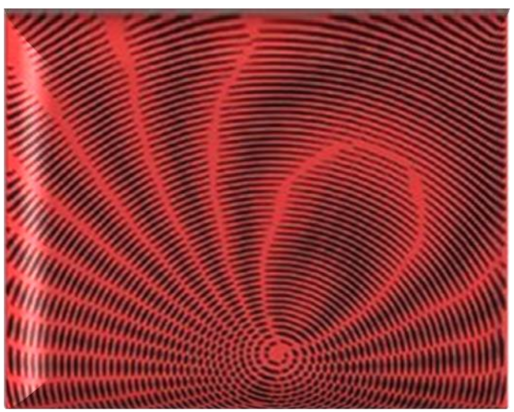
Recent Advances in Non-Linear Fiber Propagation Modeling



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Thanks!

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Context

- Presentation on the GN model three years ago at OFC

- In the meantime:
  - the GN model has enjoyed widespread adoption and utilization in many different contexts
  - *on the other hand* its shortcomings have been clearly pointed out, and then studied and understood

- New models have since appeared that address or avoid those shortcomings

Context - II

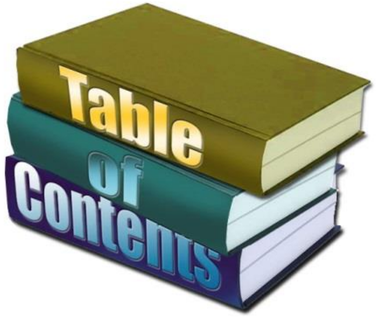
- Several *peculiar and specific aspects* of non-linearity generation have also come to the forefront:
    - long-correlated nonlinear phase and polarization noise
    - the impact of co-propagating ASE
    - symbol rate optimization
    - format-dependence of non-linearity generation
    - the depletion of signal power (“pump depletion”)
    - impact of Raman
    - others…
- All of these effects are being addressed and studied in depth, and sophisticated models are being proposed to better account for them
- As a whole *a wealth of modeling results have been published over the last three years* and the trend is continuing strong

credit: http://www.nfafranchiseconsultants.com/alternatives-financial-performance-representations/

- Which effects are important in my system and which are not ?
- Do I really need to use more complex models?
- What is the accuracy that I may expect from the various models ?
- *What model should I use/trust for my system ?*

this version of the tutorial

www.optcom.polito.it



credit http://newsroom.unl.edu/announce/snr/2761/15222

- The GN-model: an in-depth critical review
- The enhanced-GN model: pros and cons

eGN

- The specific effects:
  - long-correlated phase/polarization noise
  - impact of Raman amplification
  - co-prop ASE noise and signal depletion

credit: http://greenpediatrics.com/homeopathy-what-how-and-why/

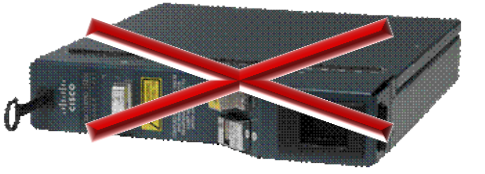
- The future: more advanced models and beyond

GN-model

a bit of retrospection

- About 2007-2008 it finally became clear that the coherent revolution would definitely take place

- Surprisingly, the optimum scenario turned out to be that of no dispersion compensation !
  - that was new and uncharted territory



credit: http://www.cisco.com/c/en/us/products/collateral/optical-networking/ons-15200-series-dwdm-systems/datasheet_c78-728877.html

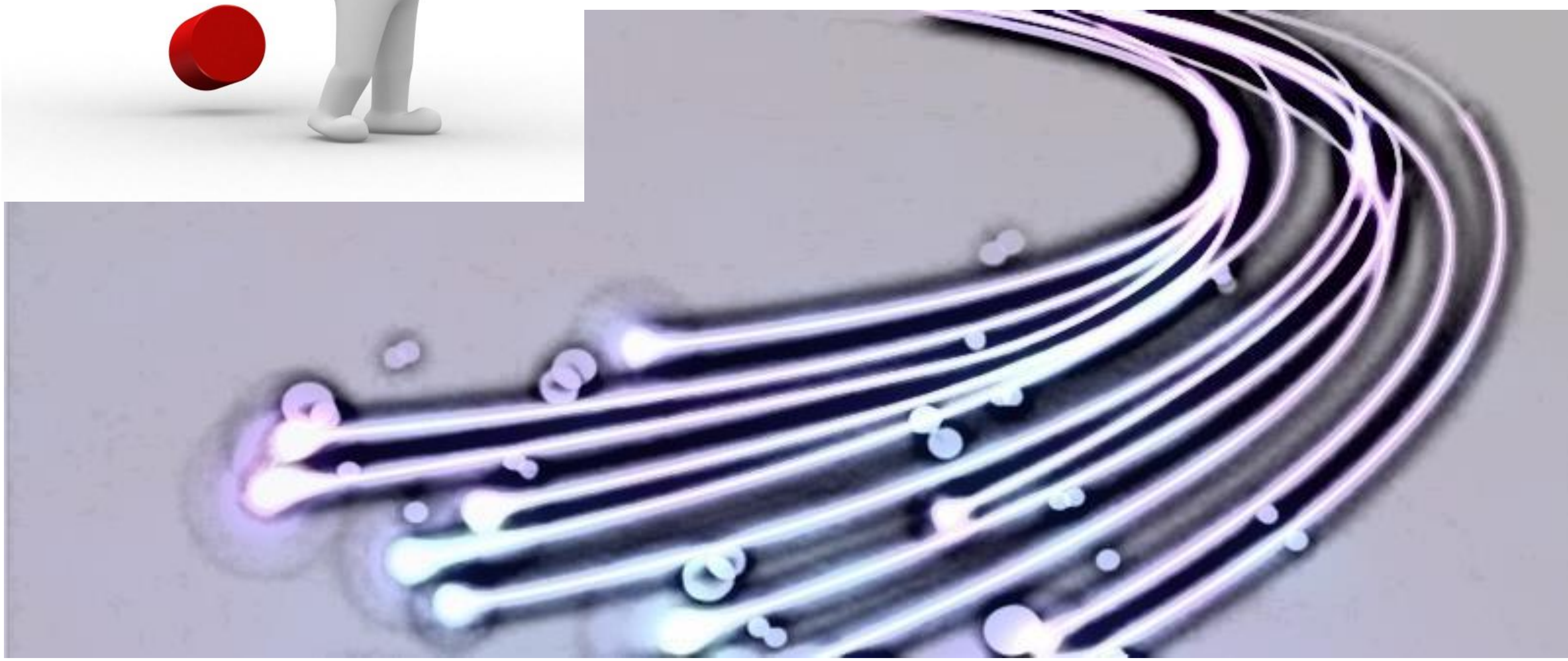
- Of course split step simulations were possible, but (especially then) with limited effectiveness

- Some system modeling *guidance* was needed to make sense of this new situation
  - a *practical and manageable* tool was necessary
  - *accuracy should be good* (though perfection not required)

credit: http://travel-representatives.com/

what needs to be modeled ?

credit: http://www.hillsborococ.org/
what-is-the-problem/



credit: http://fios.verizon.com/beacon/fiber-optics-vs-coaxial-cables/

the non-linear OSNR

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$$\mathrm{OSNR} = \frac{P_{\mathrm{ch}}}{P_{\mathrm{ASE}}}$$

the non-linear OSNR

$$\mathrm{OSNR} = \frac{P_{\mathrm{ch}}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}}$$

a model needs to allow to estimate P_{NLI} efficiently and with acceptable accuracy

- NLI: Non-Linear Interference, the disturbance created by non-linear effects

what is the fundamental quantity ?

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$$\mathrm{OSNR} = \frac{P_{\mathrm{ch}}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}}$$

models must provide the NLI PSD

$$P_{\mathrm{ASE}} = \int_{B_{\mathrm{OSNR}}} G_{\mathrm{ASE}} \, df$$

$$P_{\mathrm{NLI}} = \int_{B_{\mathrm{OSNR}}} G_{\mathrm{NLI}}(f) \, df$$

the underlying “physics”

Manakov

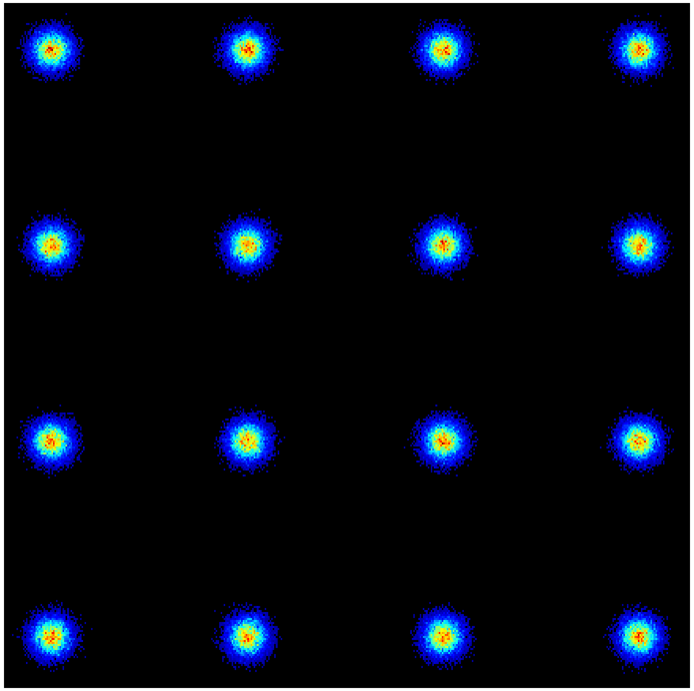
$$\frac{\partial E_x(z,t)}{\partial z} = j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}E_x(z,t) - \alpha E_x(z,t) - j\gamma\frac{8}{9}\left[\left|E_x(z,t)\right|^2 + \left|E_y(z,t)\right|^2\right]E_x(z,t)$$

$$\frac{\partial E_y(z,t)}{\partial z} = j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}E_y(z,t) - \alpha E_y(z,t) - j\gamma\frac{8}{9}\left[\left|E_x(z,t)\right|^2 + \left|E_y(z,t)\right|^2\right]E_y(z,t)$$

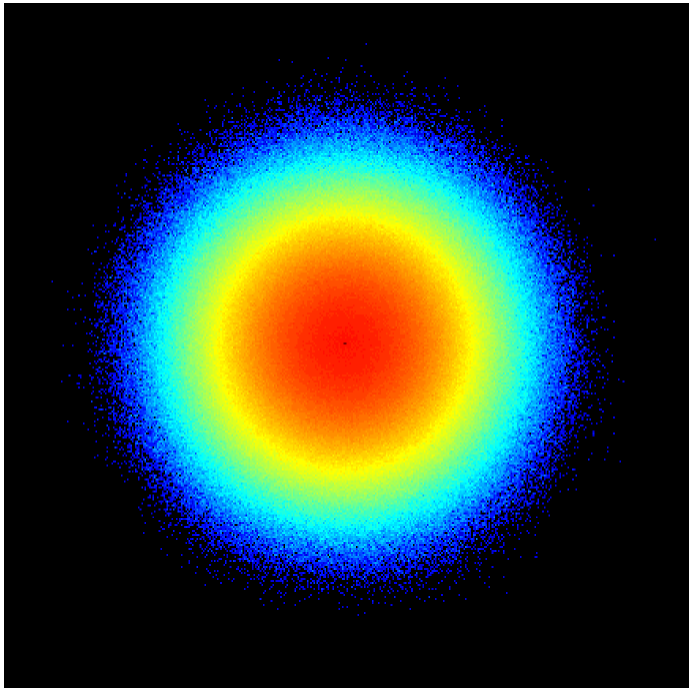
perturbation approach

the GN model assumes that the dispersed signal essentially behaves as Gaussian noise

the Gaussian "blob"



32 GBaud
400 km SMF



first-order Gaussian
(but not so higher order pdf's)

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Manakov

$$\frac{\partial E_x(z,t)}{\partial z} = j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}E_x(z,t) - \alpha E_x(z,t) - j\gamma\frac{8}{9}\left[\left|E_x(z,t)\right|^2 + \left|E_y(z,t)\right|^2\right]E_x(z,t)$$

$$\frac{\partial E_y(z,t)}{\partial z} = j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}E_y(z,t) - \alpha E_y(z,t) - j\gamma\frac{8}{9}\left[\left|E_x(z,t)\right|^2 + \left|E_y(z,t)\right|^2\right]E_y(z,t)$$

perturbation approach

the GN model assumes that the dispersed signal essentially behaves as Gaussian noise

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

The GN-model reference formula (GNRF)

the GN-model family tree (to 2013)

- A. Splett, C. Kurtzke, K. Petermann, ECOC ’93, vol. 2, p. 41,1993.

- Jau Tang, JLT, vol.20, no.7, p. 1095, 2002.

- H. Louchet et al., PTL, vol.15, p. 1219, 2003.

M. Nazarathy et al, Opt. Exp., vol.16, p. 15777, 2008

Xi Chen, W. Shieh, Opt. Exp., vol. 18, p. 19039, 2010

for OFDM

“GN model” name used here for the first time

- P. Poggiolini et al., PTL, vol. 23, p. 742 2011

- A. Carena et al., JLT, v. 30, p. 1524, 2012

P. Serena, A. Bononi, JLT, v. 31, p. 3489, 2013

P. Johannisson, M. Karlsson, JLT, v. 31, p. 1273, 2013

A. Bononi, O. Beucher, P. Serena, OE, vol. 21, p. 32254, 2013

P. Johannisson, M. Karlsson, JLT, v. 31, p. 1273, 2013

S. J. Savory, PTL, vol. 25, p.961, 2013

GN-model main papers

OPTCOM

- [1] A. Splett, C. Kurzke, and K. Petermann, “Ultimate Transmission Capacity of Amplified Optical Fiber Communication Systems Taking into Account Fiber Nonlinearities,” *in Proc. ECOC 1993,* vol. 2, pp. 41-44, 1993.
- [2] Jau Tang, “The Channel Capacity of a Multispan DWDM System Employing Dispersive Nonlinear Optical Fibers and an Ideal Coherent Optical Receiver,” *J. Lightwave Technol.,* vol. 20, pp. 1095-1101, 2002.
- [3] H. Louchet et al., “Analytical Model for the Performance Evaluation of DWDM Transmission Systems,” *IEEE Phot. Technol. Lett., vol. 15, pp.* 1219-1221, Sept. 2003.
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- [5] M. Nazarathy, J. Khurgin, R. Weidenfeld, Y. Meiman, Pak Cho, R. Noe, I. Shpantzer, V. Karagodsky “Phased-Array Cancellation of Nonlinear FWM in Coherent OFDM Dispersive Multi-Span Links,” *Optics Express,* vol. 16, pp. 15778-15810, 2008.
- [6] X. Chen and W. Shieh, “Closed-Form Expressions for Nonlinear Transmission Performance of Densely Spaced Coherent Optical OFDM Systems,” *Optics Express,* vol. 18, pp. 19039-19054, 2010.
- [7] W. Shieh and X. Chen, “Information Spectral Efficiency and Launch Power Density Limits Due to Fiber Nonlinearity for Coherent Optical OFDM Systems,” *IEEE Photon. Journal,* vol. 3, pp. 158-173, 2011.
- [8] P. Poggiolini, A. Carena, V. Curri, G. Bosco, F. Forghieri, “Analytical Modeling of Non-Linear Propagation in Uncompensated Optical Transmission Links,” *IEEE Photon. Technol. Lett.,* vol. 23, pp. 742-744, 2011.
- [9] Torrengo E, Cigliutti R, Bosco G, Carena A, Curri V, Poggiolini P, Nespola A, Zeolla D, Forghieri F. Experimental validation of an analytical model for nonlinear propagation in uncompensated optical links. *Opt Express* 2011;19(26):B790–B798.
- [9] A. Carena, V. Curri, G. Bosco, P.Poggiolini, F. Forghieri, “Modeling of the Impact of Non-Linear Propagation Effects in Uncompensated Optical Coherent Transmission Links,” *J. of Lightw. Technol.,* vol. 30, pp. 1524-1539, May 15th 2012.
- [10] P. Poggiolini “The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems,” *J. of Lightwave Technol.*, vol. 30, no. 24, pp. 3857-3879, Dec. 15 2012.
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- [12] Nespola A, Straullu S, Carena A, Bosco G, Cigliutti R, Curri V, Poggiolini P, Hirano M, Yamamoto Y, Sasaki T, Bauwelinck J,Verheyen K, Forghieri F. GN-model validation over seven fiber types in uncompensated PM-16QAM Nyquist-WDM links. *IEEE Photonics Technol Lett* 2014;26(2):206–209.
- [13] Serena P, Bononi A. “An alternative approach to the Gaussian noise model and its system implications.” *J Lightwave Technol* 2013;31(22):3489–3499.
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- [16] V. Curri et al., “Extension and validation of the GN model for non-linear interference to uncompensated links using Raman amplification,” Optics Express, v. 21., no. 3, pp. 3308-3317, Feb. 2013.

Many other models exist

- There are many (variously overlapping) *families of models*
- A non-exhaustive list is:
  - time domain
  - frequency domain
  - Volterra-based
  - first order perturbation
  - higher-order
  - regular perturbation (RP, with variants)
  - logarithmic perturbation (LP, with variants)
  - pulse-collision based
  - more classes sub-classes based on specific assumptions and approximations…
- *The GN model is a frequency-domain RP first-order model*
- with the distinctive assumption of the signal being dealt with as (colored) Gaussian noise

Non-linear papers I

OPTCOM

Non-exhaustive list of prominent non-linearity modeling papers
(using other approaches than the GN model)

1. C. R. Menyuk, 'Pulse propagation in an elliptically birefringent Kerr medium,' *IEEE J. Quantum Electron.*, vol. 25, no. 12, pp. 2674-2682, Dec. 1989.

2. S. G. Evangelides Jr., L. F.Mollenauer, J. P. Gordon, and N. S. Bergano, 'Polarization multiplexing with solitons,' *J. Lightwave Technol.*, vol. 10, no. 1, pp. 28-35, Jan. 1992.

3. D. Marcuse, C. R. Menyuk, and P. K. A. Wai, 'Application of the Manakov-PMD equation to studies of signal propagation in optical fibers with randomly varying birefringence,' *J. Lightwave Technol.*, vol. 15, no. 9, pp. 1735-1746, Sept. 1997.

4. A. Vannucci, P. Serena, and A. Bononi, 'The RP method: a new tool for the iterative solution of the nonlinear Schrodinger equation,' *J. Lightwave Technol.*, vol. 20, no. 7, pp. 1102-1112, July 2002.

5. K.V. Peddanarappagari and M. Brandt-Pearce 'Volterra series transfer function of single-mode fibers,' *J. of Lightwave. Technol.*, vol. 15, no. 12, pp. 2232-2241, Dec. 1997.

6. A. Mecozzi, C. Balslev Clausen, and M. Shtaif, 'Analysis of intrachannel nonlinear effects in highly dispersed optical pulse transmission,' *IEEE Photon. Technol. Lett.*, vol. 12, no. 4, pp. 392-394, Apr. 2000.

7. E. E. Narimanov and P. P. Mitra, 'The channel capacity of a fiber optics communication system: perturbation theory,' *J. Lightwave Technol.*, vol. 20, no. 3, pp. 530-537, Mar. 2002.

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9. J. P. Gordon and L. F. Mollenauer, 'Phase noise in photonic communications systems using linear amplifiers,' *Opt. Lett.*, vol. 15, no. 23, pp. 1351-1353, 1990.

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11. A. Mecozzi, 'Limits to long haul coherent transmission set by the Kerr nonlinearity and noise of the inline amplifiers,' *J. Lightwave. Technol.*, vol. 12, no. 11, pp. 1993-2000, Nov. 1994.

Non-linear papers II

12. G. Bellotti, M. Varani, C. Francia, and A. Bononi, 'Intensity distortion induced by cross-phase modulation and chromatic dispersion in optical-fiber transmissions with dispersion compensation,' *IEEE Photon. Technol. Lett.*, vol. 10, no. 12, pp. 1745-1747, Dec. 1998.

13. A. Cartaxo, 'Cross-phase modulation in intensity modulation-direct detection WDM systems with multiple optical amplifiers and dispersion compensators,' *J. Lightw. Technol.*, vol. 17, no. 2, pp. 178-190, Feb. 1999.

14. R. Hui, K. R. Demarest, and C. T. Allen, 'Cross-phase modulation in multispan WDM optical fiber systems,' *J. Lightwave. Technol.*, vol. 17, no. 6, pp. 1018-1026, Jun. 1999.

15. A.Mecozzi, C. Balslev Clausen, andM. Shtaif, 'System impact of intrachannel nonlinear effects in highly dispersed optical pulse transmission,' *IEEE Phot. Technol. Lett.*, vol. 12, no. 12, pp. 1633-1635, Dec. 2000.

16. P. P. Mitra and J. B. Stark, 'Nonlinear limits to the information capacity of optical fiber communications,' *Nature*, vol. 411, no. 6841, pp. 1027-1030, Jun. 2001.

17. B. Xu and M. Brandt-Pearce, 'Comparison of FWM- and XPM-induced crosstalk using the Volterra series transfer function method,' *J. Lightwave. Technol.*, vol. 21, no. 1, pp. 40-53, Jan. 2003.

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Non-linear papers III

22. K.-P. Ho and H.-C. Wang, ‘Comparison of nonlinear phase noise and intrachannel four-wave mixing for RZ-DPSK signals in dispersive transmission systems,’ *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1426-1428, July 2005.

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27. A.Mecozzi, ‘A unified theory of intra-channel nonlinearity in pseudolinear phase-modulated transmission,’ *IEEE Photon. J.*, vol. 2, no. 5, pp. 728-735, Aug. 2010.

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29. J. Reis and A. Teixeira, ‘Unveiling nonlinear effects in dense coherent optical WDM systems with Volterra series,’ *Optics Express*, vol. 18, no. 8, pp. 8660-8670, Apr. 2010.

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31. Chongjin Xie, ‘Fiber Nonlinearities in 16QAM Transmission Systems,’ in *Proc. ECOC 2011*, paper We.7.B.6, Geneva (CH), Sept. 2011.

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Non-linear papers IV

OPTCOM

33. A. Mecozzi and R. J. Essiambre, “Nonlinear Shannon limit in pseudolinear coherent systems”, vol. 30, no. 12, pp. 2011—2024, June 2012.

34. A. Bononi, P. Serena, N. Rossi, E. Grellier, and F. Vacondio, ‘Modeling nonlinearity in coherent transmissions with dominant intrachannel-four-wavemixing,’ *Optics Express*, vol. 20, pp. 7777-7791, 26 March 2012.

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Comments

- Many of these models are similar and almost equivalent
- *Many are more sophisticated and more accurate than the GN model*

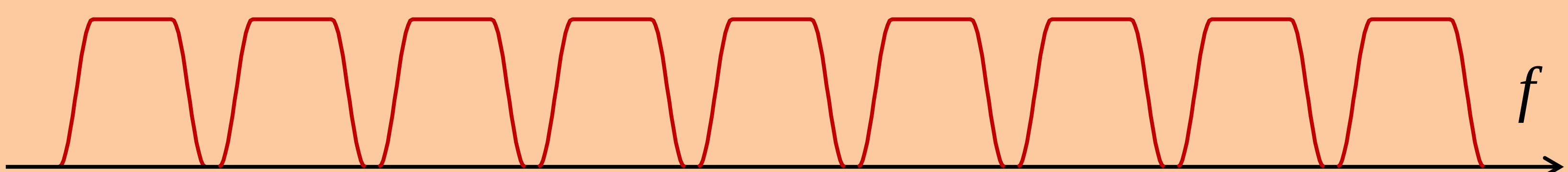
- Perhaps the GN model:
  - strikes a balance between complexity and accuracy
  - this might explain its good reception and wide use

- TBD in a few minutes

the GNRF

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

transmission spectrum $G_{\mathrm{WDM}}(f)$



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

the "link function":
it is the "FWM efficiency"
of the whole link

the GNRF

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

it contains
the full description of the link
span by span, amplifier by amplifier

the GNRF

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

for identical spans with lumped amplification:

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

list of symbols

- In the following:
  - α loss coefficient
  - β_2 dispersion coefficient
  - γ fiber non-linearity coefficient
  - N_s number of spans
  - L_s span length
  - R channel symbol rate
  - P_{ch} power per channel
  - L_{eff} span effective length: $L_{\mathrm{eff}} = \dfrac{1-\exp(-2\alpha L_s)}{2\alpha}$

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

single-span FWM efficiency

for identical spans with lumped amplification:

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

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

easy to integrate

for <u>identical spans</u> with lumped amplification:

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

OPTCOM

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

cross-span “resonance”

for identical spans with lumped amplification:

$$\gamma^2L_{\text{eff}}^2\left|\frac{1-e^{-2\alpha L_s}e^{j4\pi^2\beta_2L_s(f_1-f)(f_2-f)}}{1-j2\pi^2\beta_2\alpha^{-1}(f_1-f)(f_2-f)}\right|^2\frac{\sin^2\left(2N_s\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}$$

OPTCOM

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

nasty to integrate

for identical spans with lumped amplification:

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

The incoherent GNRF

- It turns out that, through a somewhat drastic (but justifiable) approximation:

$$\frac{\sin^2\left(2N_s\pi^2(f_1-f)(f_2-f)\beta_2 L_s\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)\beta_2 L_s\right)} \rightarrow N_s$$

Poggiolini P, Bosco G, Carena A, Curri V, Jiang Y, Forghieri F. "The GN model of fiber non-linear propagation and its applications." J Lightwave Technol 2014;32(4):694-721

- This is equivalent to saying that the NLI noise created in each span sums up in power (*incoherently)* at the receiver

- The incoherent GN model is born…

A strange paradox...

$$G_{\mathrm{NLI}}(f)=\frac{16}{27}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_{\mathrm{WDM}}(f_1)G_{\mathrm{WDM}}(f_2)G_{\mathrm{WDM}}(f_1+f_2-f)\cdot$$

$$\cdot\left|\mu(f_1,f_2,f)\right|^2 \mathrm{d}f_1\mathrm{d}f_2$$

for <u>identical spans</u> with lumped amplification:

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

A strange paradox…

$$G_{\mathrm{NLI}}(f) = \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\mathrm{WDM}}(f_1) G_{\mathrm{WDM}}(f_2) G_{\mathrm{WDM}}(f_1 + f_2 - f) \cdot$$

$$\cdot \left| \mu(f_1, f_2, f) \right|^2 \mathrm{d}f_1 \mathrm{d}f_2$$

for identical spans with lumped amplification:

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

the incoherent GNRF

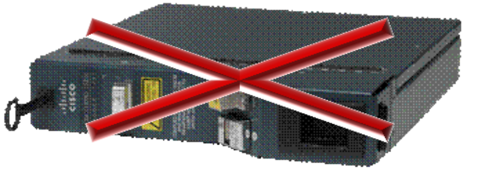
$$G_{\mathrm{NLI}}(f)=N_s\frac{16}{27}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_{\mathrm{WDM}}(f_1)G_{\mathrm{WDM}}(f_2)G_{\mathrm{WDM}}(f_1+f_2-f)\cdot$$

$$\cdot\gamma^2L_{\mathrm{eff}}^2\left|\frac{1-e^{-2\alpha L_s}e^{j4\pi^2\beta_2L_s(f_1-f)(f_2-f)}}{1-j2\pi^2\beta_2\alpha^{-1}(f_1-f)(f_2-f)}\right|^2\,\mathrm{d}f_1\mathrm{d}f_2$$

integral can be easily dealt with numerically in a matter of seconds

a bit of retrospection

- About 2007-2008 it finally became clear that the coherent revolution would definitely take place
- Surprisingly, the optimum scenario turned out to be that of no dispersion compensation !
  - that was new and uncharted territory



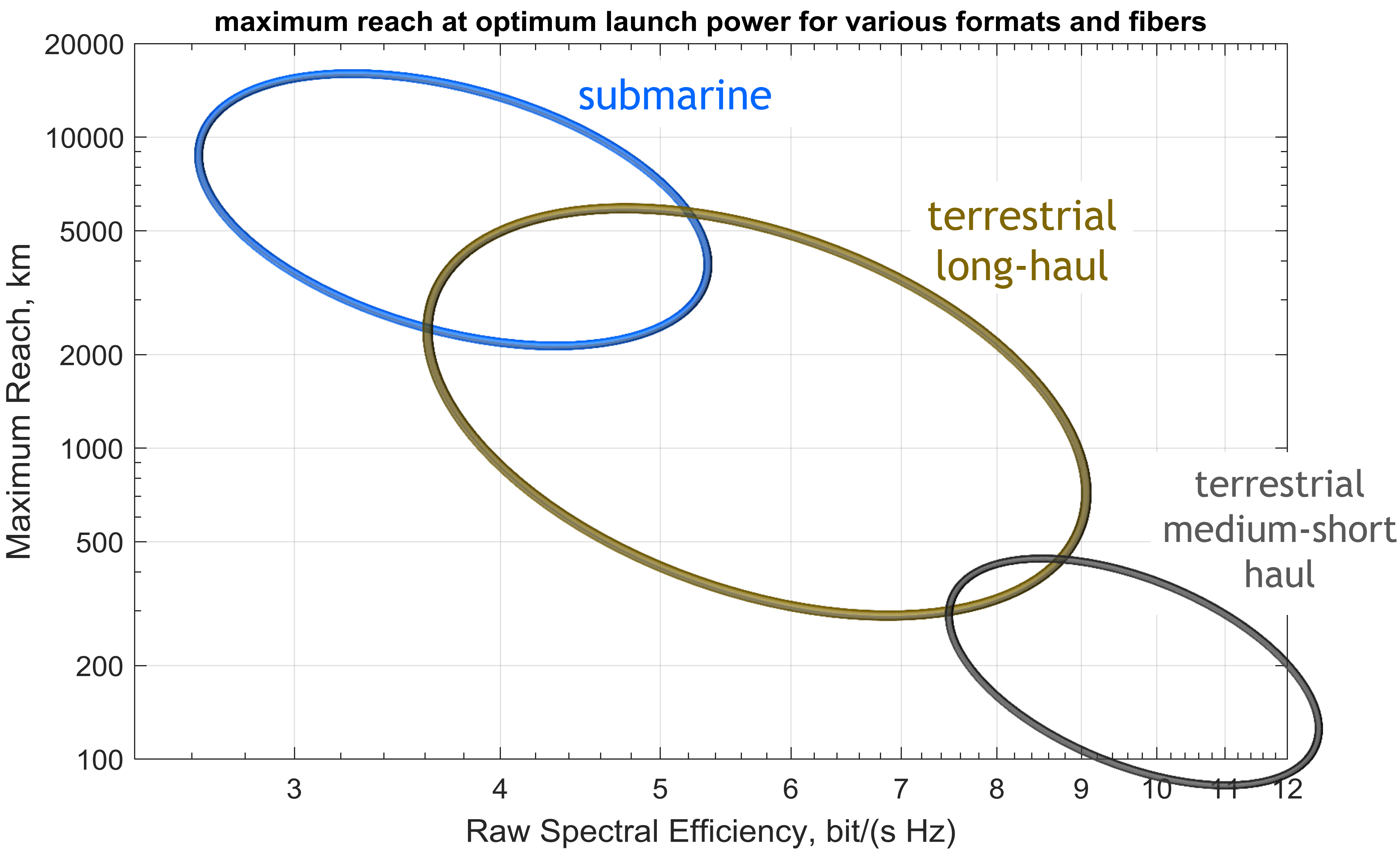
credit: http://www.cisco.com/c/en/us/products/collateral/optical-networking/ons-15200-series-dwdm-systems/datasheet_c78-728877.html

- Of course split step simulations were possible, but (especially then) with limited effectiveness
- Some system modeling *guidance* was needed to make sense of this new situation
  - a *practical and manageable* tool was necessary
  - *accuracy should be good* (though perfection not required)

credit: http://travel-representatives.com/

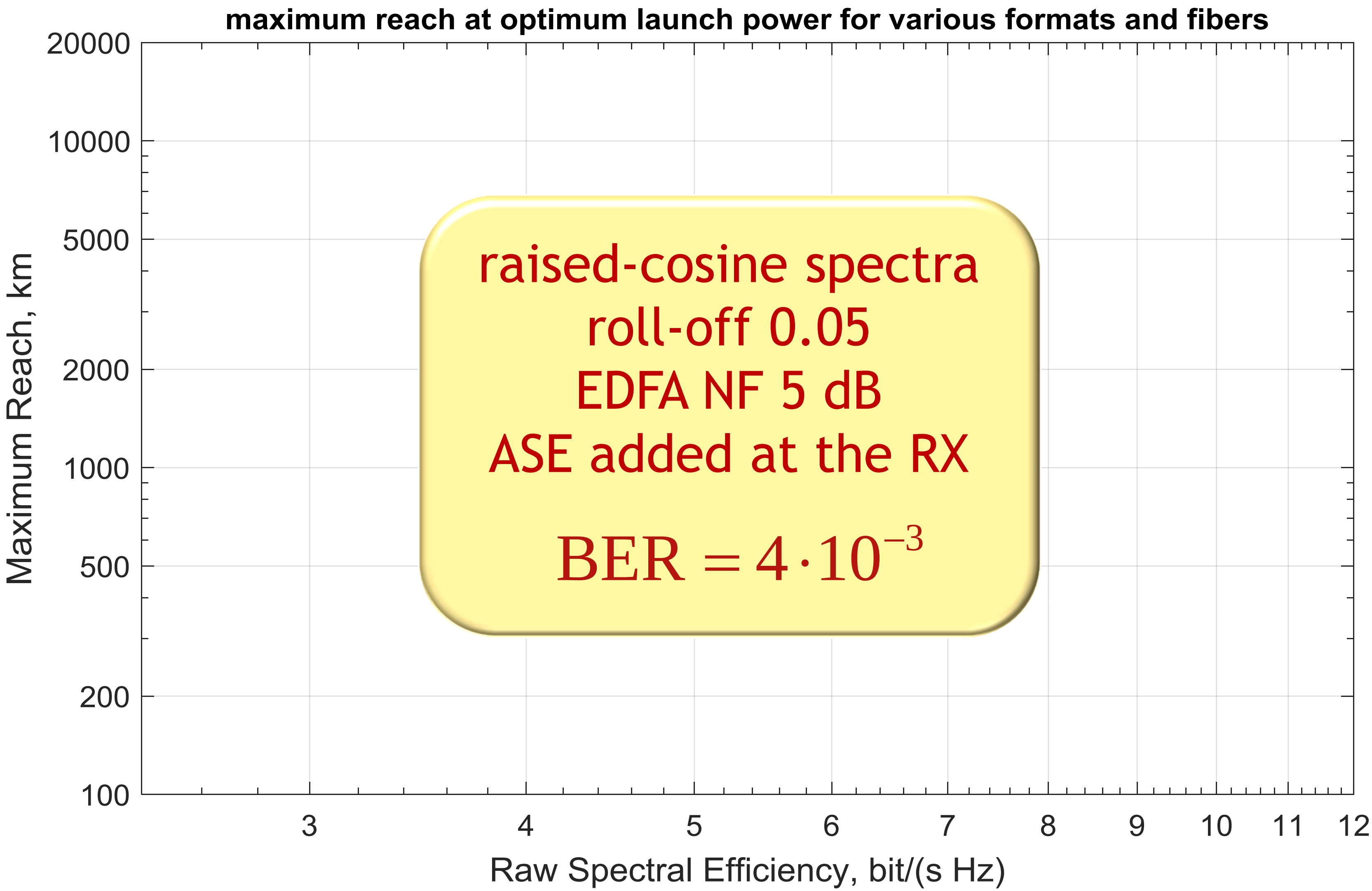
credit: http://www.dtvisiontech.com/2015_12_01_archive.html

The big picture



The big picture

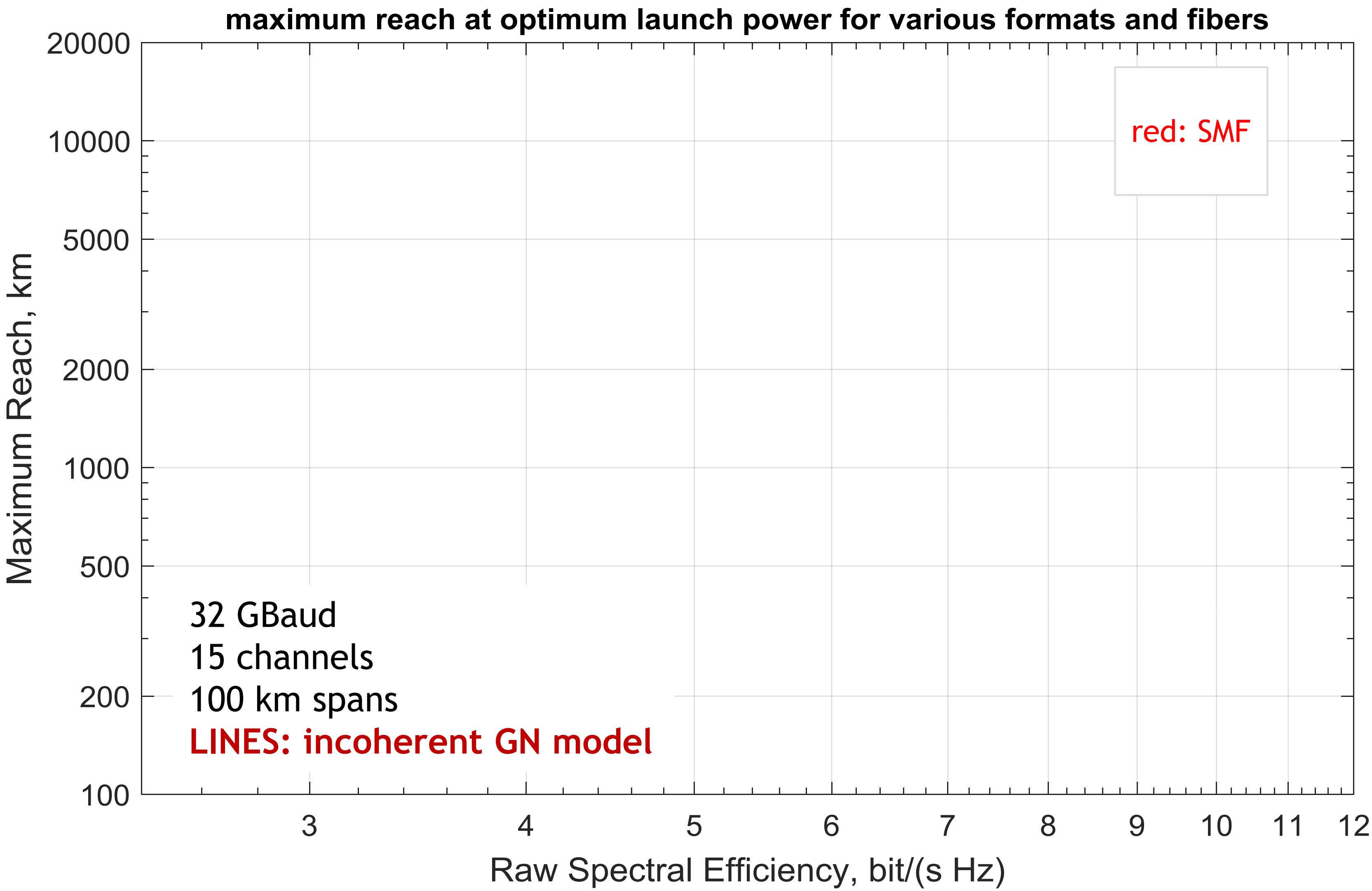
OPTCOM



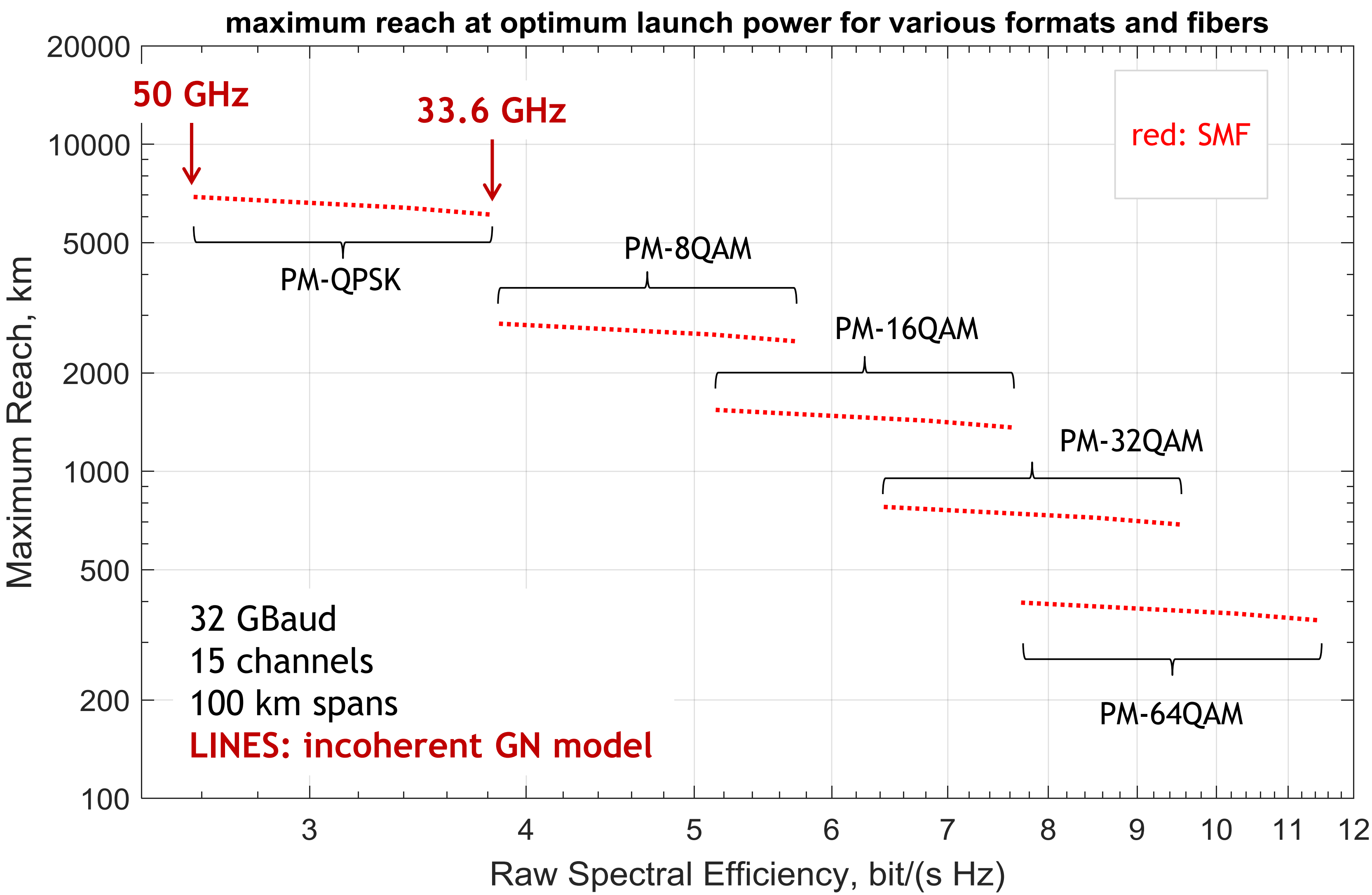
raised-cosine spectra
roll-off 0.05
EDFA NF 5 dB
ASE added at the RX

$$\mathrm{BER} = 4 \cdot 10^{-3}$$

The big picture



The big picture



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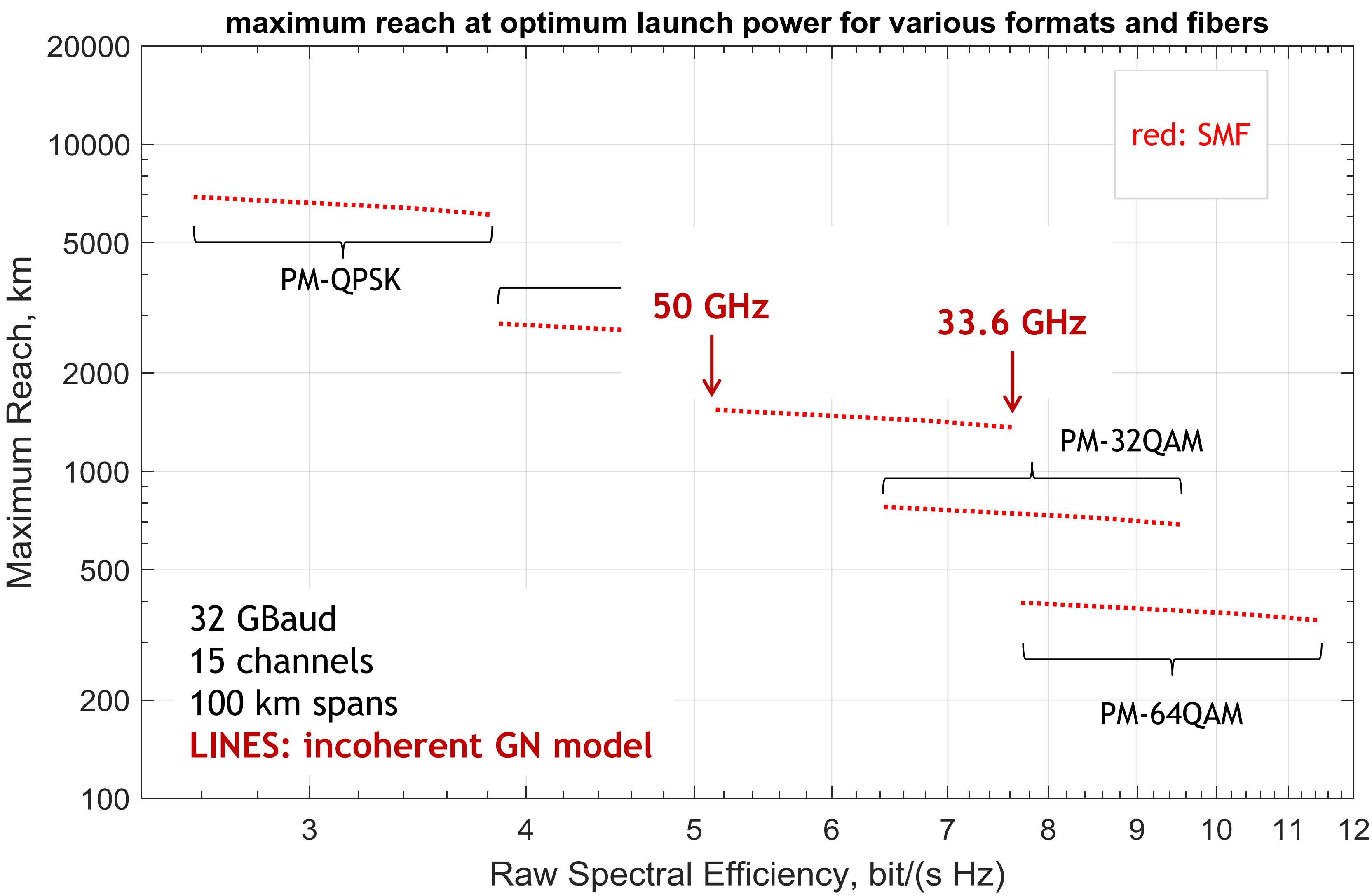
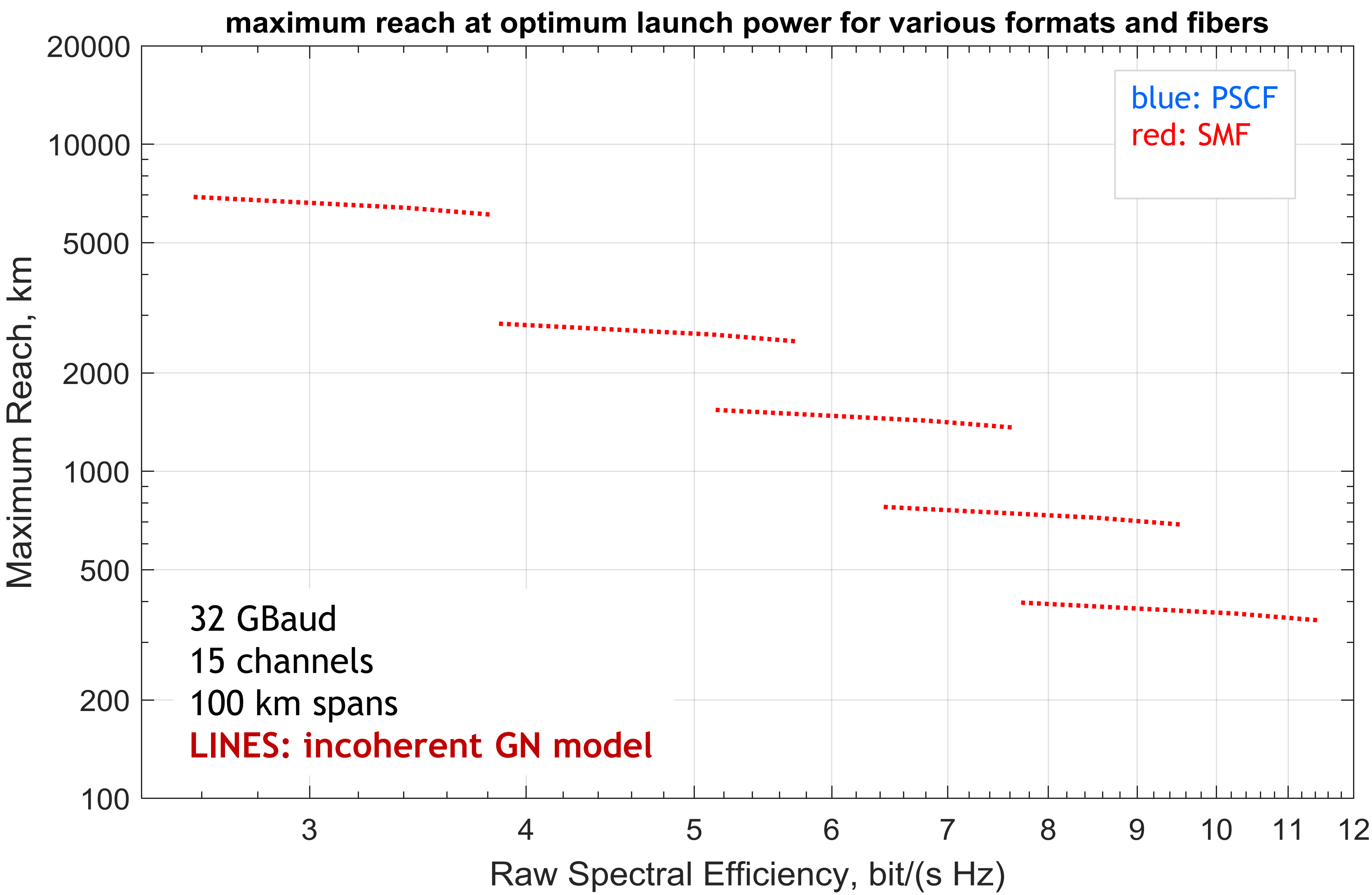
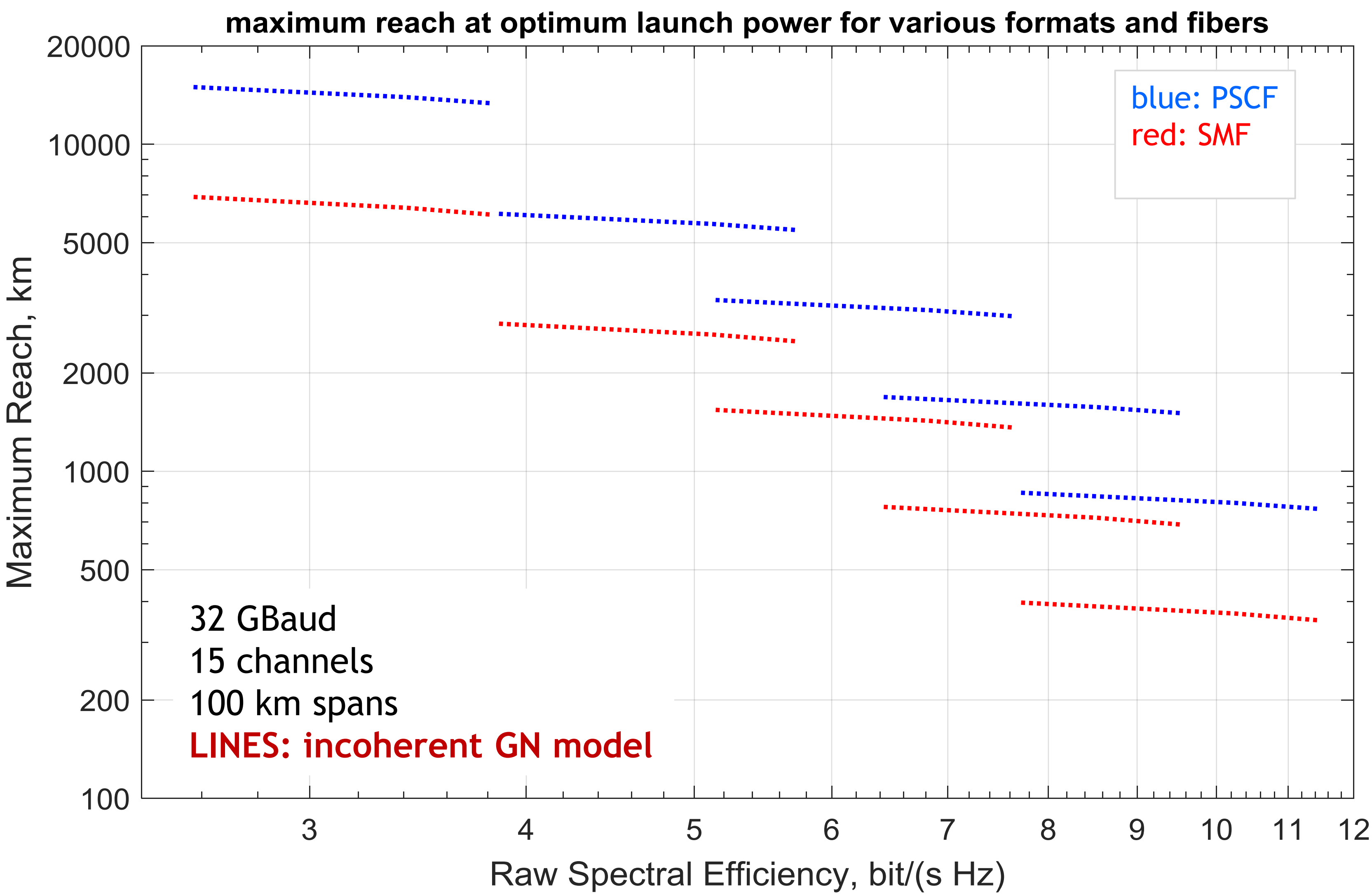


