Model for Nonlinear Interference Noise in Raman-amplified WDM Systems

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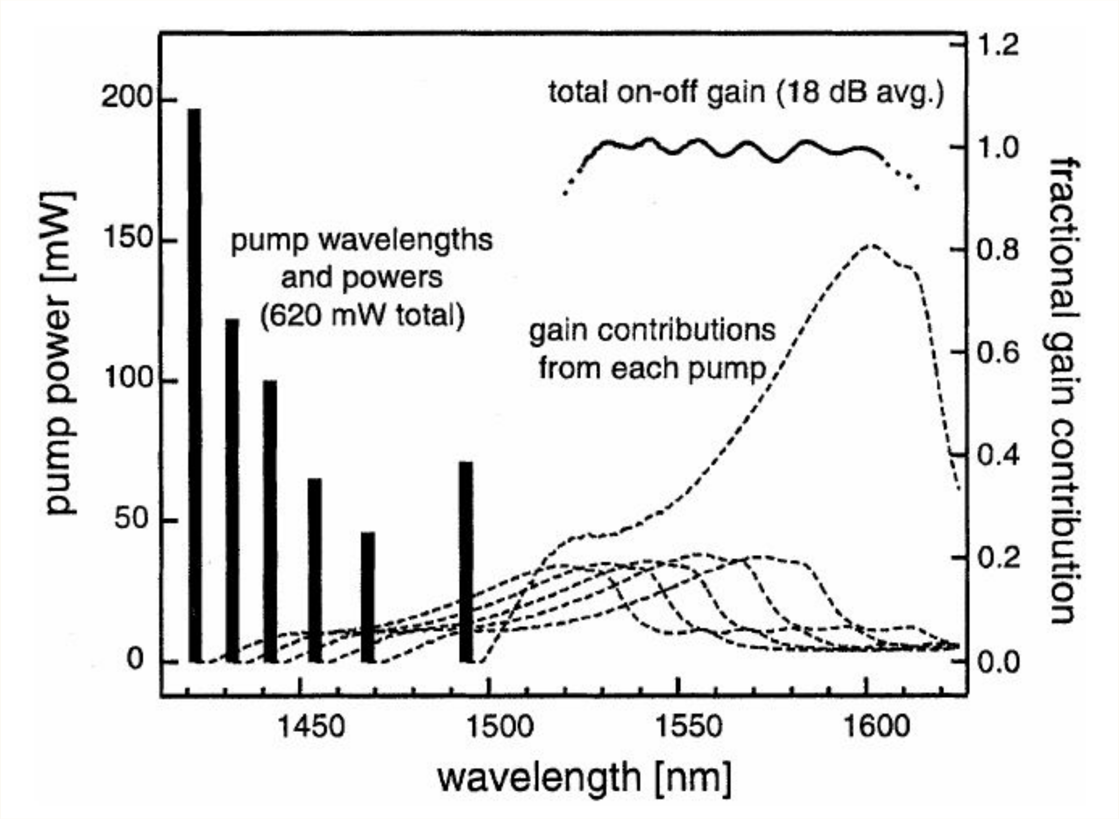
Outline

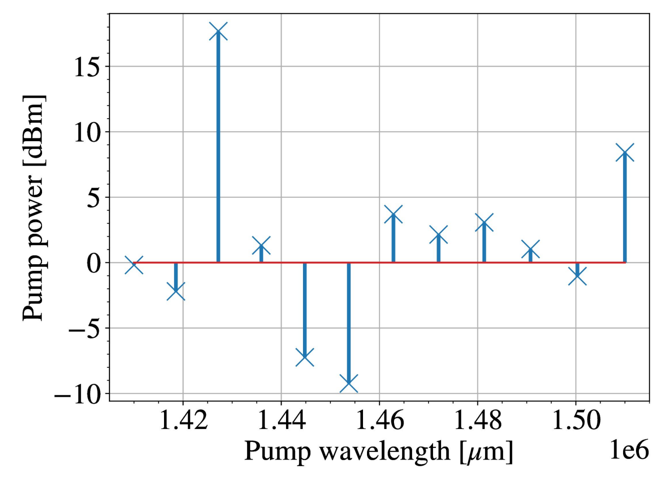
- Brief **introduction** to Raman-amplified WDM systems and **motivation** on the study of NonLinear Interference Noise (NLIN).

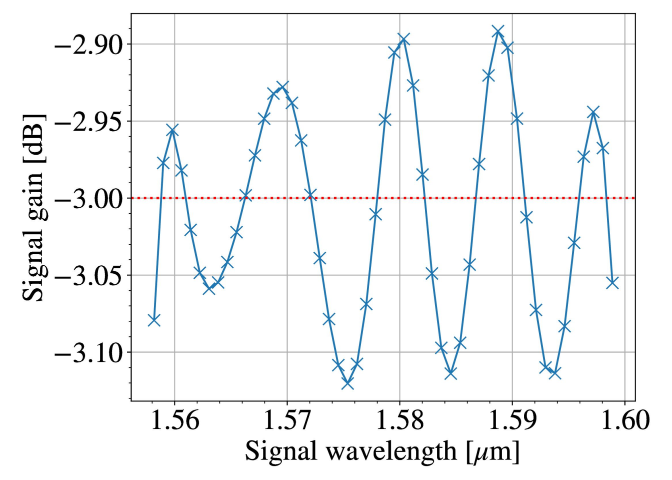
- Illustration of the **extension** of the existing **model** for NLIN, for these systems.

