Nonlinear Interference Noise

Open questions on NLIN and the prospects of its mitigation

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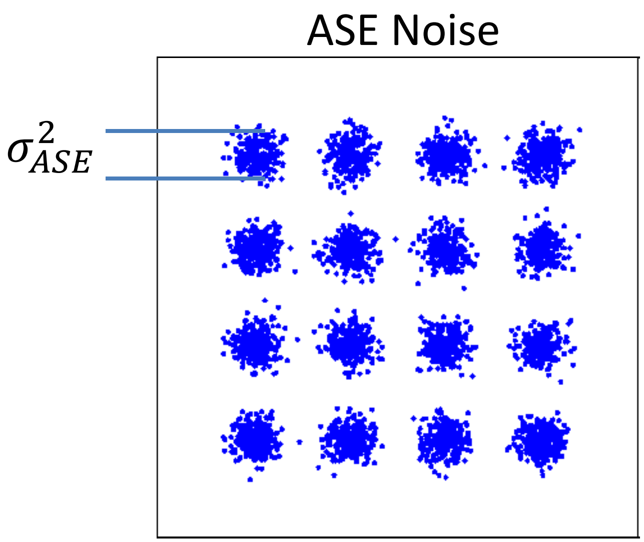
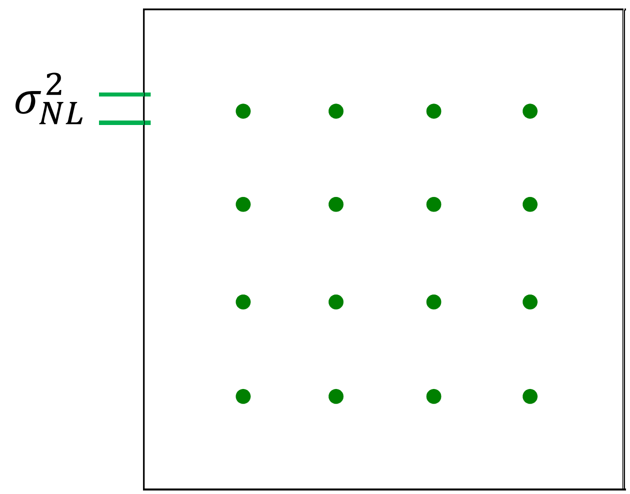
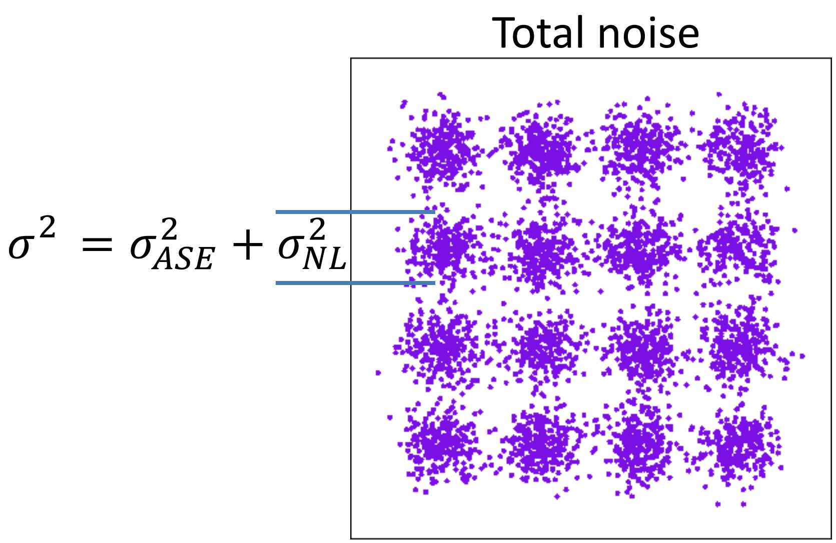
Outline

- Introduce the issue
- BER performance estimation
- Shaping codes for nonlinearity mitigation

Nonlinear interference noise (NLIN)





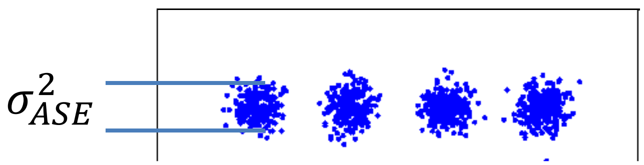


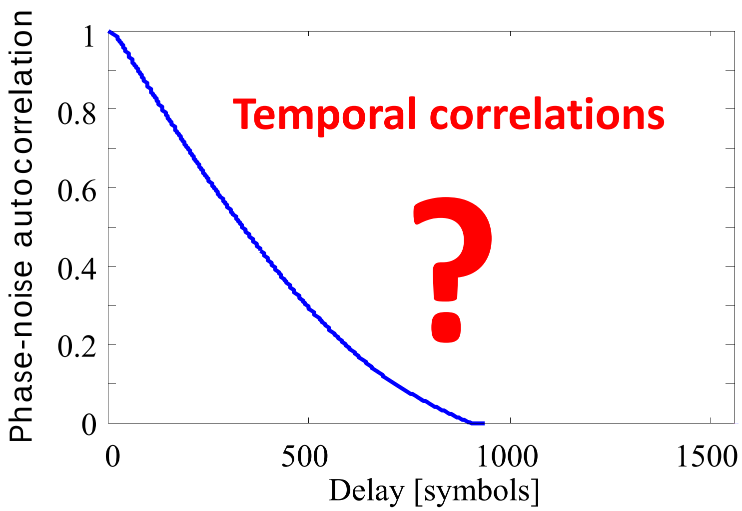
$$\mathbf{SNR} = \frac{P}{\sigma^2_{ASE} + \sigma^2_{NL}}$$

