

# 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,  
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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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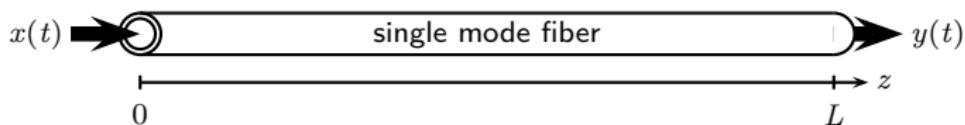
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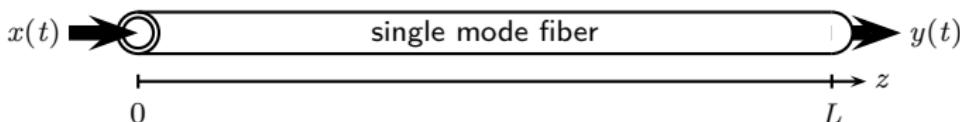
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4. Bit mapper optimization for protograph codes

# Fiber-Optical Channel Modeling

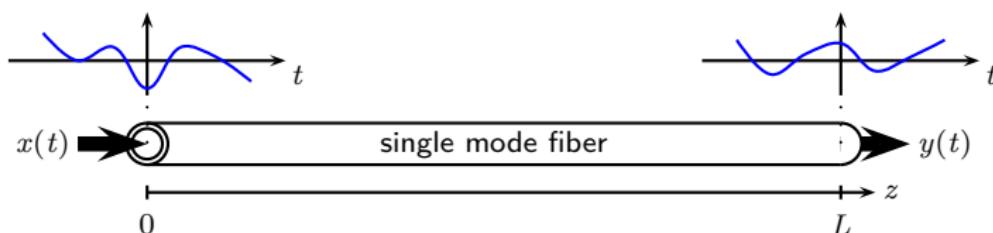


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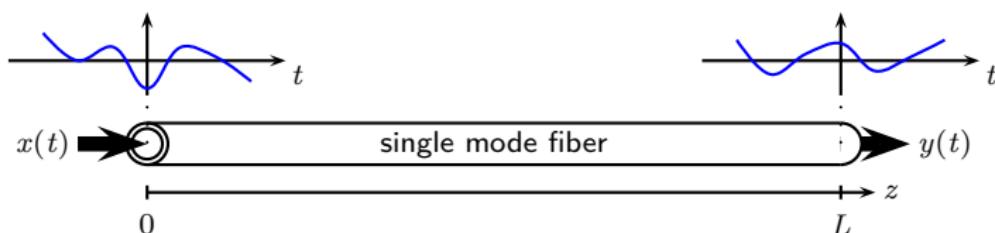
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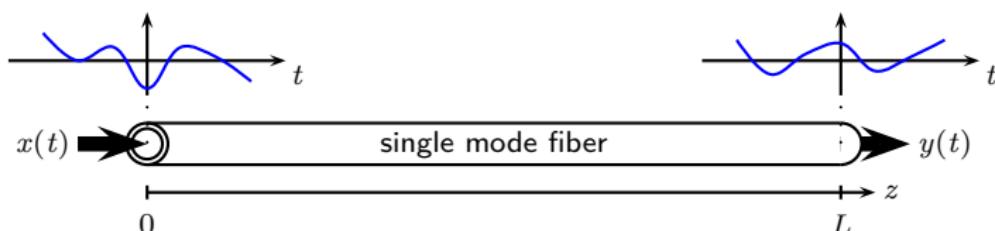
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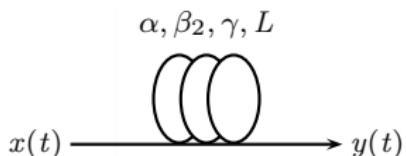


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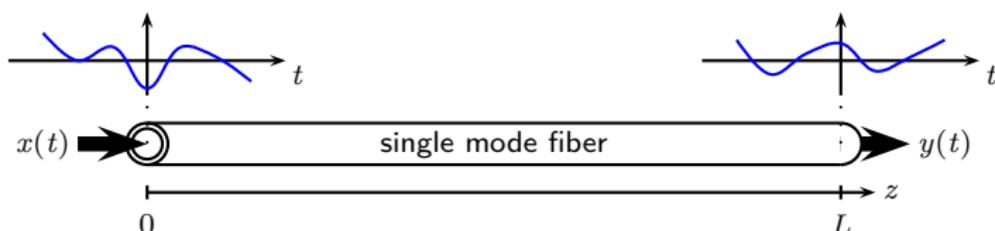
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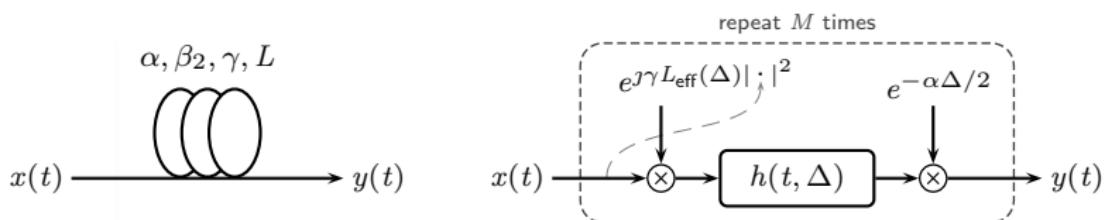
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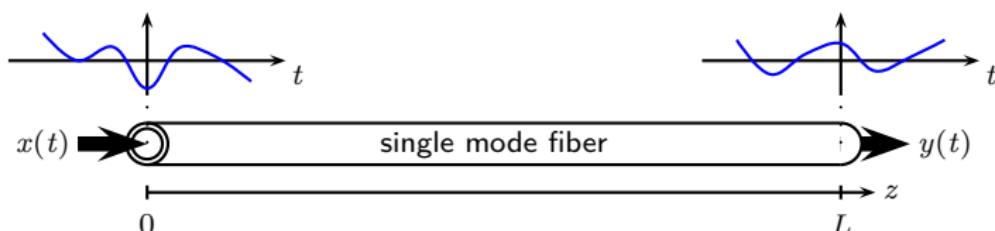
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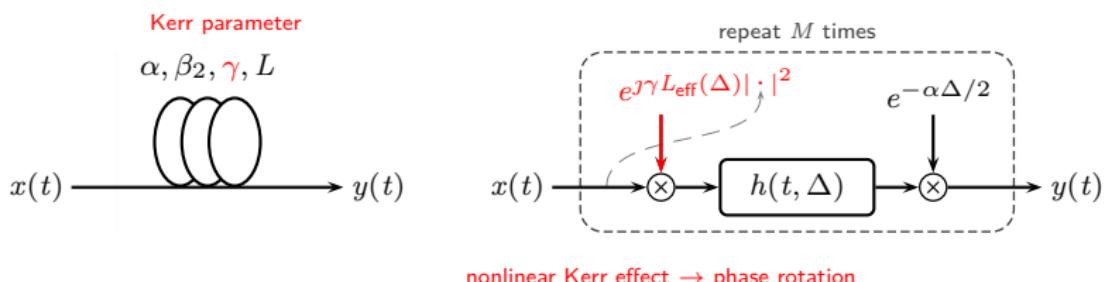
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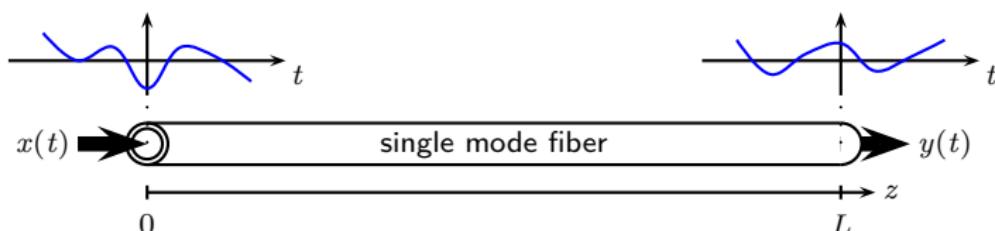
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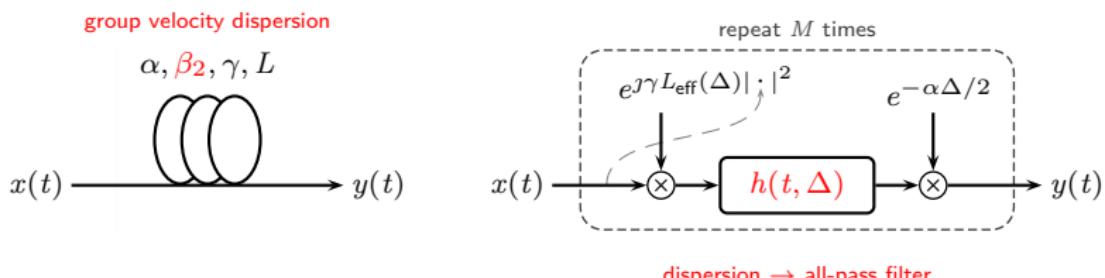
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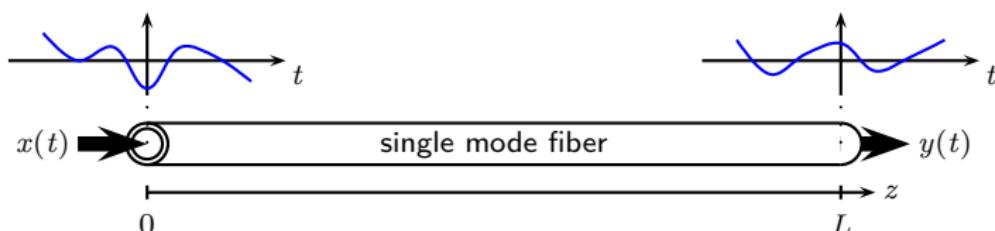
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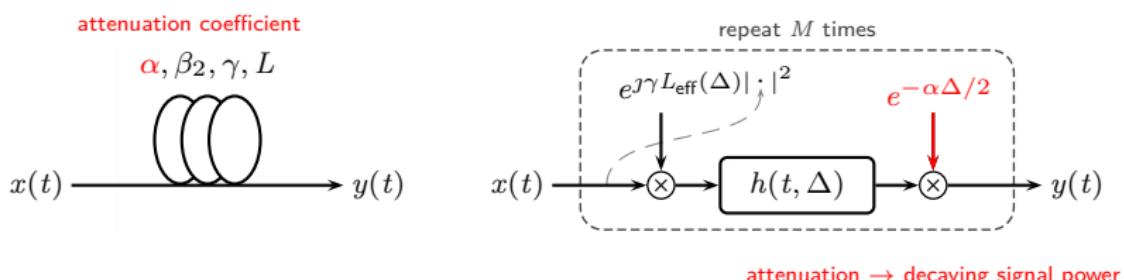
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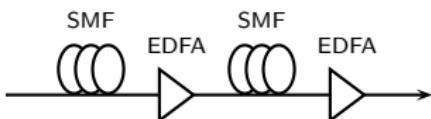
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- Periodic **signal amplification** along the transmission path **leads to noise**

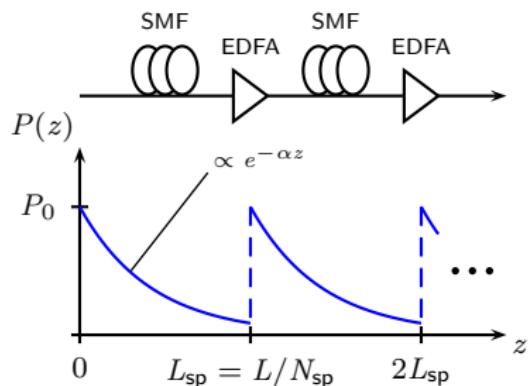
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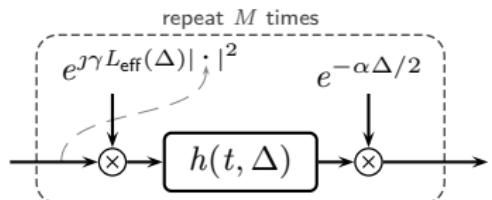
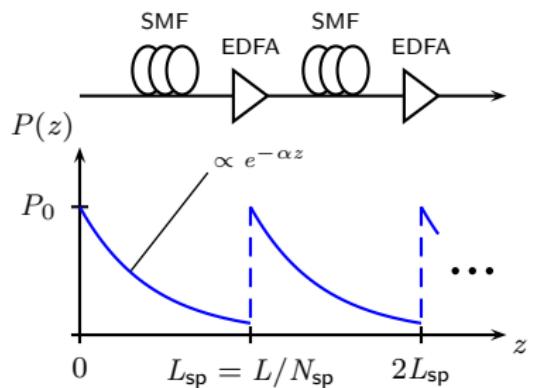
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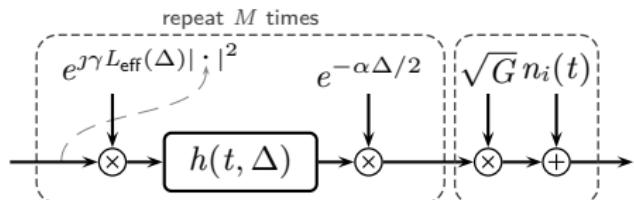
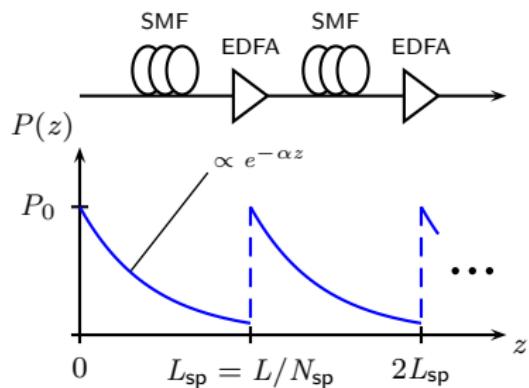
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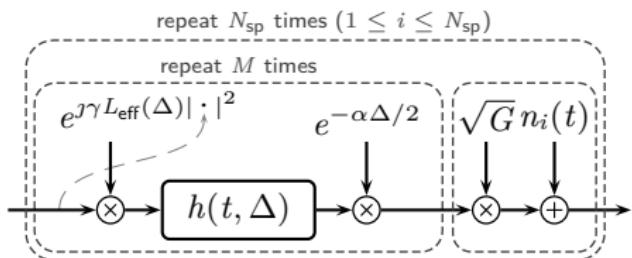
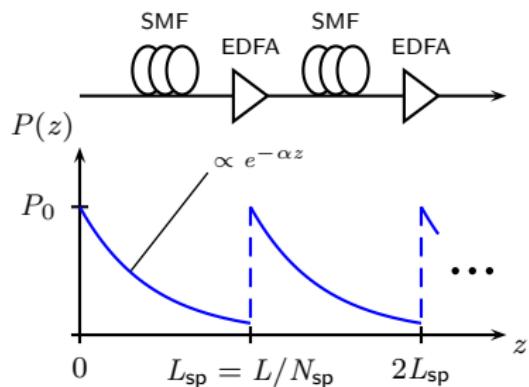
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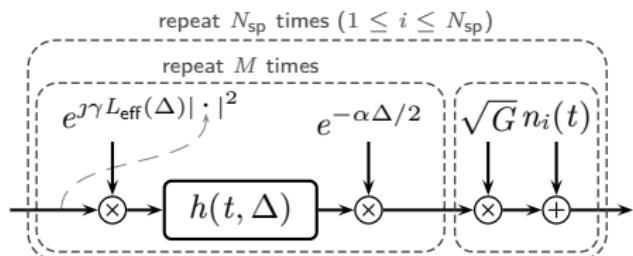
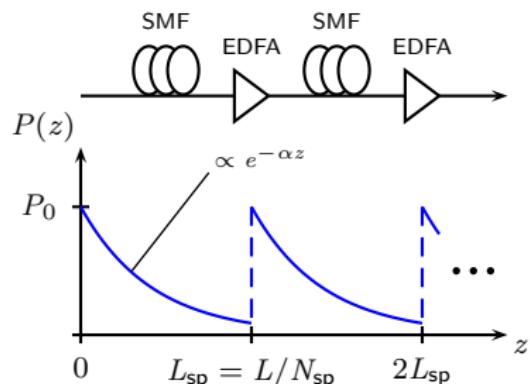
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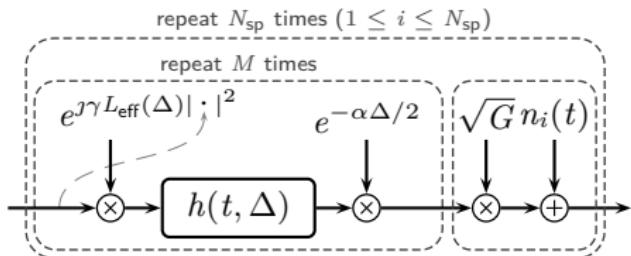
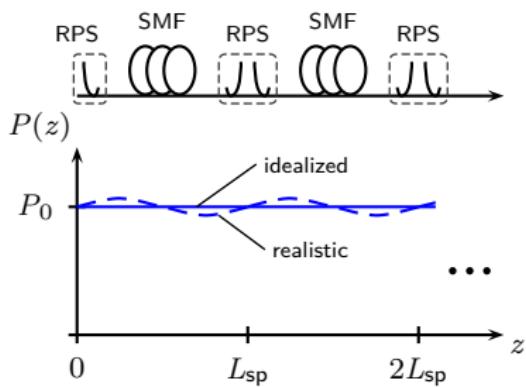
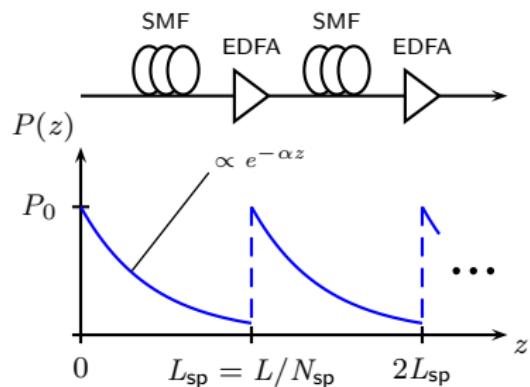
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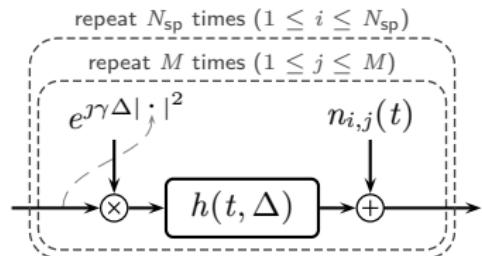
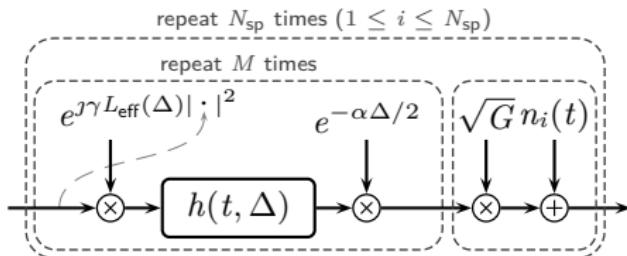
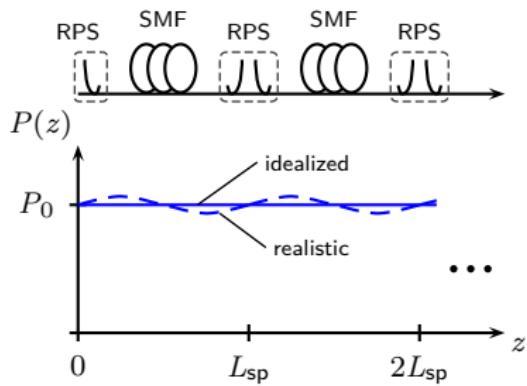
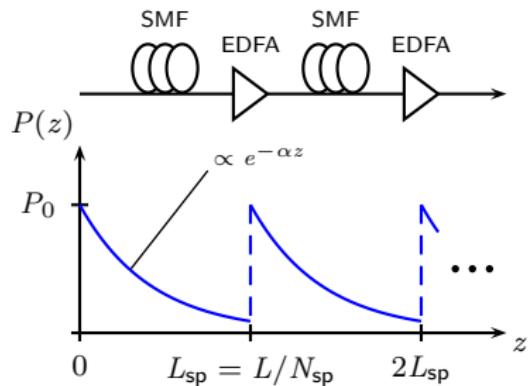
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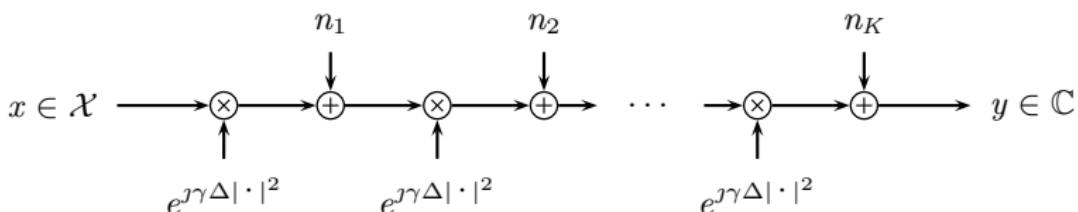
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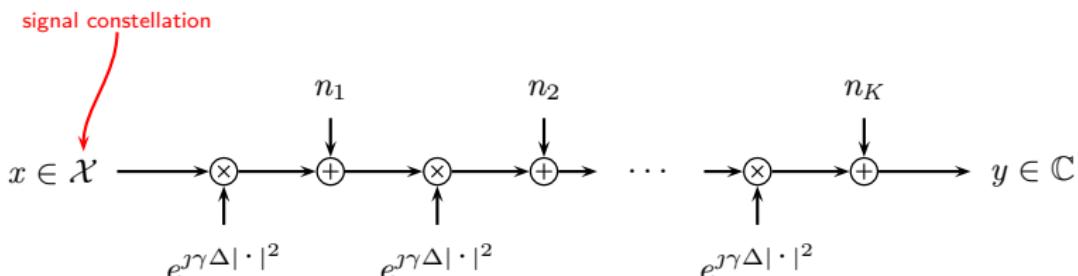
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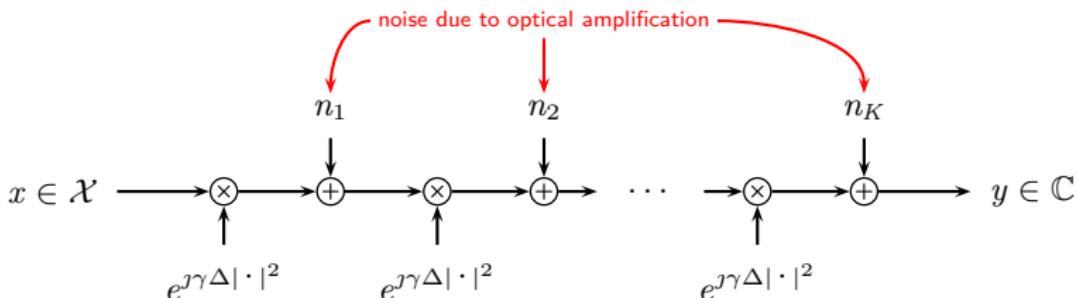
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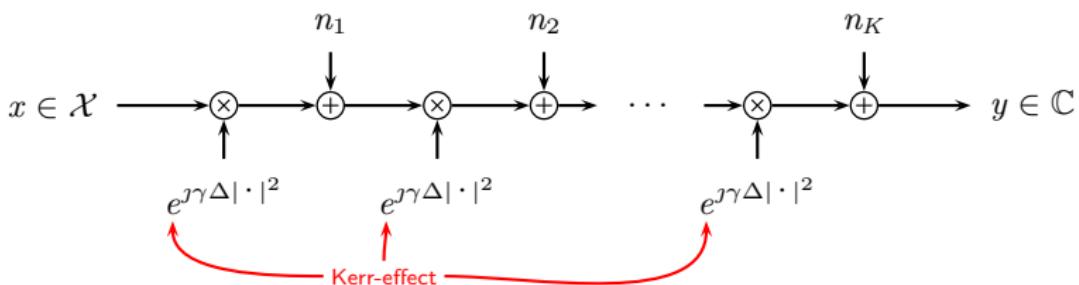
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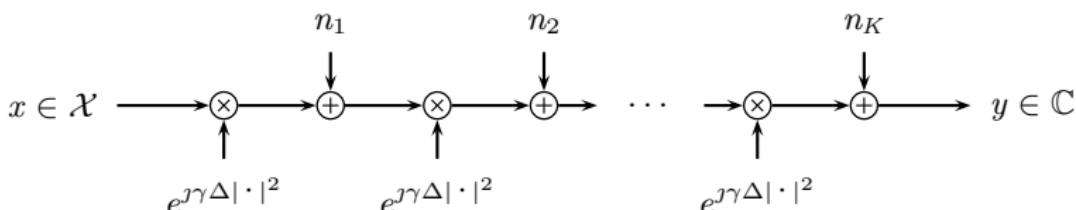
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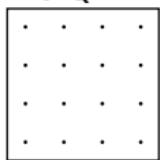


