Modeling and Mitigation of Nonlinear Effects in Uncompensated Coherent Optical Transmission Systems

Gabriella Bosco

Politecnico di Torino – Department of di Electronics and Telecommunications

Thanks!

- A. Carena
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- L. Bertignono
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- F. Forghieri

Outline

- **Modeling of fiber nonlinearity**
  - Modeling approximations
  - The GN/EGN model family
  - Non-linearity modeling for high symbols rates and Gaussian constellations

- **Mitigation of fiber nonlinearity**
  - Theoretical limits
  - Practical performance limits

MODELING OF FIBER NONLINEARITY

Non-linear fiber propagation models

- Any form of analytical description of the non-linear behaviour of the optical fiber
- Example: coupled non-linear Schrödinger equations

$$\boxed{\begin{aligned} \frac{\partial A_x}{\partial z} + \beta_{1x}\frac{\partial A_x}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A_x}{\partial t^2} + \frac{\alpha}{2}A_x = i\gamma(|A_x|^2 + B|A_y|^2)A_x \\ \frac{\partial A_y}{\partial z} + \beta_{1y}\frac{\partial A_y}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A_y}{\partial t^2} + \frac{\alpha}{2}A_y = i\gamma(|A_y|^2 + B|A_x|^2)A_y \end{aligned}}$$

G. P. Agrawal, Nonlinear Fiber Optics, 4th edition. Academic Press, 2007, Chapter 6.

  - Numerical integration within a Monte-Carlo simulation environment
- Goal: to find simpler yet accurate models in order to quantify the system impact of the fiber non-linear behaviour

Families of models

- Examples:
  - time domain
  - frequency domain
  - Volterra-based
  - first order perturbation
  - higher-order perturbation
  - regular perturbation (RP, with variants)
  - logarithmic perturbation (LP, with variants)
  - pulse-collision based
  - more classes and sub-classes based on specific assumptions and approximations…

- In this talk, I will focus on **frequency-domain RP first-order models**

Modeling approximations

- Manakov equation
- Perturbation approach
- NLI as additive Gaussian noise
- Locally white NLI
- Signal Gaussianity
- Incoherent NLI accumulation

Manakov equation

$$\begin{cases} \dfrac{\partial A_x(z,t)}{\partial z} = j\dfrac{\beta_2}{2}\dfrac{\partial^2}{\partial t^2}A_x(z,t) - \alpha A_x(z,t) - j\gamma\dfrac{8}{9}\left[\left|A_x(z,t)\right|^2 + \left|A_y(z,t)\right|^2\right]A_x(z,t) \\ \dfrac{\partial A_y(z,t)}{\partial z} = j\dfrac{\beta_2}{2}\dfrac{\partial^2}{\partial t^2}A_y(z,t) - \alpha A_y(z,t) - j\gamma\dfrac{8}{9}\left[\left|A_x(z,t)\right|^2 + \left|A_y(z,t)\right|^2\right]A_y(z,t) \end{cases}$$

- It's based on an analytical average over the random evolution of the state-of-polarization (SOP) along the fiber
- It captures the non-linear effects of one polarization onto the other, but averages over the fast dynamic of SOP variations
- It neglects both linear and nonlinear effects of PMD

First-order regular perturbation

- <u>Assumptions:</u>
  - The signal propagates linearly from input to output
  - At each point along the fiber, it excites fiber nonlinearity and creates the NLI disturbance
  - At the end of the fiber, the linearly propagated signal and the NLI are summed (NLI noise can be represented as an additive noise term)

$$s_{WDM}^{NL}(t) = s_{WDM}(t) + \boxed{s_{NLI}(t)}$$

NON-LINEAR INTERFERENCE (NLI)

- In the framework of first-order perturbation analyses, the NLI power is proportional to P_{ch}^3:

$$\boxed{P_{NLI} = \eta P_{ch}^3}$$

  - where η is a coefficient that depends on the fiber parameters and the transmitted signal characteristics.

NLI additive Gaussian noise approximation

- Assumption:
  - the NLI at the output of the link can be represented as additive Gaussian noise, circular and independent of either the signal or ASE noise

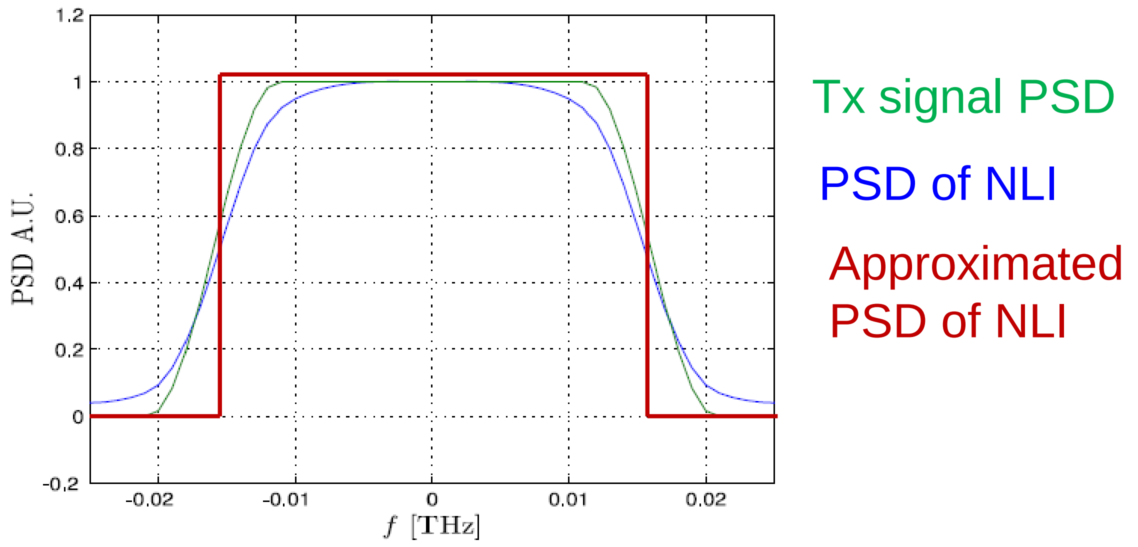
- Key implication: the channel performance can be characterized based on a modified “non-linear” OSNR:

$$\boxed{OSNR_{NL} = \frac{P_{ch}}{P_{ASE} + P_{NLI}}}$$

  - P_{ch} : power of channel under test
  - P_{ASE} : power of ASE noise
  - P_{NLI} is the power of NLI

Locally white NLI noise approximation

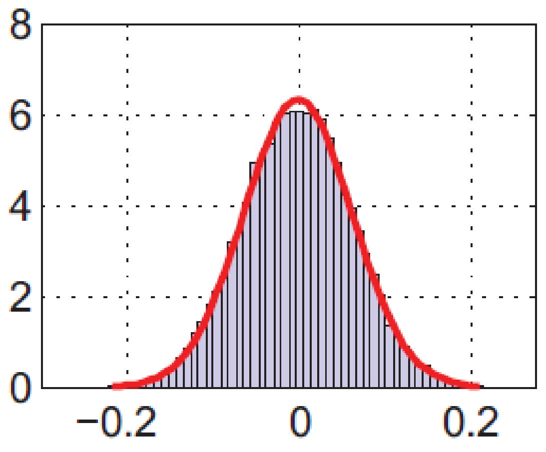
- Assumption:
  - the PSD of NLI is locally flat (over a single channel bandwidth)



- This assumption is acceptable for approximate system performance assessment.
- It should be removed for high-accuracy predictions.

The signal Gaussianity approximation

- Assumption:
  - the transmitted signal can be modeled as a stationary circular Gaussian noise, whose PSD is shaped as the PSD of the actually transmitted WDM channels.



500 km of SSMF fiber

- This approximation allows to drastically simplify the model derivation and strongly decreases the model final analytical complexity.

- Using this assumption, the impact of NLI is always overestimated for QAM transmission formats.

The incoherent NLI accumulation approximation

- <u>Assumption:</u>
  - the NLI produced in each span adds up incoherently (i.e., in power) at the receiver site.

$$G_{NLI}(f) \approx \sum_{n=1}^{N_{span}} G_{NLI}^{(n)}(f)$$

  - In reality, the NLI contributions should be added together coherently (i.e., at the field level) keeping both their amplitude and phase into account

- The accuracy of this approximation is quite poor at very low span count and at very low channel count.

The EGN-GN model family

Assumption	EGN model	GN model	iGN model
Manakov equation	X	X	X
1st order regular perturbation	X	X	X
Signal Gaussianity		X	X
Incoherent NLI accumulation			X
NLI as additive Gaussian noise	*Approximations that can be applied to all models in order to simplify the computations*		
Locally white NLI			

- **iGN** – *P. Poggiolini et al., "Analytical Modeling of Nonlinear Propagation in Uncompensated Optical Transmission Links", IEEE Photon. Technol. Lett.* ***23****(11), p. 742 (2011).*
- **GN** – *P. Poggiolini "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems,"J. Lightwave Technol.* ***30****(24), p.3857 (2012).*
- **EGN** – *A. Carena et al., "EGN model of non-linear fiber propagation," Opt. Exp.* ***22****(13), p. 16335, 2014.*

The simplest iGN closed-form solution

- All approximations listed in the previous slide, plus …
  - Equal spans
  - Equal channels (same power, same spectrum with bandwidth ~R_s)