- Description of the consequences ,in terms of noise performances, by using **numerical simulations**.

Raman-amplified WDM systems: equalized amplification







[1] J. Bromage, *JLT* (2004).
[2] G. Marcon et al., *JLT* (2021).

Nonlinear Interference Noise

The model by Dar and Mecozzi [3] assumes **perfect amplification**, thus using NLSE of the form

$$\frac{\partial}{\partial z}u = -i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}u + i\gamma\left|u\right|^2 u,$$

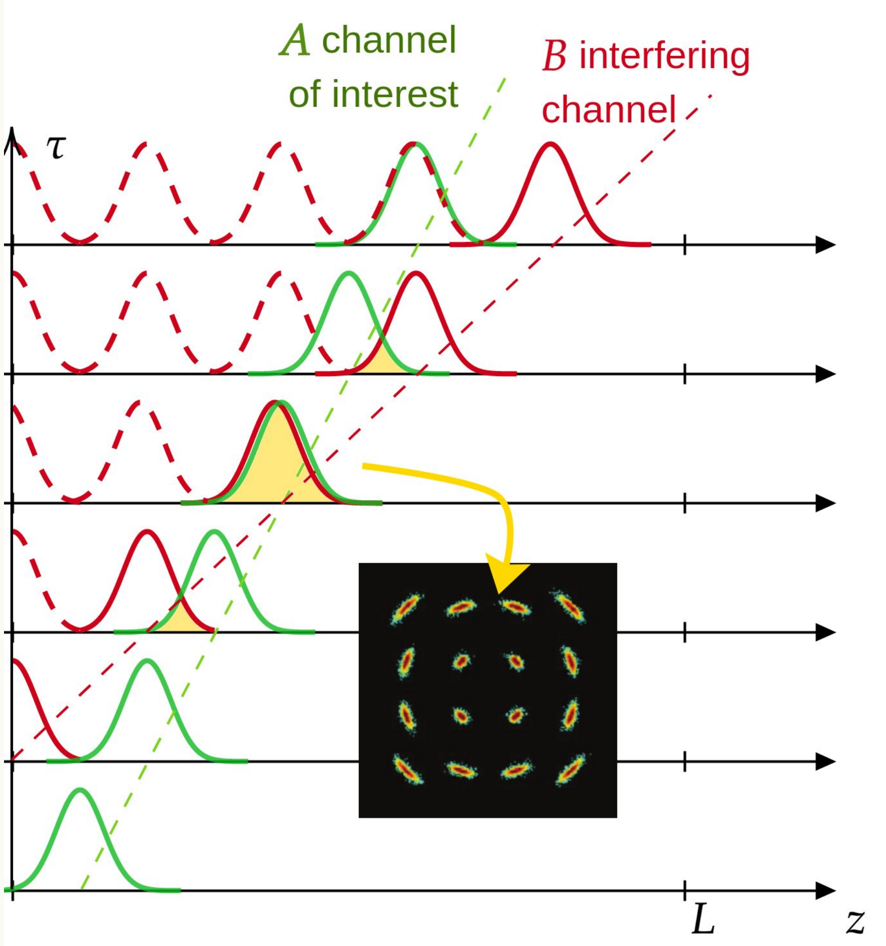
and obtains **phase noise variance** using first order perturbation theory,

$$\Delta a_0 = i2\gamma a_0 \sum_m \left|b_m\right|^2 X_{0,m,m},$$

$$X_{0,m,m} = \int_0^L dz \int_{-\infty}^{+\infty} dt \left|g^{(0)}(z,t)\right|^2 \left|g^{(0)}\left(z, t - mT - \beta_2\Omega z\right)\right|^2.$$

Analytical solution is found by assuming to have **high dispersion**, with the approximation

$$X_{0,m,m} \approx \frac{1}{\beta_2\Omega}\,.$$



[3] R. Dar et al., *Opt. Express* (2013).

