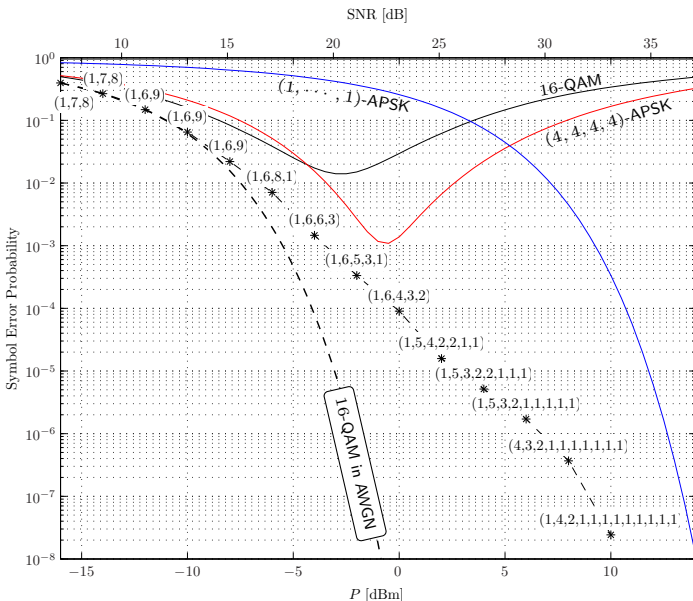
Optimizing the Number of Rings and Points per Ring



Optimizing the Number of Rings and Points per Ring



Optimizing the Number of Rings and Points per Ring



Zero-Dispersion Fiber with Polarization Multiplexed Signals

Zero-Dispersion Fiber with Polarization Multiplexed Signals

- Extension of the previous channel model to **polarization multiplexed signals**

Zero-Dispersion Fiber with Polarization Multiplexed Signals

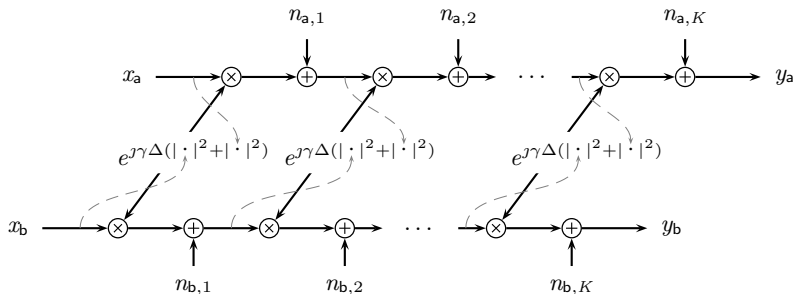
- Extension of the previous channel model to **polarization multiplexed signals**
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Zero-Dispersion Fiber with Polarization Multiplexed Signals

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Zero-Dispersion Fiber with Polarization Multiplexed Signals

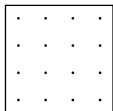
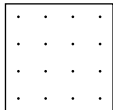
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Power Dependent Phase Noise

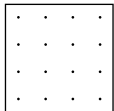
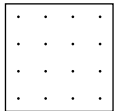
Power Dependent Phase Noise

PM-16-QAM



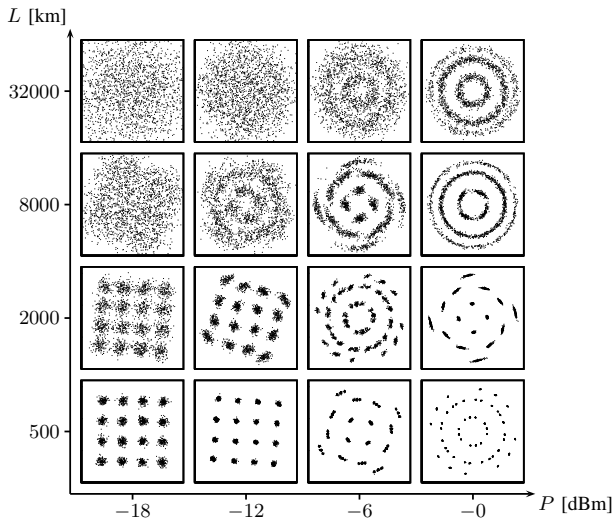
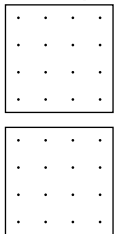
Power Dependent Phase Noise