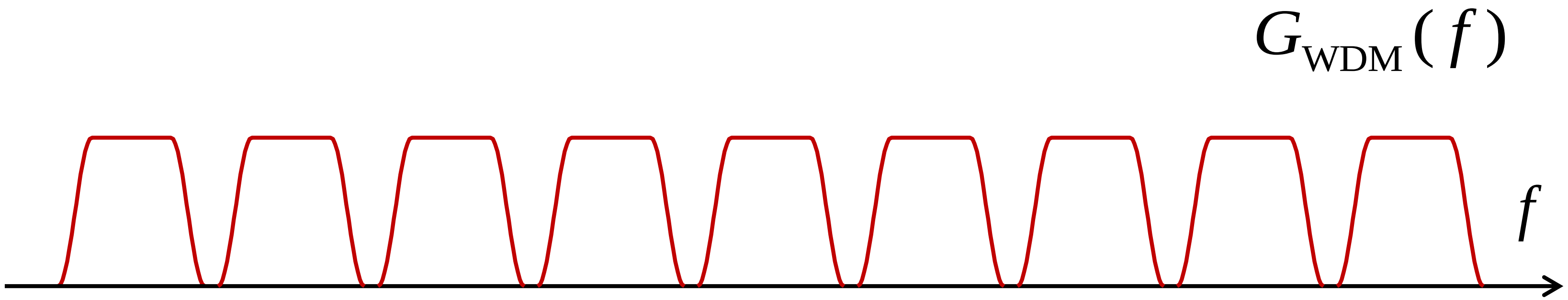
$$G_{\mathrm{NLI}}(f_c) = N_{span} \frac{16}{27} \frac{\gamma^2 L_{\mathrm{eff}}^2 P_{\mathrm{ch}}^3}{\pi |\beta_2| \alpha R_s^3} \operatorname{asinh}\left(\frac{\pi^2}{2\alpha} |\beta_2| R_s^2 \left[N_{\mathrm{ch}}^2 \right]^{\frac{R_s}{\Delta f}} \right)$$

- The model equations become more and more complex, as well as more and more accurate, as the various assumptions are removed

The GN-model reference formula

$$\boxed{G_{\mathrm{NLI}}(f) = \frac{16}{27}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G_{\mathrm{WDM}}(f_1)G_{\mathrm{WDM}}(f_2)G_{\mathrm{WDM}}(f_1+f_2-f)\cdot\left|\mu(f_1,f_2,f)\right|^2 \; df_1 df_2}$$

FWM efficiency of the whole link



- For identical spans with lumped amplification:

$$\left|\mu(f_1,f_2,f)\right|^2 = \gamma^2 L_{\mathrm{eff}}^2 \left|\frac{1-e^{-2\alpha L_s} e^{j4\pi^2\beta_2 L_s (f_1-f)(f_2-f)}}{1-j2\pi^2\beta_2\alpha^{-1}(f_1-f)(f_2-f)}\right|^2 \frac{\sin^2\left(2N_s\pi^2(f_1-f)(f_2-f)\beta_2 L_s\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)\beta_2 L_s\right)}$$

Components of NLI

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Short-correlated circular noise

Mainly format-independent

Long-correlated phase and polarization rotation (PPRN) noise

Format-dependent

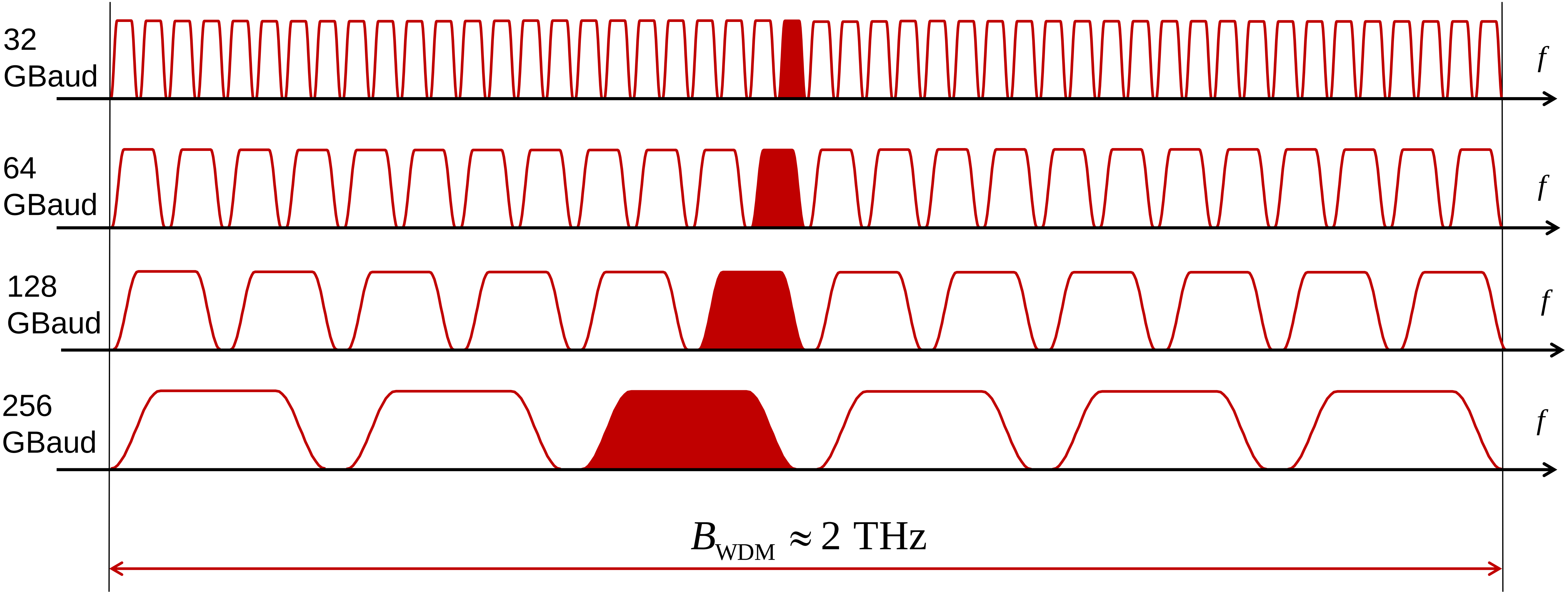
- Negligible for constant-modulus formats
- Increases with the cardinality of the constellation
- Maximum for Gaussian constellation
- Can be partially mitigated by CPE

PRACTICAL IMPLICATION

If all the long-correlated phase noise is ideally taken out, then any PM-QAM system is well described by the EGN model, calculated as if PM-QPSK was transmitted (**EGN-cm** model)

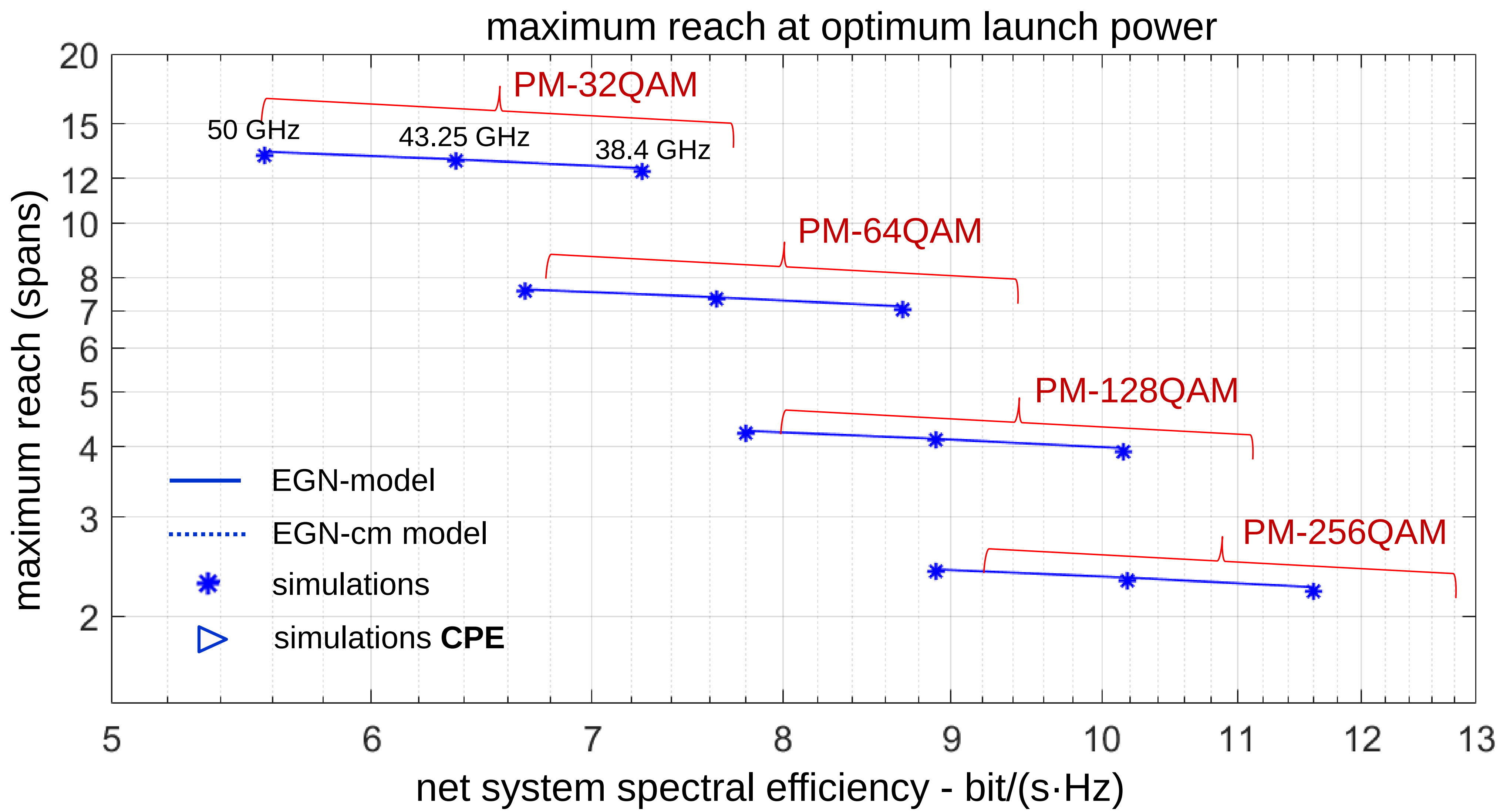
Non-Linearity Modeling for High Symbol Rates and Gaussian Constellations

Very different scenarios …



P. Poggiolini et al., "Non-Linearity Modeling at Ultra-High Symbol Rates," Proc. Of OFC 2018, San Diego (USA), Mar. 2018.