Computation of total phase noise

The phase noise variance is

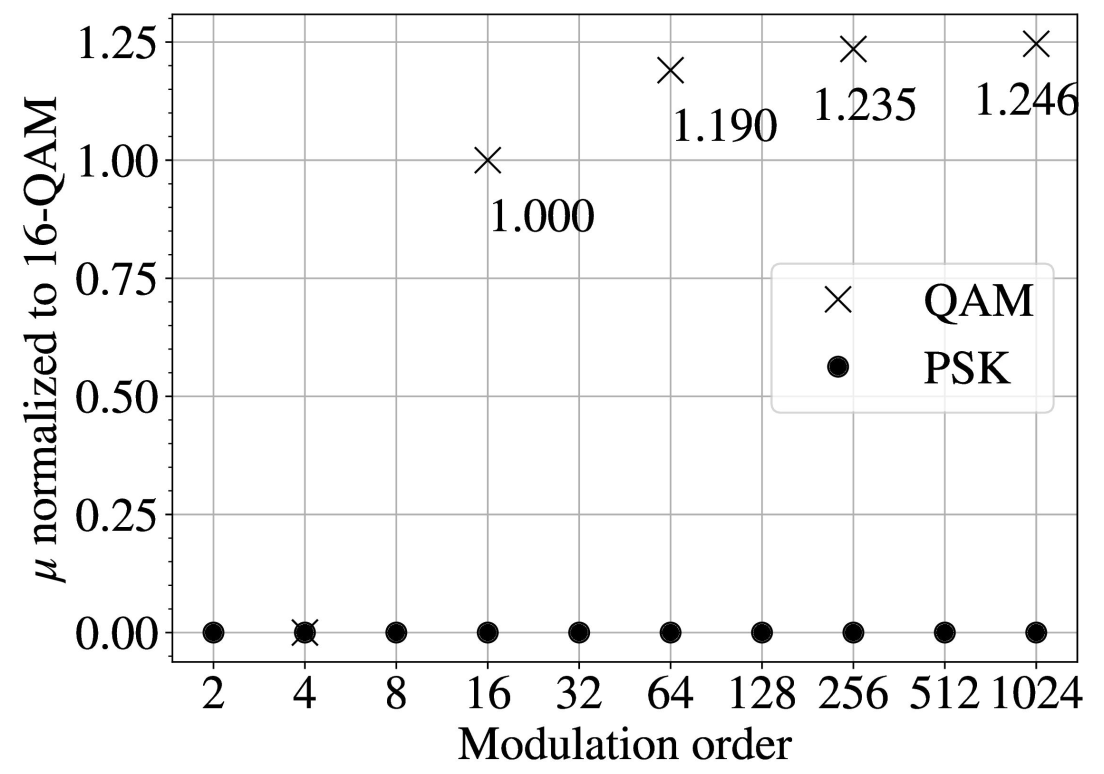
$$\Delta\theta^2 = 4\gamma^2 \underbrace{\left(\mathbb{E}\left[|b_0|^4\right] - \mathbb{E}\left[|b_0|^2\right]^2\right)}_{\text{modulation format}} \underbrace{\sum_m X_{0,m,m}^2}_{\text{pulse overlap}}$$

and the expression can be decomposed as

$$\Delta\theta^2 = 4\gamma^2 (P_B T)^2 \mu \sum_m X_{0,m,m}^2,$$

$$\mu = \left(\frac{\mathbb{E}\left[|b_0|^4\right]}{\mathbb{E}\left[|b_0|^2\right]^2} - 1\right),$$

separating impacts of *pulse overlaps*, *input power* and *baud rate*, and *modulation format*.

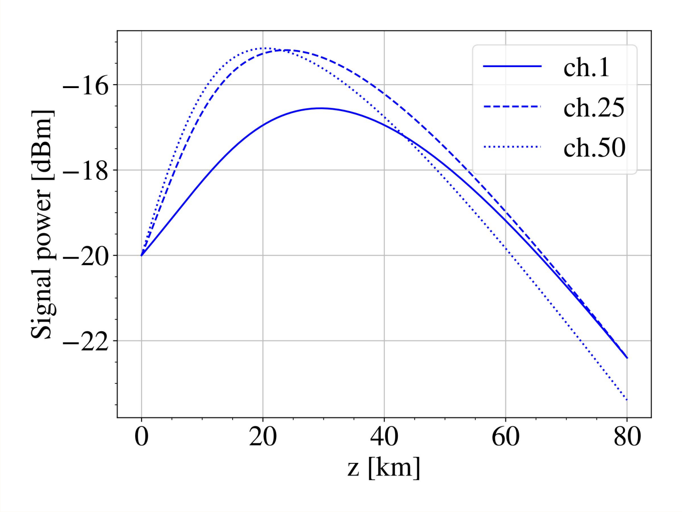


Waves power evolution over fiber length

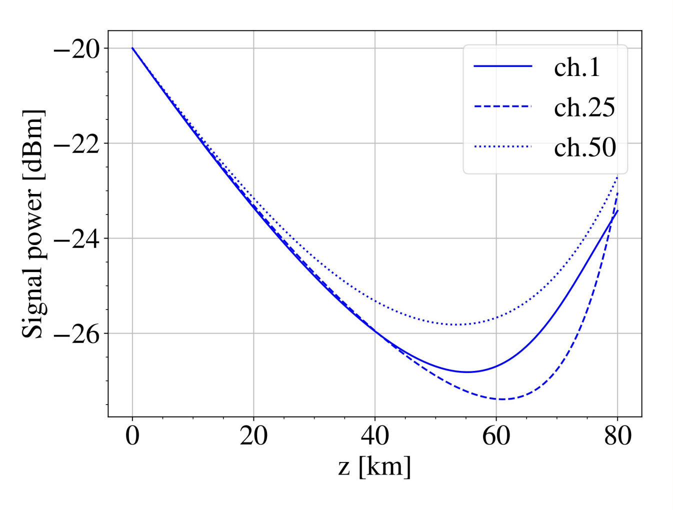
Power evolution equations accounting for **Raman gain** function C_R, and **attenuation**, are the following:

$$\pm\frac{dP_i^{\pm}}{dz} = -\alpha_s P_i^{\pm} + \left[\sum_{j\neq i} C'_{Ri,j}\left[P_j^{+} + P_j^{-}\right]\right] P_i^{\pm}, \qquad C'_{Ri,j} = \begin{cases} C_R\left(\lambda_i, \lambda_j\right) & \text{if } \lambda_i > \lambda_j \\ \frac{\lambda_i}{\lambda_j} C_R\left(\lambda_j, \lambda_i\right) & \text{if } \lambda_i < \lambda_j . \end{cases}$$

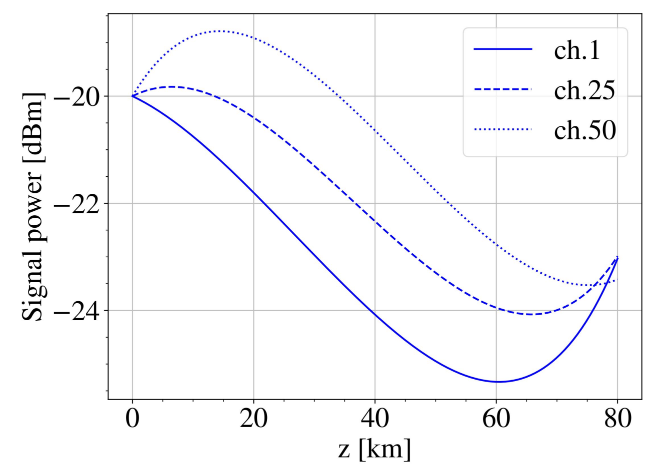
Results for -20dBm input power level, optimization for -3dB gain:



Copumping



Counterpumping



Bidirectional pumping

[1] J. Bromage, *JLT* (2004).

Coupled nonlinear Schrödinger equation model

Channel dependence of Raman gain and attenuation is encoded in a coupled equation model:

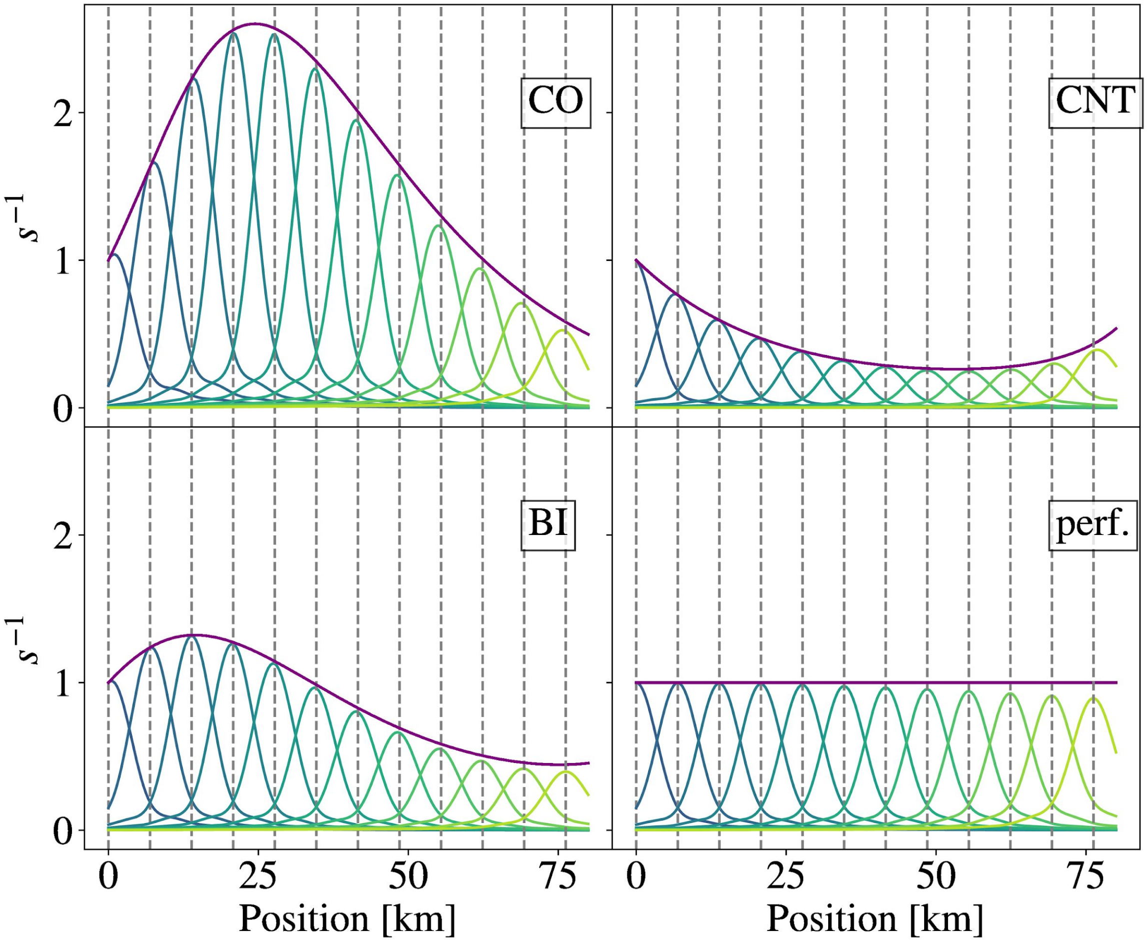
$$\frac{\partial}{\partial z}u_A = -i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}u_A + \\ + i\gamma\left(f_A(z)\left|u_A\right|^2 + 2f_B(z)\left|u_B\right|^2\right)u_A$$