PM-16-QAM



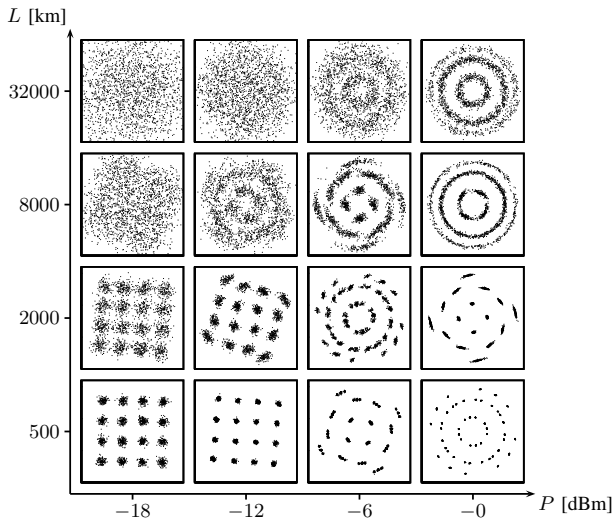
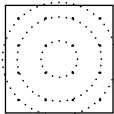
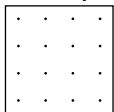
Power Dependent Phase Noise

PM-16-QAM



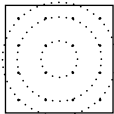
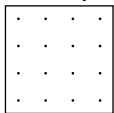
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PM-16-QAM

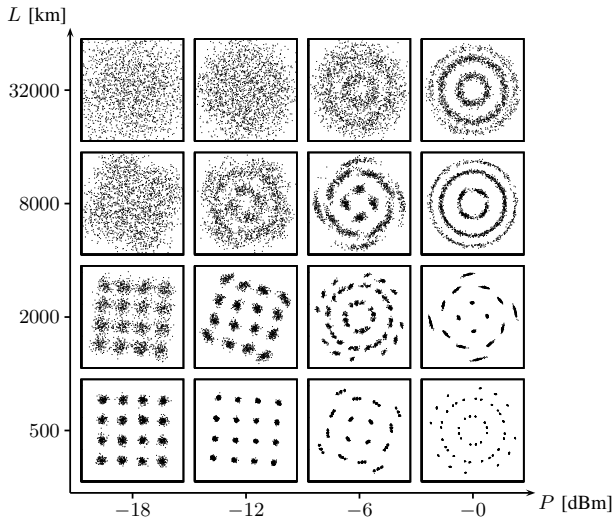


Power Dependent Phase Noise

PM-16-QAM



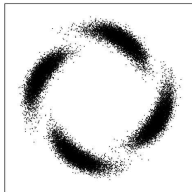
Simplification: PM- M -PSK
(only one amplitude level)



Nonlinear Phase Compensation

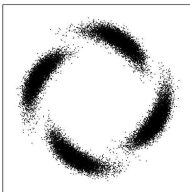
Nonlinear Phase Compensation

Scatterplot for pol. a

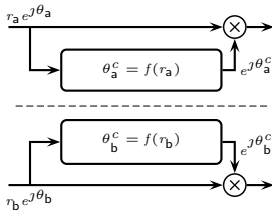


Nonlinear Phase Compensation

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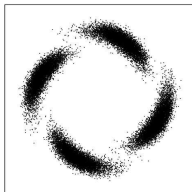


separate compensation in each polarization

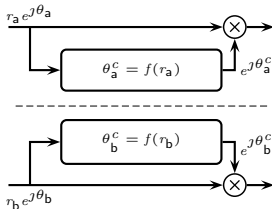


Nonlinear Phase Compensation

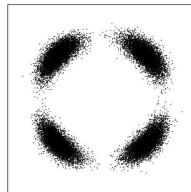
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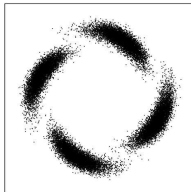