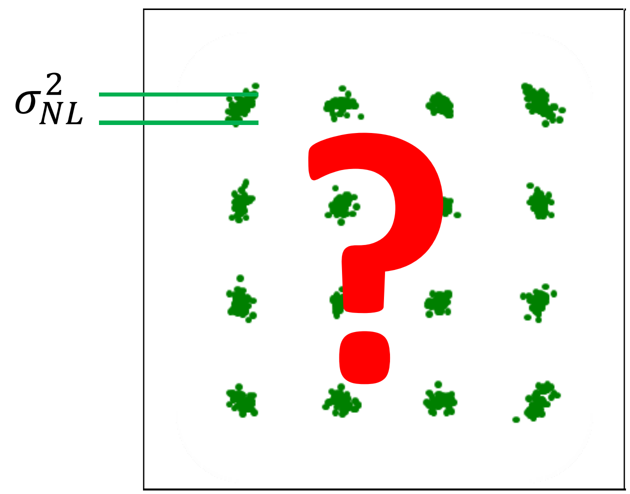
Under the assumptions of
Additivity, Gaussianity,
Circularity, Whiteness

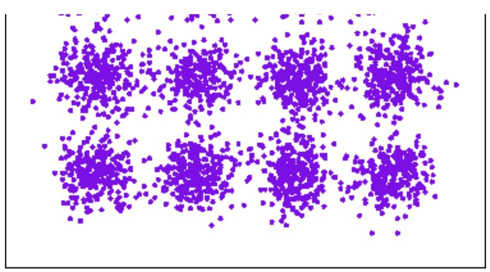
BER

Nonlinear interference noise (NLIN)









$$\mathbf{SNR} = \frac{P}{\sigma^2_{ASE} + \sigma^2_{NL}}$$

Under the assumptions of
Additivity, Gaussianity,
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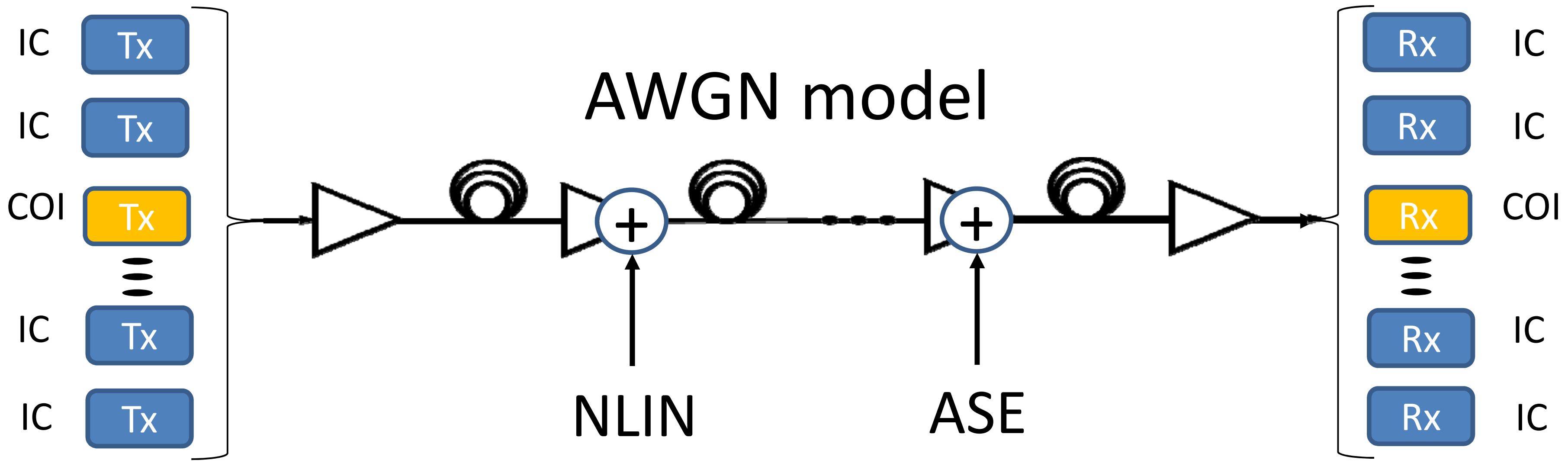
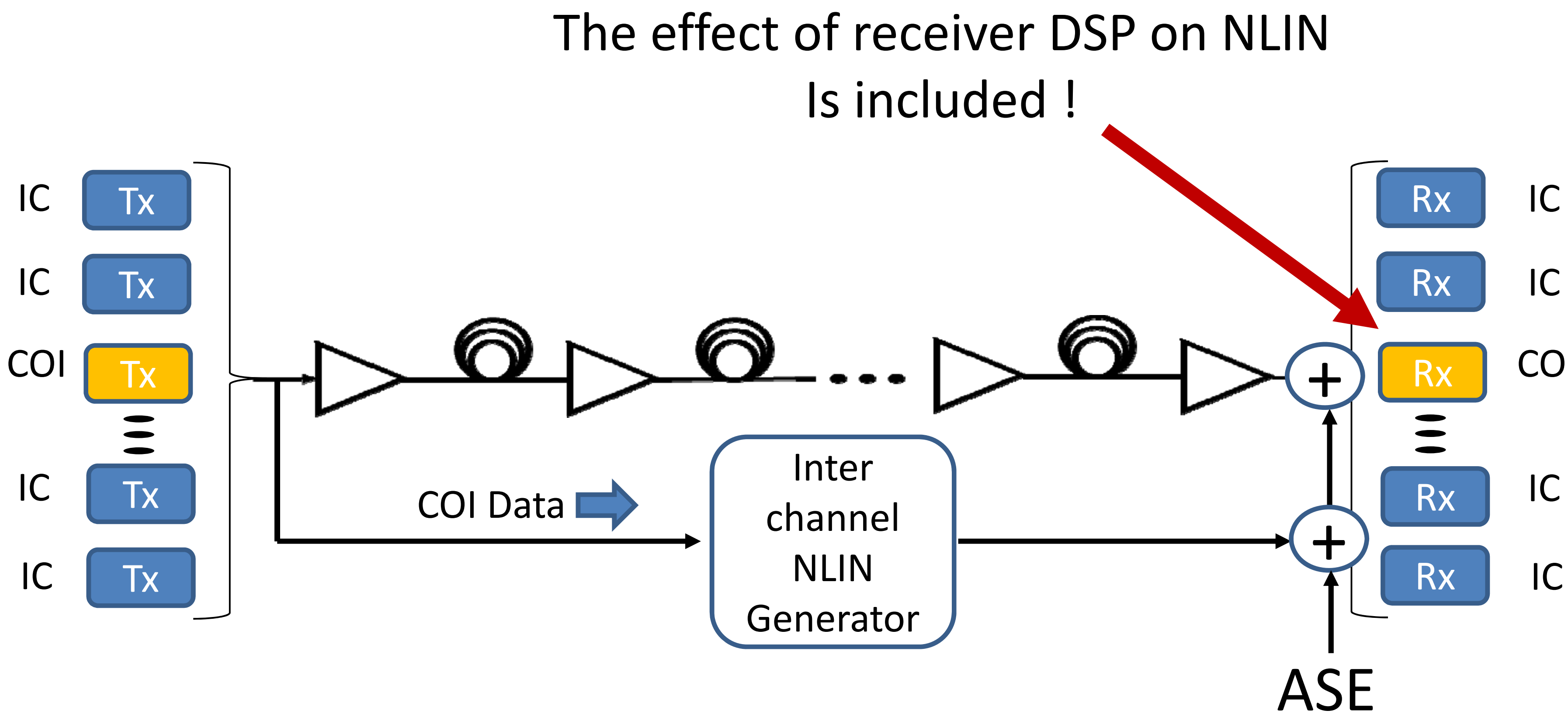
BER

