A Covariance Matrix Method for Accurate Bit Error Rates in a DWDM CRZ System

OFC 2003

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BER Calculation: Common Approaches

❶ **Full Monte Carlo simulations + Gaussian extrapolation** [Bergano]

- **+** : few assumptions, simple
- **–** : computationally very expensive, pdfs are not Gaussian

❷ **Optical white noise at receiver** [Marcuse, Winzer]

- **+** : very fast, deterministic
- **–** : noise-free transmission, no signal-noise interaction

❸ **CW transmission linearization + analytic pdfs** [Hui, Bosco, Mazurczyk]

- **+** : very fast, deterministic, includes parametric gain
- **–** : no data modulation in signal-noise interaction during transmission

None of these approaches is well-validated

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The Covariance Matrix Method

R. Holzlöhner, *et al.*, J. Lightwave Technol. **20**, pp. 389–400 (2002)

- **For modulated data with multiple bits and channels**
- **Deterministic fiber propagation model:**
  - Includes nonlinear interactions between signal and noise
  - Neglects nonlinear noise-noise interactions in the fiber
  - Propagates the optical noise covariance matrix
- **Receiver model includes:**
  - Realistic optical and electrical filters
  - Quadratic noise-noise interactions

We compute the noise covariance matrix deterministically

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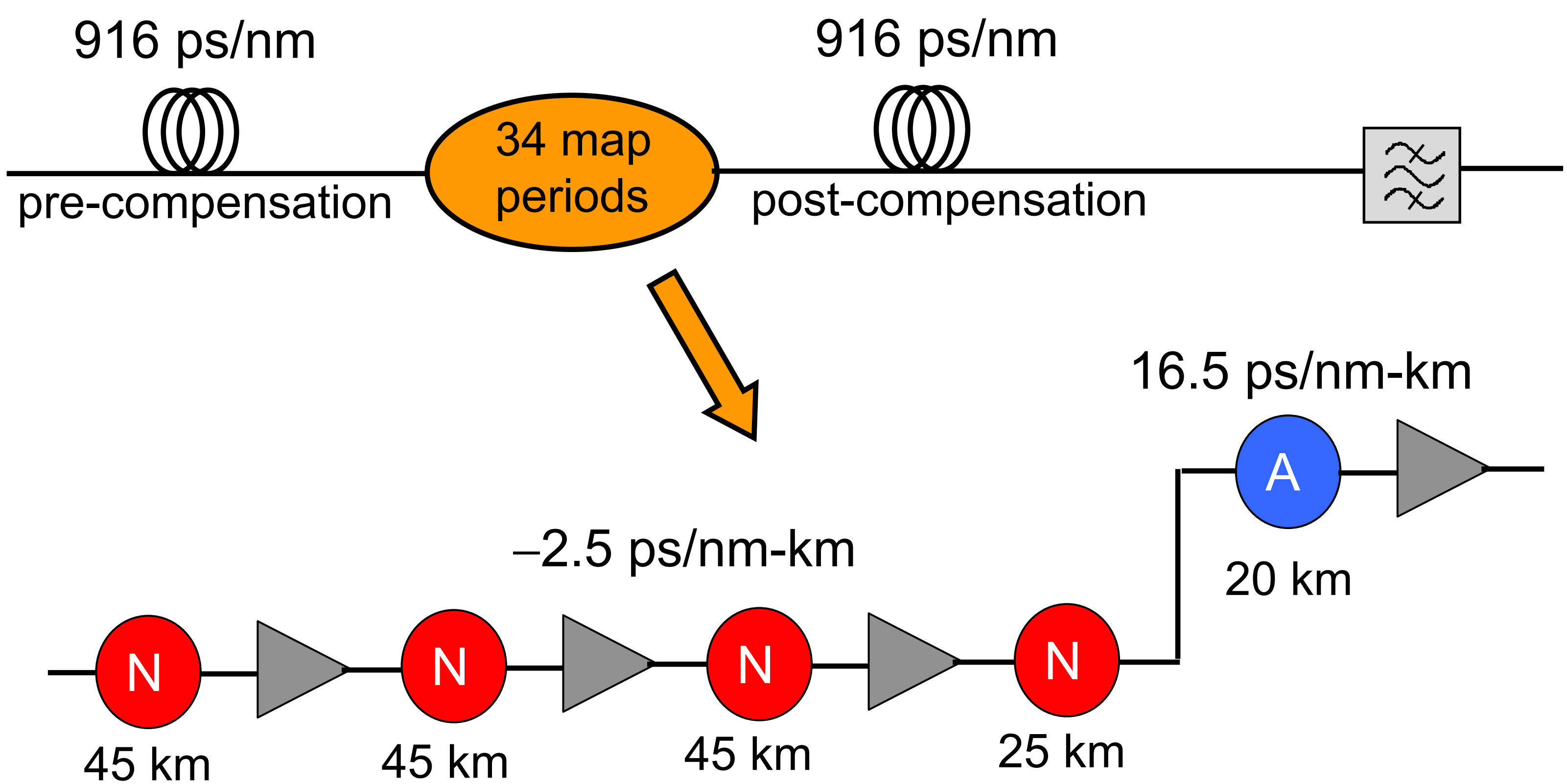
Test System: CRZ DWDM