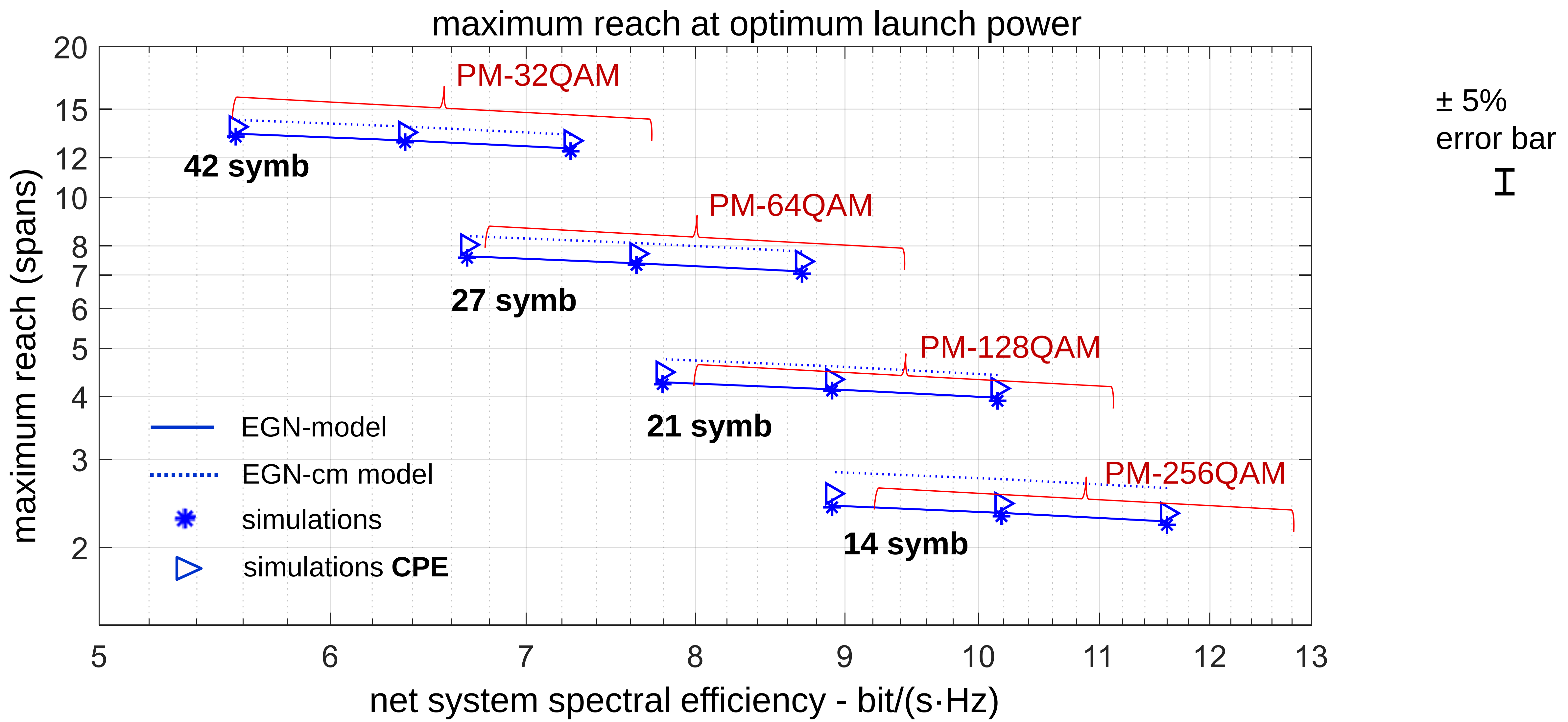
32 Gbaud - 48 channels - SMF - 100km spans



