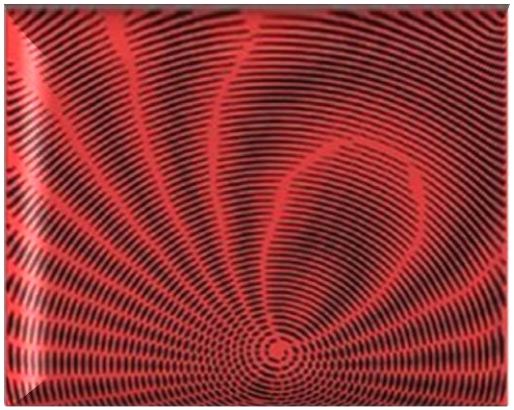
OPTCOM

# On the Ultimate Potential of Symbol-Rate Optimization for Increasing System Maximum Reach



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*Presenter: Pierluigi Poggiolini*

# Context

- One of the currently hottest topics in system research is: *non-linearity mitigation*
- Many groups are tackling this problem
- The key requirements are:
  - *reasonable processing complexity*
  - *effectiveness must not drop off vs. WDM bandwidth*

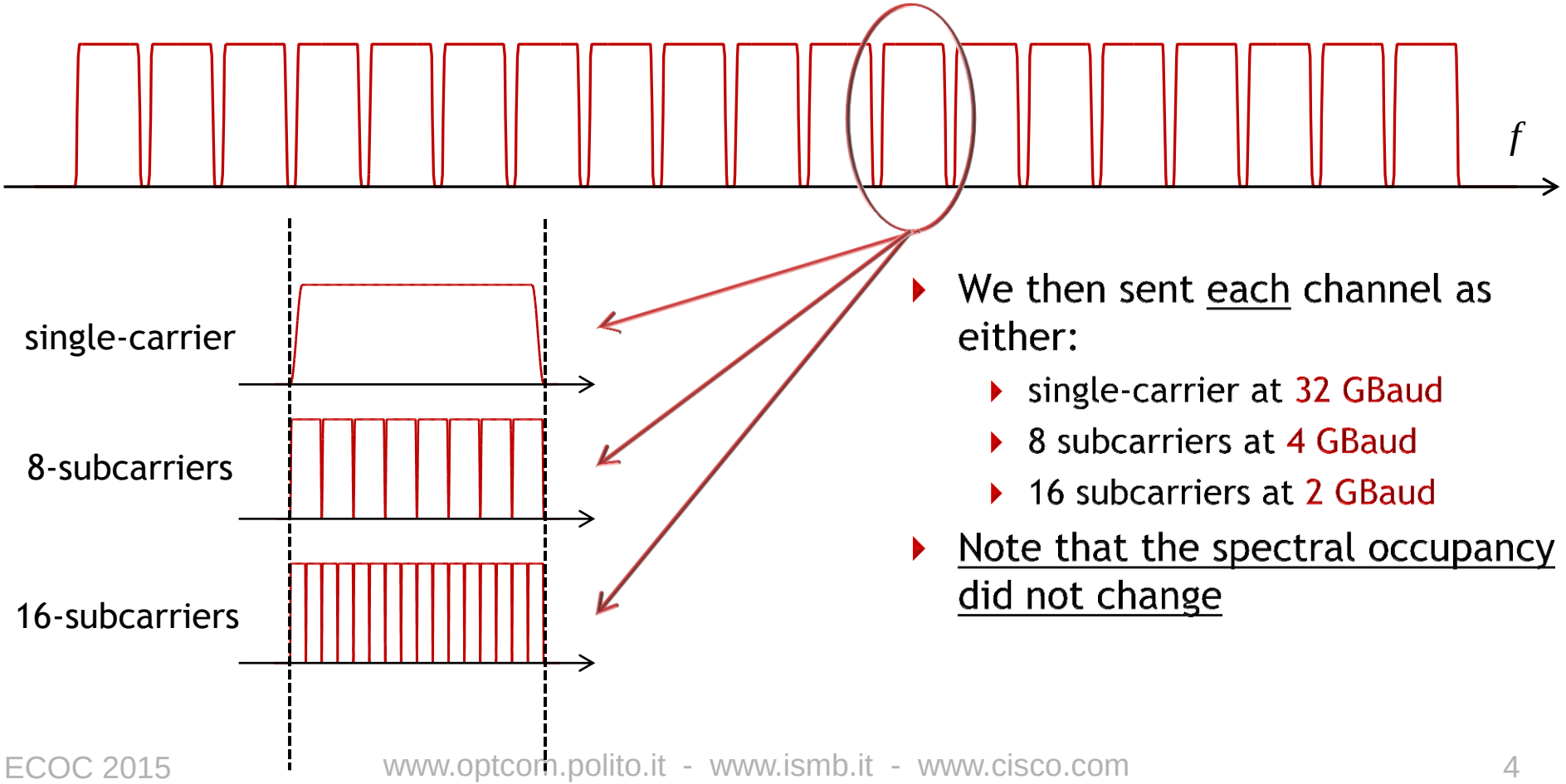
# A promising technique

**SRO**
**Symbol Rate Optimization**

- Low symbol rates provide some amount of non-linearity mitigation
- Optimum rates are in the 1 to 4 GBaud range for SMF and PSCF
- Can be done using subcarrier multiplexing

# Our experiment Mo.3.6.3

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




- We then sent <u>each</u> channel as either:
  - single-carrier at 32 GBaud
  - 8 subcarriers at 4 GBaud
  - 16 subcarriers at 2 GBaud
- <u>Note that the spectral occupancy did not change</u>

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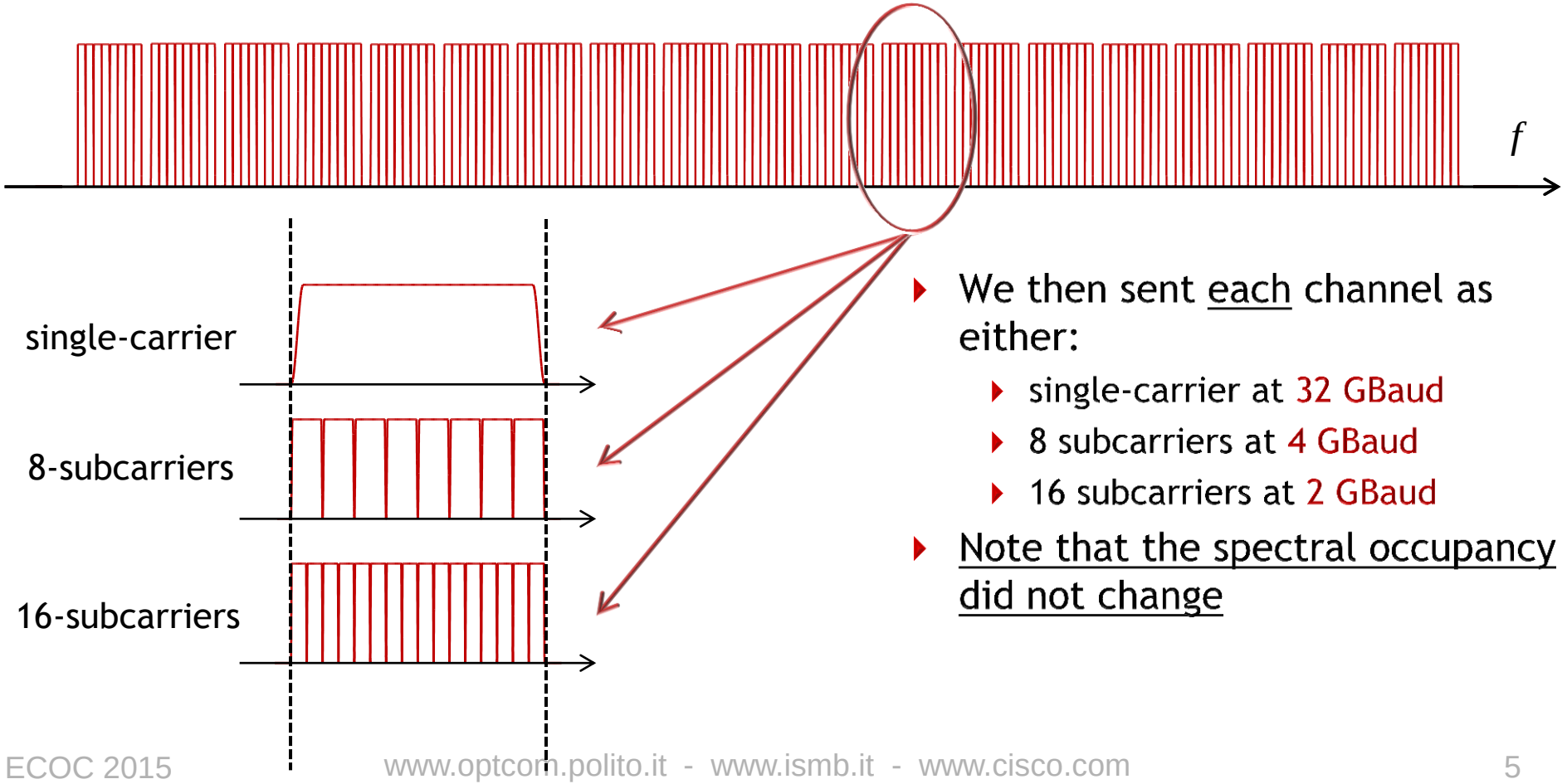