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- Extensive work on this model, e.g., [Mecozzi, 1994], [Turitsyn et al., 2003], [Ho, 2005], [Yousefi and Kschischang, 2011]

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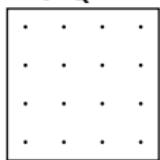
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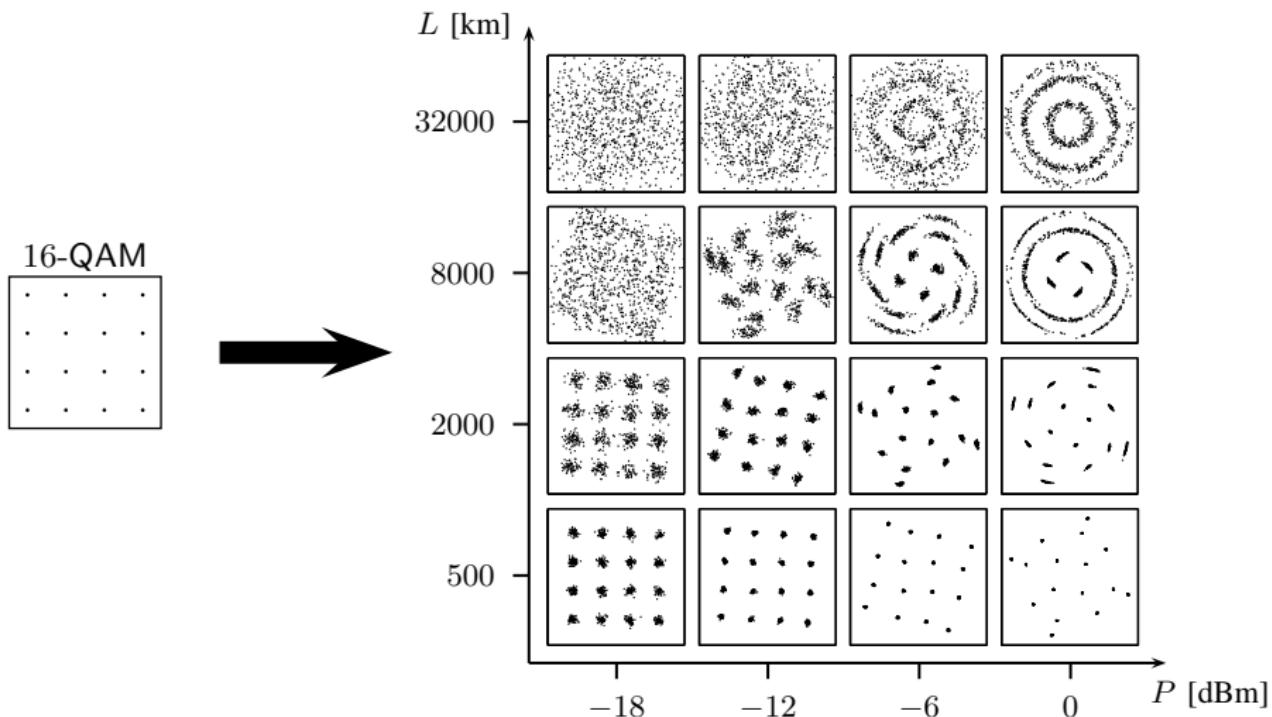


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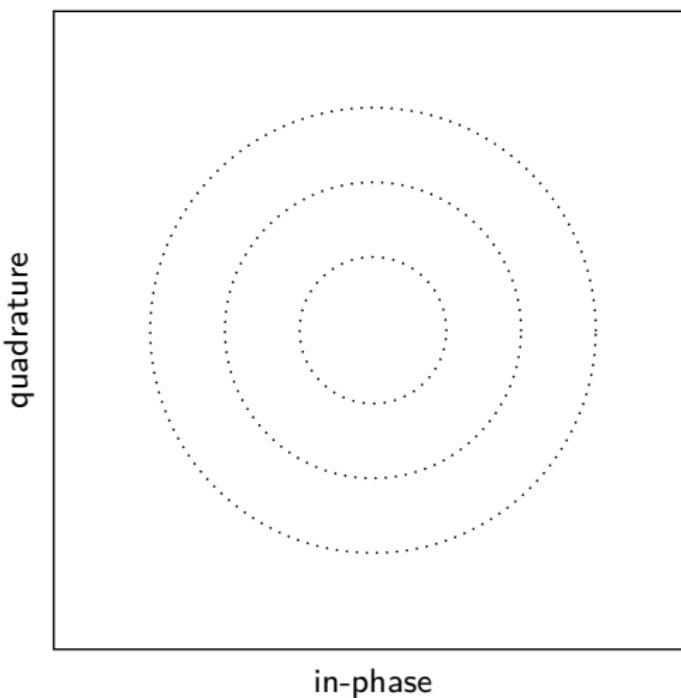
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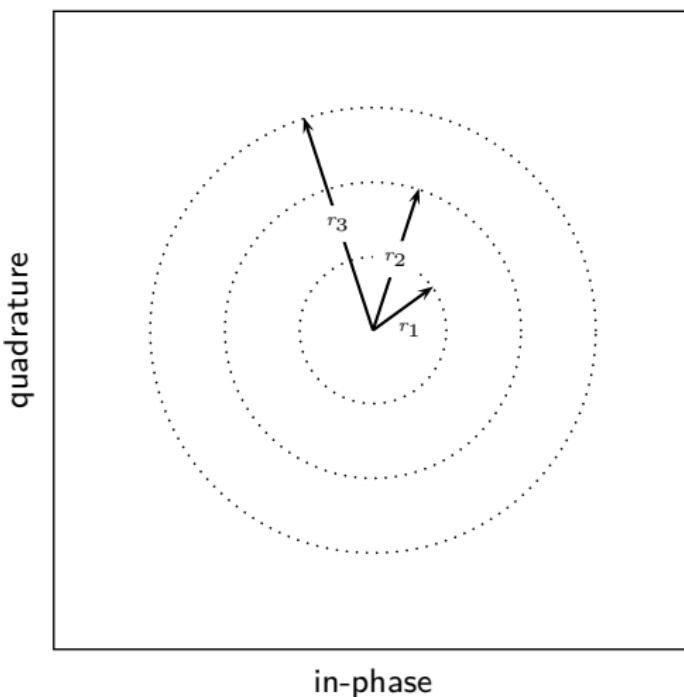
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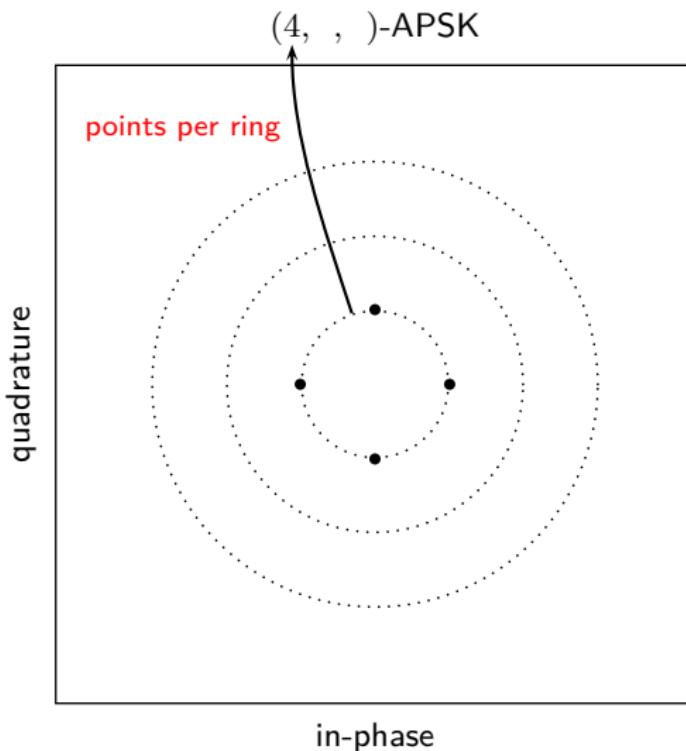


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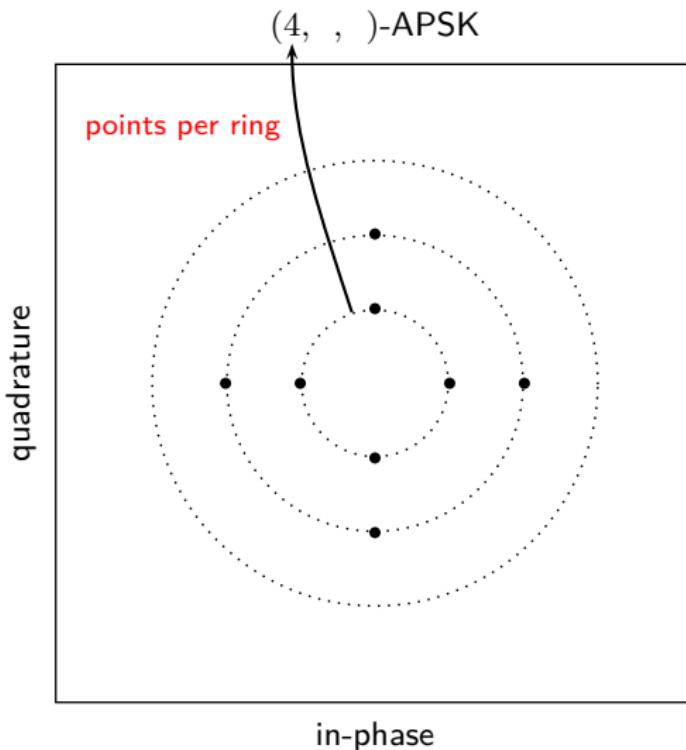
( , , )-APSK