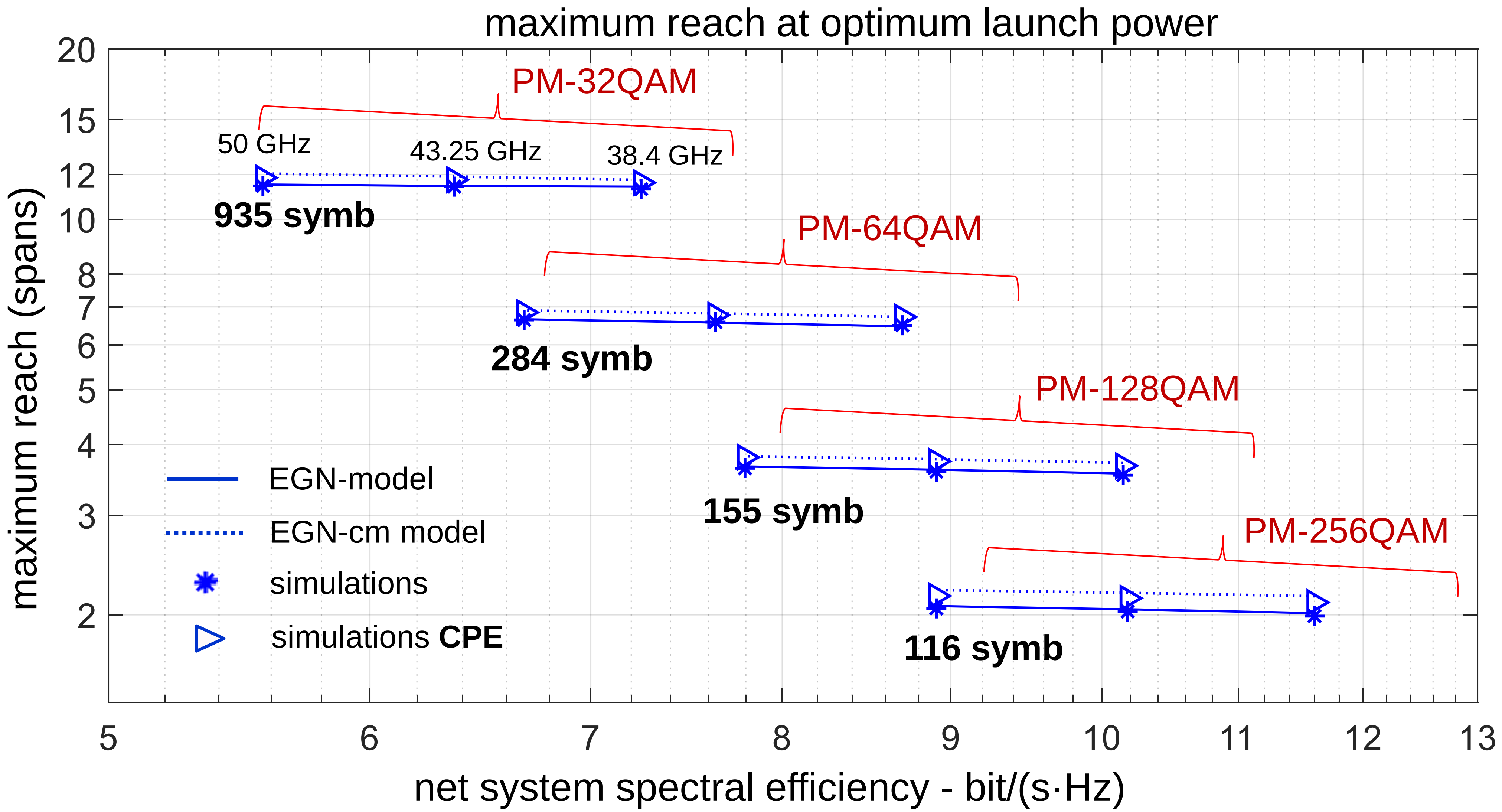
± 5%
error bar

OPTCOM

32 Gbaud - 48 channels - SMF - 100km spans



256 Gbaud - 6 channels - SMF - 100km spans



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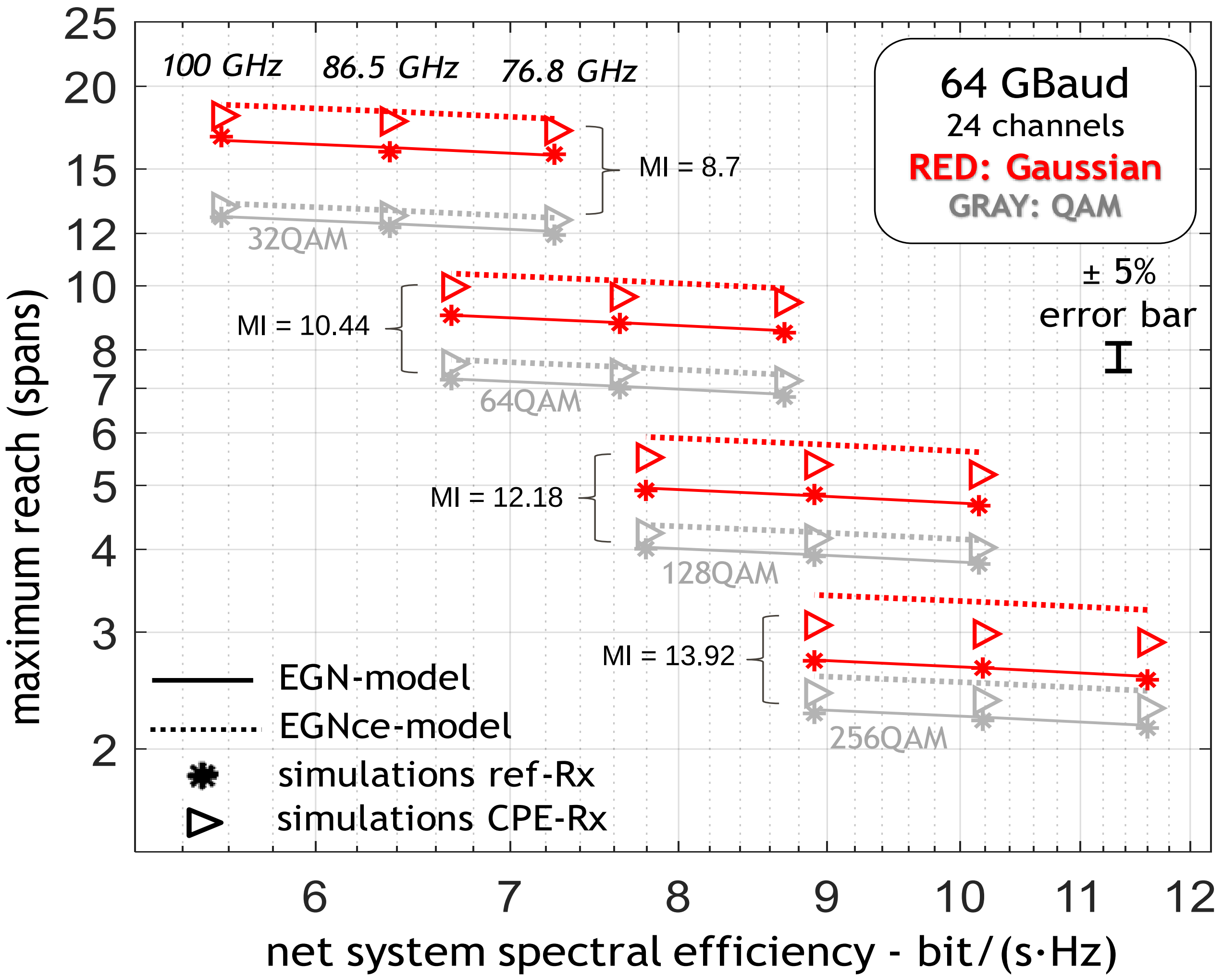
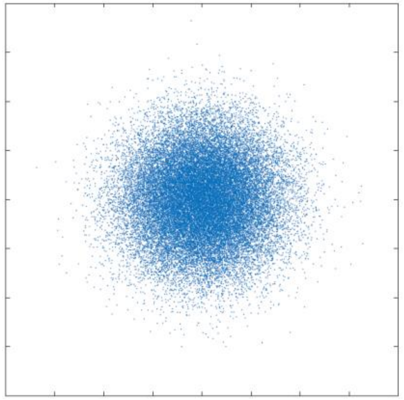
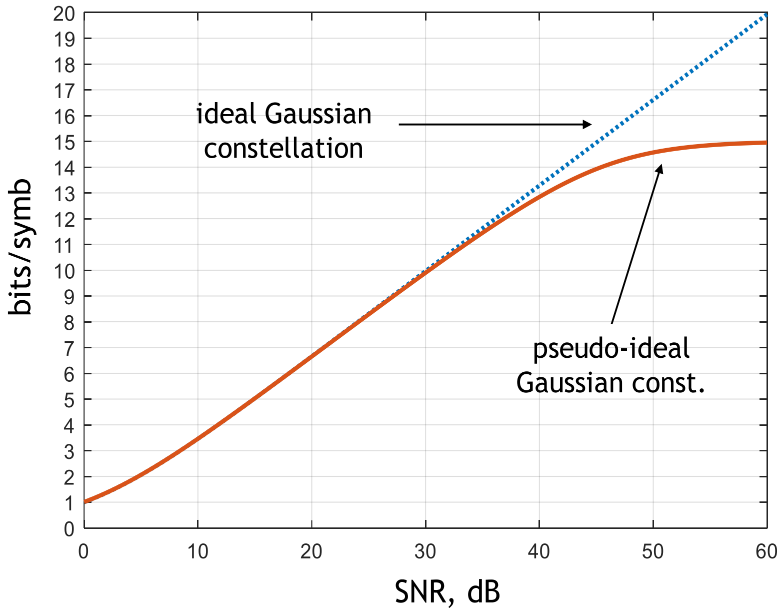
Gaussian constellations – 64 Gbaud



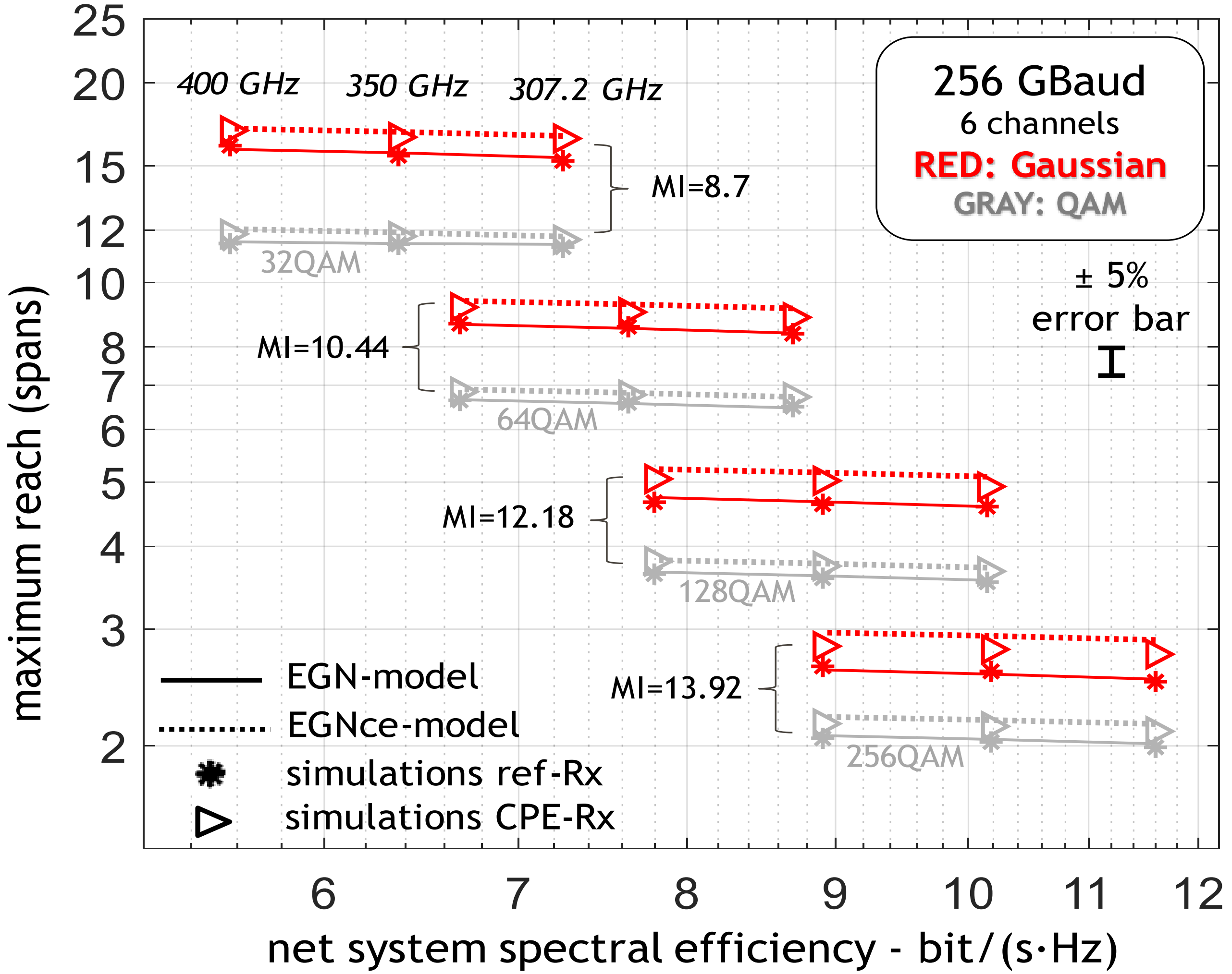
Pseudo-Ideal Gaussian constellation

(2^{15} points)





Gaussian constellations – 256 Gbaud



P. Poggiolini et al., "Non-Linearity Modeling for Gaussian-Constellation Systems at Ultra-High Symbol Rates," Proc. Of ECOC 2018, Rome (Italy), Sep. 2018.

Key take-aways

- The EGN model appears to be extremely reliable, across all the explored parameter space (ultra-high symbol rates, QAM and Gaussian constellations).
- It coincides with the much computationally simpler GN model for Gaussian constellations.
- Going towards higher symbol rates, the NLPN decreases, as shown by the EGN-cm model → mitigating it is easier.
- NLPN has a stronger impact on Gaussian-like constellations [*] → averaging (correlation-based) non-linear phase-noise mitigation shows relatively small gain.

[*] D. Pilori, L. Bertignono, A. Nespola, F. Forghieri, and G. Bosco, "Comparison of probabilistically shaped 64QAM with lower cardinality uniform constellations in long-haul optical systems," Journal of Lightwave Technology, vol. 36, no. 2, pp. 501–509, Jan 2018.

MITIGATION OF FIBER NONLINEARITY

NLI mitigation techniques

- Several nonlinearity compensation and mitigation techniques have been proposed to reduce the power of the NLI noise.