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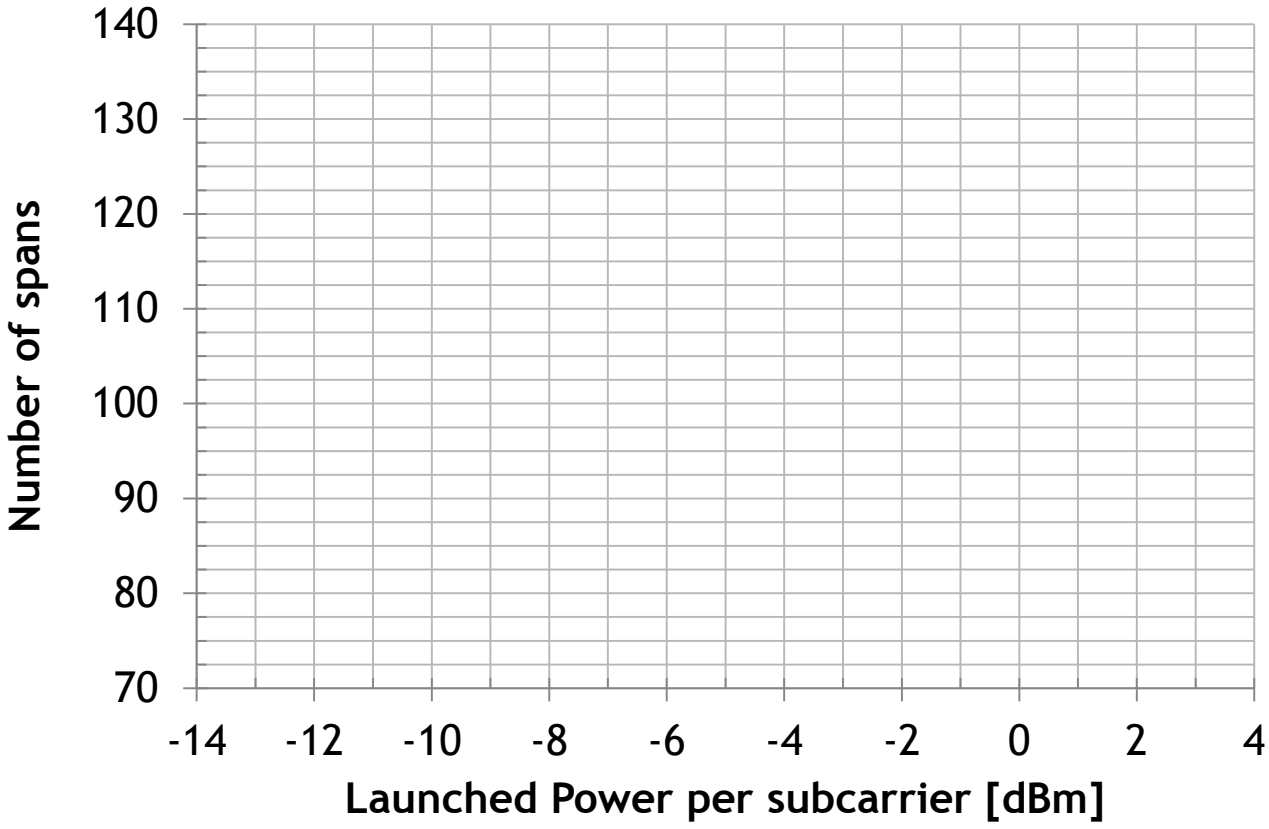
# Reach curves at BER $10^{-2}$