Submarine 10 Gb/s CRZ system, 6100 km, 50 GHz channel spacing



Strong pulse overlap

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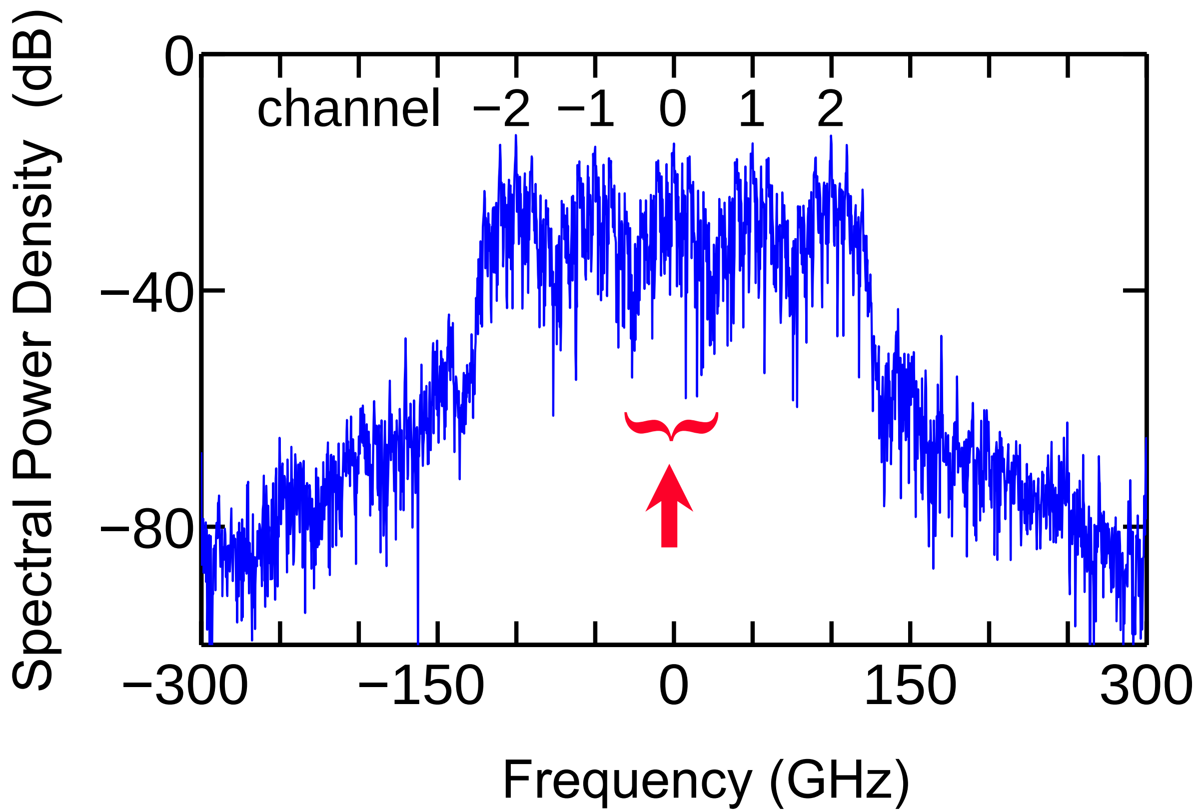
R. Holzlöhner, *et al.*, Photon. Technol. Lett. **14**, pp. 1079–1081 (2002)