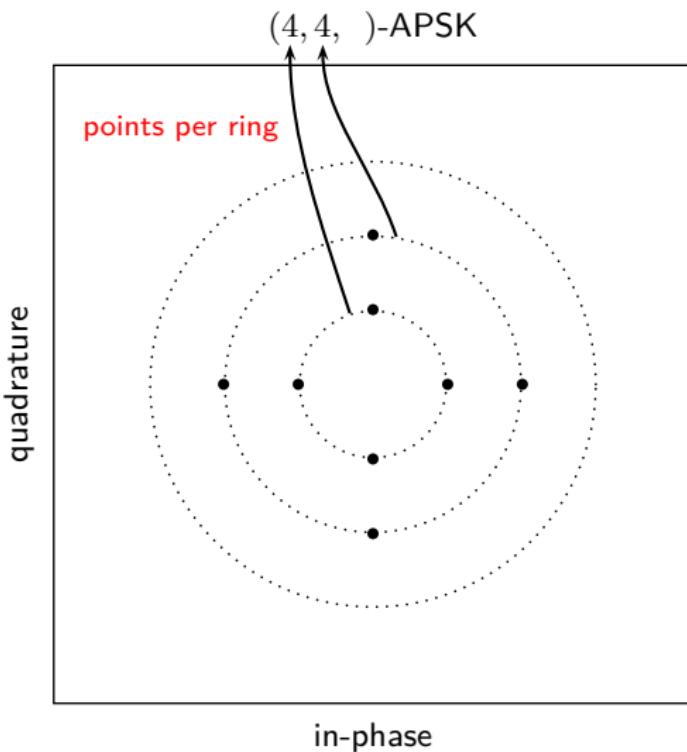
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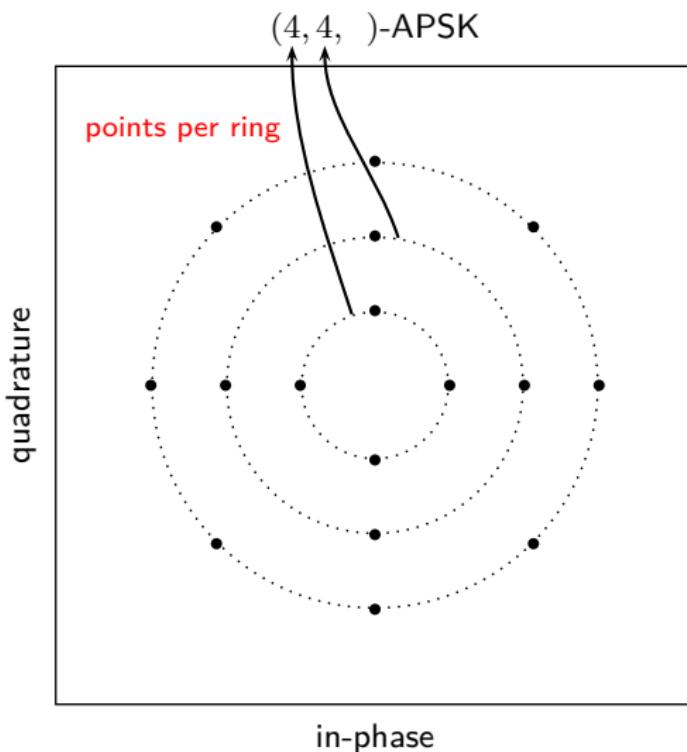
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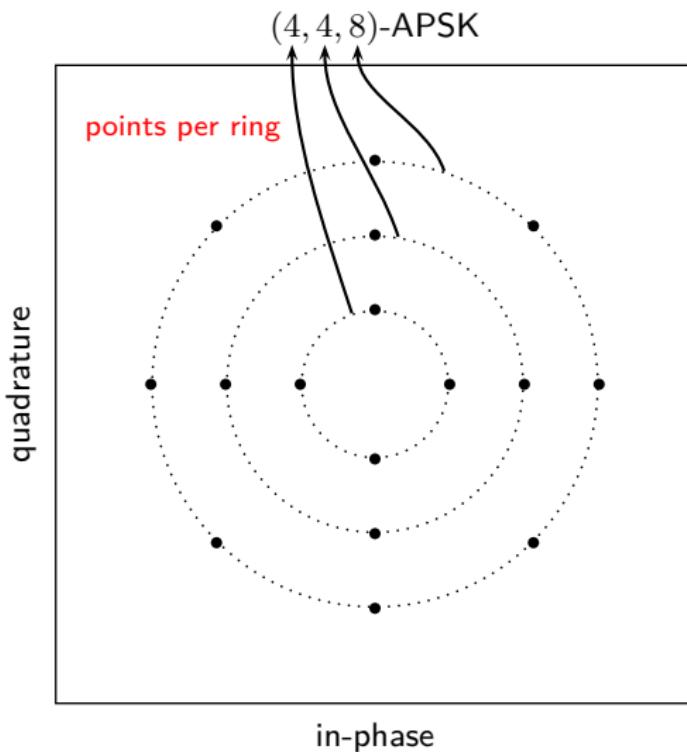
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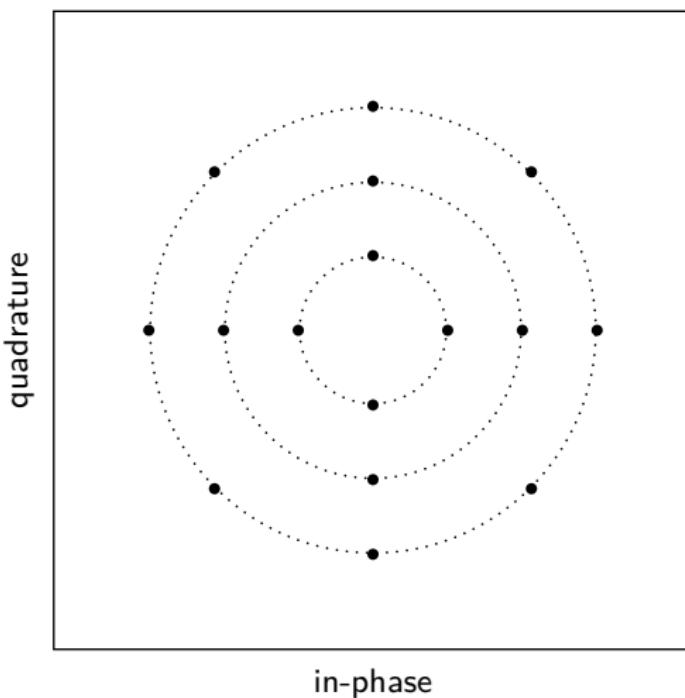


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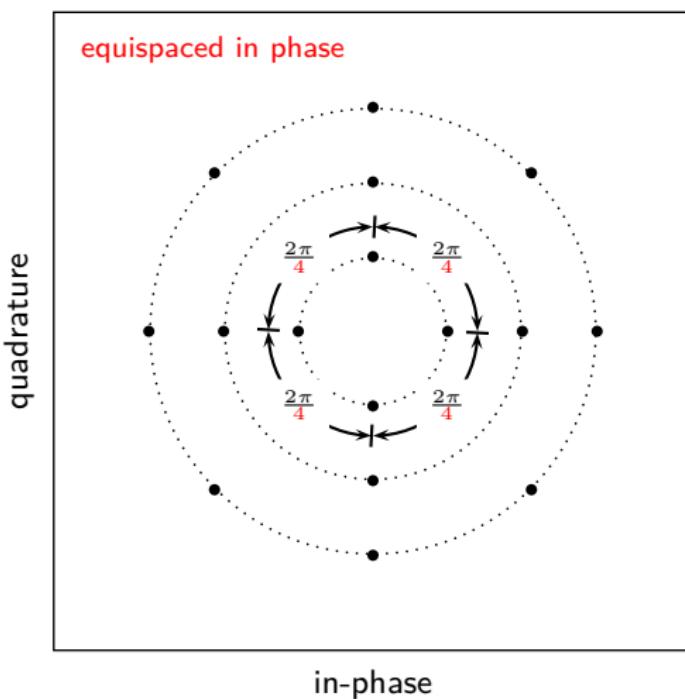
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(4, 4, 8)-APSK



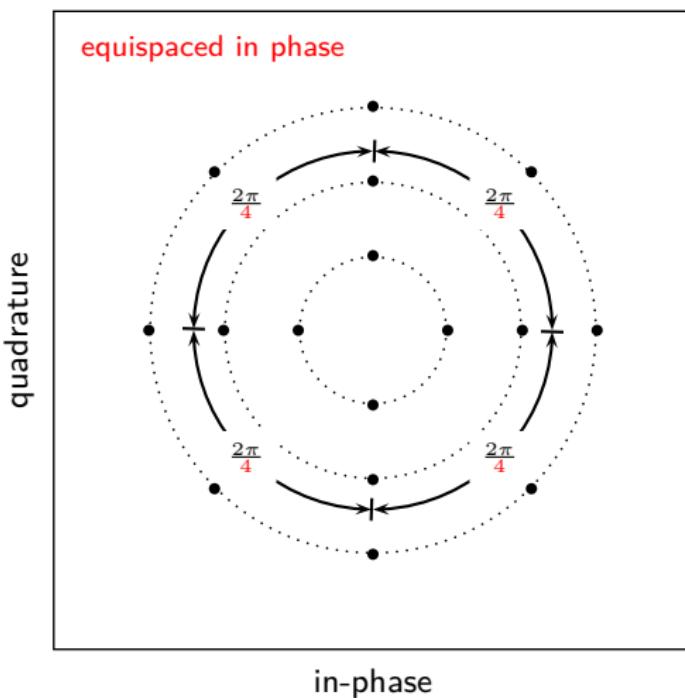
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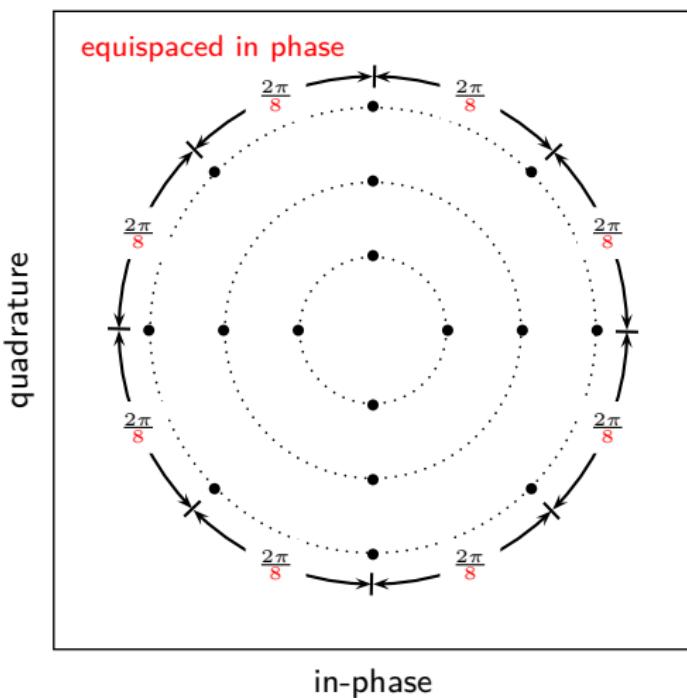
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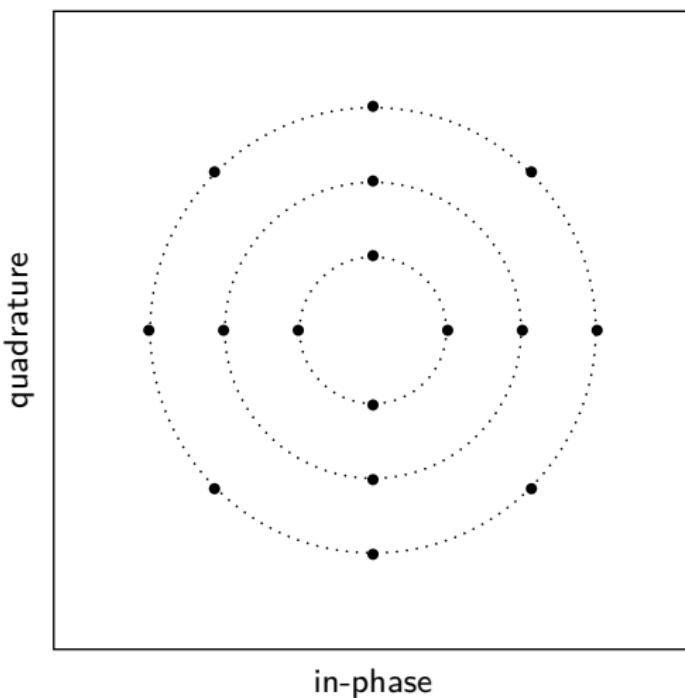
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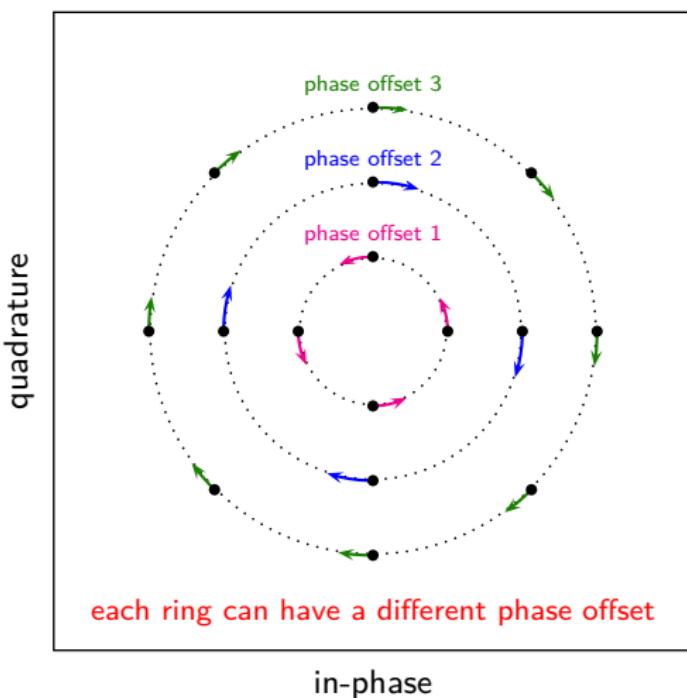
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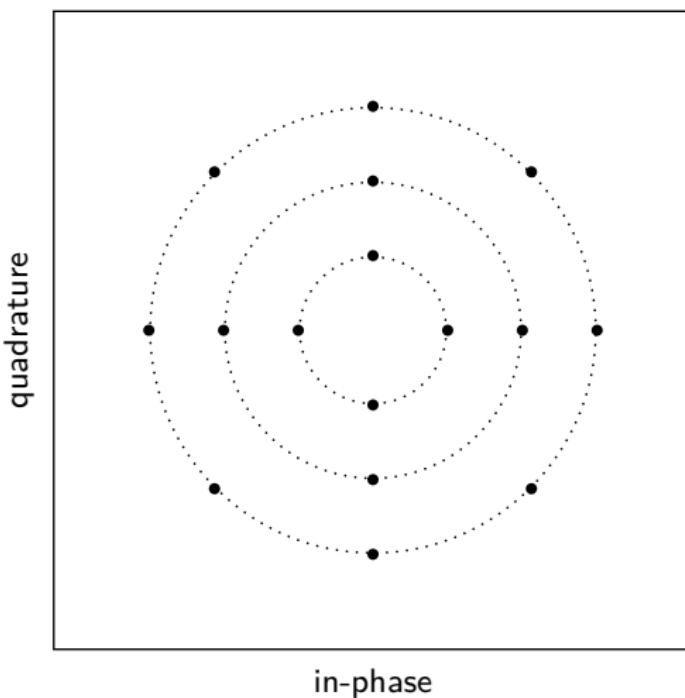
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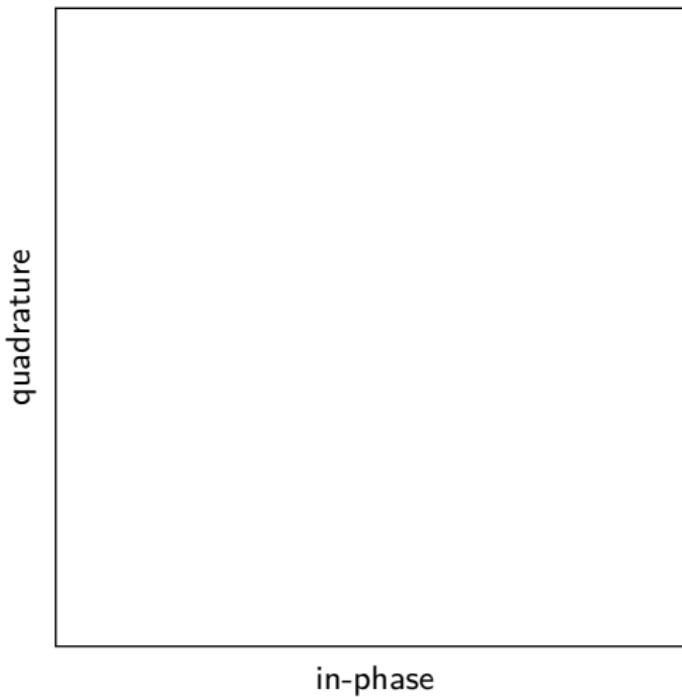


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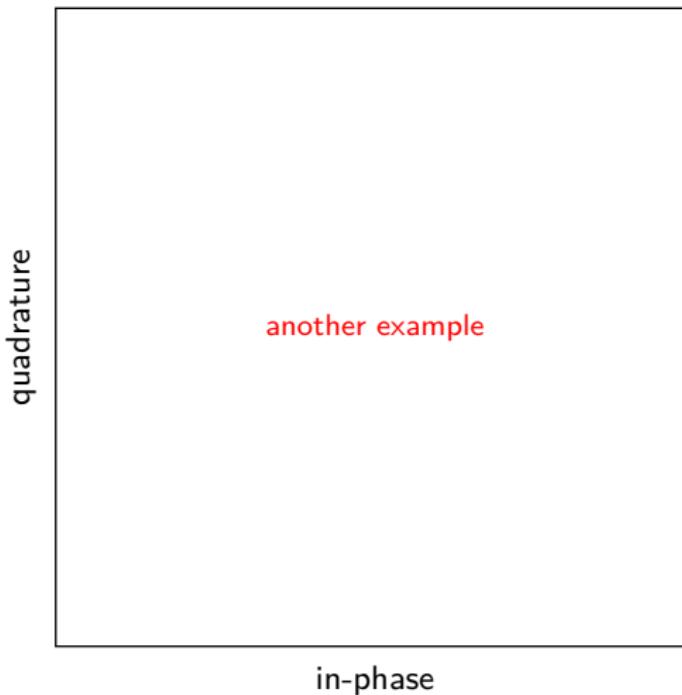
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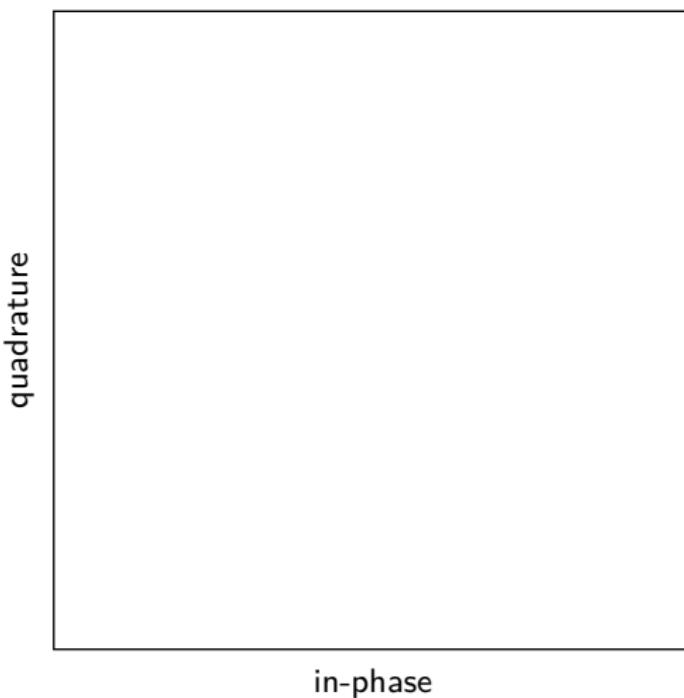