## PSCF, span length 108 km, all EDFA



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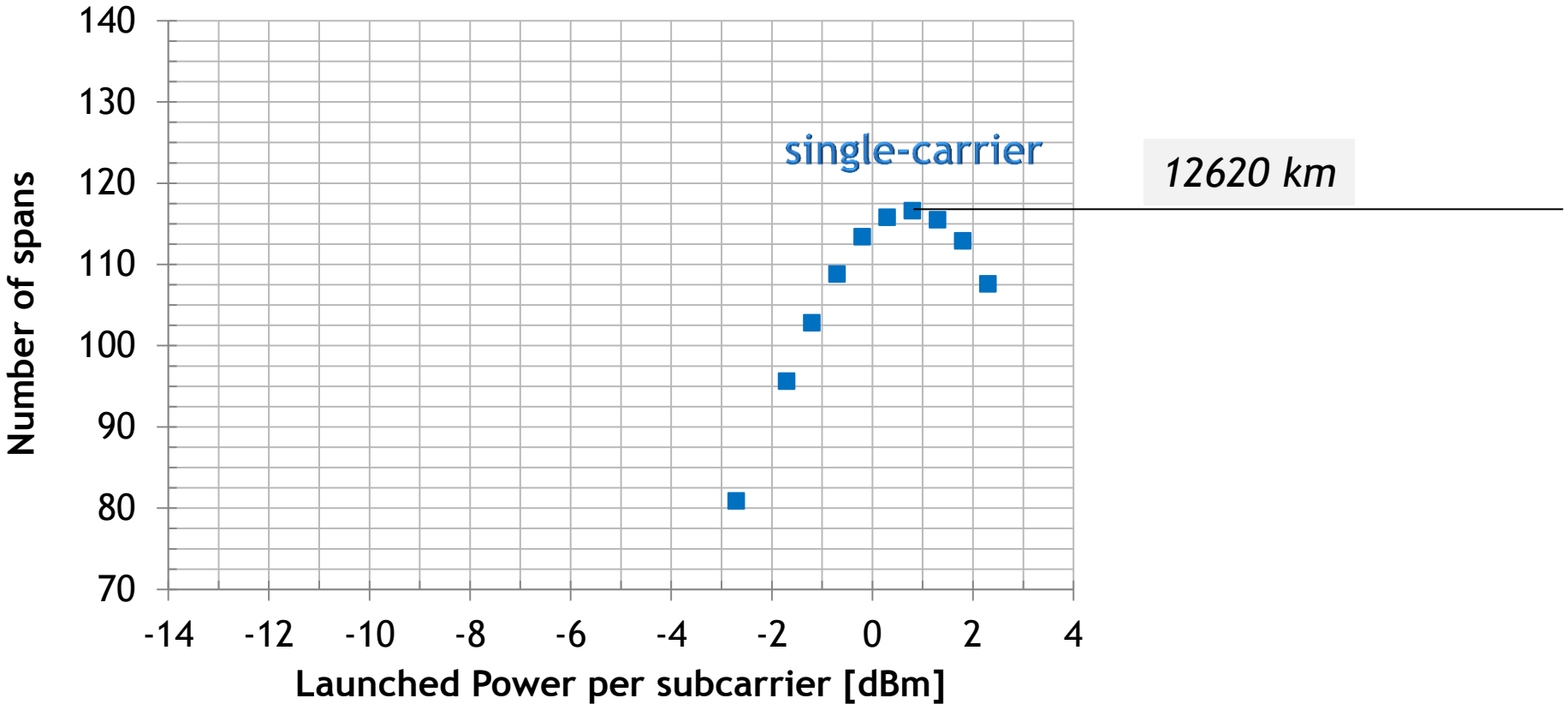
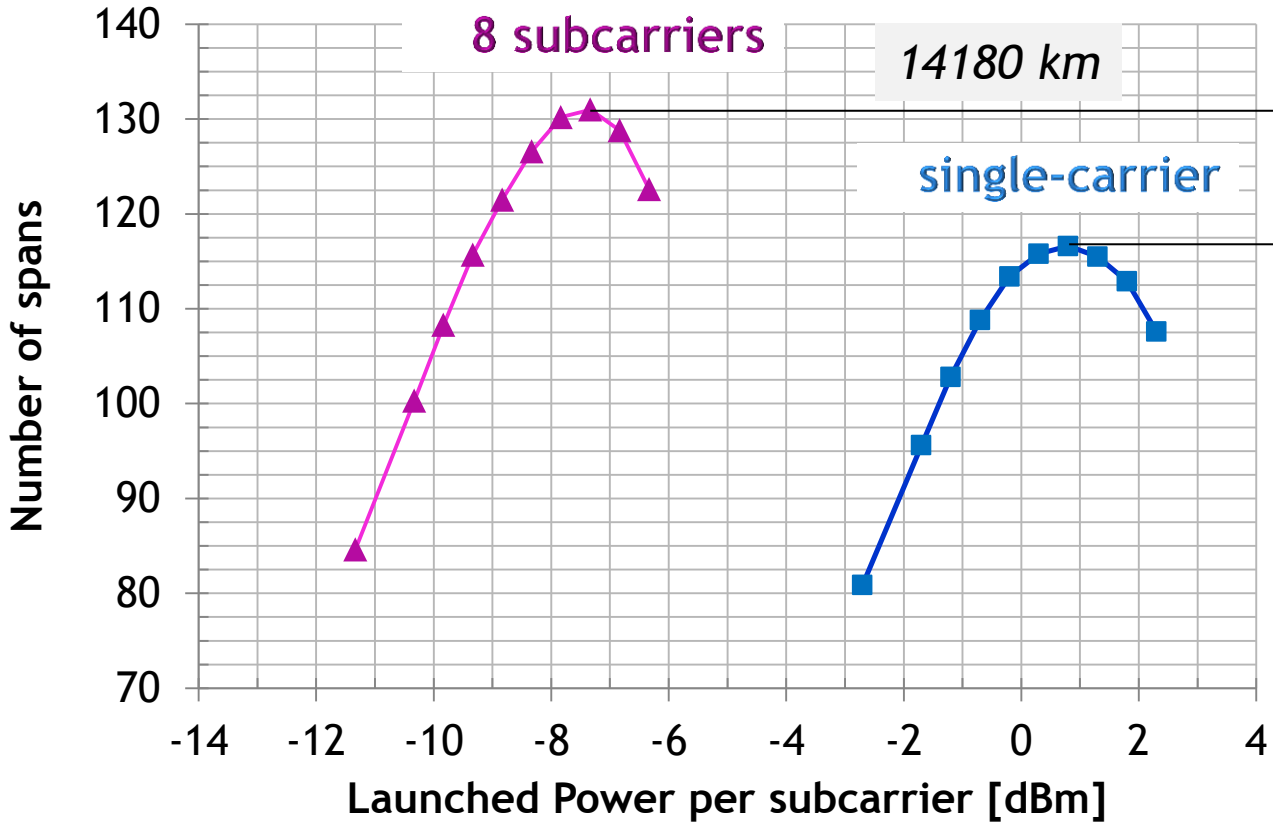


# Reach curves at BER $10^{-2}$

PSCF, span length 108 km, all EDFA




***12.4 % reach increase***

**prediction:**
**24 subcarriers**
**15%-16% gain**

PSCF fiber kindly provided by

SUMITOMO ELECTRIC

single-carrier and 8 subcarrier had same btb sensitivity

# Papers on symbol-rate optimization

- simulative/theoretical:


- W. Shieh and Y. Tang, 'Ultrahigh-speed signal transmission over nonlinear and dispersive fiber optic channel: the multicarrier advantage,' IEEE Photonics J., vol. 2, no. 3, pp. 276-283, June 2010.
- L. B. Du and A. J. Lowery, 'Optimizing the subcarrier granularity of coherent optical communications systems,' Optics Expr., vol. 19, no. 9, pp. 8079, Apr. 2011.
- A. Bononi, N. Rossi and P. Serena, 'Performance dependence on channel baud-rate of coherent single-carrierWDM systems,' in Proc. of ECOC 2013, paper Th.1.D.5, London (UK), Sept. 2013.
- Q. Zhuge, B. Chatelain, and D. V. Plant, 'Comparison of intra-channel nonlinearity tolerance between reduced-guard-interval CO-OFDM systems and nyquist single carrier systems,' in Proc. of OFC 2012, paper OTh1B.3, LosAngeles (CA), Mar. 2012.
- P. Poggiolini, Y. Jiang, A. Carena, G. Bosco, F. Forghieri, "Analytical results on system maximum reach increase through symbol rate optimization," Proc. OFC 2015, paper Th3D.6, Los Angeles (USA), Mar. 2015.

# Experiments on SRO…

- Meng Qiu, Qunbi Zhuge, Xian Xu, M. Chagnon, M. Morsy-Osman, and David V. Plant 'Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems,' in Proc. OFC 2014, paper Tu3J.2, San Francisco (CA), Mar. 2014.

- J. Fickers, et al., "Multicarrier Offset-QAM for Long-Haul Coherent Optical Communications," J. of Ligthw. Technol., Vol. 32, n. 4, p. 4671, Dec. 2014 (showed no advantage of SRO: could have been hampered by btb penalties)

- Fatih Yaman, et al., "First Quasi-Single-Mode Transmission over Transoceanic Distance using Few-mode Fibers," Proc. OFC, post-deadline paper Th5C.7, Los Angeles, Mar. 2015. (Main thrust of paper was however FMF and DSP)

- A. Nespola, L. Bertignono, G. Bosco, A.Carena, Y. Jiang, S.M. Bilal, P. Poggiolini, S. Abrate, F. Forghieri "Experimental demonstration of fiber nonlinearity mitigation in a WDM multi-subcarrier coherent optical system," **Proc. ECOC 2015, paper Mo.3.6.3**, Valencia (ES), Sept. 2015

- Hisao Nakashima, et al., "Experimental investigation of nonlinear tolerance of subcarrier multiplexed signals with spectrum optimization," **Proc. ECOC 2015, paper Mo.3.6.4**, Valencia (ES), Sept. 2015

