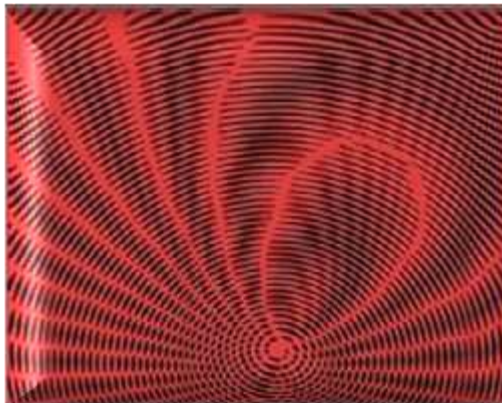


Recent Advances in Non-Linear Fiber Propagation Modeling



Pierluigi Poggiolini

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- ▶ To the OFC 2016 Technical Program Committee

- ▶ To Yanchao Jiang



- ▶ To Antonello Nespola e Luca Bertignono



- ▶ To Andrea Carena and Gabriella Bosco

- ▶ To Mattia Cantono, Dario Piori and Fernando Guiomar and all other OptCom group members



- ▶ To CISCO Photonics for supporting the research



- ▶ To Fabrizio Forghieri, Stefano Piciaccia, Chris Fludger, Thomas Duthel and many others from CISCO

- ▶ 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

- ▶ 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



- ▶ 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





▶ 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

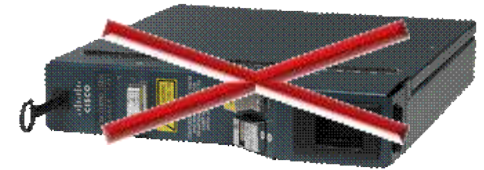


credit: <http://greenpediatrics.com/homeopathy-what-how-and-why/>

▶ The future: more advanced models and beyond

GN-model

- ▶ 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
- ▶ 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)



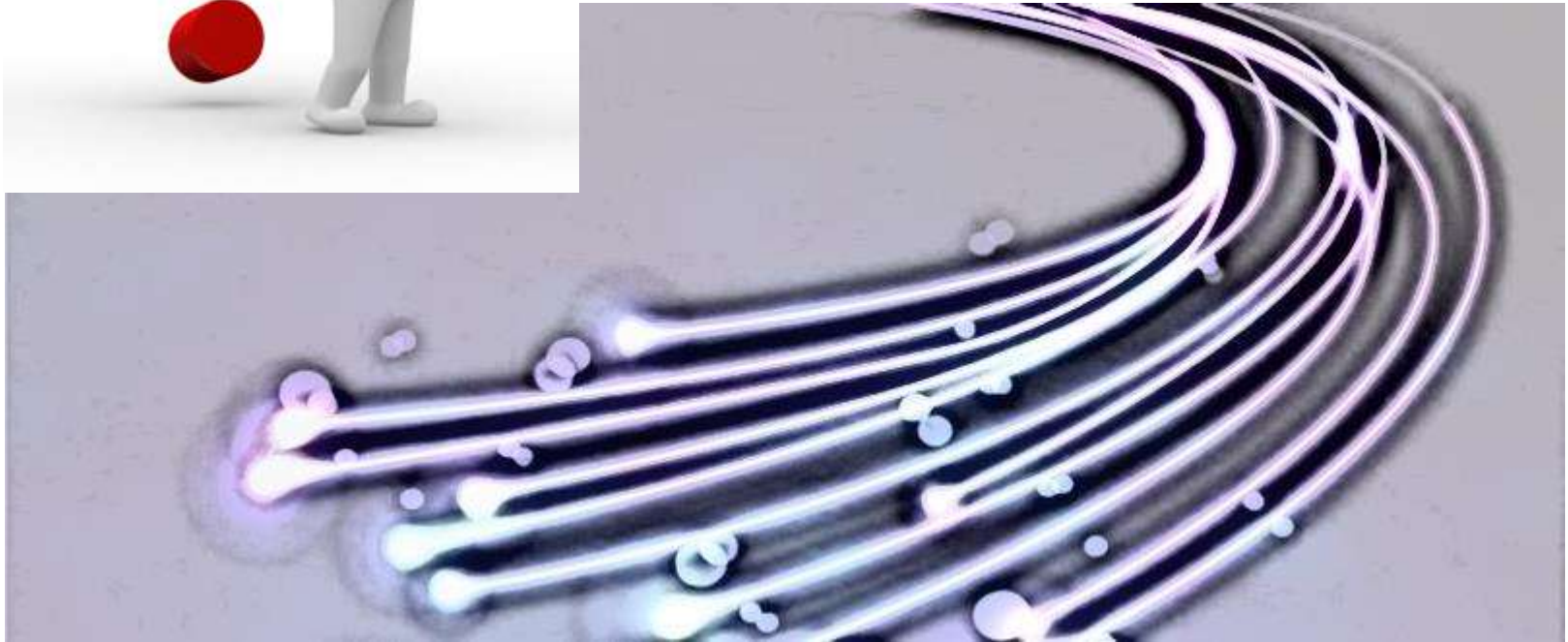
credit:
http://www.cisco.com/c/en/us/products/colateral/optical-networking/ons-15200-series-dwdm-systems/datasheet_c78-728877.html



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

what needs to be modeled ?

credit: [http://www.hillsborococ.org/
what-is-the-problem/](http://www.hillsborococ.org/what-is-the-problem/)



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

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

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

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 ?

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

models must
provide
the NLI PSD

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

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

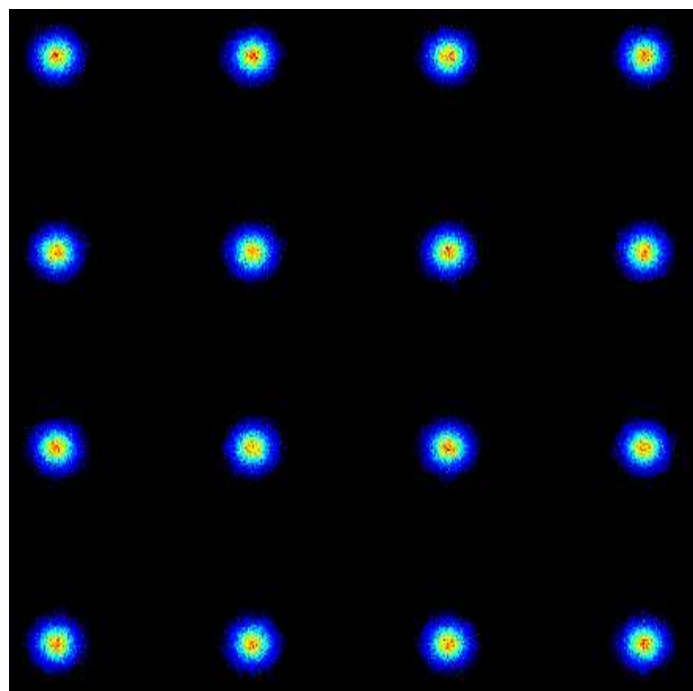
Manakov

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

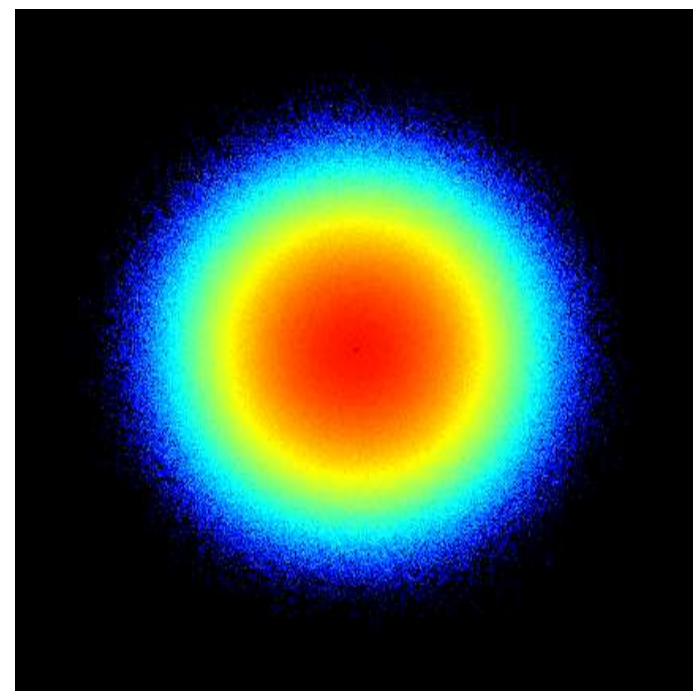
$$\frac{\partial E_y(z,t)}{\partial z} = j \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2} E_y(z,t) - \alpha E_y(z,t) - j\gamma \frac{8}{9} \left[|E_x(z,t)|^2 + |E_y(z,t)|^2 \right] E_y(z,t)$$