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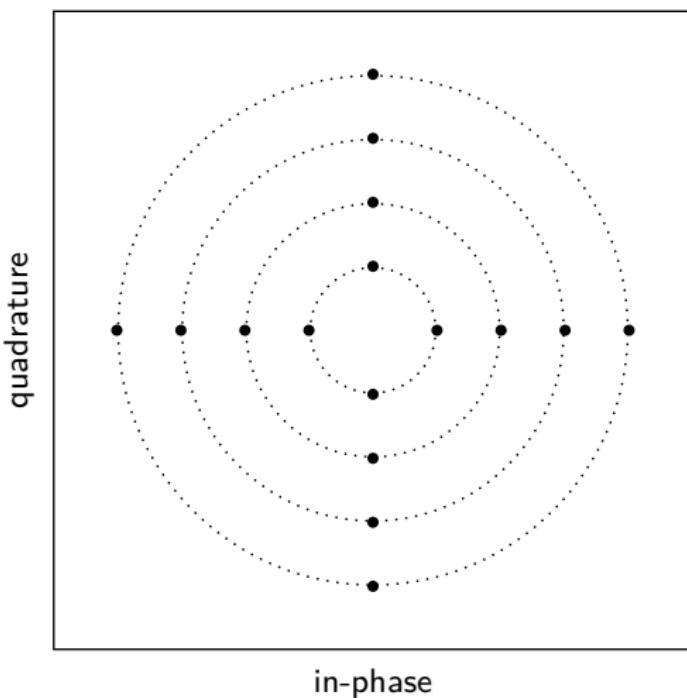
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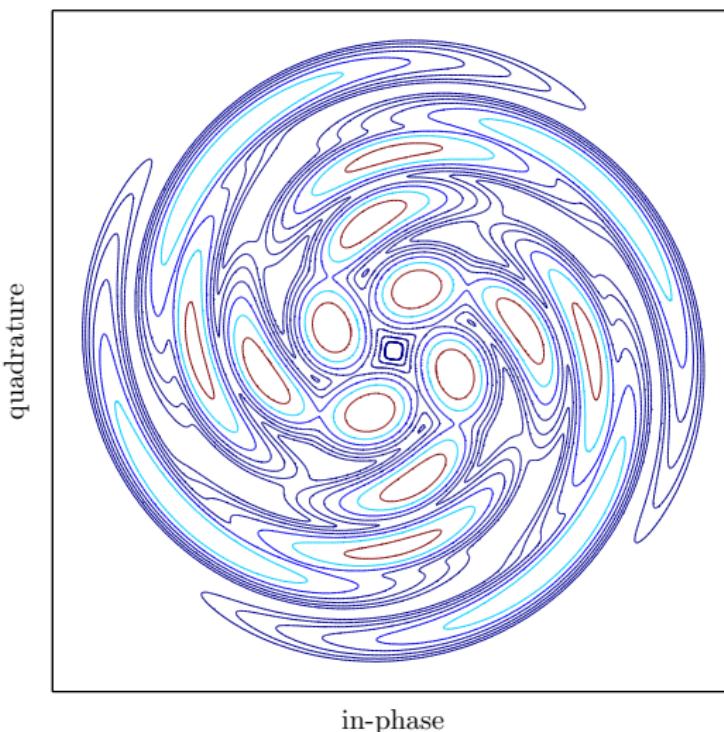


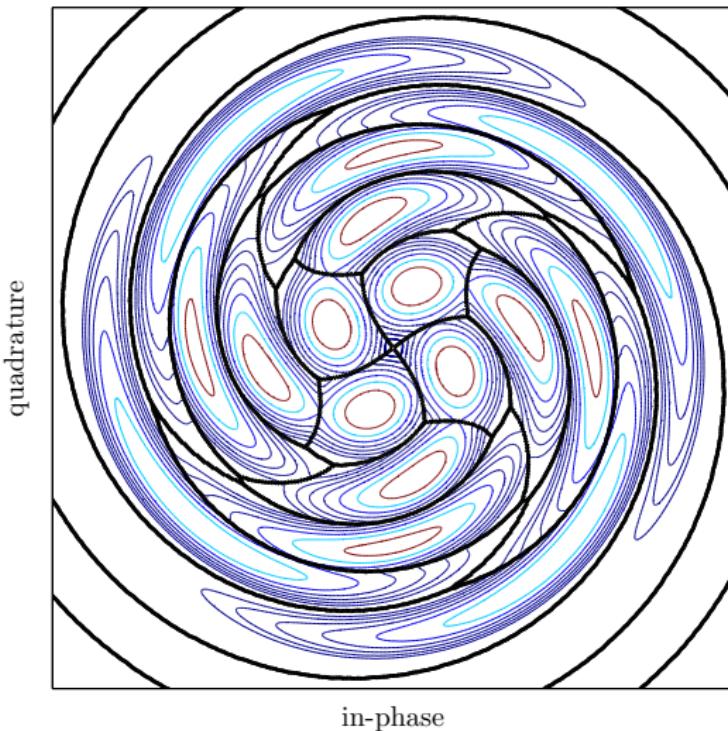
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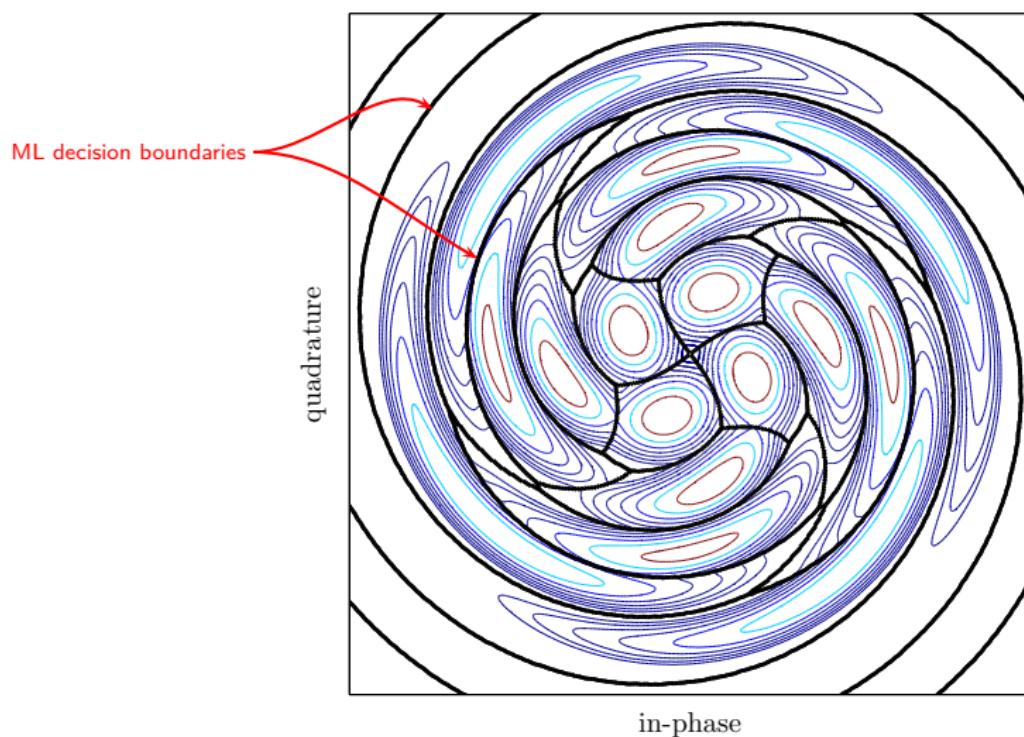
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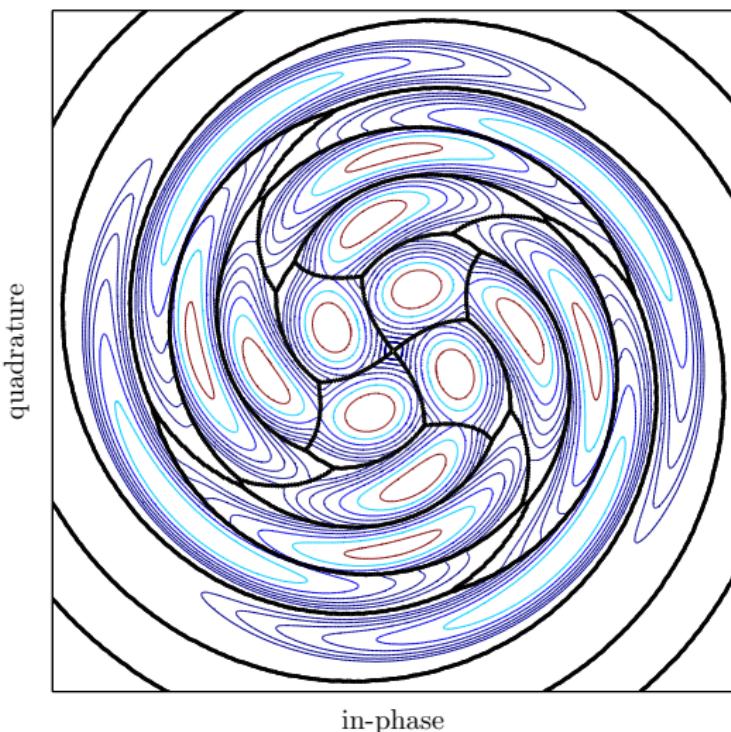


# PDF for (4,4,4,4)-APSK at $P = -4$ dBm, $L = 5500$ km

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

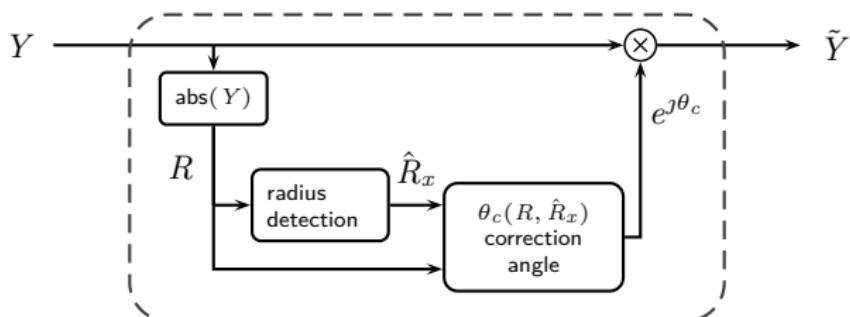
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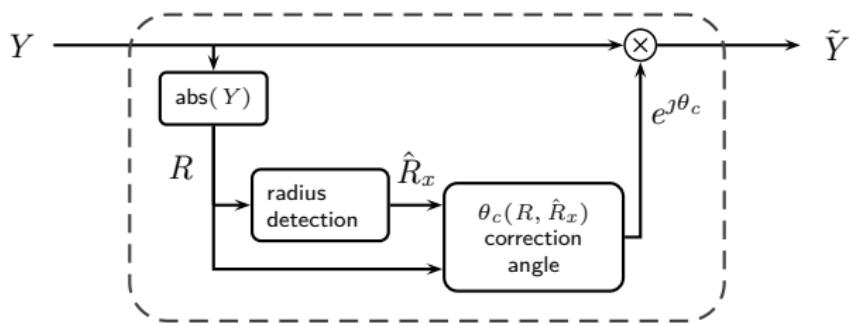
ML detection possible,  
but not practical.

# Nonlinear Phase Postcompensation

## Nonlinear Phase Postcompensation

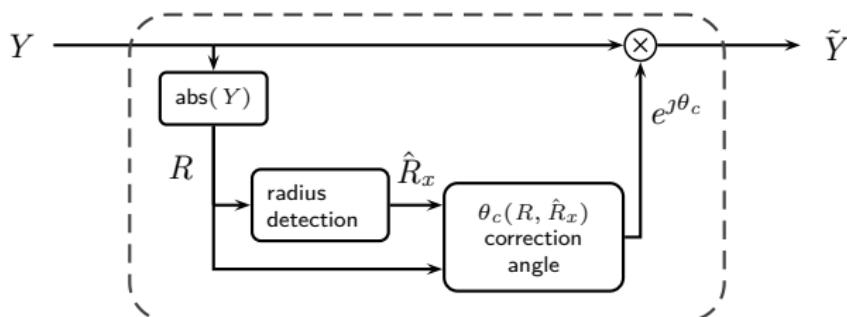


## Nonlinear Phase Postcompensation



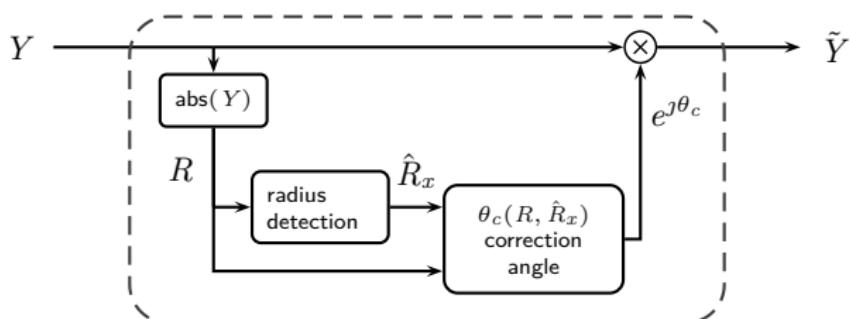
- Building block for suboptimal (but practical) **two-stage detector**

## Nonlinear Phase Postcompensation



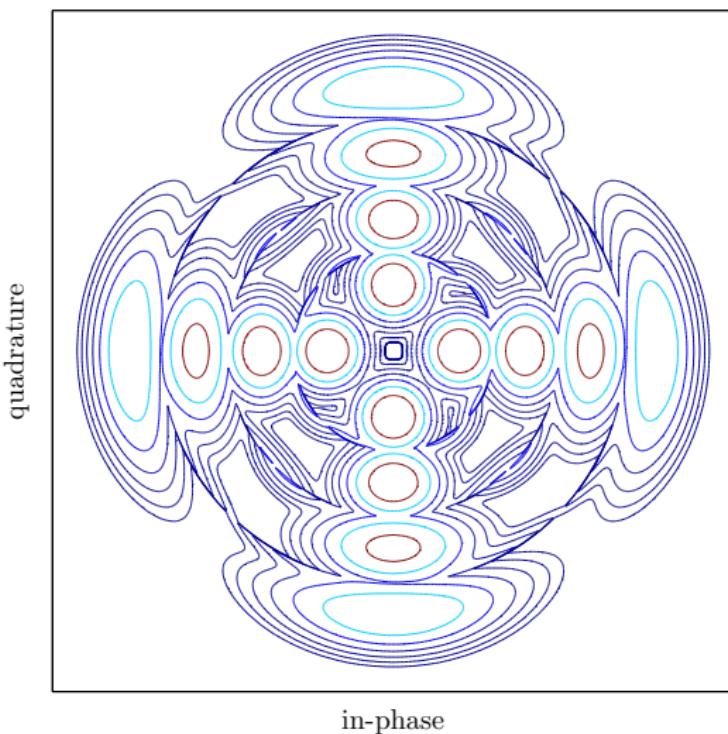
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## Nonlinear Phase Postcompensation

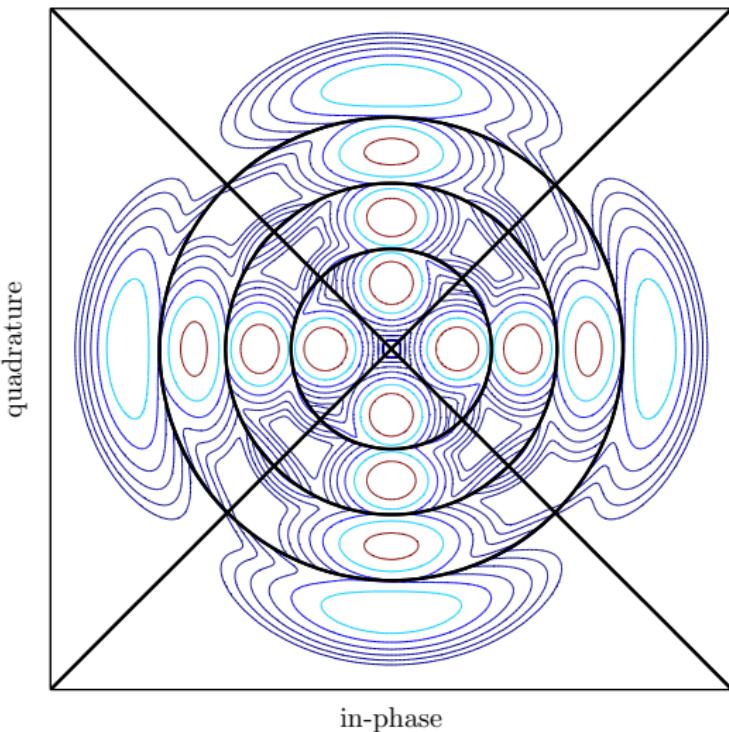


- Building block for suboptimal (but practical) **two-stage detector**
- Characterization of the PDF of  $\tilde{Y}$
- Necessary to compute, e.g., bit error probability