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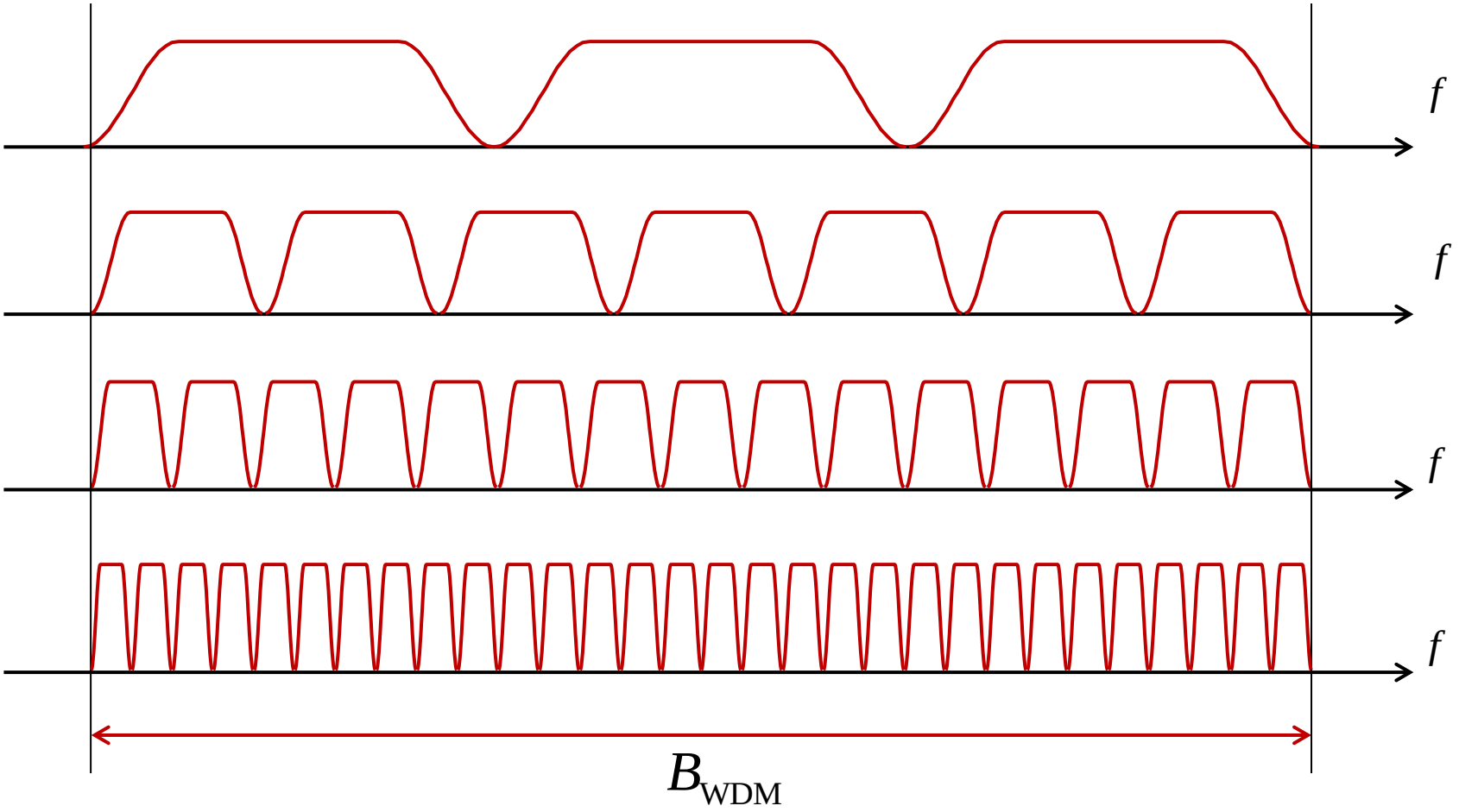
# Questions…

- How would SRO do in a C-band system?
- How does SRO compare to backward propagation when going towards C-band?
- Can the SRO and BP be combined ?
- How about other formats than PM-QPSK?

# How to study SRO ?



# Which quantity to analyze ?

$$\tilde{G}_{\mathrm{NLI}} = G_{\mathrm{NLI}} / G_{\mathrm{ch}}^{3}$$

average PSD of NLI over the center channel

PSD of the transmitted signal

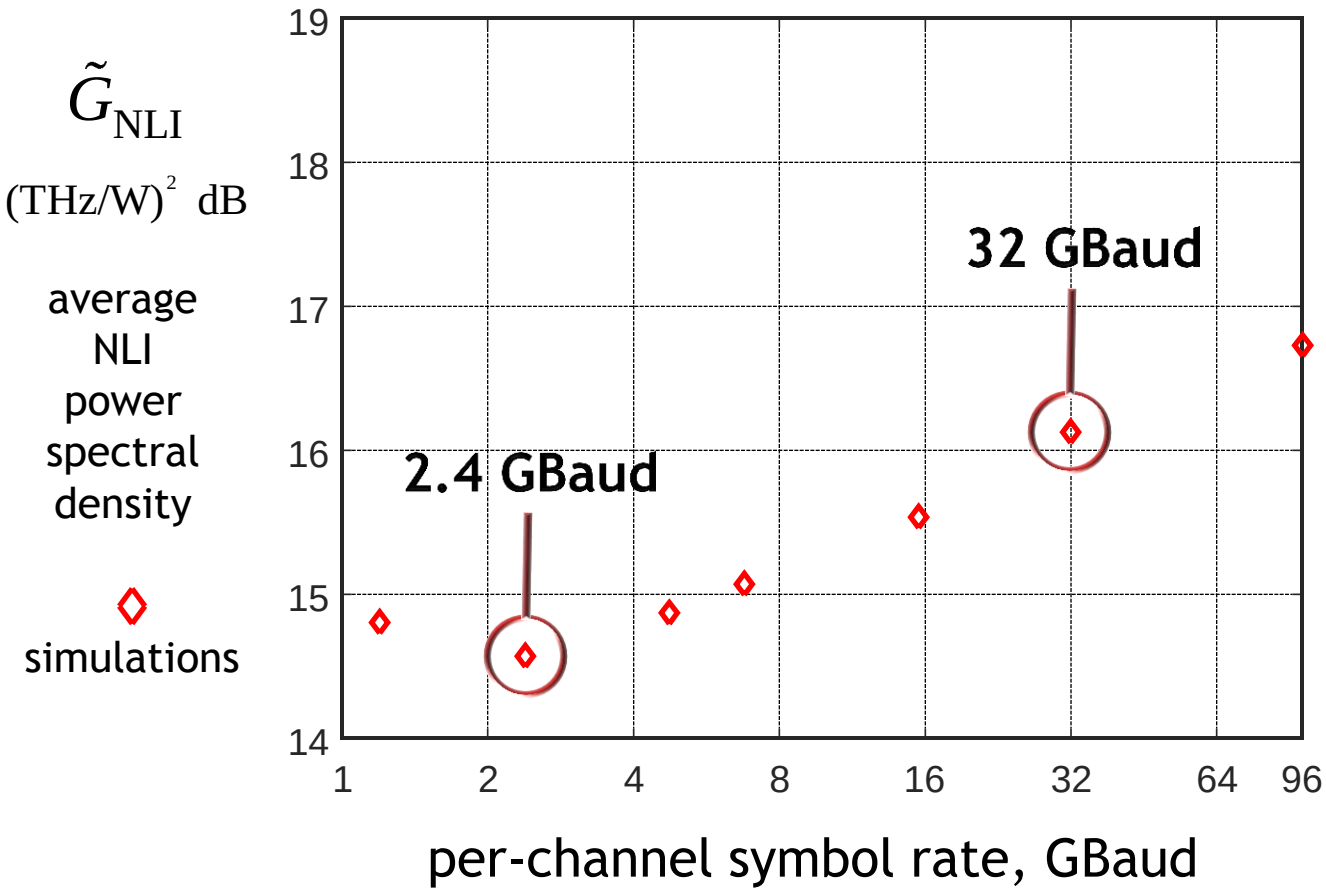
**a constant value**

across different symbol rates means

**same maximum reach**

# 500 GHz WDM bandwidth

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



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- SRO is very accurately modeled using the EGN-model

A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini and F. Forghieri, 'EGN model of non-linear fiber propagation,' Optics Express, vol. 22, no. 13, pp.16335-16362, June 2014.