**perturbation
approach**

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



32 GBaud
400 km SMF



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

Manakov

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

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

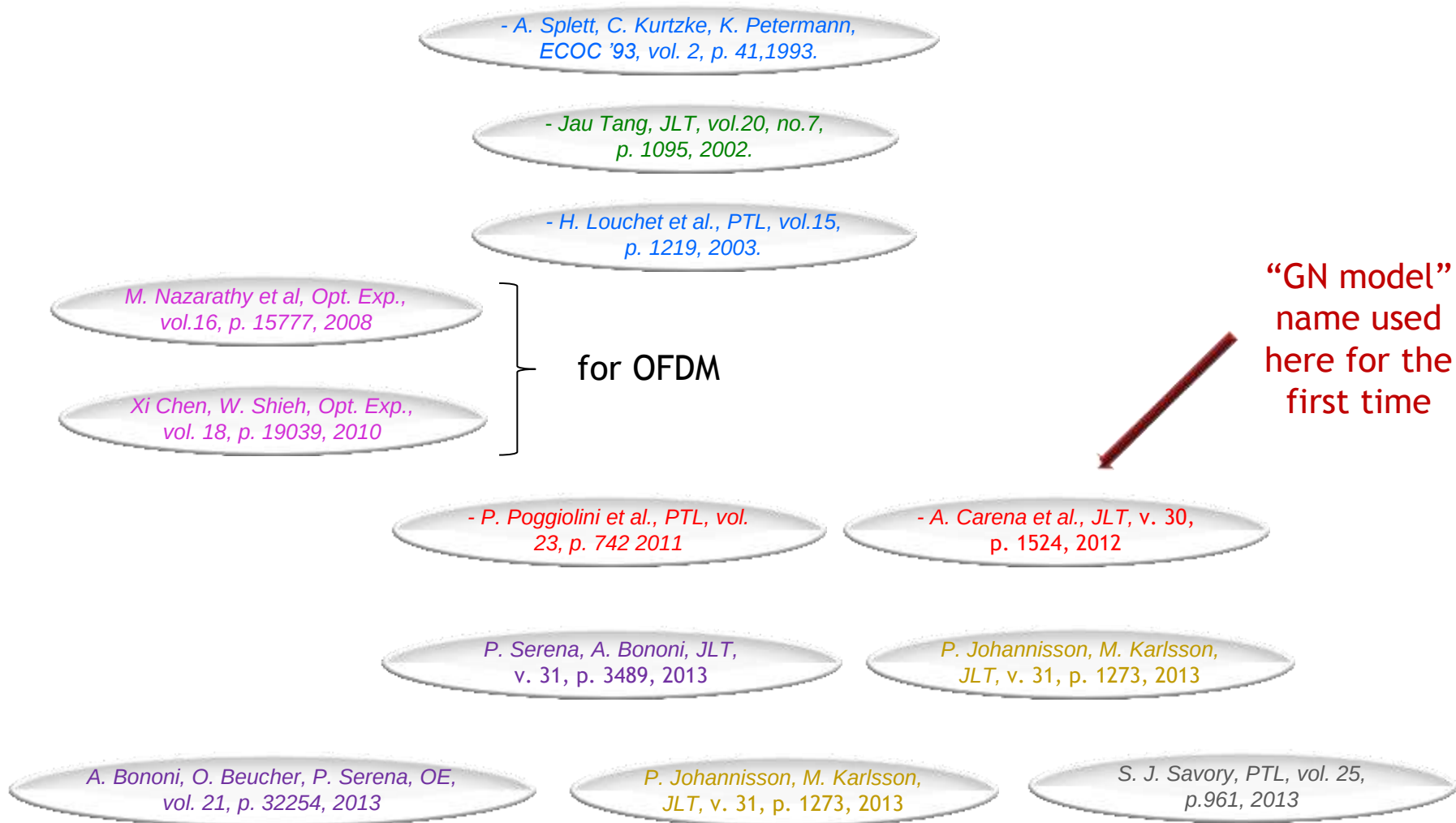
**perturbation
approach**

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

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

**The GN-model reference formula
(GNRF)**

the GN-model family tree (to 2013)



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

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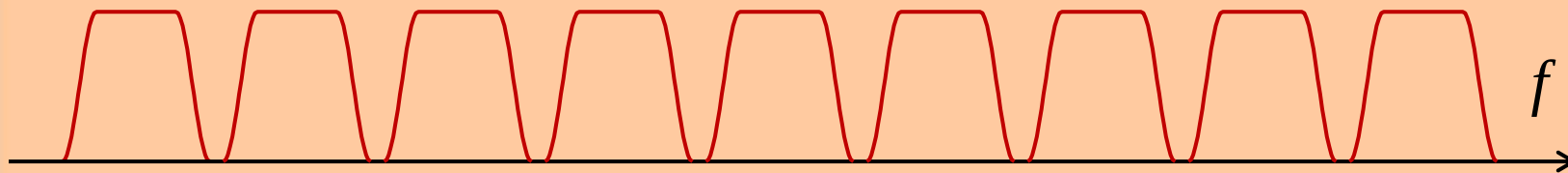
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- ▶ Many of these models are similar and almost equivalent
- ▶ *Many are more sophisticated and more accurate than the GN model*
- ▶ Perhaps the GN model:
 - ▶ strikes a balance between complexity and accuracy
 - ▶ this might explain its good reception and wide use
- ▶ TBD in a few minutes

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

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



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

$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$

**the “link function”:
it is the “FWM efficiency”
of the whole link**

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

$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$

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

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

for identical spans with lumped amplification:

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

► 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:
$$L_{\text{eff}} = \frac{1 - \exp(-2\alpha L_s)}{2\alpha}$$

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

single-span FWM efficiency

for identical spans with lumped amplification:

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

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

easy to integrate

for identical spans with lumped amplification:

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

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

cross-span “resonance”

for identical spans with lumped amplification:

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

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

nasty to integrate

for identical spans with lumped amplification:

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

- ▶ 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...

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

for identical spans with lumped amplification:

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

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

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

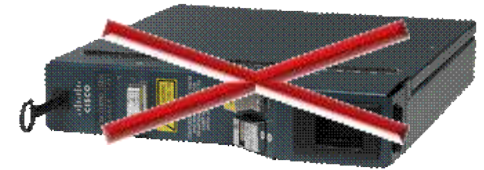
for identical spans with lumped amplification:

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

$$G_{\text{NLI}}(f) = N_s \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\text{WDM}}(f_1) G_{\text{WDM}}(f_2) G_{\text{WDM}}(f_1 + f_2 - f) \cdot \\ \cdot \gamma^2 L_{\text{eff}}^2 \left| \frac{1 - e^{-2\alpha L_s} e^{j4\pi^2 \beta_2 L_s (f_1 - f)(f_2 - f)}}{1 - j2\pi^2 \beta_2 \alpha^{-1} (f_1 - f)(f_2 - f)} \right|^2 df_1 df_2$$

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

- ▶ 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
- ▶ 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)