after compensation

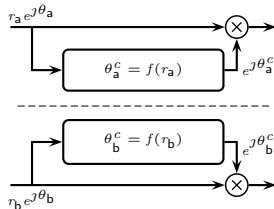


Nonlinear Phase Compensation

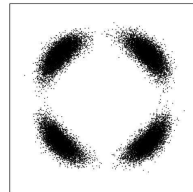
Scatterplot for pol. a



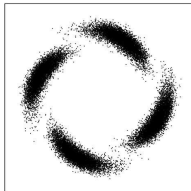
separate compensation in each polarization



after compensation

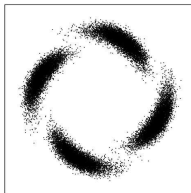


Scatterplot for pol. a

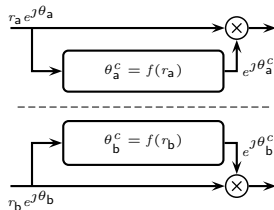


Nonlinear Phase Compensation

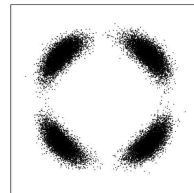
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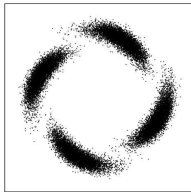
separate compensation in each polarization



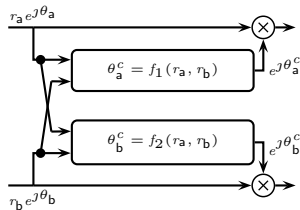
after compensation



Scatterplot for pol. a

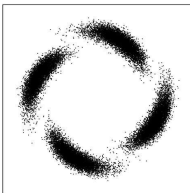


compensation based on both received amplitudes

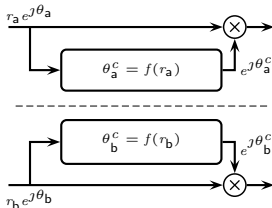


Nonlinear Phase Compensation

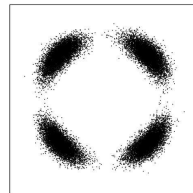
Scatterplot for pol. a



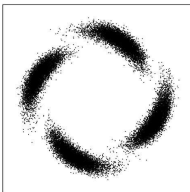
separate compensation in each polarization



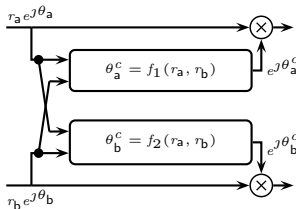
after compensation



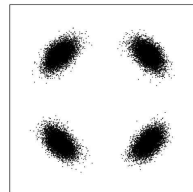
Scatterplot for pol. a



compensation based on both received amplitudes

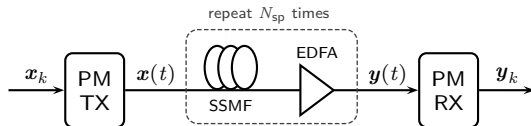


after compensation

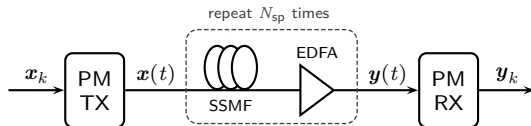


less phase noise → better SER

Channel Model for PM Transmission including Dispersion

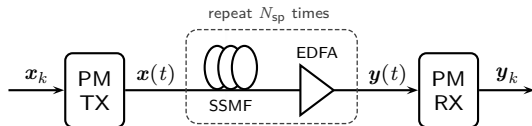


Channel Model for PM Transmission including Dispersion



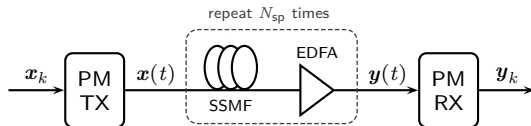
- Dispersive fibers, $\beta_2 \neq 0$

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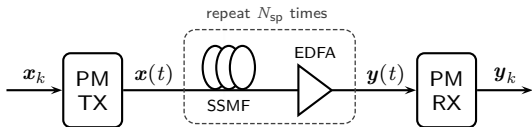
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Channel Model for PM Transmission including Dispersion