$$\frac{\partial}{\partial z}u_B = -\Delta\beta_1\frac{\partial}{\partial t}u_B - i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}u_B + \\ + i\gamma\left(f_B(z)\left|u_B\right|^2 + 2f_A(z)\left|u_A\right|^2\right)u_B$$

The **perturbation method** can be used in an analogous way, obtaining

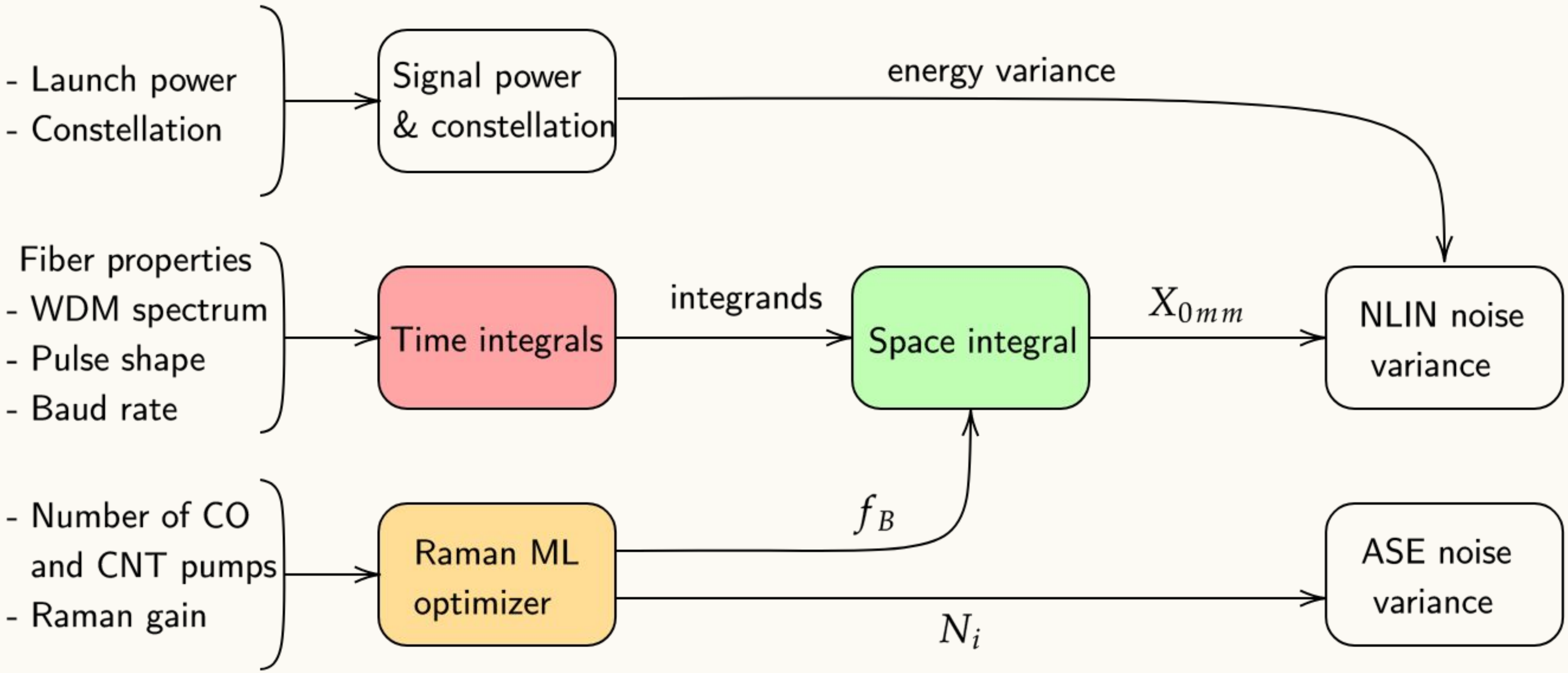
$$X_{0,m,m} = \int_0^L dz f_B(z)\int_{-\infty}^{+\infty} dt \times \\ \times \left|g^{(0)}(z,t)\right|^2\left|g^{(0)}\left(z,t-mT-\beta_2\Omega z\right)\right|^2$$

However, in this case, high dispersion approximation can **not** be used.