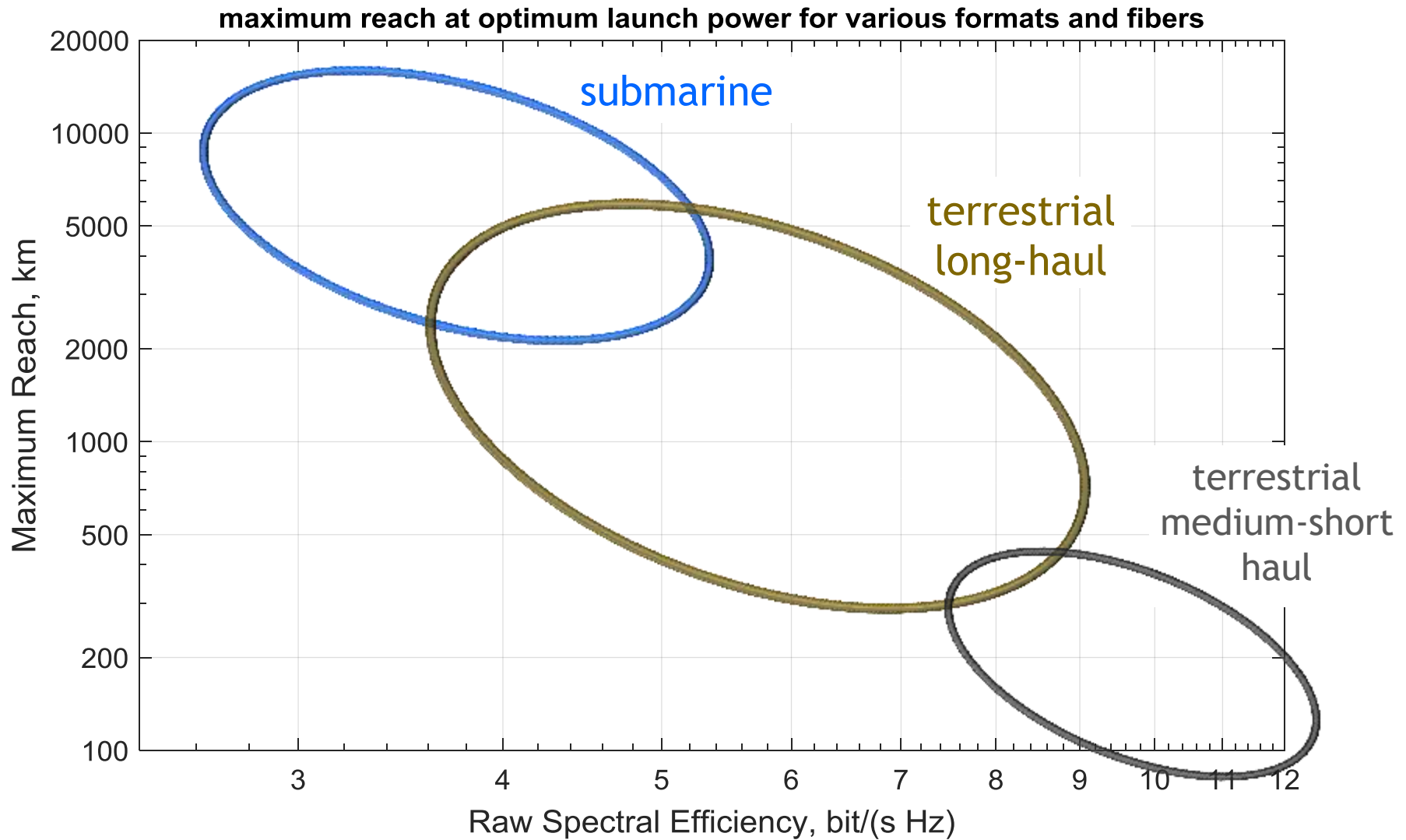
credit:
http://www.cisco.com/c/en/us/products/colateral/optical-networking/ons-15200-series-dwdm-systems/datasheet_c78-728877.html