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- Under some assumptions, several works give theoretical justification for a **Gaussian noise (GN) model**, e.g., [Beygi et al., 2012], [Carena et al., 2012]

Illustration of the Statistical Relationship

Illustration of the Statistical Relationship

PM-16-QAM

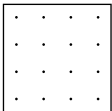
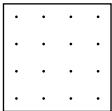


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PM-16-QAM

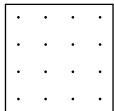
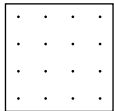
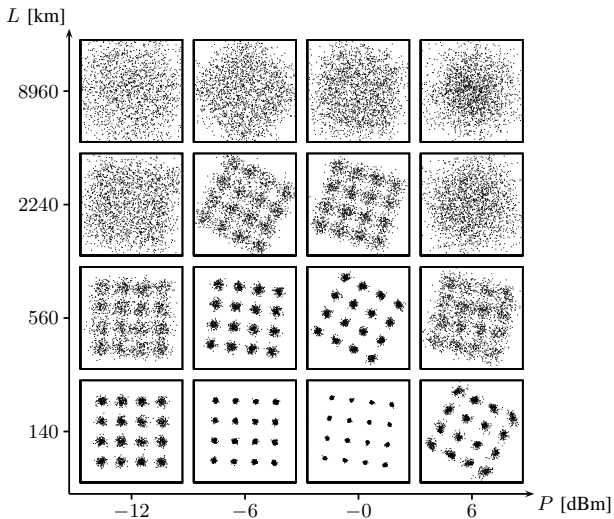
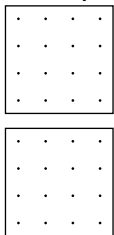
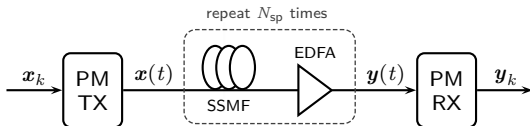


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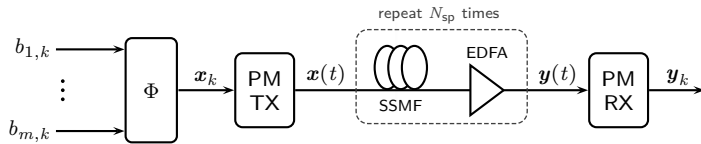
PM-16-QAM



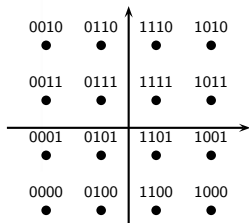
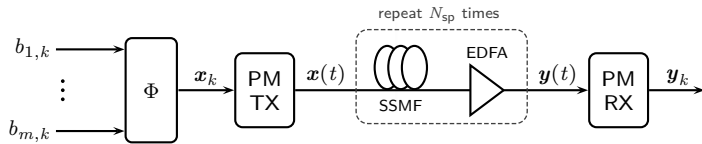
Bit Mapper Optimization for Soft-Decision FEC



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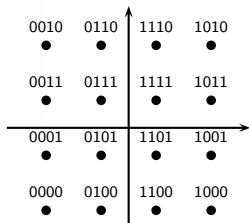
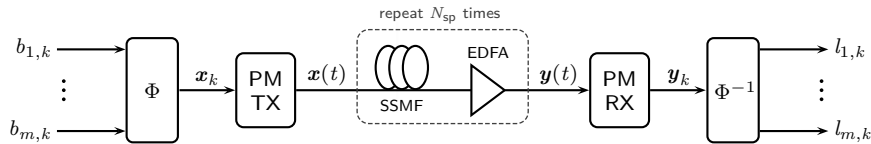