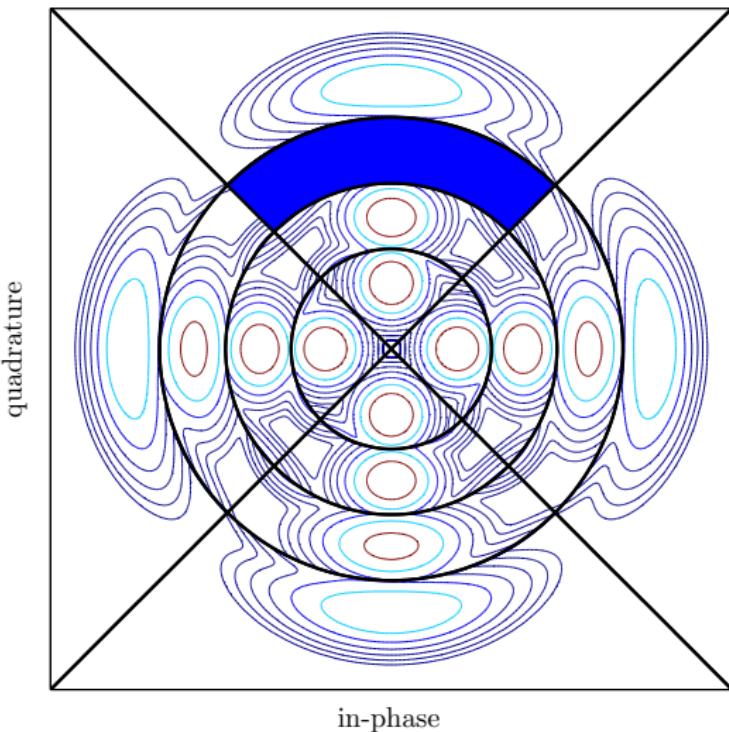
## Two-Stage Detection



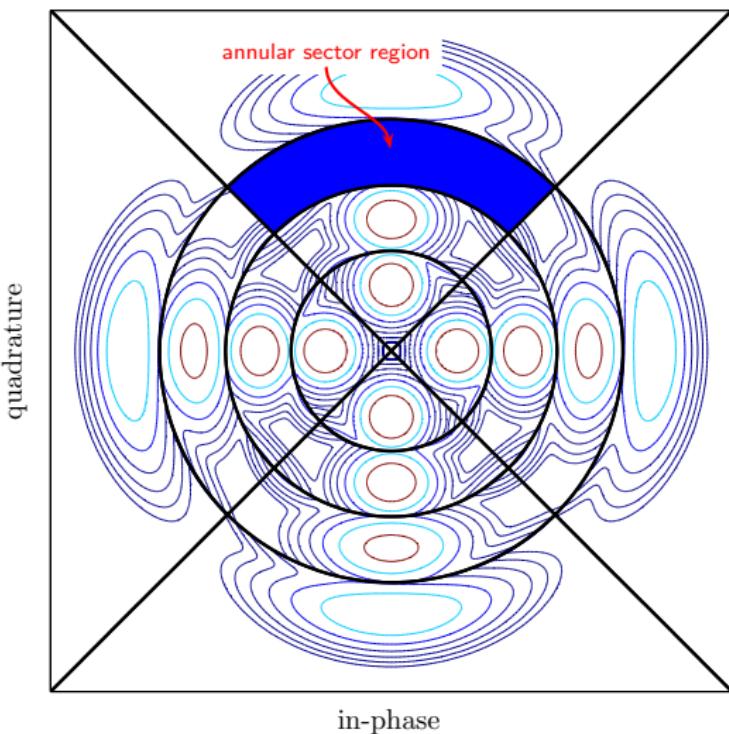
## Two-Stage Detection



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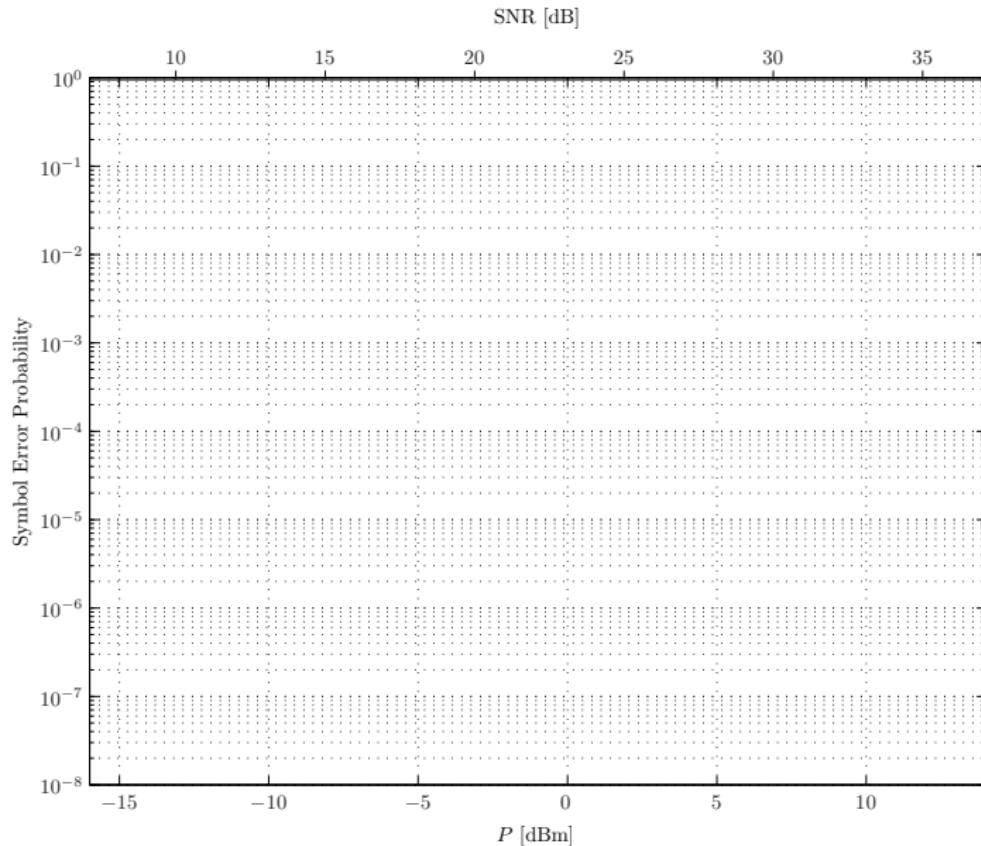


## Two-Stage Detection

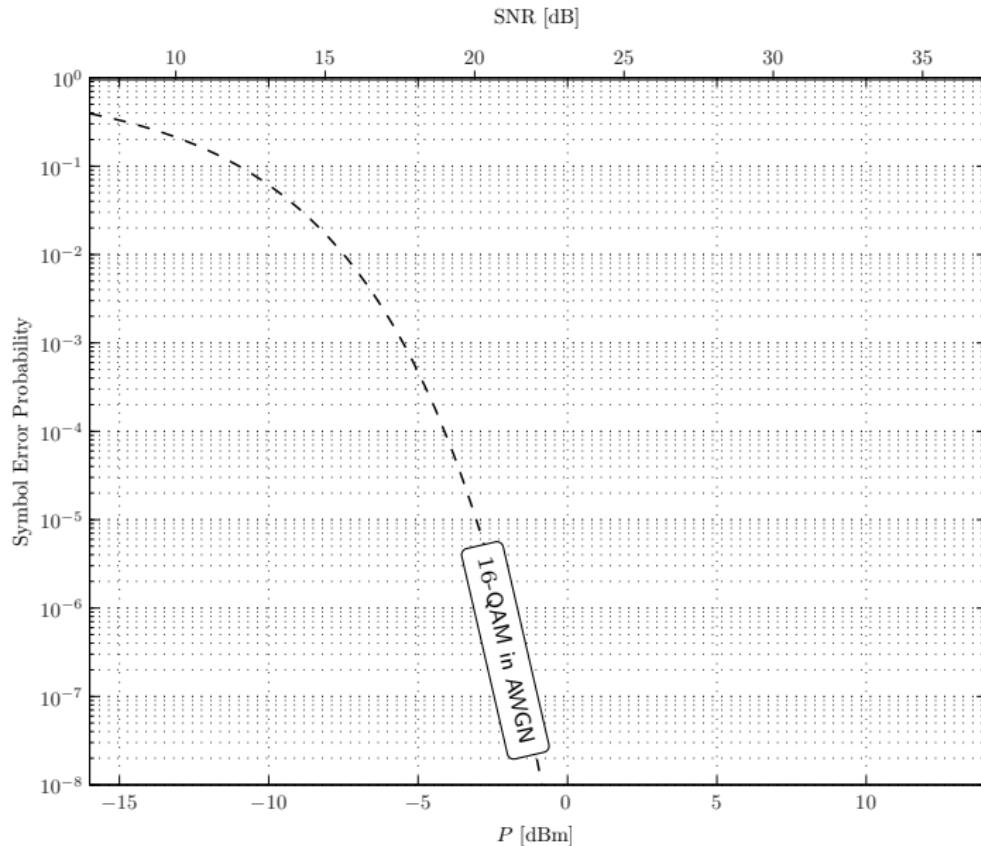


# Optimizing the Number of Rings and Points per Ring

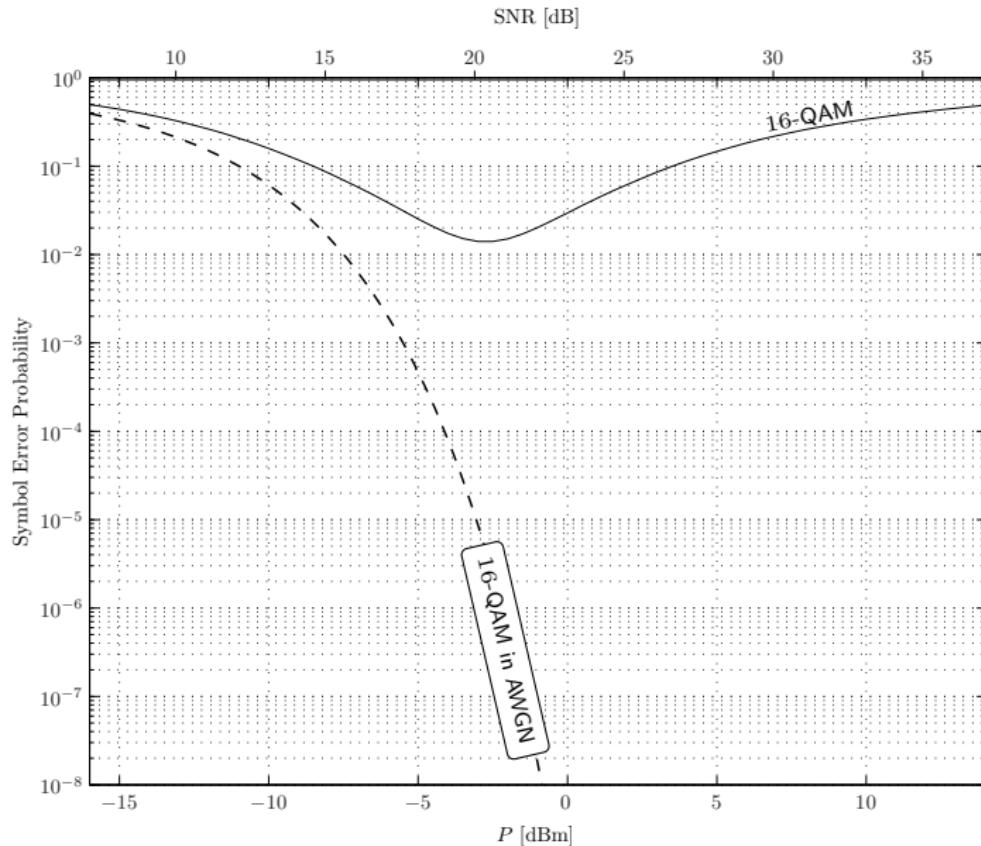
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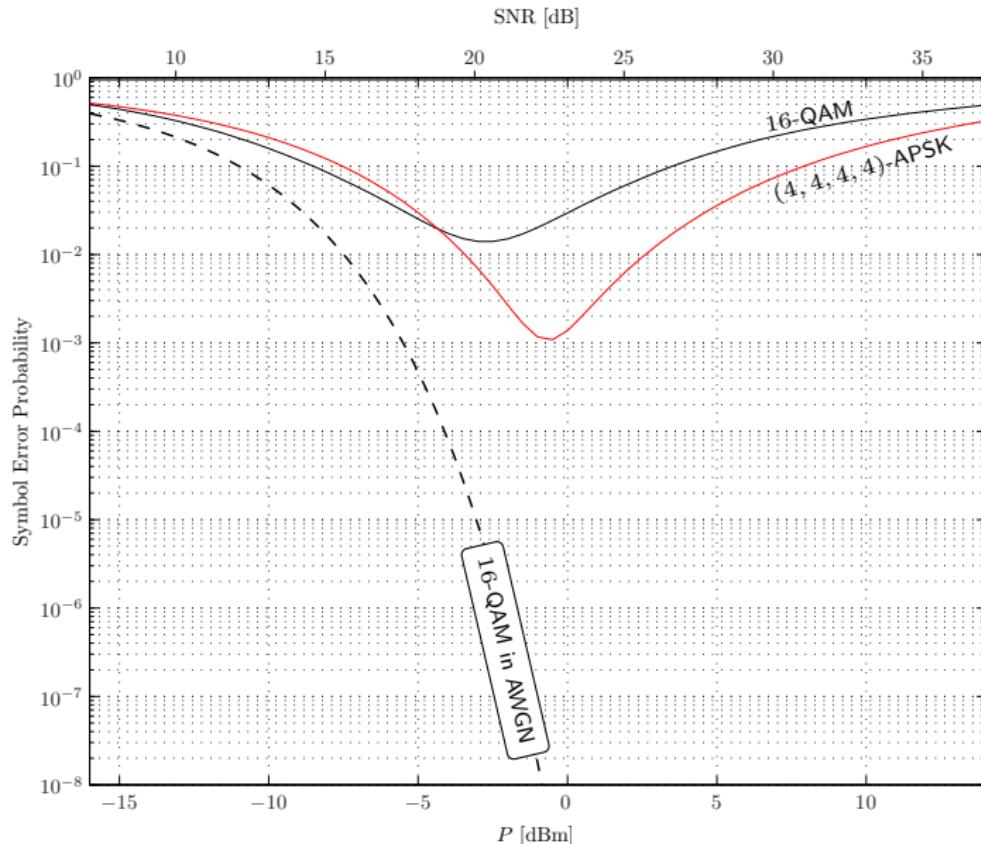
# Optimizing the Number of Rings and Points per Ring



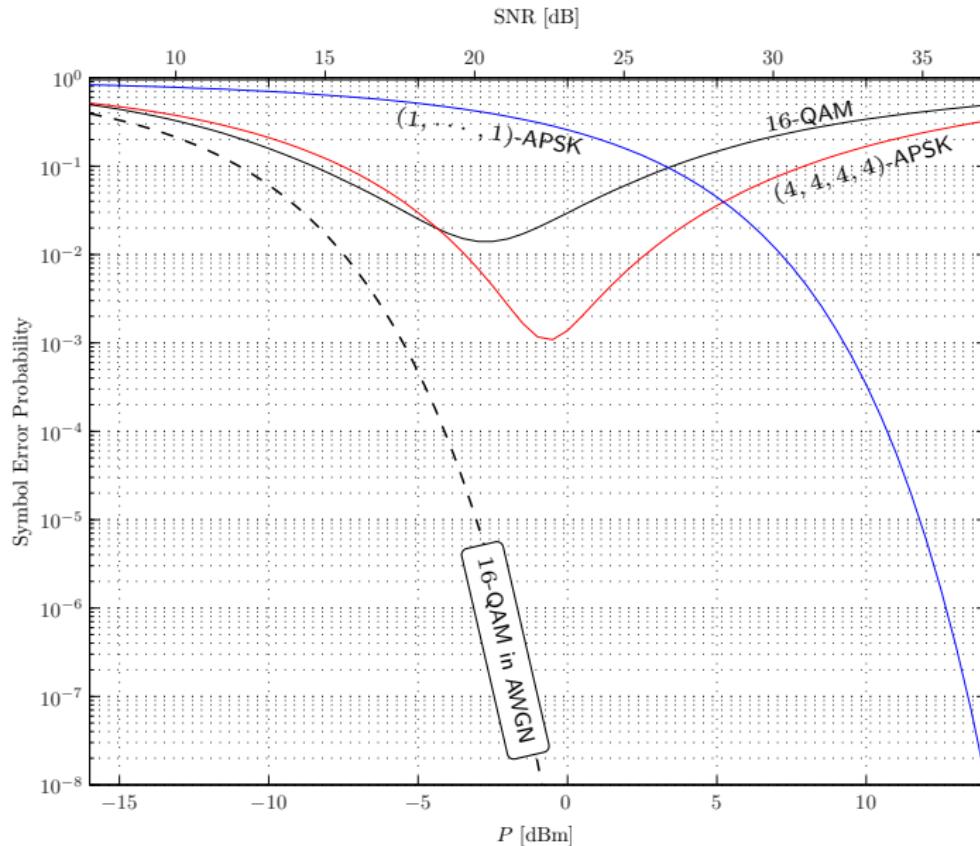
# Optimizing the Number of Rings and Points per Ring



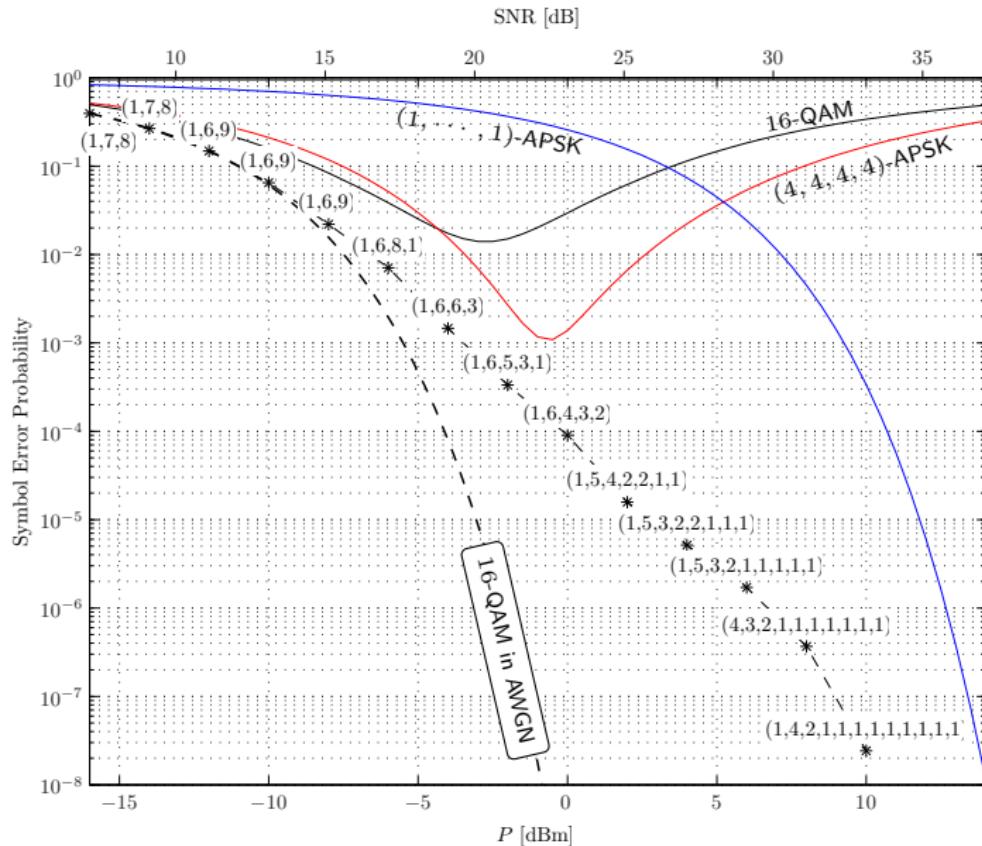
# Optimizing the Number of Rings and Points per Ring