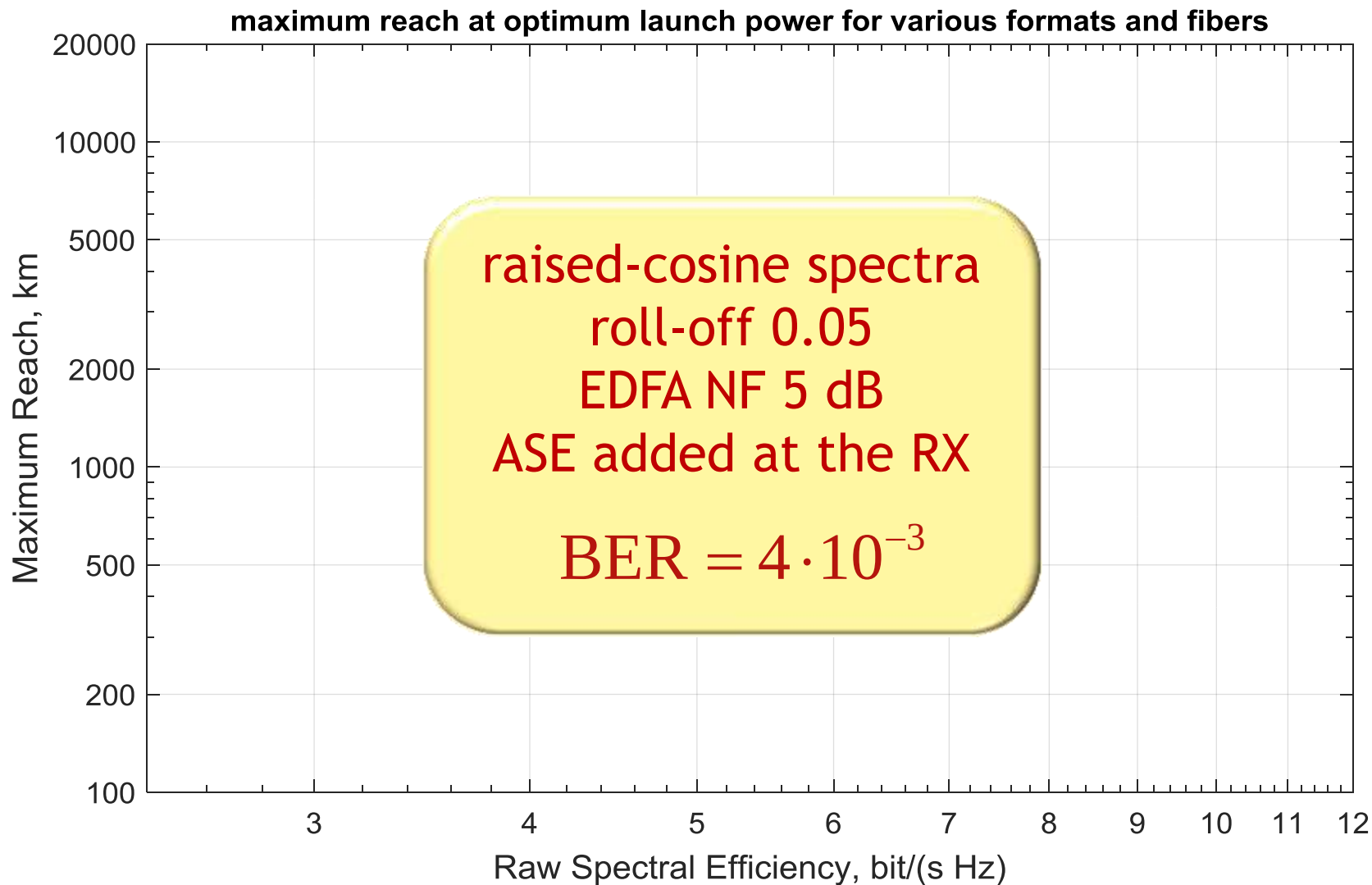


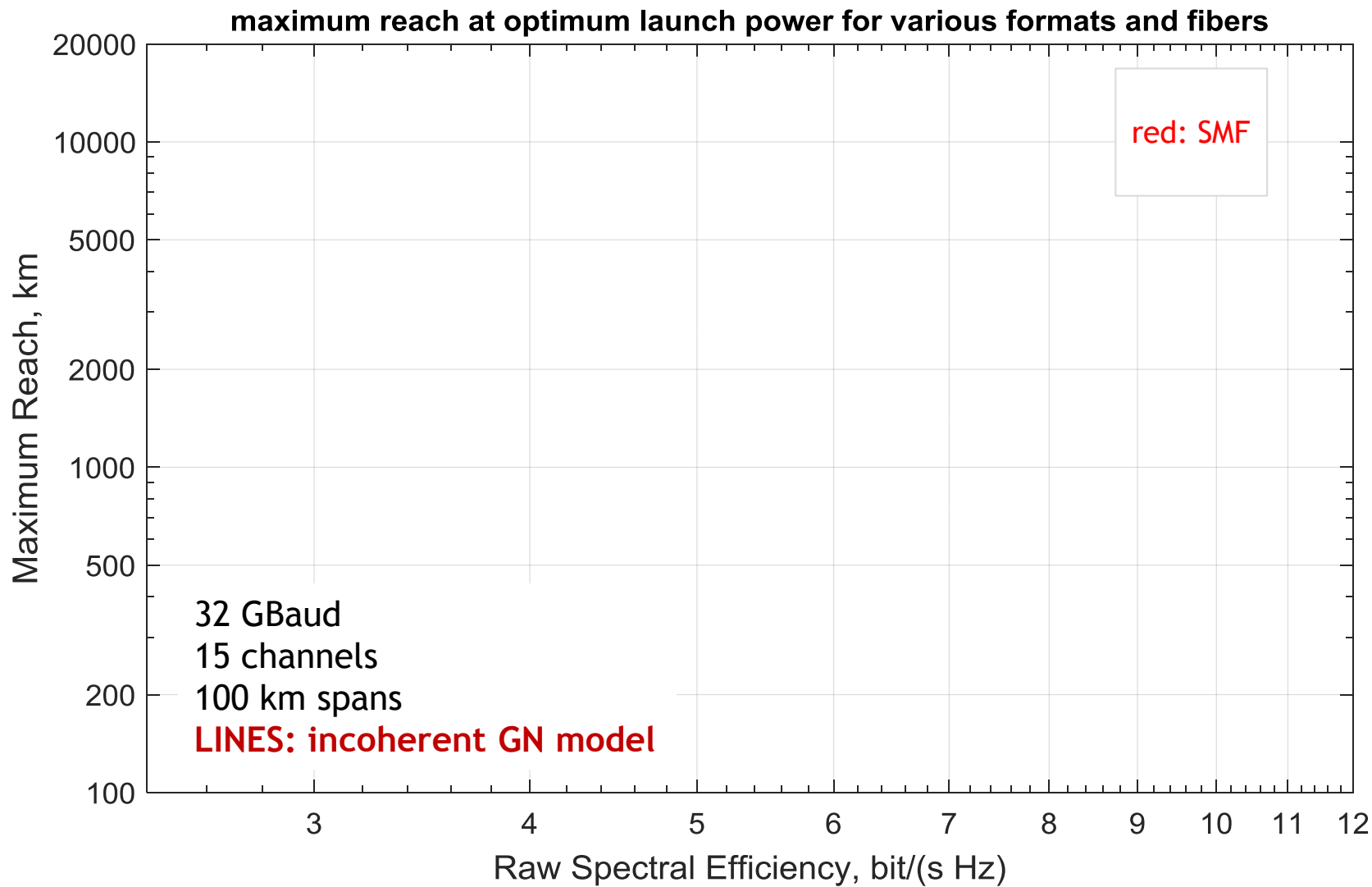
credit: <http://travel-representatives.com/>

