The nonlinear noise increases linearly with the transmission distance as:

\[ \text{OSNR}^{(p)}_{NL} = \frac{P_m}{B_{ref}(N_{ave} + G_N^{(p)} N_L)} \]  

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

\[ G_{NL, intra}^{(p)} = \frac{G_{NL}^2}{X} \left( \sum_{\omega \neq p} \int_{-B_{ref}/2}^{B_{ref}/2} \left| \eta(\Delta \omega_{ppp}) \right|^2 d\Delta \omega_1 d\Delta \omega_2 \right) \]

\[ + 2 \sum_{\omega \neq p} \int_{-B_{ref}/2}^{B_{ref}/2} \left| \eta(\Delta \omega_{ppp}) \right|^2 d\Delta \omega_1 d\Delta \omega_2 \]  

The nonlinear noise increases linearly with the transmission distance as:

\[ G_{NL, AS}^{(p)} = G_{NL}^{(p)} \cdot N_{sp} \]  

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 \( p \):

\[ \text{OSNR}^{(p)}_{NL} = \frac{P_m}{B_{ref}(N_{ave} + G_N^{(p)} N_L)} \]  

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

\[ G_{NL, intra}^{(p)} = \frac{G_{NL}^2}{X} \left( \sum_{\omega \neq p} \int_{-B_{ref}/2}^{B_{ref}/2} \left| \eta(\Delta \omega_{ppp}) \right|^2 d\Delta \omega_1 d\Delta \omega_2 \right) \]

\[ + 2 \sum_{\omega \neq p} \int_{-B_{ref}/2}^{B_{ref}/2} \left| \eta(\Delta \omega_{ppp}) \right|^2 d\Delta \omega_1 d\Delta \omega_2 \]  

The nonlinear noise increases linearly with the transmission distance as:

\[ G_{NL, AS}^{(p)} = G_{NL}^{(p)} \cdot N_{sp} \]  

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.

\[ \rho^{(p)} = \frac{G_{NL, intra}^{(p)}}{G_{NL, intra}^{(p)} + G_{NL, inter}^{(p)}} = \frac{G_{NL, intra}^{(p)}}{G_{NL, tot}^{(p)}} \]  

**System Design**

- Modulation Format: QPSK
- Pulse shaping: Root raised cosine filtering
- Roll Off: \( \alpha_{RO} = 0.001 \)
- Symbol Rate: 28.01 GHz
- Number of WDM channels: 9
- Channel spacing: 28.01 GHz
- Total optical Bandwidth: \( B_{opt} \approx 290 \text{GHz} \) per channel
- Span length: 80 km
- Number of Spans: 1 – 25
- Fiber Core Radius: \( a = 9 \mu m \)
- Numerical Aperture: 0.25
- Attenuation: \( a = 0.24 \text{dB/km} \)
- Nonlinear parameter: \( n_2 = 2.6 \cdot 10^{-20} \text{m}^2/\text{W} \)
- Differential Mode Delay \( \Delta t_{DP, f} \):
  - \( \Delta t_{DP, f} \cdot \text{LP}_{01} = \text{LP}_{12a/b} \cdot 0.1 \text{ps/km} \)
  - \( \Delta t_{DP, f} \cdot \text{LP}_{01} = \text{LP}_{12a/b} \cdot 0.3 \text{ps/km} \)
  - Chromatic Dispersion (all modes): 15 ps/nm/km

**Validation: Transmission Distance**

**Validation: Differential Mode Delay**

**References**

3. G. Rademacher et al. “Nonlinear Gaussian Noise Model for Multi-Mode Fibers with Space-Division Multiplexing,”Submitted for publication

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