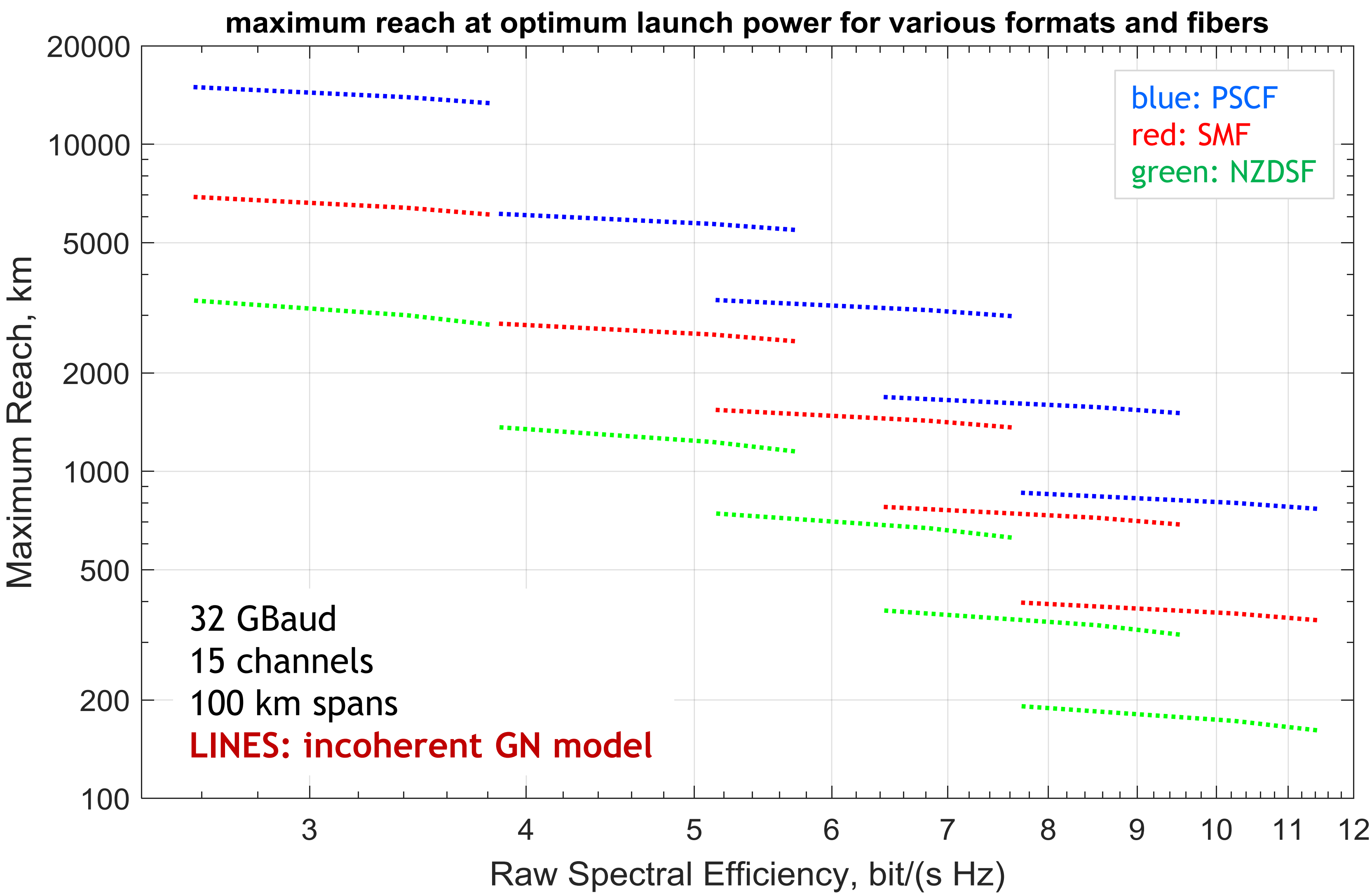
The big picture



The big picture



The big picture

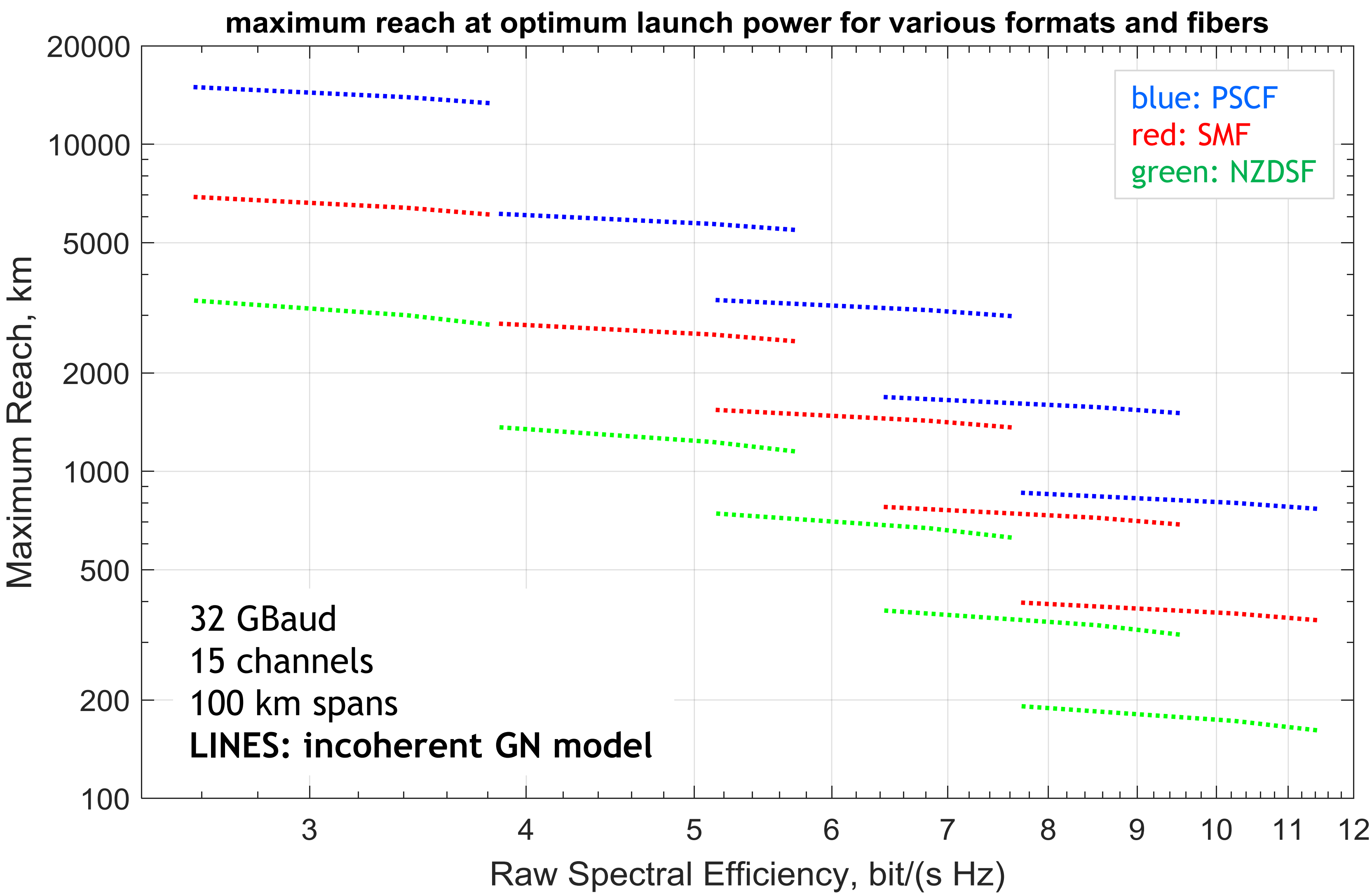


Fiber data

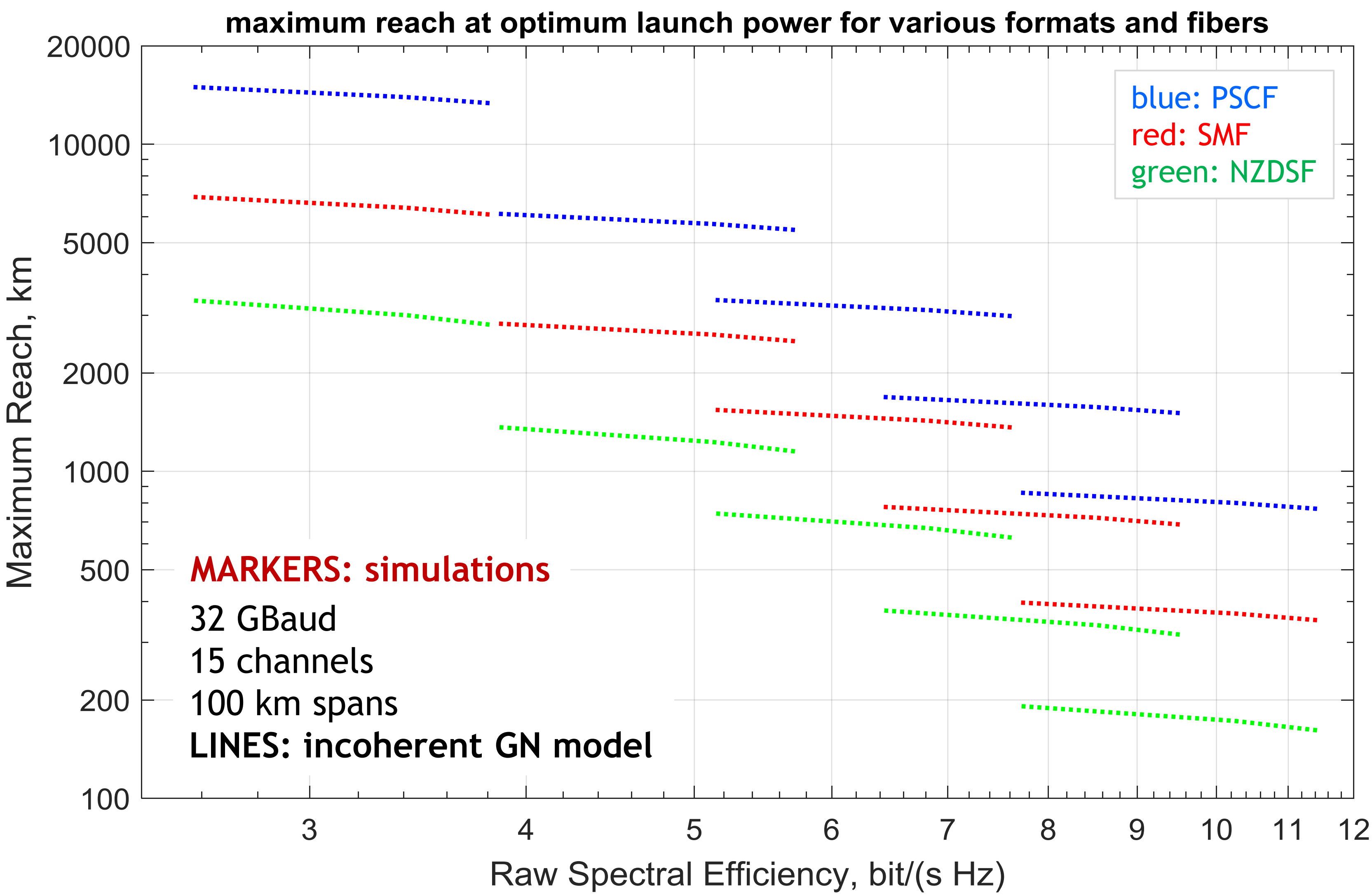
	dispersion D ps/(nm km)	loss α dB/km	non-linearity γ 1/(W km)
PSCF	20.1	0.17	0.8
SMF	16.7	0.2	1.3
NZDSF (E-LEAF)	3.8	0.22	1.5

The big picture

OPTCOM

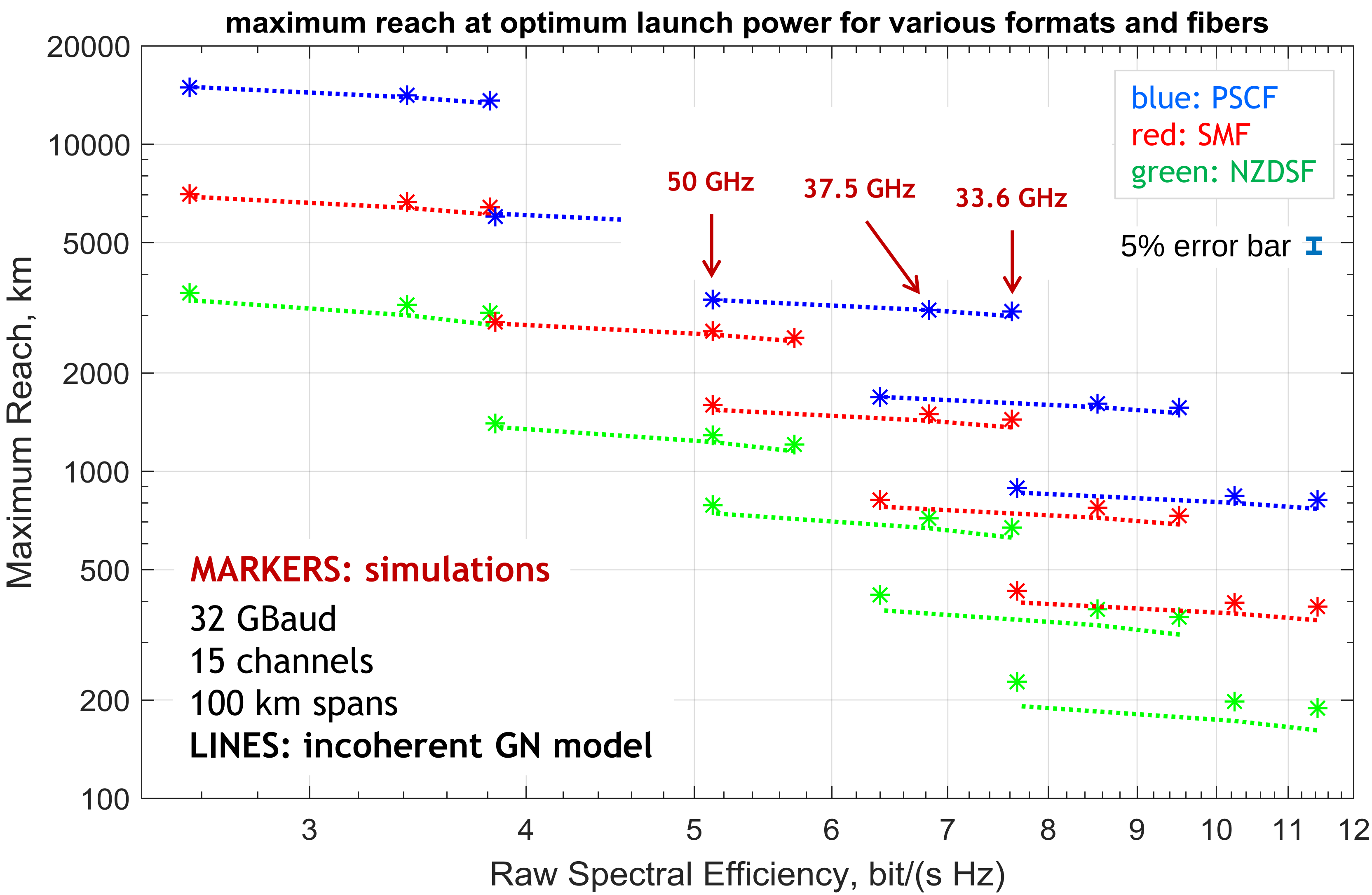


The big picture



The big picture

OPTCOM



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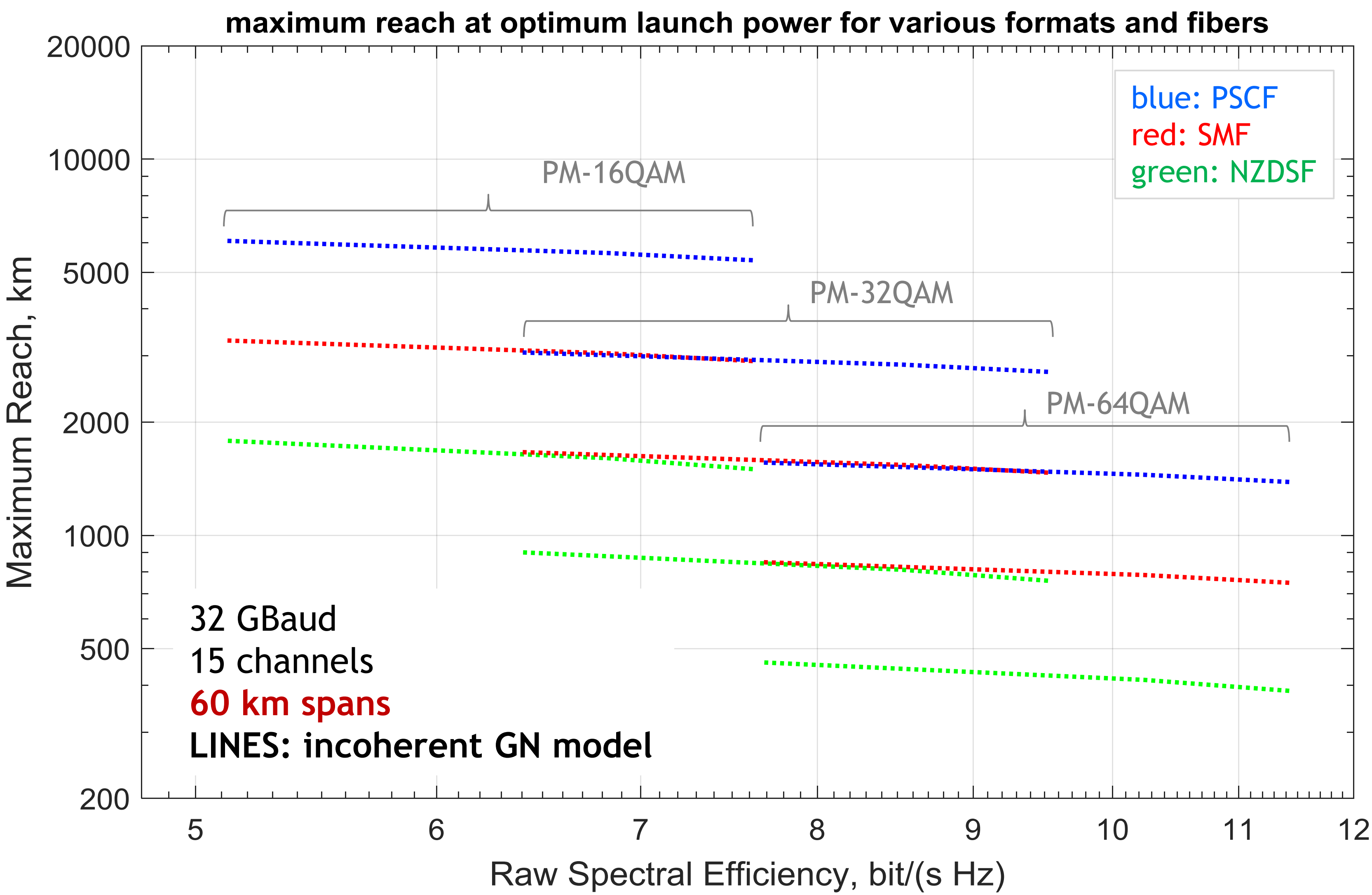
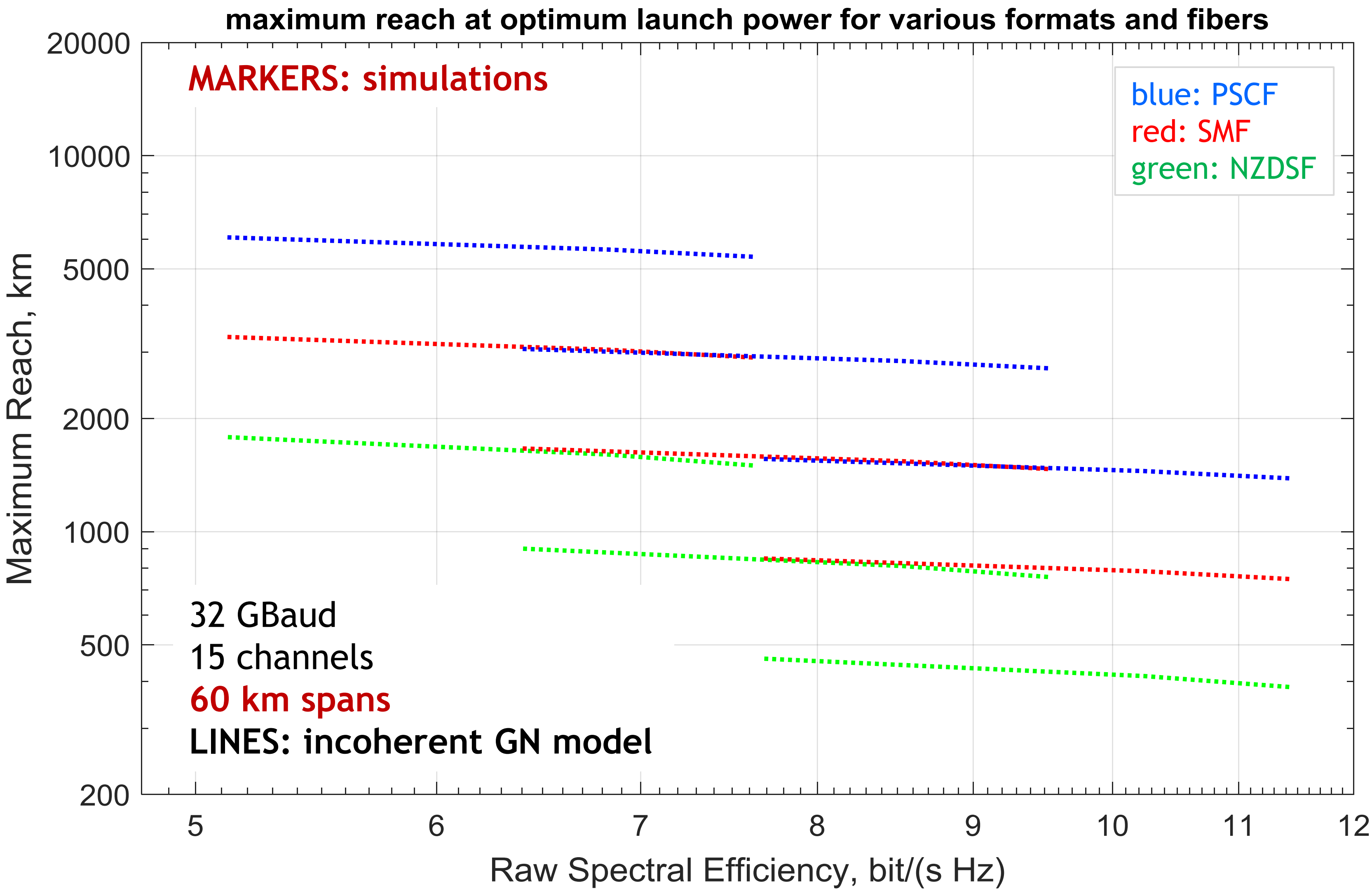


The big picture



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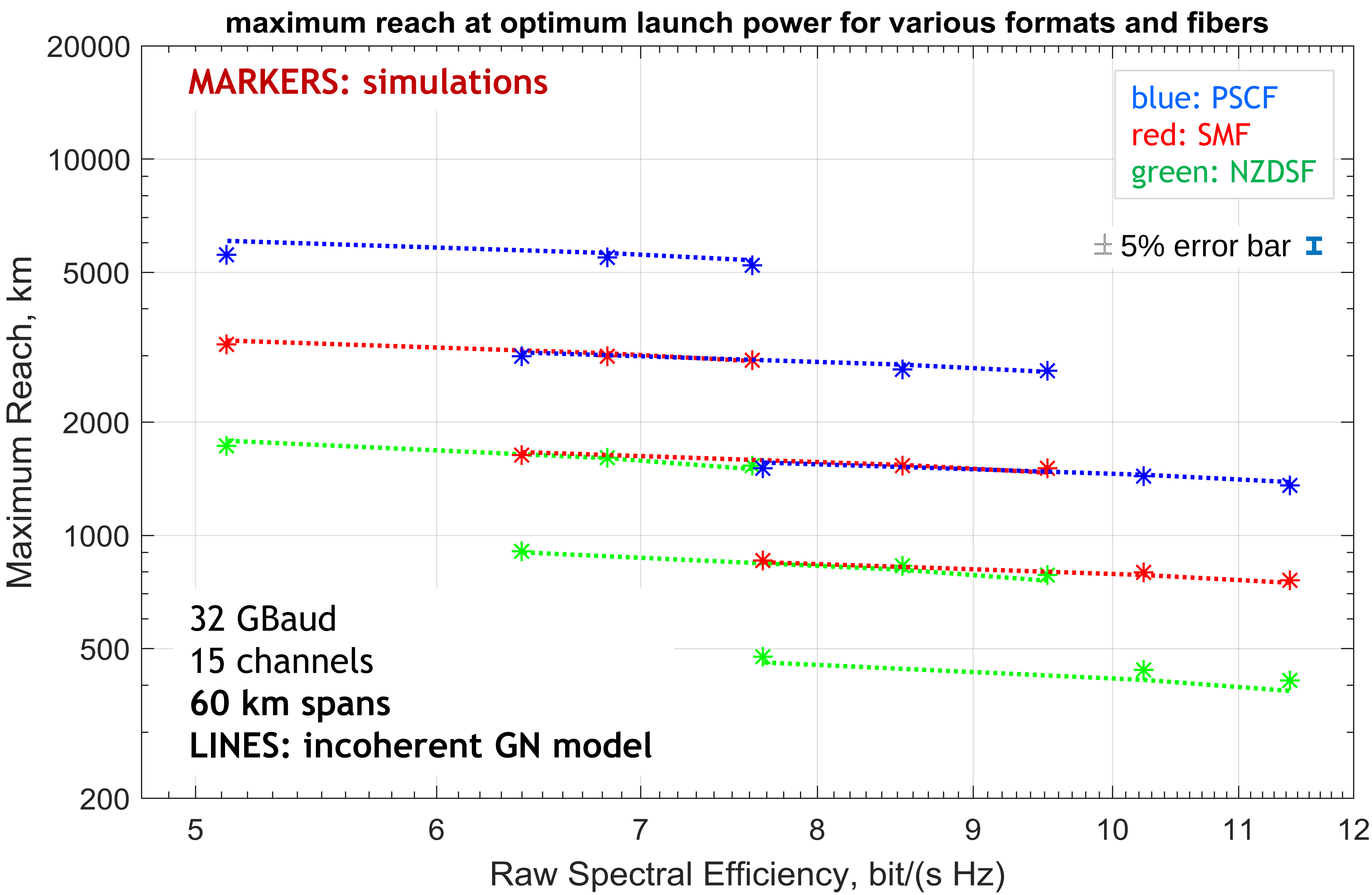


Caveats

- 15 channels is a limited number
- Going to a higher number, max reach estimation becomes more pessimistic
- You may expect a 5%-10% underestimation of max reach for fully-loaded systems

credit: https://www.koozai.com/blog/analytics/predictive-analytics-and-digital-campaigns/

The *incoherent* GNRF…

$$G_{\mathrm{NLI}}(f) = N_s \frac{16}{27} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G_{\mathrm{WDM}}(f_1) G_{\mathrm{WDM}}(f_2) G_{\mathrm{WDM}}(f_1+f_2-f) \cdot$$

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

if span loss is greater than 10-12 dB this term can be neglected

The simplest *incoherent* GNRF…

$$G_{\text{NLI}}(f) = N_s \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\text{WDM}}(f_1) G_{\text{WDM}}(f_2) G_{\text{WDM}}(f_1 + f_2 - f) \cdot$$

$$\cdot \frac{\gamma^2 L_{\text{eff}}^2}{1 + 4\pi^4 \beta_2^2 \alpha^{-2} (f_1 - f)^2 (f_2 - f)^2} \, \mathrm{d}f_1 \mathrm{d}f_2$$

- *it can be integrated analytically !*
  (with some approximations)

The simplest *incoherent* GNRF…

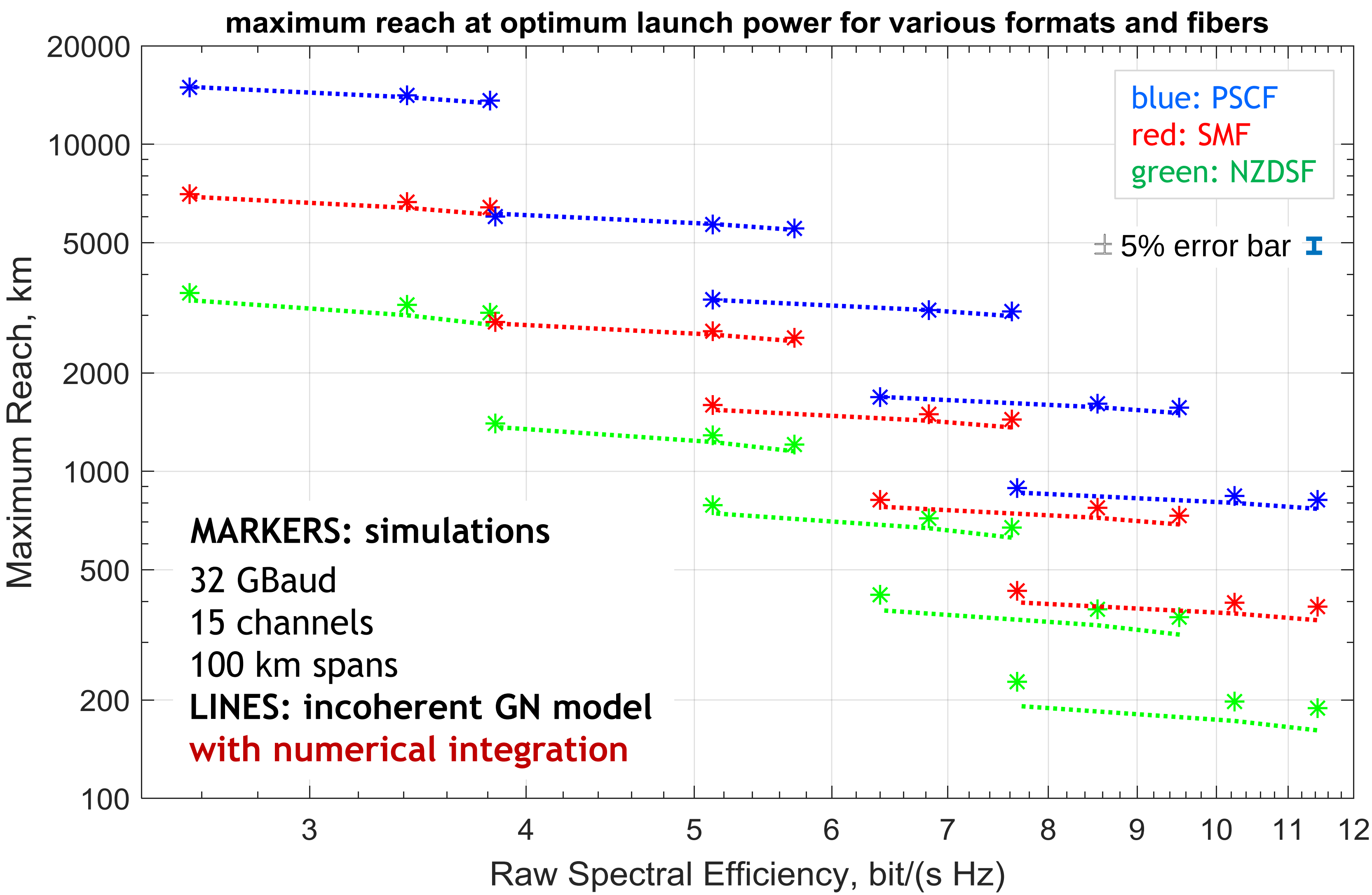
OPTCOM

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

P. Poggiolini "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *J. of Lightwave Technol.*, vol. 30, no. 24, pp. 3857-3879, Dec. 15 2012.

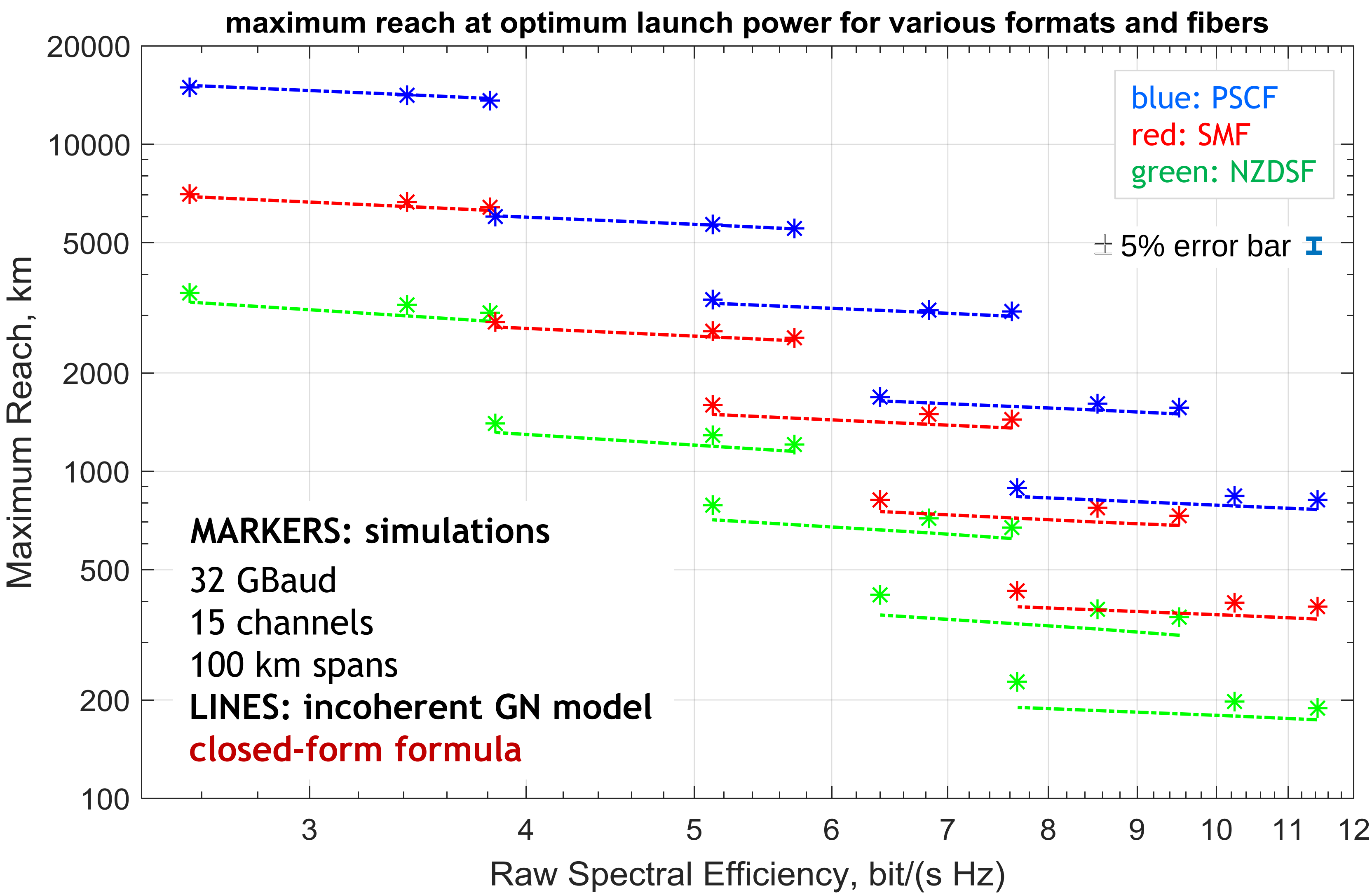
- Other versions address non-uniform spans and all-different channels:
  - P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, F. Forghieri, 'The GN model of fiber non-linear propagation and its applications,' *J. of Lightw.Technol.*, vol. 32, no. 4, pp. 694-721, Feb. 2014.
  - P. Johannisson and M. Karlsson, "Perturbation analysis of nonlinear propagation in a strongly dispersive optical communication system," *J. Lightw. Technol.*, vol. 31, no. 8, pp. 1273–1282, Apr. 15, 2013.

The big picture

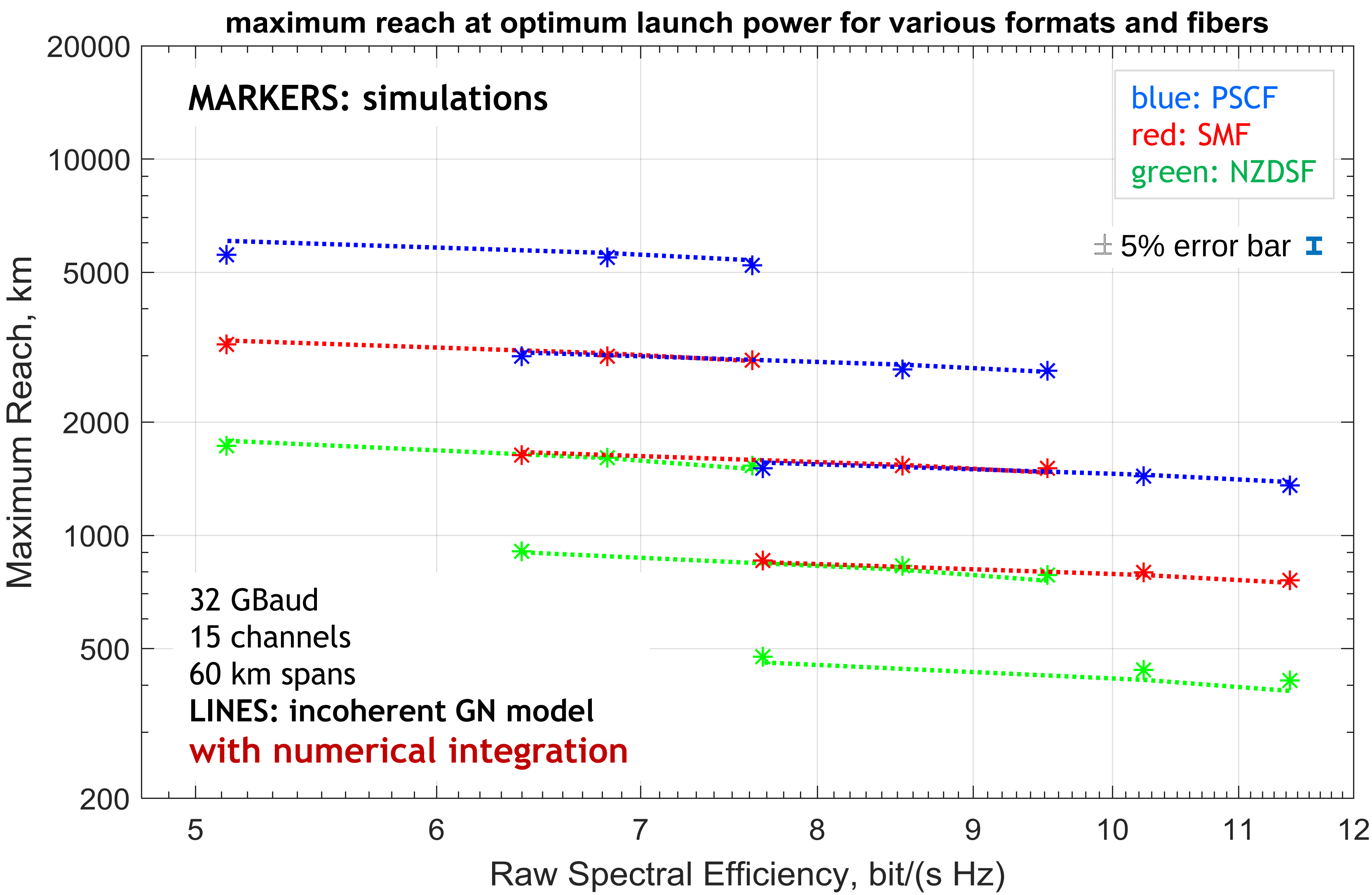


The big picture

OPTCOM



The big picture



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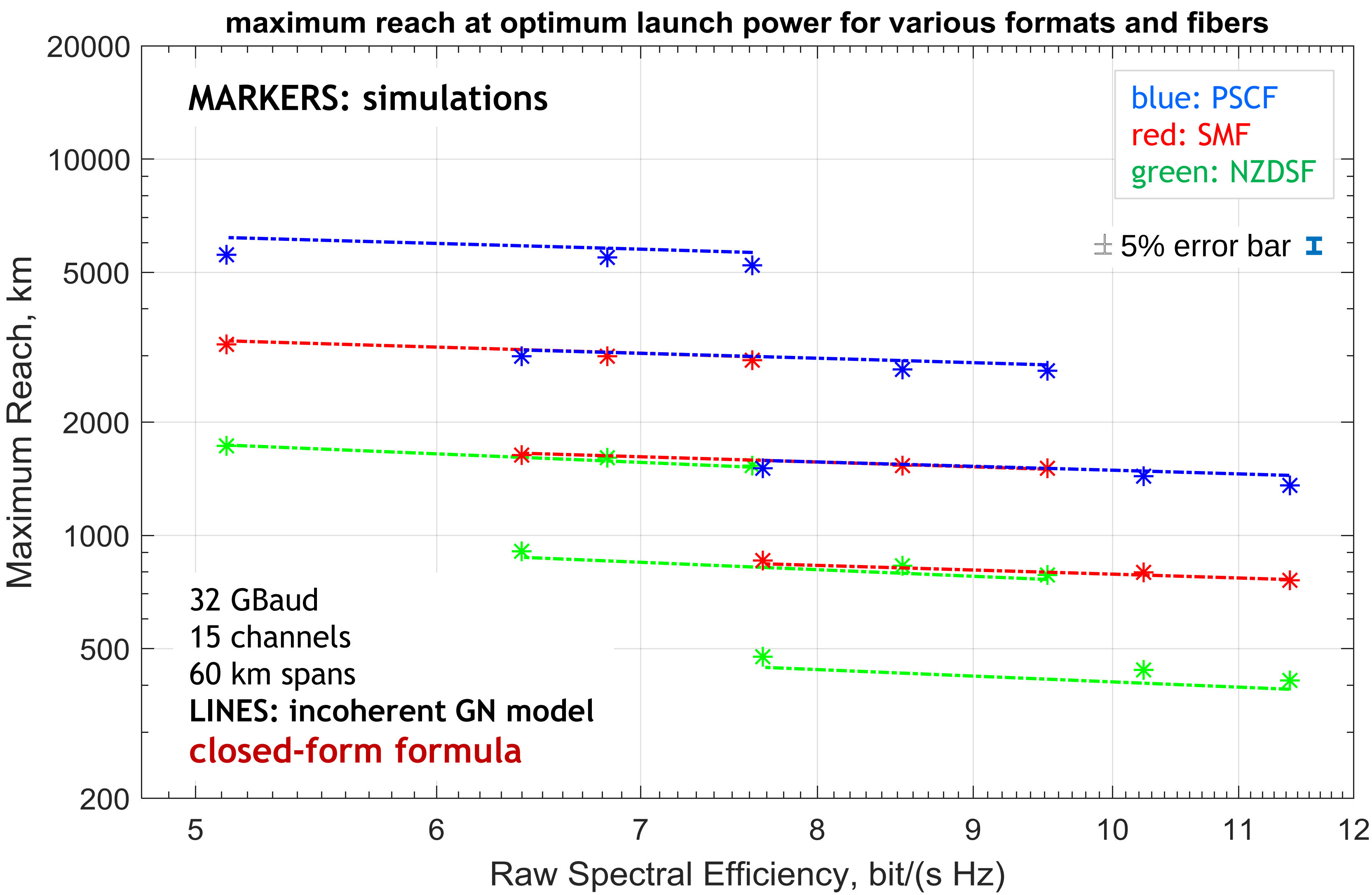


The simplest *incoherent* GNRF…

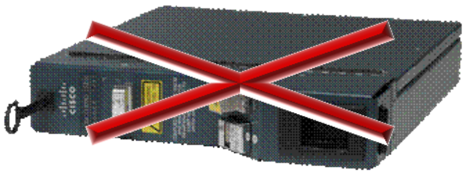
$$P_{\mathrm{NLI}} = N_s \frac{16}{27} \frac{\gamma^2 L_{\mathrm{eff}}^2 P_{\mathrm{ch}}^3}{\pi |\beta_2| \alpha R^2} \operatorname{asinh}\left(\frac{\pi^2}{2\alpha} |\beta_2| R^2 \left[N_{\mathrm{ch}}^2 \right]^{\frac{R_s}{\Delta f}} \right)$$

Various restrictions apply, do not use:

- below 20 GBaud
- below D=3 ps/(nm km)
- with span loss less than 10-12 dB

a bit of retrospection

- About 2007-2008 it finally became clear that the coherent revolution would definitely take place
- Surprisingly, the optimum scenario turned out to be that of no dispersion compensation !
  - that was new and uncharted territory



credit: http://www.cisco.com/c/en/us/products/collateral/optical-networking/ons-15200-series-dwdm-systems/datasheet_c78-728877.html

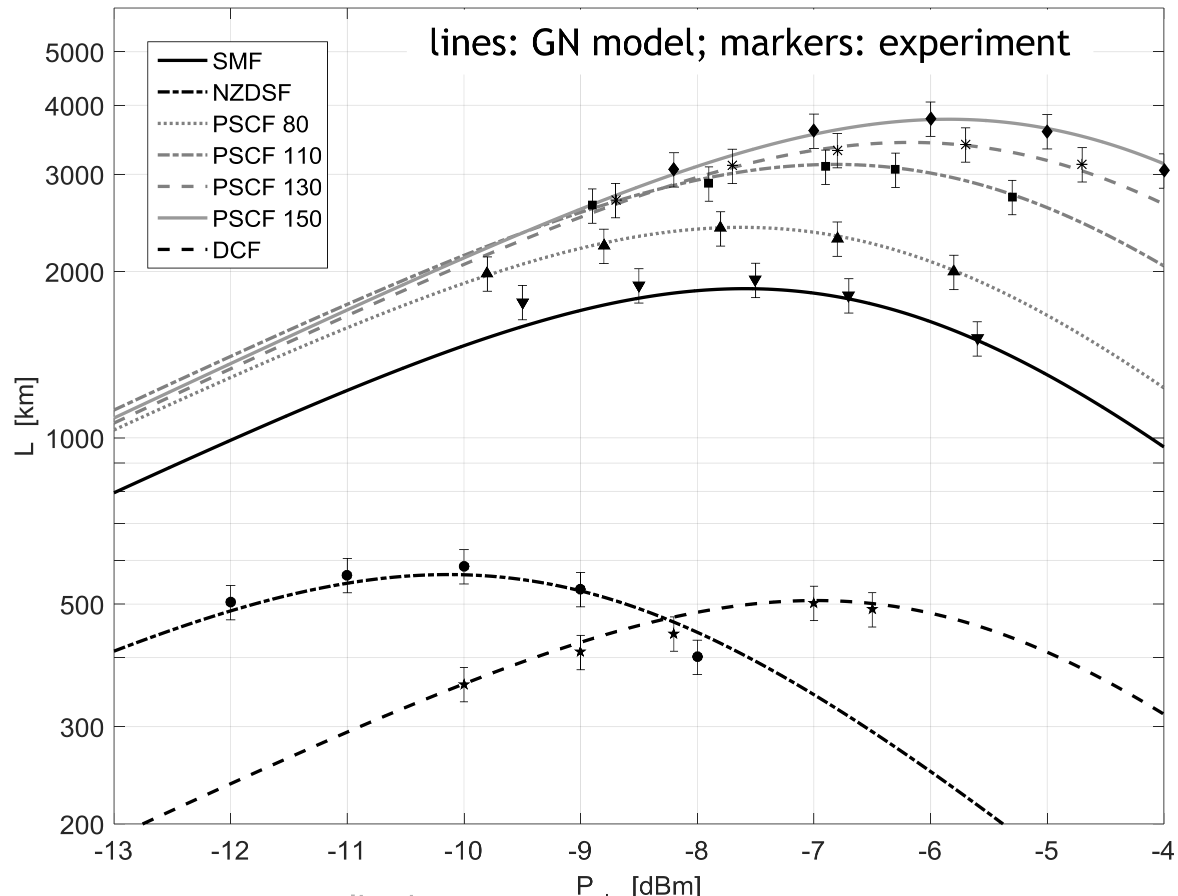
- Of course split step simulations were possible, but (especially then) with limited effectiveness
- Some system modeling *guidance* was needed to make sense of this new situation
  - a *practical and manageable* tool was necessary
  - *accuracy should be good* (though perfection not required)

credit: http://travel-representatives.com/

The seven fiber experiment

- Validation experiments are relatively few
- One comprehensive attempt used 7 different fibers with PM-16QAM
  A. Nespola, S. Straullu, A. Carena, G. Bosco, R. Cigliutti, V. Curri, P. Poggiolini, M. Hirano, Y. Yamamoto, T. Sasaki, J. Bauwelinck, K. Verheyen, and F. Forghieri, 'GN-model validation over seven fiber types in uncompensated PM-16QAM Nyquist-WDM links,' *IEEE Photon. Technol. Lett.*, vol. 26, no. 2, pp. 206-209, Jan. 2014

- Within the limitations of experimental uncertainties, it actually found quite good agreement
- In general, **more model validation experiments would be very welcome !!**



Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- Over a wide-range of *conventional* system scenarios, at 32 GBaud, *the incoherent GN model* provides a favorable accuracy-vs.-complexity trade-off

- This makes it particularly well-suited for real-time physical-layer awareness for network management

Problem solved?

https://www.flickr.com/photos/wingedwolf/5471047557 http://www.improfestuk.co.uk/2014/problem-solved.html

credit: http://www.improfestuk.co.uk/2014/problem-solved.html

credit: https://www.flickr.com/photos/wingedwolf/5471047557

credit: http://www.improfestuk.co.uk/2014/problem-solved.html

well, not quite… !

Several limitations…

- The (incoherent) GN model does not work well:
  - at low symbol rates (< 10 - 16 GBaud)
  - with close-to-ideal distributed amplification
  - over short links
  - etc.

- It does not allow to study:
  - pre-dispersion
  - the effect of low symbol rates on NLI generation
  - the “finer” effects of formats on NLI generation
  - etc.