- For different reasons, neither the GN-model nor advanced XPM models were able to account for it

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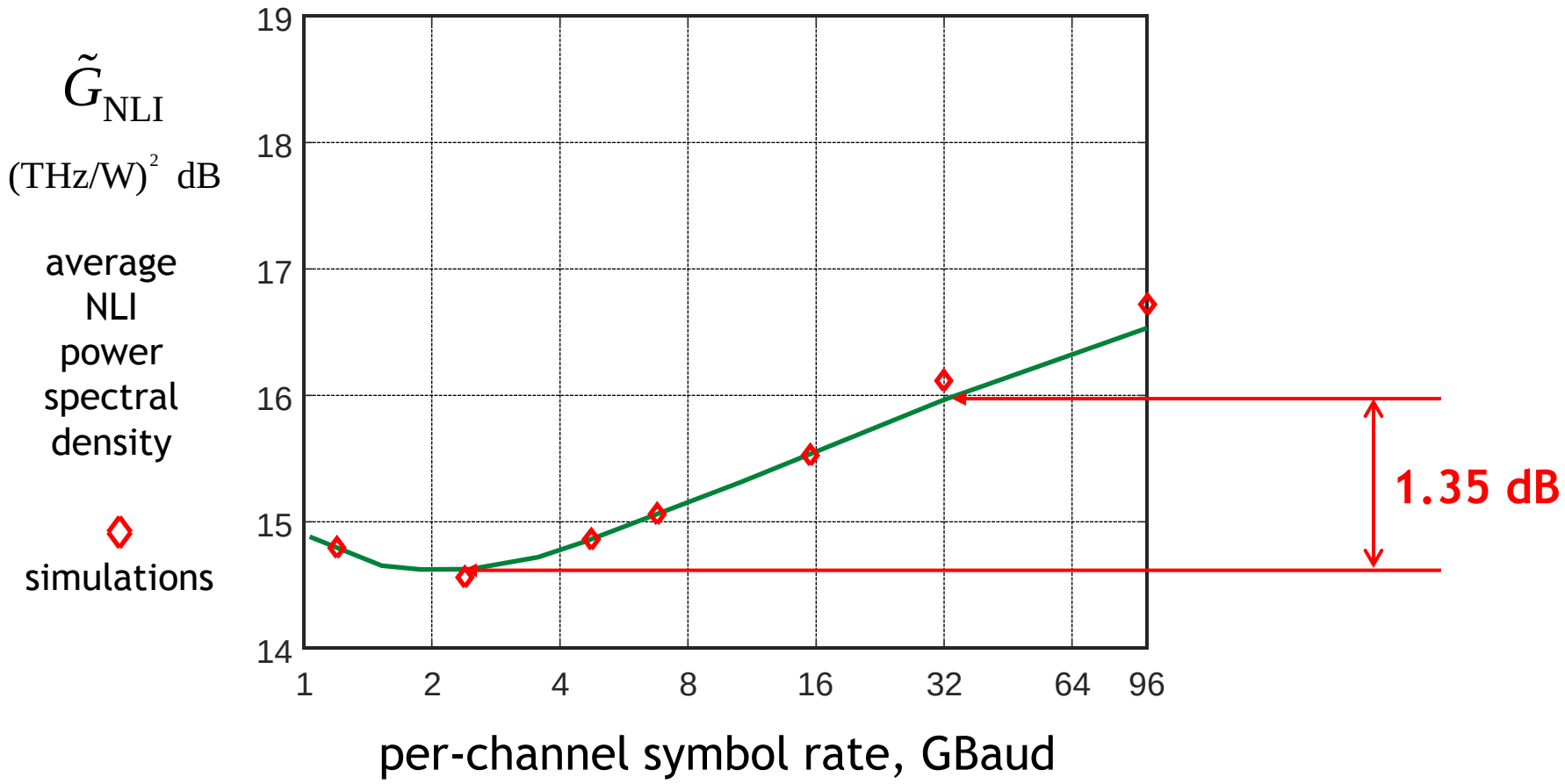


# max reach ?

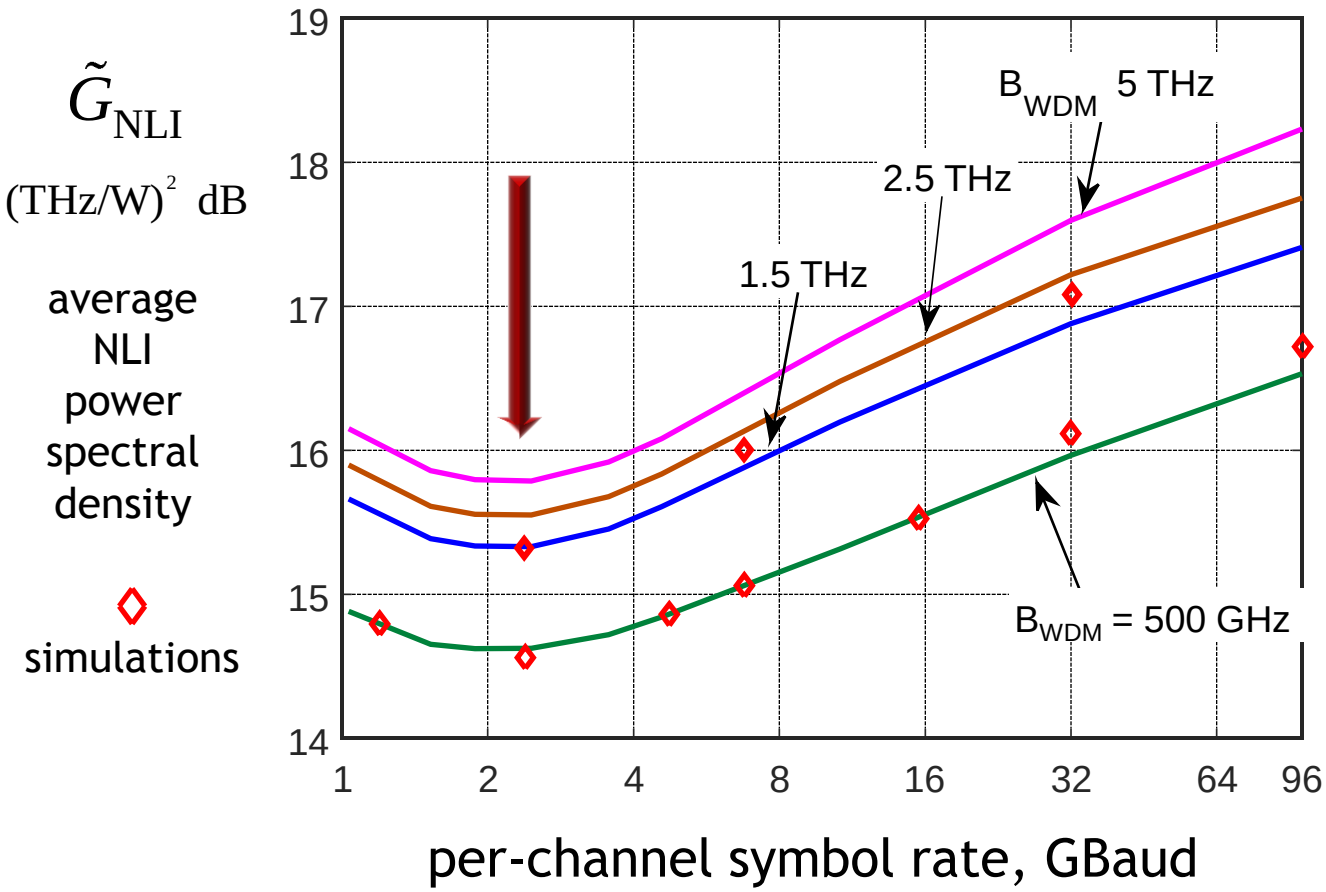
- How does ***NLI mitigation*** translate into **max reach gains?**

$$\Delta L_{\mathrm{max,dB}} \approx -\frac{1}{3}\Delta \tilde{G}_{\mathrm{NLI,dB}}$$

- 1 dB mitigation → 8% max reach gain
- 1.35 dB mitigation → 11% max reach gain

# Up to full C-band

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



# The optimum symbol rate

$$R_{\text{opt}} = \sqrt{\frac{2}{\pi |\beta_2| N_{\text{span}} L_{\text{span}}}}$$

# The optimum symbol rate

$$R_{\text{opt}} = \sqrt{\frac{2}{\pi |\beta_2| L_{\text{tot}}}}$$

- Ok for quasi-Nyquist WDM systems with approximately equal span length and lumped amplification

- It is based on the EGN model closed-form asymptotic theory developed in:
  - P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, 'A simple and effective closed-form GN model correction formula accounting for signal non-Gaussian distribution,' J. of Lightw. Technol., vol. 33, no. 2, pp. 459-473, Jan. 2015.