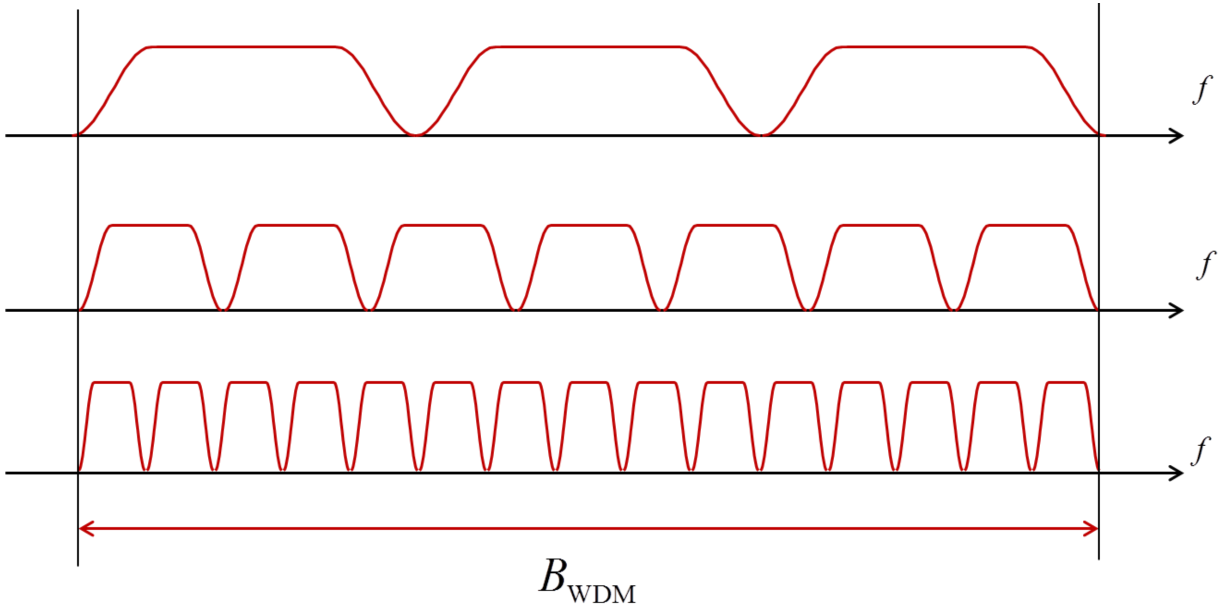
- In the following, we will focus on:
  - digital backpropagation (DBP)
  - symbol-rate optimization (SRO)

Ideal gains of SRO and DBP (predicted by the models)

The analyzed set-up

- **What is the symbol rate which minimizes NLI ?...**
  …having fixed:
  - the total WDM bandwidth (B_{WDM}=504 GHz, 1.5 THz, 2.5 THz, 5 THz)
  - the modulation format and roll-off (PM-QPSK or PM-16QAM, ρ=0.05)
  - the relative frequency spacing (Δf=1.05 R_s)

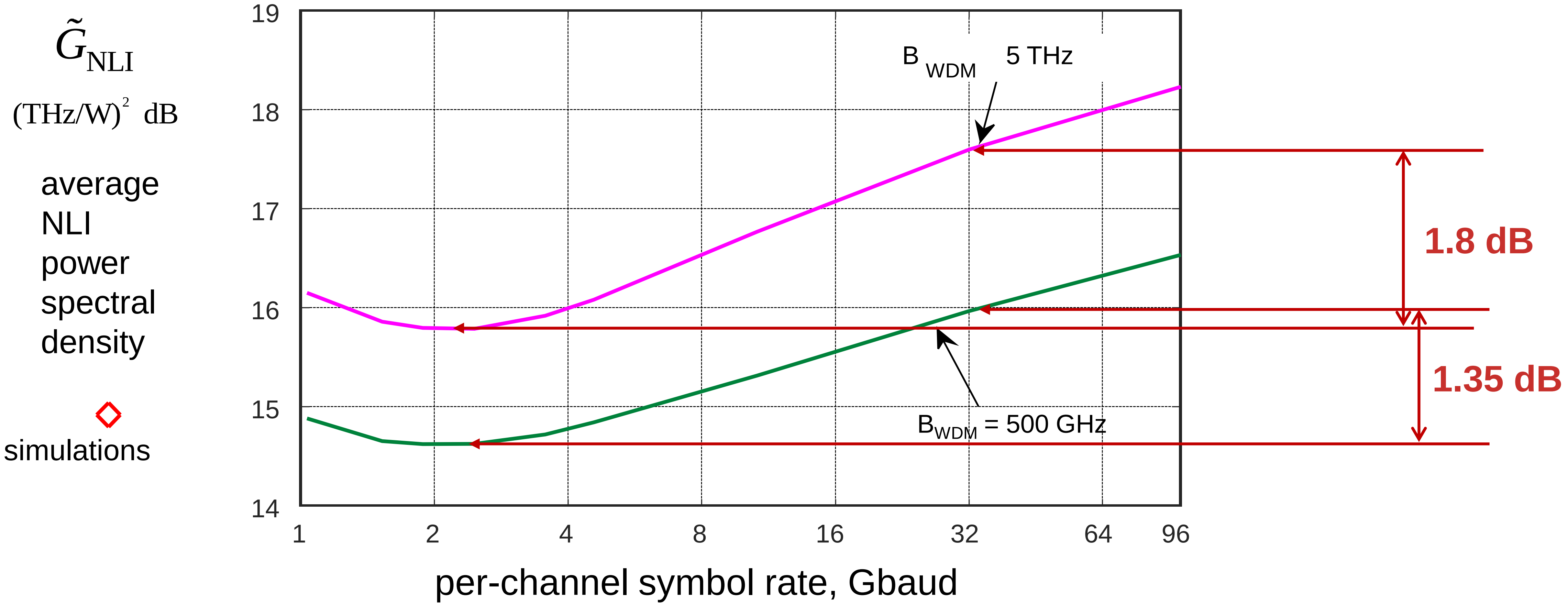
- EDFA-only amplification (F=5 dB)
- SSMF fiber (100-km span length)



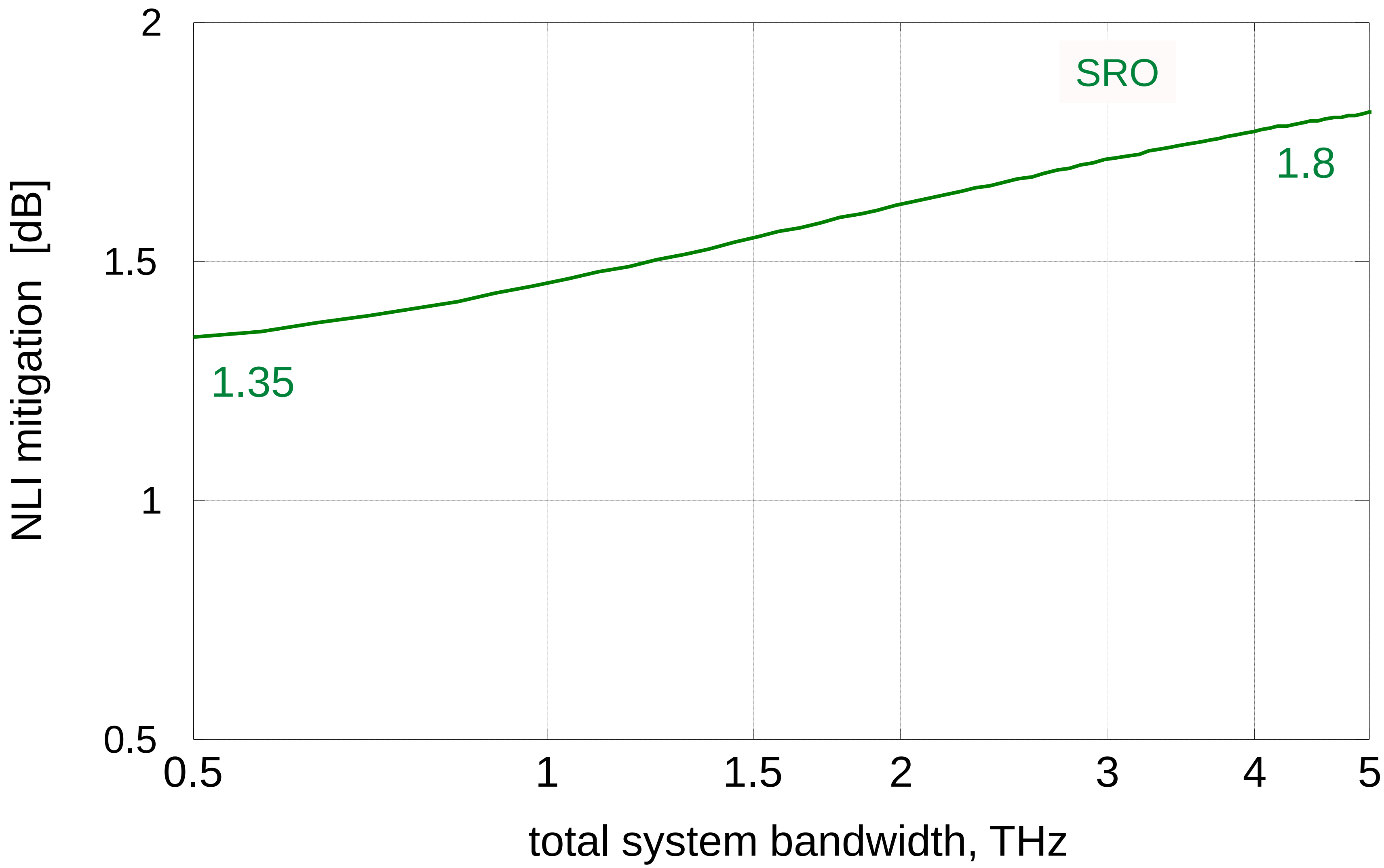
P. Poggiolini et al., "Analytical and experimental results on system maximum reach increase through symbol rate optimization," J. Lightw. Technol., 34(8), p. 1872 (2016).