A strange paradox…

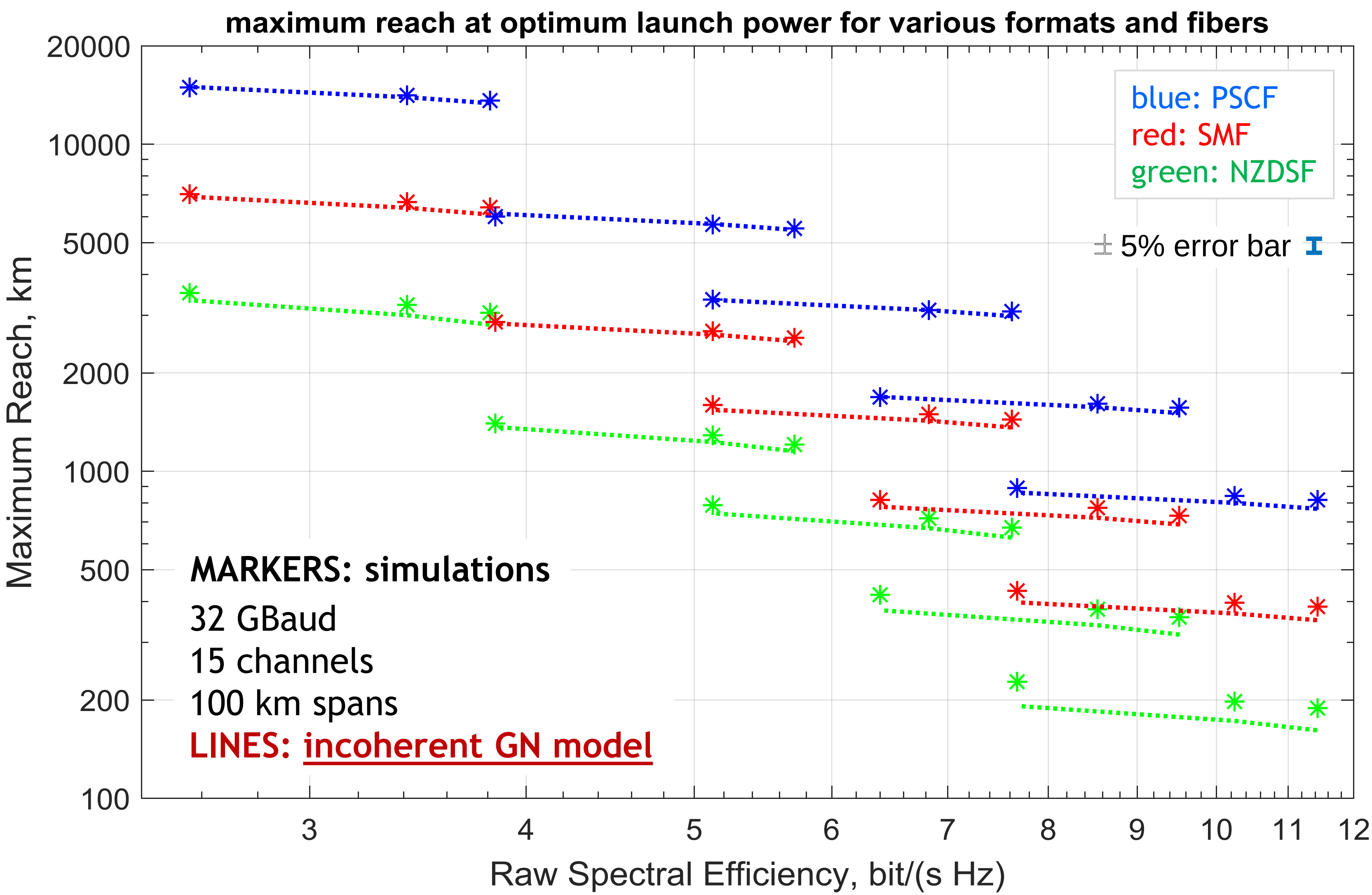
$$G_{\mathrm{NLI}}(f)=\frac{16}{27}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_{\mathrm{WDM}}(f_1)G_{\mathrm{WDM}}(f_2)G_{\mathrm{WDM}}(f_1+f_2-f)\cdot$$

$$\cdot\left|\mu(f_1,f_2,f)\right|^2\,\mathrm{d}f_1\mathrm{d}f_2$$

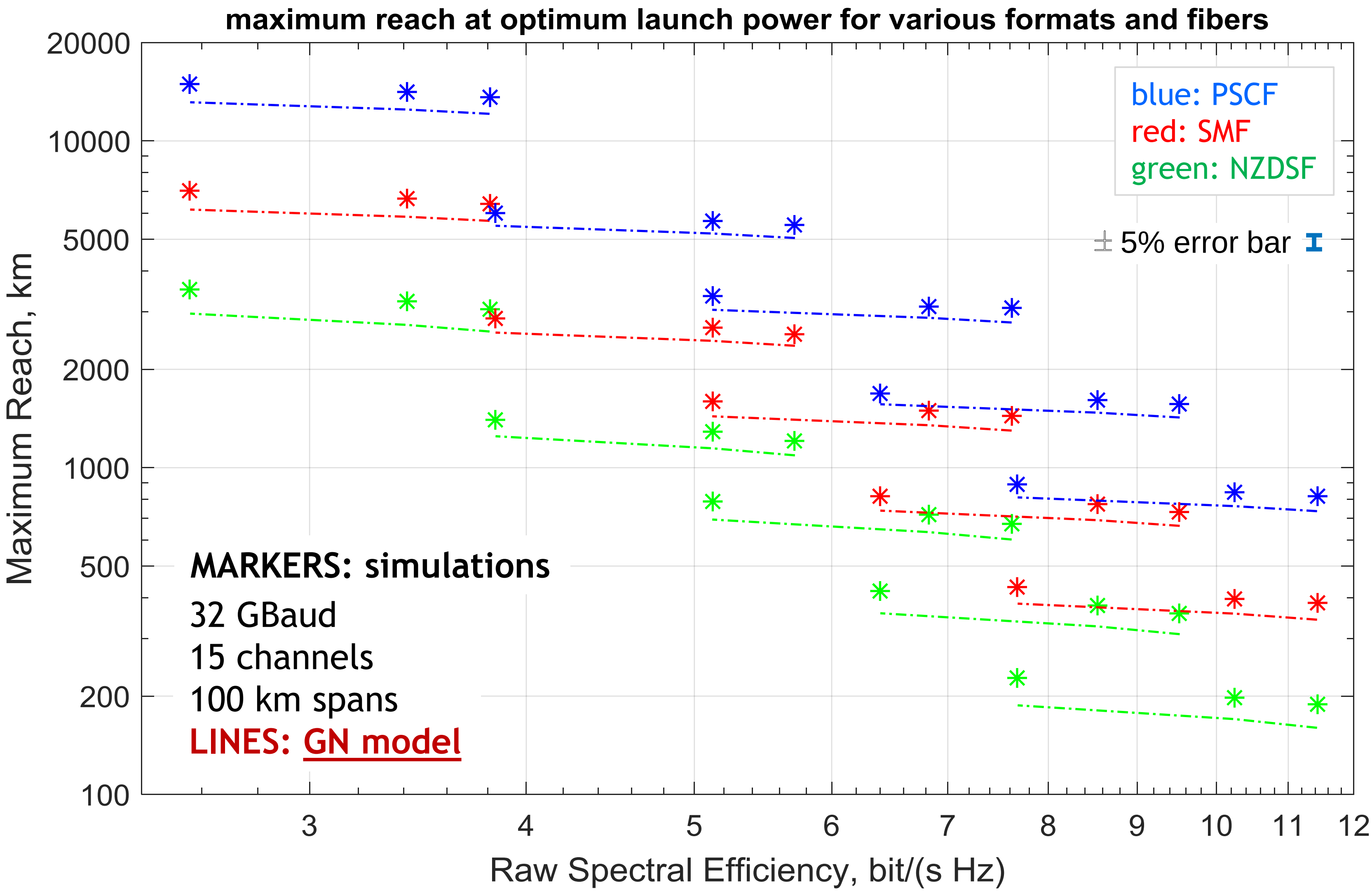
for <u>identical spans</u> with lumped amplification:

$$\gamma^2L_{\mathrm{eff}}^2\left|\frac{1-e^{-2\alpha L_s}e^{j4\pi^2\beta_2L_s(f_1-f)(f_2-f)}}{1-j2\pi^2\beta_2\alpha^{-1}(f_1-f)(f_2-f)}\right|^2\cdot\frac{\sin^2\left(2N_s\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}$$

The big picture



The big picture



the paradox

- The GN model uses one *fewer* approximation than the *incoherent* GN model

- *and yet it is less accurate… Why ?*

- A detailed, in-depth investigation of these models was necessary

- To do that, ***the right "probe"*** was needed

  - maximum reach is the end-user most relevant quantity…

  - …but *unfortunately it is not "sensitive" enough* for in-depth modeling studies

max reach vs. P_{NLI} errors

- How sensitive is max-reach, to NLI estimation errors?

$$\Delta L_{\text{max,dB}} \approx -\frac{1}{3}\Delta P_{\text{NLI,dB}}$$

- 1 dB NLI error → 8% max reach error
- 3 dB NLI error → 26% max reach error

- Also, looking at max reach we only test the model “at max reach” but do know not if it is accurate elsewhere along the link

The right "probe"

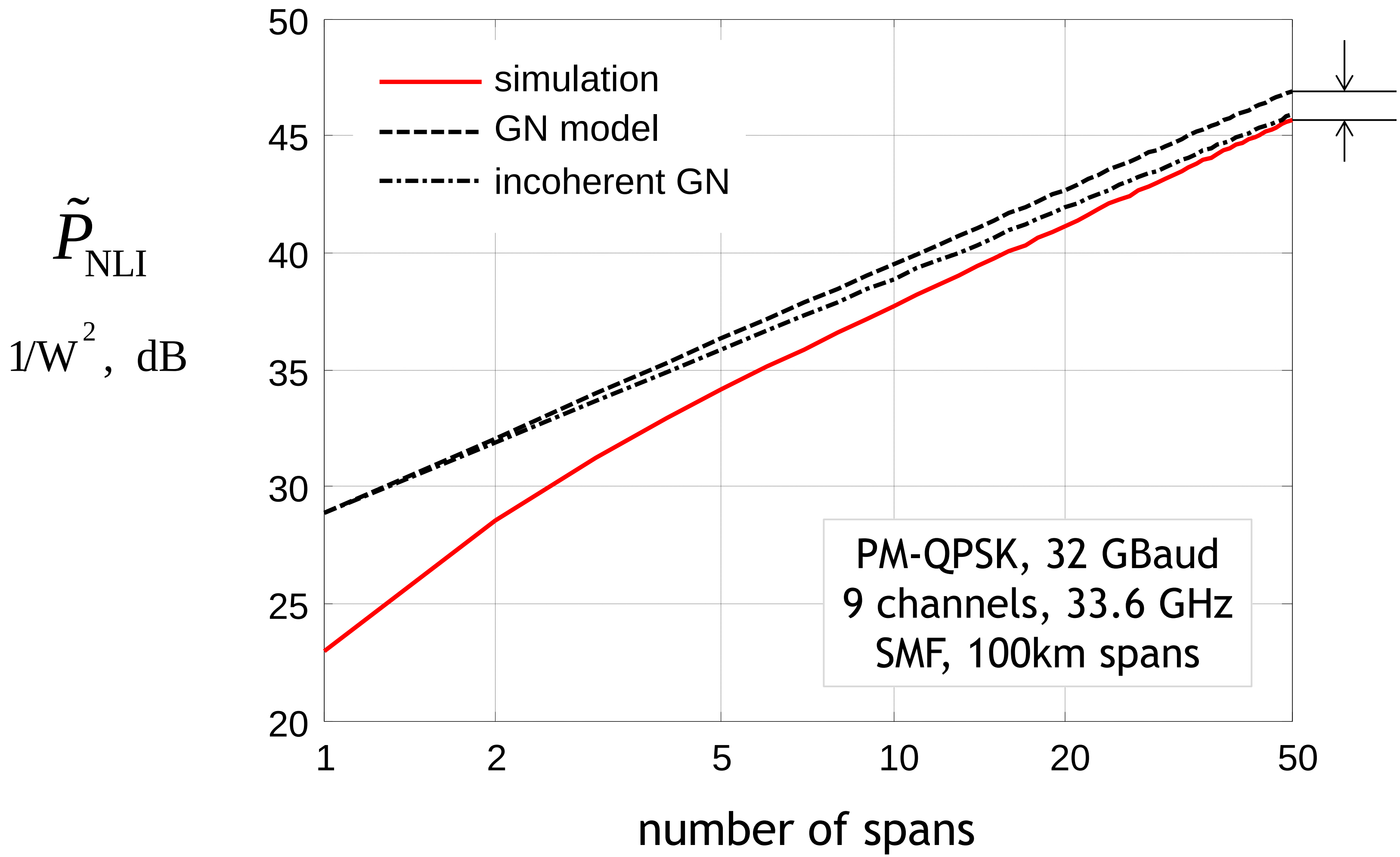
- *The right thing to look at is span-by-span NLI:*

$$P_{\mathrm{NLI}}\left(n_{\mathrm{span}}\right)$$

- To have a <u>launch-power-independent</u> quantity you can normalize it:

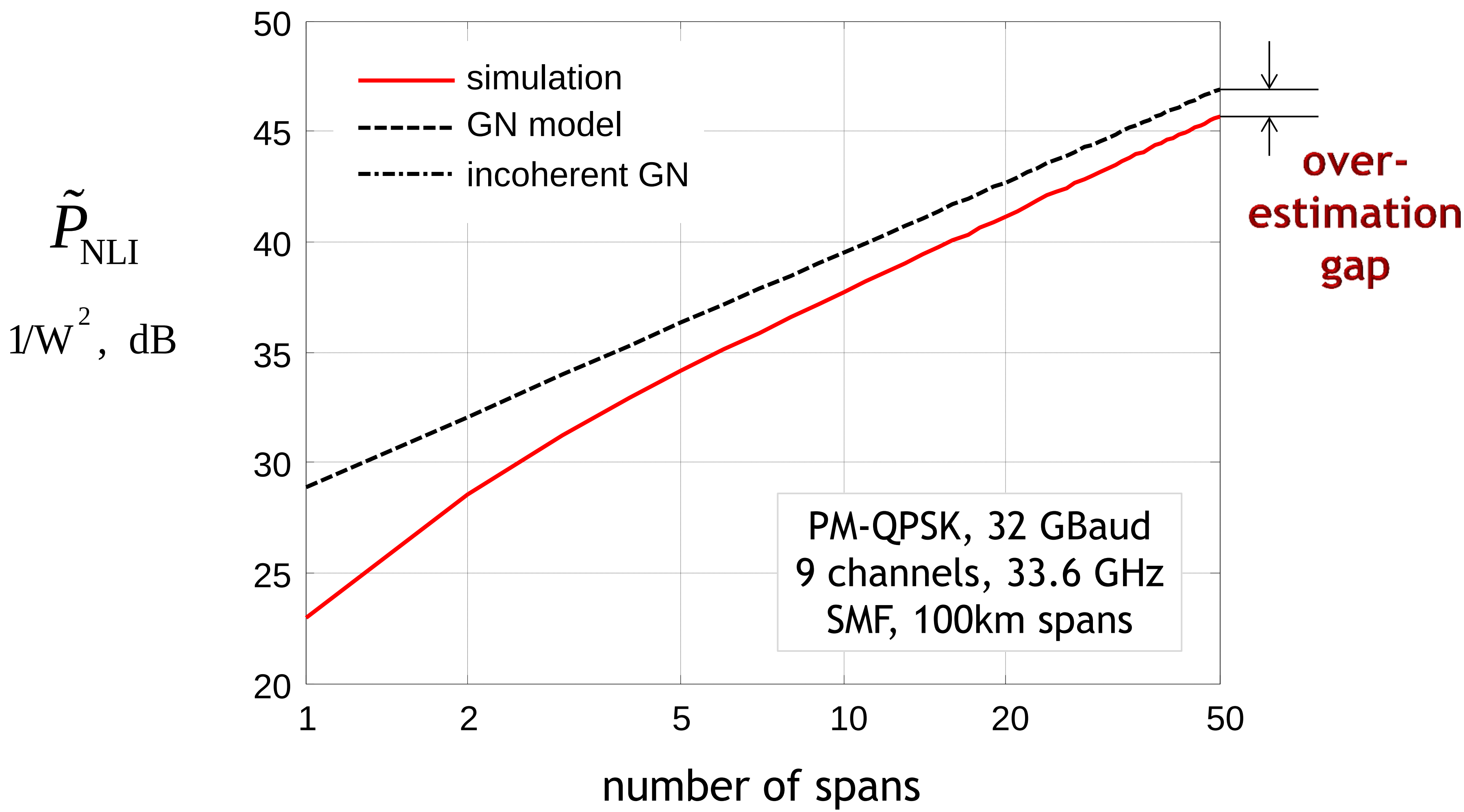
$$\boxed{\tilde{P}_{\mathrm{NLI}} = P_{\mathrm{NLI}} / P_{\mathrm{ch}}^{3}}$$

NLI accumulation study



Carena, G. Bosco, V. Curri, P. Poggiolini, and F. Forghieri, 'Impact of the transmitted signal initial dispersion transient on the accuracy of the GN-model of non-linear propagation,' **Proc. of ECOC 2013**, paper Th.1.D.4, London (UK), Sept. 2013.

NLI accumulation study



Carena, G. Bosco, V. Curri, P. Poggiolini, and F. Forghieri, 'Impact of the transmitted signal initial dispersion transient on the accuracy of the GN-model of non-linear propagation,' **Proc. of ECOC 2013**, paper Th.1.D.4, London (UK), Sept. 2013.

Towards a more sophisticated model

- It is possible to remove the GN model “overestimation gap” by “correcting” the signal Gaussianity assumption

- Put it shortly, the GN model considers just the “second moment” of the launched signal

- If higher moments (4^{th} and 6^{th}) are taken into account, then *the GN model tendency to NLI overestimation can be completely removed*

Towards a more sophisticated model

- *The inclusion of the 4th moment was worked out and published, for the XPM contribution to NLI:*

R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, 'Properties of nonlinear noise in long, dispersion-uncompensated fiber links,' *Optics Express*, vol.21, no.22, pp.25685-25699, Nov. 2013.

- We then completed the new model deriving all contributions, including FWM and SPM:

Carena A, Bosco G, Curri V, Jiang Y, Poggiolini P, Forghieri F. 'EGN model of non-linear fiber propagation,' *Optics Express*, vol. 22, no. 13, pp.16335-16362, June 2014. Extended appendices version on www.arXiv.org

EGN-model

the EGN-model family tree

R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, *OE*, vol.21, pp.25685, Nov. 2013.

A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini, F. Forghieri, *OE*, vol. 22, pp.16335, June 2014.

R. Dar, M. Feder, A. Mecozzi, M. Shtaif, *OE*, vol. 22, p. 14199, 2014

P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, F. Forghieri, *JLT*, vol. 33, p. 459, 2015.

R. Dar, M. Feder, A. Mecozzi, M. Shtaif, *JLT*, vol. 33, p. 1044, 2015

P. Serena, A. Bononi, *JLT*, vol. 33, p. 1459, 2015

R. Dar, M. Feder, A. Mecozzi, M. Shtaif, *JLT*, vol. 34, p. 593, 2016

P. Serena, *JLT*, vol. 34, p. 1476, 2016

The EGN model

- *EGN model* stands for "enhanced GN model"

- The EGN model consists of the GN model and of a "correction" term:

$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f) - G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

- *For PM-QAM systems the "correction" always <u>decreases</u> NLI*
  - <u>this shows the GN-model to be some sort of "upper bound" to NLI</u>

The EGN model

- *If the constellation is Gaussian,* then

$$G_{\text{NLI}}^{\text{EGN}}(f) = G_{\text{NLI}}^{\text{GN}}(f) - \cancel{G_{\text{NLI}}^{\text{corr}}(f)}$$

- This might have interesting implications for probabilistic shaping

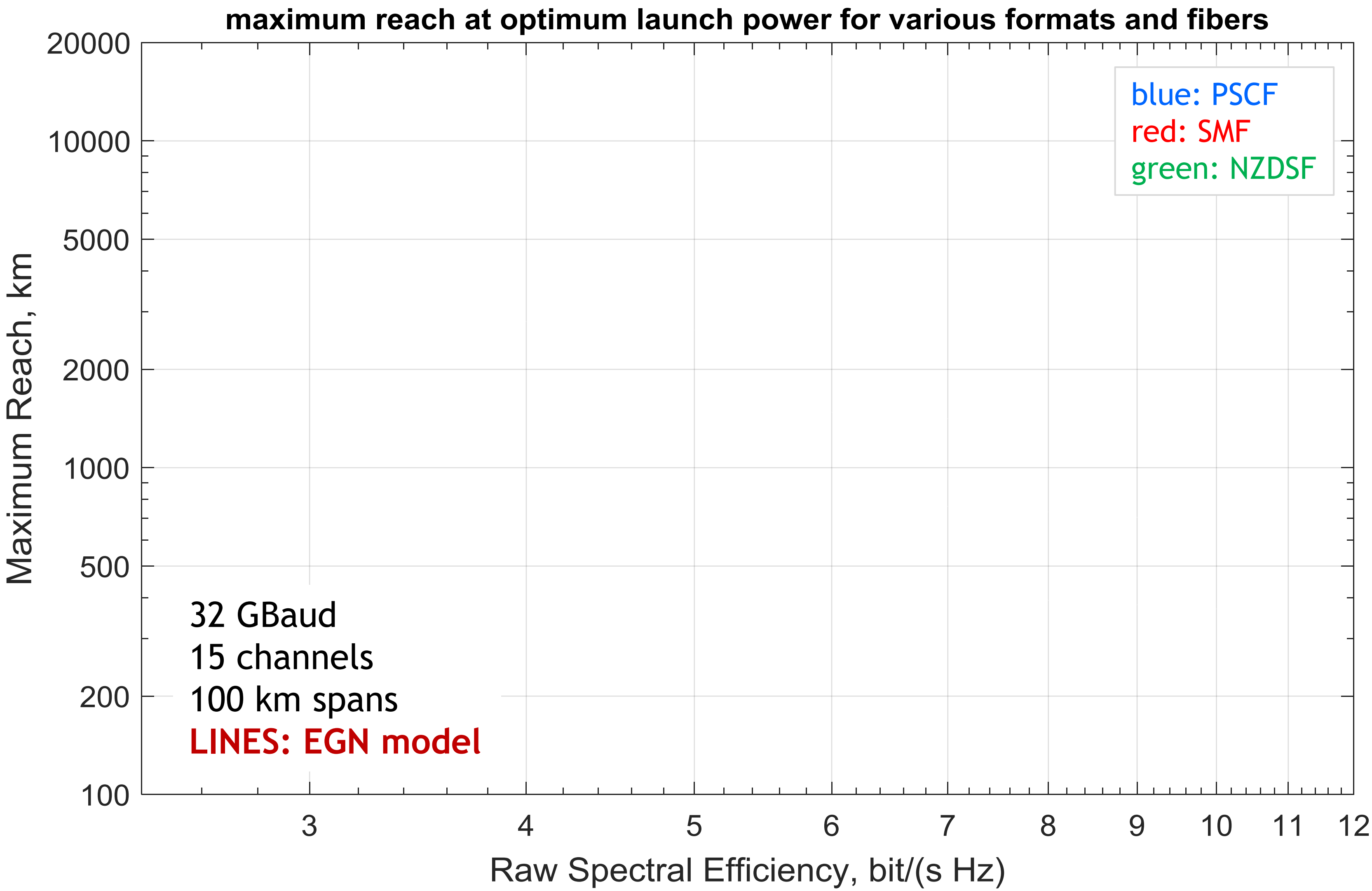
$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f) - G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

performance first...

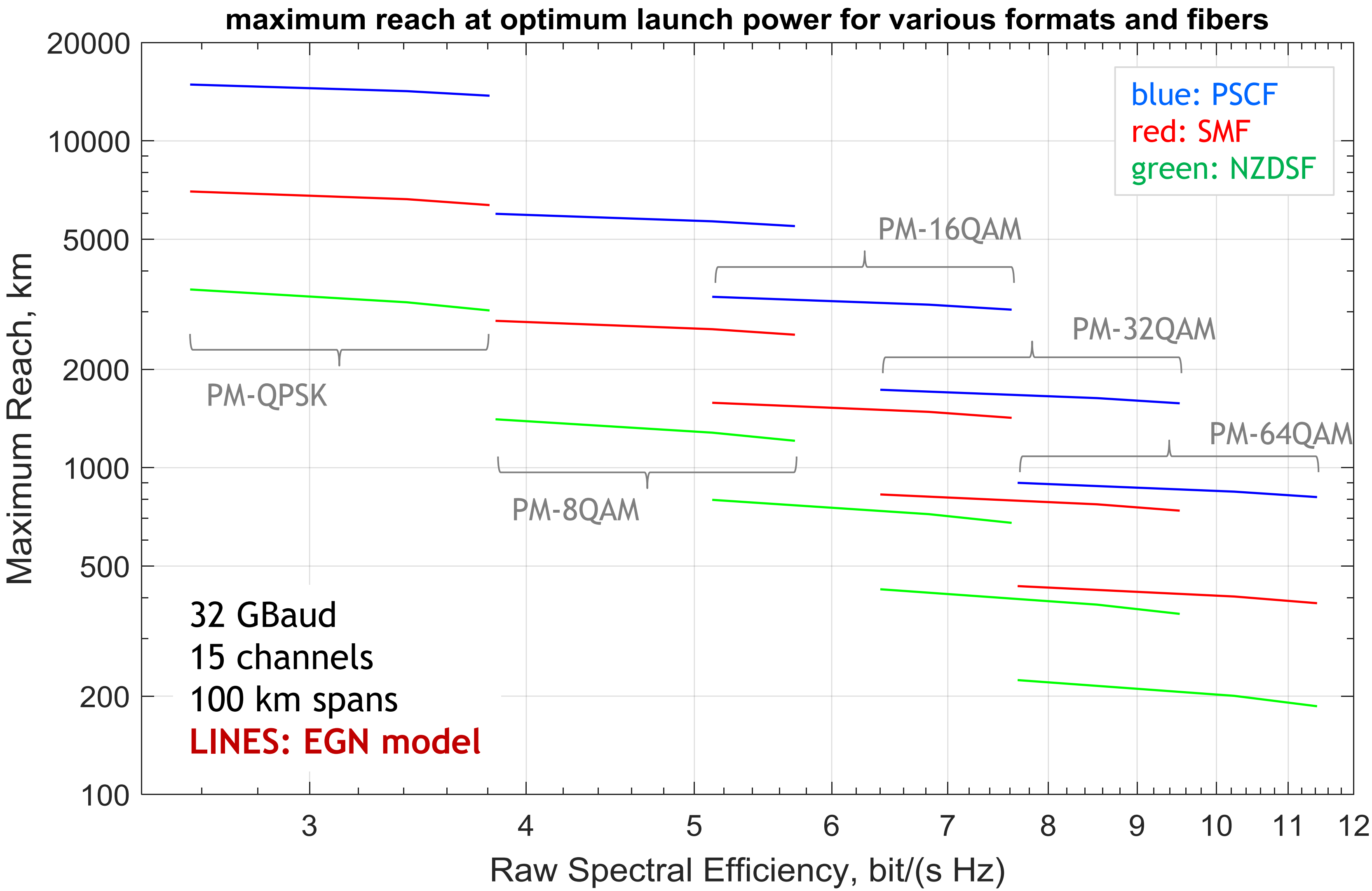
credit: http://www.dtvisiontech.com/2015_12_01_archive.html

The big picture

OPTCOM

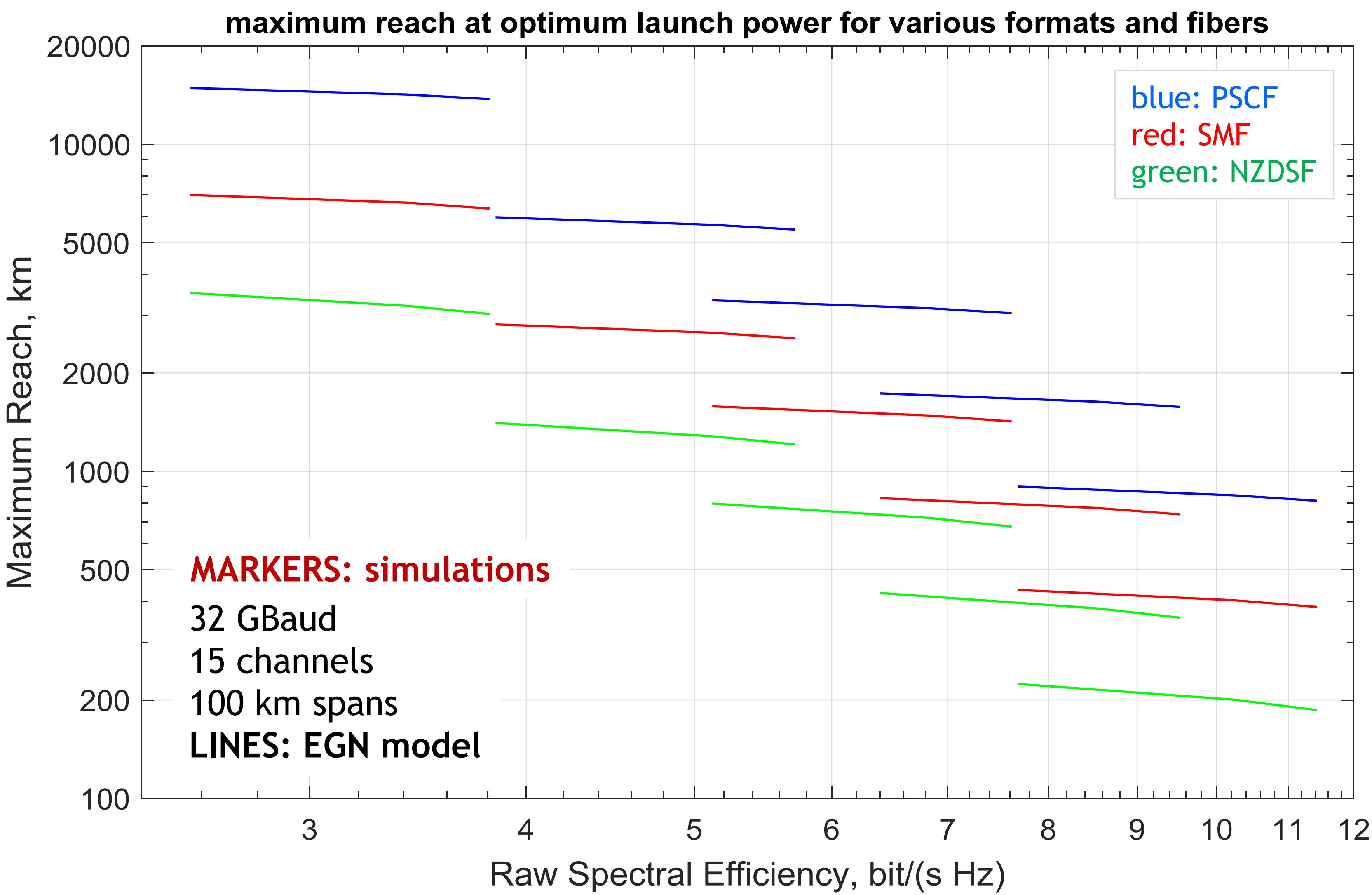


The big picture

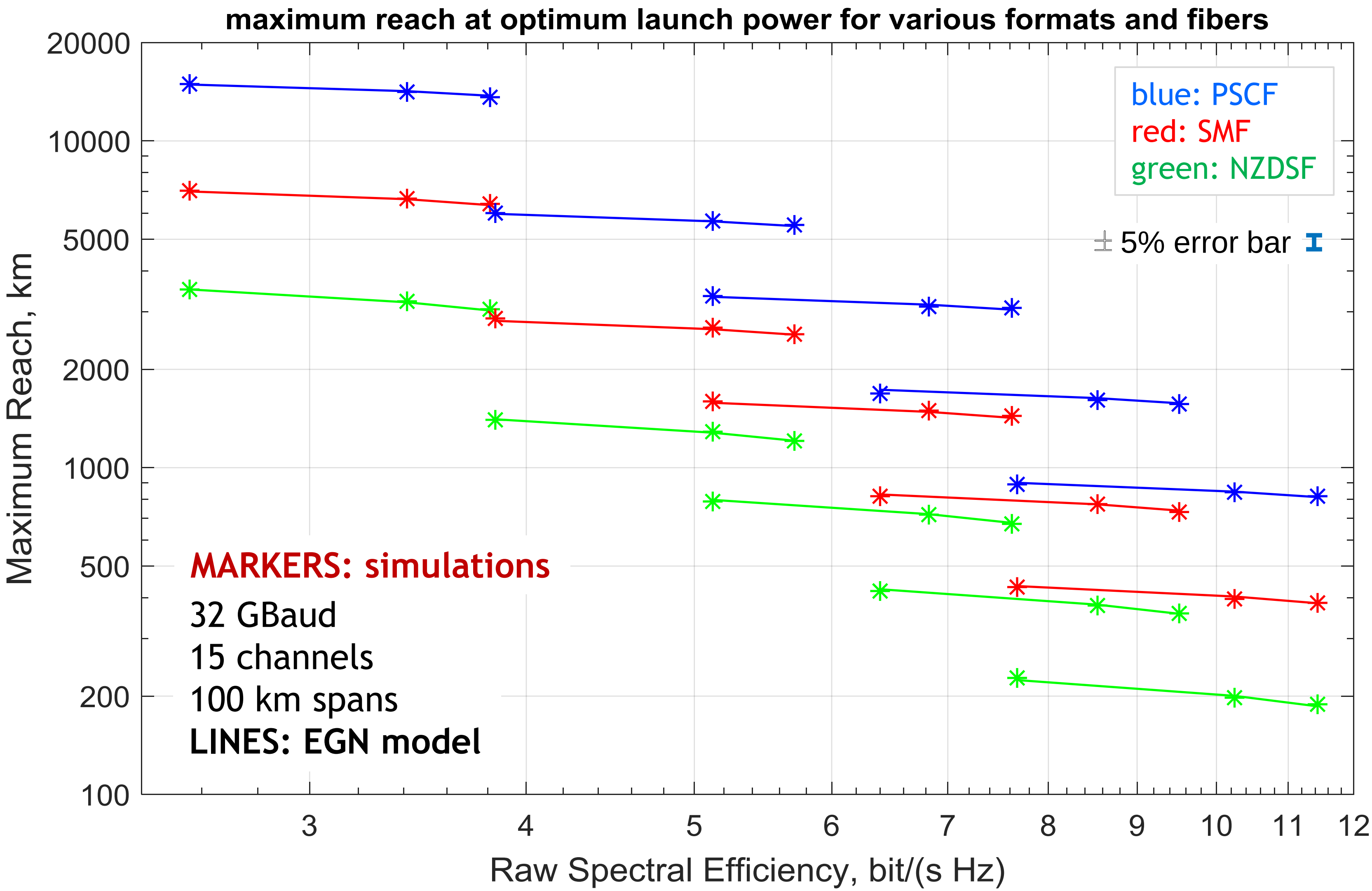


The big picture

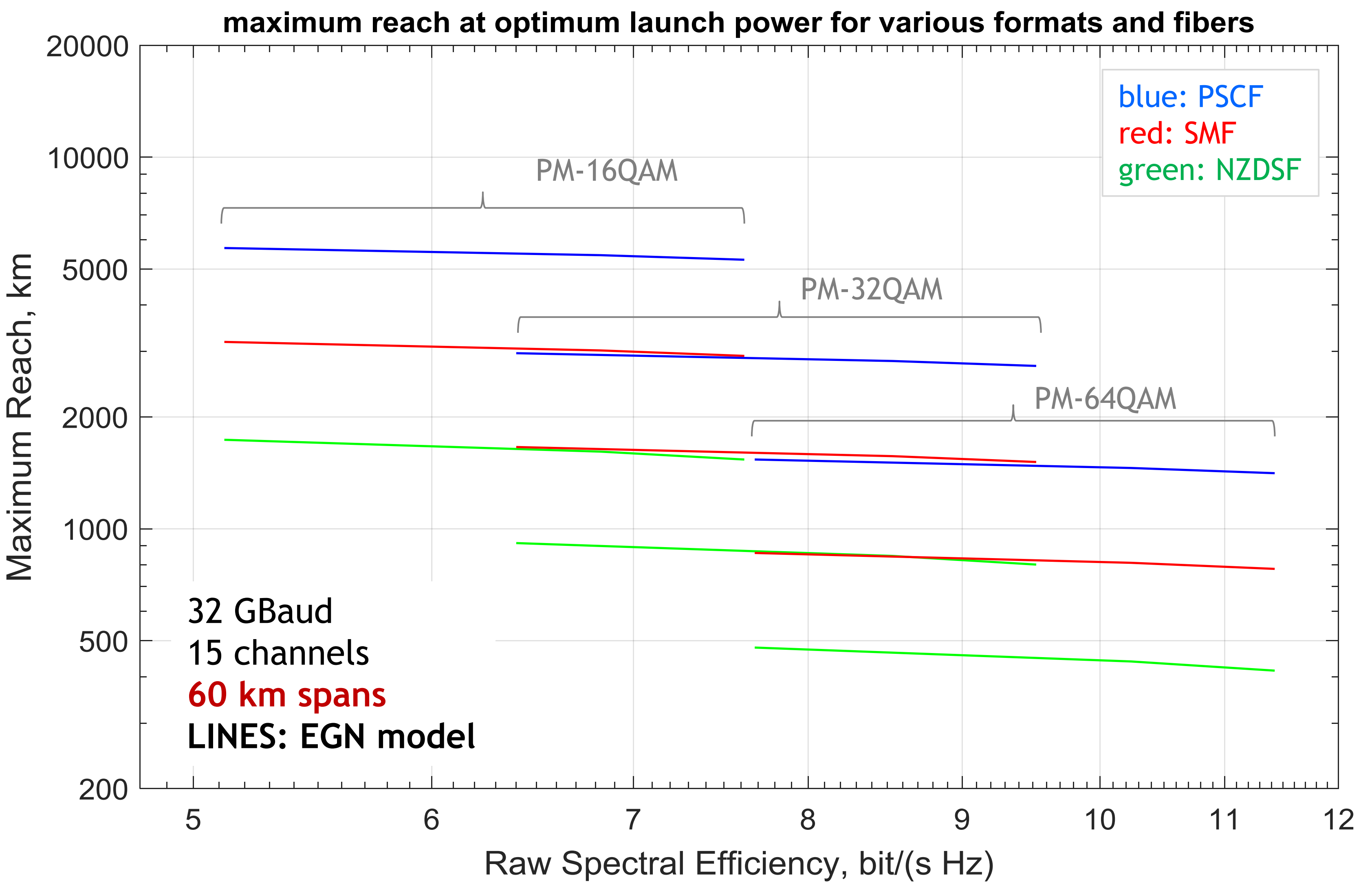
OPTCOM



The big picture

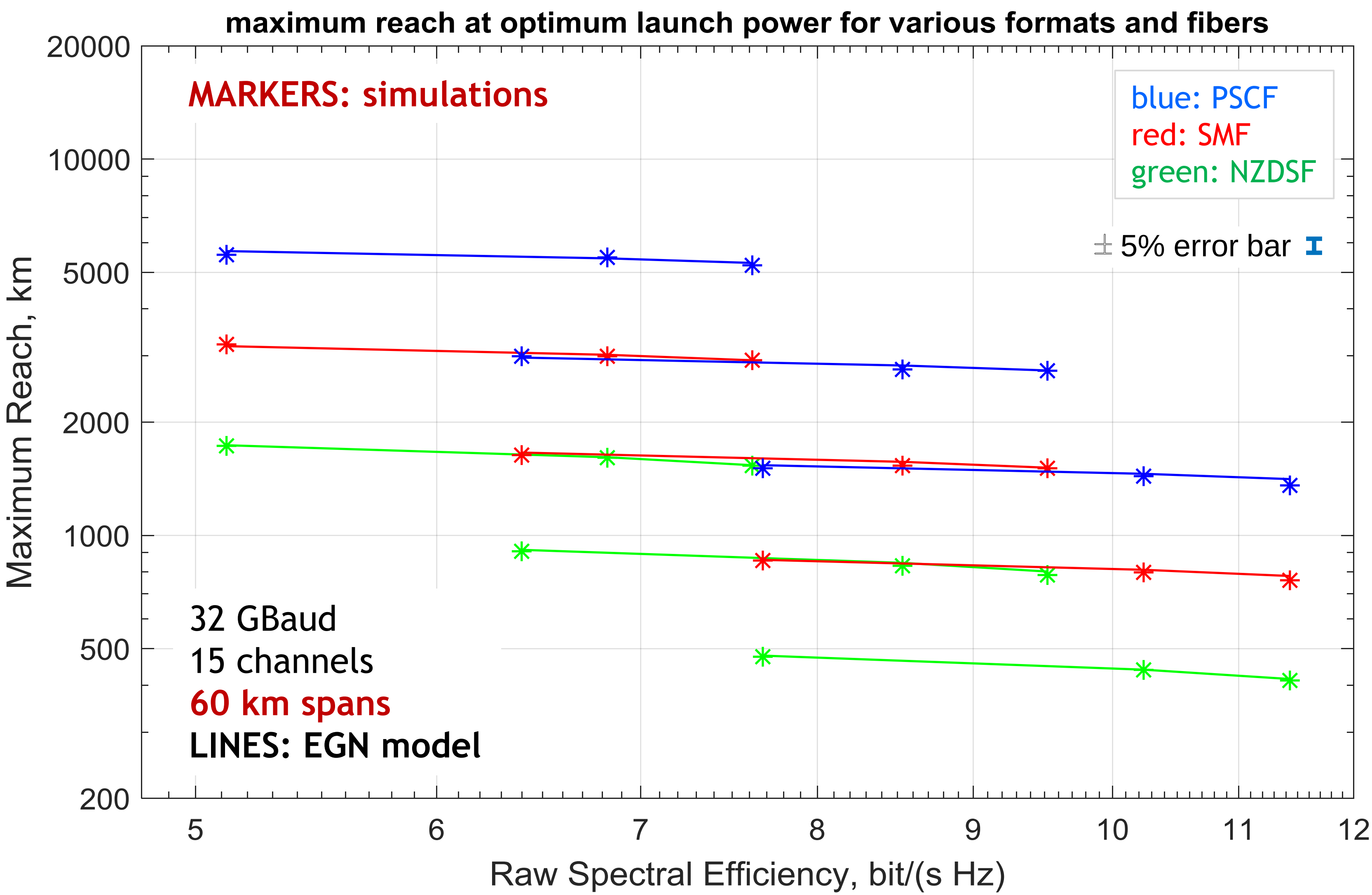


The big picture



The big picture

OPTCOM



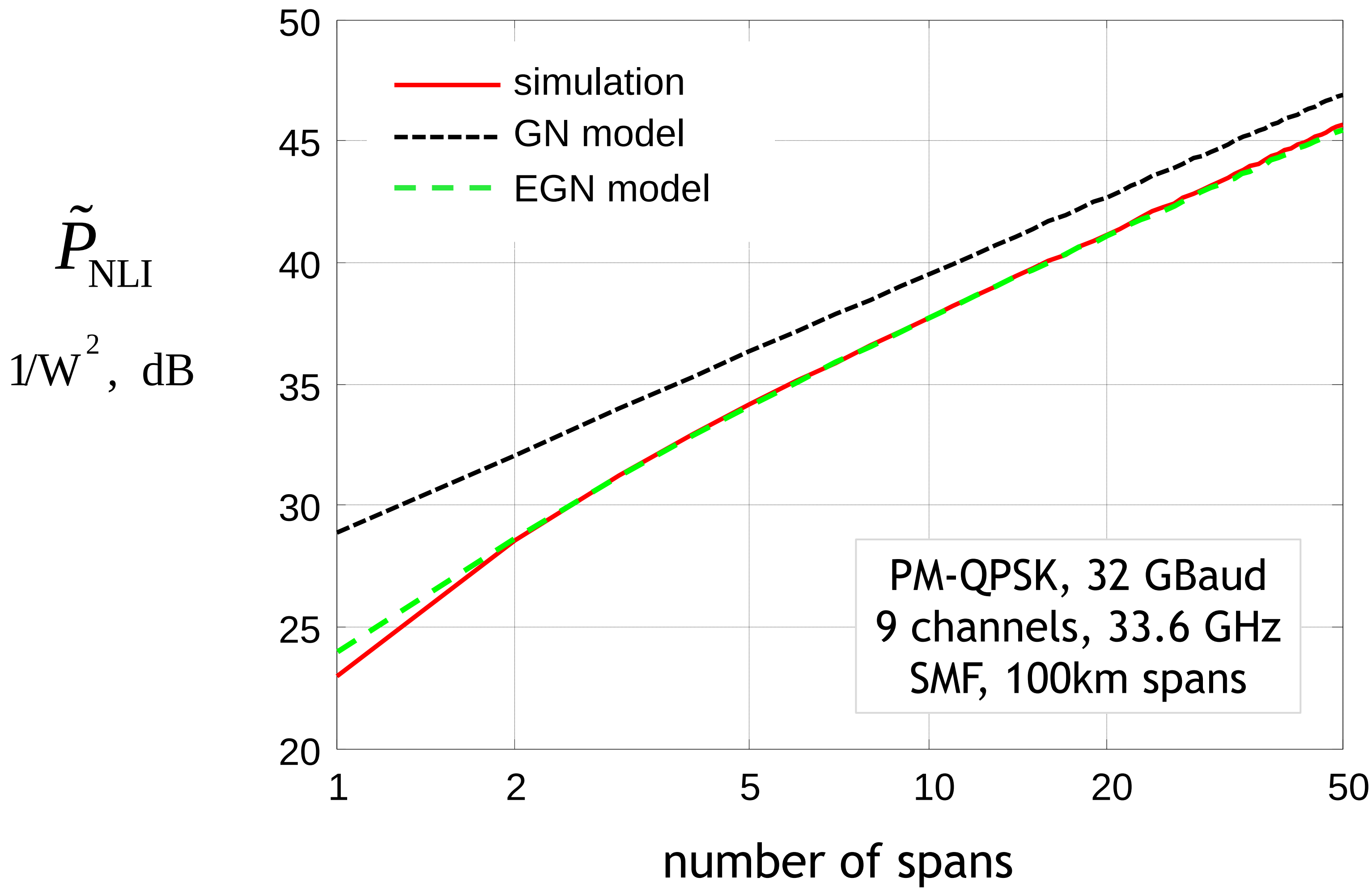
The more sensitive probe

- But maximum reach is not very sensitive…

- Let’s look at the more sensitive probe:

$$\tilde{P}_{\text{NLI}}\left(n_{\text{span}}\right)$$

NLI accumulation study

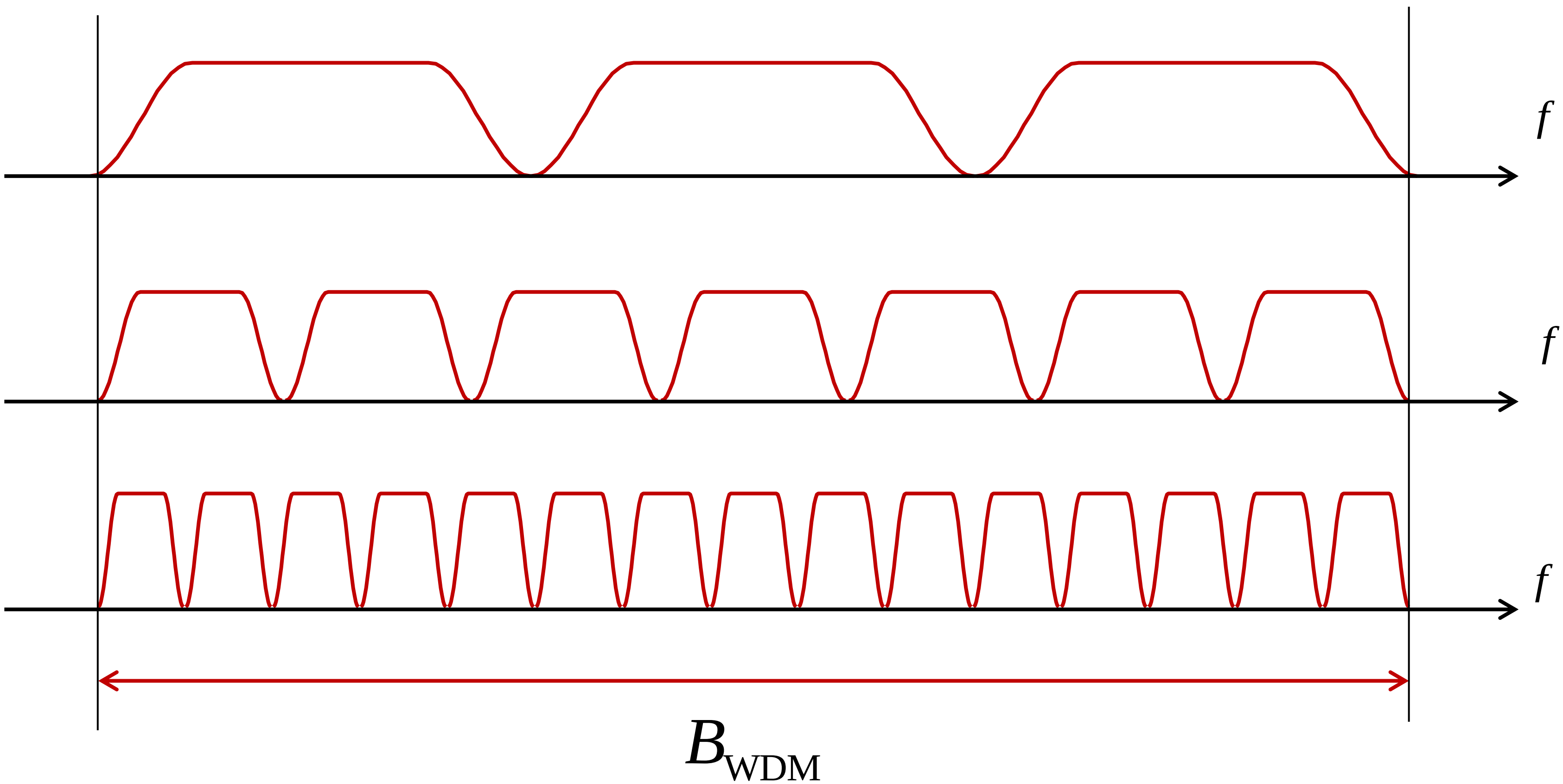


Carena A, Bosco G, Curri V, Jiang Y, Poggiolini P, Forghieri F. ‘EGN model of non-linear fiber propagation,’ *Optics Express*, vol. 22, no. 13, pp.16335–16362, June 2014.