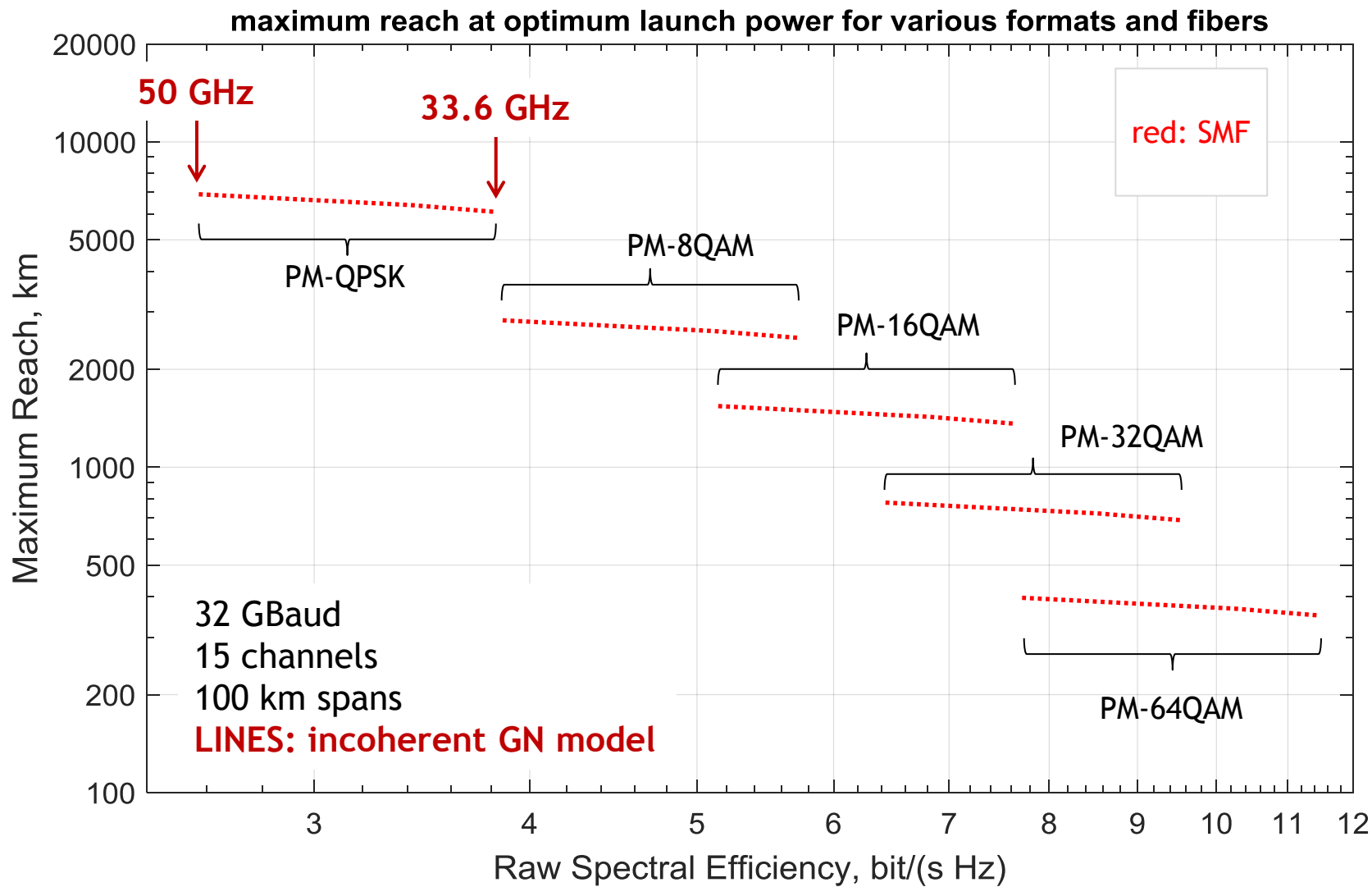


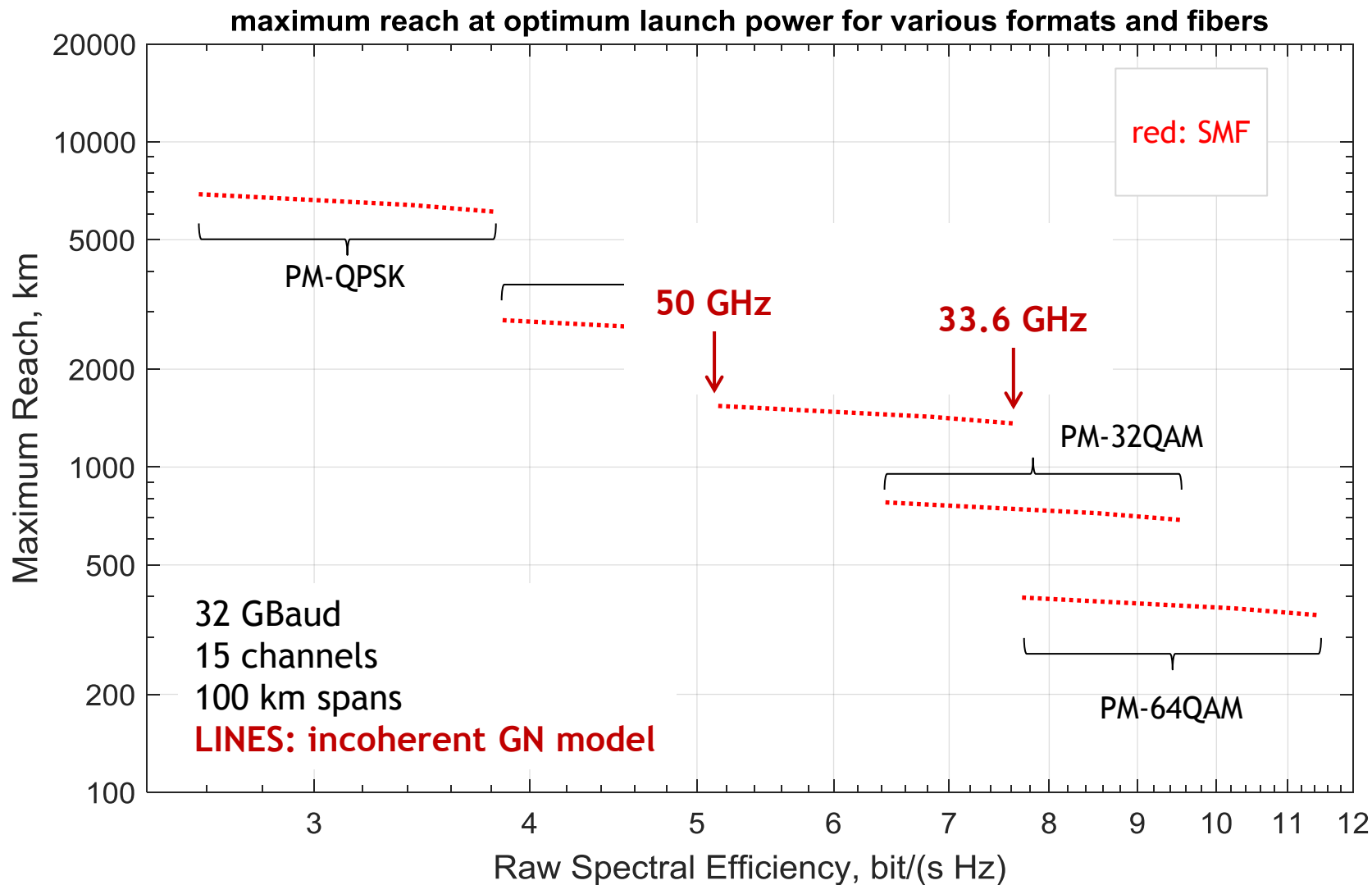
credit: http://www.dtvisiontech.com/2015_12_01_archive.html