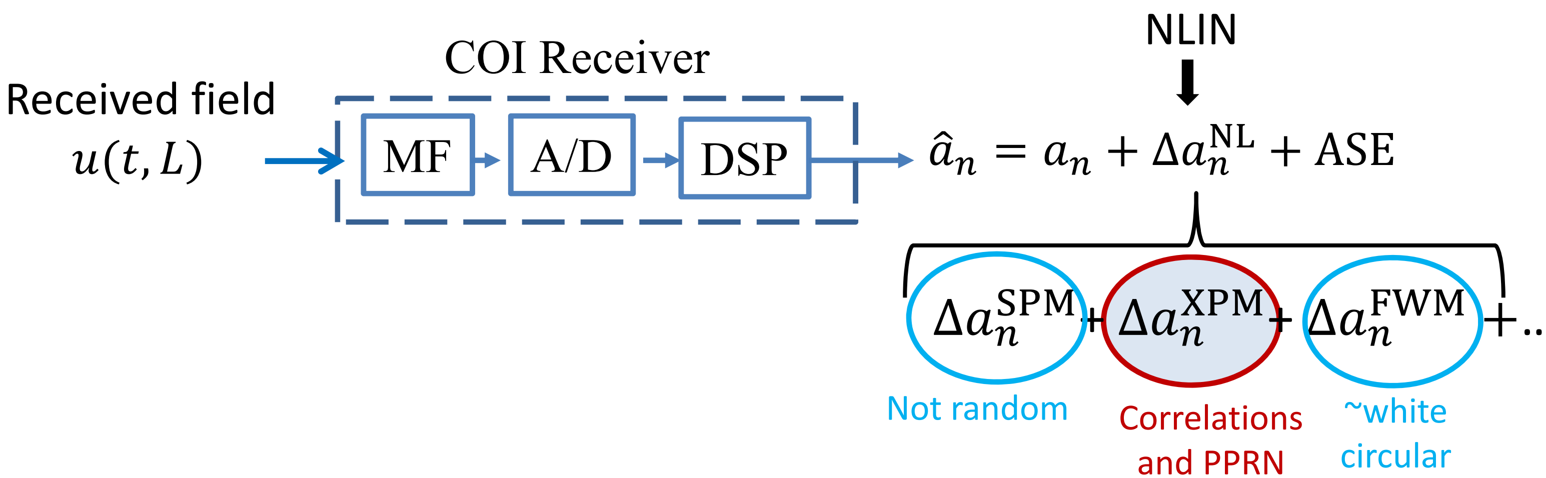
Modeling the BER performance

Ori Golani


IC
Tx
IC
Tx
COI
Tx
IC
Tx
IC
Tx
AWGN model
NLIN
ASE
Rx
IC
Rx
IC
Rx
COI
Rx
IC
Rx
IC



A virtual lab for BER assessment



$$\Delta a_n^{\mathrm{XPM}} = i\gamma \sum_l \mathbf{R}_l^{(n)} |a_{n+l}\rangle$$