Low symbol rates

- One of the main weaknesses of the GN model is *low symbol rates*
  - especially together with low dispersion
- Can the EGN model deal with those ?
- We have so far looked at 32 GBaud only
- Let's now explore *low symbol rates*, too, and see if the EGN model can manage them

SRO - symbol rate optimization



Constraint: identical total throughput

Which quantity to analyze ?

$$\cancel{\tilde{P}_{\mathrm{NLI}} = P_{\mathrm{NLI}} / P_{\mathrm{ch}}^3}$$

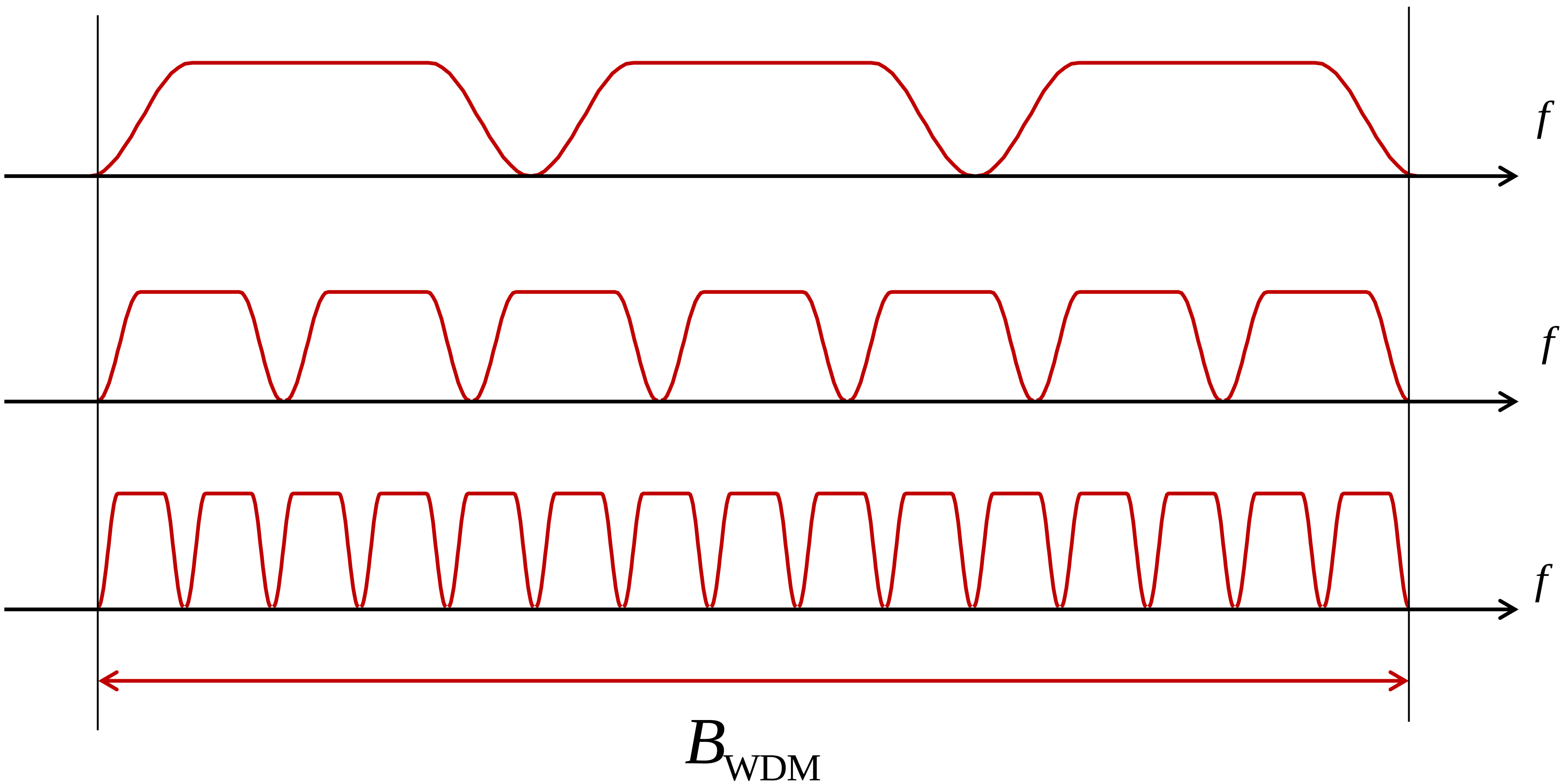
$$\boxed{\tilde{G}_{\mathrm{NLI}} = G_{\mathrm{NLI}} / G_{\mathrm{ch}}^3}$$

a constant value

while dividing B_{WDM} into more channels

means same maximum reach

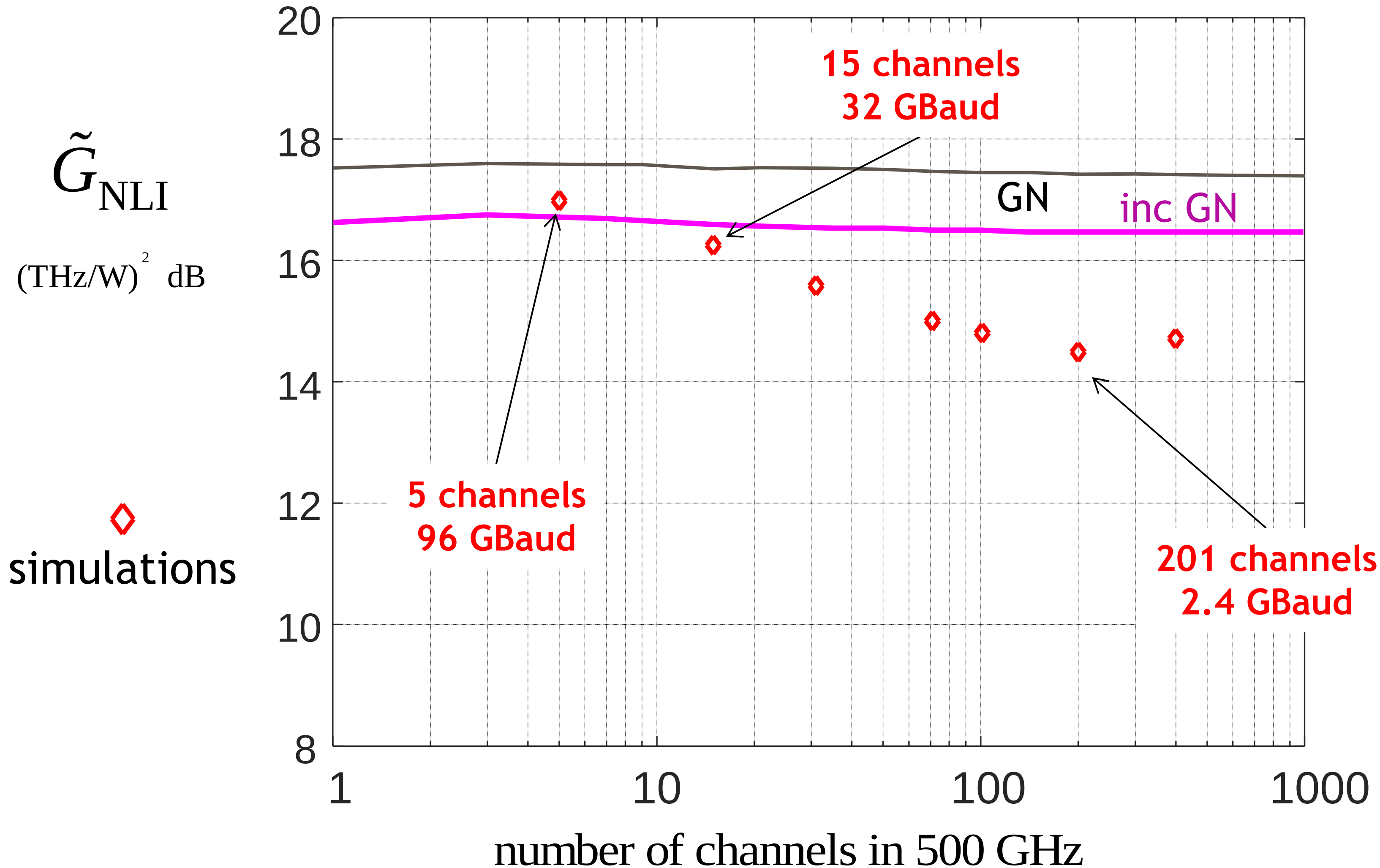
SRO - symbol rate optimization



Constraint: identical total throughput

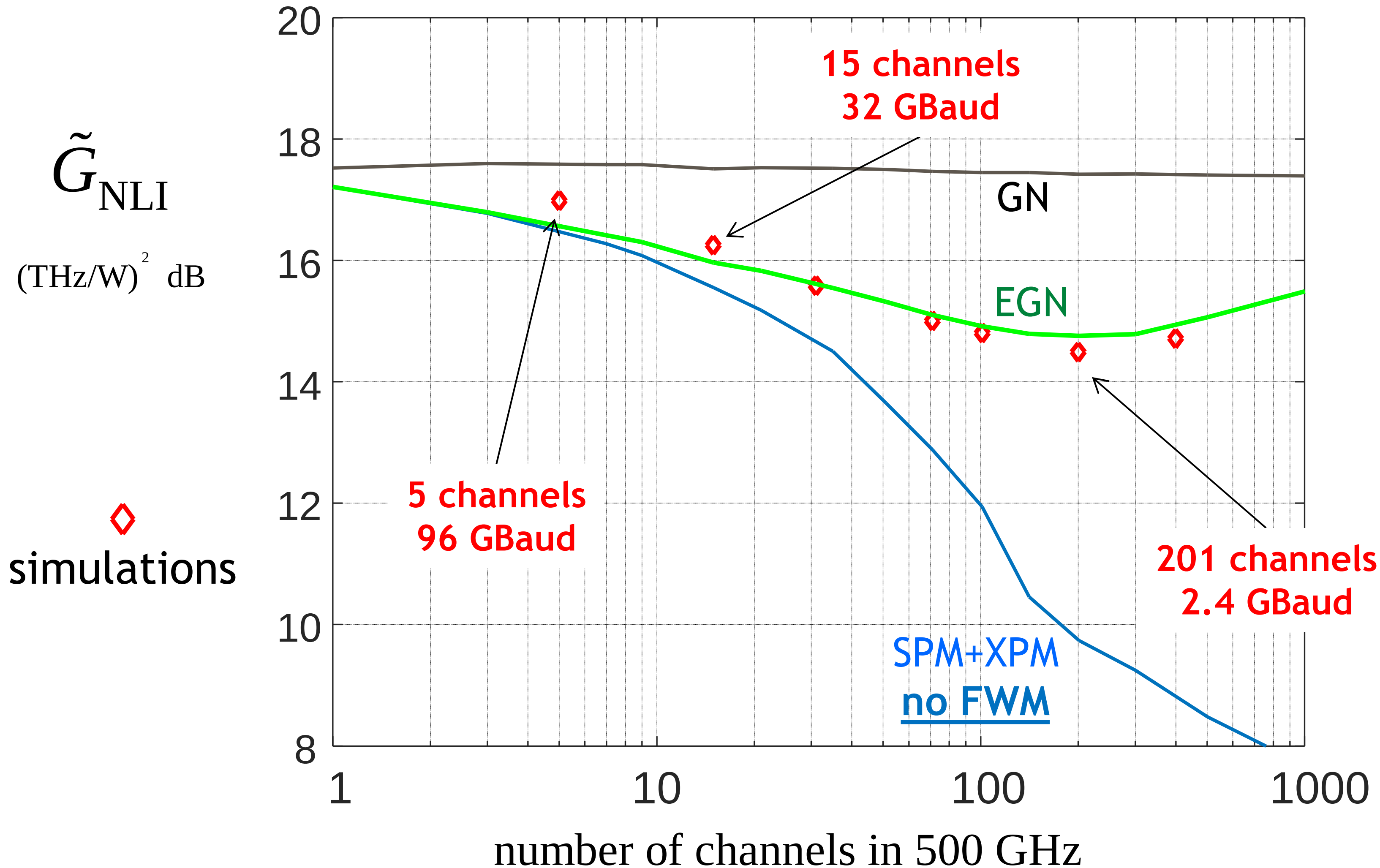
SMF - 50 spans

- B_{WDM} **= 500 GHz**, PM-QPSK, 100 km spans, spacing 1.05 x (symb. rate)



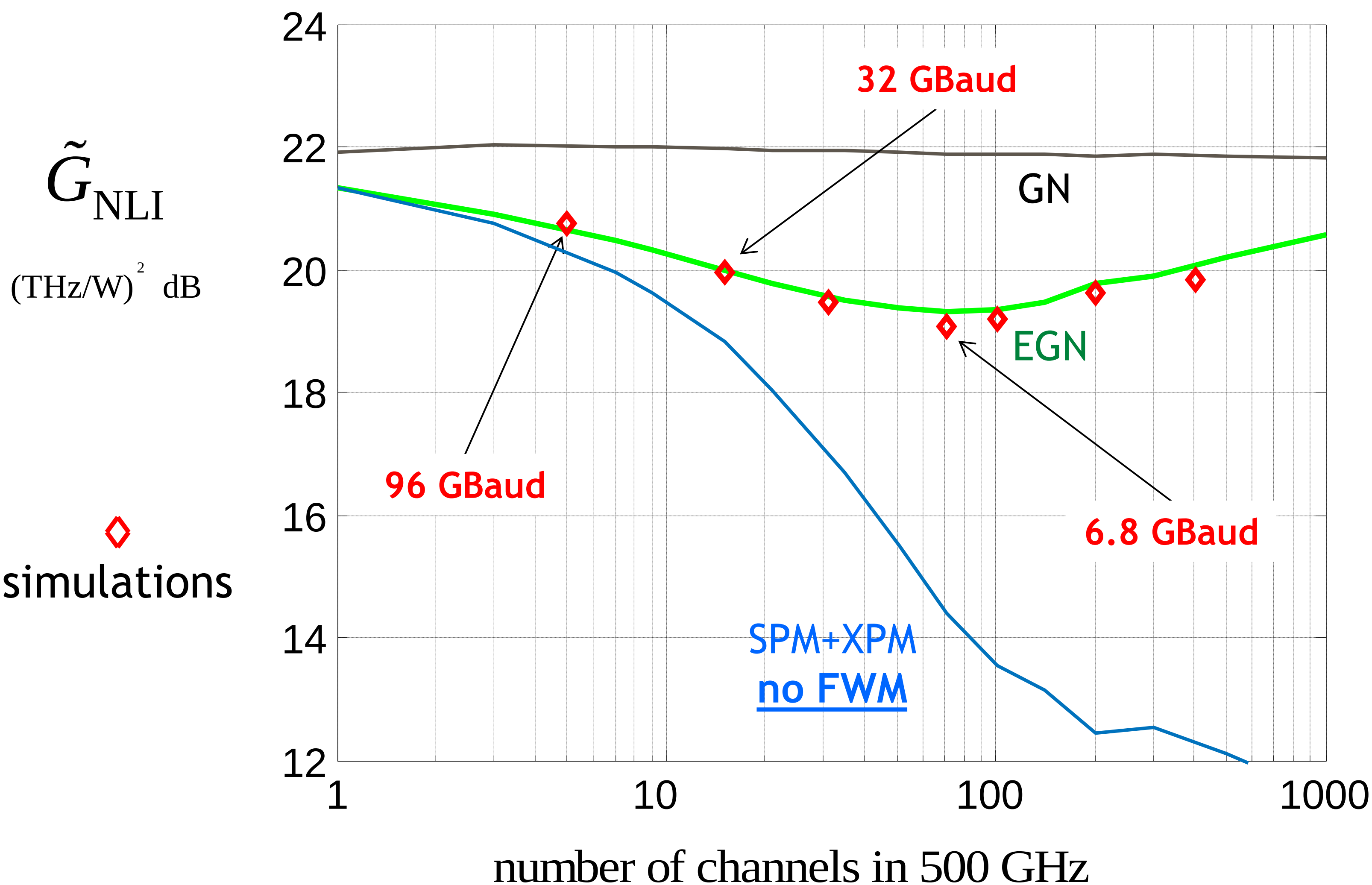
SMF - 50 spans

- B_{WDM} = **500 GHz**, PM-QPSK, 100 km spans, spacing 1.05 x (symb. rate)



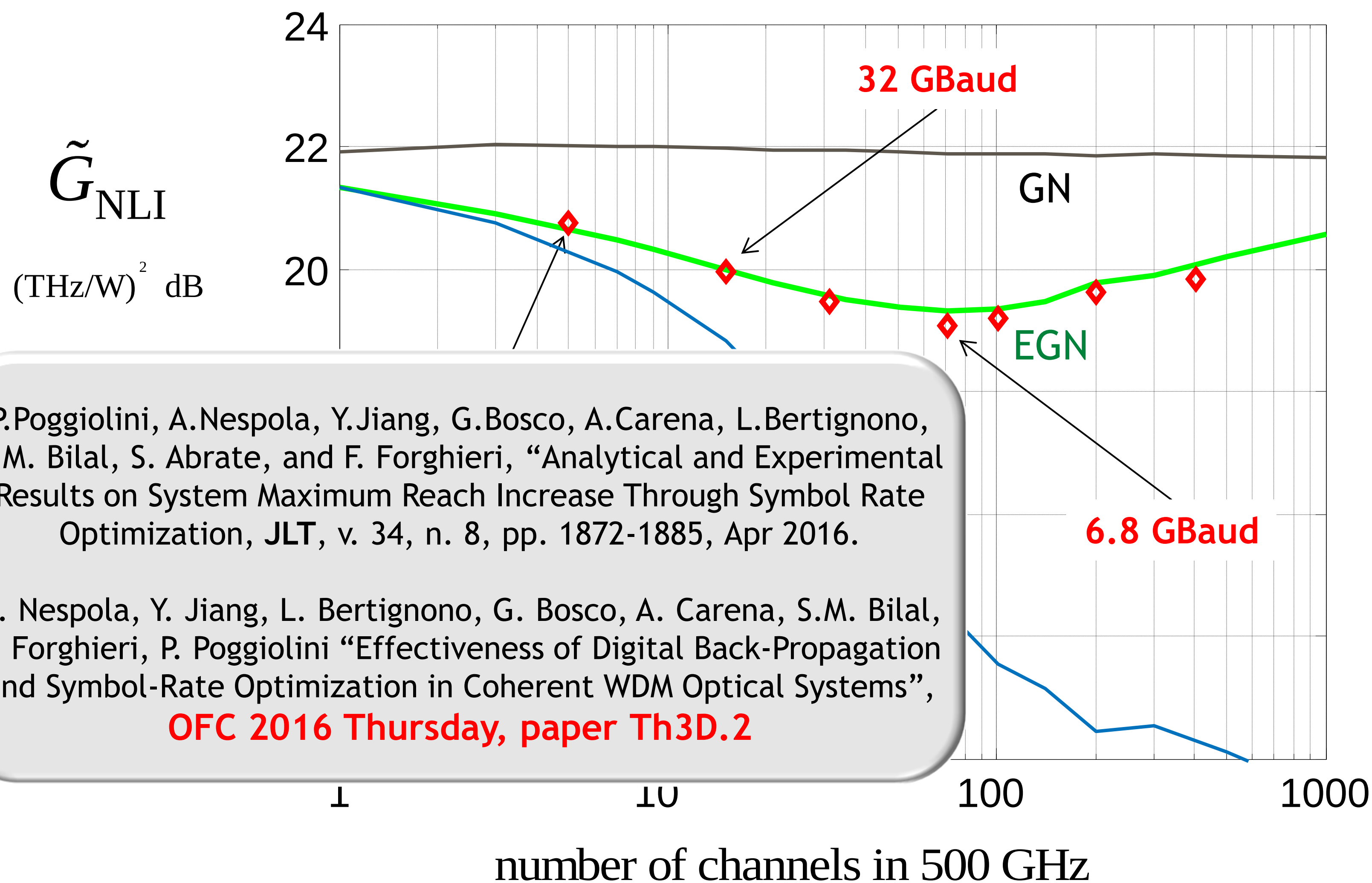
NZDSF - 30 spans

- B_{WDM} **= 500 GHz**, PM-QPSK, 100 km spans, spacing 1.05 x (symb. rate)



NZDSF - 30 spans

- **B_{WDM} = 500 GHz**, PM-QPSK, 100 km spans, spacing 1.05 x (symb. rate)



P.Poggiolini, A.Nespola, Y.Jiang, G.Bosco, A.Carena, L.Bertignono, S.M. Bilal, S. Abrate, and F. Forghieri, “Analytical and Experimental Results on System Maximum Reach Increase Through Symbol Rate Optimization, **JLT**, v. 34, n. 8, pp. 1872-1885, Apr 2016.

A. Nespola, Y. Jiang, L. Bertignono, G. Bosco, A. Carena, S.M. Bilal, F. Forghieri, P. Poggiolini “Effectiveness of Digital Back-Propagation and Symbol-Rate Optimization in Coherent WDM Optical Systems”, **OFC 2016 Thursday, paper Th3D.2**

Papers on SRO

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[11] P. Poggiolini, A. Carena, Y. Jiang, G. Bosco, and F. Forghieri, “On the ultimate potential of symbol-rate optimization for increasing system maximumreach,” presented at theEur.Conf.Optical Communication,Valencia, Spain, Sep. 2015, paper We.4.6.2.

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[13] A. Carbo, J. Renaudier, R. Rios-Mller, P. Tran, and G. Charlet, “Experimental analysis of non linear tolerance dependency of multicarrier modulations versus bandwidth efficiency,” presented at the Eur. Conf. Optical Communication, Valencia, Spain, Sep. 2015, paper Th.2.6.6.

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- *The EGN model is <u>really very accurate</u> across a very wide range of systems*

- including <u>low-symbol rate</u>, <u>low dispersion</u>, <u>short systems</u>, pre-dispersed, unconventional, etc...
- both for max-reach *and* for detailed span-by-span P_{NLI} studies
- It is a very significant *"baseline benchmark"* for other models

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- **Caution must be used when discarding FWM terms from the EGN model**

- Do not do it for low-rate multi-subcarrier systems
- Do not do it on low-dispersion fibers and with tight channel spacing

credit: https://www.dreamhost.com/blog/2009/05/13/broken-browsers-part-one/

well, wait a minute…

The EGN model formulas

$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f) - G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

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

$$G_{\mathrm{NLI}}^{\mathrm{corr}}(f) = G_{\mathrm{SPM}}^{\mathrm{corr}}(f) + G_{\mathrm{X1\text{-}XPM}}^{\mathrm{corr}}(f) + \sum_{i=2}^{4} G_{\mathrm{X}i}^{\mathrm{corr}}(f) + \sum_{i=1}^{3} G_{\mathrm{M}i}^{\mathrm{corr}}(f)$$

SPM XPM FWM

The SPM correction

$$G_{\text{SPM}}^{\text{corr}}(f) = P_m^3\left[\Phi_m\, \kappa_m^{\text{SPM}}(f) + \Psi_m\, \varsigma_m^{\text{SPM}}(f)\right]$$

$$\begin{aligned}
\kappa_m^{\text{SPM}}(f) = \frac{80}{81} R_m^2 \int_{f_m-B_m/2}^{f_m+B_m/2} df_1 \int_{f_m-B_m/2}^{f_m+B_m/2} df_2 \int_{f_m-B_m/2}^{f_m+B_m/2} df_2' \cdot \\
|s_m(f_1)|^2 s_m(f_2) s_m^*(f_2') s_m^*(f_1+f_2-f) s_m(f_1+f_2'-f) \cdot \\
\mu(f_1, f_2, f)\, \mu^*(f_1, f_2', f) \\
+\frac{16}{81} R_m^2 \int_{f_m-B_m/2}^{f_m+B_m/2} df_1 \int_{f_m-B_m/2}^{f_m+B_m/2} df_2 \int_{f_m-B_m/2}^{f_m+B_m/2} df_2' \cdot \\
|s_m(f_1+f_2-f)|^2 s_m(f_1) s_m(f_2) s_m^*(f_1+f_2-f_2') s_m^*(f_2') \cdot \\
\mu(f_1, f_2, f)\, \mu^*(f_1+f_2-f_2', f_2', f)
\end{aligned}$$

$$\begin{aligned}
\varsigma_m^{\text{SPM}}(f) = \frac{16}{81} R_m \int_{f_m-B_m/2}^{f_m+B_m/2} df_1 \int_{f_m-B_m/2}^{f_m+B_m/2} df_2 \int_{f_m-B_m/2}^{f_m+B_m/2} df_1' \int_{f_m-B_m/2}^{f_m+B_m/2} df_2' \cdot \\
s_m(f_1) s_m(f_2) s_m^*(f_1+f_2-f) s_m^*(f_1') s_m^*(f_2') s_m(f_1'+f_2'-f) \cdot \\
\mu(f_1, f_2, f)\, \mu^*(f_1', f_2', f)
\end{aligned}$$

$s_n(f)$ is the Fourier transform of the pulse used by the n-th channel, and:

$$G_{\text{WDM}}(f) = \sum_{n=1}^{N_{\text{ch}}} P_n R_n \left|s_n(f - f_n)\right|^2$$

The XPM (or X1) correction

$$G_{\text{X1-XPM}}^{\text{corr}}(f) = P_m \sum_{\substack{n=1 \\ n\neq m}}^{N_{\text{ch}}} P_n^2 \Phi_n \kappa_n^{\text{X1-XPM}}(f)$$

$$\kappa_{\text{X1-XPM}}^{n}(f) = \frac{80}{81} R_m R_n \int_{f_m - B_m/2}^{f_m + B_m/2} df_1 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2^{'} \cdot$$

$$\left|s_m(f_1)\right|^2 s_n(f_2) s_n^*(f_2^{'}) s_n^*(f_1 + f_2 - f) s_n(f_1 + f_2^{'} - f) \cdot$$

$$\mu(f_1, f_2, f)\mu^*(f_1, f_2^{'}, f)$$

The FWM X2, X3 and X4 corrections

$$G_{\mathrm{X2}}^{\mathrm{corr}}(f)=\Phi_m P_m^2\sum_{\substack{n=m-1\\ n\neq m}}^{m+1}P_n\kappa_{\mathrm{X2}}^n(f)$$

$$\kappa_{\mathrm{X2}}^n(f)=\frac{80}{81}R_mR_n\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_m-B_m/2}^{f_m+B_m/2}df_2\int_{f_m-B_m/2}^{f_m+B_m/2}df_2'\cdot$$
$$|s_n(f_1)|^2 s_m(f_2)s_m^*(f_2')s_m^*(f_1+f_2-f)s_m(f_1+f_2'-f)\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1,f_2',f)$$

$$G_{\mathrm{X3}}^{\mathrm{corr}}(f)=\Phi_m P_m^2\sum_{\substack{n=m-1\\ n\neq m}}^{m+1}P_n\kappa_{\mathrm{X3}}^n(f)$$

$$\kappa_{\mathrm{X3}}^n(f)=\frac{16}{81}R_mR_n\int_{f_m-B_m/2}^{f_m+B_m/2}df_1\int_{f_m-B_m/2}^{f_m+B_m/2}df_2\int_{f_m-B_m/2}^{f_m+B_m/2}df_2'\cdot$$
$$|s_n(f_1+f_2-f)|^2 s_m(f_1)s_m(f_2)s_m^*(f_2')s_m^*(f_1+f_2-f_2')\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1+f_2-f_2',f_2',f)$$

$$G_{\mathrm{X4}}^{\mathrm{corr}}(f)=\sum_{\substack{n=m-1\\ n\neq m}}^{m+1}P_n^3\left[\Phi_n\kappa_{\mathrm{X4}}^n(f)+\Psi_n\varsigma_{\mathrm{X4}}^n(f)\right]$$

$$\varsigma_{\mathrm{X4}}^n(f)=\frac{16}{81}R_n\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_n-B_n/2}^{f_n+B_n/2}df_2\int_{f_n-B_n/2}^{f_n+B_n/2}df_1'\int_{f_n-B_n/2}^{f_n+B_n/2}df_2'\cdot$$
$$s_n(f_1)s_n(f_2)s_n^*(f_1+f_2-f)s_n^*(f_1')s_n^*(f_2')s_n(f_1'+f_2'-f)\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1',f_2',f)$$

$$\kappa_{\mathrm{X4}}^n(f)=\frac{80}{81}R_n^2\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_n-B_n/2}^{f_n+B_n/2}df_2\int_{f_n-B_n/2}^{f_n+B_n/2}df_2'\cdot$$
$$|s_n(f_1)|^2 s_n(f_2)s_n^*(f_2')s_n^*(f_1+f_2-f)s_n(f_1+f_2'-f)\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1,f_2',f)$$
$$+\frac{16}{81}R_n^2\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_n-B_n/2}^{f_n+B_n/2}df_2\int_{f_n-B_n/2}^{f_n+B_n/2}df_2'\cdot$$
$$|s_n(f_1+f_2-f)|^2 s_n(f_1)s_n(f_2)s_n^*(f_1+f_2-f_2')s_n^*(f_2')\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1+f_2-f_2',f_2',f)$$

The FWM M1, M2 and M3 corrections

$$G_{\mathrm{M1}}^{\mathrm{corr}}(f)=\sum_{\substack{n=m-1\\ n\neq m}}^{m+1} P_n \sum_{l=l_{\min}}^{l_{\max}} P_l^2 \Phi_l \kappa_{\mathrm{M1}}^l(f)$$

when $n=m-1,\ l_{\min}=n+2,\ l_{\max}=N_{\mathrm{ch}}$;
when $n=m+1,\ l_{\min}=1,\ l_{\max}=n-2$.

$$G_{\mathrm{M2}}^{\mathrm{corr}}(f)=\sum_{\substack{n=m-1\\ n\neq m}}^{m+1} P_n \sum_{l=l_{\min}}^{l_{\max}} P_l^2 \Phi_l \kappa_{\mathrm{M2}}^l(f)$$

when $n=m-1,\ l_{\min}=1,\ l_{\max}=n-1$;
when $n=m+1,\ l_{\min}=n+1,\ l_{\max}=N_{\mathrm{ch}}$.

$$\kappa_{\mathrm{M1}}^l(f)=\frac{80}{81}R_nR_l\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_l-B_l/2}^{f_l+B_l/2}df_2\int_{f_l-B_l/2}^{f_l+B_l/2}df_2'\cdot$$
$$\left|s_n(f_1)\right|^2 s_l(f_2)s_l^*(f_2')s_l^*(f_1+f_2-f)s_l(f_1+f_2'-f)\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1,f_2',f)$$

$$\kappa_{\mathrm{M2}}^l(f)=\frac{80}{81}R_nR_l\int_{f_n-B_n/2}^{f_n+B_n/2}df_1\int_{f_l-B_l/2}^{f_l+B_l/2}df_2\int_{f_l-B_l/2}^{f_l+B_l/2}df_2'\cdot$$
$$\left|s_n(f_1)\right|^2 s_l(f_2)s_l^*(f_2')s_l^*(f_1+f_2-f)s_l(f_1+f_2'-f)\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1,f_2',f)$$

$$G_{\mathrm{M3}}^{\mathrm{corr}}(f)=\sum_{\substack{n=1\\ n\neq m,m\pm1}}^{N_{\mathrm{ch}}} P_nP_l^2\Phi_l\kappa_{\mathrm{M3}}^l(f)$$

when n is odd, $l=(n+5)/2$;
when n is even, $l=n/2+2,n/2+3$.

$$\kappa_{\mathrm{M3}}^l(f)=\frac{16}{81}R_nR_l\int_{f_l-B_l/2}^{f_l+B_l/2}df_1\int_{f_l-B_l/2}^{f_l+B_l/2}df_2\int_{f_l-B_l/2}^{f_l+B_l/2}df_2'\cdot$$
$$\left|s_n(f_1+f_2-f)\right|^2 s_l(f_1)s_l(f_2)s_l^*(f_2')s_l^*(f_1+f_2-f_2')\cdot$$
$$\mu(f_1,f_2,f)\mu^*(f_1+f_2-f_2',f_2',f)$$

The "constellation moments"

- There are two factors that weigh all these formulas: Φ and Ψ
- They are related to the fourth and sixth moments of the transmitted QAM constellations:

$$\Phi = 2 - \frac{\mathrm{E}\left\{|a|^4\right\}}{\mathrm{E}\left\{|a|^2\right\}} \qquad \Psi = -\frac{\mathrm{E}\left\{|a|^6\right\}}{\mathrm{E}\left\{|a|^2\right\}} + 9\frac{\mathrm{E}\left\{|a|^4\right\}}{\mathrm{E}\left\{|a|^2\right\}} - 12$$

where a is a complex RV representing the QAM constellation points

- Interestingly, ***if the constellation is Gaussian***, then

$$\Phi = \Psi = 0 \quad \rightarrow \quad G_{\mathrm{NLI}}^{\mathrm{corr}} = 0$$

and therefore:

$$\boxed{G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f)}$$

So, is the EGN usable ?

- Despite its complexity *it can be implemented* in its entirety and run with reasonable computation time

- We have used the full EGN model to perform several *full C-band calculations*, for instance looking at limits of DBP and SRO
  - P.Poggiolini, A.Nespola, Y.Jiang, G.Bosco, A.Carena, L.Bertignono, S.M. Bilal, S. Abrate, and F. Forghieri, "Analytical and Experimental Results on System Maximum Reach Increase Through Symbol Rate Optimization, JLT, v. 34, n. 8, pp. 1872-1885, Apr 2016.
  - A. Nespola, Y. Jiang, L. Bertignono, G. Bosco, A. Carena, S.M. Bilal, F. Forghieri, P. Poggiolini "Effectiveness of Digital Back-Propagation and Symbol-Rate Optimization in Coherent WDM Optical Systems", **OFC 2016 Thursday, paper Th3D.2**

- An *exhaustive and very insightful C-band investigation of DBP* has been carried out using the full EGN model (and other modeling)

R. Dar, P. Winzer "On the Limits of Digital Back-Propagation in Fully Loaded WDM Systems," PTL, in pre-print, available on IEEE Xplore.

making the EGN simpler

- Is there a way to obtain a much simpler EGN correction?

$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f) - G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

- It is indeed possible to write *"asymptotic"* *closed-form* *expressions of the correction term*

Asymptotic correction formulas

- These formulas are *asymptotic in the number of spans*, they get more accurate as the number of spans goes up

- Initially proposed here:
  - 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.

- Now *substantially improved and extended* to better handle low Baud rates and low dispersion, up to C band

- <u>*See extra slides at the bottom of this file*</u>
- Only the key take-away is reported in the next slide

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- The asymptotic EGN correction formula(s) are convenient low-complexity approximations for max-reach studies

- Being "asymptotic" in the number of spans, they *should be used with caution* in short-reach systems (< 300 km)

EGN model limitations

- So one limitation of the EGN model is *complexity*

- Another limitation is that *some "special effects"* *cannot be "singled out"*

- One of them is *non-linear phase and polarization noise*

Special effect #1

OPTCOM

non-linear phase and polarization noise

The EGN model "agnosticism"

- The EGN model accurately estimates the overall power of NLI on the received channel:

$$P_{\mathrm{NLI}}$$

- This quantity *includes* NLI power of different types
  - short-correlated quasi-circular noise
  - ~~*long-correlated* phase noise~~
  - ~~*long-correlated* polarization noise~~
- The EGN model *cannot discriminate among them*

Key Questions

- What is the *system impact* of long-correlated phase and polarization noise ?
  - for instance, on the «big pictures»?
  - do we have to worry about it ?

- Can their removal be *factored into the EGN model*?

long-correlated phase noise

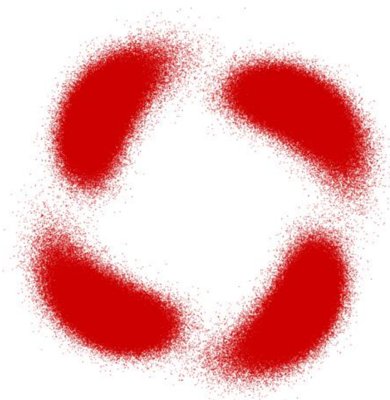
- The first paper (in "coherent systems" time) that closed-form characterized the long-correlation of LC-PN:

Marco Secondini and Enrico Forestieri, "Analytical Fiber-Optic Channel Model in the Presence of Cross-Phase Modulation", PTL, vol. 24, pp. 2016-2019, Nov. 2012

- Several other papers have addressed phase noise since:
  - M. Secondini, E. Forestieri, and G. Prati, "Achievable information rate in nonlinear WDM fiber-optic systems with arbitrary modulation formats and dispersion maps," J. Lightwave Technol. 31, 3839–3852 (2013).
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, 'Properties of nonlinear noise in long, dispersion-uncompensated fiber links,' *Optics Express*, vol. 21, no. 22, pp. 25685-25699, Nov. 2013.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, 'Accumulation of nonlinear interference noise in fiber-optic systems,' *Optics Express*, vol. 22, no. 12, pp. 14199-14211, June 2014.
  - M. Secondini, E. Forestieri, "On XPM Mitigation in WDM Fiber-Optic Systems", PTL, vol. 26, pp. 2252- 2255, Nov. 2014.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, 'Inter-Channel Nonlinear Interference Noise in WDM Systems: Modeling and Mitigation,' *J. of Lightwave Technol.*, vol. 33, no. 5, pp. 1044-1053, Mar. 2015.
  - R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, 'Pulse collision picture of inter-channel nonlinear interference in fiber-optic communications,' *J. of Lightwave Technol.*, vol. 34, no. 2, pp. 593-607, Jan. 2016.
- Some very interesting experimental work has been done as well :
  - T. Fehenberger, N. Hanik, T. A. Eriksson, P. Johannisson, M. Karlsson, "On the Impact of Carrier Phase Estimation on Phase Correlations in Coherent Fiber Transmission", 2015 Tyrrhenian International Workshop on Digital Communications (TIWDC), available on IEEE Xplore.
  - Carsten Schmidt-Langhorst, Robert Elschner, Felix Frey, Robert Emmerich, Colja Schubert, "Experimental Analysis of Nonlinear Interference Noise in Heterogeneous Flex-Grid WDM Transmission", ECOC 2015, paper Tu.1.4.3, Sept. 2015.

but what is NL phase noise?

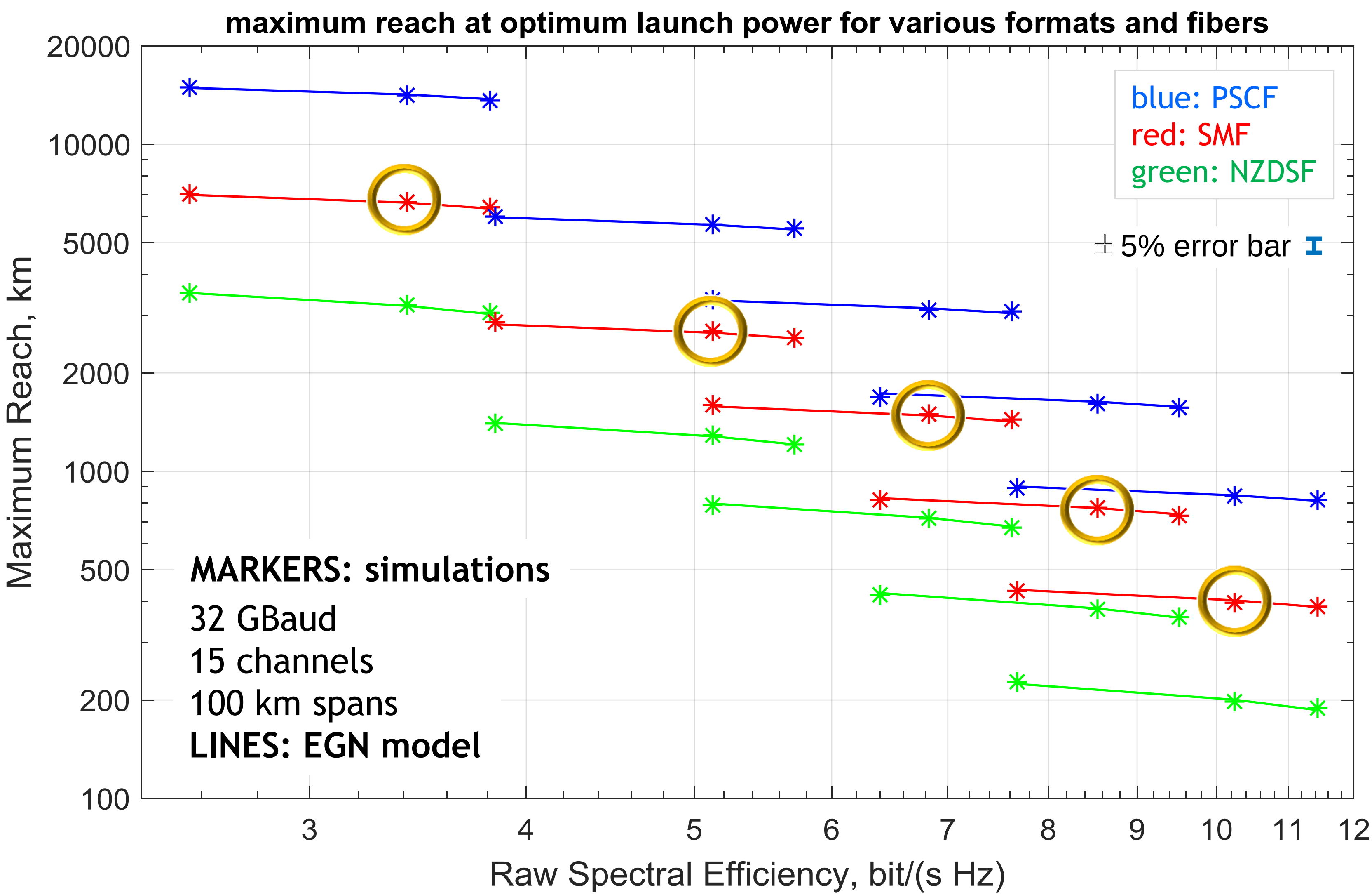
- At the beginning of the coherent revolution era, many people expected to see QPSK constellations like this:



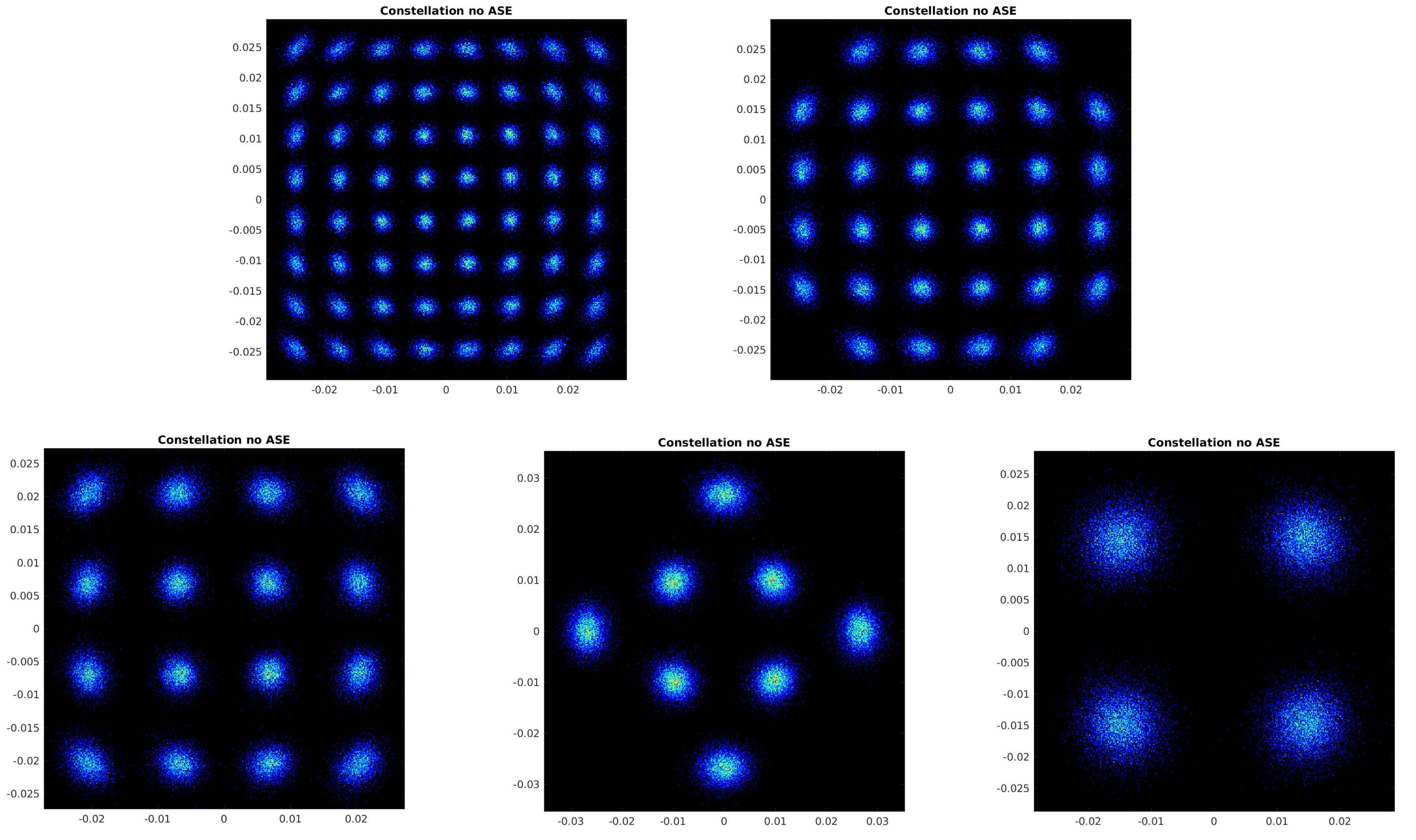
- This is indeed what you get at very high launch power per channel
  - [1] S. L.I. Olsson, M. Karlsson, P. A. Andrekson “Nonlinear phase noise mitigation in phase-sensitive amplified transmission systems”, Optics Express, vol. 23, p. 11724, May 2015.

- In typical long-haul systems, however, *phase noise is milder*

The big picture



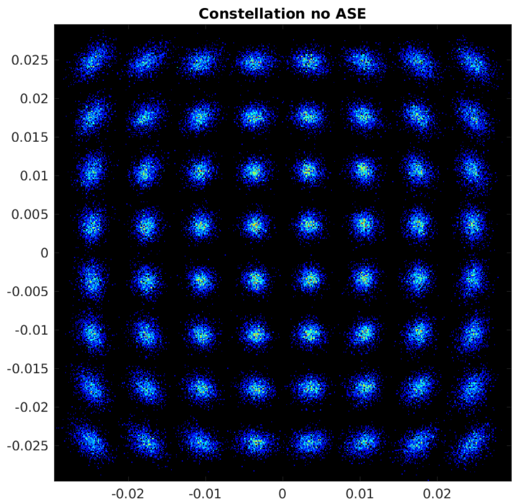
NL phase noise

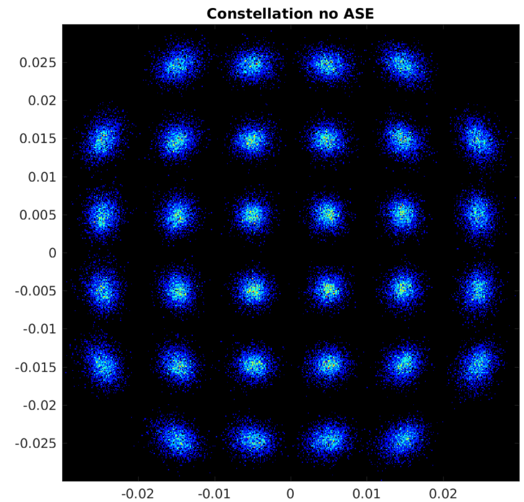


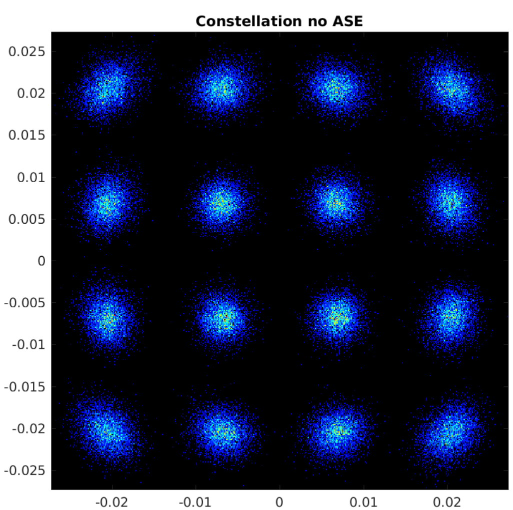
no ASE, at max-reach

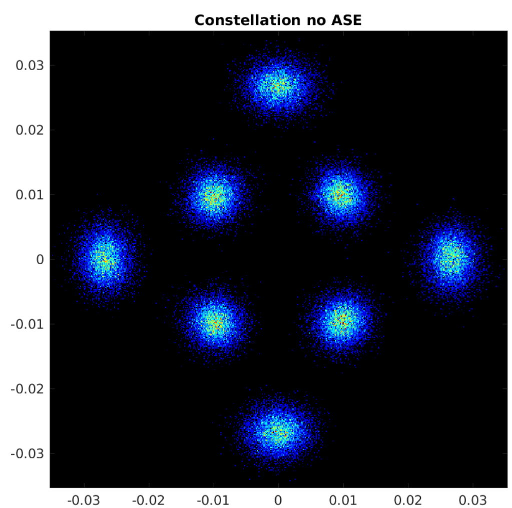
NL phase noise

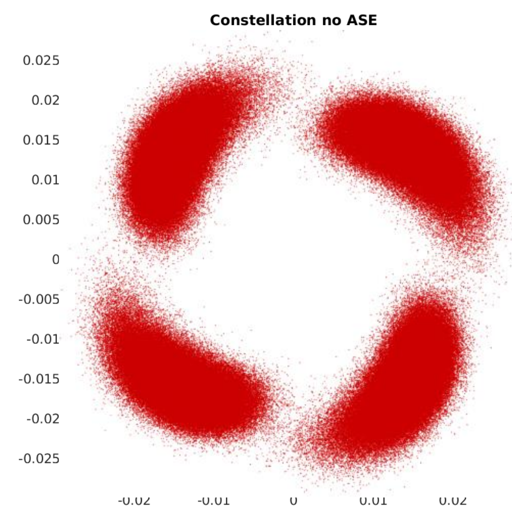
OPTCOM





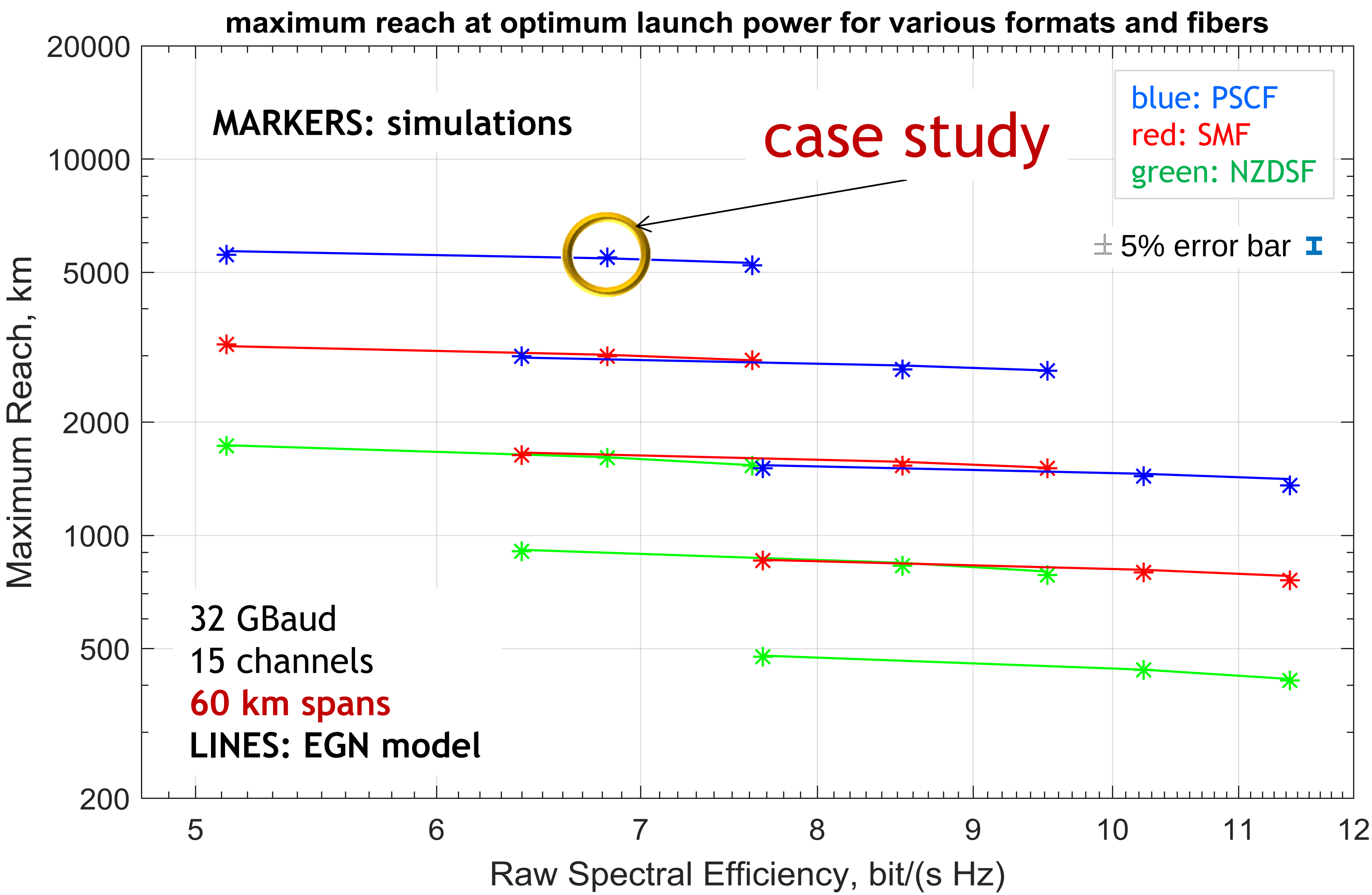






no ASE, at max-reach

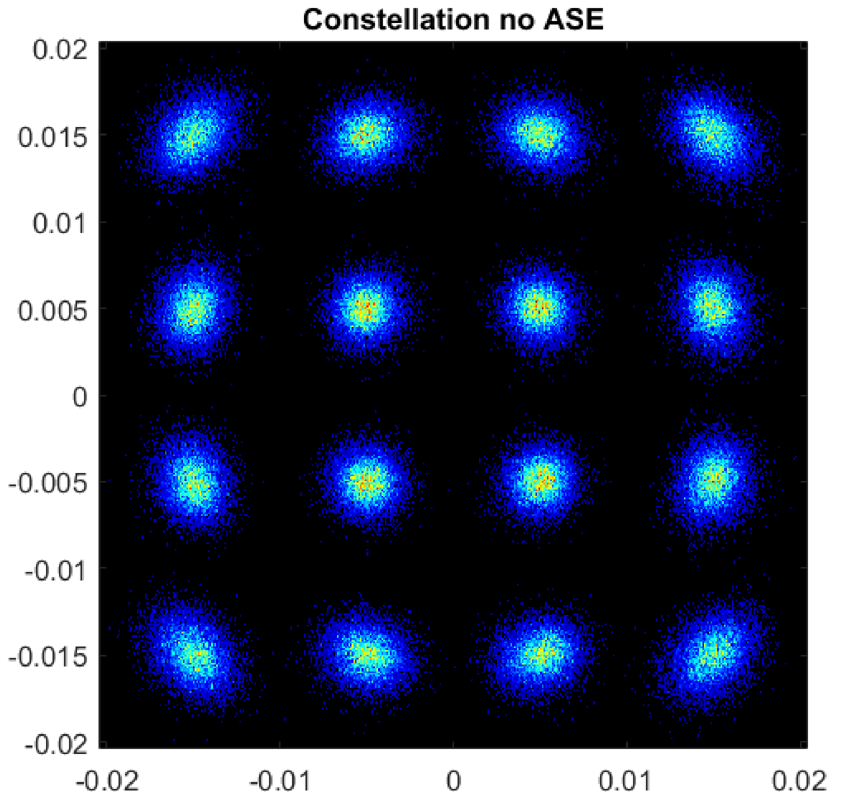
The big picture

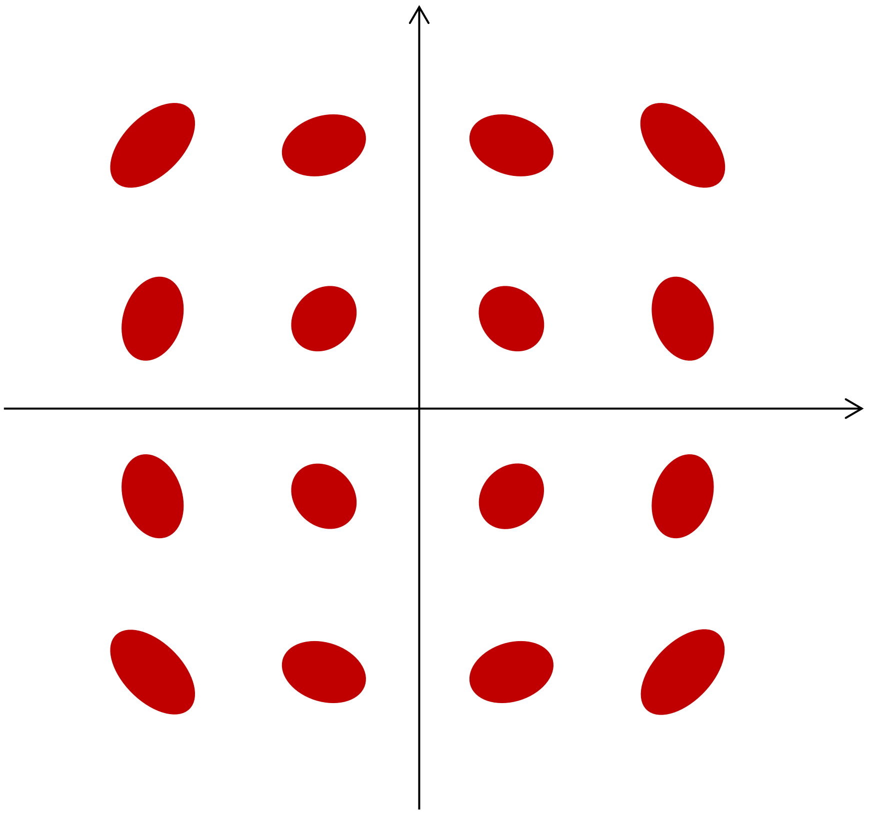


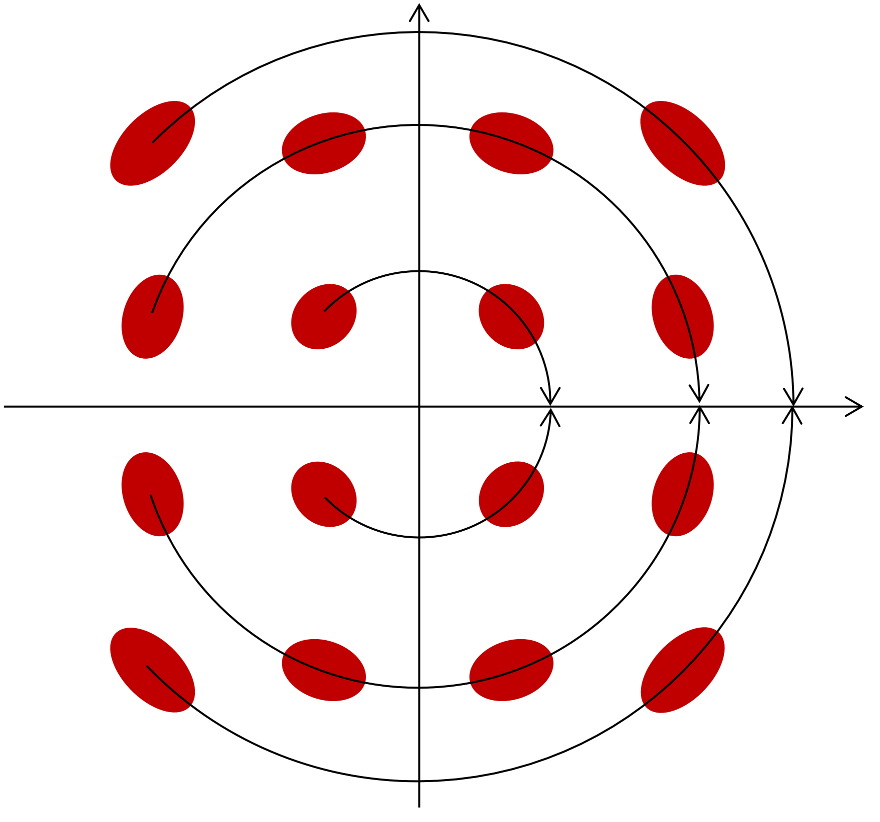
Can anything be done?