Bit Mapper Optimization for Soft-Decision FEC



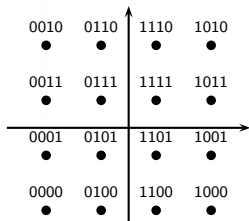
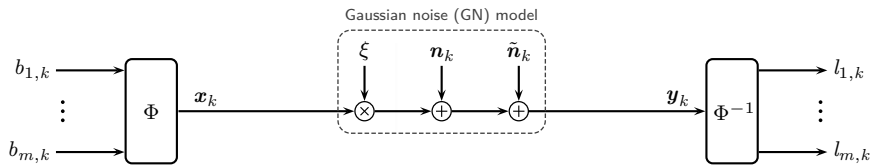
(in both polarizations)

Bit Mapper Optimization for Soft-Decision FEC



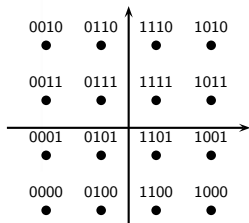
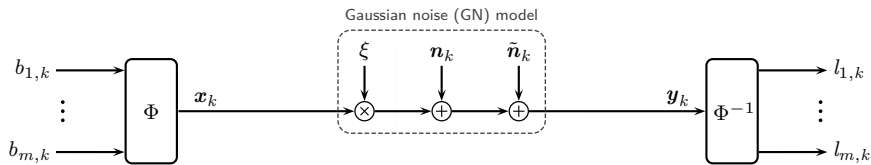
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Bit Mapper Optimization for Soft-Decision FEC

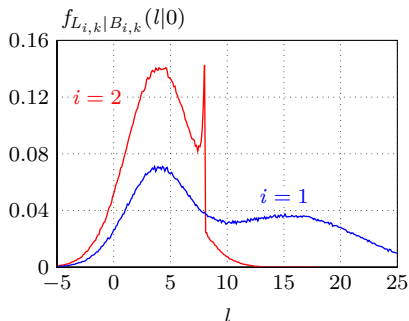


(in both polarizations)

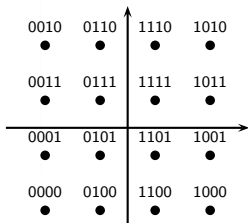
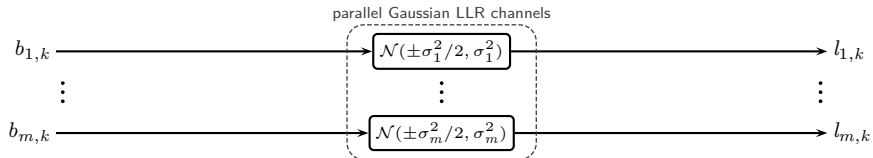
Bit Mapper Optimization for Soft-Decision FEC



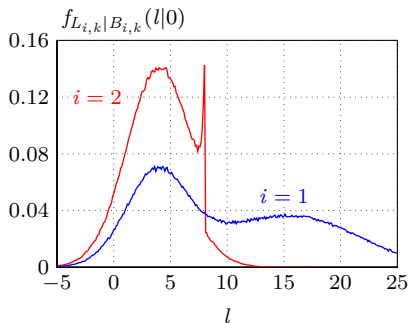
(in both polarizations)



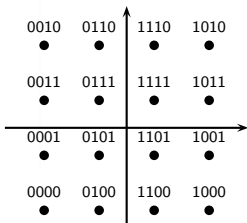
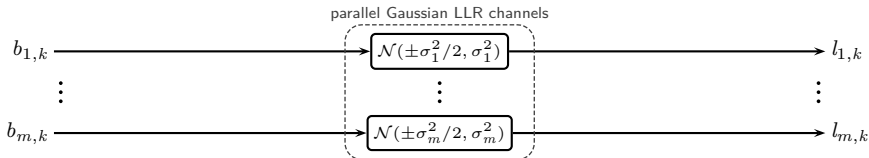
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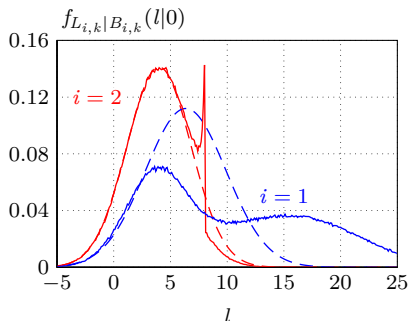
(in both polarizations)