f_B

Numerical simulations



- Launch power
- Constellation

Signal power & constellation

energy variance

Fiber properties
- WDM spectrum
- Pulse shape
- Baud rate

Time integrals

integrands

Space integral

X_{0mm}

NLIN noise variance

- Number of CO and CNT pumps
- Raman gain

Raman ML optimizer

f_B

N_i

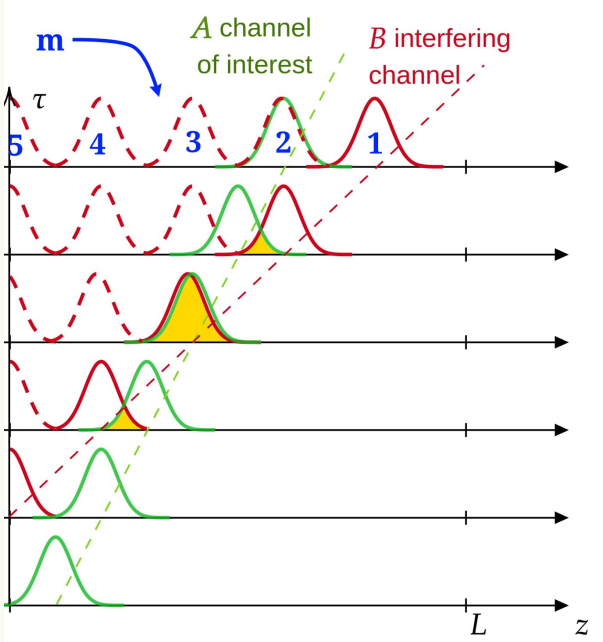
ASE noise variance

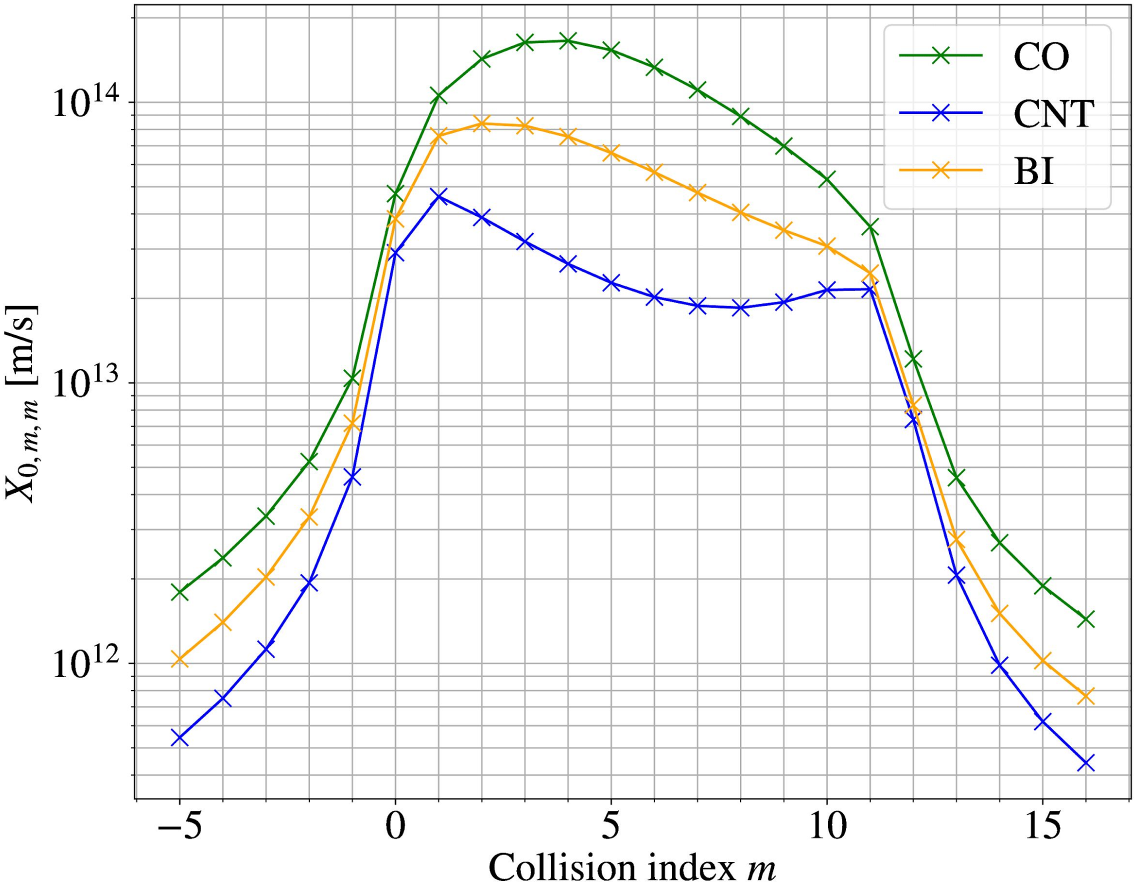
Computation of the collisions

Computing the coefficient for each collision, **differences between pumping schemes** are evident.

Channels are 49 (interfering) and 50, with -20dBm input power.