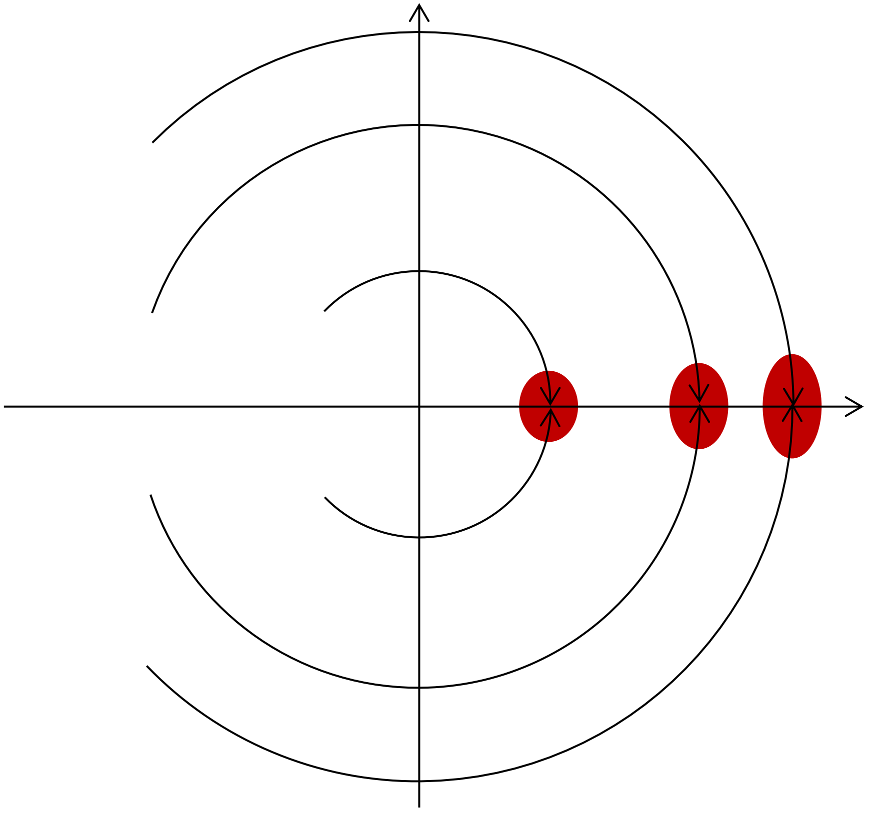
- CASE STUDY:

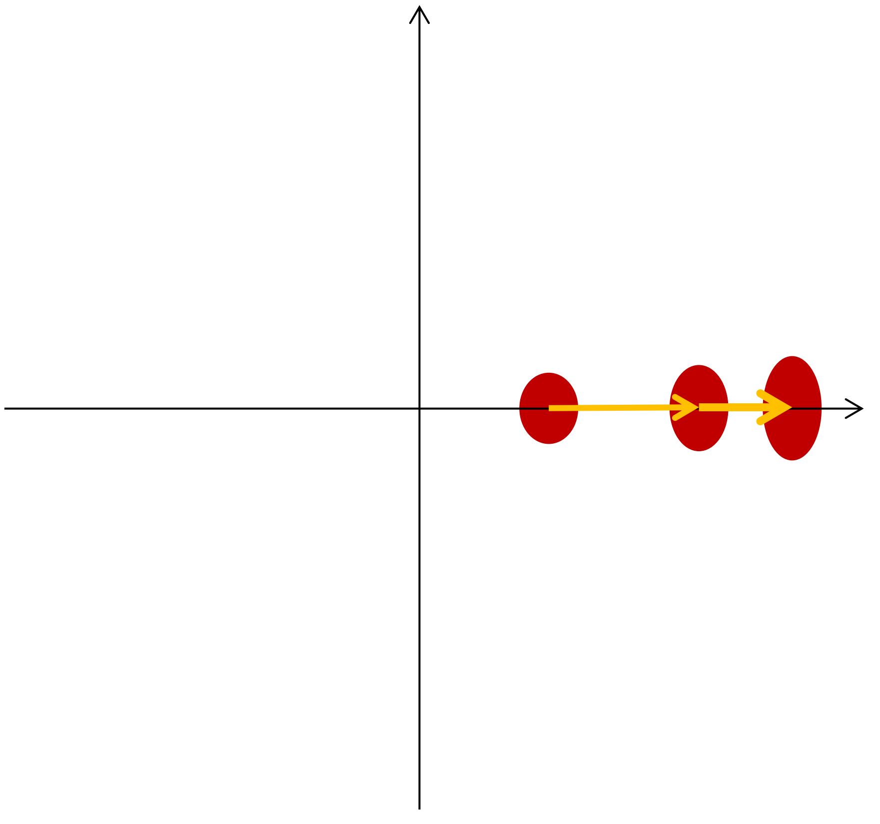
PSCF, **60km spans**, PM-16QAM, 15 channels, **at 6000 km** (about max reach)



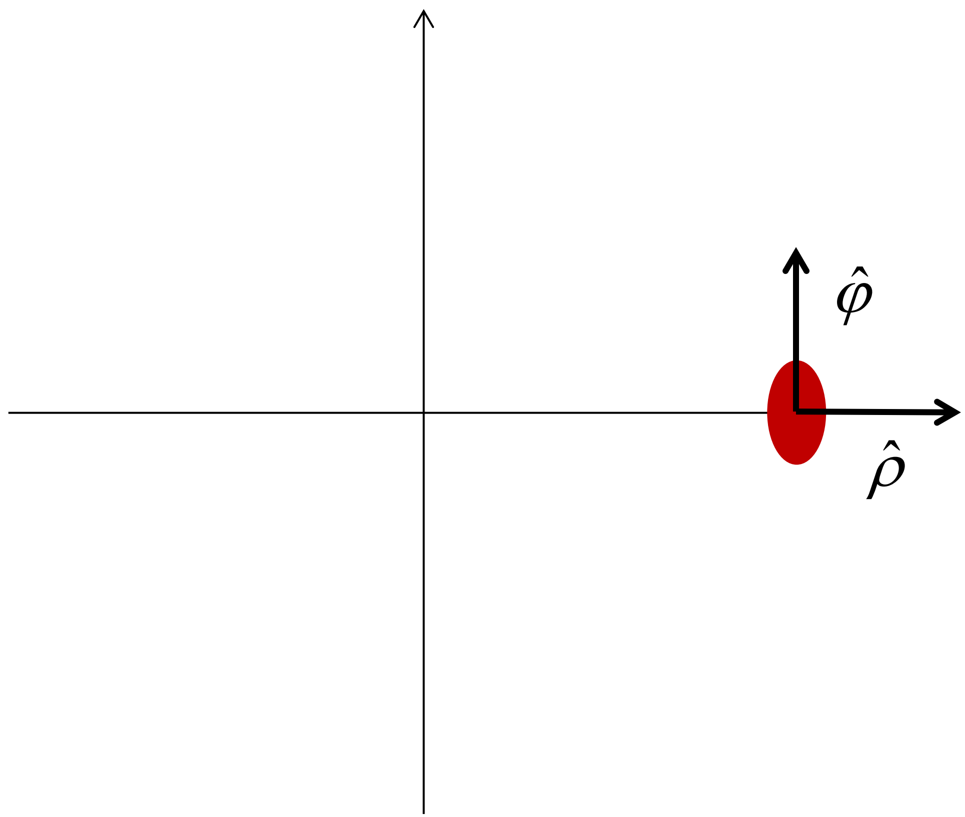






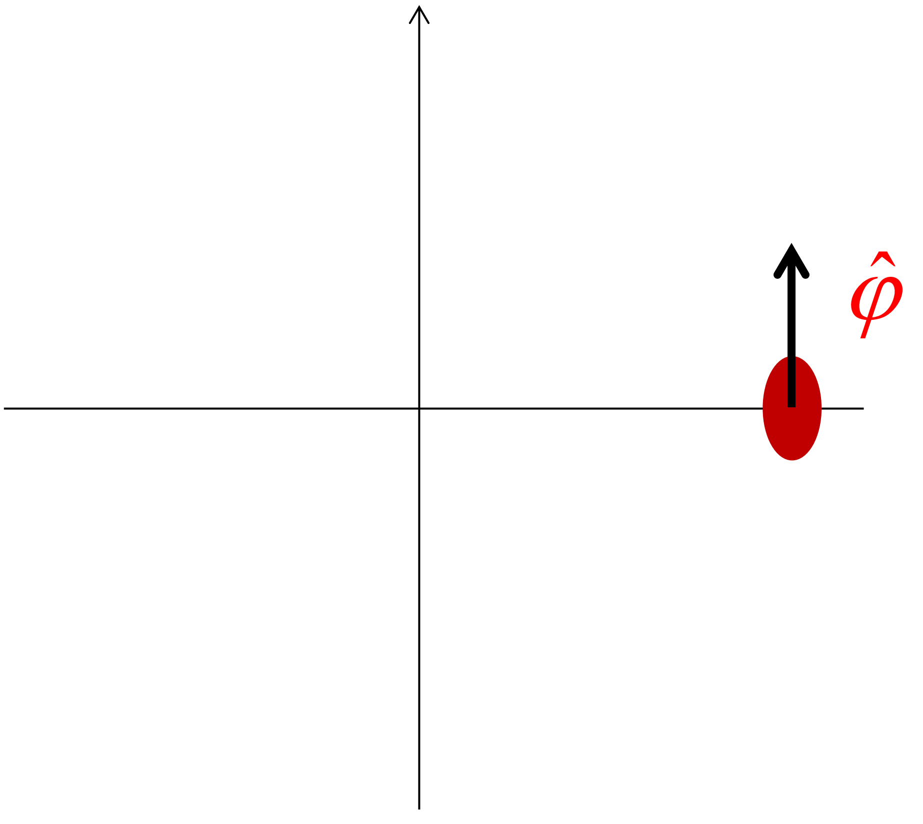


the “single dot”

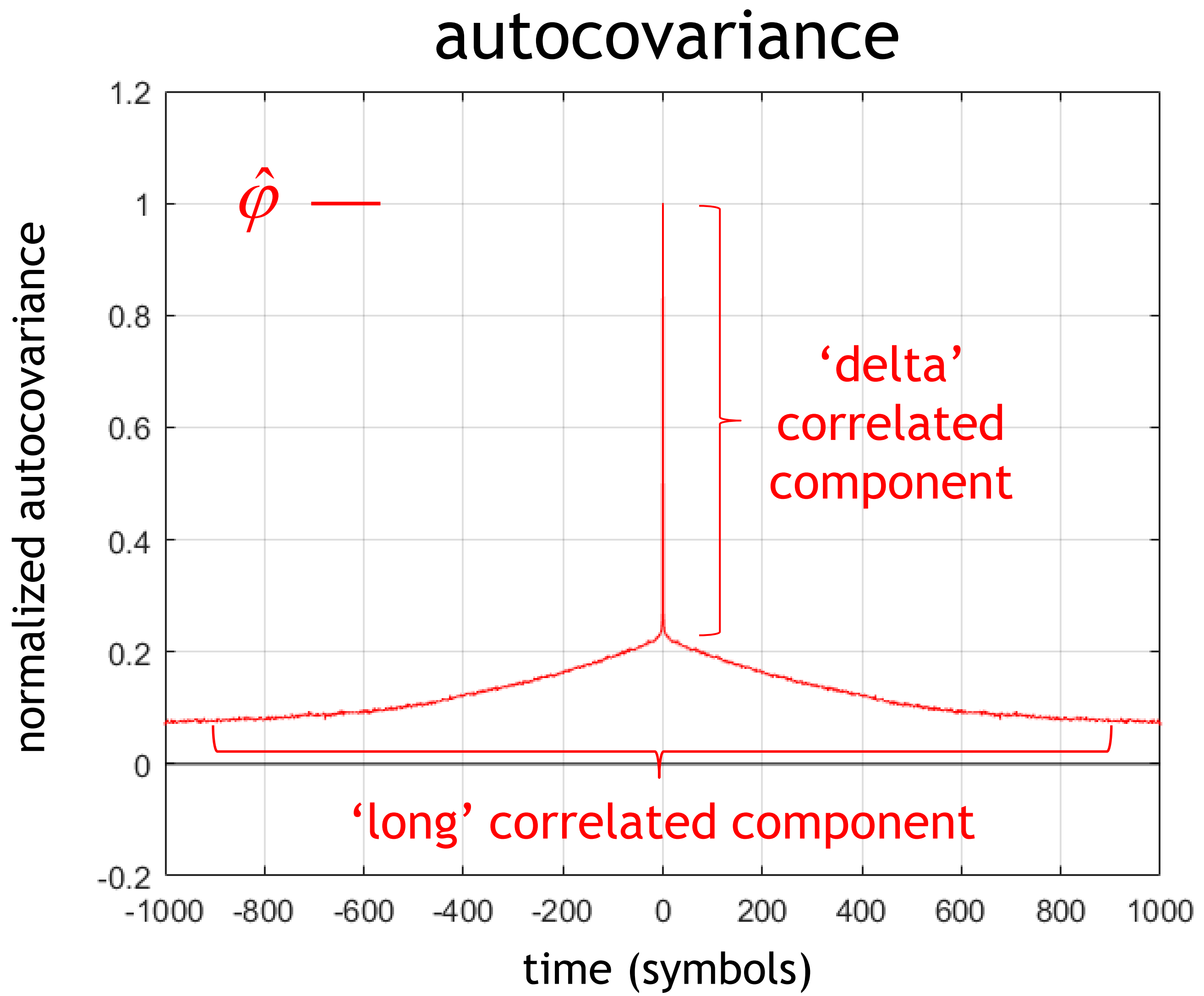


Carsten Schmidt-Langhorst, Robert Elschner, Felix Frey, Robert Emmerich, Colja Schubert, “Experimental Analysis of Nonlinear Interference Noise in Heterogeneous Flex-Grid WDM Transmission”, ECOC 2015, paper Tu.1.4.3, Sept. 2015.

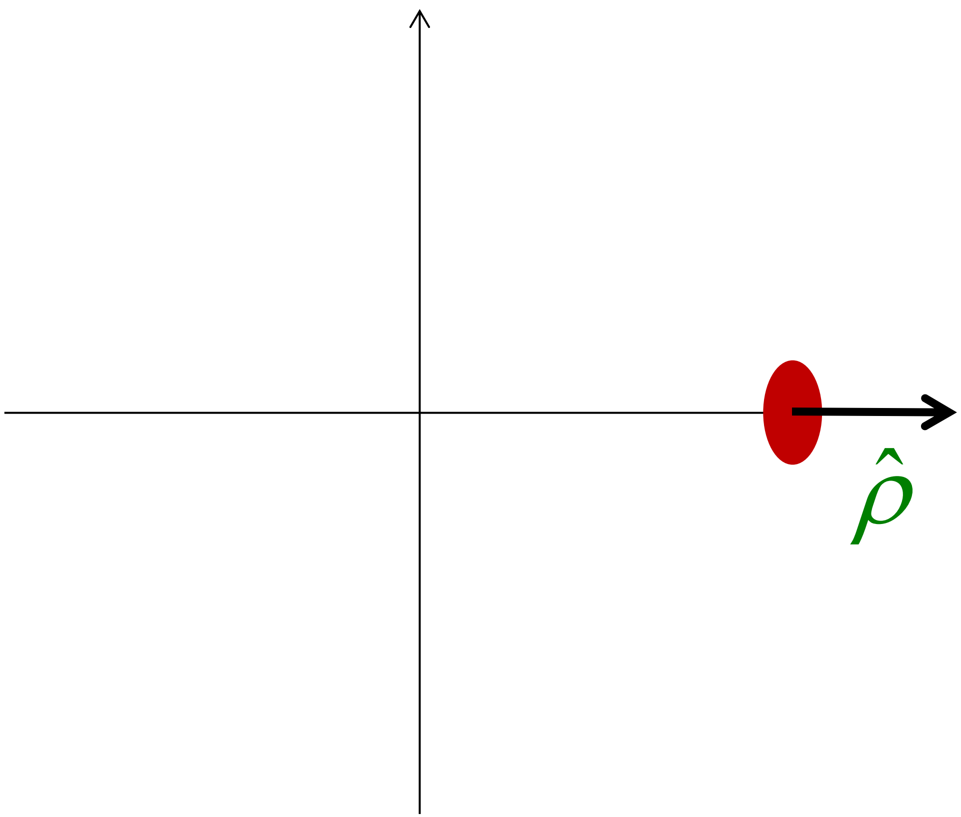
the “single dot”

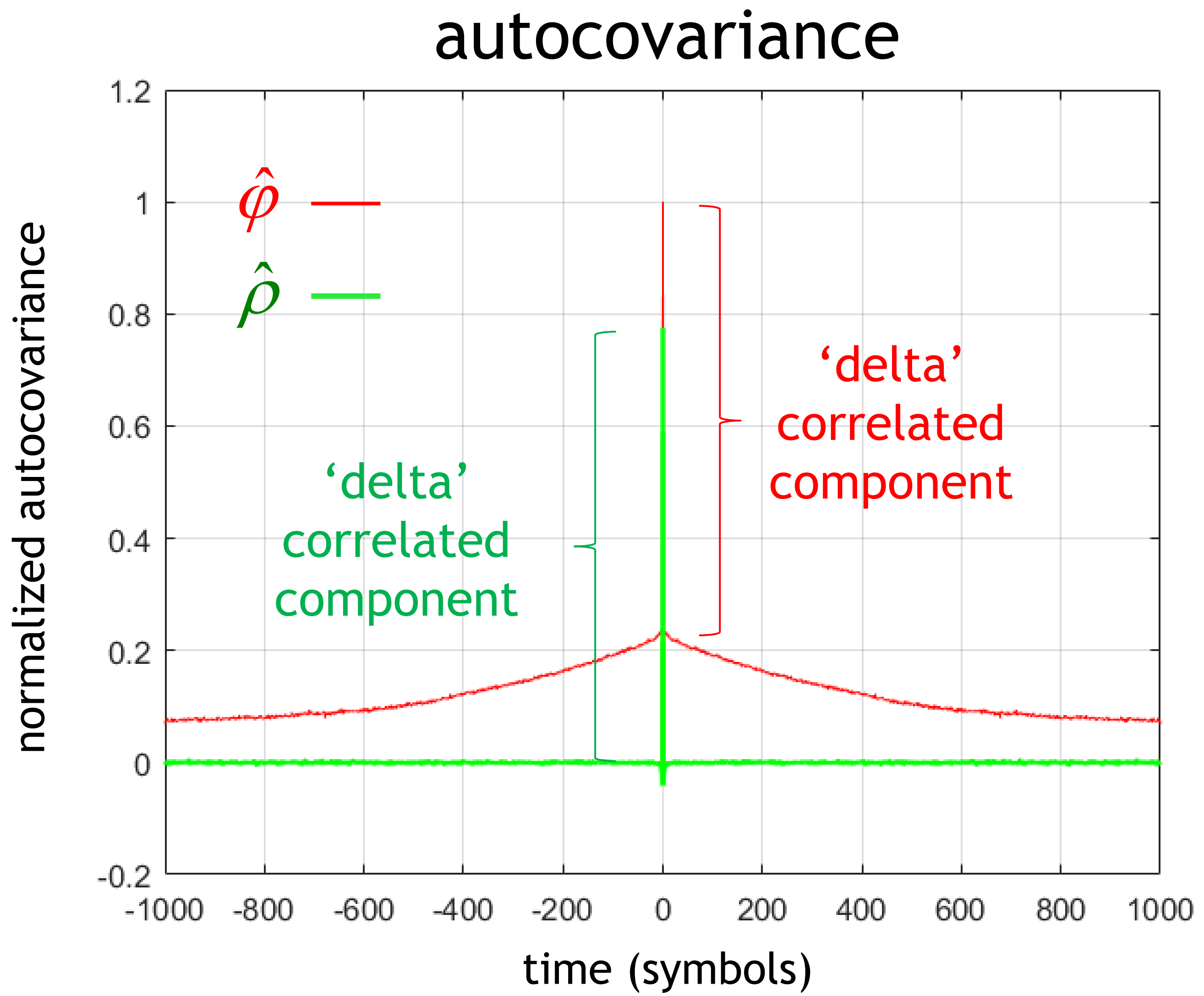


analyzing phase noise



the “single dot”




autocovariance
$\hat{\varphi}$
$\hat{\rho}$
'delta' correlated component
'delta' correlated component
normalized autocovariance
time (symbols)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-1000
-800
-600
-400
-200
0
200
400
600
800
1000

PN removal algorithm

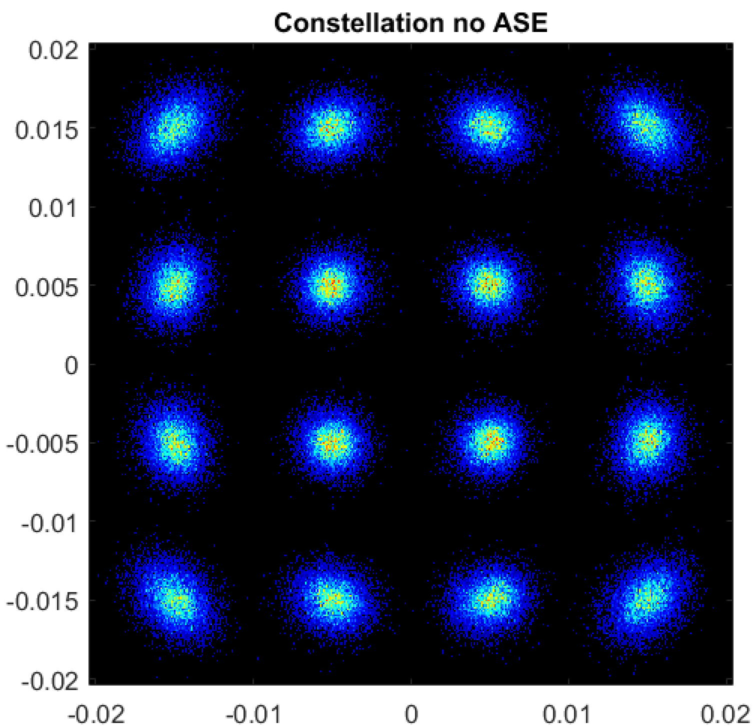
- To estimate (and then remove) long-correlated phase-noise, we used the PN-receiver as proposed in

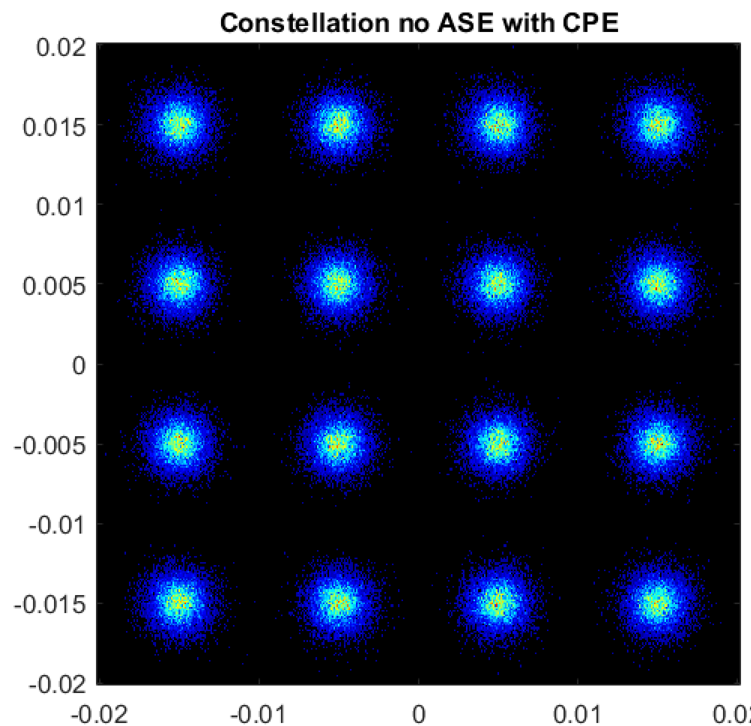
T. Fehenberger, M. P. Yankov, L. Barletta, and N. Hanik, “Compensation of XPM interference by blind tracking of the nonlinear phase in WDM systems with QAM input,” ECOC, Sep. 2015.

- **Notice:** CPE is done *independently* on the two polarizations
  - this means that *the phase noise component of polarization noise* is also being removed

Does it work?

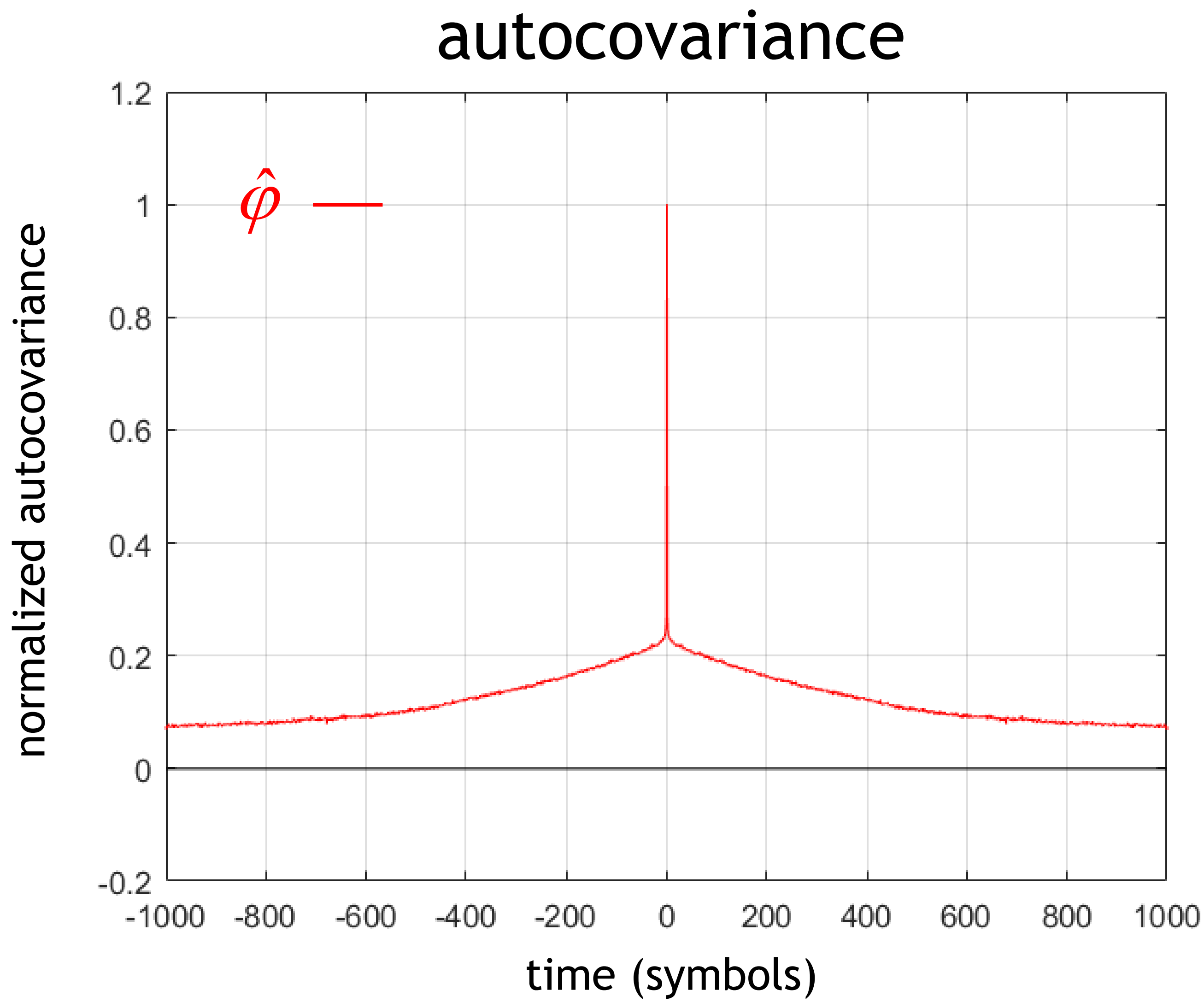
- <u>CASE STUDY:</u>
  PSCF, 60km spans, PM-16QAM, 15 channels, at 6000 km (about max reach)





- at least "visually", phase noise is gone

before CPE


autocovariance
$\hat{\varphi}$
normalized autocovariance
time (symbols)
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0.8
0.6
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-400
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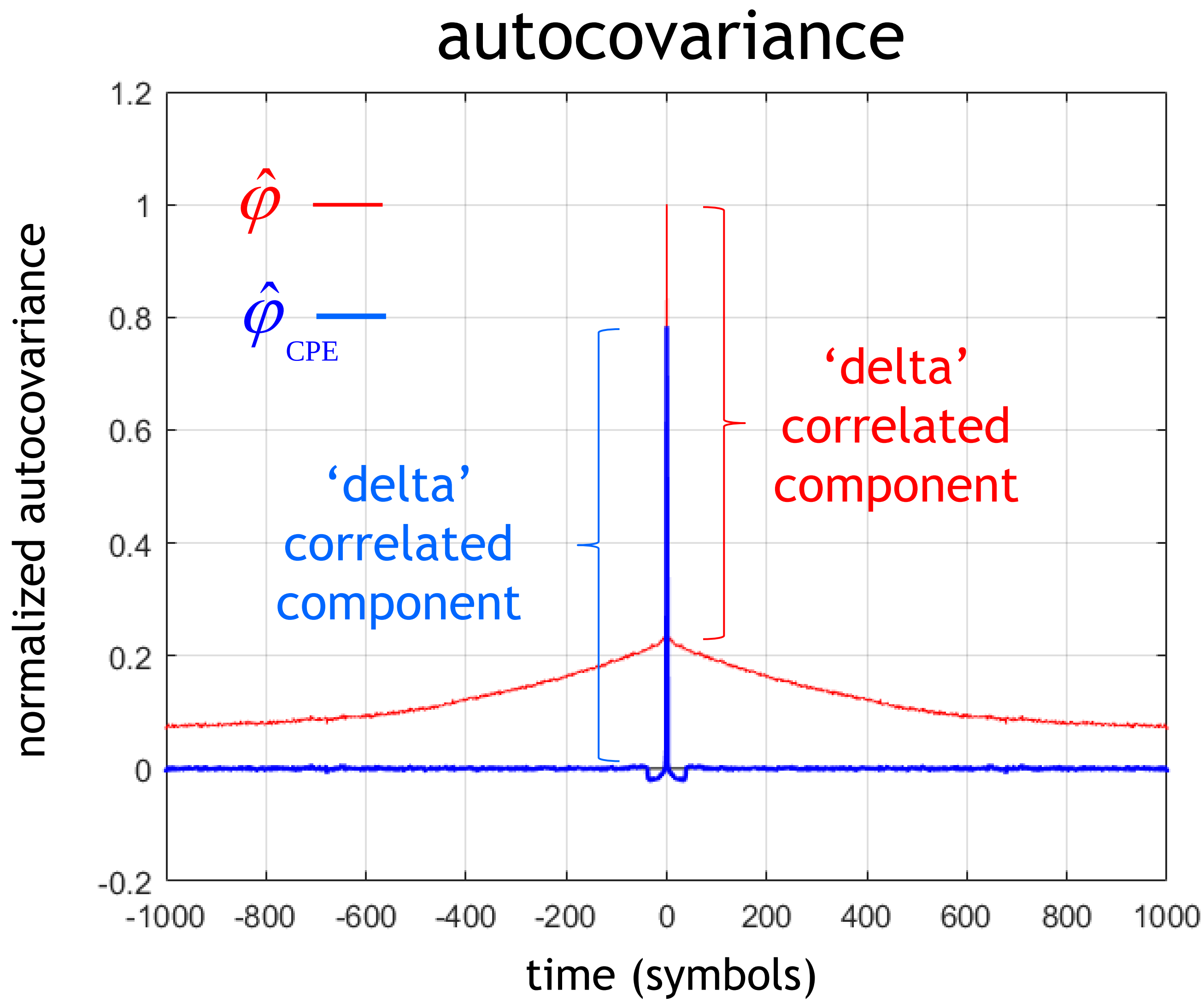
200
400
600
800
1000

after CPE


autocovariance
$\hat{\varphi}$
$\hat{\varphi}_{CPE}$
'delta' correlated component
'delta' correlated component
normalized autocovariance
time (symbols)
1.2
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0.8
0.6
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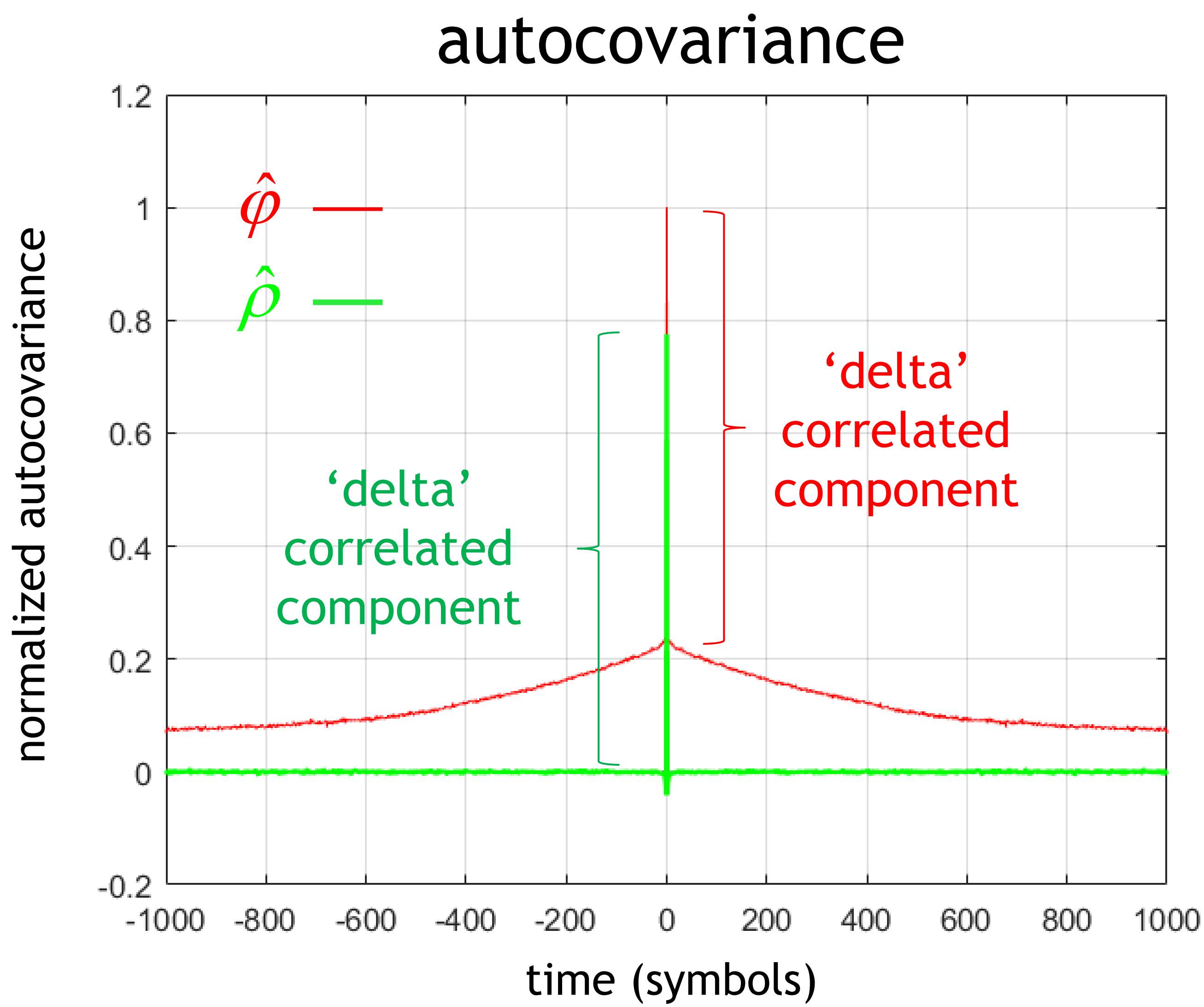
autocovariance
$\hat{\varphi}$
$\hat{\rho}$
'delta' correlated component
'delta' correlated component
normalized autocovariance
time (symbols)
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0.8
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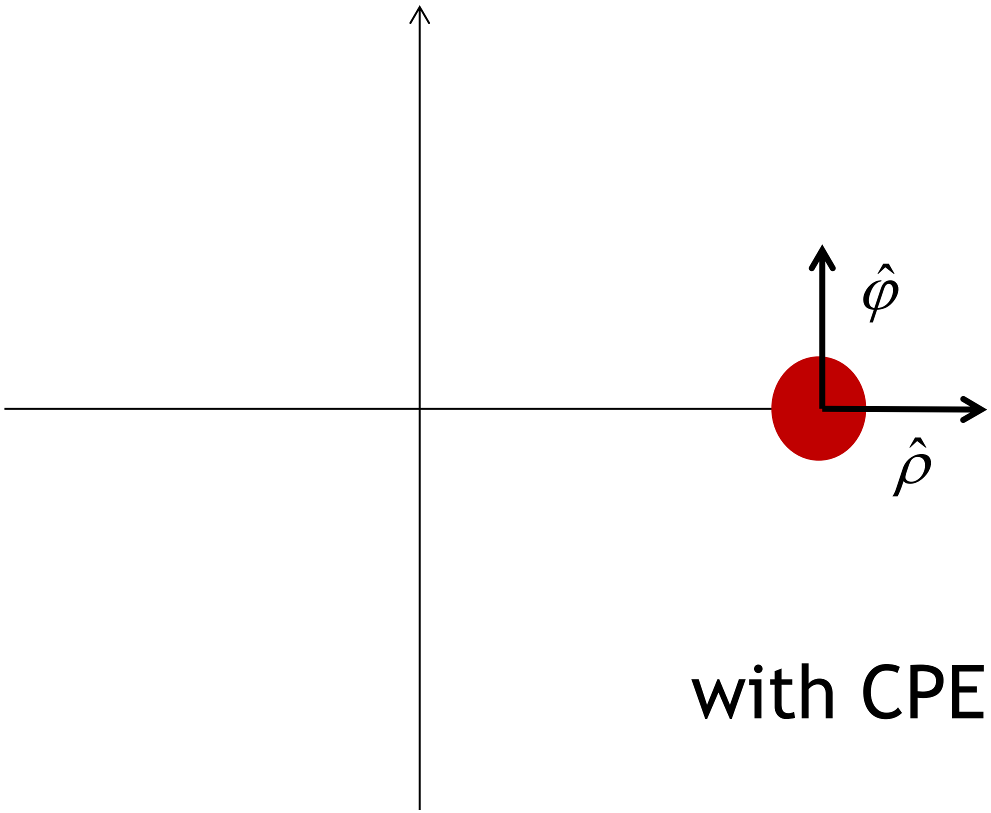
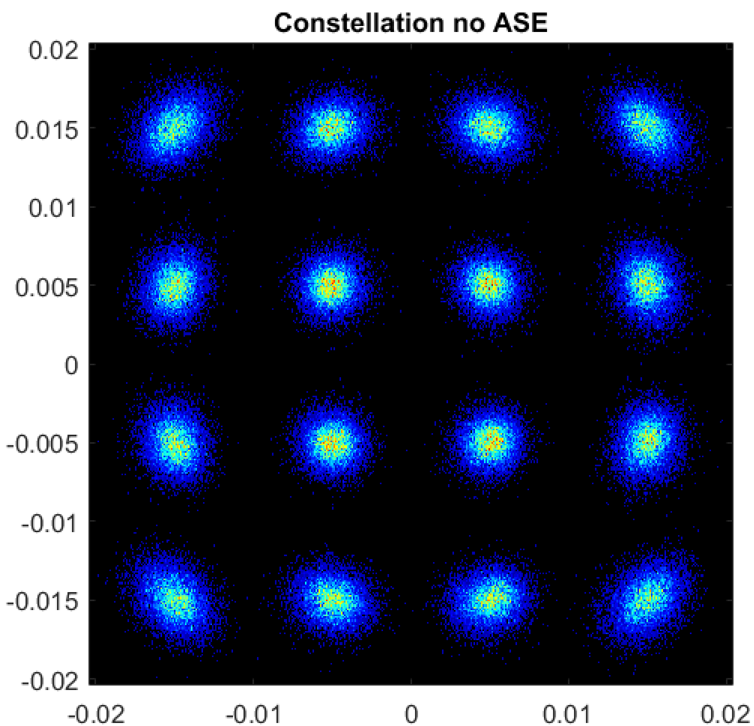
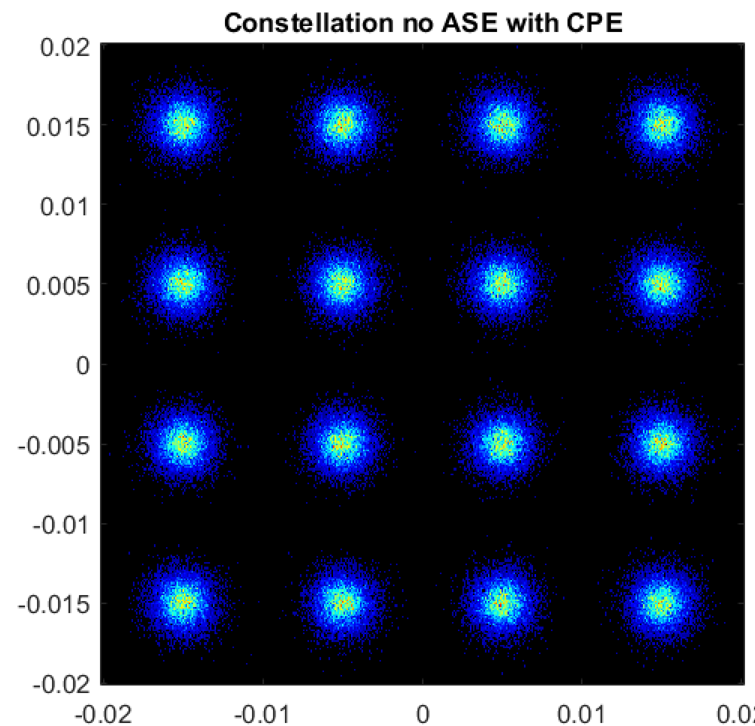


with CPE

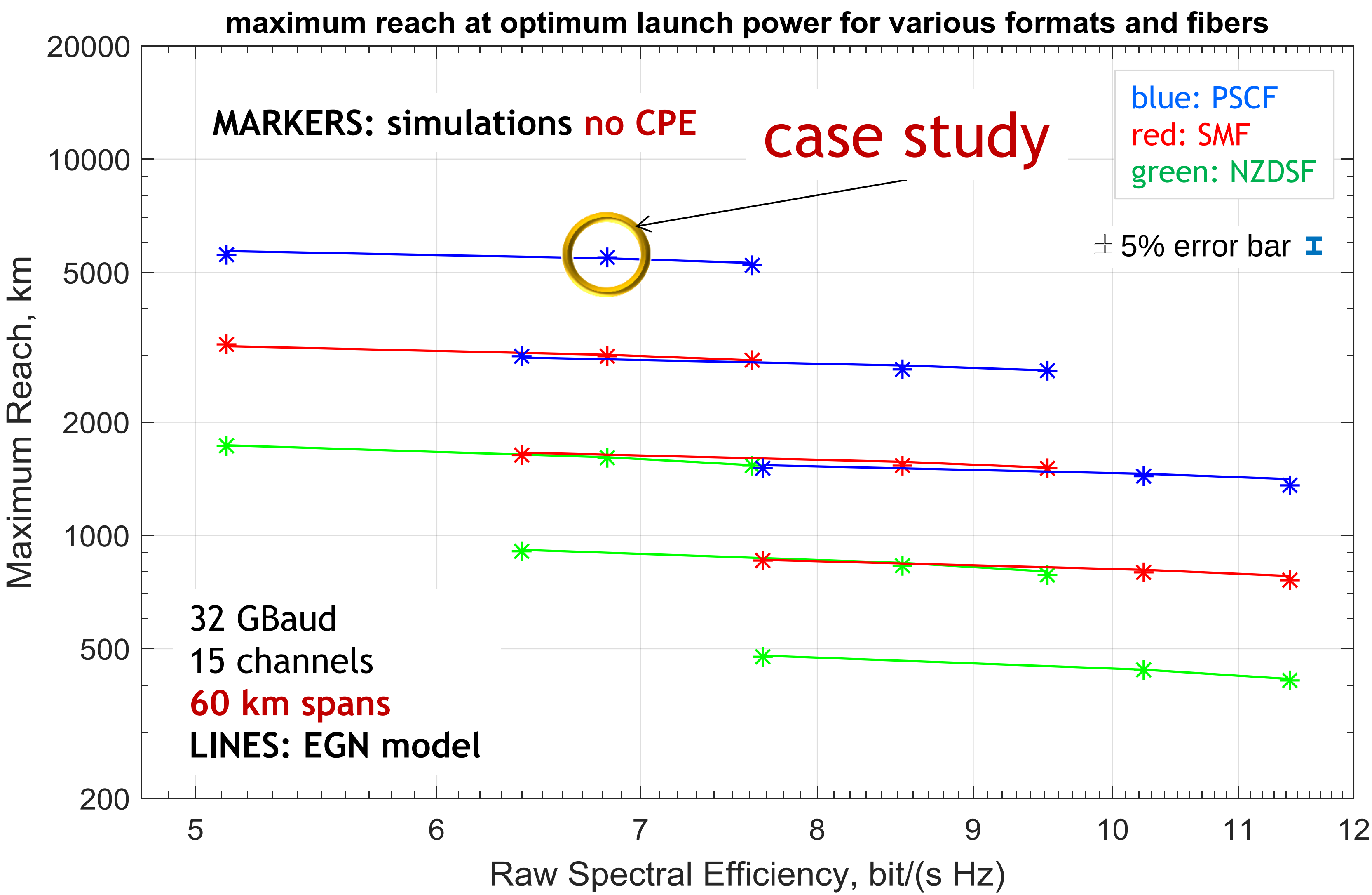
Does it work?