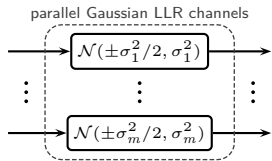
Bit Mapper Optimization for Soft-Decision FEC



(in both polarizations)

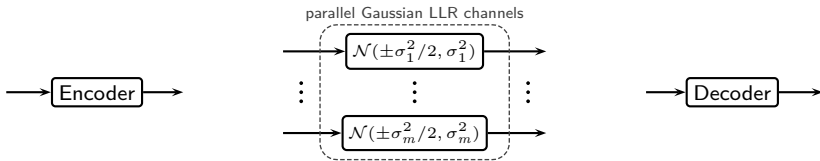


Bit Mapper Optimization for Soft-Decision FEC



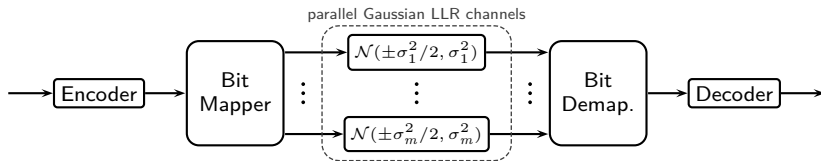
- Approximate setup: **parallel Gaussian LLR channels with different qualities** (constellation size determines the number of channels)

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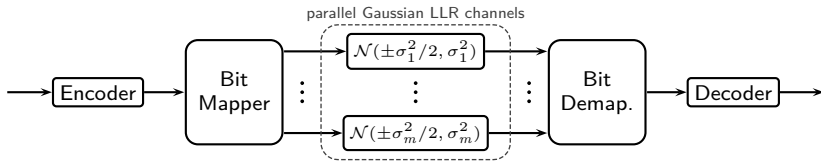
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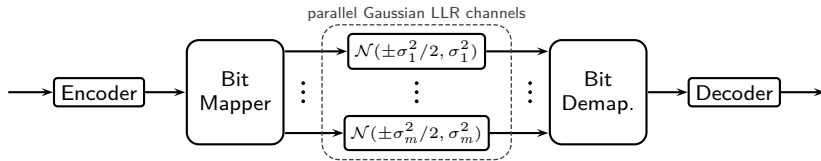
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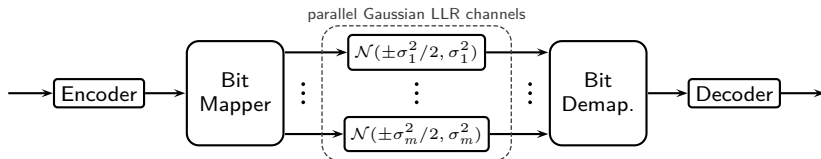
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$$\text{codeword} = (c_1, c_2, c_3, c_4, c_5, c_6, \dots)$$