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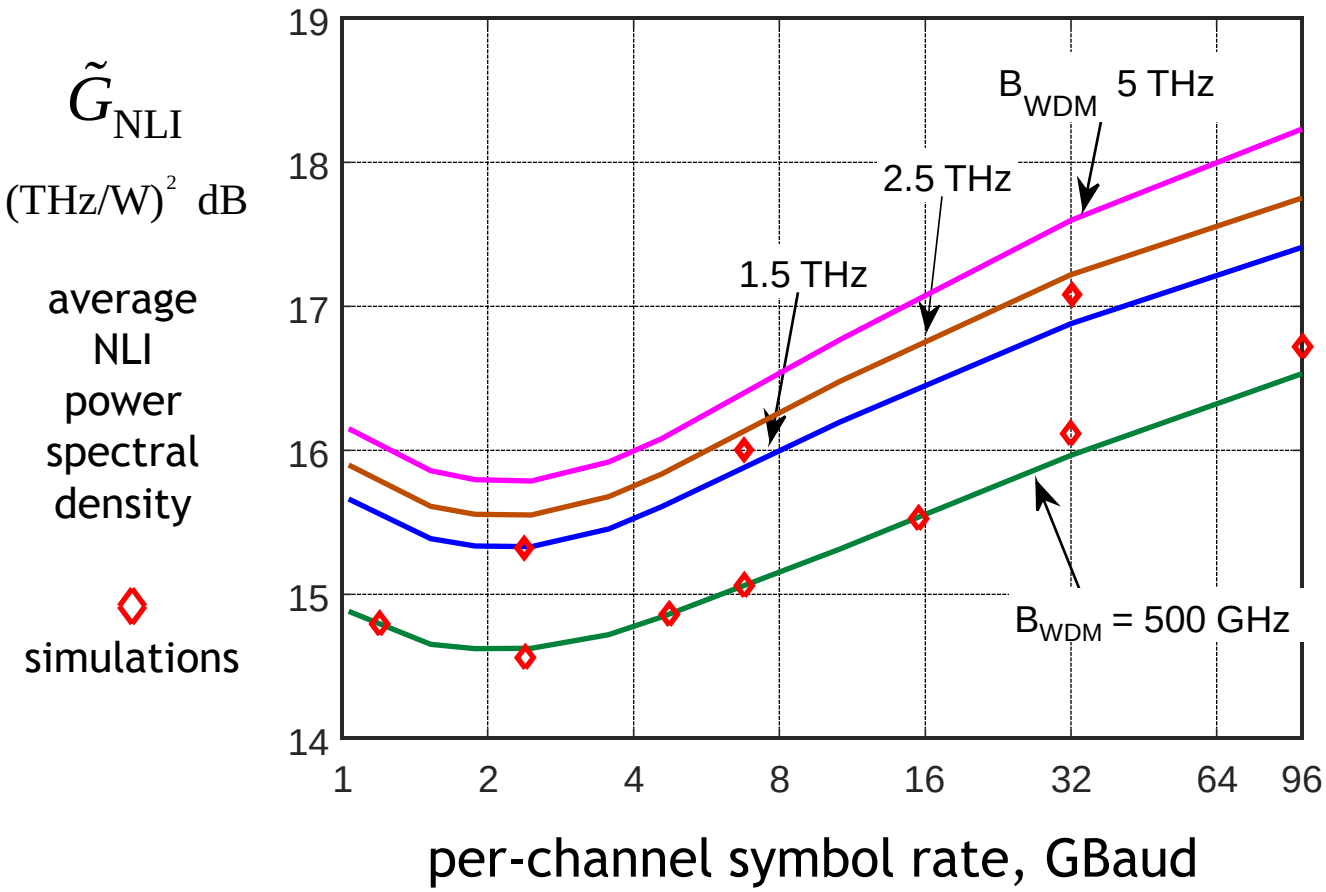
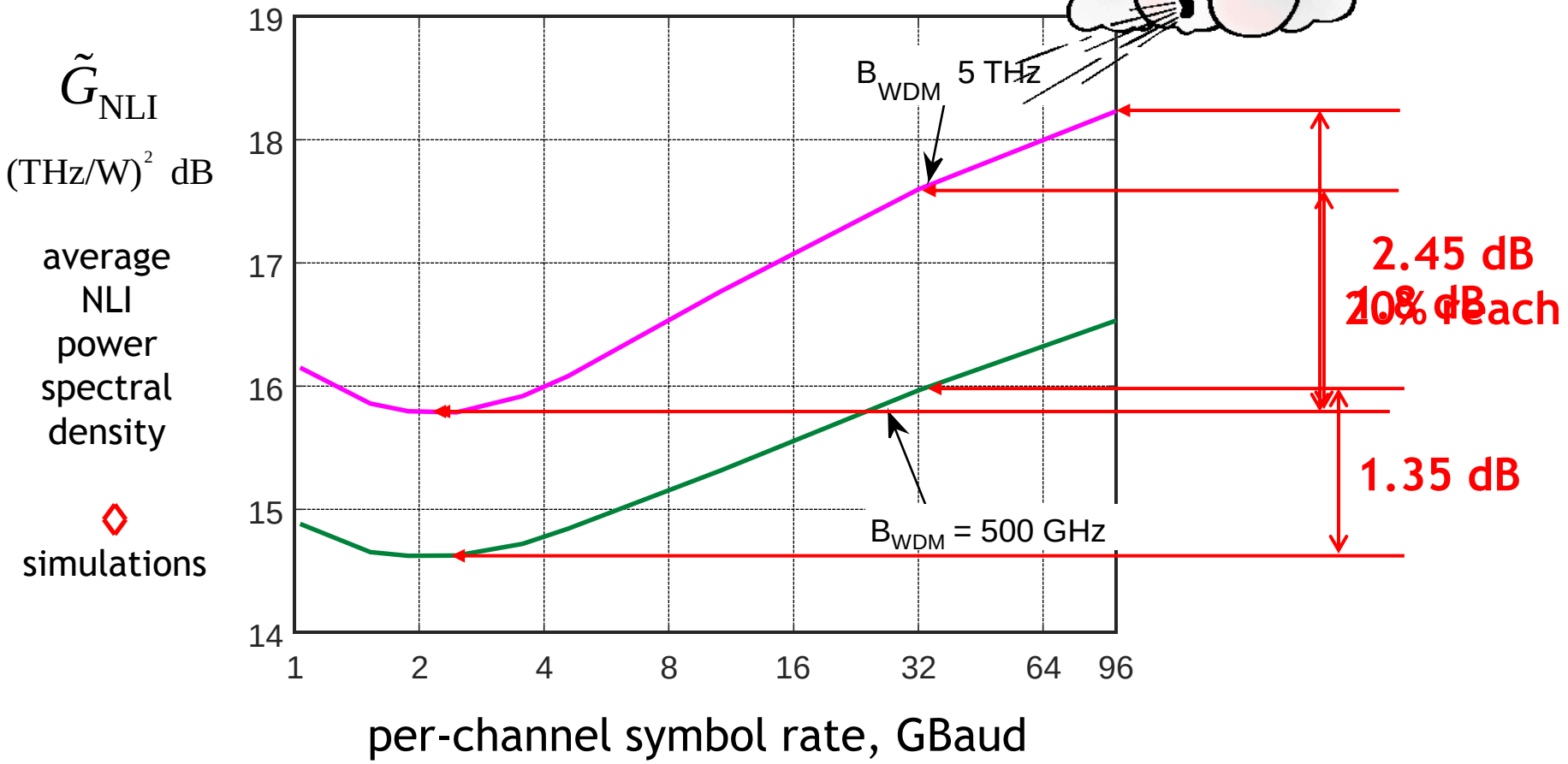


# Up to full C-band

- **PM-QPSK,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 10[illegible]pans, 50 spans**