Time varying ISI

Time varying ISI

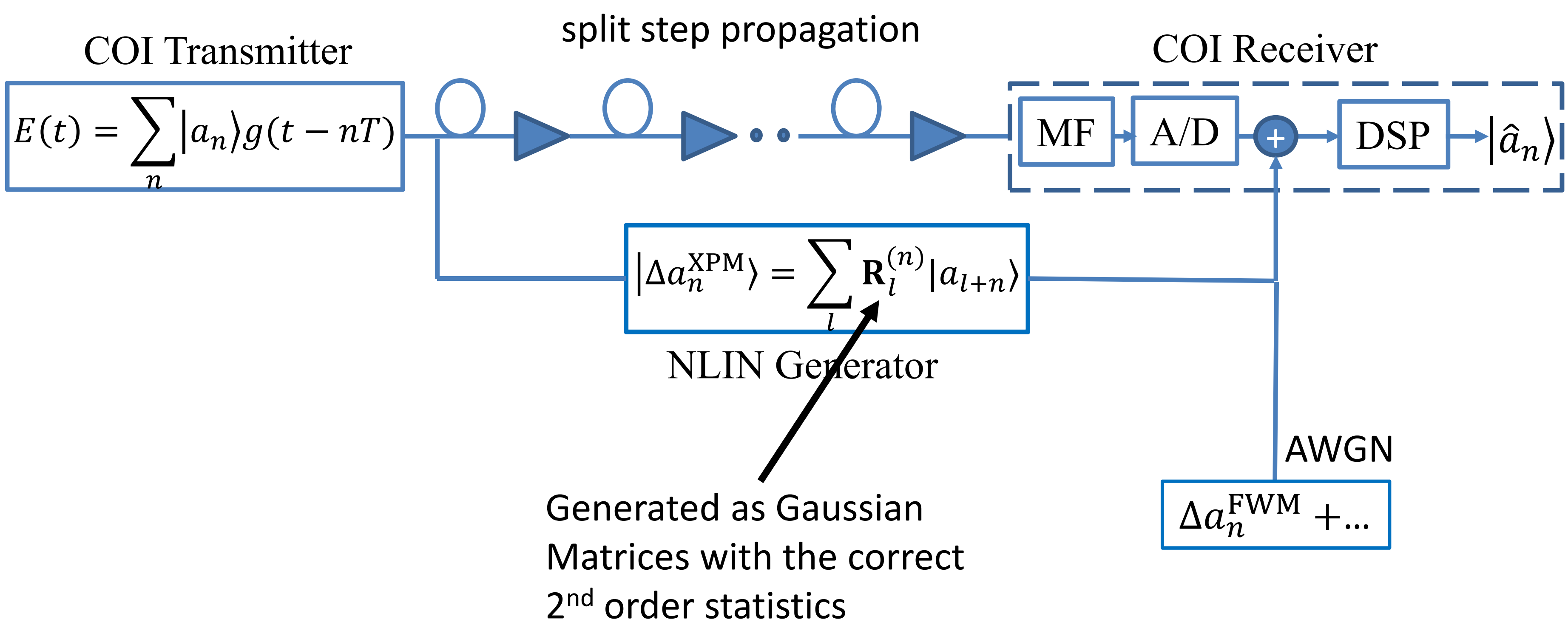
$$\Delta a_n^{\mathrm{XPM}} = i\gamma \sum_l \mathbf{R}_l^{(n)} |a_{n+l}\rangle$$

2X2 Matrix ISI

$$\mathbf{R}_l^{(n)} = \sum_{h,k,q} X_{h-n,k-n,l}^{q} \left(\langle b_k^q | b_h^q \rangle \mathbf{I} + |b_h^q\rangle\langle b_k^q|\right)$$

$$\mathbf{R}_l^{(n)} = \kappa \mathbf{I} + \begin{pmatrix} r_{l_{xx}}^{(n)} & r_{l_{xy}}^{(n)} \\ r_{l_{yx}}^{(n)} & r_{l_{yy}}^{(n)} \end{pmatrix}$$

Virtual Lab


COI Transmitter
$E(t) = \sum_n |a_n\rangle g(t - nT)$
split step propagation
COI Receiver
MF
A/D
DSP
$|\hat{a}_n\rangle$
$|\Delta a_n^{\mathrm{XPM}}\rangle = \sum_l \mathbf{R}_l^{(n)} |a_{l+n}\rangle$
NLIN Generator
AWGN
$\Delta a_n^{\mathrm{FWM}} + \ldots$
Generated as Gaussian
Matrices with the correct
2nd order statistics

Numerical validation

Comparing the results of the virtual lab with those of split-step simulations

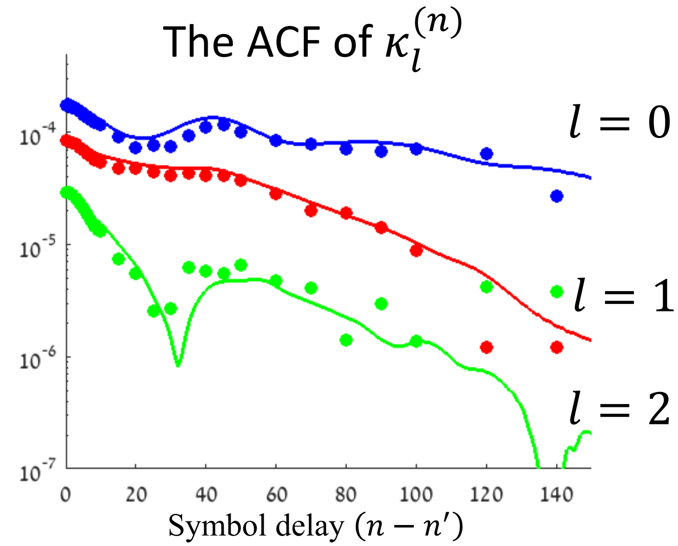
5 X 100 km system,
Standard SMF,
32 Gbaud, 16 QAM,
50 GHz channel spacing