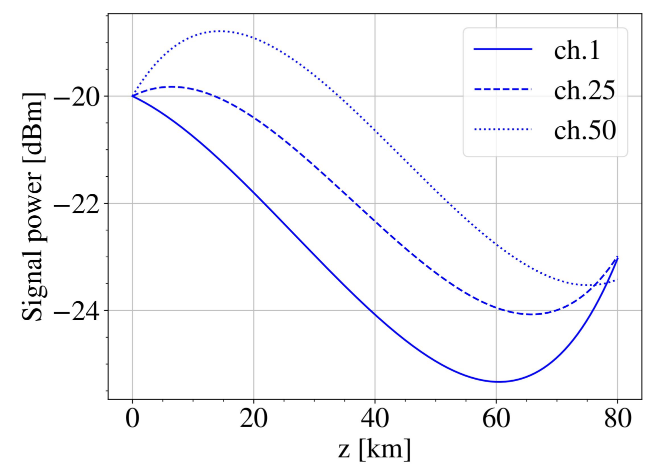
CO: 8 copropagating pumps,
CNT: 10 counterpropagating pumps,
BI: 8 co-, 2 counterpropagating pumps.



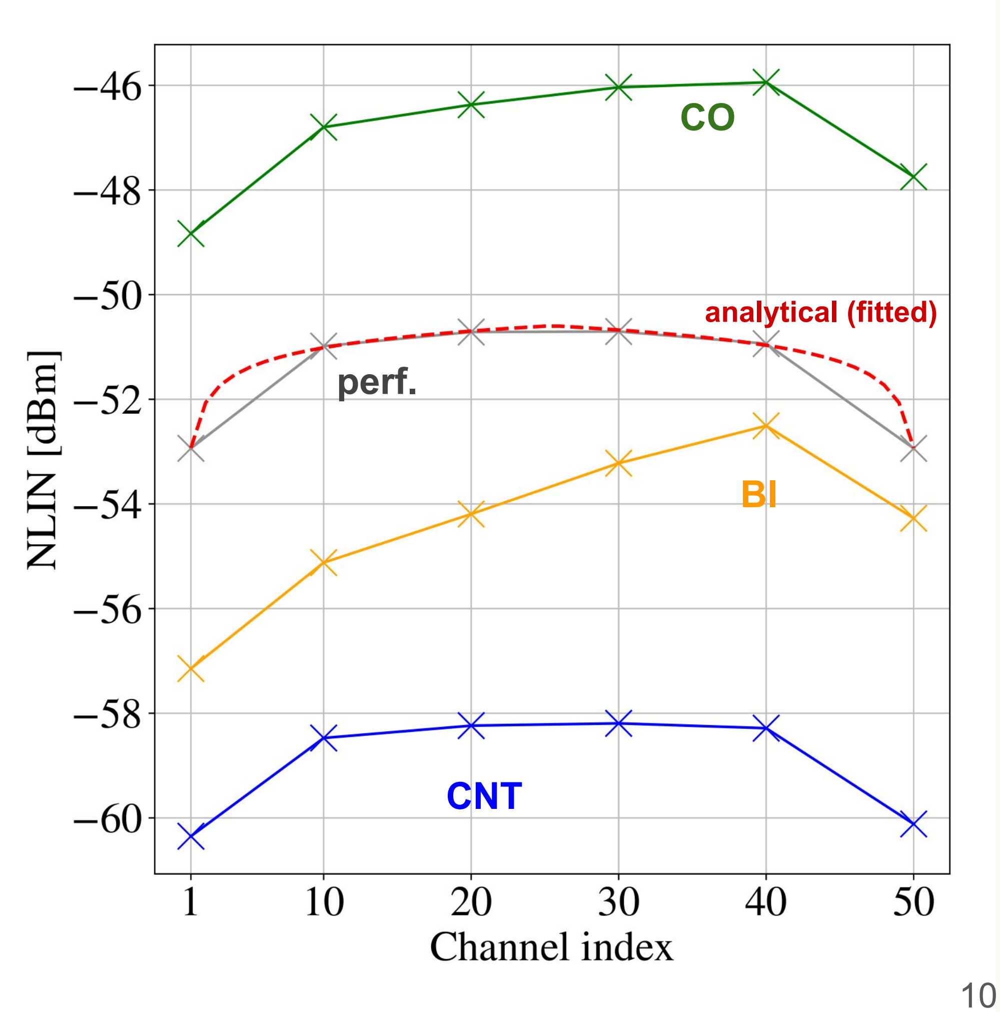


Impact of the position of the channel of interest

Asymmetry is due to different signal **power evolution profiles**.
This is particularly visible for the bidirectional case.



The **perfect amplification** profile is reported for comparison.