# 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

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

# Zero-Dispersion Fiber with Polarization Multiplexed Signals

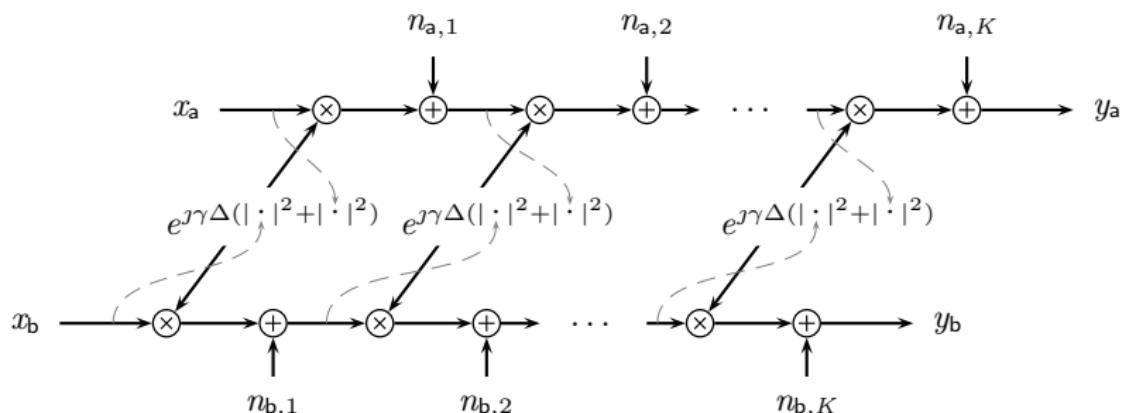
- Extension of the previous channel model to **polarization multiplexed signals**
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[Beygi et al., 2011]

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# Zero-Dispersion Fiber with Polarization Multiplexed Signals

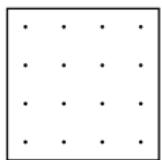
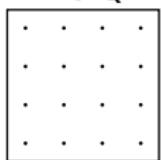
- Extension of the previous channel model to **polarization multiplexed signals**
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## Power Dependent Phase Noise

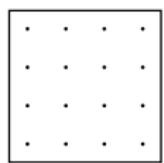
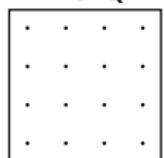
# Power Dependent Phase Noise

PM-16-QAM



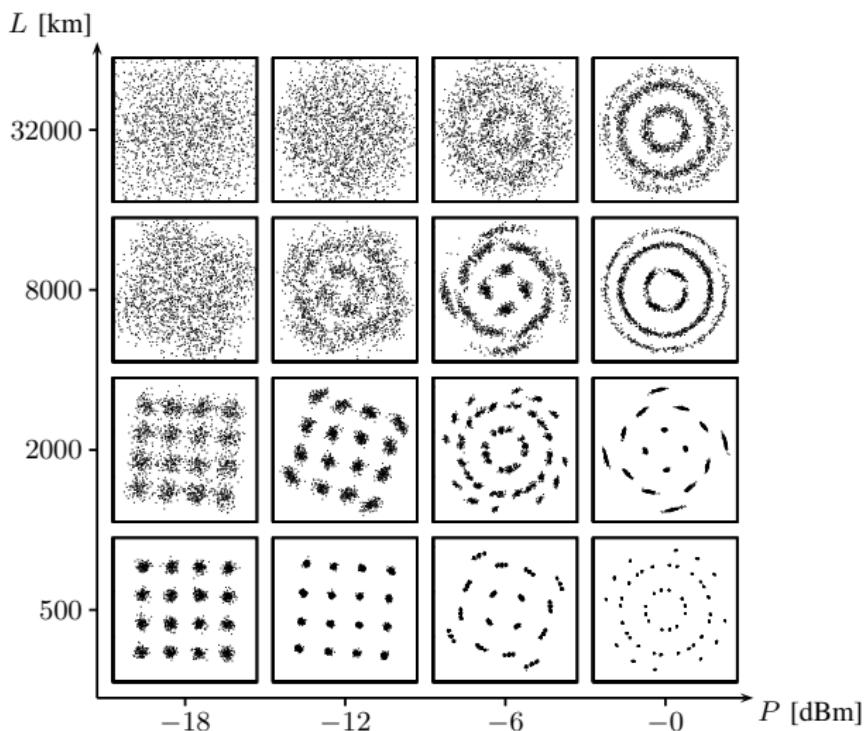
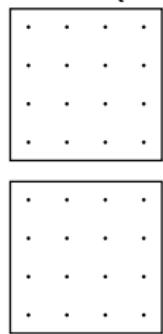
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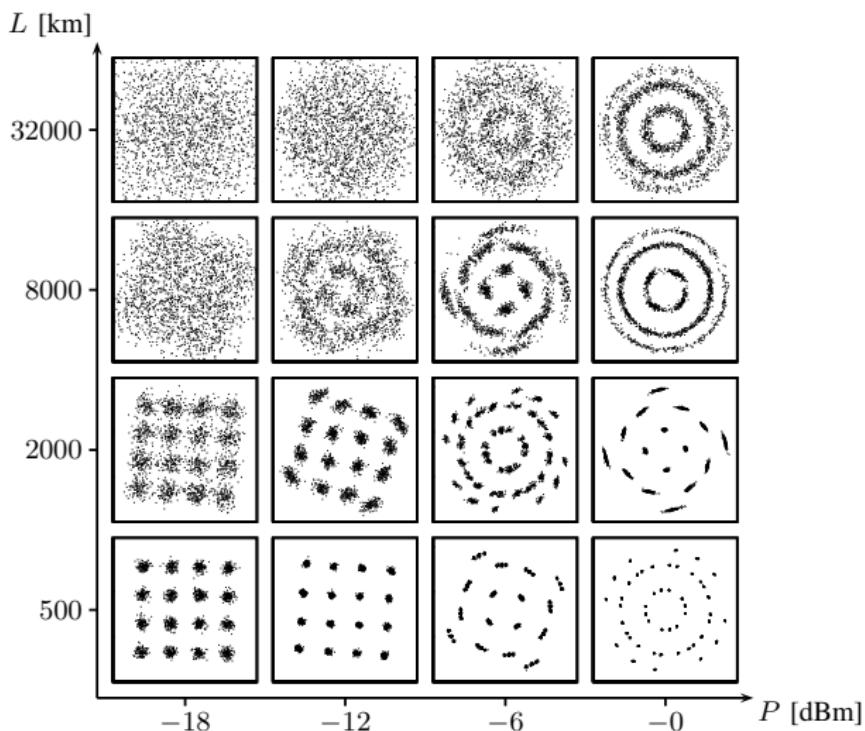
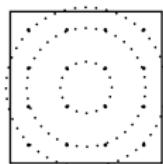
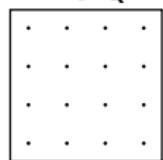
## Power Dependent Phase Noise

PM-16-QAM



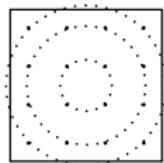
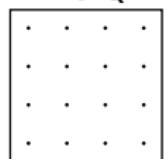
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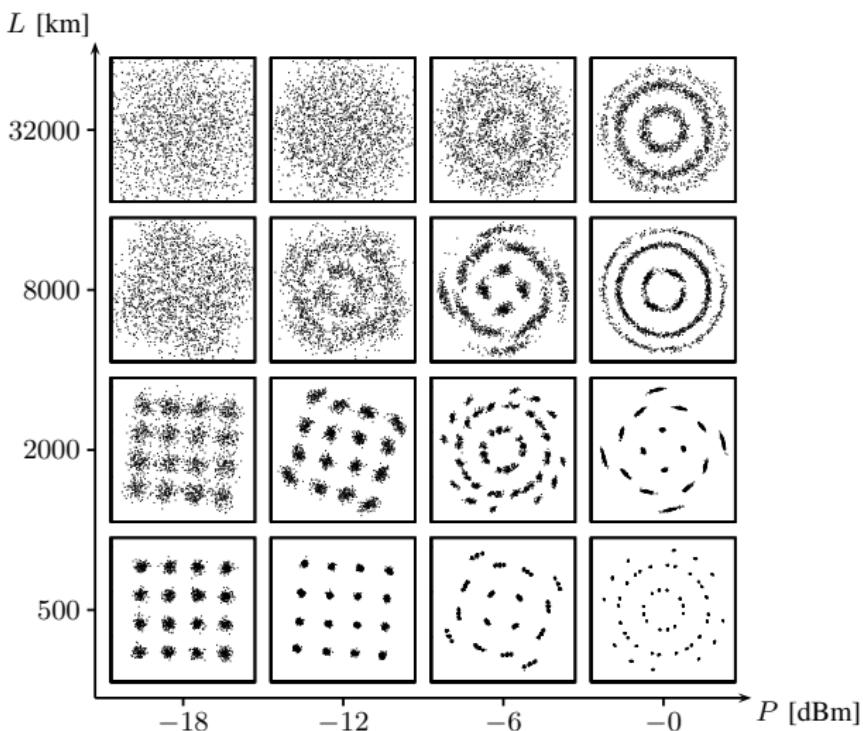


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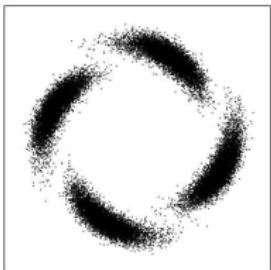
Simplification: PM- $M$ -PSK  
(only one amplitude level)



## Nonlinear Phase Compensation

# Nonlinear Phase Compensation

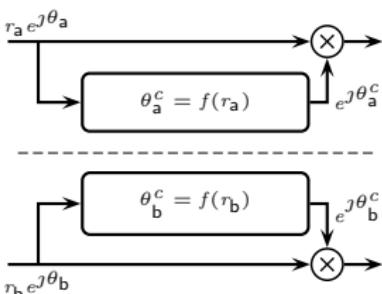
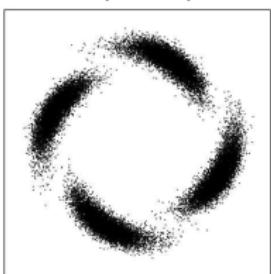
Scatterplot for pol. a



# Nonlinear Phase Compensation

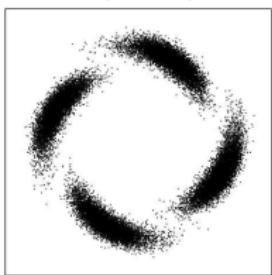
separate compensation in each polarization

Scatterplot for pol. a

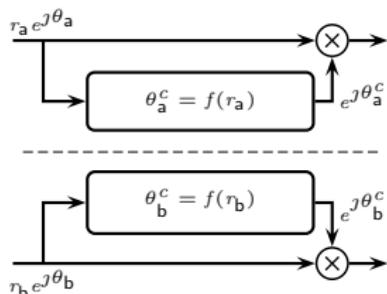


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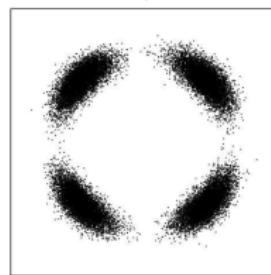
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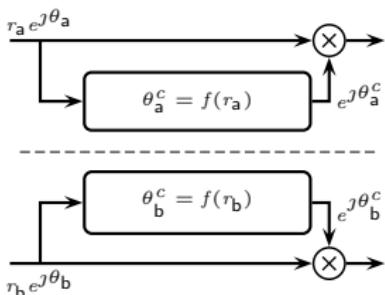
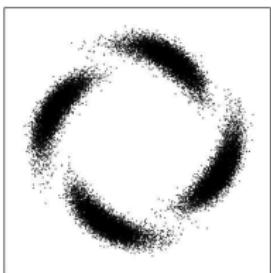
after compensation



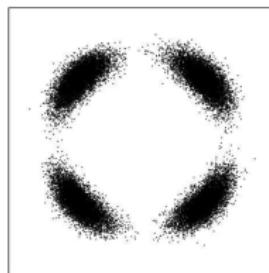
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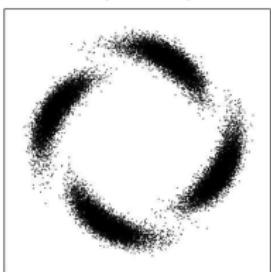
Scatterplot for pol. a



after compensation



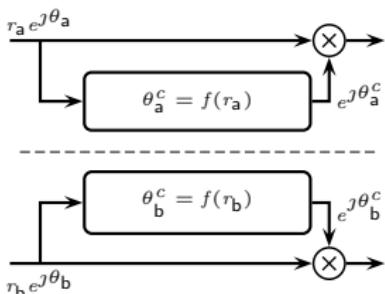
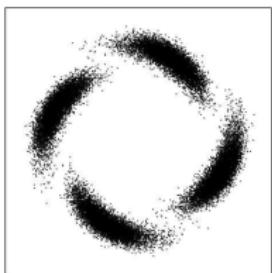
Scatterplot for pol. a



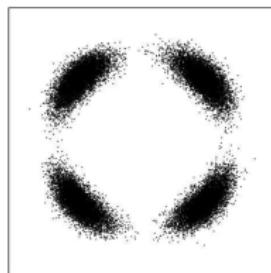
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Scatterplot for pol. a

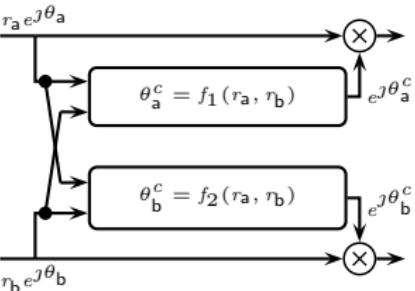
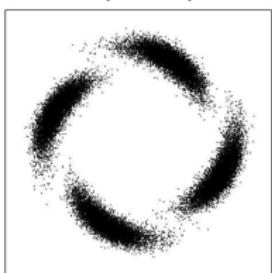


after compensation



compensation based on both received amplitudes

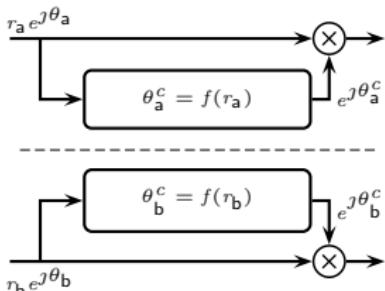
Scatterplot for pol. a



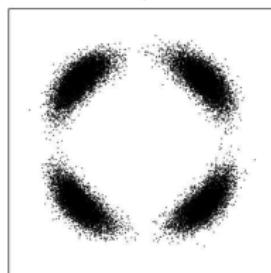
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separate compensation in each polarization

Scatterplot for pol. a

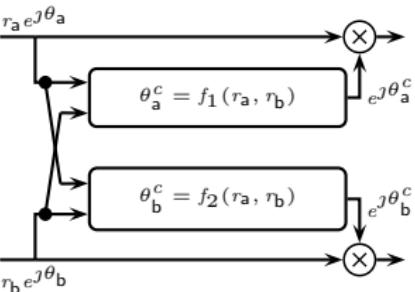
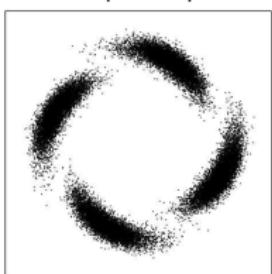


after compensation

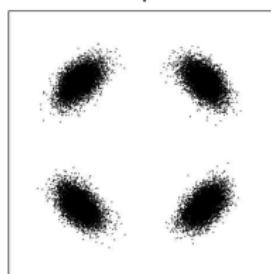


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Scatterplot for pol. a

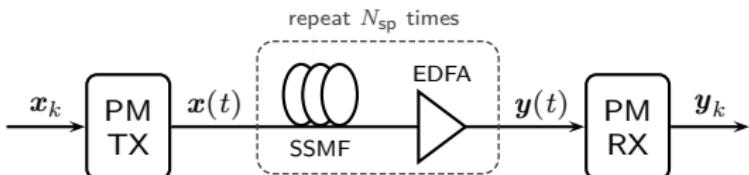


after compensation

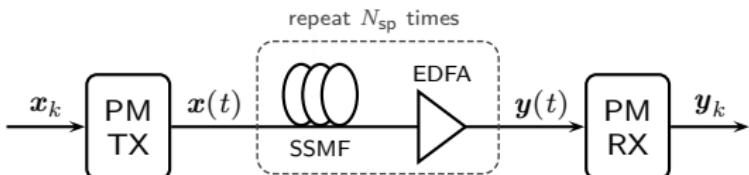


less phase noise → better SER

# Channel Model for PM Transmission including Dispersion

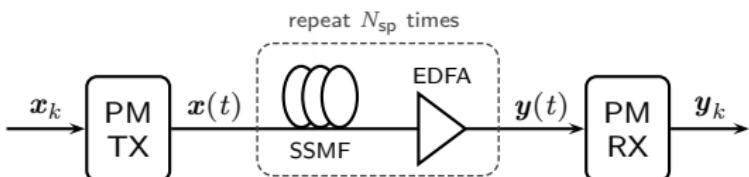


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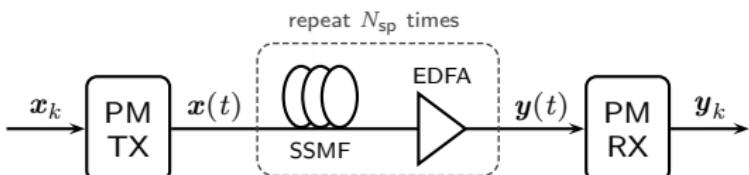
- Dispersive fibers,  $\beta_2 \neq 0$

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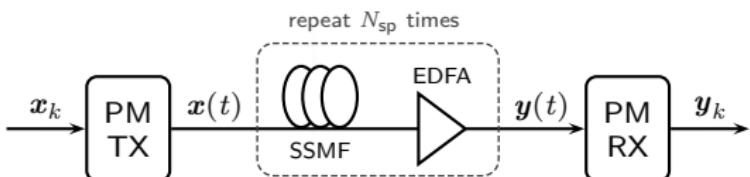
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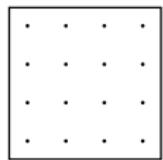
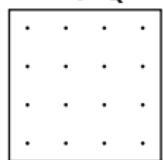


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- No exact characterization of the statistical relationship between transmitted symbols  $x_k = (x_{a,k}, x_{b,k})$  and received samples  $y_k = (y_{a,k}, y_{b,k})$
- Under some assumptions, several works give theoretical justification for a **Gaussian noise (GN) model**, e.g., [Beygi et al., 2012], [Carena et al., 2012]

## Illustration of the Statistical Relationship

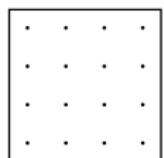
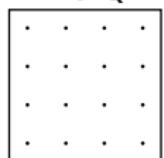
# Illustration of the Statistical Relationship