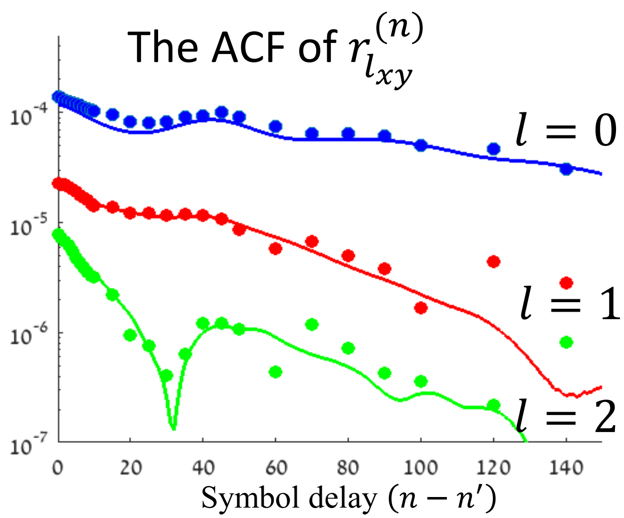
Split-step vs. Virtual Lab

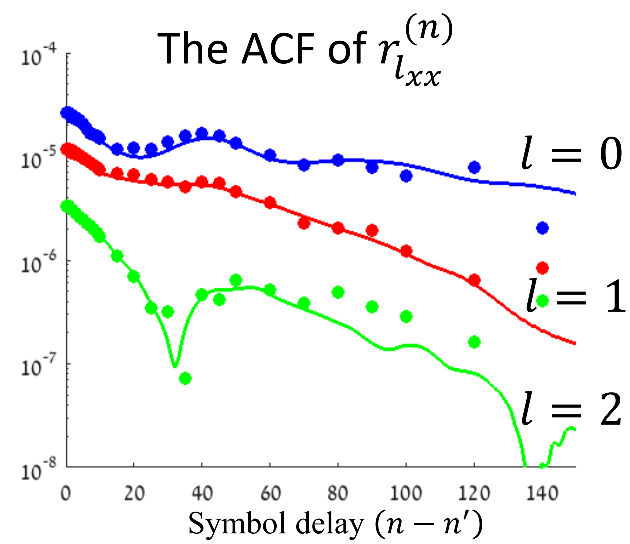
A few Examples

Autocorr. functions of several coefficients.