DWDM System Modeling

Noise analysis for channel 0



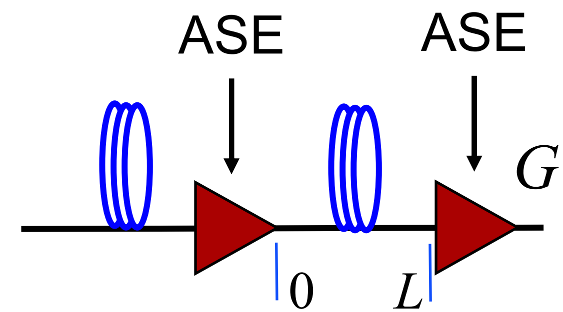
32-bit PRBS
in all channels
(contains all
5-bit patterns)

Simulating five channels is sufficient*

* Yu, *et al.*, Photon. Technol. Lett. **12**, pp. 443–445 (2002)

How to Compute the Covariance Matrix

Linearize the nonlinear Schrödinger equation:



$$\frac{\partial \boldsymbol{a}}{\partial z} = \mathrm{R}(z)\boldsymbol{a} \;\Rightarrow\; \boldsymbol{a}(L) = \boldsymbol{\Psi}\boldsymbol{a}(0)$$

$$\mathrm{K}_{ij} = \langle \boldsymbol{a}_i \boldsymbol{a}_j \rangle, \quad \dim(\mathrm{K}) = 280 \times 280$$

$$\mathrm{K}(L) = G\,\boldsymbol{\Psi}\mathrm{K}(0)\boldsymbol{\Psi}^{\mathrm{T}} + \eta\,\mathbf{I}$$

ASE input

Compute Ψ by perturbing each of the frequency modes separately

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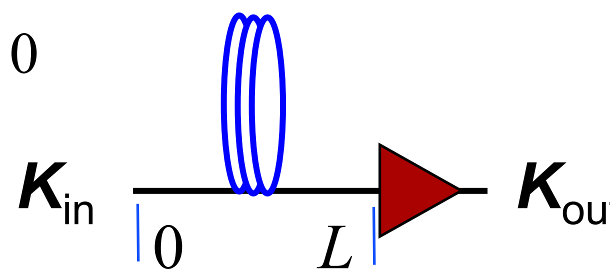
Algorithm

The following is done for each fiber span and each frequency k:

1. Perturb the noise-free signal in k at $z = 0$
2. Filter out central channel at $z = L$



3. Separate the pulses by compensating accumulated dispersion
4. Remove the phase jitter of each pulse, invert step 3

Evaluate $\mathbf{\Psi}$, propagate the covariance matrix

This approach neglects interchannel noise-noise correlations

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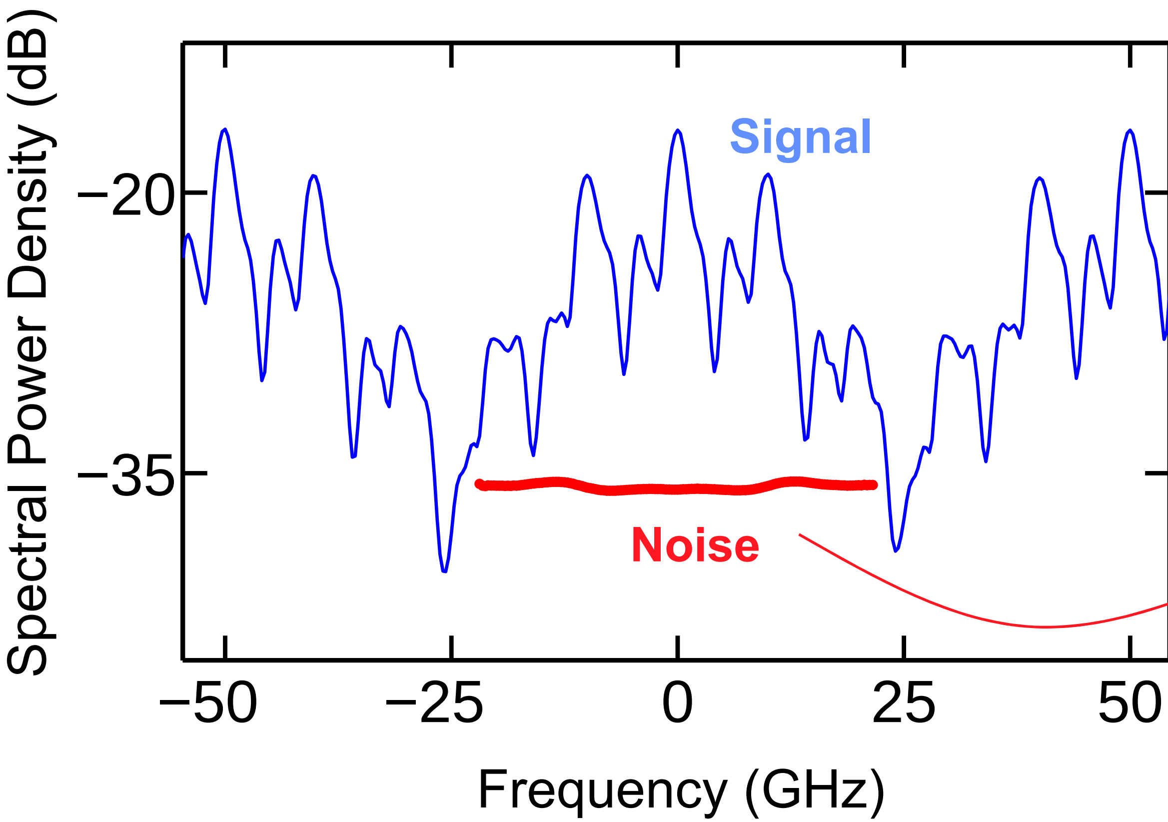
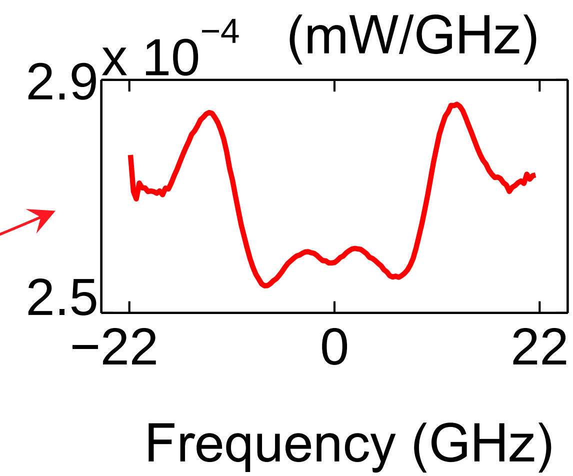
Results



OSNR in channel 0:
11.2 dB



Optical noise at the receiver is not white !