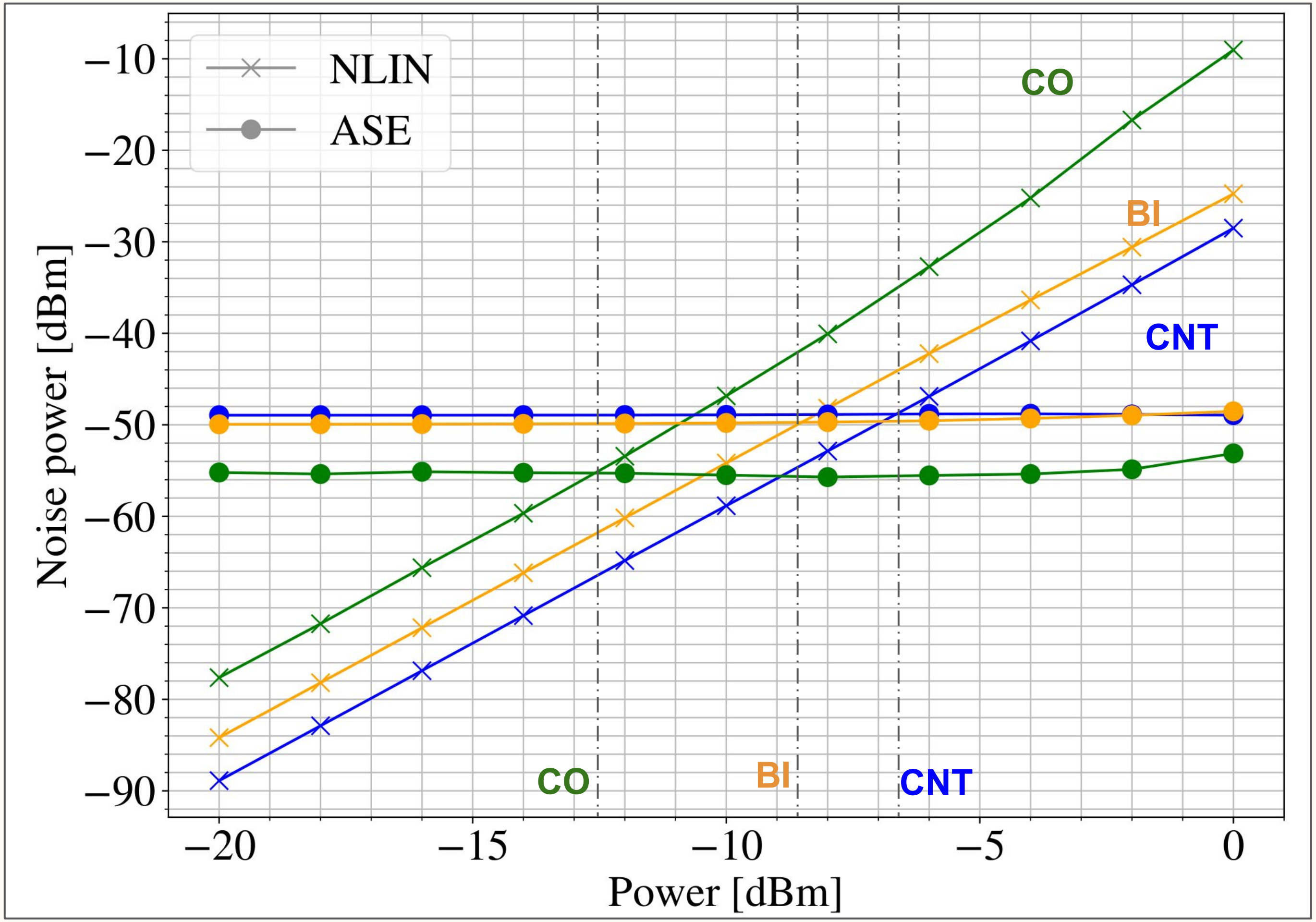
Impact of the launch power

ASE performance is similar in the various pumping schemes.

It is the dominant noise in the **low power regime**.

The **crossover** power level between regimes increases by preferring counterpropagating pumps.

Plot is the average of 6 equally spaced channels of interest.



Conclusions

In this work we studied

- How to generalize the **idealized model** for NLIN to **Raman-amplified WDM links**.
- The integration of the pumping scheme with **optimized equalization** into NLIN computations.
- The dependency of NLIN from **input power** and WDM **channel position**, and its comparison with ASE.

Further work may involve

- Study of NLIN dependence from **link length**, and comparison with ASE in this scenario.
- Design of an **optimization scheme** able to tackle not only flatness of the gain, but also **noise** performance.

Thanks for the attention

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References

[1] J. Bromage, «Raman amplification for fiber communications systems», *Journal of Lightwave Technology*, vol. 22, n. 1, pagg. 79–93, 2004.

[2] G. Marcon, A. Galtarossa, L. Palmieri, e M. Santagiustina, «Model-Aware Deep Learning Method for Raman Amplification in Few-Mode Fibers», *Journal of Lightwave Technology*, vol. 39, n. 5, pagg. 1371–1380, mar. 2021.

[3] R. Dar, M. Feder, A. Mecozzi, e M. Shtaif, «Properties of nonlinear noise in long, dispersion-uncompensated fiber links»,*Optics Express*, vol. 21, n. 22, pag. 25685, ott. 2013.

[4] R. Dar, M. Feder, A. Mecozzi, e M. Shtaif, «Accumulation of nonlinear interference noise in fiber-optic systems»,*Optics Express, OE*, vol. 22, n. 12, pagg. 14199–14211, giu. 2014.