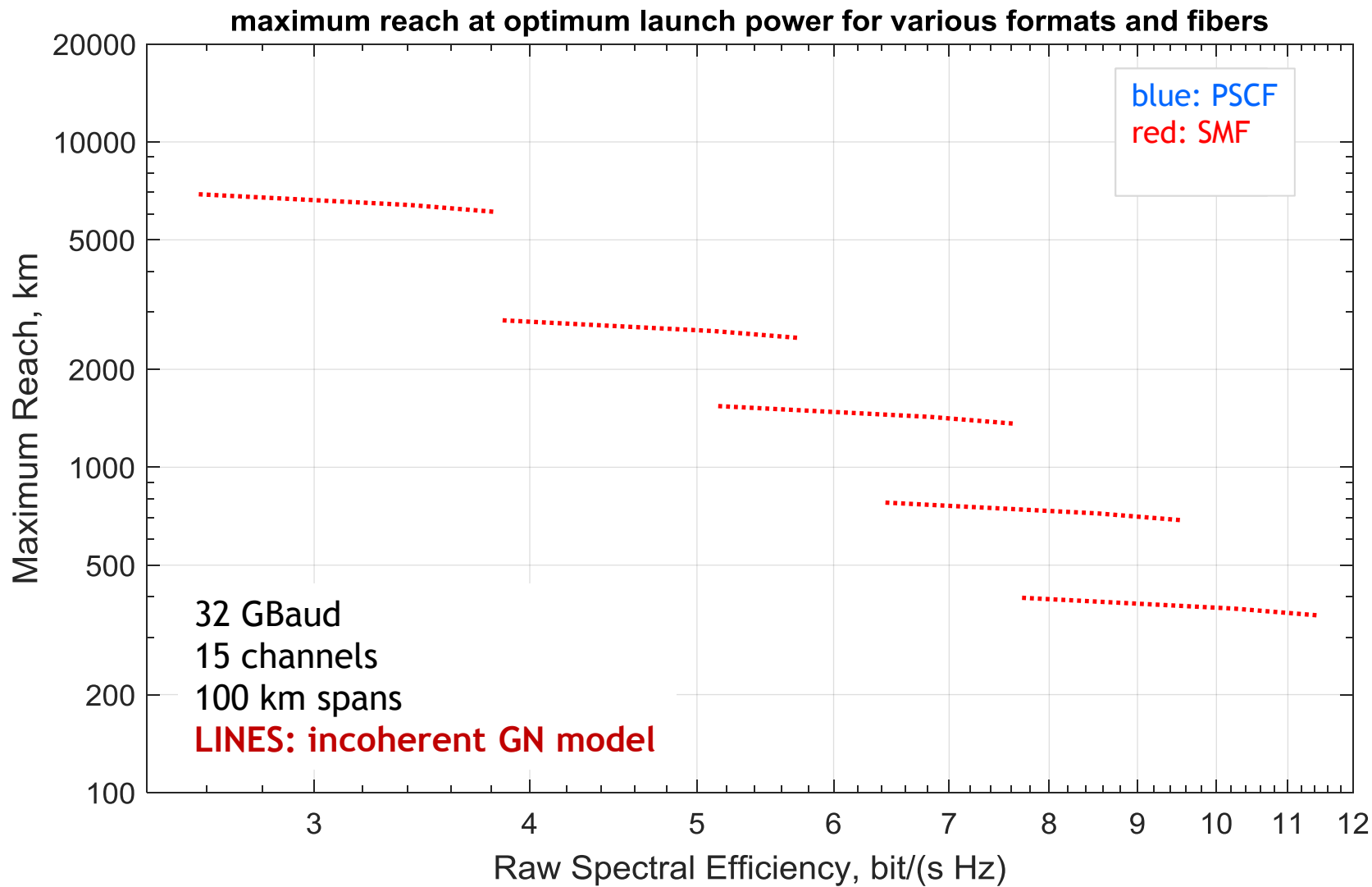


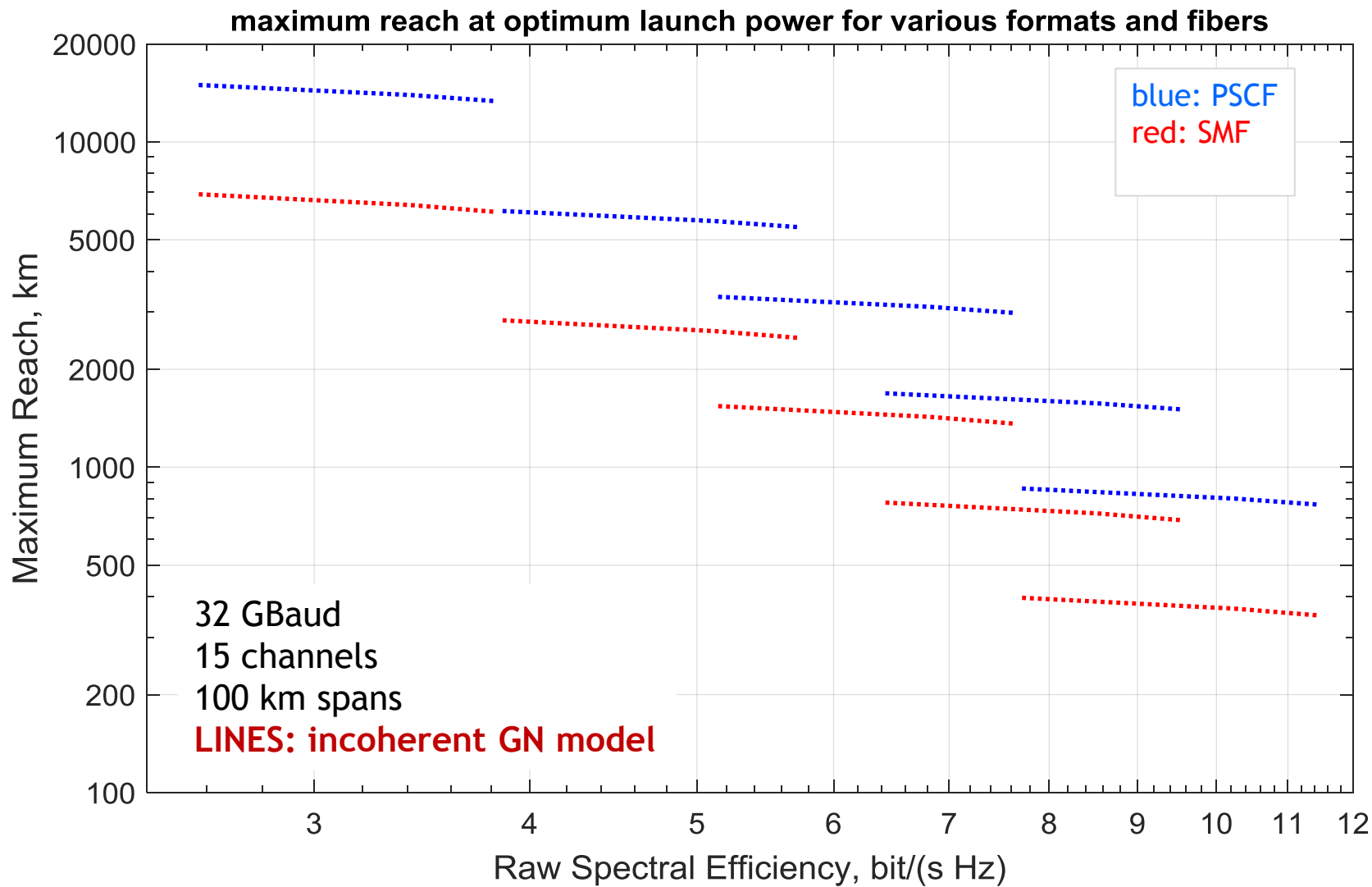


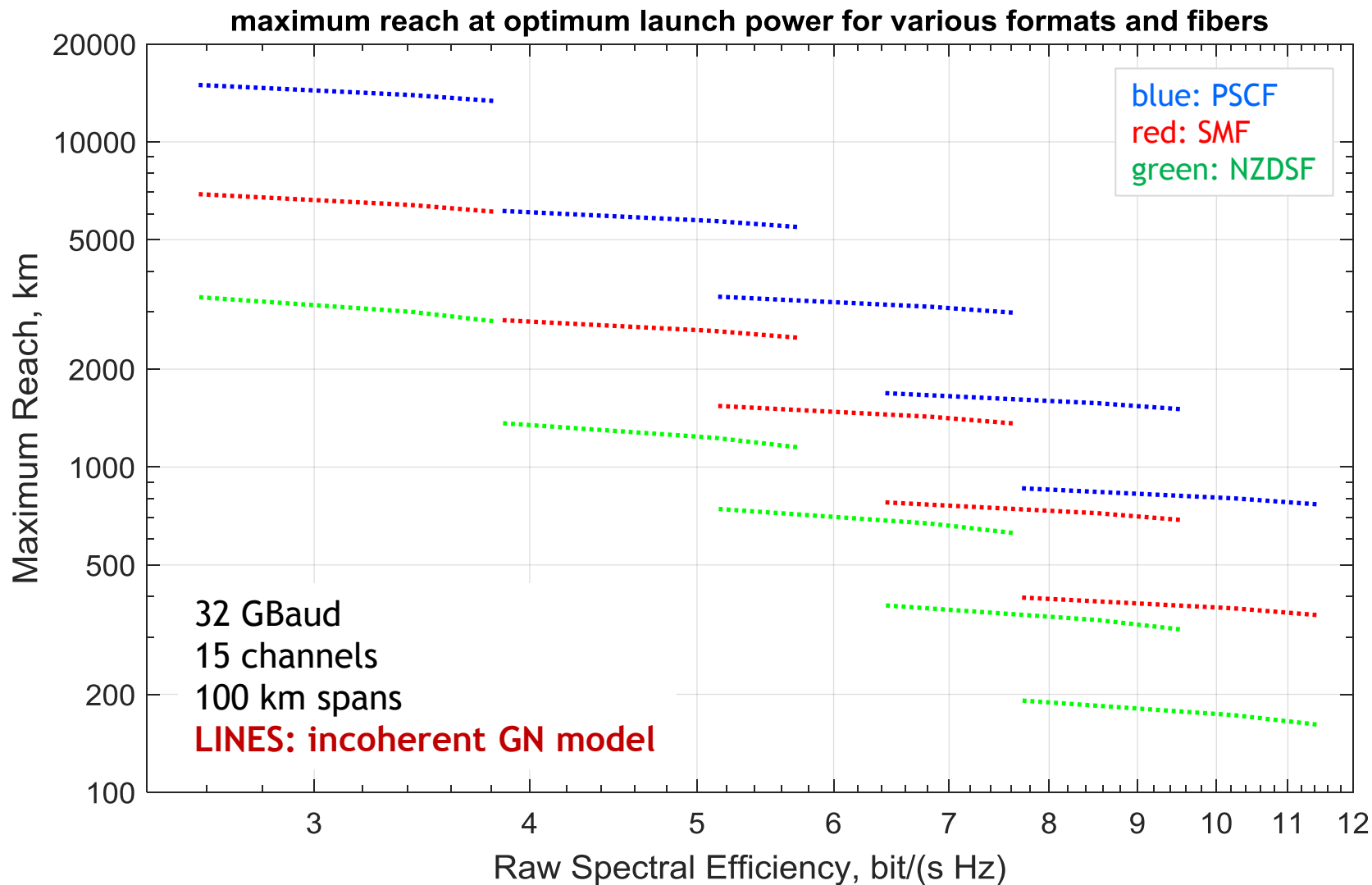




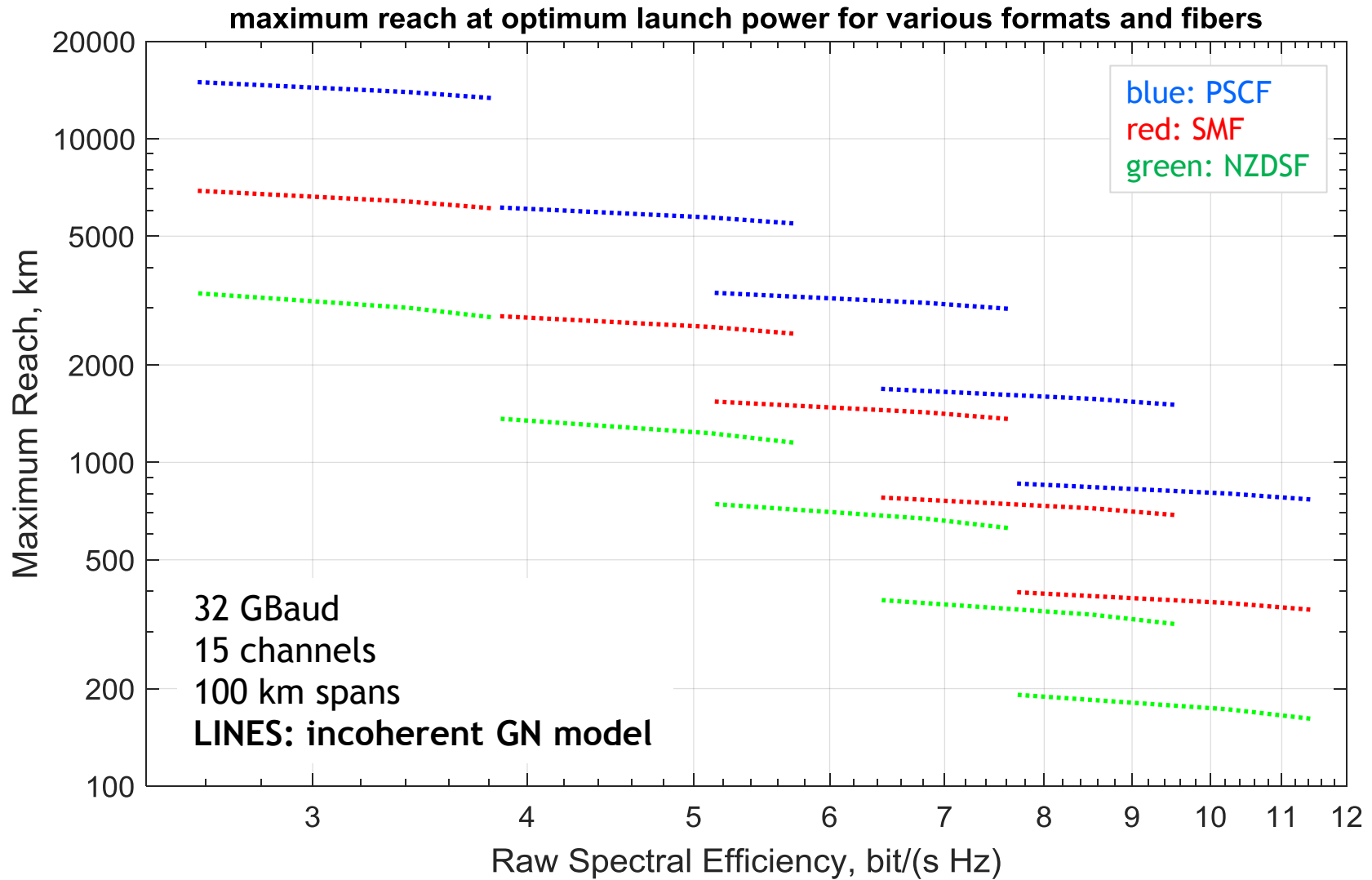