# Backward Propagation vs. SRO

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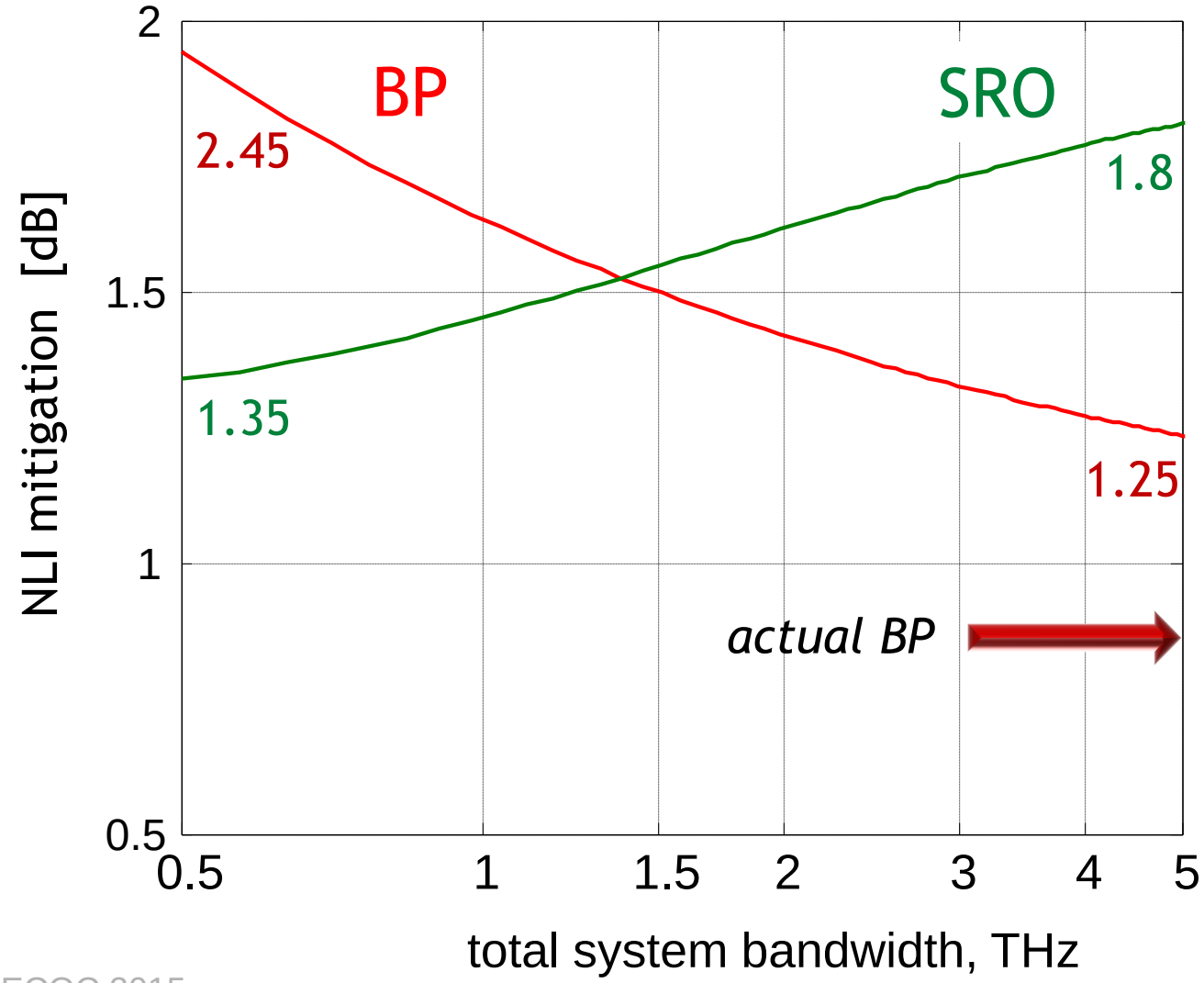


- All curves drawn using the FULL EGN model
- SRO: between 32 GBaud and the optimum rate 2.4 GBaud
- BP: ***ideal*** backward propagation over the 32 GBaud center channel

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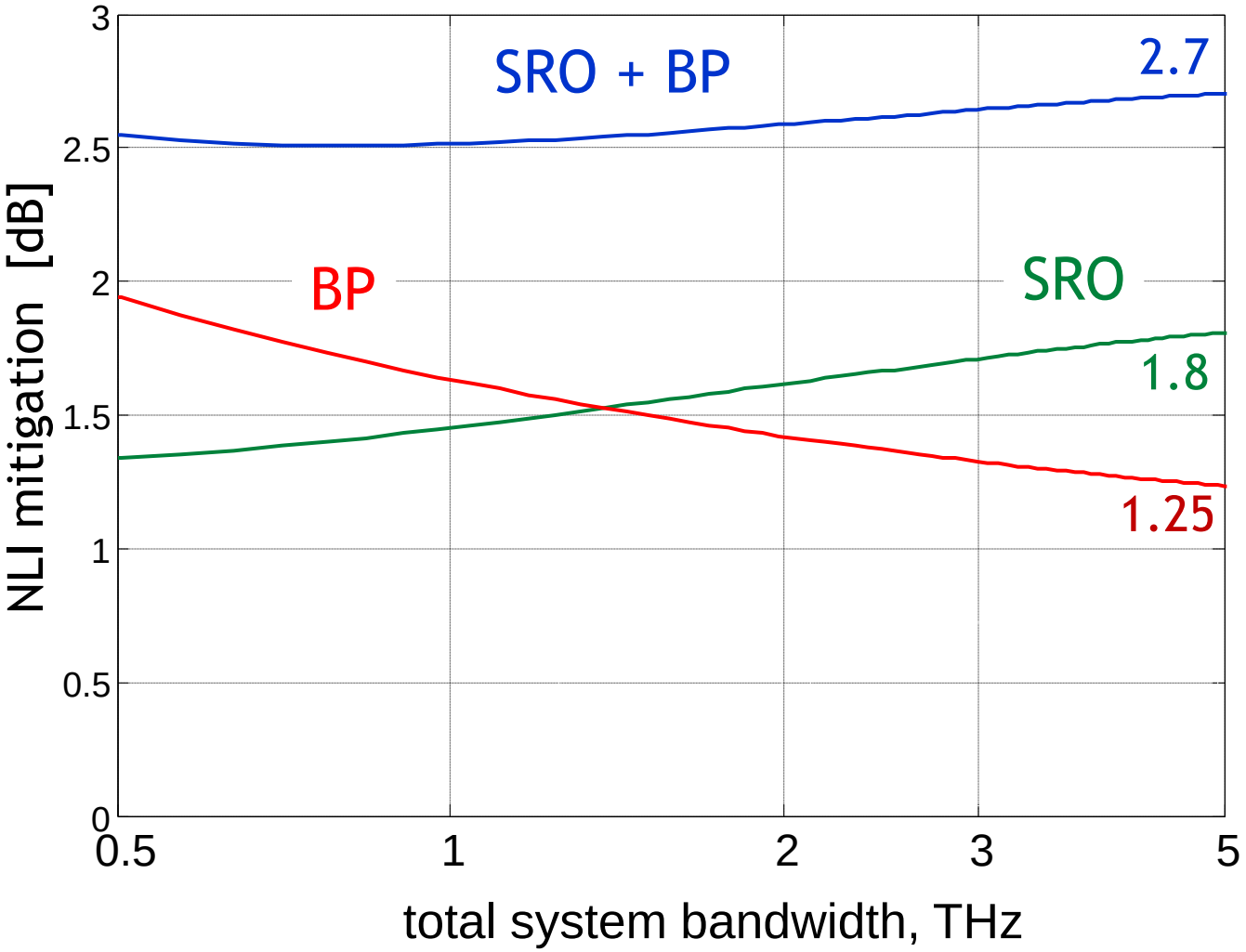
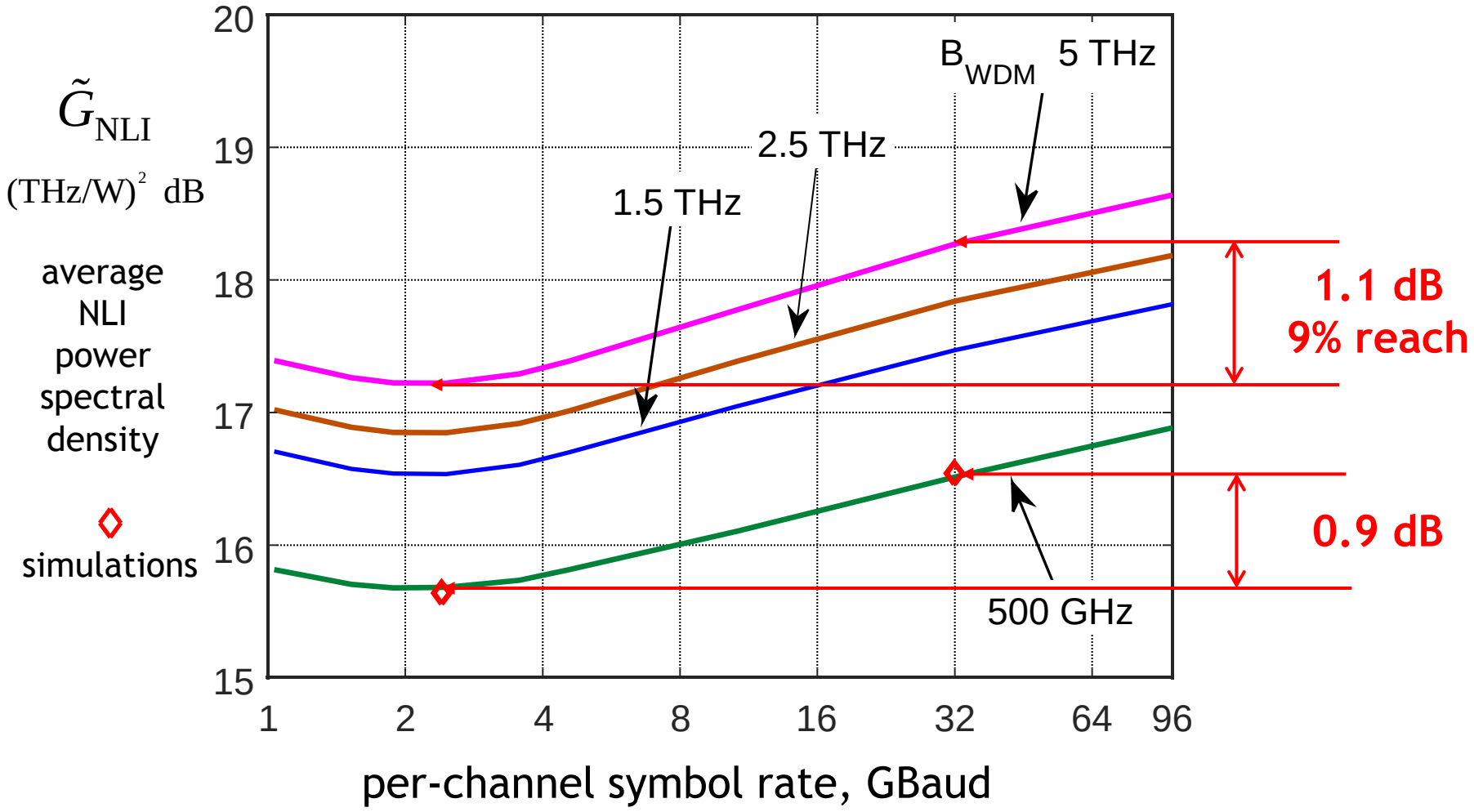