Protograph LDPC Codes

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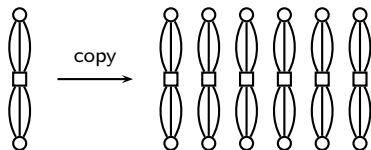
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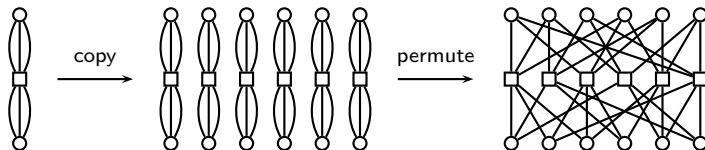
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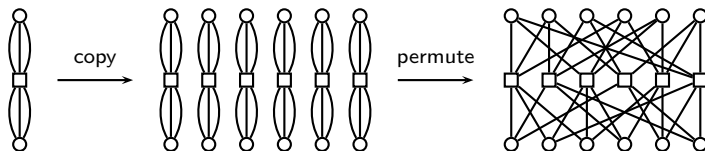
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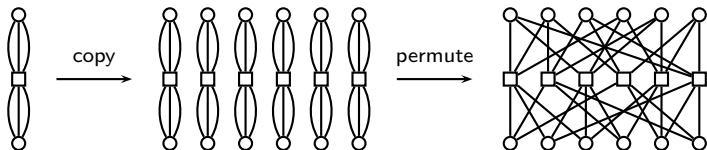
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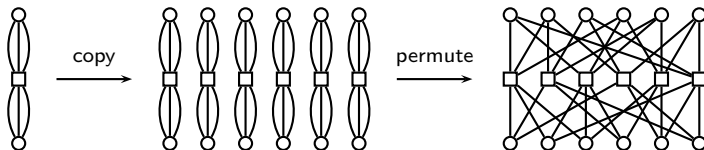
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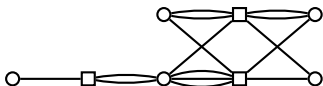
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Protograph LDPC Codes

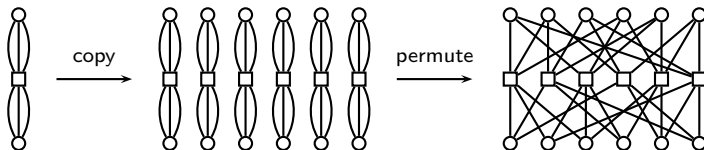


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AR4JA codes

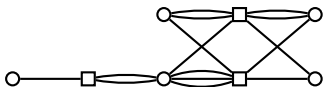


Protograph LDPC Codes

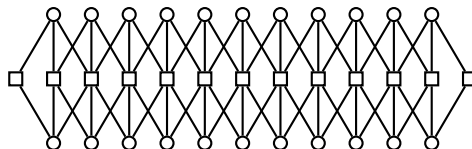


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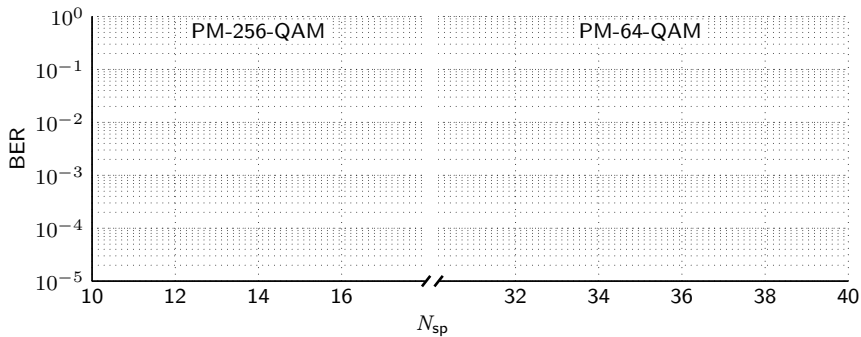
AR4JA codes