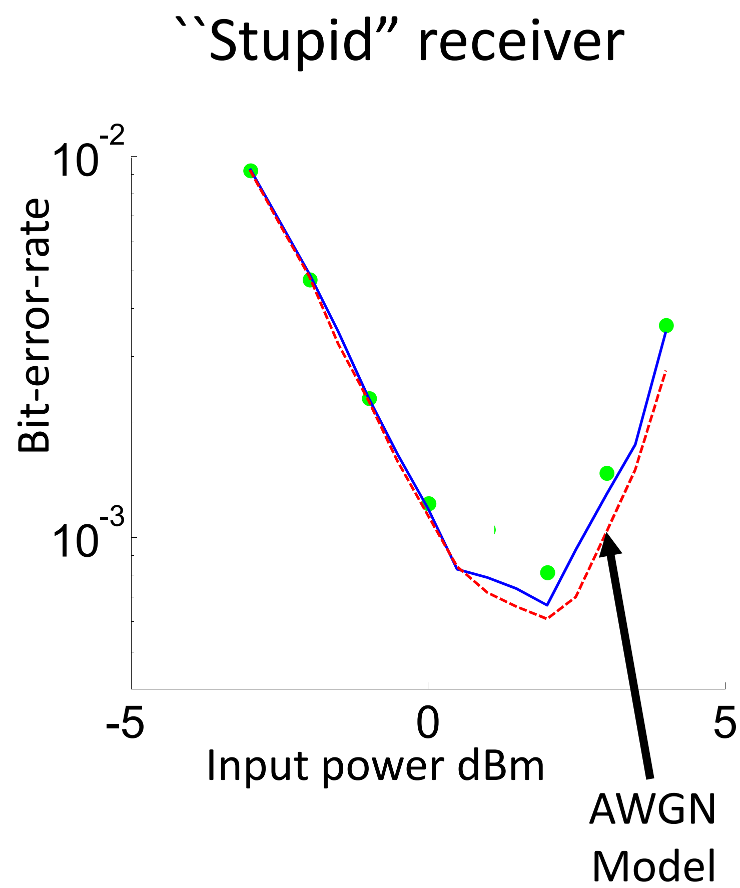
With 11 WDM channels

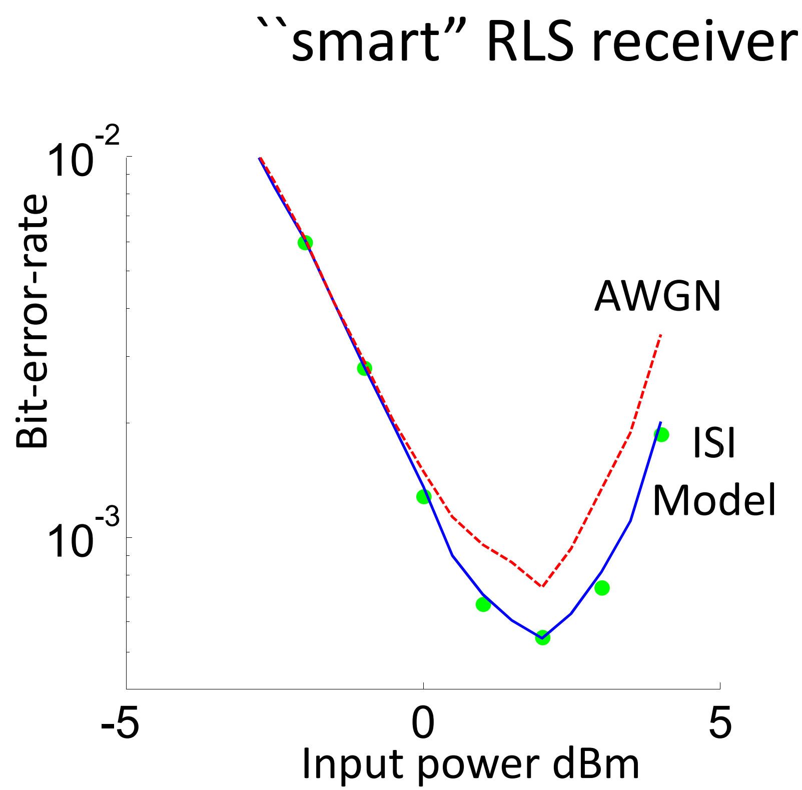






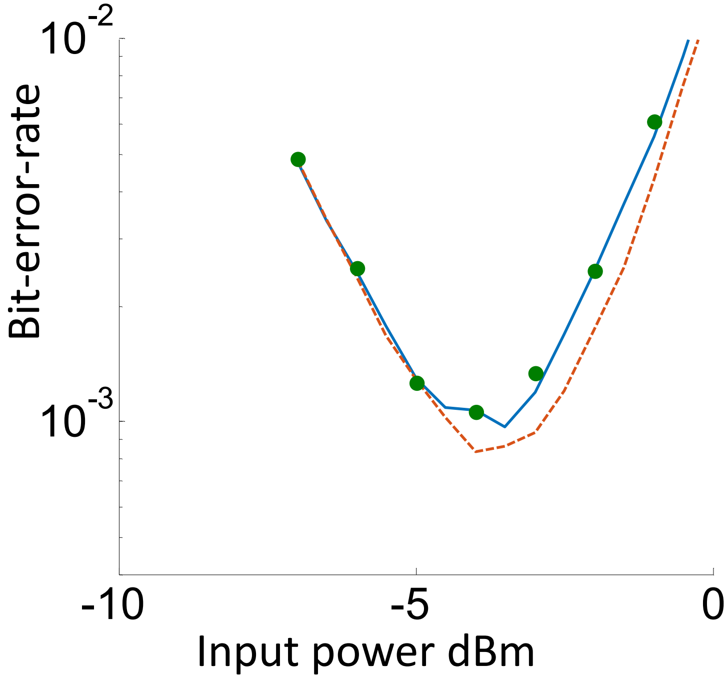
Validation in BER assessment



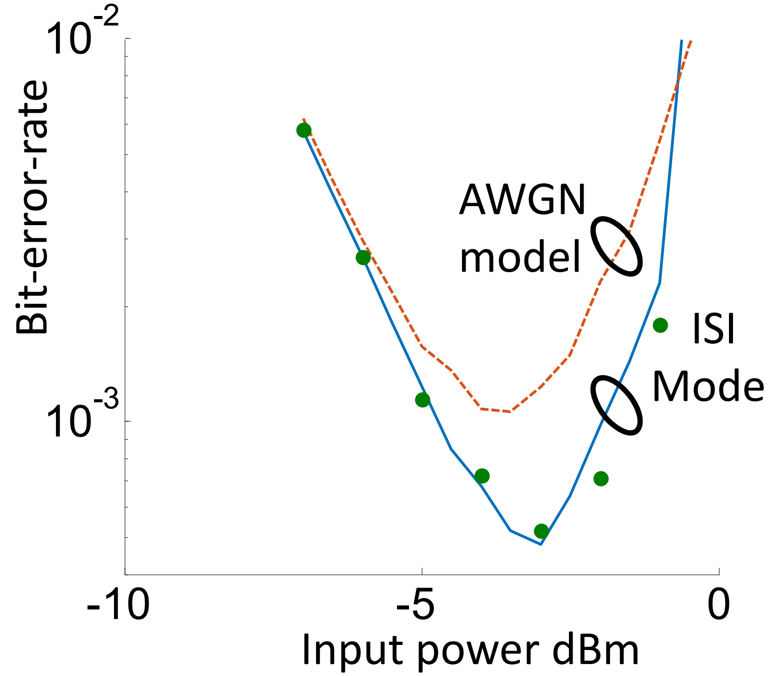


Validation in BER assessment

``Stupid" receiver

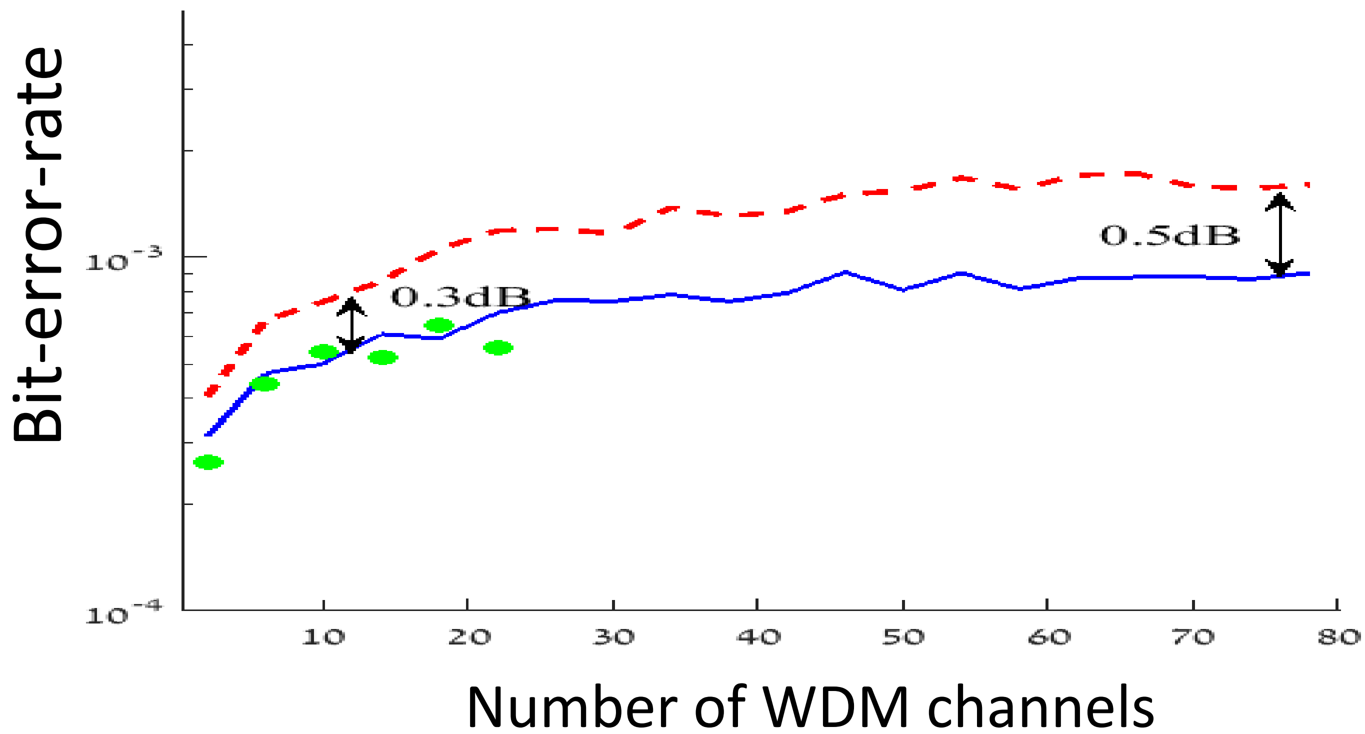


``smart" RLS receiver



Application: BER in a fully loaded system

``smart" RLS receiver



Other applications

- Analysis (e.g. capacity estimation)
- Performance prediction for routing decisions
- Parameter optimization
- Testing new DSP algorithms, codes etc.

Shaping for the Nonlinear Channel

Omri Geller

Shaping Principles

- Uniform QAM modulation is not the optimal input distribution for the channel