- All curves drawn using the FULL EGN model
- SRO: between 32 GBaud and the optimum rate 2.4 GBaud
- BP: ***ideal*** backward propagation over the bandwidth of the center channel (33.6 GHz)

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



# 16QAM vs. QPSK

$$\text{mitig}^{\text{dB}}_{\text{PM-16QAM}} \approx 0.6 \cdot \text{mitig}^{\text{dB}}_{\text{PM-QPSK}}$$

# Backward Propagation vs. SRO

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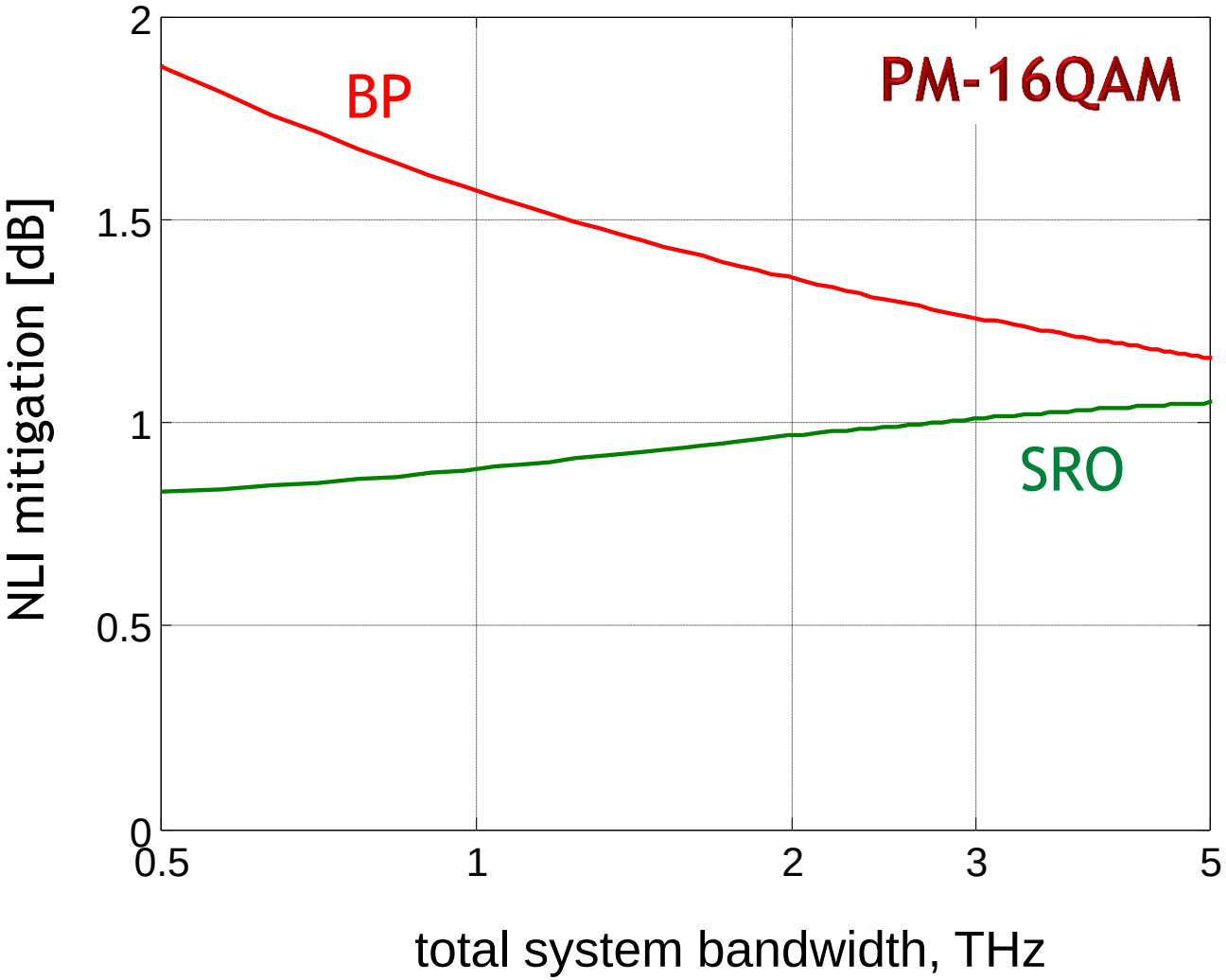


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# Trends

- SRO mitigation goes up:
  - with fiber dispersion
  - with link length
  - with total WDM bandwidth
  - as spans get shorter
- SRO goes down with PM-16QAM
  (only about 60% of PM-QPSK gains)

# Is SRO a game-changer?

downloadable at
**www.optcom.polito.it**

http://thespinnakergroupinc.com/greenbuild-san-francisco-a-game-changer/


- *Probably not…*

- The effect is there, but it is not big enough to be a game-changer
- Unfortunately gains are smaller for PM-16QAM ! (≈60%)

- However it may prove useful in some system contexts (sub, ULH, etc.)
- Also, it appears to be more effective than BP in many cases

- It puts some headwind against going to higher symbol rates
  - perhaps future 64 or 96 GBaud channels will be chopped-up into smaller-rate subcarriers to avoid large NLI penalties

# Thank you!

# How come there's a dip?

- $B_{WDM}$ = **504 GHz**, **1.92 Tb/s total,** PM-QPSK, roll-off 0.05, spacing 1.05 x (symb rate), 100 km spans