SRO prediction by EGN model

- **PM-QPSK,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**



Backward Propagation vs. SRO – PM-QPSK

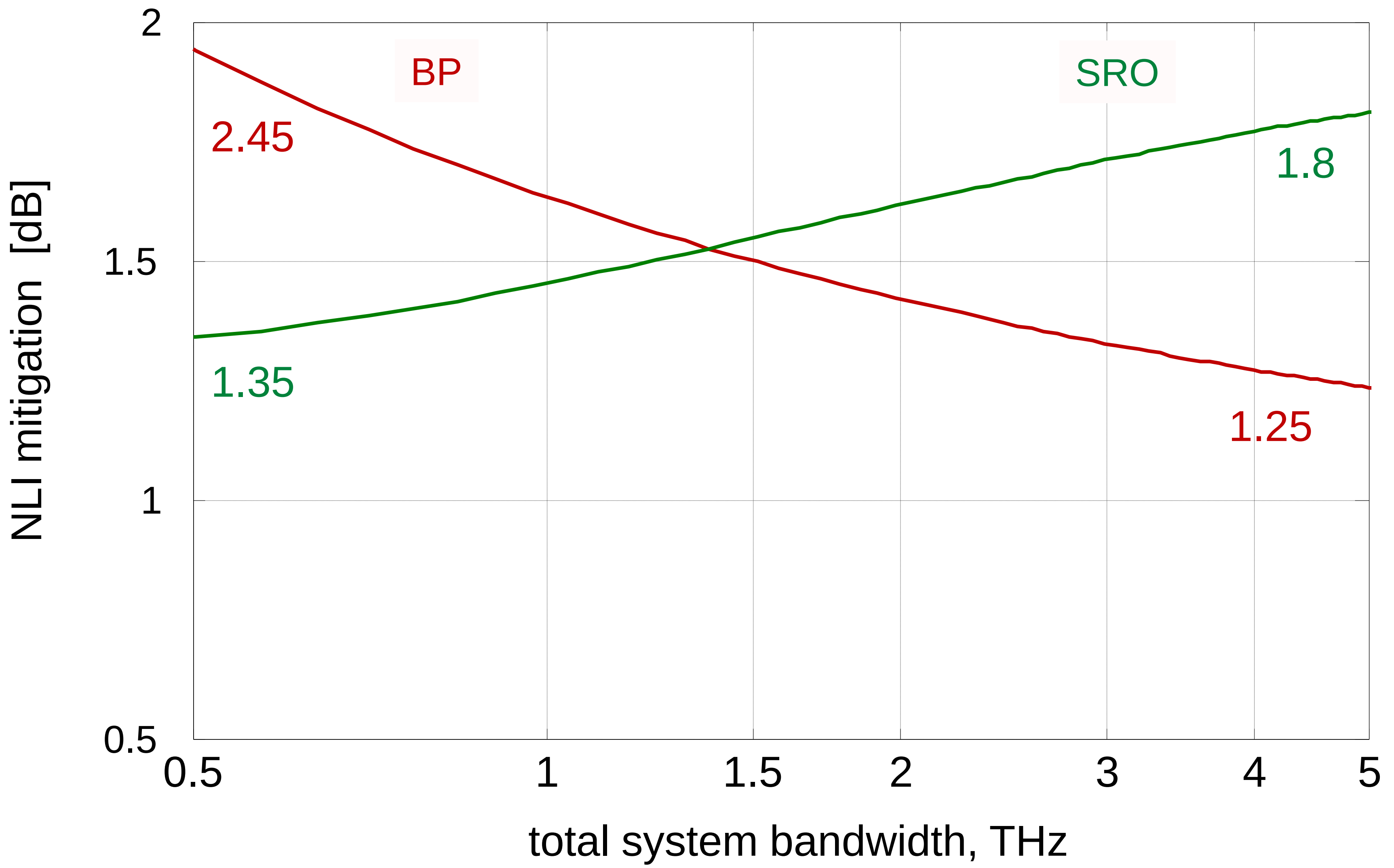


PM-QPSK, roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**

All curves drawn using the FULL EGN model

SRO: between 32 GBaud and the optimum rate (2.4 Gbaud)

Backward Propagation vs. SRO – PM-QPSK



PM-QPSK, roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**

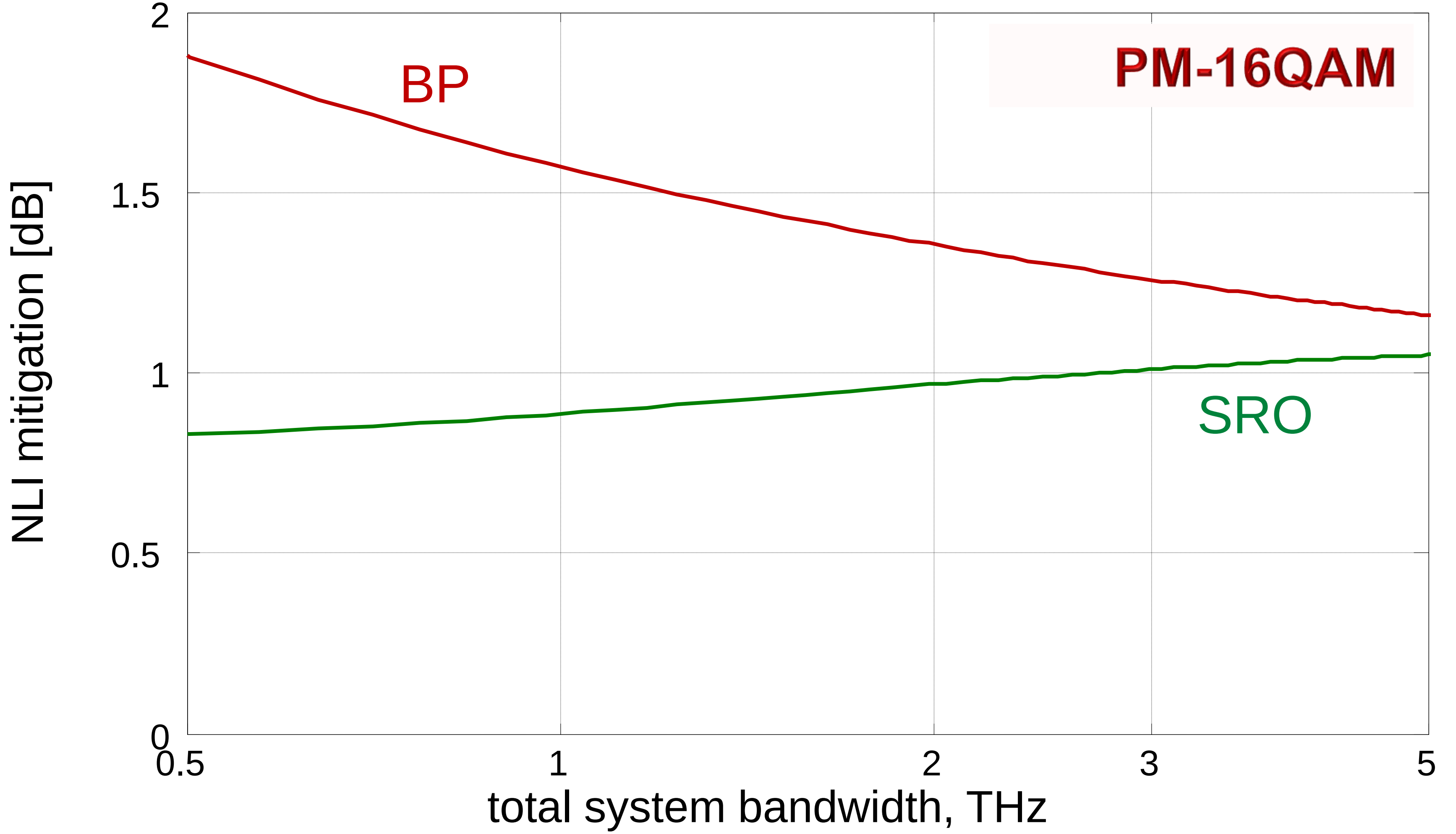
All curves drawn using the FULL EGN model

SRO: between 32 GBaud and the optimum rate (2.4 Gbaud)

BP: ***ideal*** backward propagation over the 32 GBaud center channel

Backward Propagation vs. SRO – PM-16QAM

- **PM-16QAM,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**



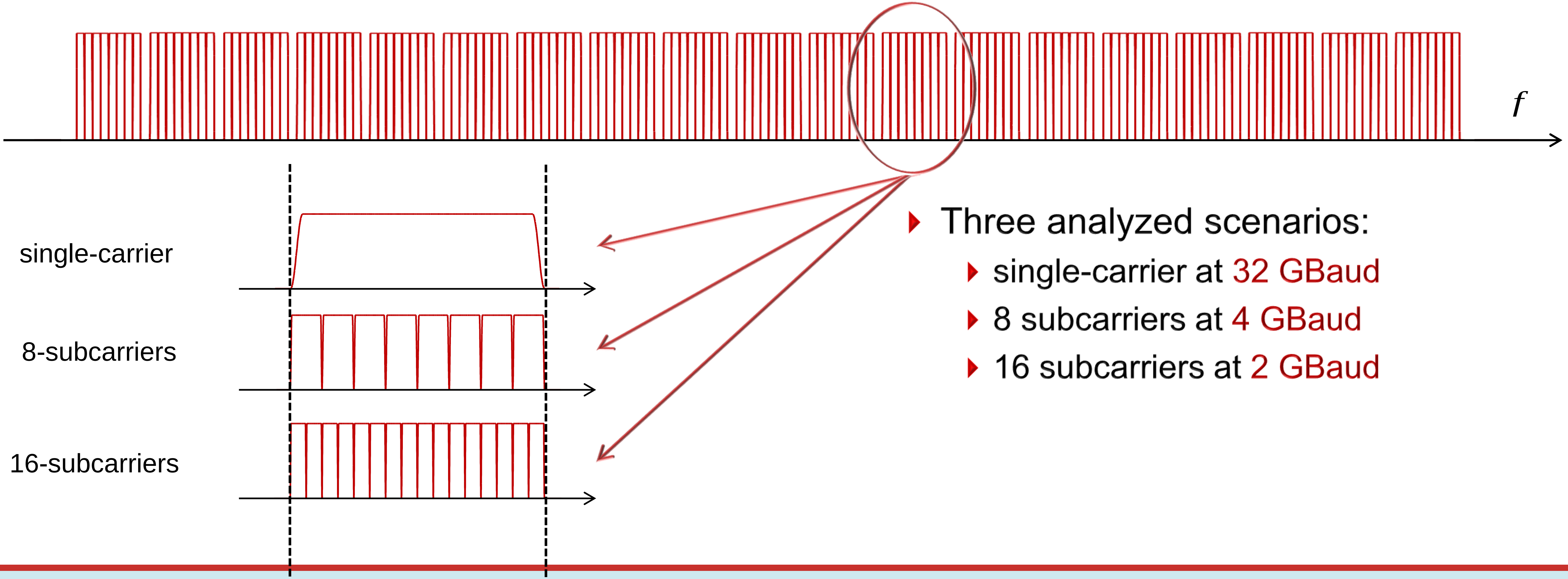
SRO: between 32 GBaud and the optimum rate (2.4 Gbaud)