PM-16-QAM



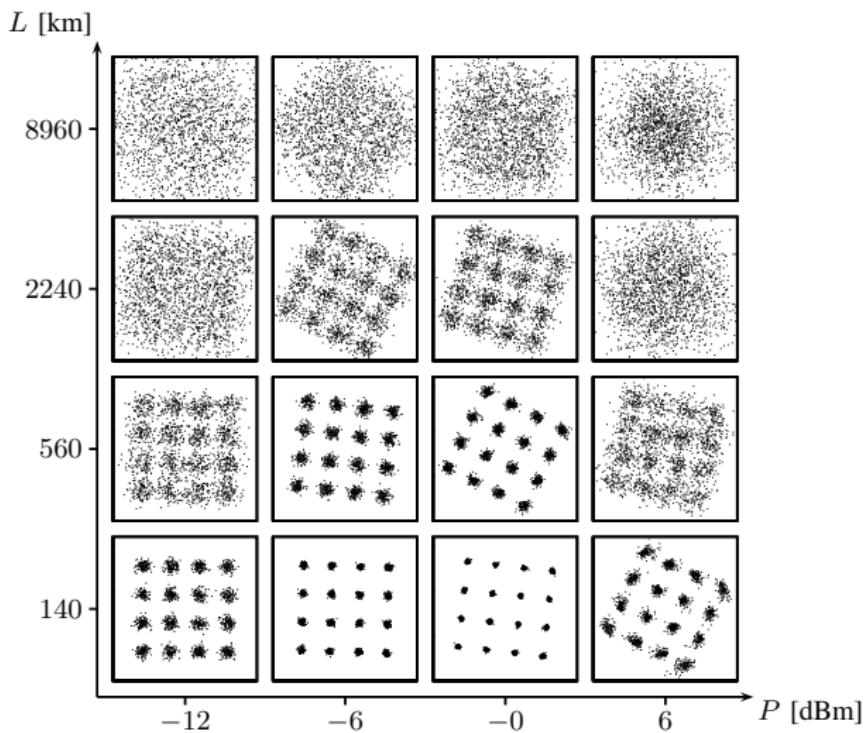
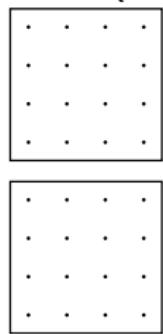
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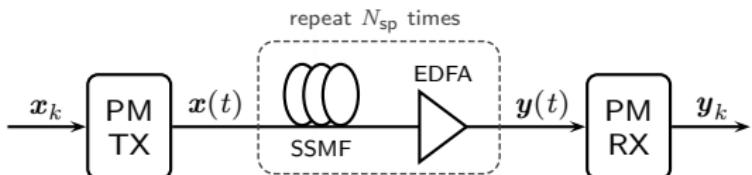


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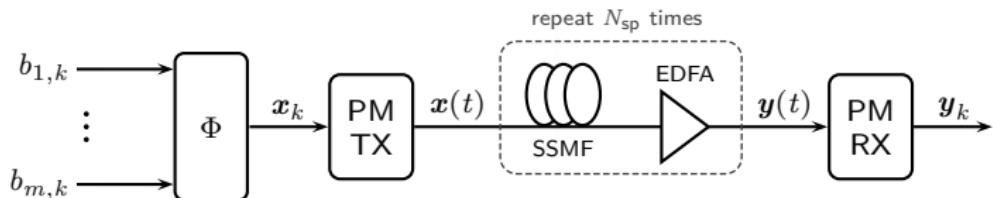
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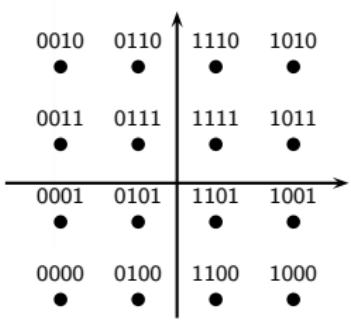
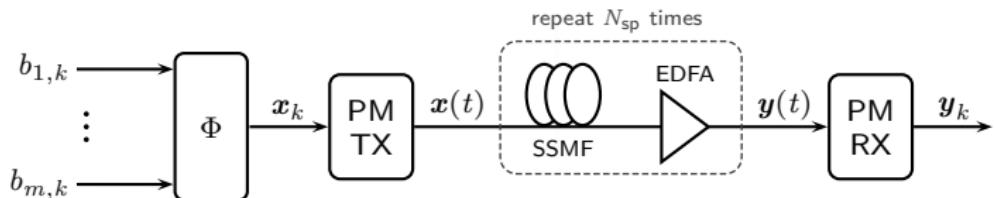
# Bit Mapper Optimization for Soft-Decision FEC



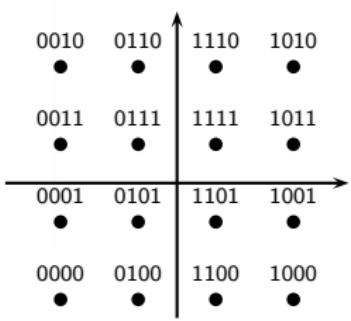
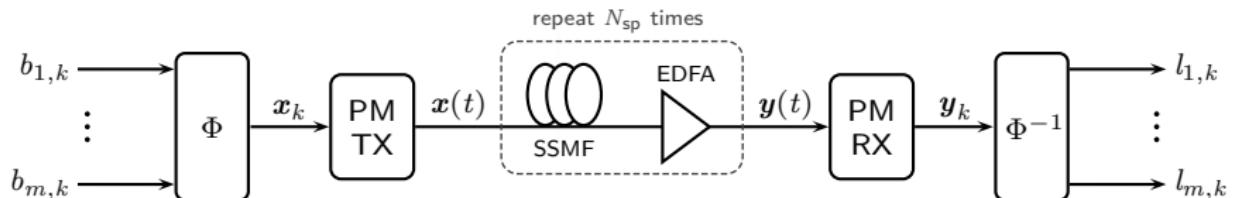
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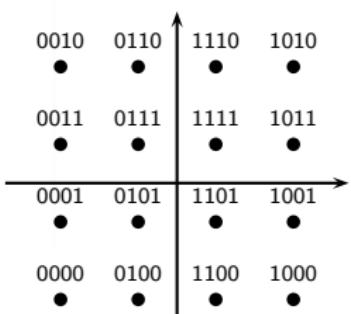
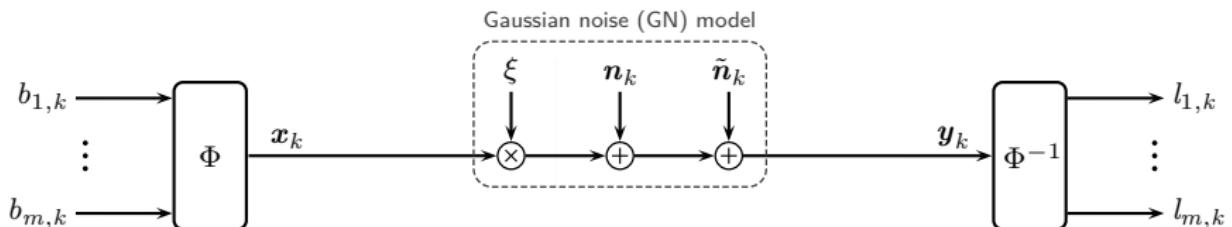
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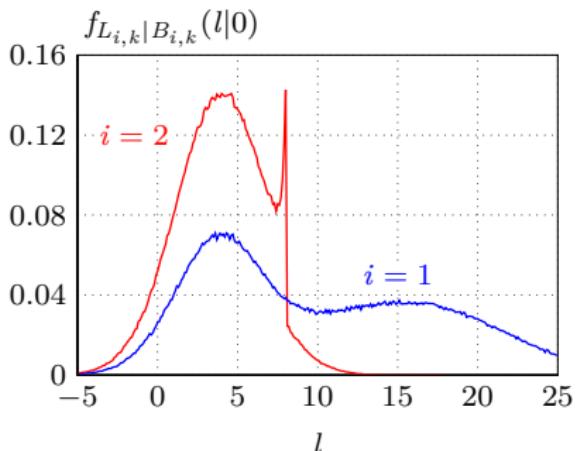
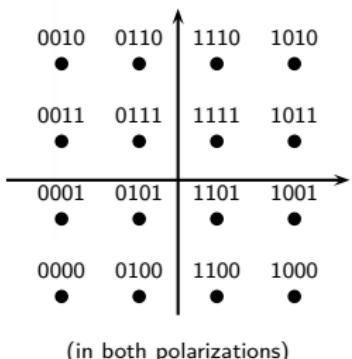
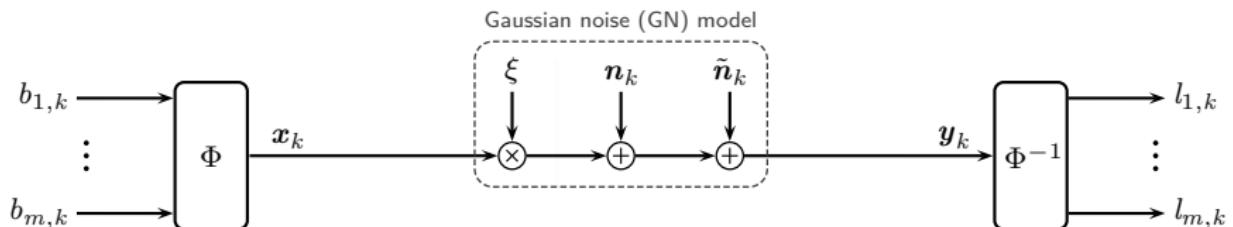
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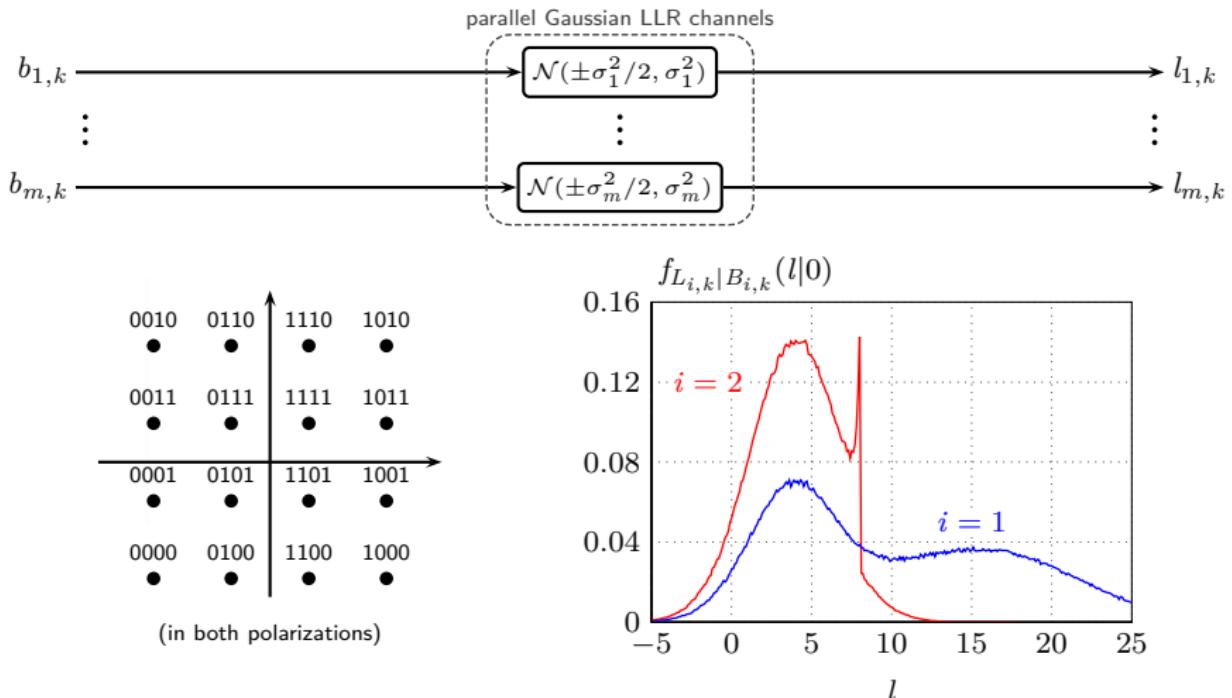
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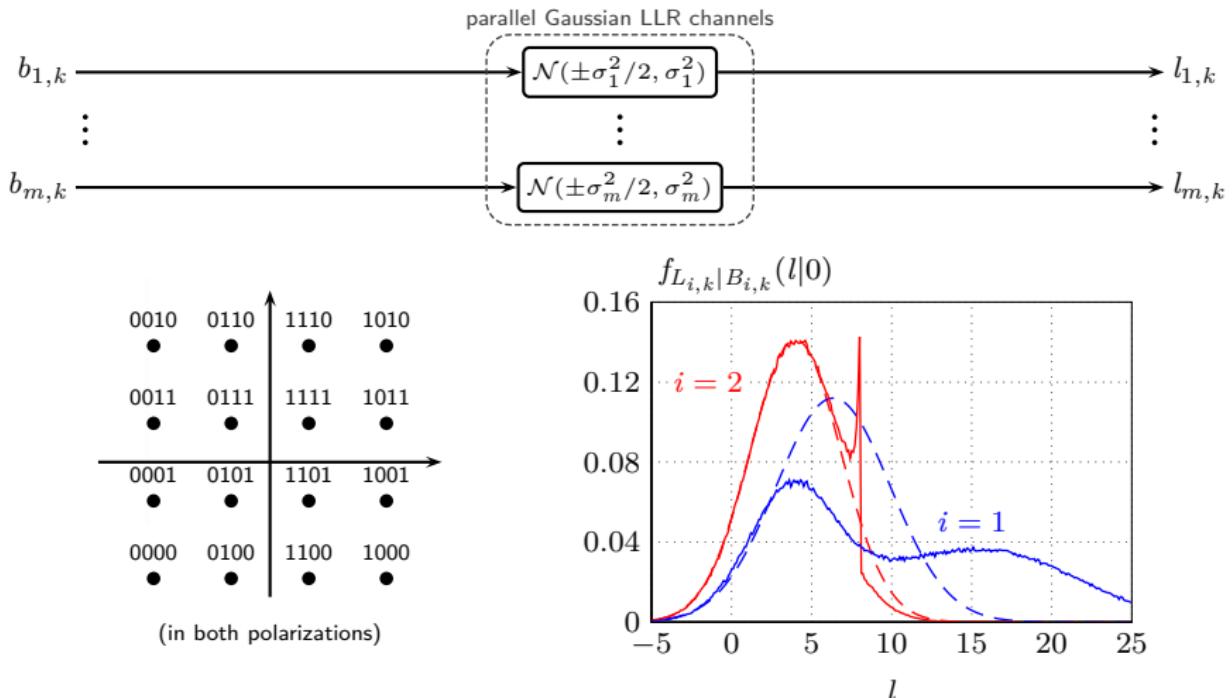
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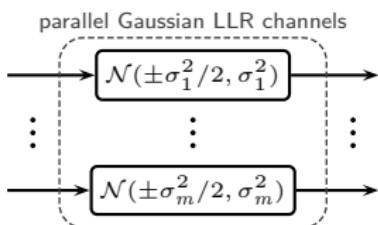
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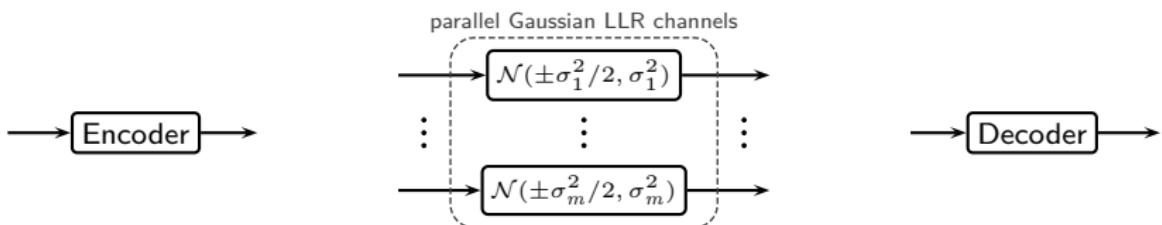


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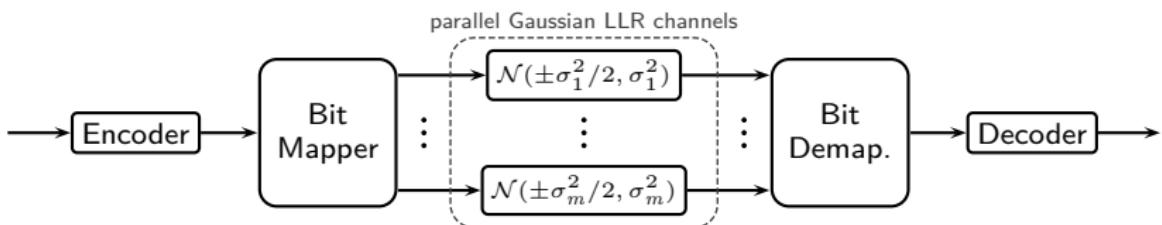
- Approximate setup: **parallel Gaussian LLR channels with different qualities**  
(constellation size determines the number of channels)

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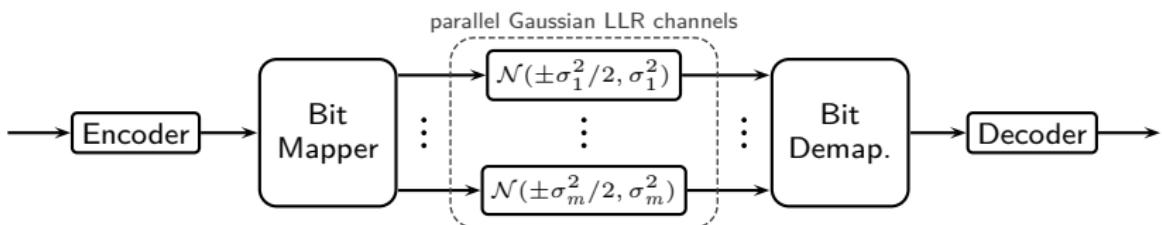
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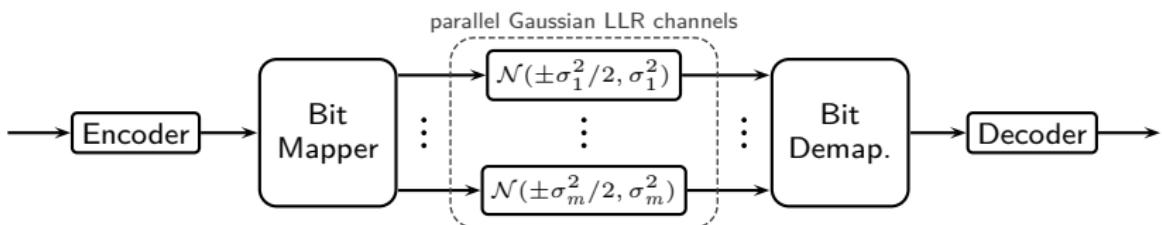
- Approximate setup: **parallel Gaussian LLR channels with different qualities** (constellation size determines the number of channels)
- Fix **one binary FEC encoder/decoder pair**
- **Bit mapper** determines the allocation of coded bits to the channels