- In linear channels with additive white Gaussian noise, the Gaussian input distribution is optimal:
  - The gain in using Gaussian vs. Uniform distribution can be upto 1.53dB (corresponding to a mutual-information gain of ½ log $^{\pi e}/_{6}$)
- In the optical, non-linear channel the input distribution affects the amount of NLIN. Theoretically, the choice of input distribution (over uniform QAM) can lead to even higher gain!

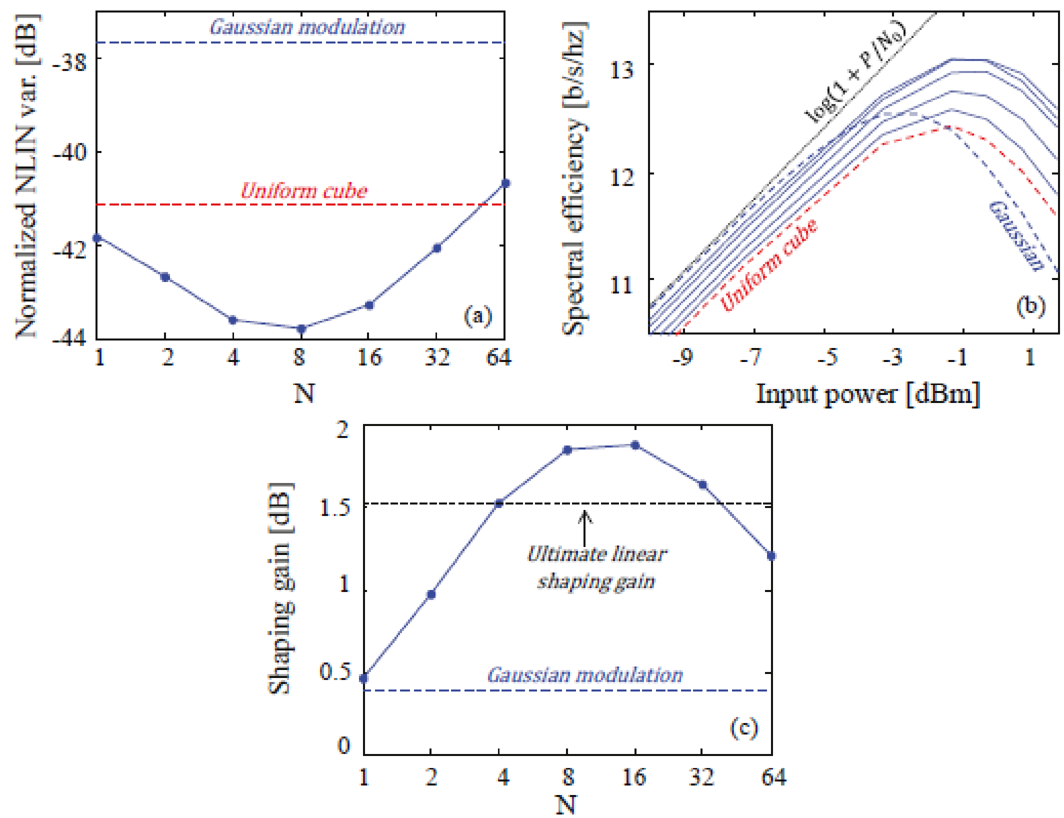
Theoretical Shaping Gain

$$\gamma_s^{OFC} = 2^{I_{max}(shaped) - I_{max}(reference)}$$

Where $I_{max}(shaped)$ and $I_{max}(reference)$ are lower bound on the corresponding MI's