BP: ***ideal*** backward propagation over the 32 GBaud center channel

Practical limitations of SRO and DBP

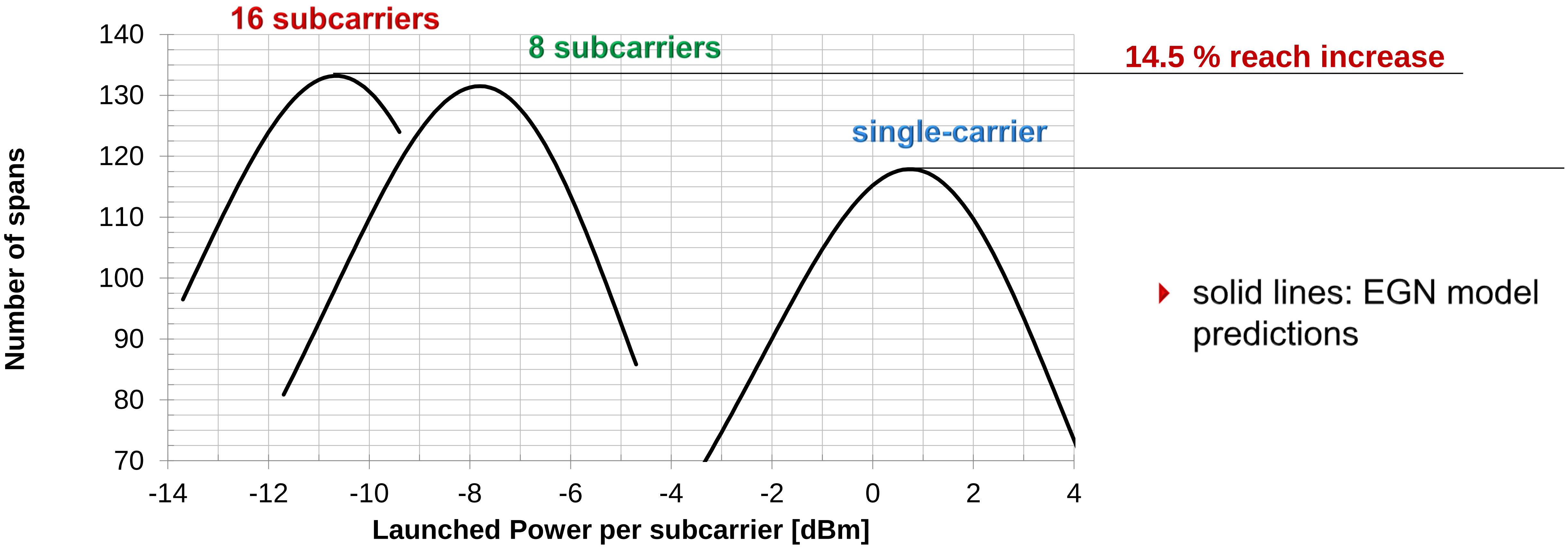
SRO through sub-carrier multiplexing

- **19 channel** WDM comb, with channel **spacing 37.5 GHz**, for a total WDM bandwidth of **710 GHz**



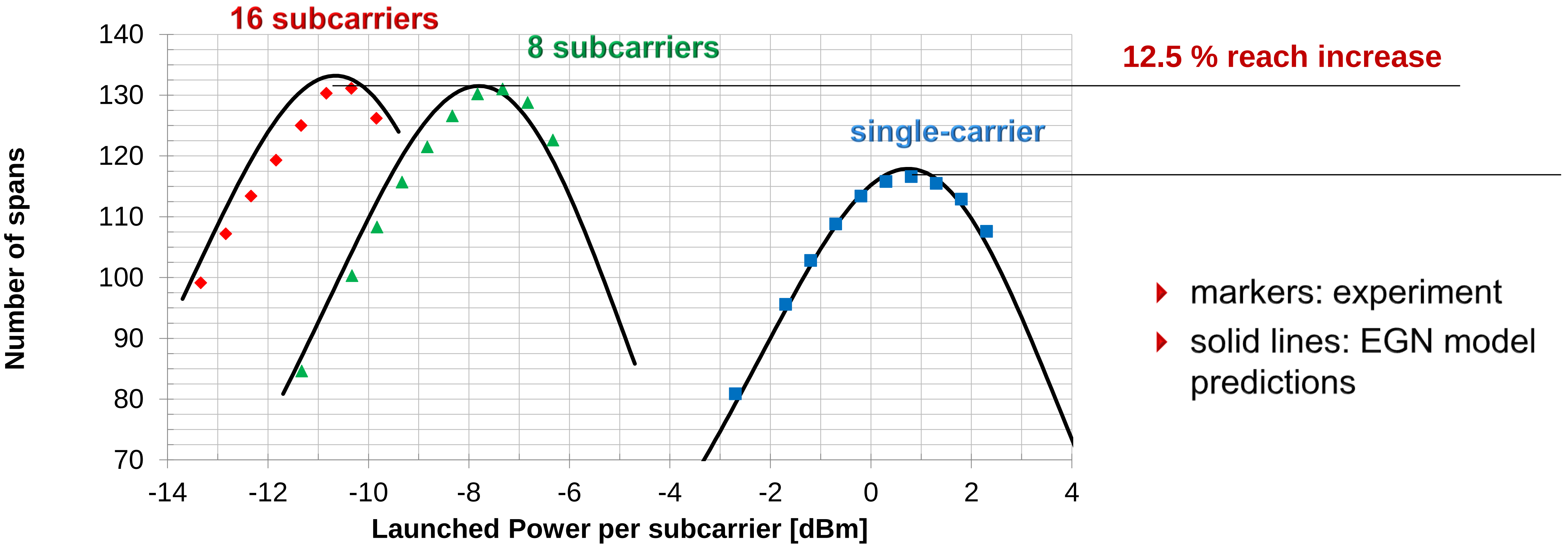
- Three analyzed scenarios:
  - single-carrier at 32 GBaud
  - 8 subcarriers at 4 GBaud
  - 16 subcarriers at 2 GBaud

Reach curves over PSCF fiber (108 km spans)



- solid lines: EGN model predictions

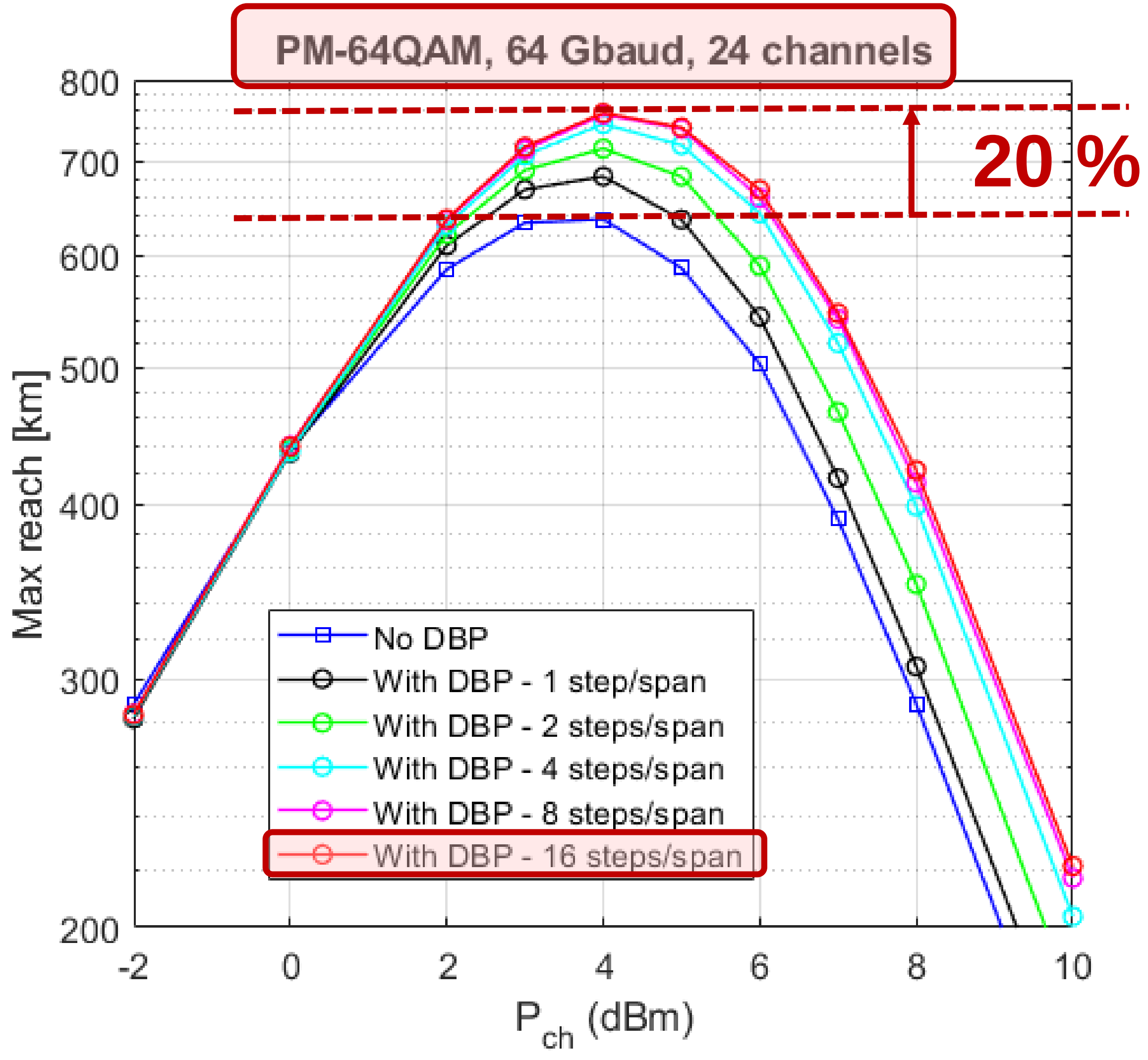
Reach curves over PSCF fiber (108 km spans)



