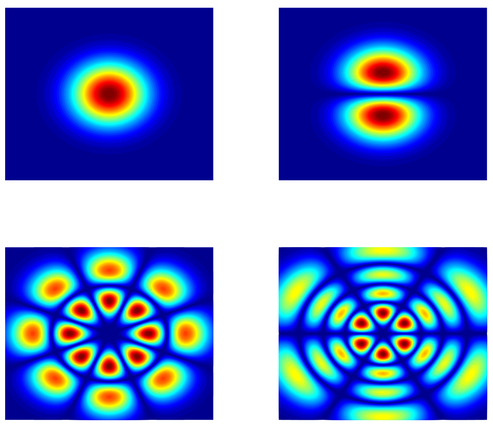
Nonlinear Gaussian Noise Model for Multi-Mode Fibers with Space-Division Multiplexing



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Introduction

We present an extension of the well accepted *Nonlinear Gaussian Noise Model* [1,2] for multi-mode fibers with Space-Division Multiplexing. We compare the analytical model with numerical simulations and find a good agreement, making the model an easy-to-use tool for the design of future fiber optical transmission systems.

Analytical Modeling

The impact of nonlinear signal distortions can be modeled through an additional noise and included in an nonlinear OSNR for fiber mode p as:

$$OSNR_{NL}^{(p)} = \frac{P_{in}}{B_{ref}(N_{ase} + G_{NL}^{(p)})} \tag{1}$$

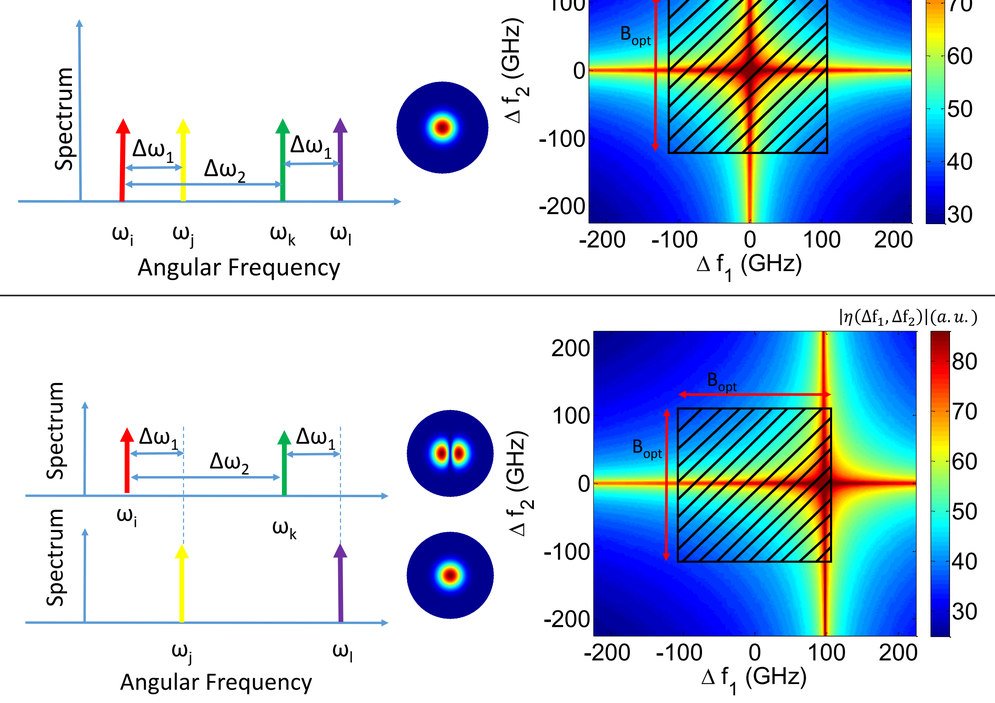
The nonlinear noise power density can be calculated as [3]:

$$G_{NL}^{(p)} = G_{TX}^3 \Bigg(\overbrace{\left(\frac{8}{9}\gamma_{pppp}\right)^2 \iint_{-B_{opt}/2}^{B_{opt}/2} \left|\eta(\Delta\beta^{(pppp)})\right|^2 d\Delta f_1 d\Delta f_2}^{\text{Intramodal nonlinear interaction: } G_{NL\_intra}} + \underbrace{2\sum_{q\neq p}\left(\frac{2}{3}\gamma_{ppqq}\right)^2 \iint_{-B_{opt}/2}^{B_{opt}/2} \left|\eta(\Delta\beta^{(ppqq)})\right|^2 d\Delta f_1 d\Delta f_2}_{\text{Intermodal nonlinear interaction: } G_{NL\_inter}} \Bigg) \tag{2}$$

The nonlinear noise increases linearly with the transmission distance as:

$$G_{NL\_MS}^{(p)} = G_{NL}^{(p)} \cdot N_{sp} \tag{3}$$

FWM in Multi-Mode Fibers

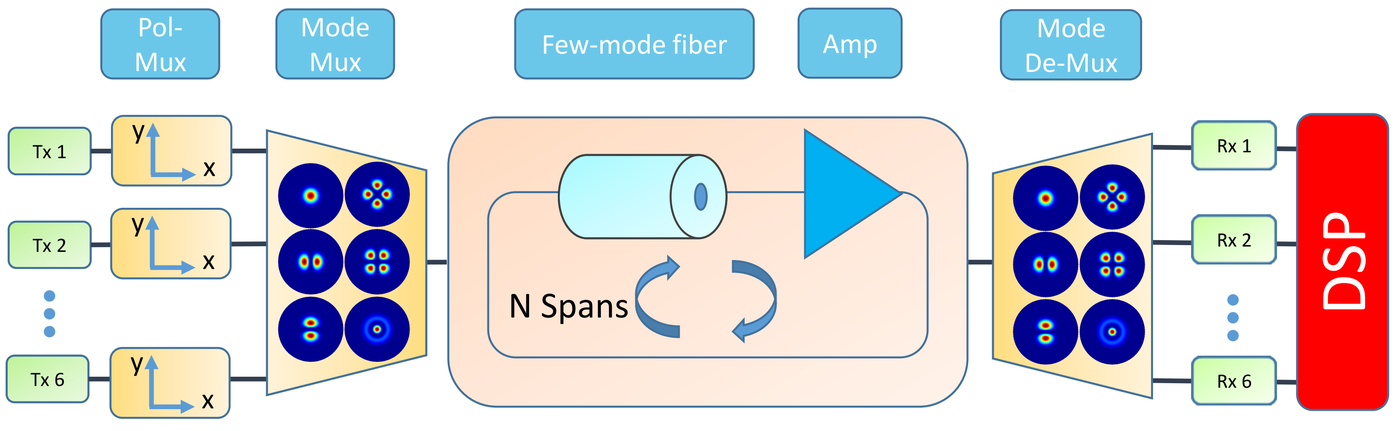


Validation Method

We define a ratio of the nonlinear noise when only considering intramodal distortion and when considering both, intra- and intermodal nonlinear distortion. In the simulation, we assess the nonlinear noise through the variance of the received constellation points.

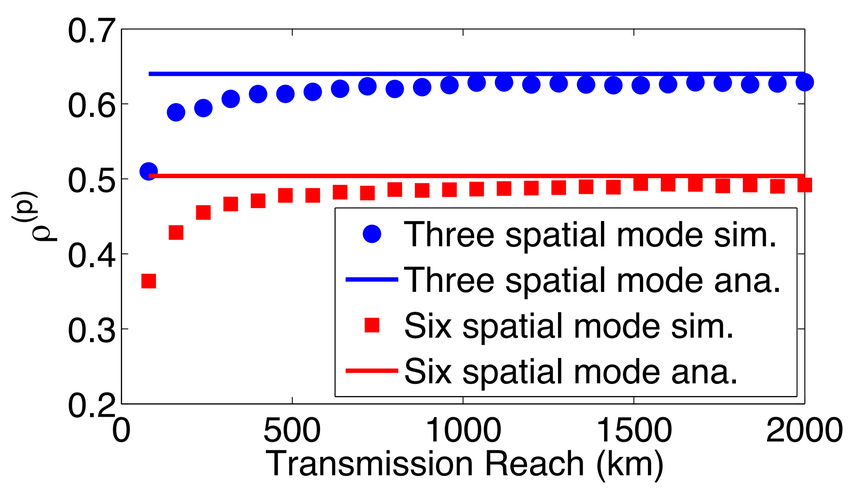
$$\rho^{(p)} = \frac{G_{NL\_intra}^{(p)}}{G_{NL\_intra}^{(p)} + G_{NL\_inter}^{(p)}} = \frac{G_{NL\_intra}^{(p)}}{G_{NL\_tot}^{(p)}} \tag{4}$$