# Bit Mapper Optimization for Soft-Decision FEC



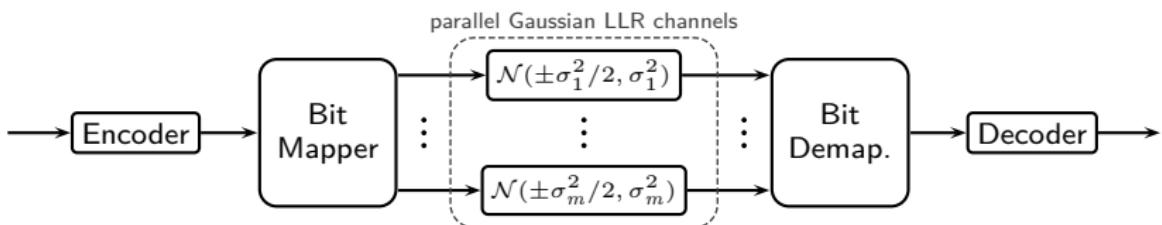
- Approximate setup: **parallel Gaussian LLR channels with different qualities** (constellation size determines the number of channels)
- Fix **one binary FEC encoder/decoder pair**
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- Optimize the **bit mapper** for a given code and signal constellation

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$$\text{codeword} = (\textcolor{blue}{c}_1, \textcolor{green}{c}_2, \textcolor{red}{c}_3, \textcolor{blue}{c}_4, \textcolor{green}{c}_5, \textcolor{red}{c}_6, \dots)$$

## Protograph LDPC Codes

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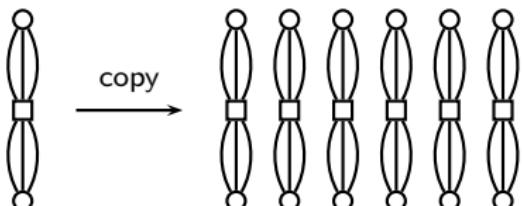
- Main idea: obtain Tanner graph from a small protograph via copy-and-permute procedure

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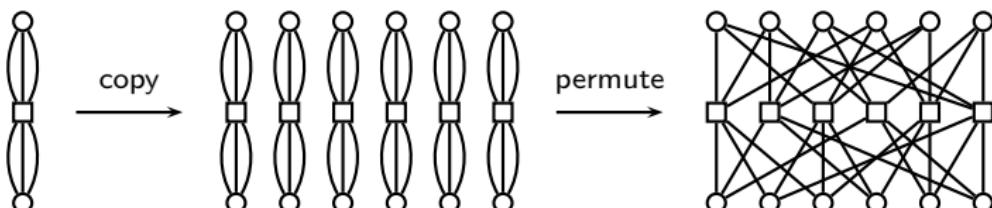
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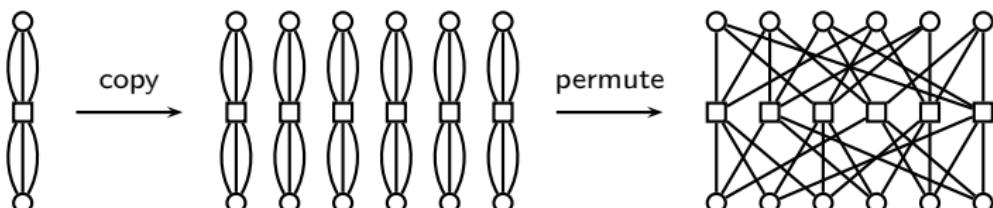
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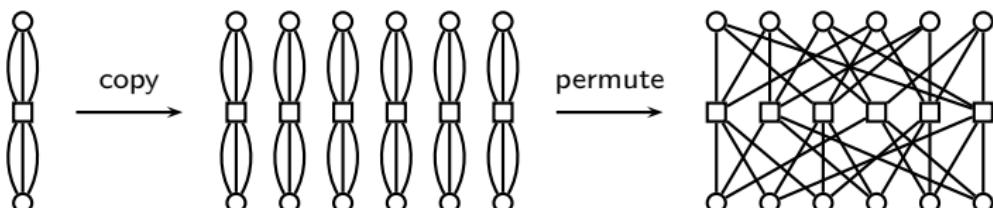
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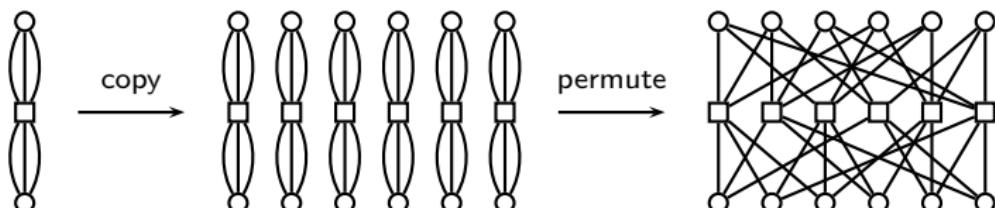
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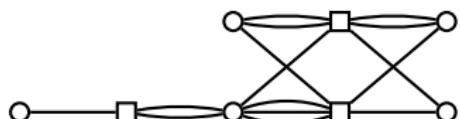
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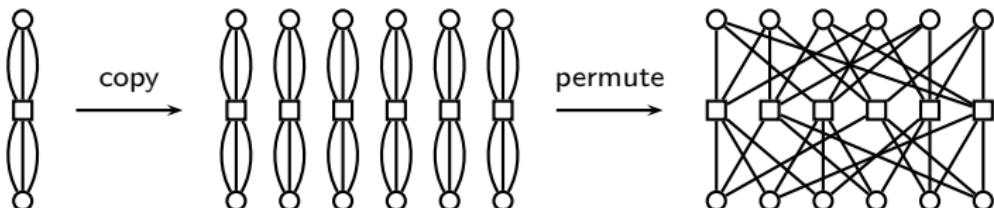


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### AR4JA codes

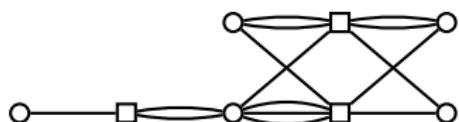


## Protograph LDPC Codes

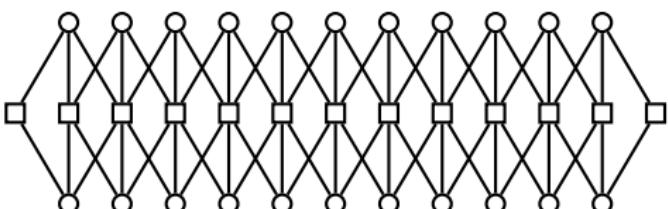


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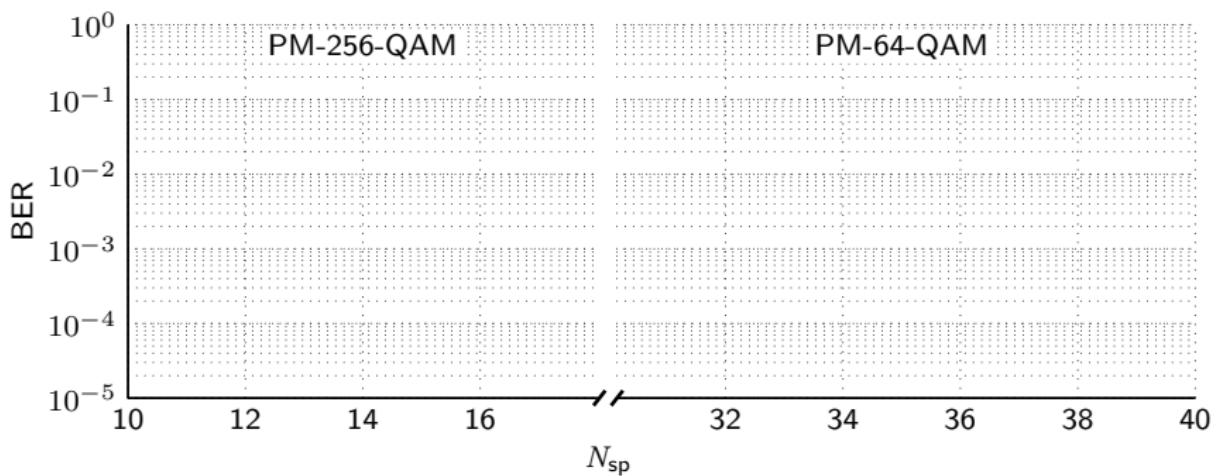
AR4JA codes



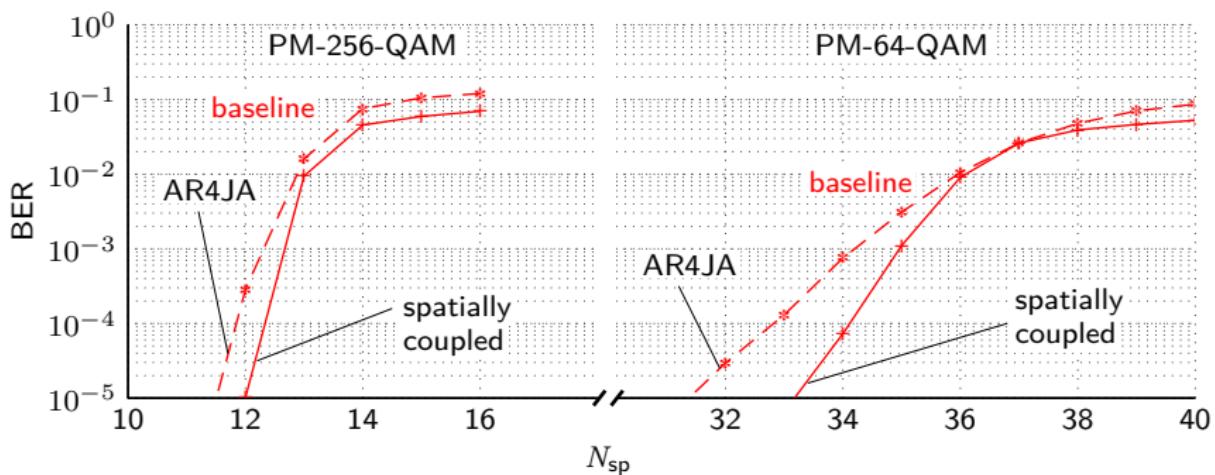
spatially coupled LDPC codes



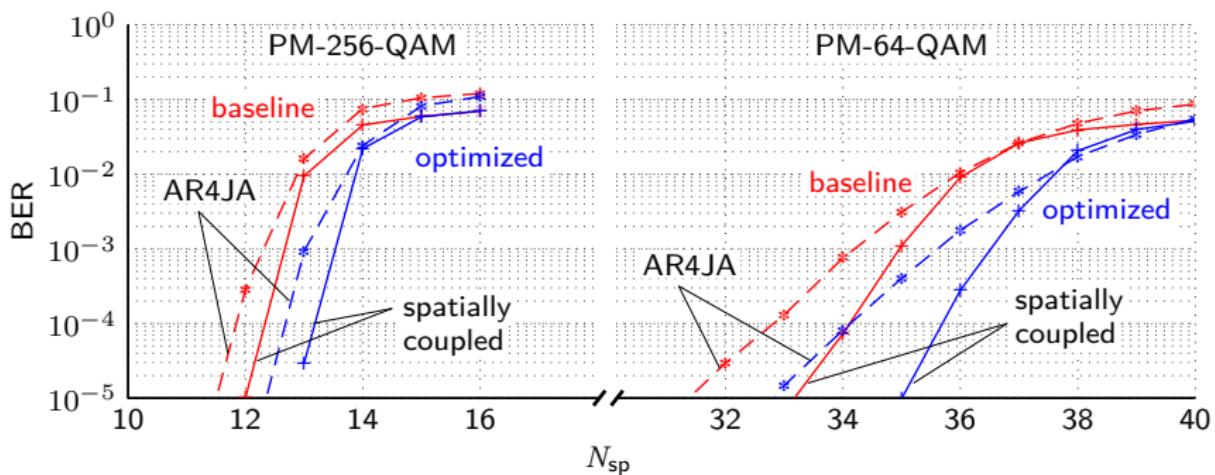
## Results



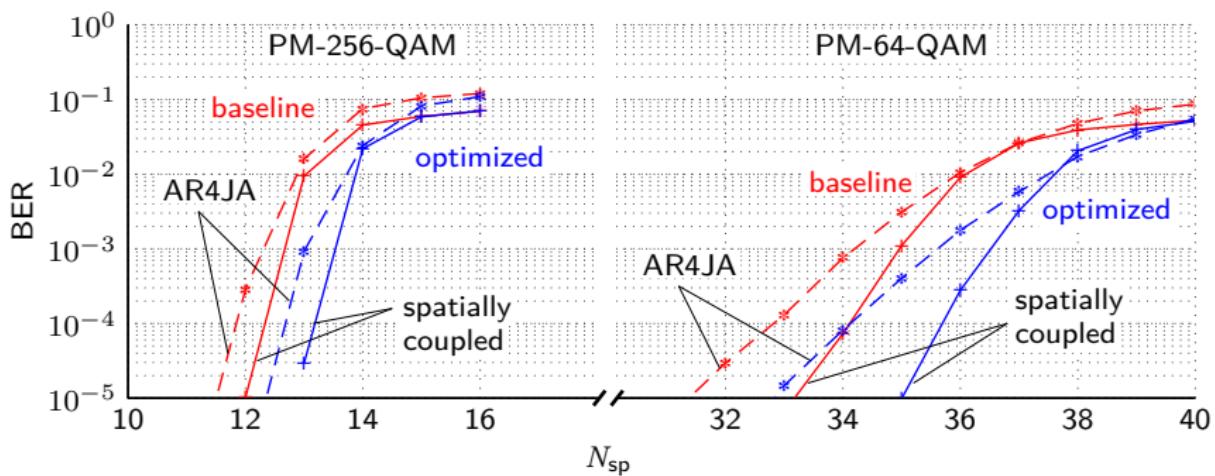
## Results



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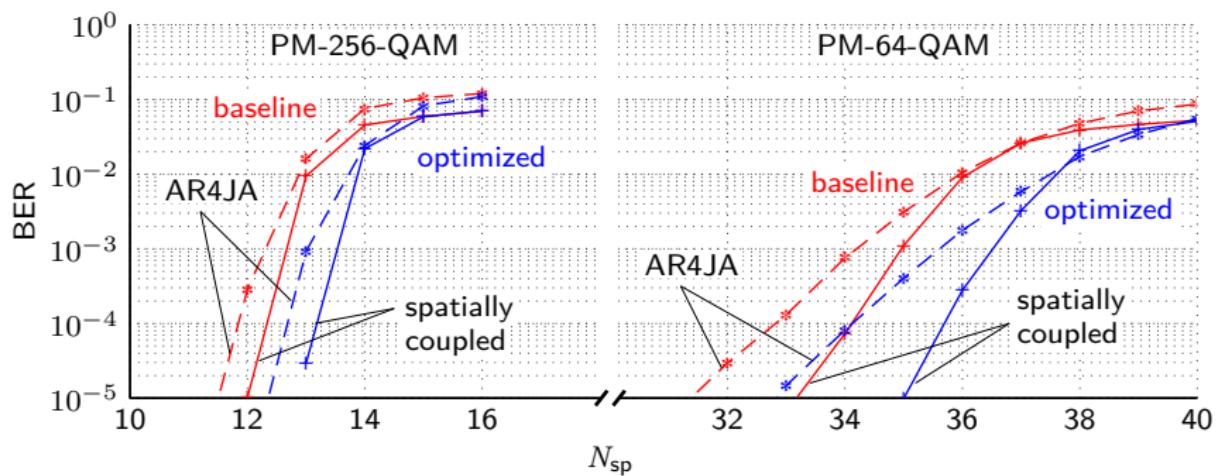


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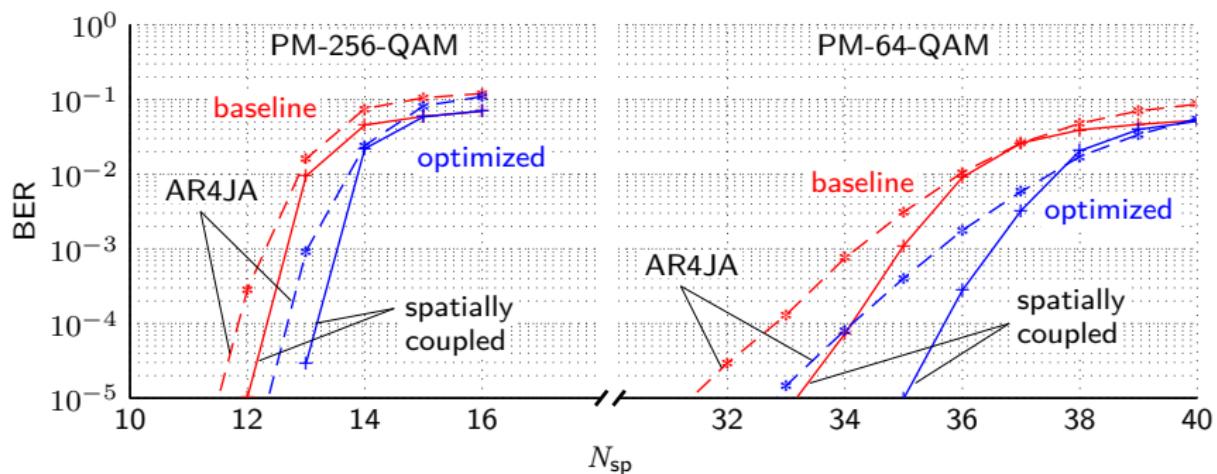
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- Full-field simulations justify the GN model approximation and parallel Gaussian LLR channel approximation

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Thank you!



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