- <u>study case</u>:
  PSCF, 60km spans, PM-16QAM, 15 channels, at 6000 km (about max reach)

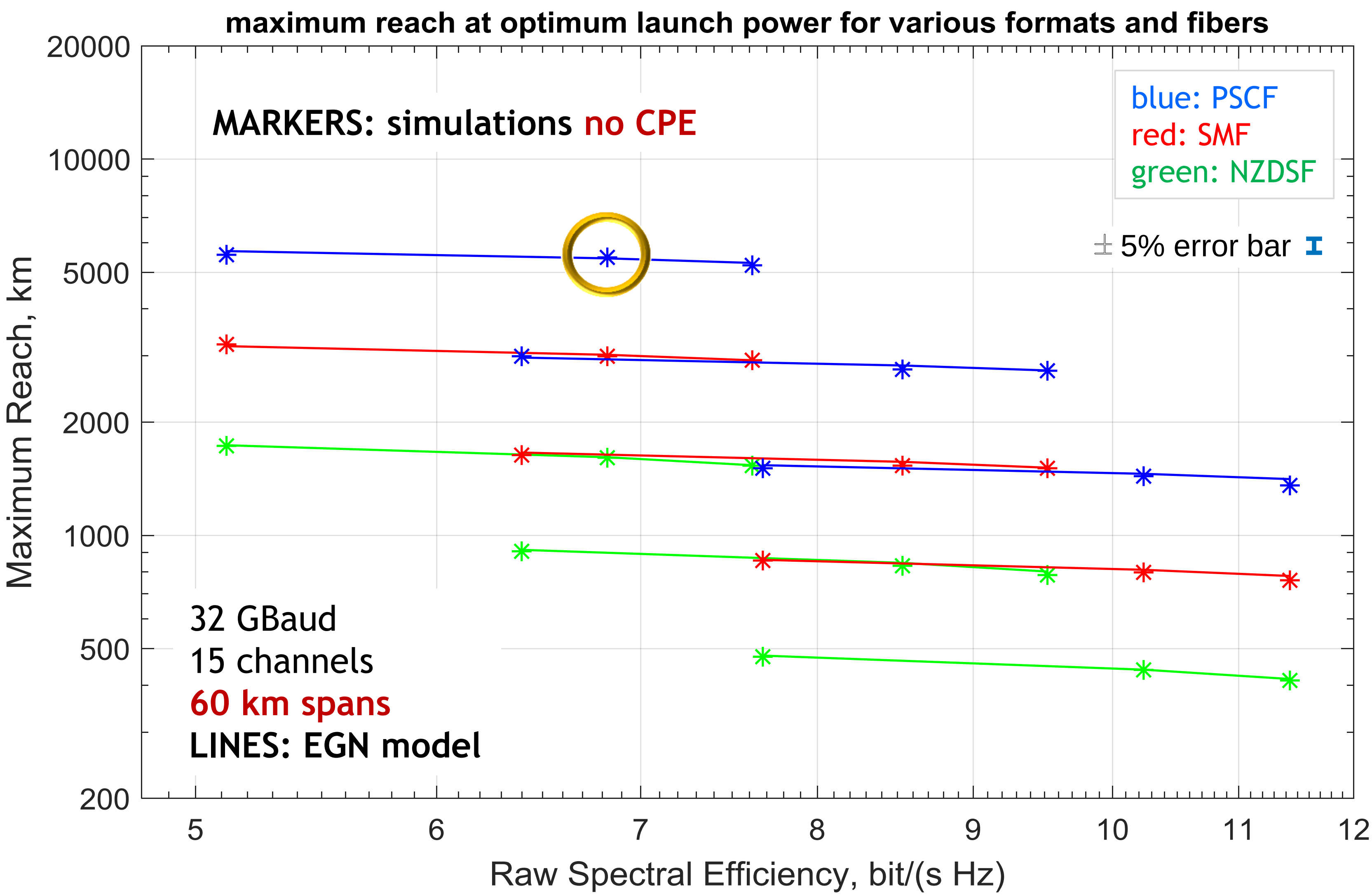




- ... but what is the system impact ?

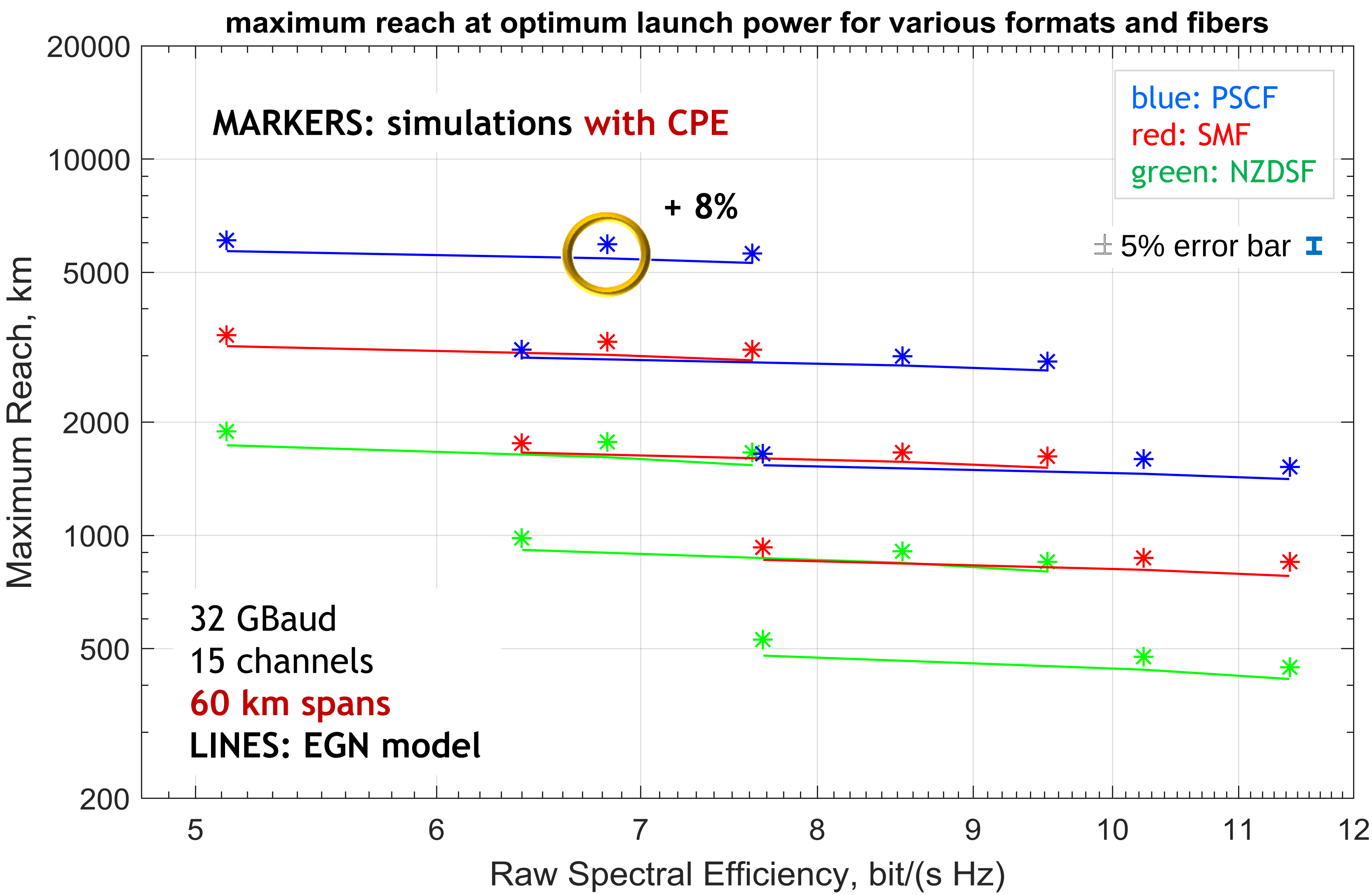

maximum reach at optimum launch power for various formats and fibers
MARKERS: simulations no CPE
case study
blue: PSCF
red: SMF
green: NZDSF
± 5% error bar
32 GBaud
15 channels
60 km spans
LINES: EGN model
Maximum Reach, km
20000
10000
5000
2000
1000
500
200
5
6
7
8
9
10
11
12
Raw Spectral Efficiency, bit/(s Hz)

The big picture

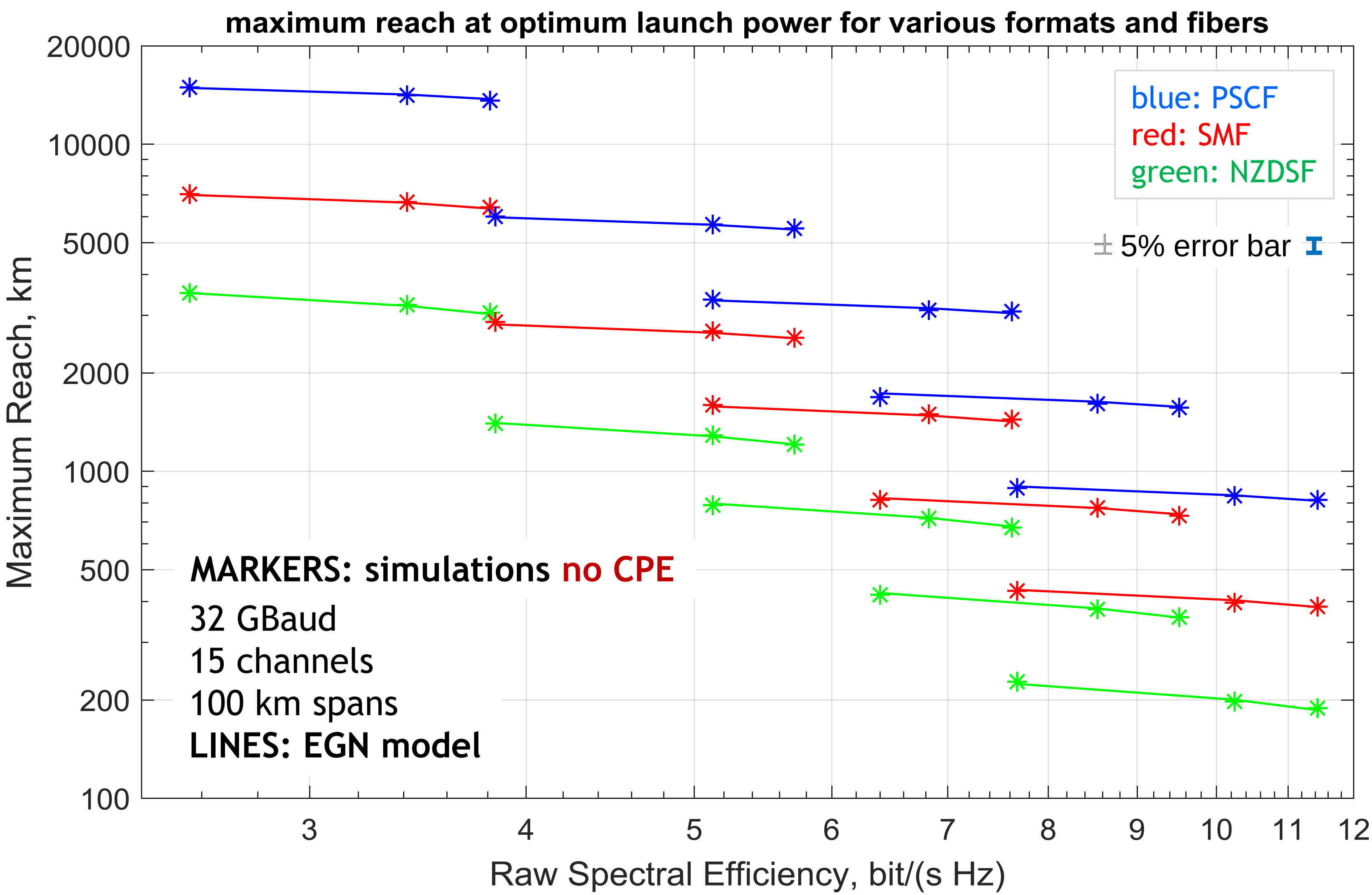


The big picture

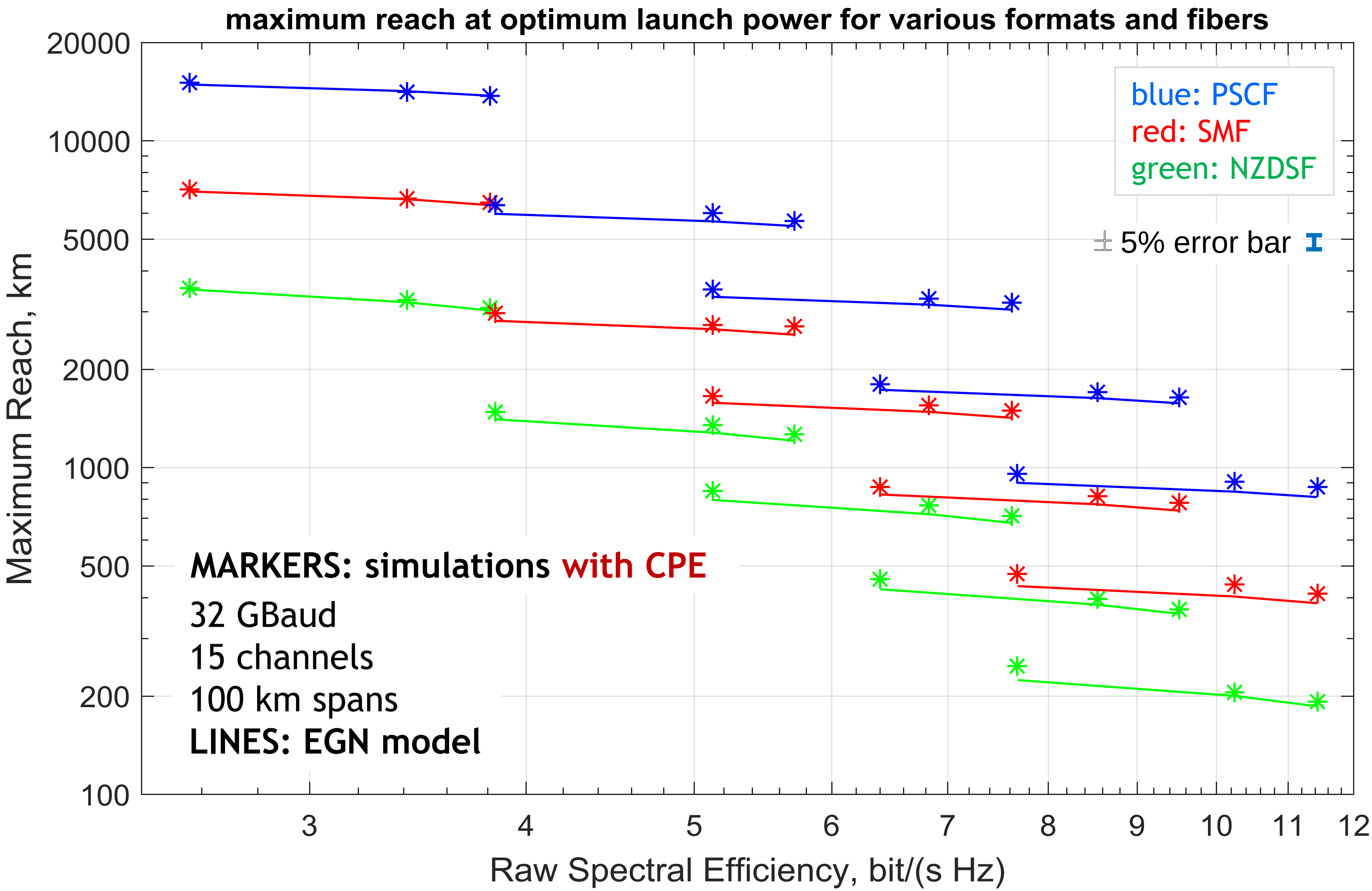
OPTCOM



The big picture



The big picture



Comments

OPTCOM

- The max-reach “CPE” gain is *substantial* for 60 km spans
  - average on the big picture is 8.6%, peak is 12%

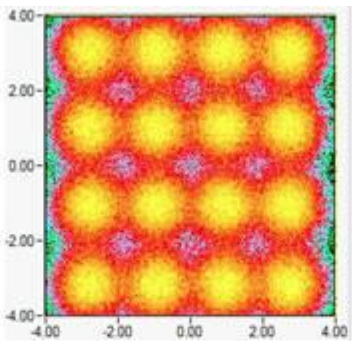
- The max-reach “CPE” gain is *modest* for 100km spans
  - average on the on the big picture is 2.5%, peak is 4.7%
  - less than 1% MR gain for PM-QPSK

- These results are in agreement with many recent papers, for instance see:
  M. Secondini, E. Forestieri, “On XPM Mitigation in WDM Fiber-Optic Systems”, PTL, vol. 26, pp. 2252- 2255, Nov. 2014.

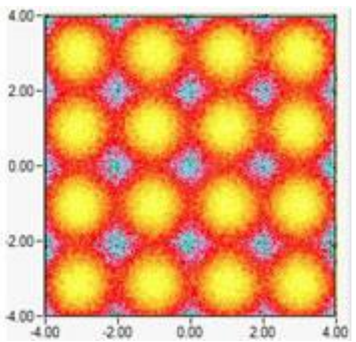
Is the gain already in the systems ?

- In actual systems, the non-linear phase-noise cancelation gain *is probably already there* due to receiver standard CPE operation

Ch108



Ch256



55 km spans
10250 km
150 μ^2 PSCF

Jin-Xing Cai, Yu Sun, Hongbin Zhang, Hussam G. Batshon, Matt Vincent Mazurczyk, Oleg V. Sinkin, Dmitri G. Foursa, and Alexei Pilipetskii, "49.3 Tb/s Transmission Over 9100 km Using C+L EDFA and 54 Tb/s Transmission Over 9150 km Using Hybrid-Raman EDFA," v. 33, n. 13, pp. 2724-2734, July 2015

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

Ideal suppression of NL phase noise in lumped-amplification systems can bring about
5%-10% max reach gains in systems with short spans, about 2%-4% in systems with long spans.

Likely, many systems already do it with their CPEs.

credit: http://www.nfafranchiseconsultants.com/alternatives-financial-performance-representations/

- Can the effect of CPE be *modeled easily* ?

Can we account for CPE?

- Can the effect of the CPE be accounted for *easily* ?

- Excellent models exist but they add further complexity
  - see the cited recent papers by
    - Secondini, Forestieri
    - Dar, Feder, Mecozzi, Shtaif

- We tried to find if there was a very simple way of assessing CPE gains, *at least approximately*, which required minimal further complexity

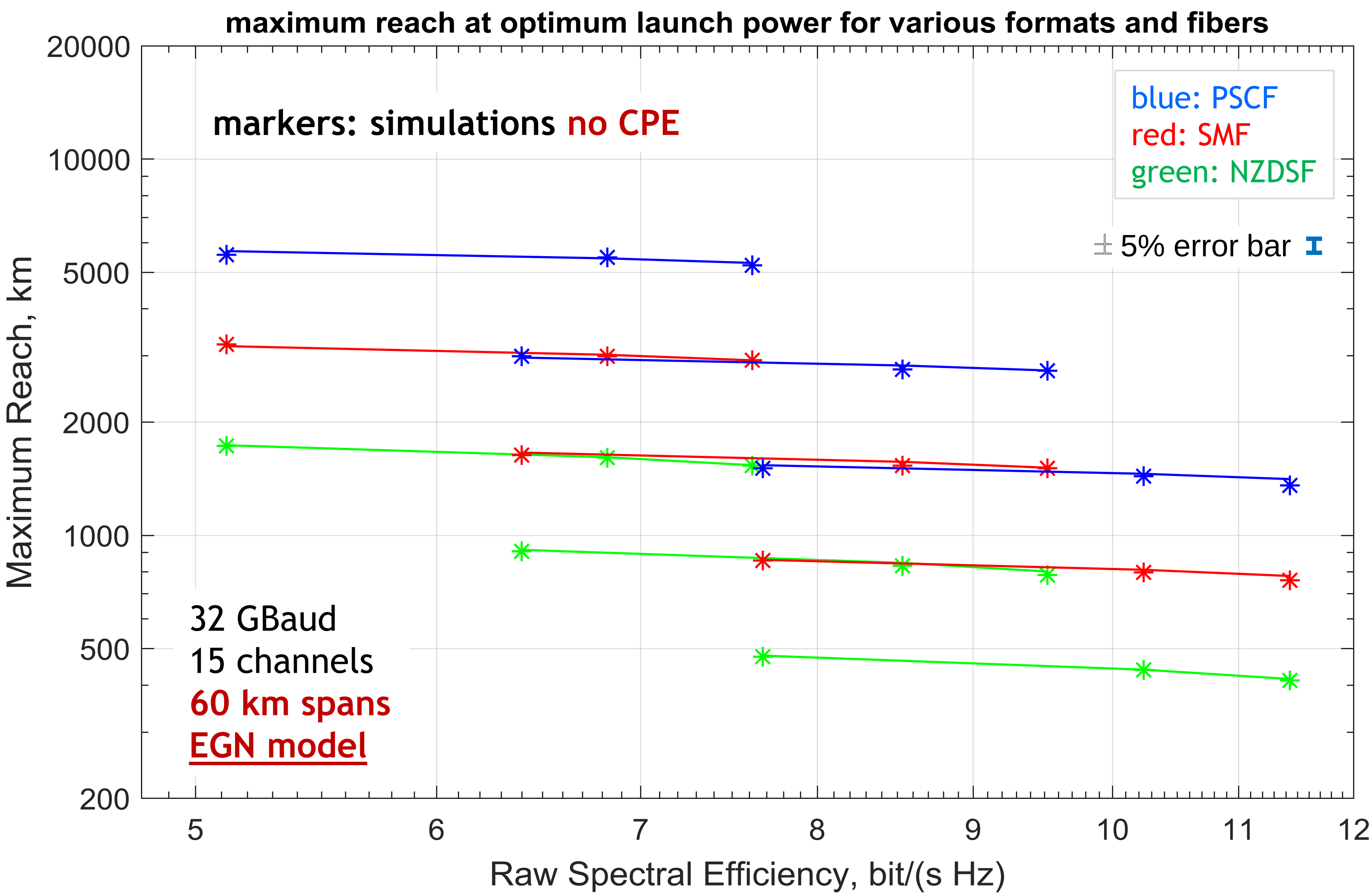
Practical implication

- Through extensive numerical investigation and with *experimental confirmation* we have found out that

  - **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

- No modeling overhead !


maximum reach at optimum launch power for various formats and fibers
markers: simulations no CPE
blue: PSCF
red: SMF
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5% error bar
32 GBaud
15 channels
60 km spans
EGN model
Maximum Reach, km
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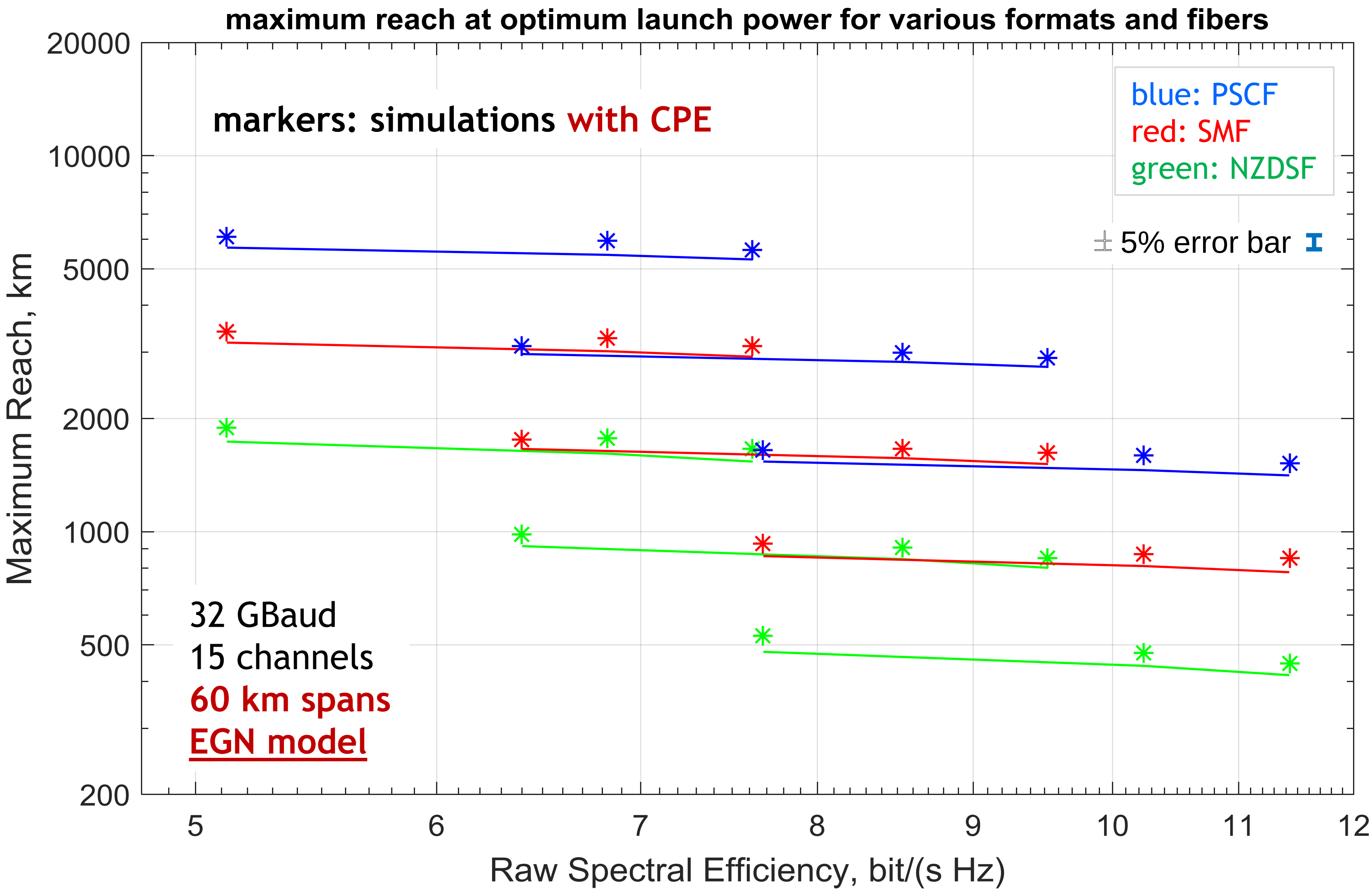
12
Raw Spectral Efficiency, bit/(s Hz)


maximum reach at optimum launch power for various formats and fibers
markers: simulations with CPE
blue: PSCF
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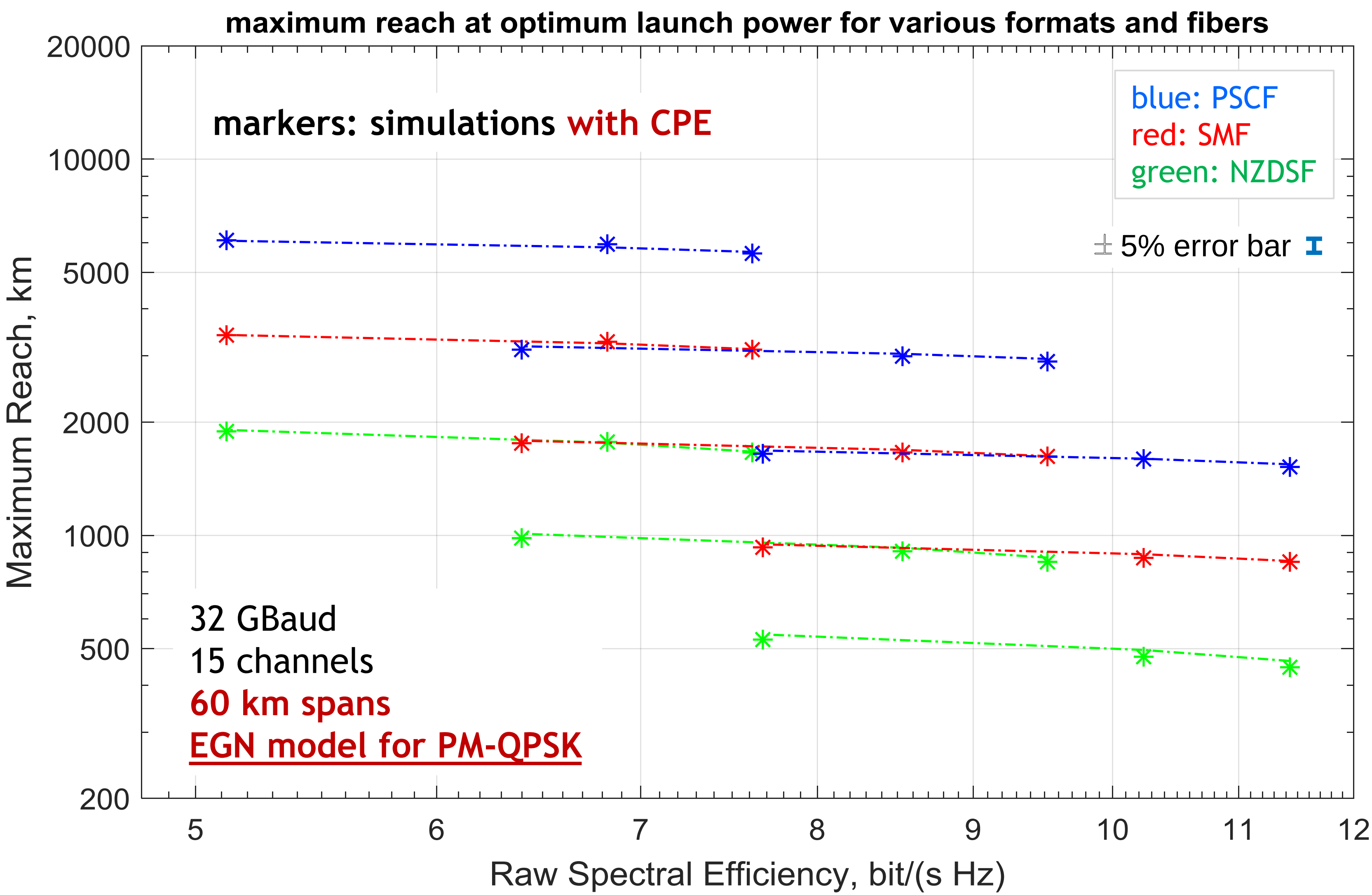
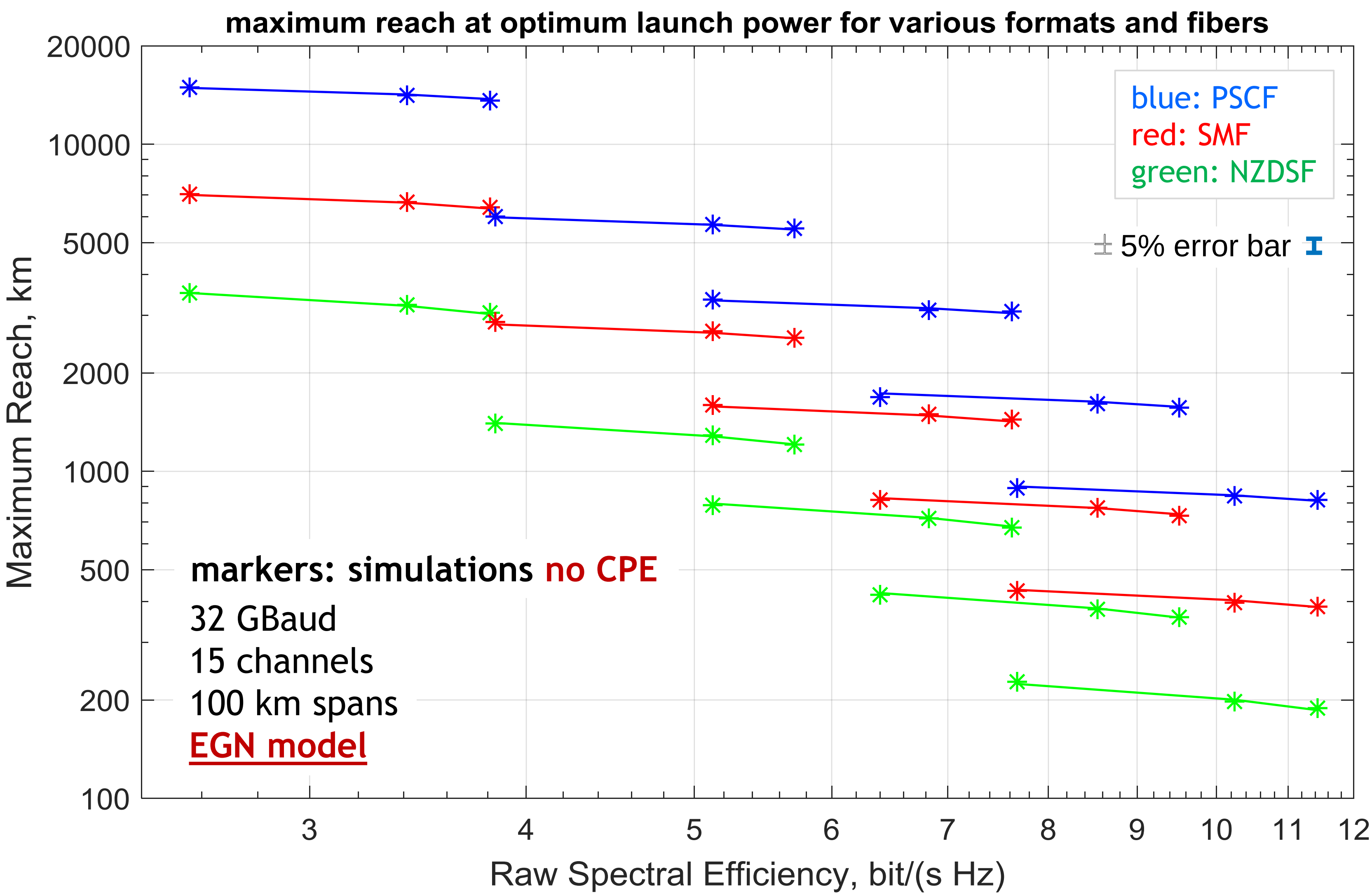
Raw Spectral Efficiency, bit/(s Hz)

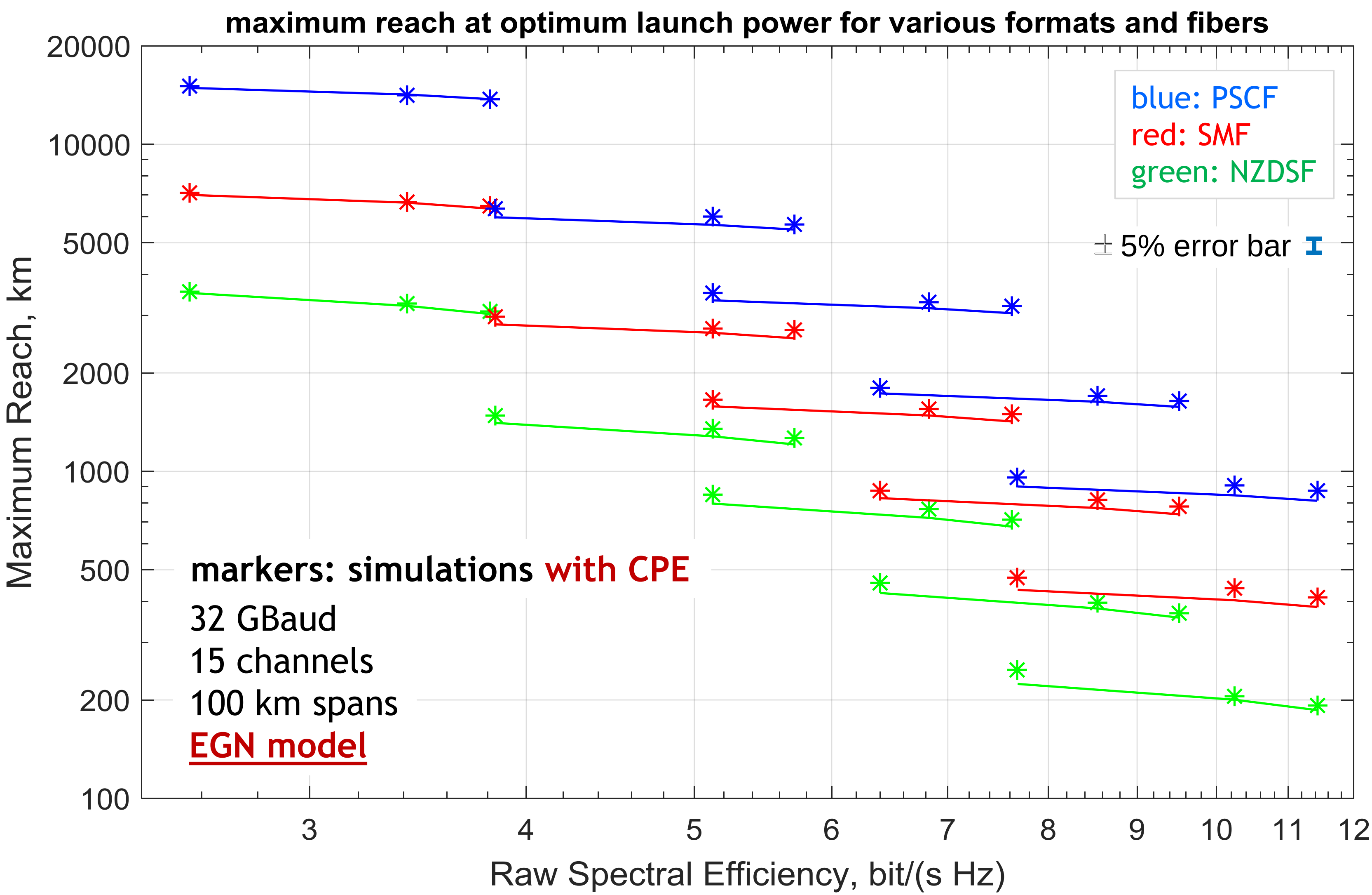
The big picture



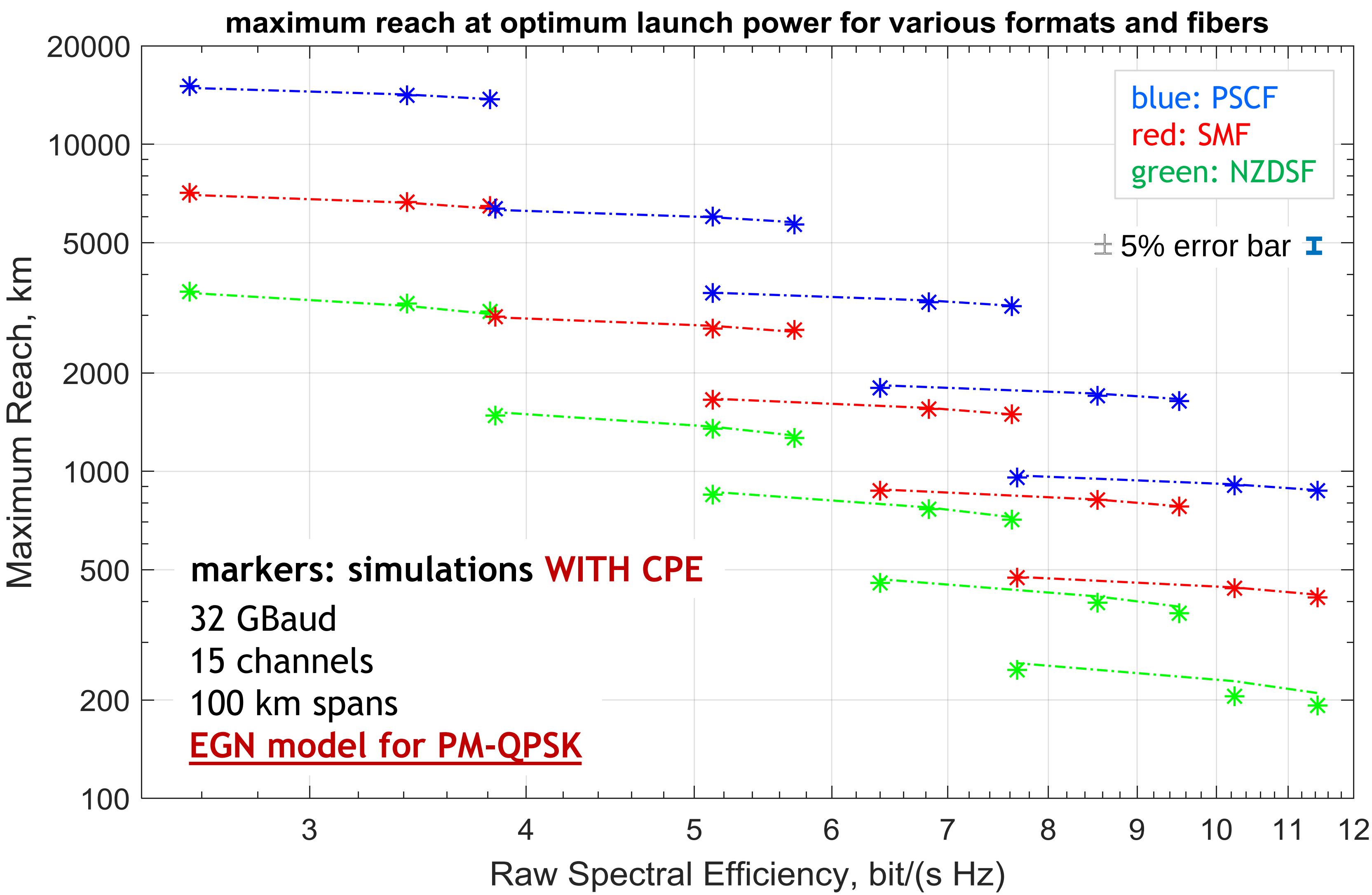
The big picture



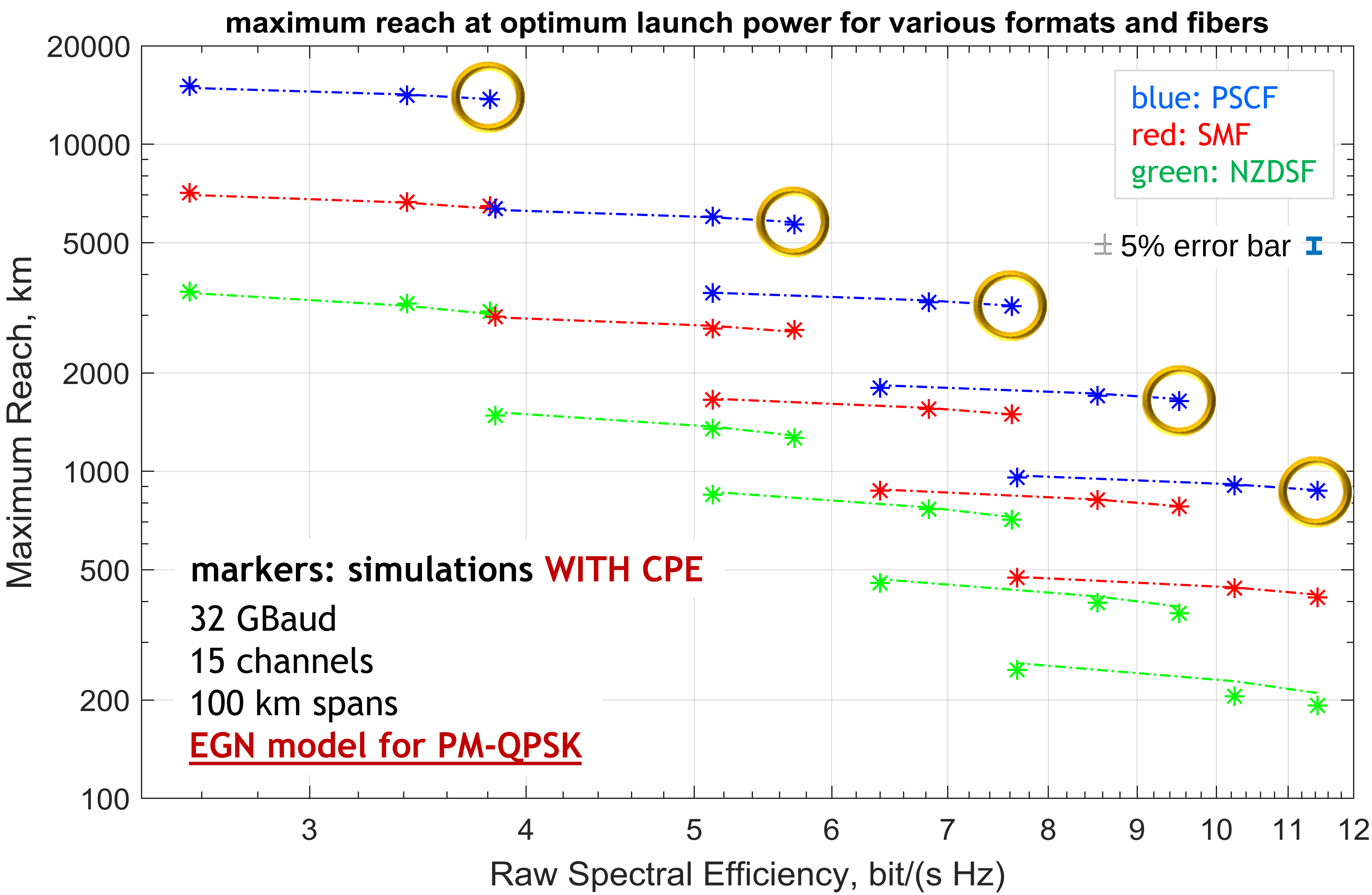
The big picture



The big picture



The big picture



NLI accumulation study

OPTCOM

$\tilde{P}_{NLI}$

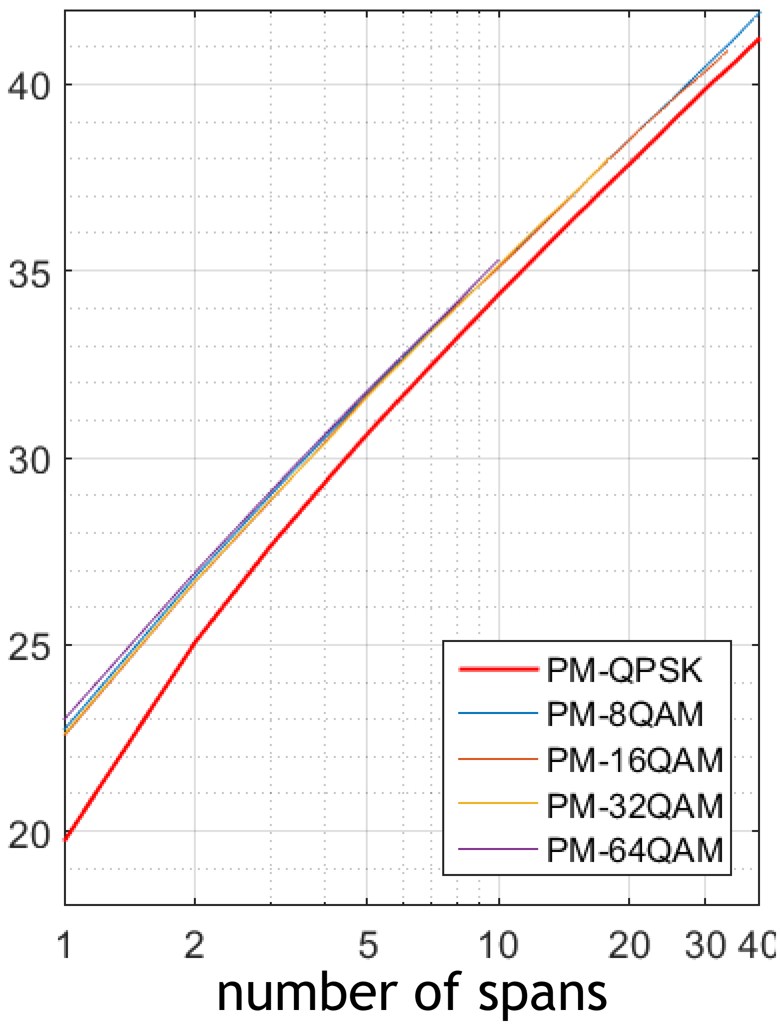
$1/W^2$

dB

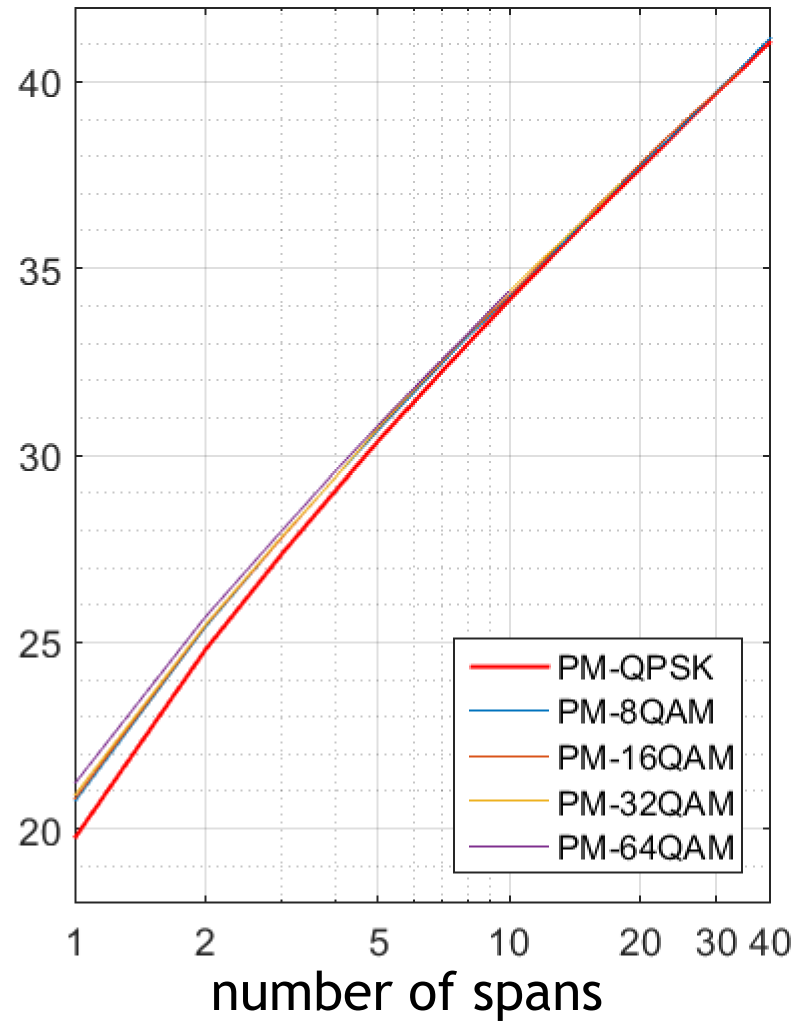
PSCF
100 km
Spans

See circles prev. slide

NO CPE



CPE



Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- When all the long-correlated phase noise is taken out ideally, then:

any PM-QAM format is well described by the EGN model calculated as if PM-QPSK was transmitted

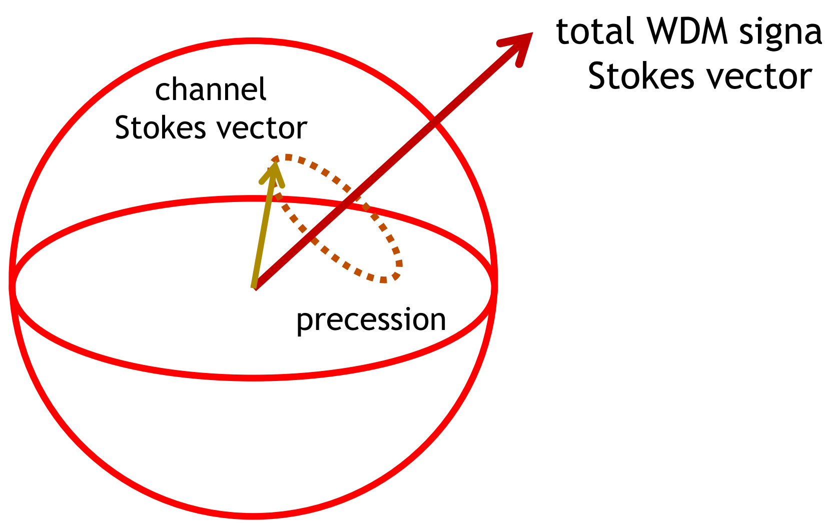
- Warning: in short-reach (< 300 km) it is difficult to take out all non-linear phase noise

Non-linear polarization noise

- What is non-linear polarization noise (PolN) ?

- Each channel Stokes vector, at each point in time/space, “precedes” about an axis, which is the overall WDM signal Stokes vector

  D. Wang and C. R. Menyuk, “Polarization Evolution Due to the Kerr Nonlinearity and Chromatic Dispersion”, JLT, vol. 17, pp. 2520-2529, Dec. 1999



Only crosstalk remains

- Polarization noise has itself a *phase* and a *crosstalk* component

- In the previous simulations, we used *two independent CPEs* to remove phase noise, one per polarization
- It turns out that this strategy already removes the phase component of the non-linear "polarization noise"

- *Only the "crosstalk component" remains to be removed*

- See more details as extra slides at the bottom of this file
- Only the key take-away is reported in the next slide

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- Introducing a cross-polarization noise estimator/canceler in the receiver may provide average reach gains of about 3%

Modeling Raman

Modeling and RAMAN

- Most models allow to take full account of Raman amplification
- Any span loss/gain profile can be inserted into the equations and numerical integration performed

- However, the most common Raman systems are:
  - backward-pumped
  - *hybrid*, with an EDFA supplying part of the gain

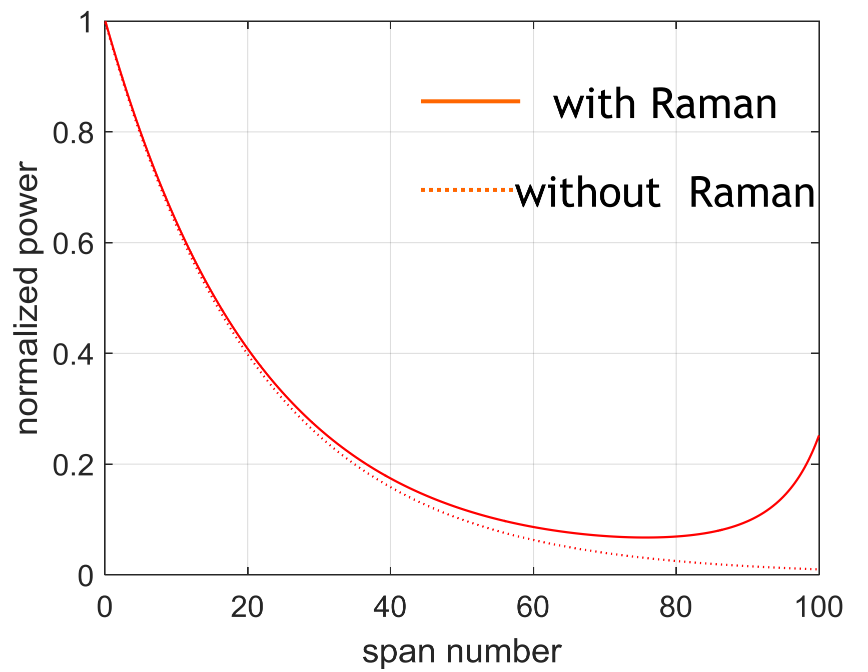
- In these systems, the effect of Raman on NLI may be rather small

  V. Curri, A. Carena, "Merit of Raman pumping in uniform and uncompensated links supporting NyWDM", JLT, v. 34, n.2, pp. 554-565, Jan. 2016.