- markers: experiment
- solid lines: EGN model predictions

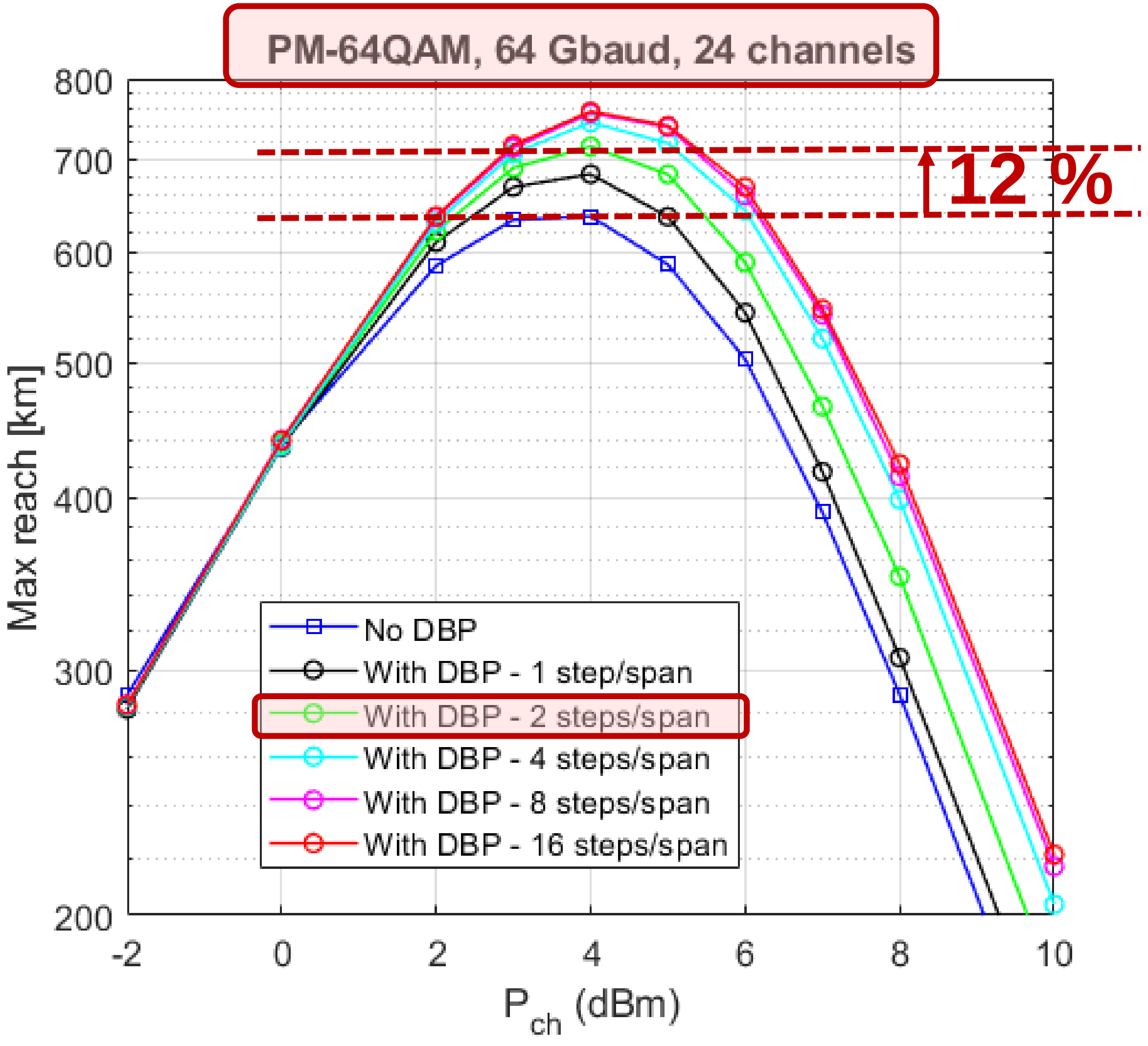
- The gain predicted by the analytical model cannot be fully exploited due to practical implementation issues (higher sensitivity to transceiver impairments and phase noise)

DBP performance vs. number of steps per span



- Modulation format: PM-64QAM
- Roll-off: 0.2
- SSMF fiber - 100 km spans
- EDFA noise figure: 6 dB
- Target GMI: 0.87*6=5.22 bit/symb → Target SNR: 17.37 dB
- Channel spacing: 1.2 R_s = 76.8 GHz
- Single-channel DBP

DBP performance vs. number of steps per span



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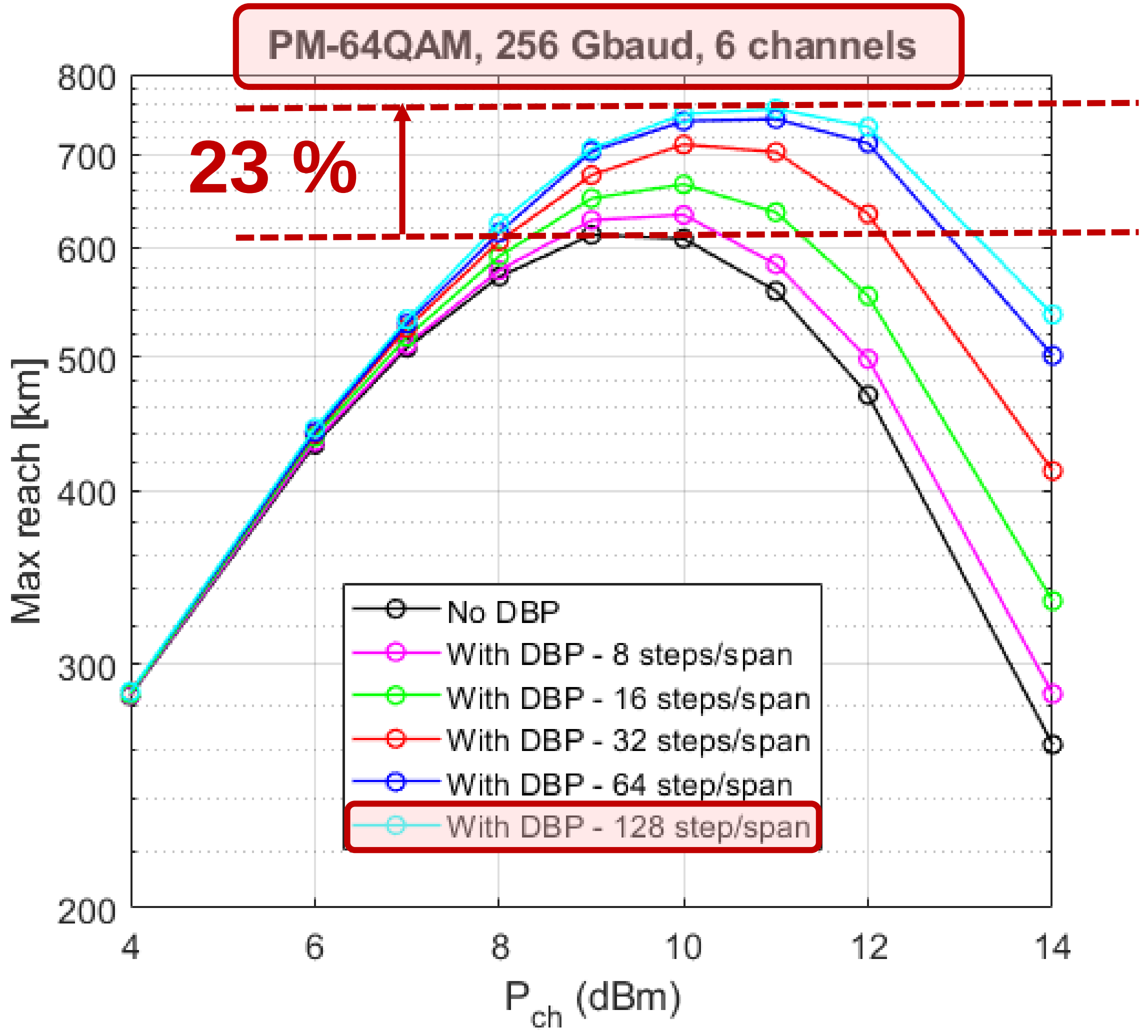

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Conclusions

- The **NLI analytical models** are useful tools to obtain an accurate prediction of the **ultimate performance** achievable by the various mitigation techniques.

- The **actual performance gain** will also depend on several implementation issues that cannot be easily included in the analytical estimations, such as:
  - sub-optimum performance of low-complexity DBP algorithms
  - higher impact of NLPN in digital multi-subcarrier systems

  which reduce the nonlinearity mitigation benefits.

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