System Design

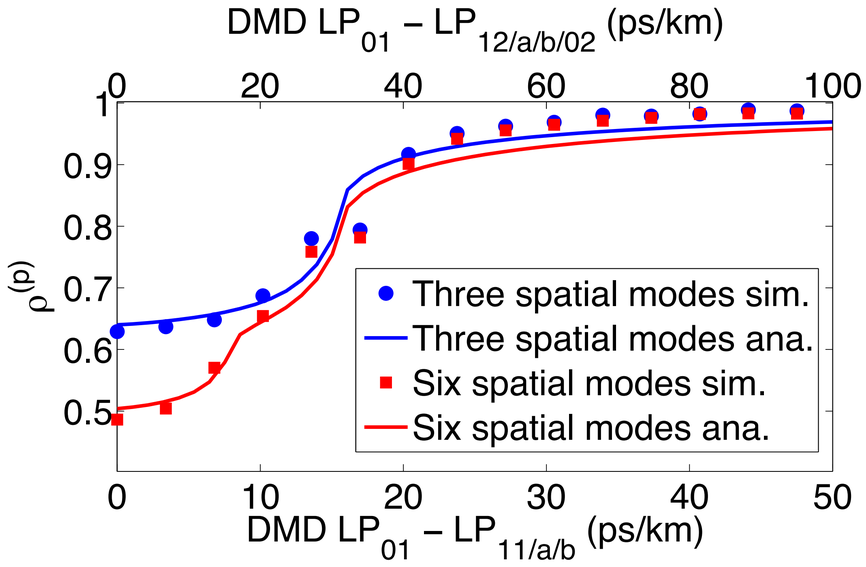


Modulation Format	QPSK
Pulse shaping	Root raised cosine filtering
Roll Off	$\alpha_{RO} = 0.001$
Symbol Rate	$28GBaud$
Number of WDM channels	9
Channel spacing	$28.01GHz$
Total optical Bandwidth	$B_{opt} \approx 250GHz$
P_{in} /WDM/MDM channel	$-6dBm$
Span length	$80km$
Number of Spans	$1 - 25$
Fiber Core Radius	$a = 9\mu m$
Numerical Aperture	0.205
Attenuation	$\alpha = 0.2dB/km$
Nonlinear parameter	$n_2 = 2.6^{-20} m^2/W$
Differential Mode Delay $LP_{01} - LP_{11a/b}$	$0 - 50ps/km$
Differential Mode Delay $LP_{01} - LP_{12a/b/02}$	$0 - 100ps/km$
Chromatic Dispersion (all modes)	$15ps/nm \cdot km$

Validation: Transmission Distance



Validation: Differential Mode Delay



References

1. A. Splett et al. "Ultimate Transmission Capacity of Amplified Optical Fiber Communication Systems taking into account Fiber Nonlinearities," In ECOC, page MoC2.4, 1993.
2. A. Carena et al. "Modeling of the Impact of Nonlinear Propagation Effects in Uncompensated Optical Coherent Transmission Links," JLT, **30** 1524–1539, 2012.
3. G. Rademacher et al. "Nonlinear Gaussian Noise Model for Multi-Mode Fibers with Space-Division Multiplexing," Submitted for publication

Acknowledgment

This work was funded by the German Research Foundation (DFG)