Power profile in the span

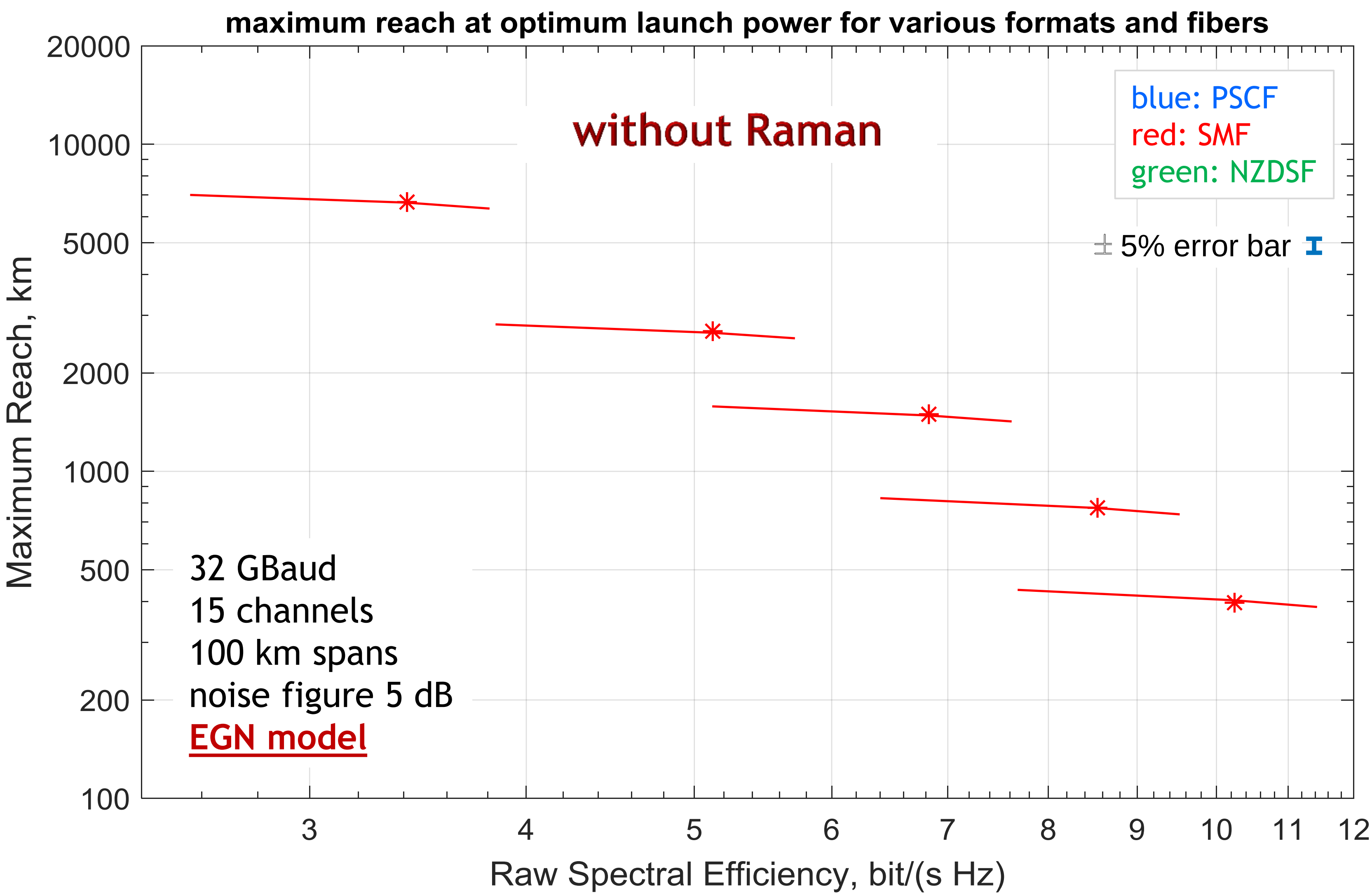
- We specifically addressed the case of
  - SMF, 100 km spans, *20 dB span loss*
  - *14 dB Raman gain*

- The signal at the end of the span is *6 dB* lower than at the beginning
  - That is, the "signal gap" is 6 dB



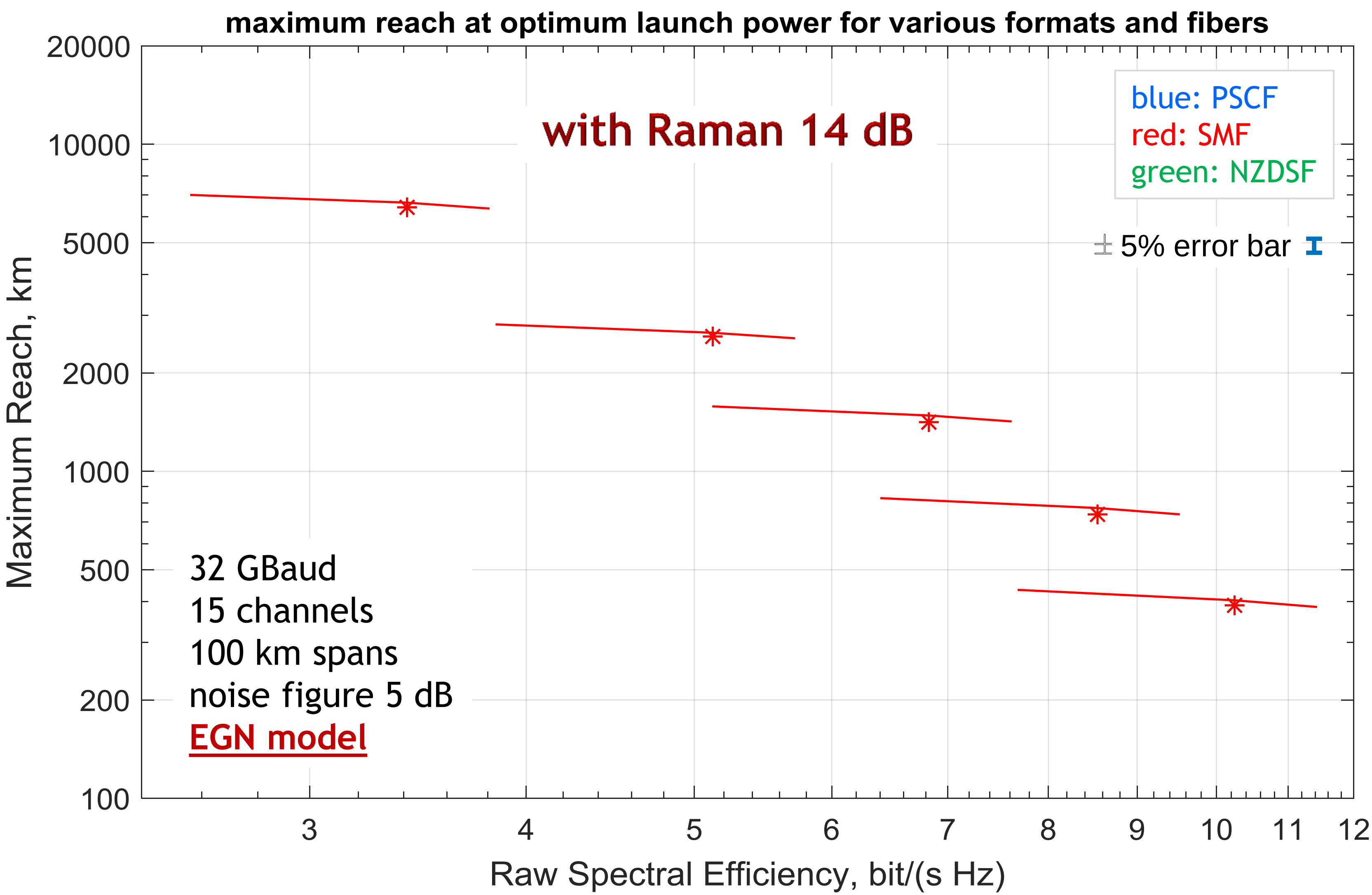
- To single-out the NLI impact, we did not change the *the span noise figure* (kept it at 5 dB)

The big picture



The big picture

OPTCOM



Comments

- The average max reach loss is about 3%, across all formats

- It actually goes down to only 2% if CPE is used
  - this means that some part of the extra NLI is in the form of long-correlated non-linear phase noise

- If the signal gap is less than 6 dB, *the link function μ needs to take Raman explicitly into account*

  - see for example Eq. (12) in:
    P. Poggiolini "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *J. of Lightwave Technol.*, vol. 30, no. 24, pp. 3857-3879, Dec. 15 2012.
  - see also:
    V. Curri et al., "Extension and validation of the GN model for non-linear interference to uncompensated links using Raman amplification," Optics Express, v. 21., no. 3, pp. 3308-3317, Feb. 2013.

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- The effect of hybrid Raman amplification on NLI generation <u>can be neglected</u> if:

- Raman is backward-pumped
- The power at the end of the span is at least <u>*6 dB lower*</u> than at the beginning of the span

Special effect #4 and #5

Modeling inline-ASE and signal depletion

Modeling and in-line ASE

- ASE noise is injected into the system at every span
- Models typically neglect its contribution to NLI generation

- This is OK as long as the ASE power is small vs. the signal power
- However, when the final Rx target OSNR is less than about 9 dB, ASE starts having a visible impact

  - Simulative evidence with phenomenological modeling corrections
    [A] P. Poggiolini, A. Carena, Y. Jiang, G. Bosco, V. Curri, and F. Forghieri, 'Impact of low-OSNR operation on the performance of advanced coherent optical transmission systems,' in *Proc. of ECOC 2014*, Cannes (FR), Sept. 2014. **Available with corrections on www.arXiv.org, paper arXiv:1407.2223.**

  - Very accurate analytical treatment in the context of the EGN model
    [B] P. Serena, "Nonlinear Signal-Noise Interaction in Optical Links With Nonlinear Equalization," JLT, vol. 34, p. 1476-1483, March 2016

- [B] also shows that ASE can have quite an impact on the effectiveness of NLI mitigation by means of backward propagation (or similar), again at low OSNR

Extra slides

- More details on ASE noise impact investigation can be found in extra slides at the bottom of this file
- Only the key take-away is reported in the next slide

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- The effects of *ASE noise and signal depletion on NLI generation* are significant only for:

$$\boxed{\mathrm{OSNR}_{\mathrm{target}} < 9\ \mathrm{dB}}$$

(*essentially only PM-QPSK is affected*)

- Exact models for ASE are now available (but are complex)
  Very accurate analytical treatment in the context of the EGN model
  P. Serena, "Nonlinear Signal-Noise Interaction in Optical Links With Nonlinear Equalization," JLT, vol. 34, p. 1476-1483, March 2016

Signal depletion

- *The power that becomes NLI noise is "stolen" from the signal, which is "depleted"*
- All first-order perturbation models neglect this effect (they all assume "undepleted signal")

Accounting for signal depletion

$$\mathrm{OSNR} = \frac{P_{\mathrm{ch}}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}}$$

$$\mathrm{OSNR} = \frac{P_{\mathrm{ch}} - P_{\mathrm{NLI}}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}}$$

H. Louchet et al., "Analytical Model for the Performance Evaluation of DWDM Transmission Systems," *IEEE Phot. Technol. Lett., vol. 15, pp.* 1219-1221, Sept. 2003.

P. Poggiolini, A. Carena, Y. Jiang, G. Bosco, V. Curri, and F. Forghieri, 'Impact of low-OSNR operation on the performance of advanced coherent optical transmission systems,' in *Proc. of ECOC 2014*, Cannes (FR), Sept. 2014. Available with corrections on www.arXiv.org, paper arXiv:1407.2223.

this simple correction is quite effective (for the center channel)

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- Signal depletion is significant when :

$$\mathrm{OSNR}_{\mathrm{target}} < 9\ \mathrm{dB}$$

(essentially only PM-QPSK is affected)

- A phenomenological correction is possible which turns out to be quite effective

The future…

credit: http://www.examiner.com/article/where-are-we-going-an-exercise-irresponsible-speculation

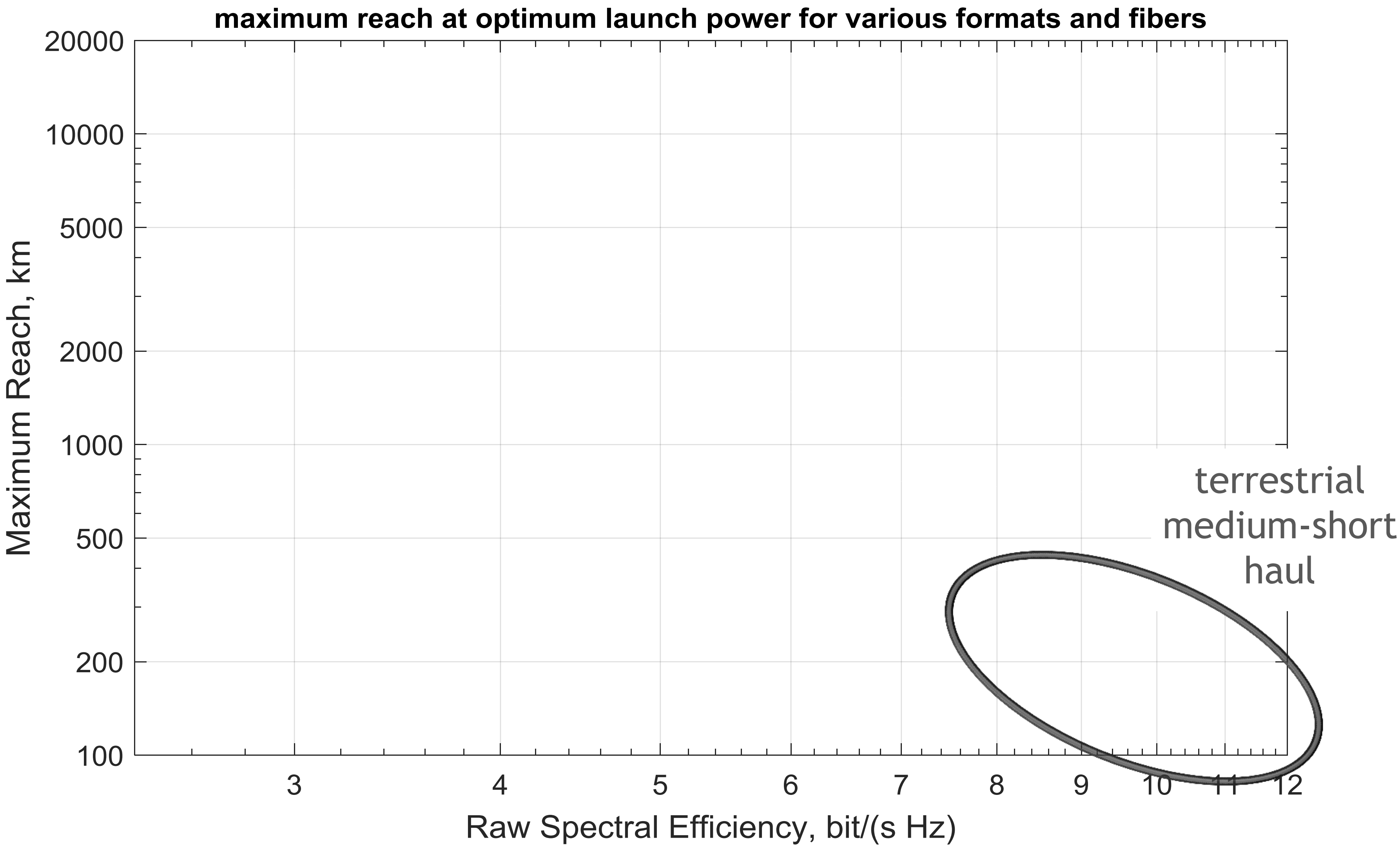
The future

- *Better wider-validity closed-form formulas*
  - which would make the EGN model easily usable, perhaps including some of the "special effects"

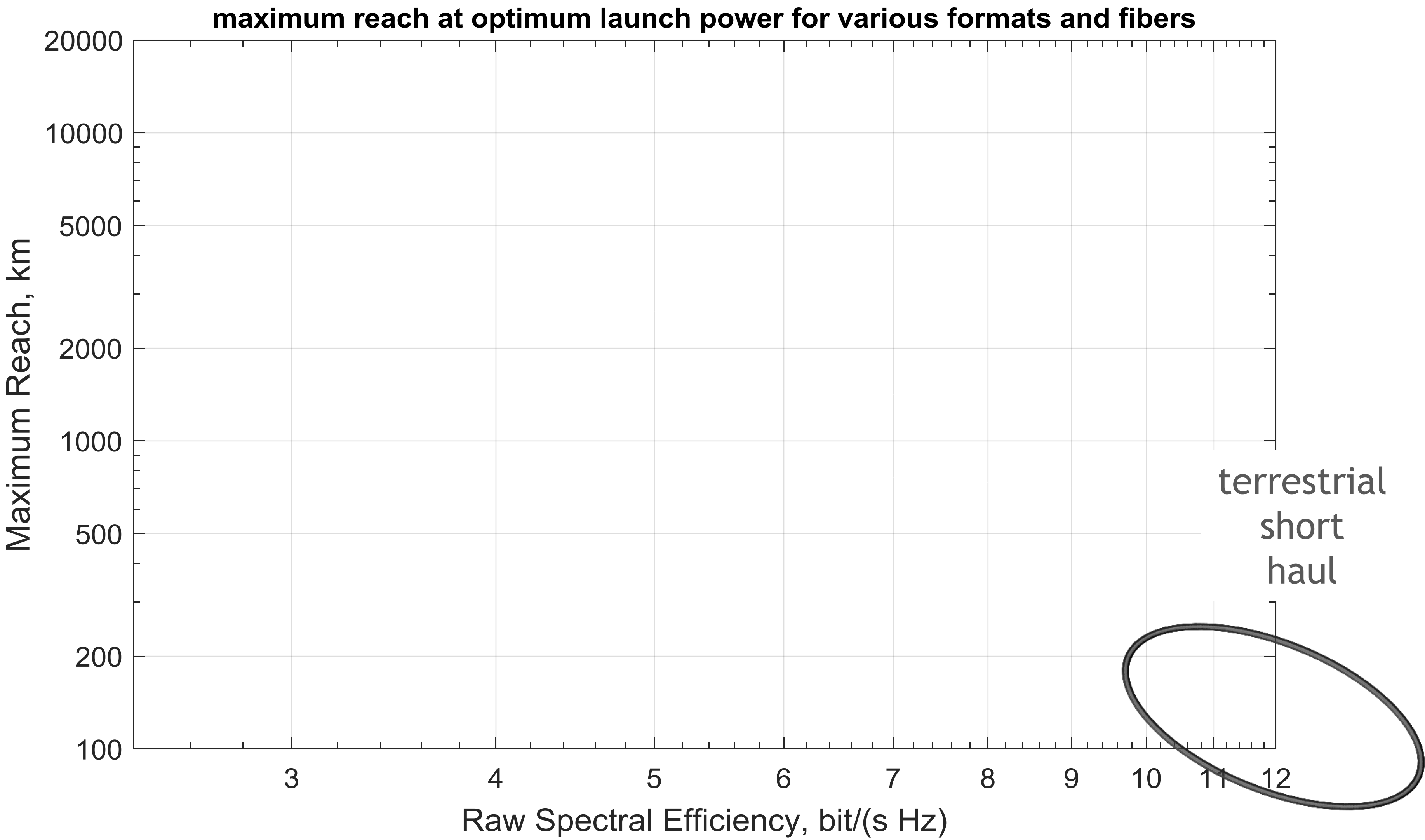
- Tackling in a practical way "*the first 100 km*" for ultra-high capacity short-reach links using super-dense constellations
  - with <u>non-linearity compensation</u> in mind:

    R. Dar, P. Winzer "On the Limits of Digital Back-Propagation in Fully Loaded WDM Systems," PTL, in pre-print, available on IEEE Xplore.

The big picture



The big picture



The future

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- Looking at the potential impact of *probabilistic shaping ("Gaussian Constellations")*

- *Transporting all the above to SDM… ???*

Conclusion...

KEY TAKE AWAY

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

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- Over a wide range of *conventional* system scenarios at 32 GBaud, *the incoherent GN model accuracy vs. simplicity is hard to beat*

- *The EGN model is a super-accurate (but complex) "baseline benchmark" model*

- The "asymptotic" EGN correction formulas can be used to simplify the EGN model, with some limitations

- Non-linear phase noise (NLPN) accounts for about *3% and 9% MR* above the EGN baseline, for long and short spans systems respectively
- *NLPN removal can be accounted for by setting EGN to PM-QPSK*

- Non-linear polarization crosstalk accounts for further *3% MR* increase

- Raman has negligible impact if backward pumped and undercompensating loss *by at least 6 dB*

- Co-propagating ASE is negligible for target *OSNR >9 dB*

- *Signal depletion* can be phenomenologically modeled in a simple way

credit: http://www.nfafranchiseconsultants.com/alternatives-financial-performance-representations/

thank you !

downloadable at www.optcom.polito.it

More slides on Asymptotic formulas

making the EGN simpler

- Is there a way to obtain a much simpler EGN correction?

$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f) = G_{\mathrm{NLI}}^{\mathrm{GN}}(f) - G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

- It is possible to write *"asymptotic"* *closed-form* *expressions of the correction term*

Asymptotic correction formulas

- These formulas are *asymptotic in the number of spans*, they get more accurate as the number of spans goes up

- Initially proposed here:
  - 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.

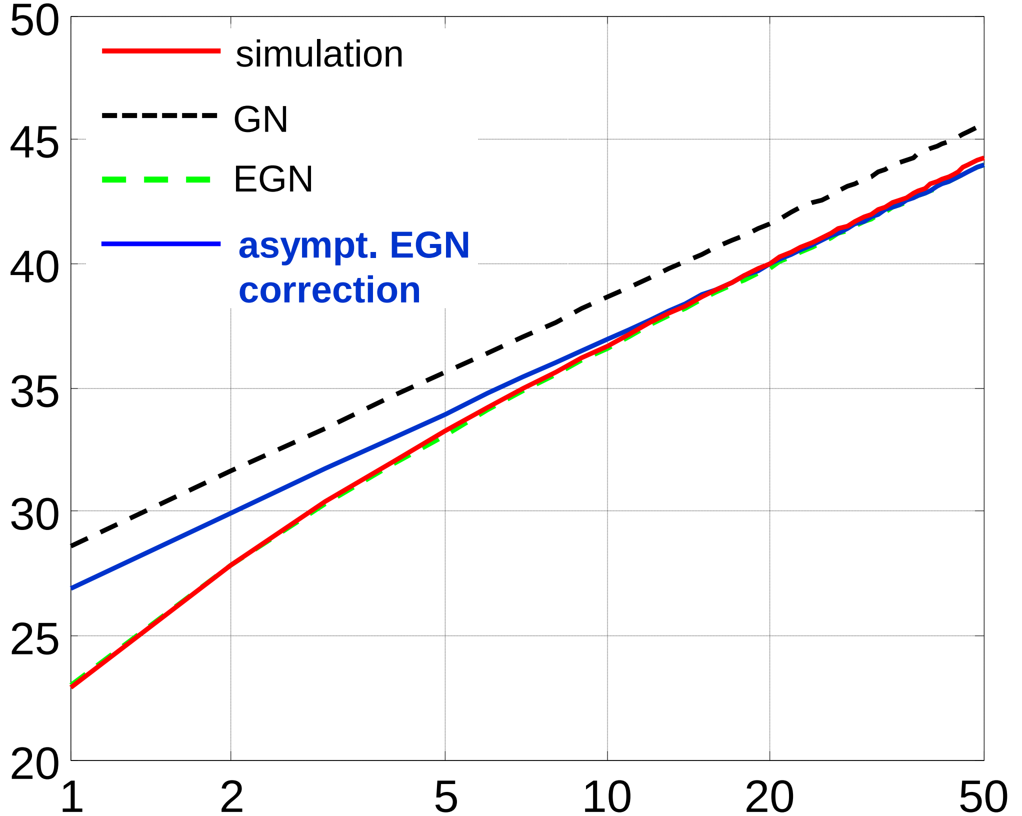
- Now *substantially improved and extended* to better handle low Baud rates and low dispersion, up to C band

The asymptotic correction

PM-QPSK, 15 channels, 32 Gbaud, 33.6 GHz spacing, roll-off 0.05, SMF, 100 km spans, (SPM removed)

$\tilde{P}_{\rm NLI}$

$1 / \mathrm{W}^2$, dB



number of spans

The (simple) asymptotic formula

- The formula for the NLI correction for the center channel in the comb is:

$$G_{\mathrm{NLI}}^{\mathrm{corr}} \approx N_s \Phi \frac{80}{81} \frac{\gamma^2 L_{\mathrm{eff}}^2 P_{\mathrm{ch}}^3}{R^2 \Delta f \pi |\beta_2| L_s} \left[\mathrm{HN}\left(\frac{N_{\mathrm{ch}}-1}{2} \right) + \frac{\Delta f}{R} \right]$$

note:

$$\mathrm{HN}(K) = \sum_{k=1}^{K} \frac{1}{k}$$

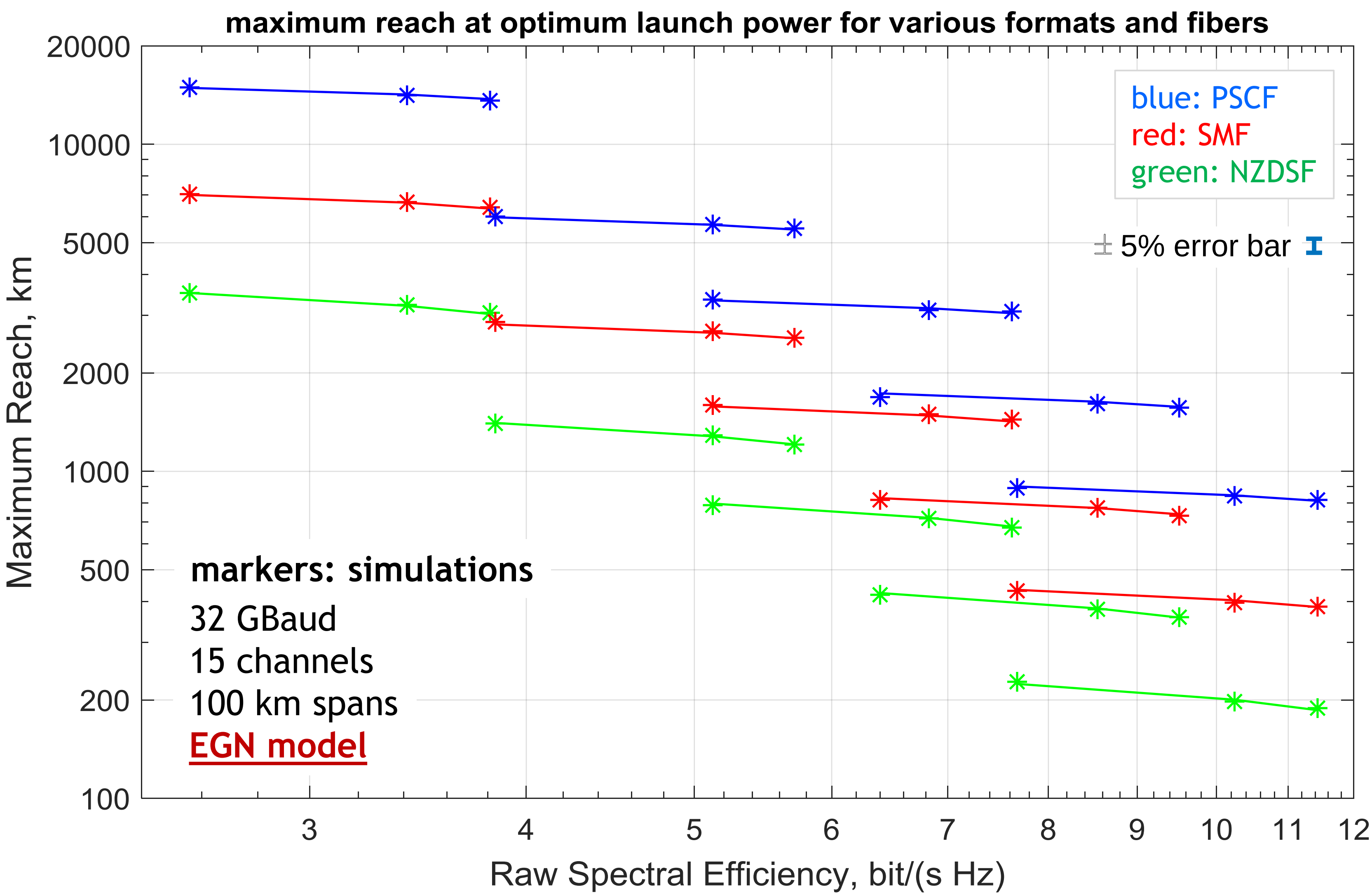
- This version assumes all identical channels but it can be generalized:
  Xiang Zhou and Chongjin Xie Editors, Enabling Technologies for High Spectral-efficiency Coherent Optical Communication Networks, John Wiley & Sons, Chapter 7, by P. Poggiolini, Y. Jiang, A. Carena, F. Forghieri, ISBN 9781118714768

- *Limitations: loses accuracy at very low symbol rates*
  - use it only when:

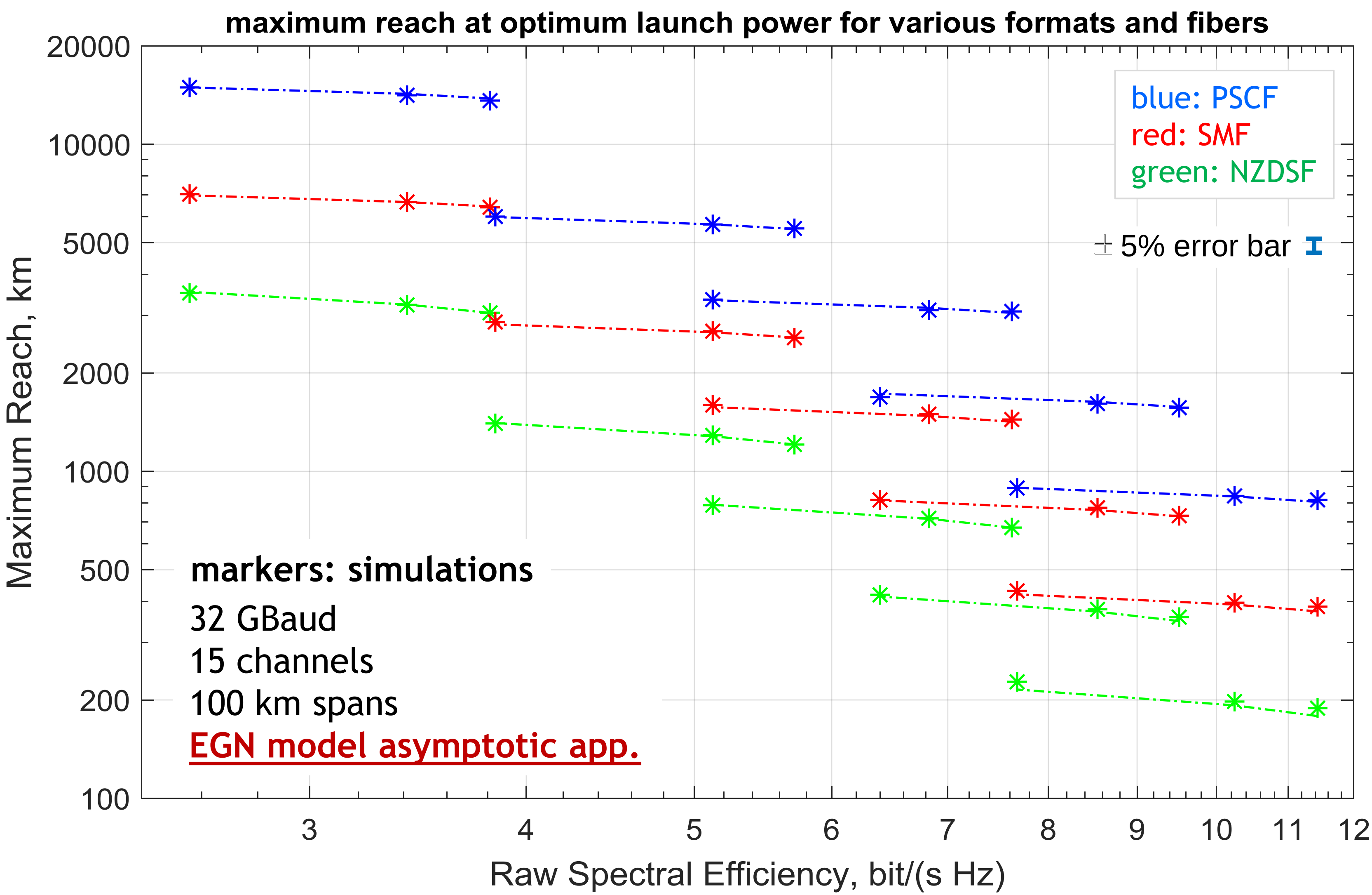
$$R \gg \sqrt{2 / \left(\pi |\beta_2| L_s N_s \right)}$$

  - for typical SMF systems the RHS is 2 to 4 GBaud, so R>10 GBaud

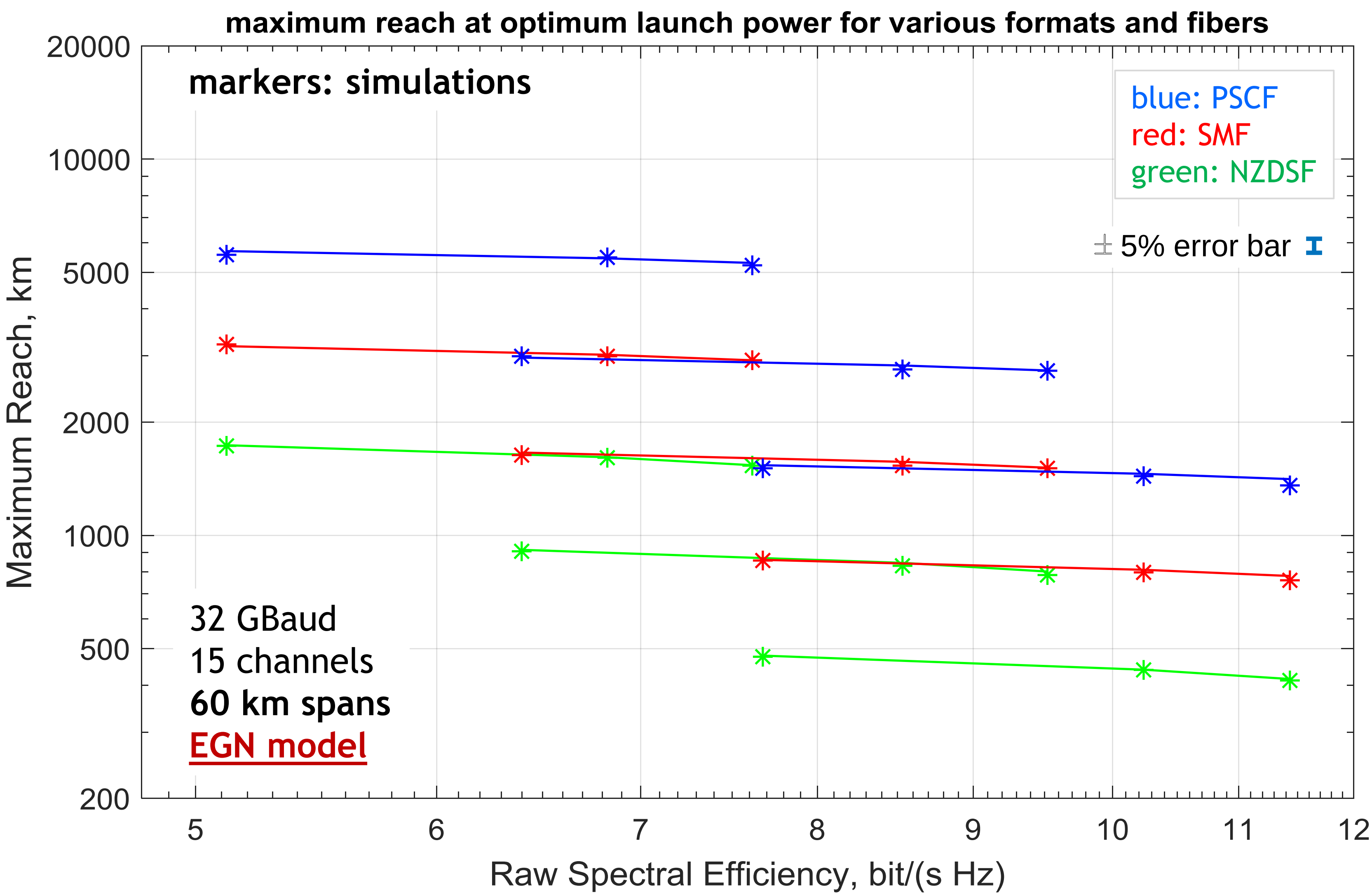
The big picture



The big picture

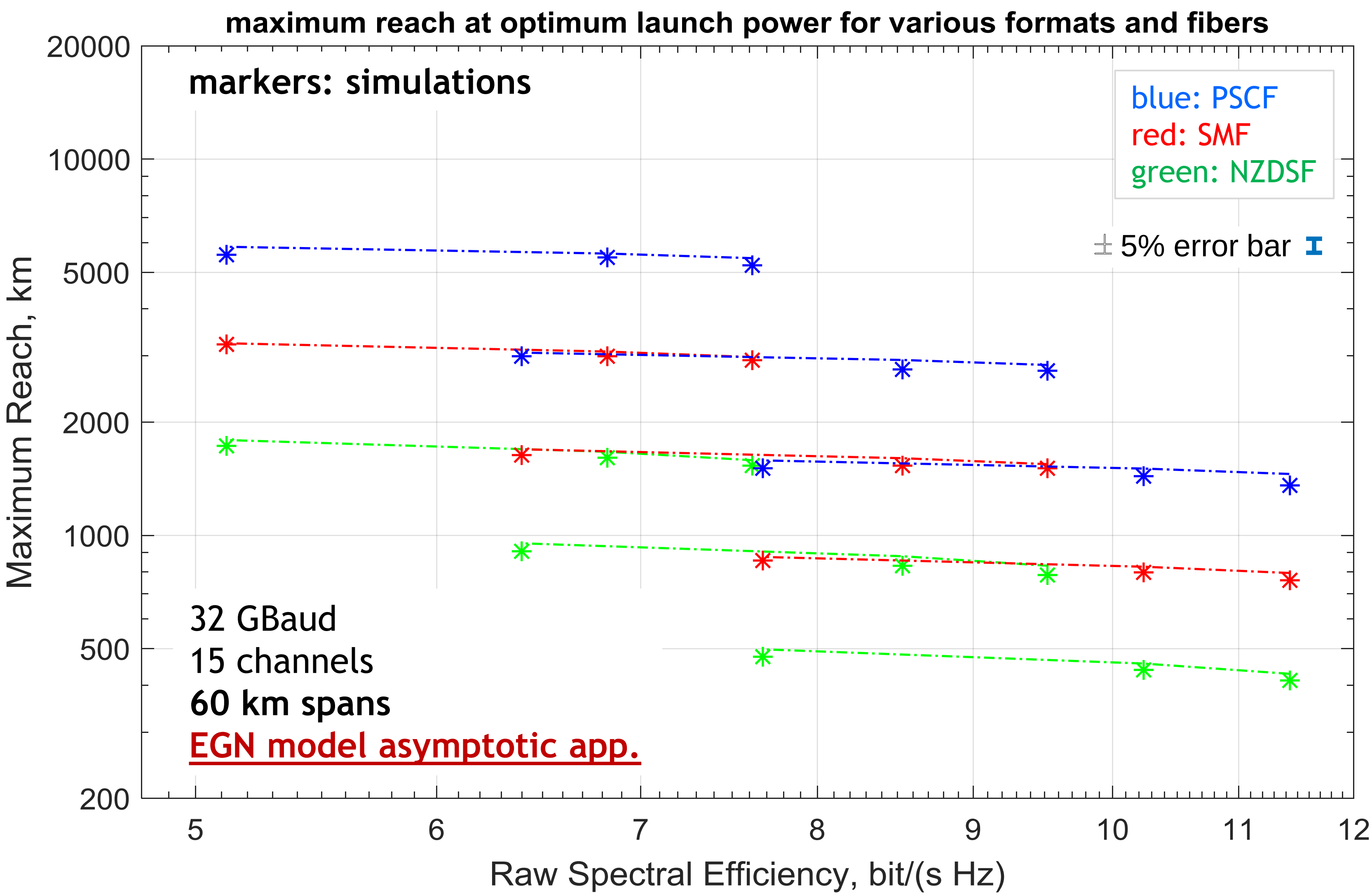


The big picture



The big picture

OPTCOM



The more complex version…

- A more complex but still closed-form formula is available which is *valid down to the optimum symbol rate*

$$G_{\text{NLI}}^{\text{corr}} \approx \Phi \frac{80}{81} R_s^{-2} \gamma^2 P_{\text{ch}}^3 \frac{L_{\text{eff}}^2}{\pi L_s \Delta f} N_s \left\{ HN\left(\left[N_{\text{ch}}-1\right]/2\right) + \frac{\Delta f}{R_s}\left(1-\frac{R_{\text{opt}}}{R_s}\right) \right.$$

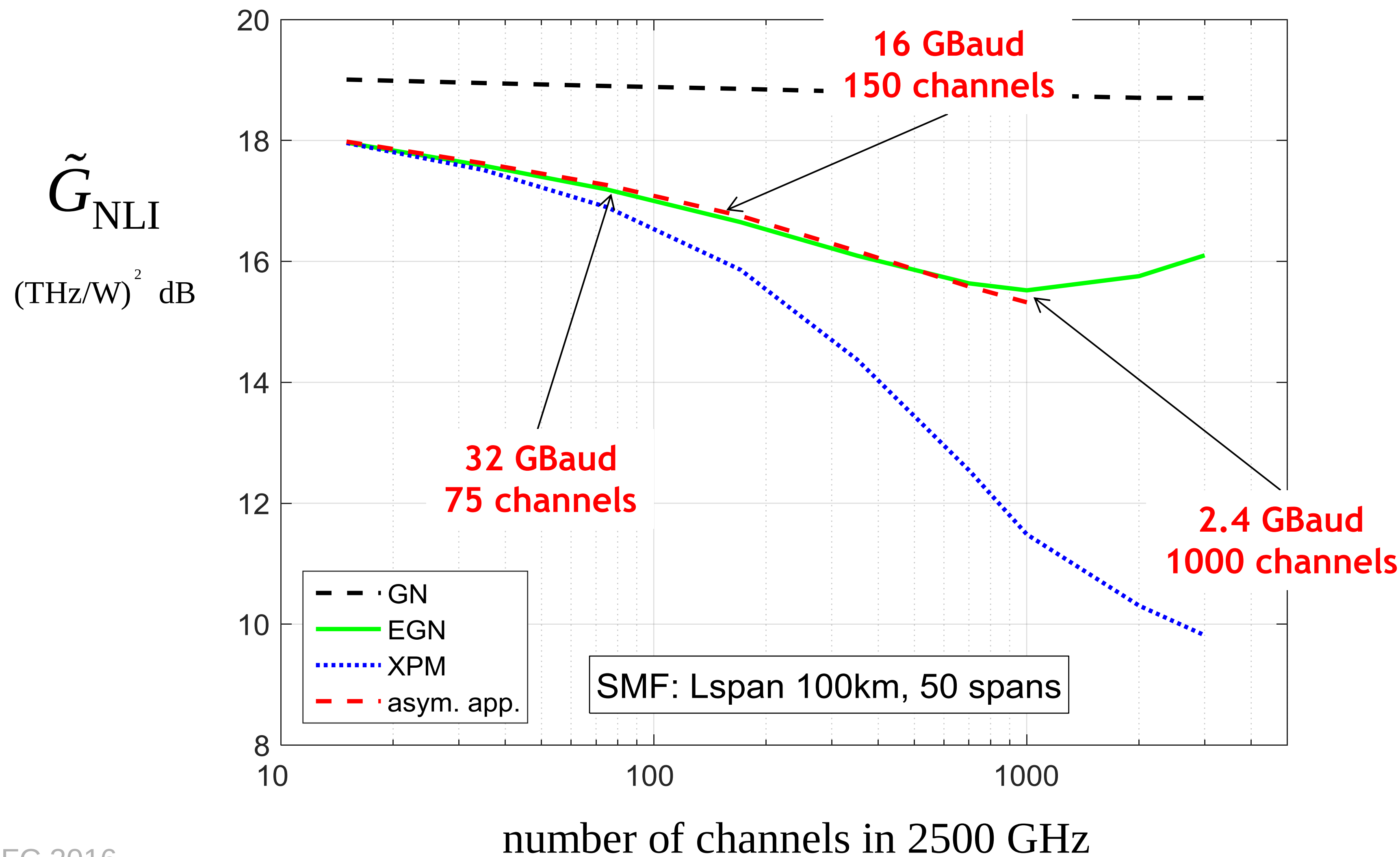
$$+\frac{\pi}{2} \sum_{n_{\text{ch}}=1}^{(N_{\text{ch}}-1)/2} \sum_{n=1}^{N_p} \frac{\Delta f}{N_s} \frac{1}{1+\frac{n^2\pi^2}{(\alpha L_s)^2}} \frac{1}{2n\pi^2} \frac{\left(1+\frac{2n_{\text{ch}}\Delta f}{nN_sR_s}\right)}{1-\left(\frac{R_s}{2n_{\text{ch}}\Delta f}\right)^2} \cdot$$

$$\left. \left[\operatorname{sinint}\left((2N_s-1)\frac{n\pi R_s}{2n_{\text{ch}}\Delta f} \right) + \operatorname{sinint}\left(\frac{n\pi R_s}{2n_{\text{ch}}\Delta f} \right) \right]^2 \right\}$$

$$N_p = \left\lfloor n_{\text{ch}} \pi \beta_2 L_s R_s \Delta f \right\rfloor \qquad R_{\text{opt}} = \sqrt{2\Big/\left(\pi \left|\beta_2\right| L_{\text{span}} N_{\text{span}}\right)}$$

Test at 2.4 THz of bandwidth

- B_{WDM} = **2.4 THz**, PM-QPSK, 100 km spans, spacing 1.05 x (symb. rate)



Key take-away

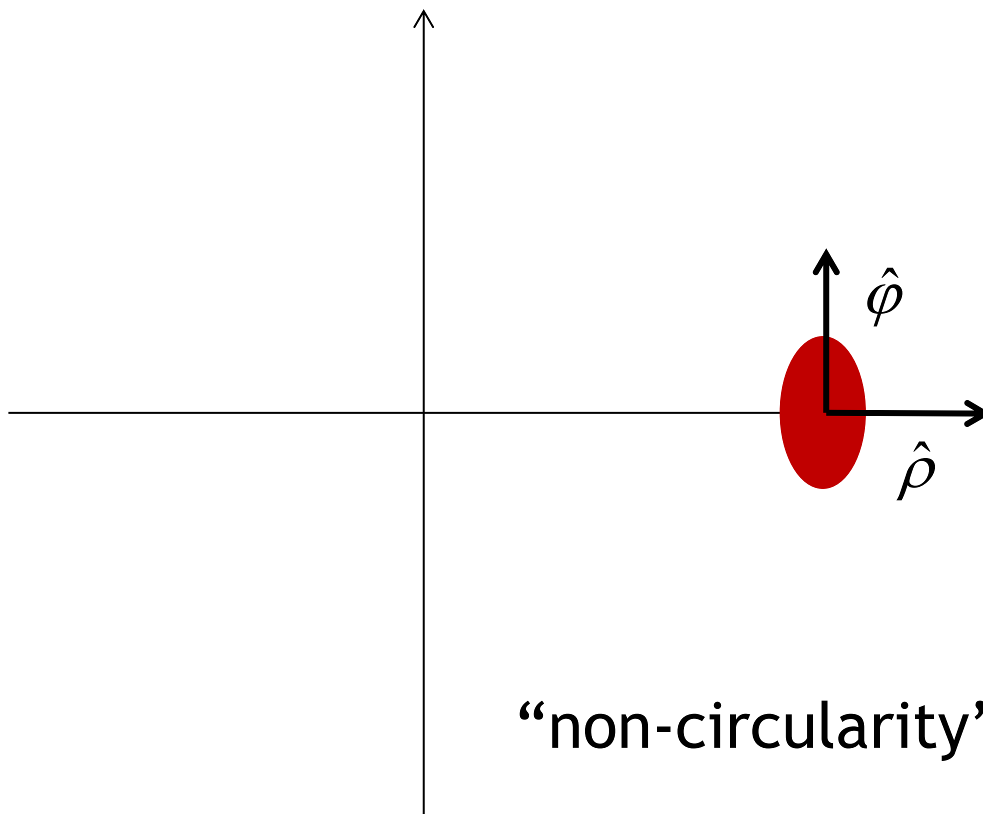
credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- The asymptotic EGN correction formula(s) are promising low-complexity solutions for max-reach studies

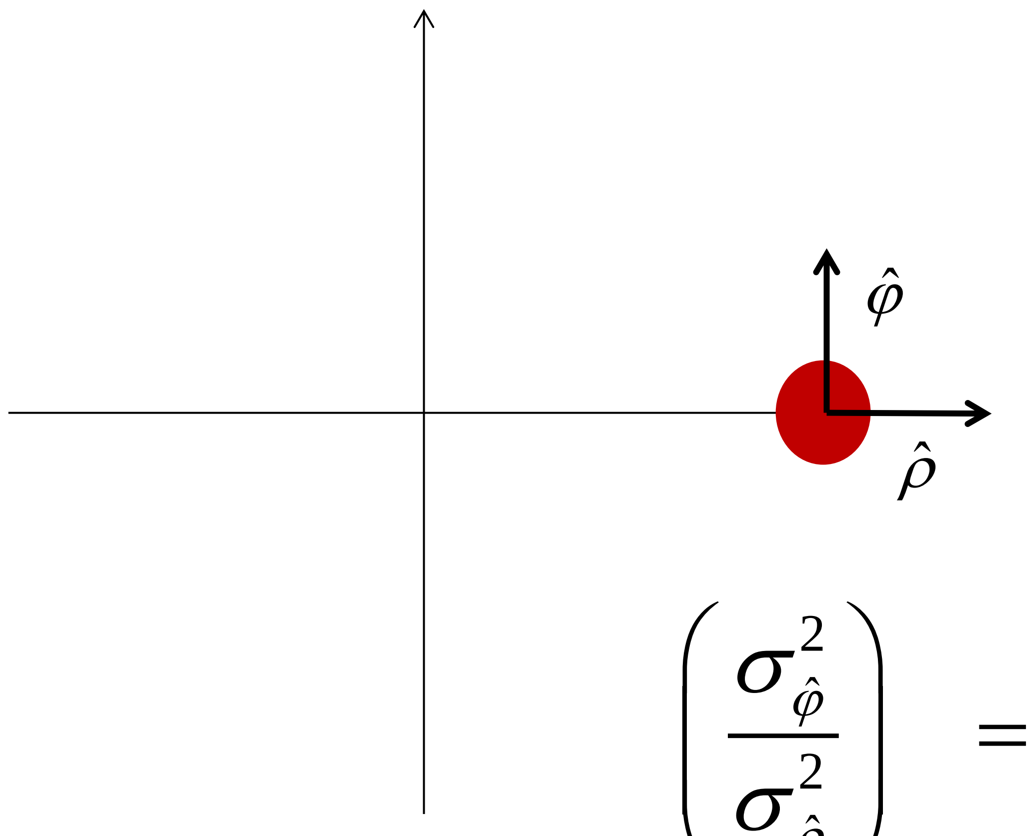
- Being “asymptotic” in the number of spans, they *should be used with caution* in short-reach systems (< 300 km)