Results:

(Gaussian, Uniform and uniform over a 2N-dim ball)



Practical Shaping

- Start with a large QAM constellation of some dimension and size.
- Keep the points that fit the desired distribution:
  - In the linear channels, keep the points with the minimal energy, to get a high dimensional ball shaped constellation

- In the optical channel, we propose the following algorithm:
  - Start with a 256 QAM constellation at some dimension N
  - Keep half the points that resides within a “shell” (or ring) constellation. Apply the “shell mapping shaping algorithm”
  - Motivation: minimal variance of the constellation energy reduces the non-linear noise. Yet, it still has good properties against the additive noise.
  - Experiments that try to reduce the polarization effect of the NLIN caused poorer gains due to resulting minimal distance

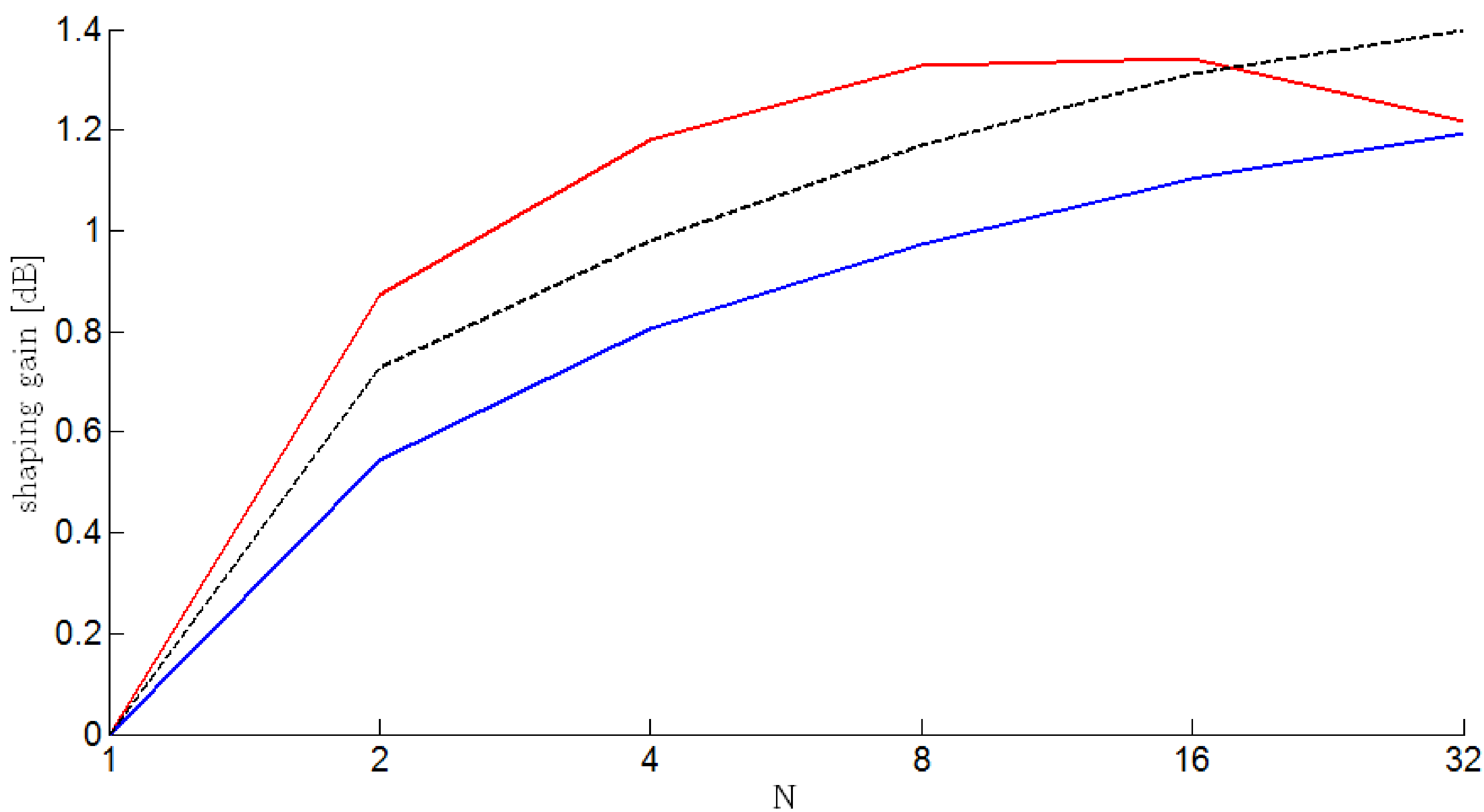
Practical Shaping (Results)

98G-Baud system.   N-Block size (2N complex dimension due to polarization)

Red –Shell mapping with best ring

Black – The theoretical minimum energy mapping (ball)

Blue – Shell mapping for minimum energy (ball)



Practical Shaping (Results)

32G-Baud system. N-Block size (2N complex dimension due to polarization)
Red –Shell mapping with best ring
Black – The theoretical minimum energy mapping (ball)
Blue – Shell mapping for minimum energy (ball)