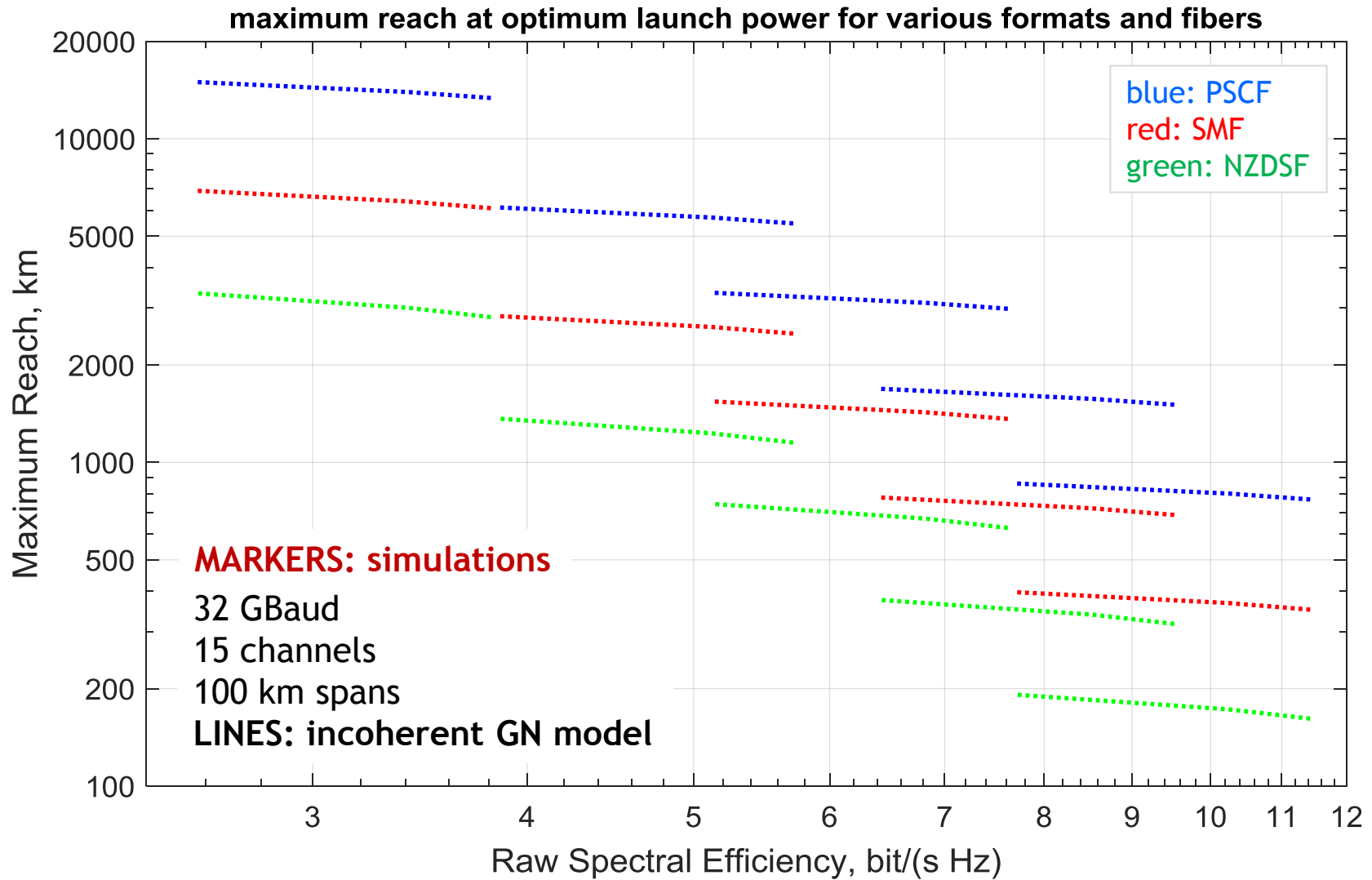


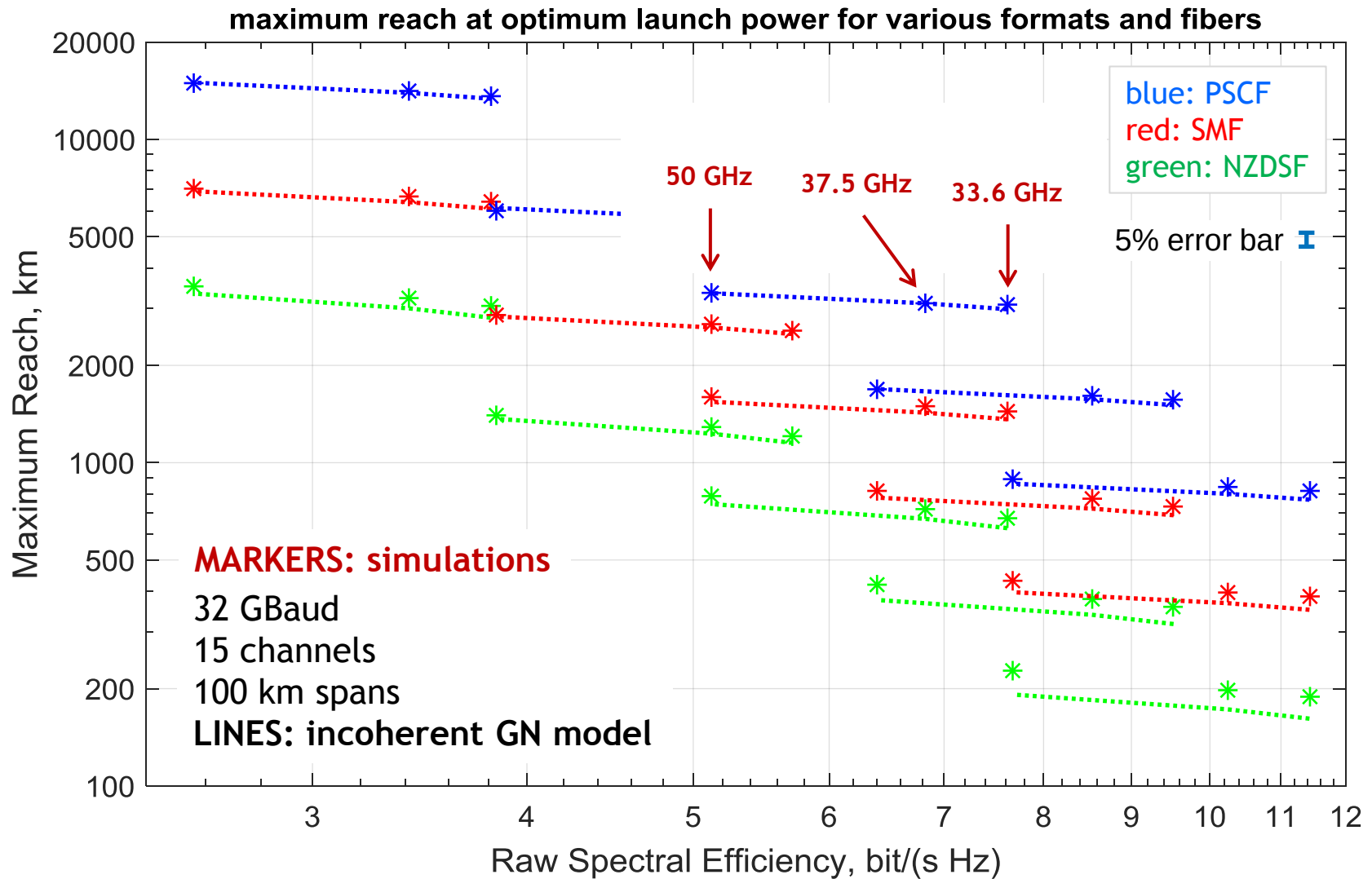


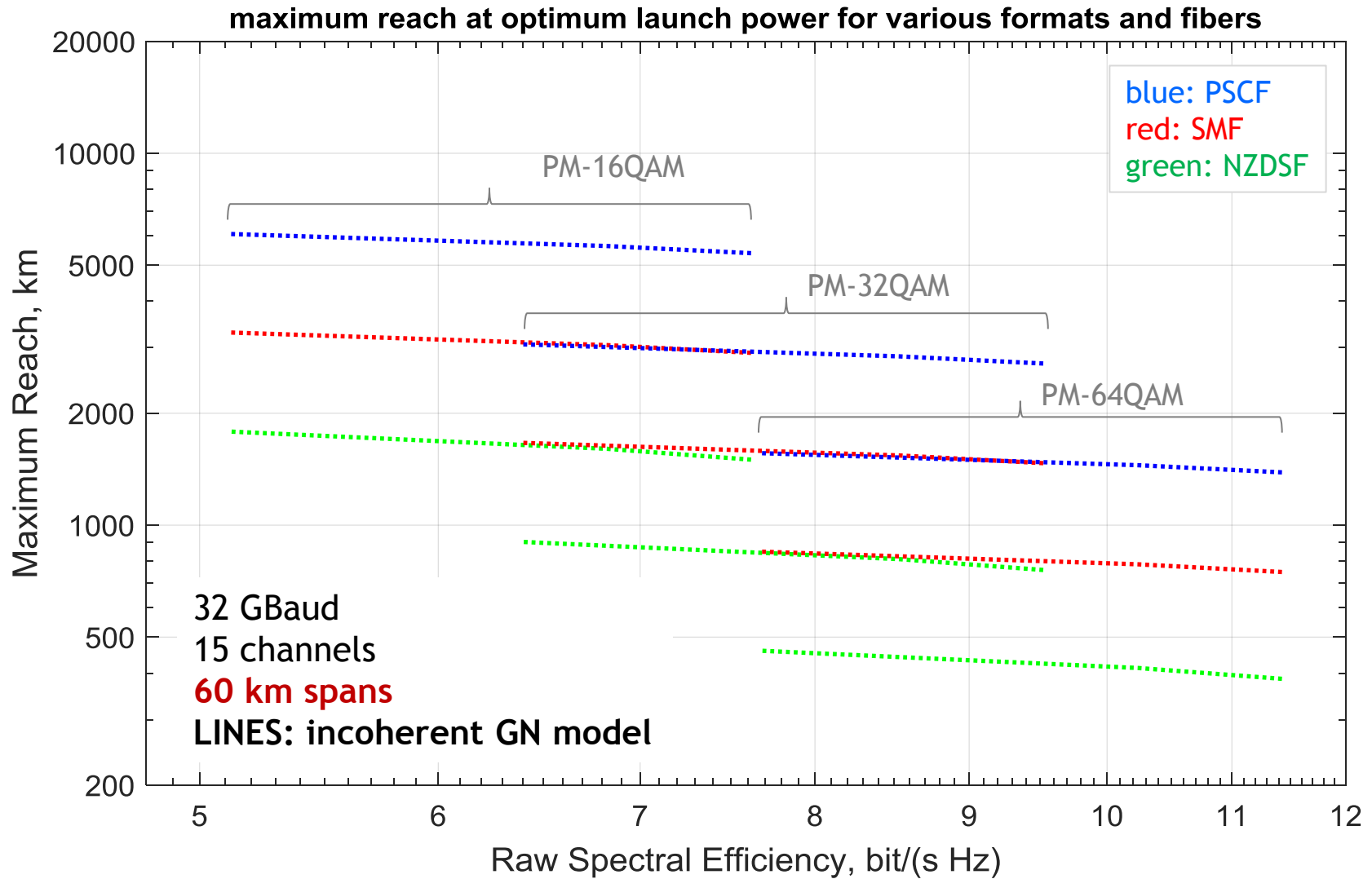