More slides on phase noise: non-circularity test on the «case study»: PSCF 60 km span PM16QAM

the “single-dot”

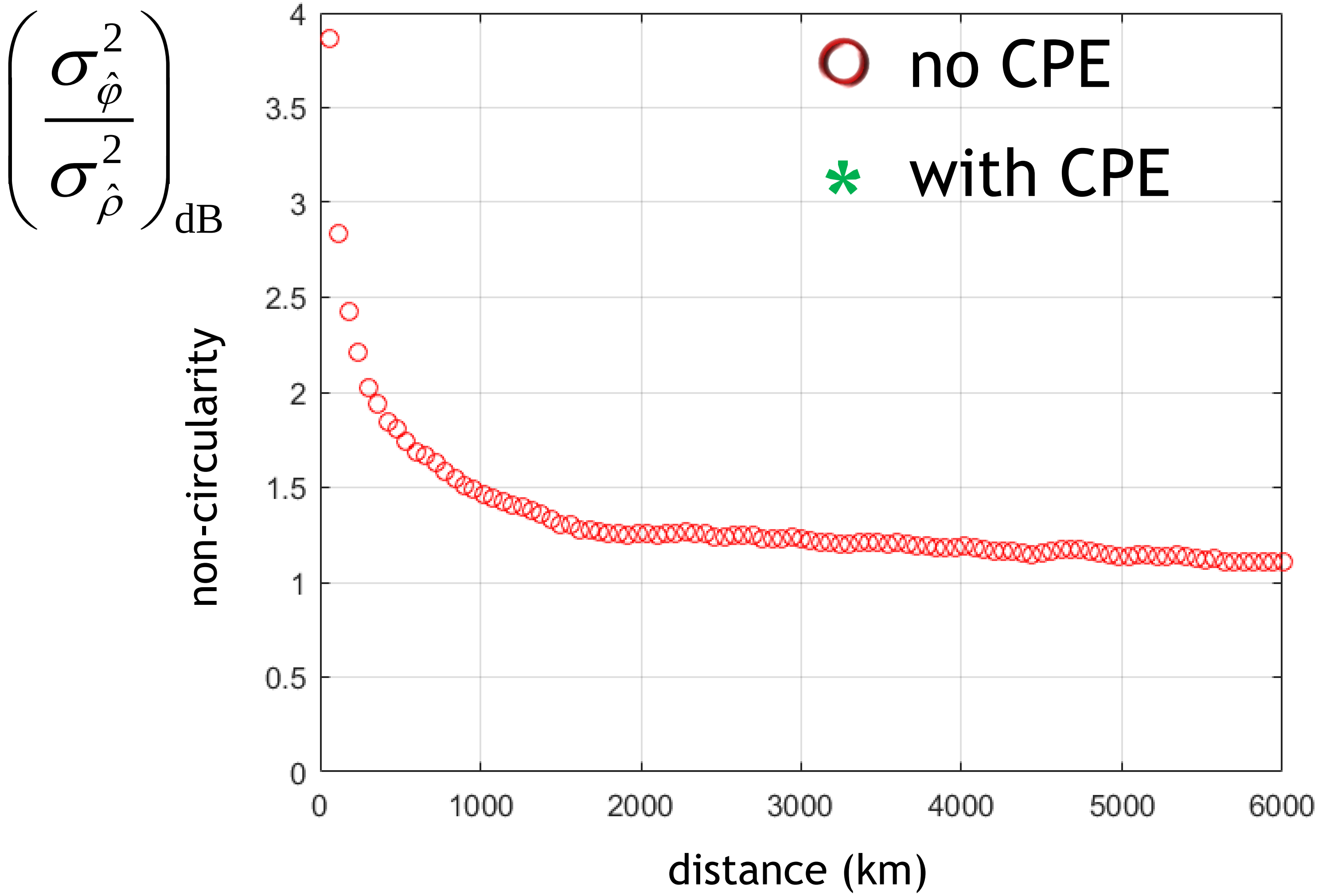


“non-circularity”: $\left(\dfrac{\sigma_{\hat{\varphi}}^{2}}{\sigma_{\hat{\rho}}^{2}}\right)_{\mathrm{dB}}$

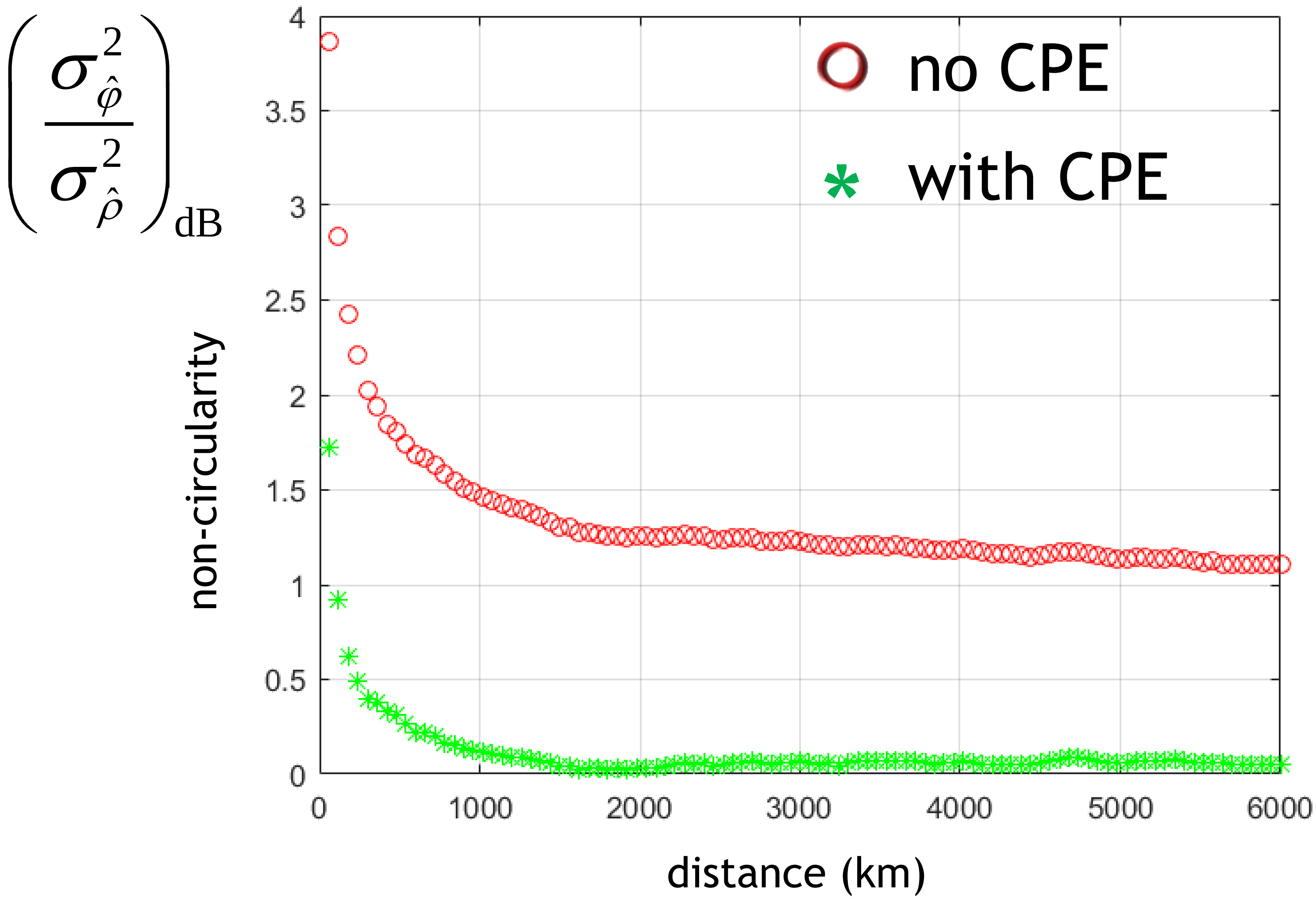


$$\left(\frac{\sigma_{\hat{\varphi}}^2}{\sigma_{\hat{\rho}}^2}\right)_{\mathrm{dB}} = 0$$

non-circularity vs. distance



non-circularity vs. distance



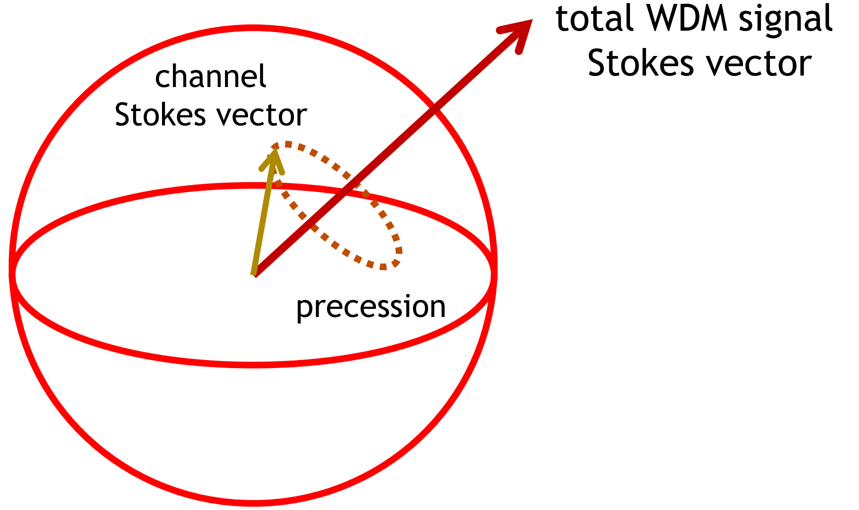
More details on non-linear polarization noise

Non-linear polarization noise

- What is non-linear polarization noise (PolN) ?

- Each channel Stokes vector, at each point in time/space, “precedes” about an axis, which is the overall WDM signal Stokes vector

  D. Wang and C. R. Menyuk, “Polarization Evolution Due to the Kerr Nonlinearity and Chromatic Dispersion”, JLT, vol. 17, pp. 2520-2529, Dec. 1999



Only crosstalk remains

- Polarization noise has itself a *phase* and a *crosstalk* component

- In the previous simulations, we used *two independent CPEs* to remove phase noise, one per polarization

- It turns out that this strategy already removes the phase component of the non-linear “polarization noise”

- *Only the “crosstalk component” remains to be removed*

PolN: Polarization Noise

- Being a *rotation in Stokes space*, it can be represented in Jones notation through a unitary matrix of unit determinant:

$$\mathbf{U}_{\text{PolN}} = \begin{bmatrix} e^{j(\Sigma+\Delta)}\cos\theta & -e^{-j(\Sigma-\Delta)}\sin\theta \\ e^{j(\Sigma-\Delta)}\sin\theta & e^{-j(\Sigma+\Delta)}\cos\theta \end{bmatrix}$$

- *Assuming PolN is small*, its effect on the x and y constellations is *approximately*:

$$s'_{\hat{x}} = s_{\hat{x}} \cdot e^{j(\Sigma+\Delta)} - s_{\hat{y}} \cdot \theta \cdot e^{-j(\Sigma-\Delta)}$$

$$s'_{\hat{y}} = s_{\hat{y}} \cdot e^{-j(\Sigma+\Delta)} + s_{\hat{x}} \cdot \theta \cdot e^{j(\Sigma-\Delta)}$$

- Renaming angles, it can be simplified into:

$$s'_{\hat{x}} = s_{\hat{x}} \cdot e^{j\varphi_1} - s_{\hat{y}} \cdot \theta \cdot e^{j\varphi_2}$$

$$s'_{\hat{y}} = s_{\hat{y}} \underbrace{\cdot e^{-j\varphi_1}}_{\text{PolN-induced phase noise}} \underbrace{+ s_{\hat{x}} \cdot \theta \cdot e^{-j\varphi_2}}_{\text{crosstalk between the two constellations}}$$

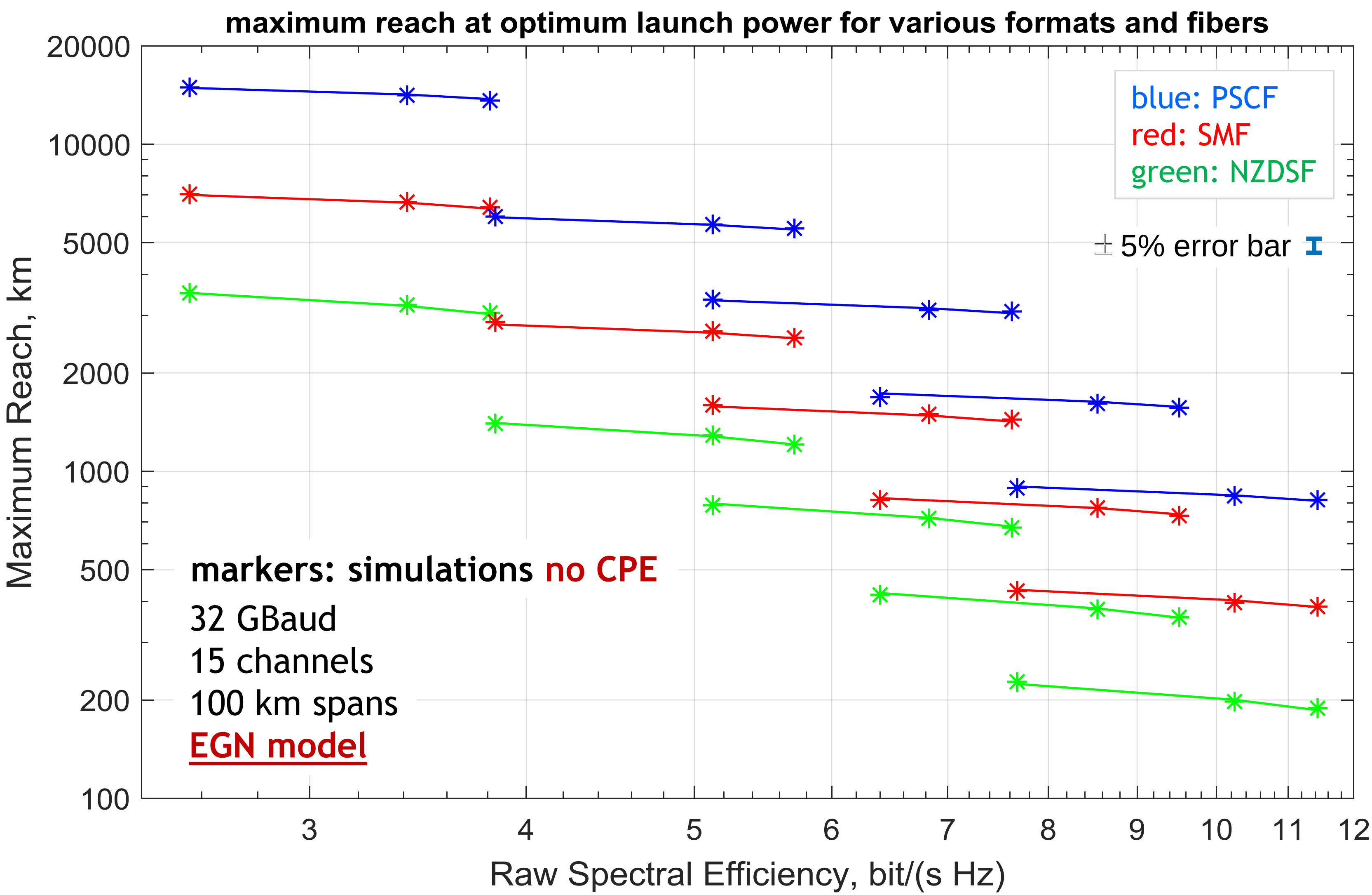
PolN-induced phase noise

if the Rx CPE works independently on the two polarizations, it already removes long-correlated PolN, too. <u>In our simulations this was the case.</u>

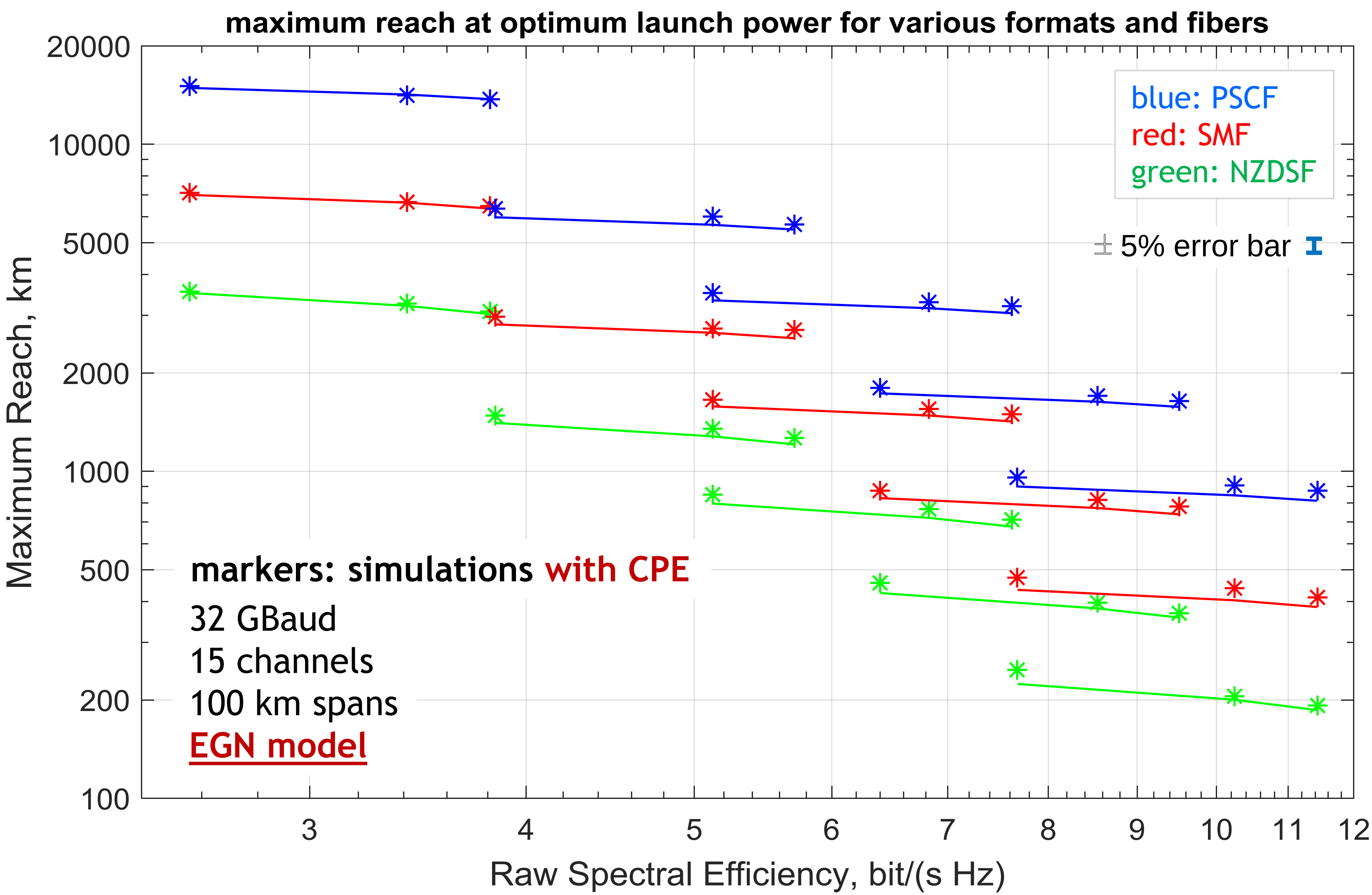
crosstalk between the two constellations

requires an "ad hoc" algorithm to estimate and remove its long-correlated (LC) part

The big picture



The big picture



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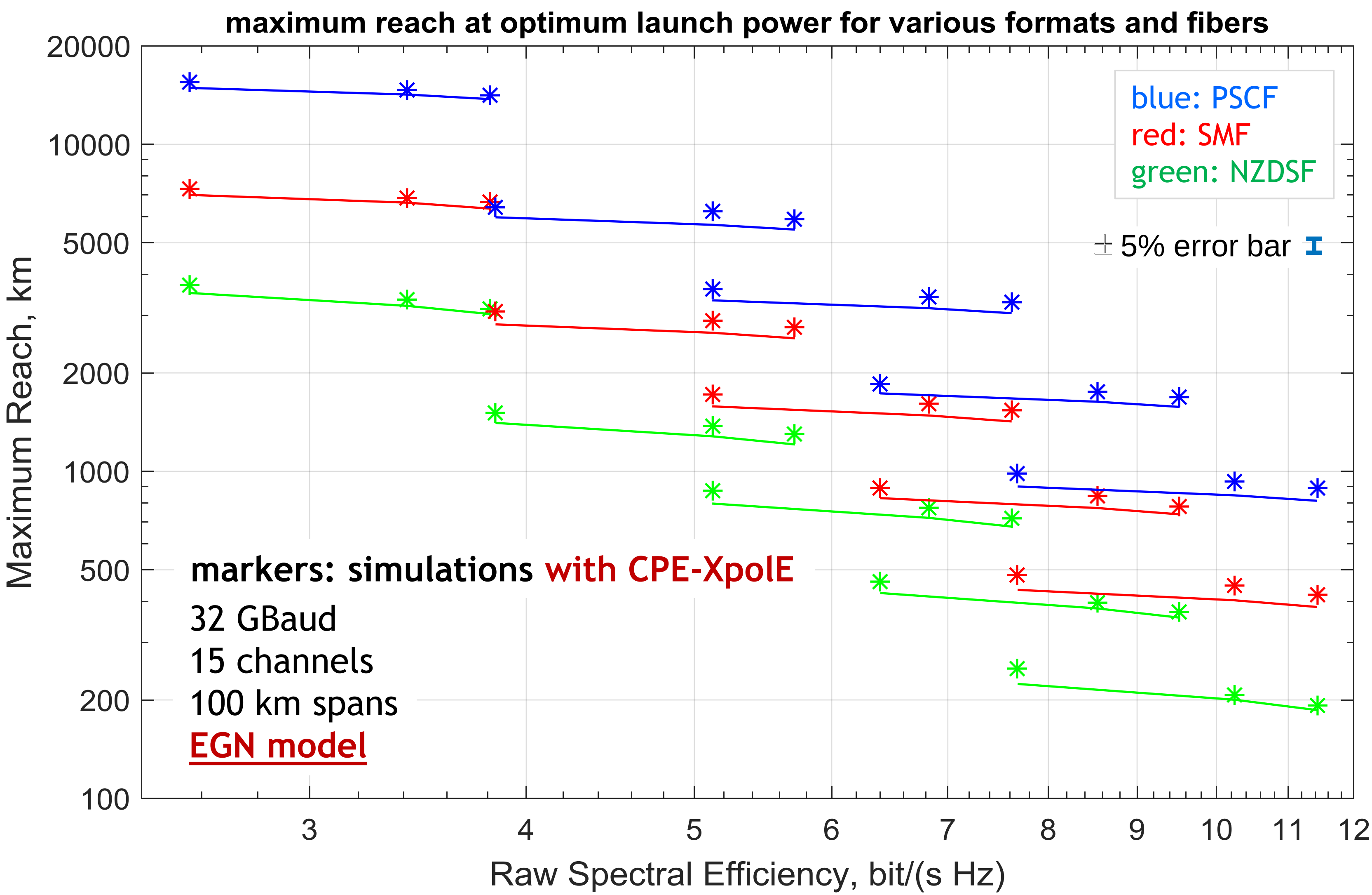

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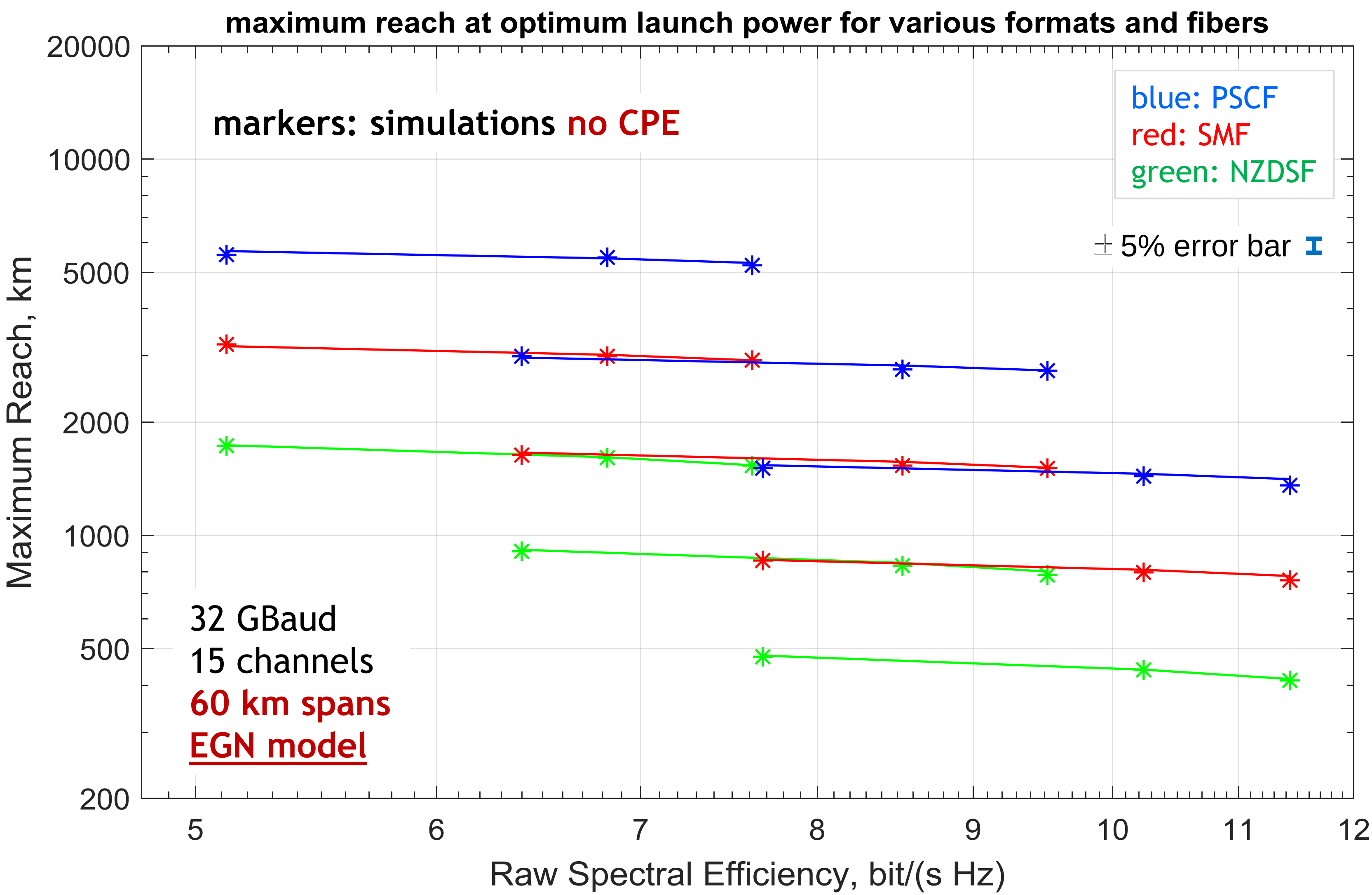

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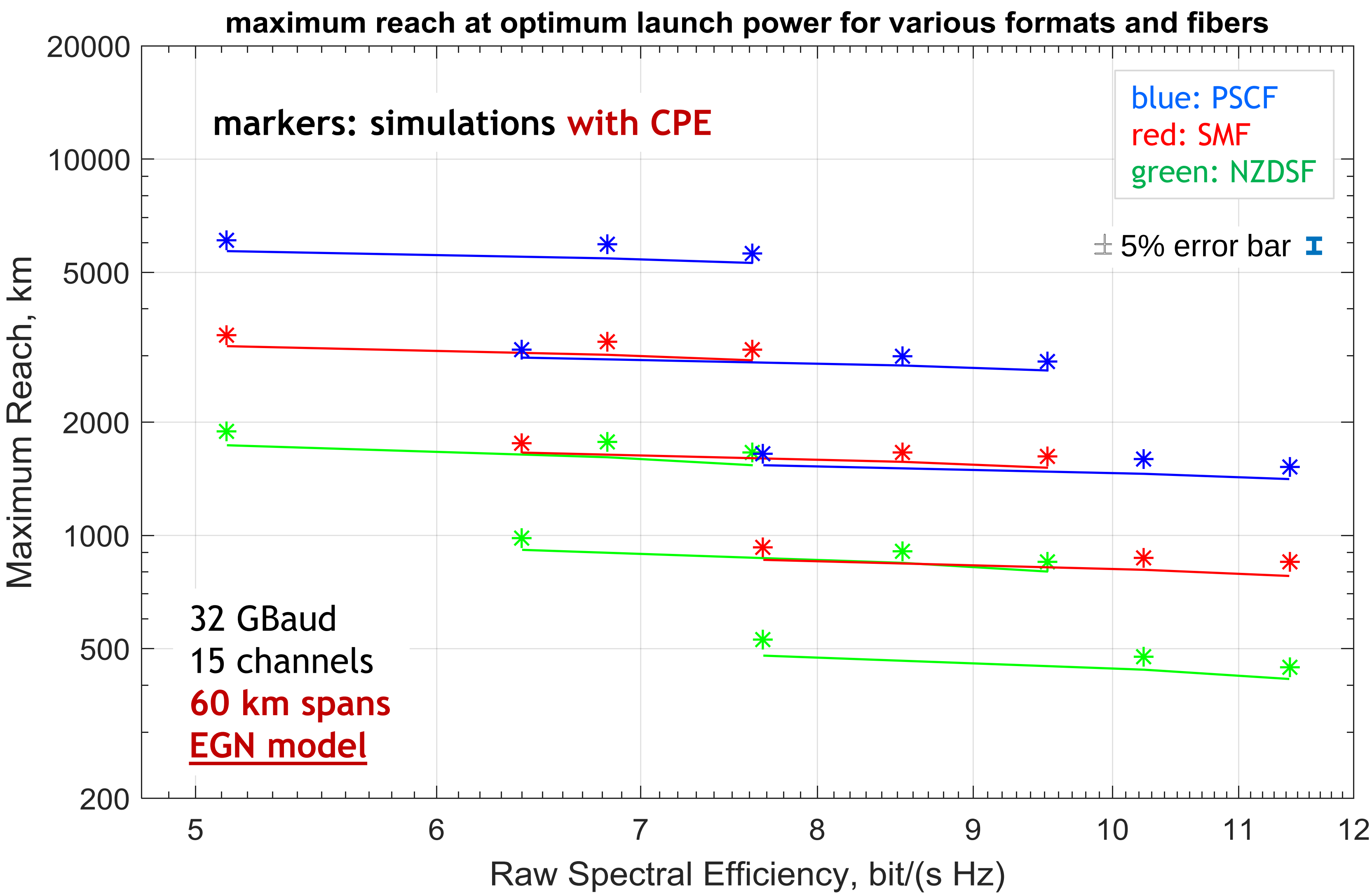

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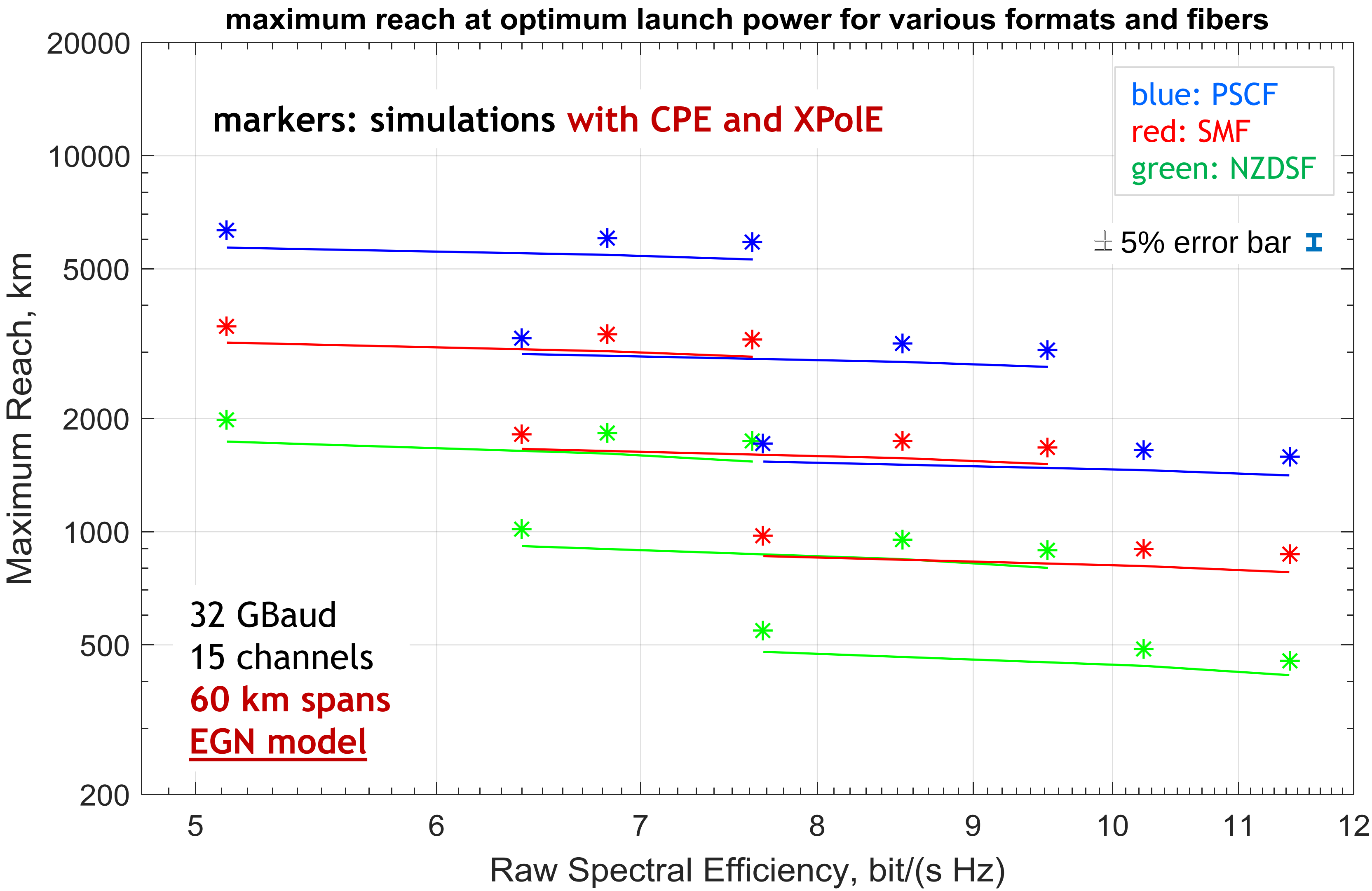

Comments

- The *further MR gain on top of CPE* is substantial for 60 km spans
  - average on "the big picture" is 3.7%, peak is 5.5%
- The *further MR gain on top of CPE* is somewhat less for 100km spans, but comparable
  - average on "the big picture" is 2.4%, peak is 5.5%
- In existing systems, the dynamic equalizer (CMA, LMS) may be able to already track and cancel some of the PolN
  - the reason is that the correlation for this effect appears even longer than that of PN
  - more investigation is needed
- *It is a good idea to include a PolN removal dedicated algorithm in Rx's to obtain performance improvement*

Key take-away

OPTCOM

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- Introducing a cross-polarization noise estimator/canceler in the receiver may provide average reach gains of about 3%

http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

More details on in-line ASE

Modeling in-line ASE

- ASE noise is actually injected into the system at every span
- Models typically neglect its contribution to NLI generation
- *But ASE does create further NLI*

Modeling and in-line ASE

- ASE noise is injected into the system at every span
- Models typically neglect its contribution to NLI generation

- This is OK as long as the ASE power is small vs. the signal power
- However, when the final Rx target OSNR is less than about 9 dB, ASE starts having a visible impact

  - Simulative evidence with phenomenological modeling corrections
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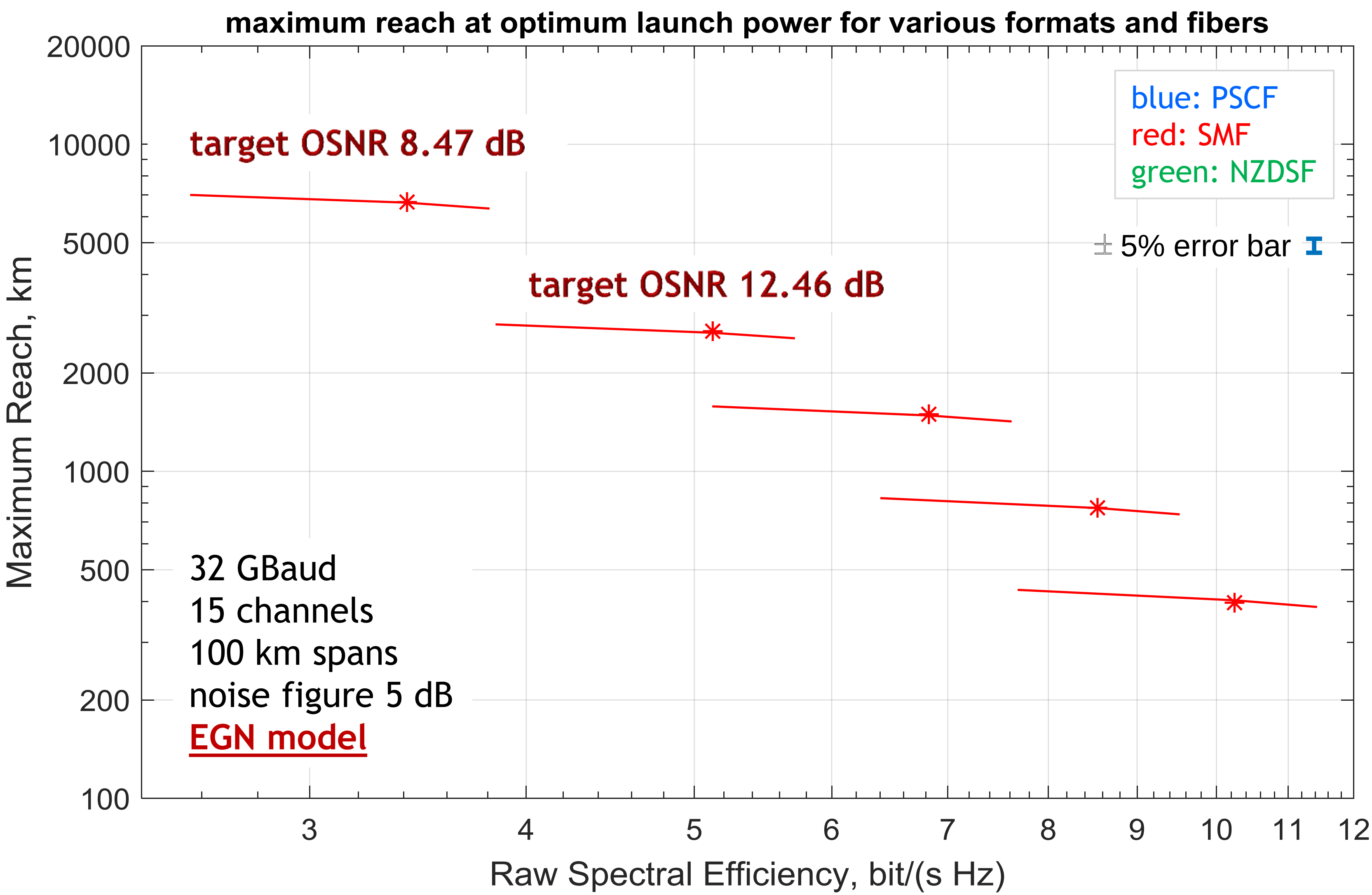
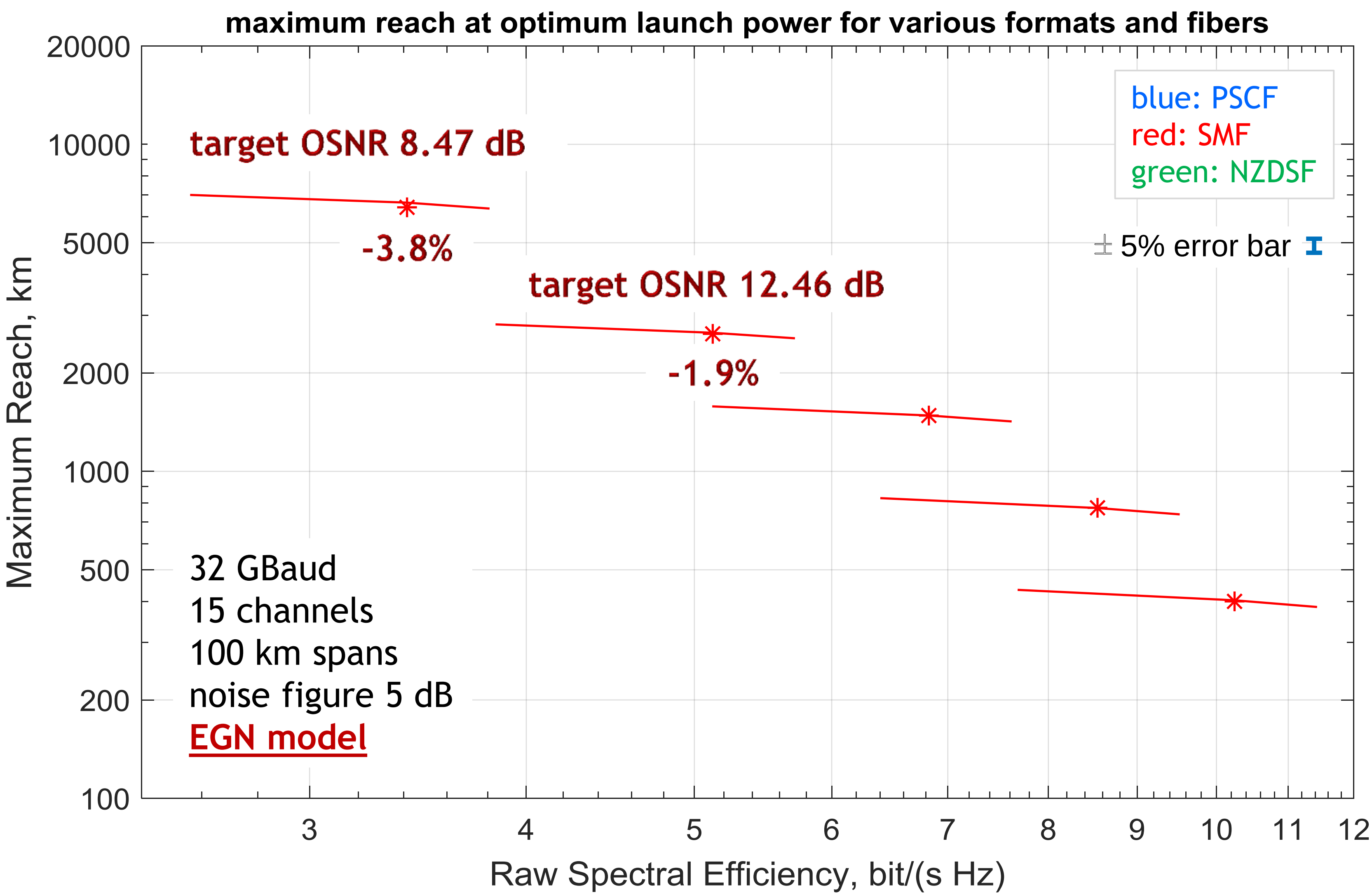
The big picture

OPTCOM



The big picture



Lower OSNRs

- Going up to BER $2.2 \cdot 10^{-2}$, then the target OSNR for PM-QPSK goes down to 6.25 dB
  - at this BER in [A] we found a reach decrease vs. the EGN prediction of about 10%

- Interestingly, only half of that loss (5%) was found in [A] to be due to ASE noise co-propagation
- The other half was due to a different phenomenon: *signal depletion*

- Signal depletion, like ASE co-propagation, matters only at low OSNR, again typically below 9 dB

Key take-away

credit: http://www.messagehouse.org/increasing-the-takeaway-ability-of-your-presentations/

- The effects of *ASE noise and signal depletion on NLI generation* are significant only for:

$$\mathrm{OSNR}_{\mathrm{target}} < 9\ \mathrm{dB}$$

(essentially only PM-QPSK is affected)

- Exact models for ASE are now available but are complex

  Very accurate analytical treatment in the context of the EGN model

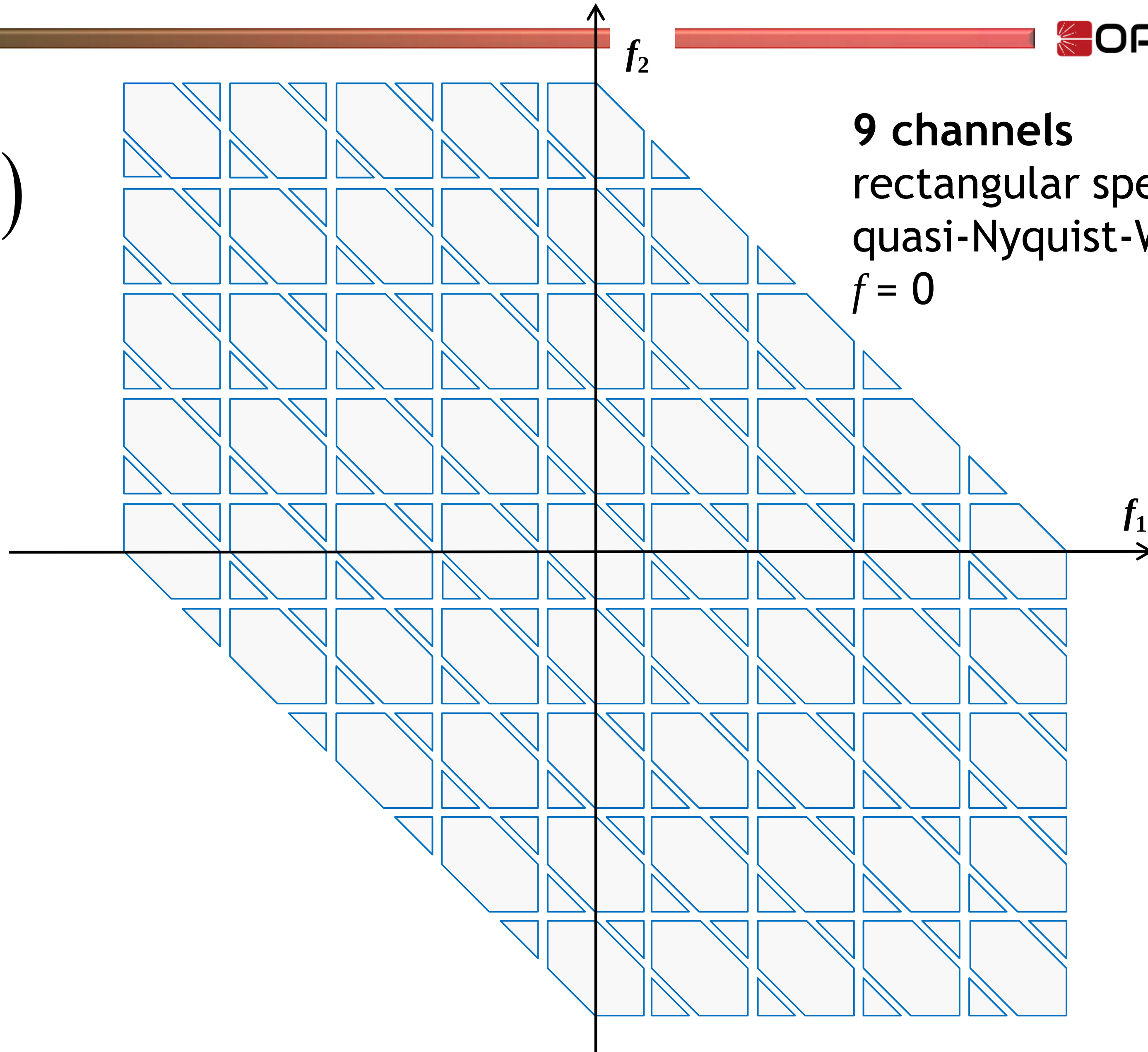
  P. Serena, “Nonlinear Signal-Noise Interaction in Optical Links With Nonlinear Equalization,” JLT, vol. 34, p. 1476-1483, March 2016

On the meaning of the EGN model correction formula contributions

The GN model "islands"

$$G_{\mathrm{NLI}}^{\mathrm{GN}}(f)$$

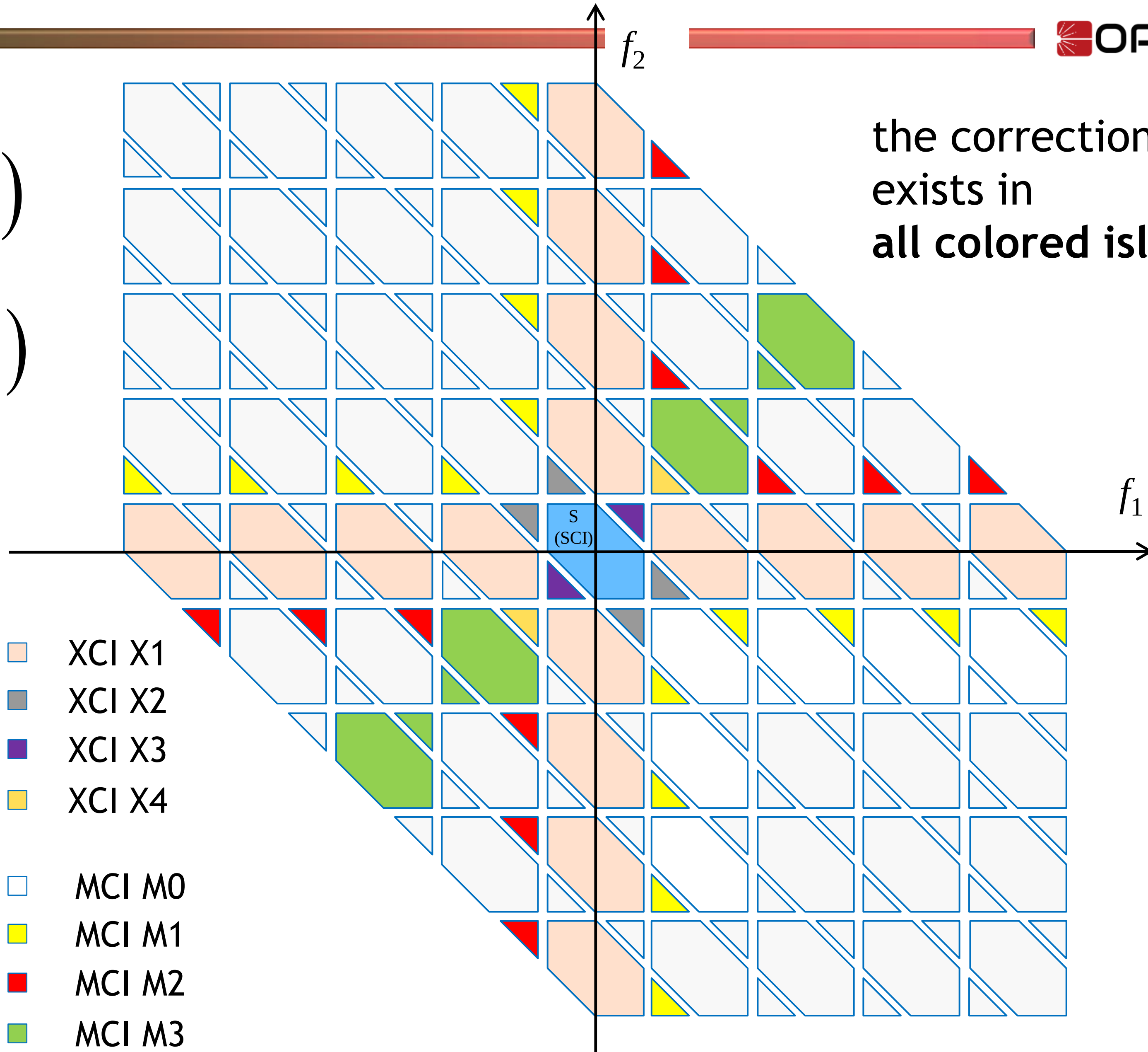
9 channels
rectangular spectra
quasi-Nyquist-WDM
$f = 0$



The correction

$$G_{NLI}^{GN}(f)$$

$$G_{NLI}^{corr}(f)$$



the correction exists in **all colored islands**