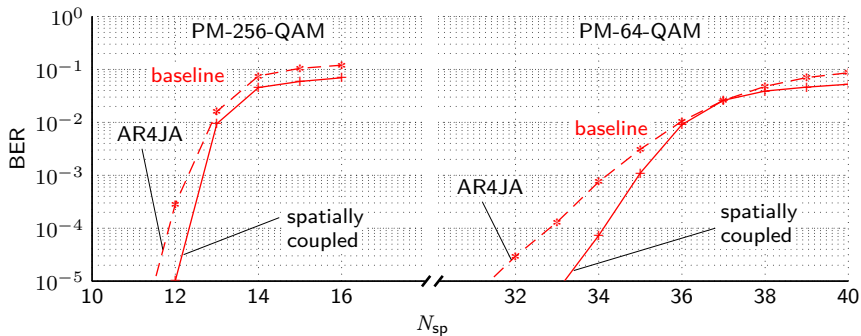
spatially coupled LDPC codes



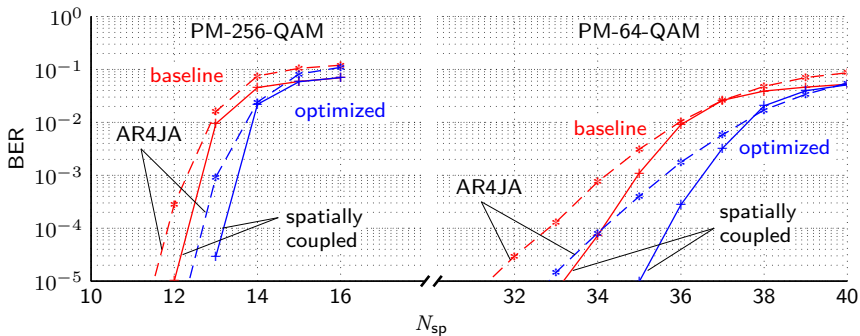
Results



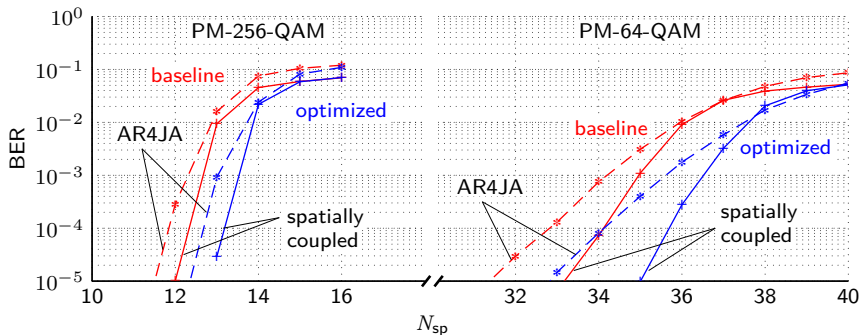
Results



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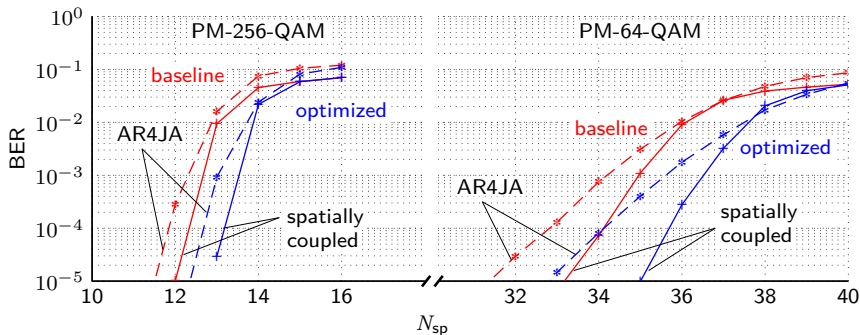


Results



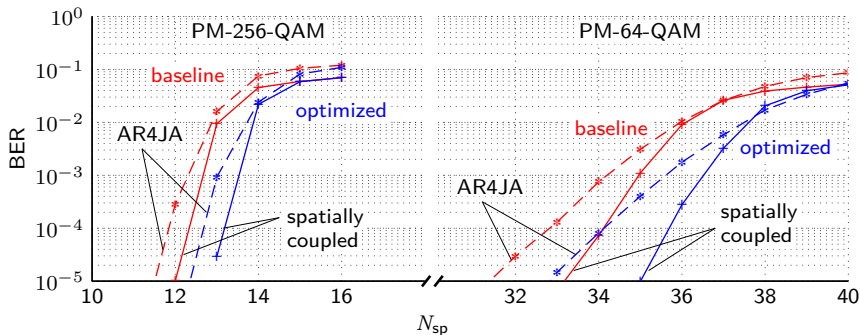
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Results



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- Full-field simulations justify the GN model approximation and parallel Gaussian LLR channel approximation

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Thank you!



References



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