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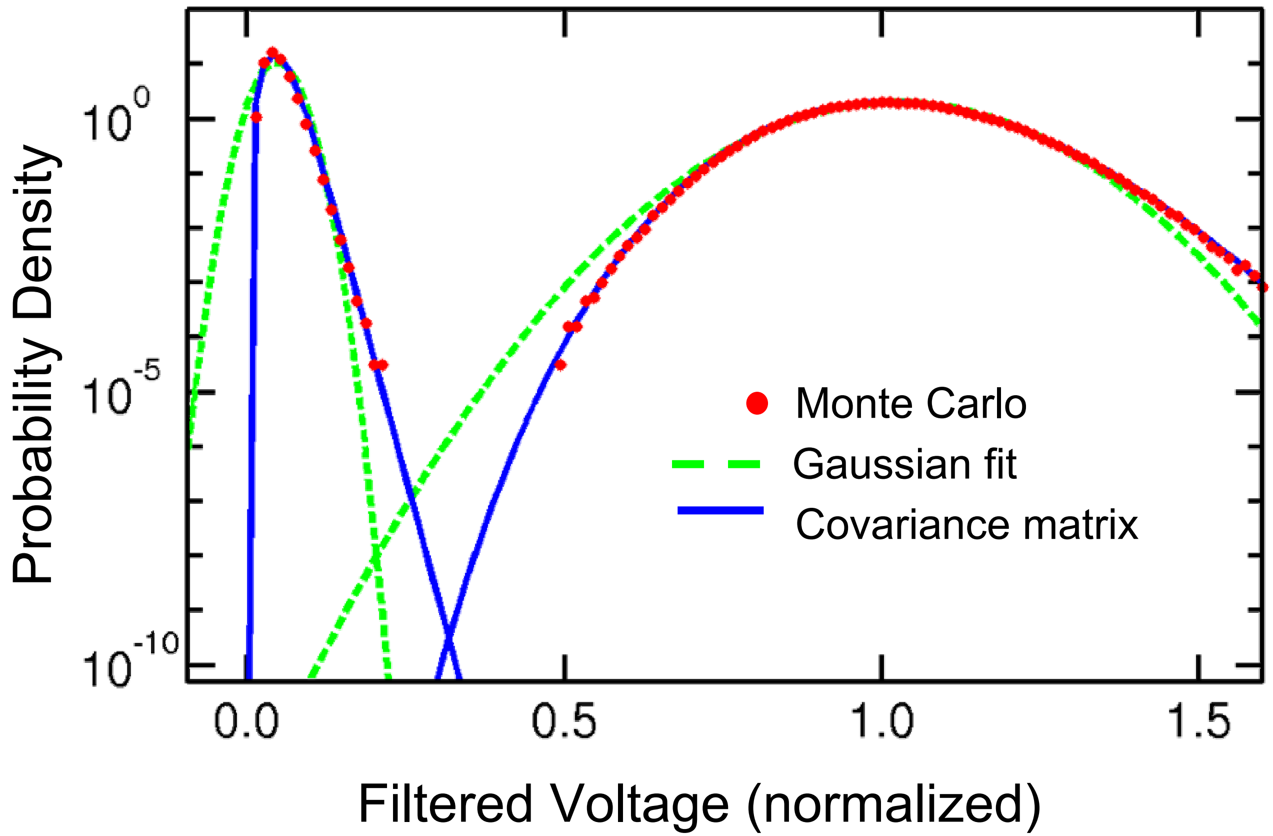
Pdfs of the Electrical Voltage



5 channels,
32 bits

Optimum BER:
3.1×10^{-12}

Optimum
Gaussian BER:
1.0×10^{-11}
$Q = 6.7$

Excellent agreement between Covariance Matrix Method and Monte Carlo simulations*

* Holzlöhner, *et al.*, CLEO 2003, talk CThJ, to appear

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Conclusions

1. We validated the Covariance Matrix Method for a DWDM CRZ system

2. Number of relevant modes the same as in single-channel system

3. Good scaling behavior

4. Computational cost equals 280 noise-free simulation runs!

Covariance Matrix Method is highly accurate and relatively fast

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