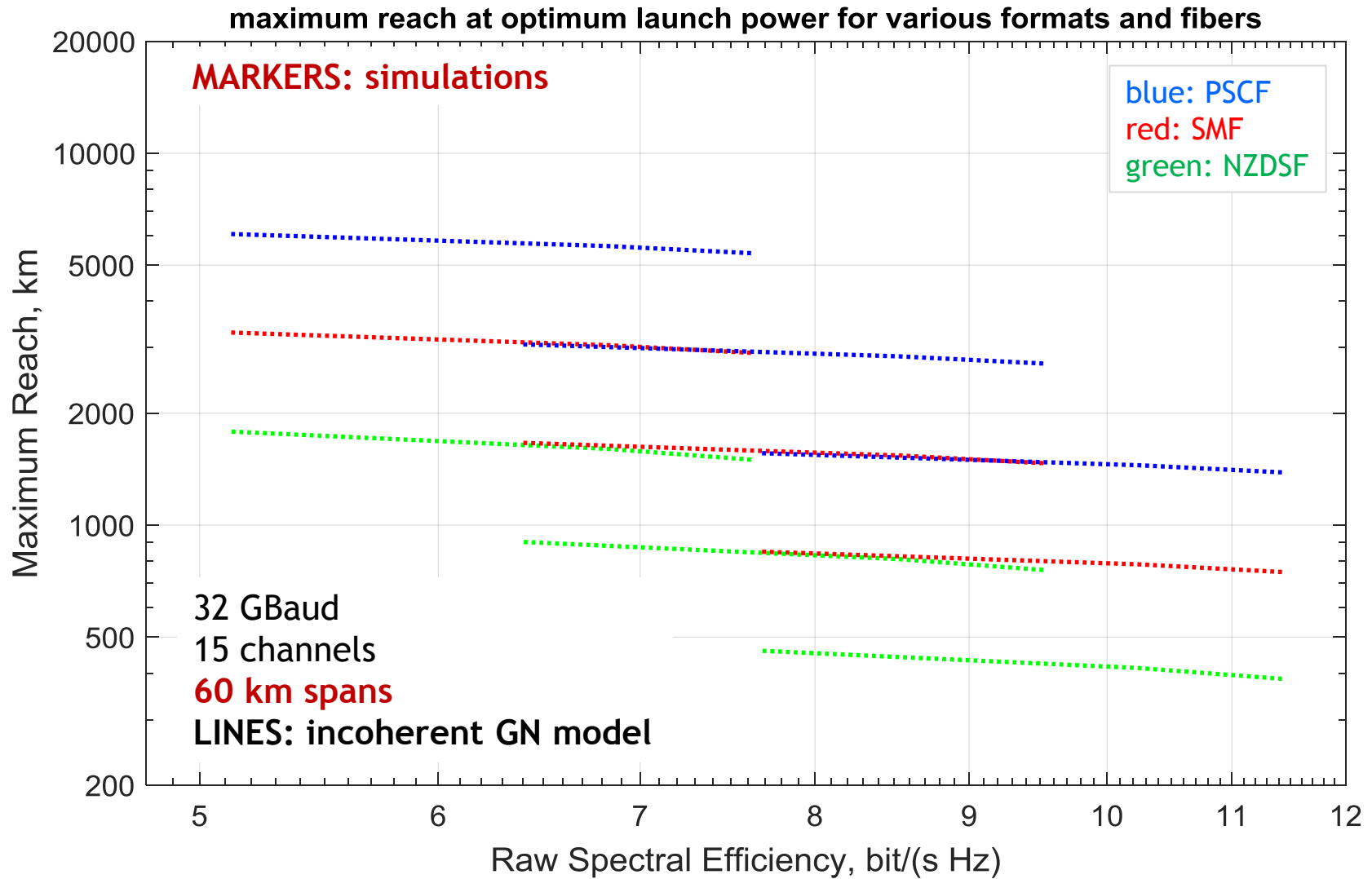
	dispersion D ps/(nm km)	loss α dB/km	non-linearity γ 1/(W km)
PSCF	20.1	0.17	0.8
SMF	16.7	0.2	1.3
NZDSF (E-LEAF)	3.8	0.22	1.5

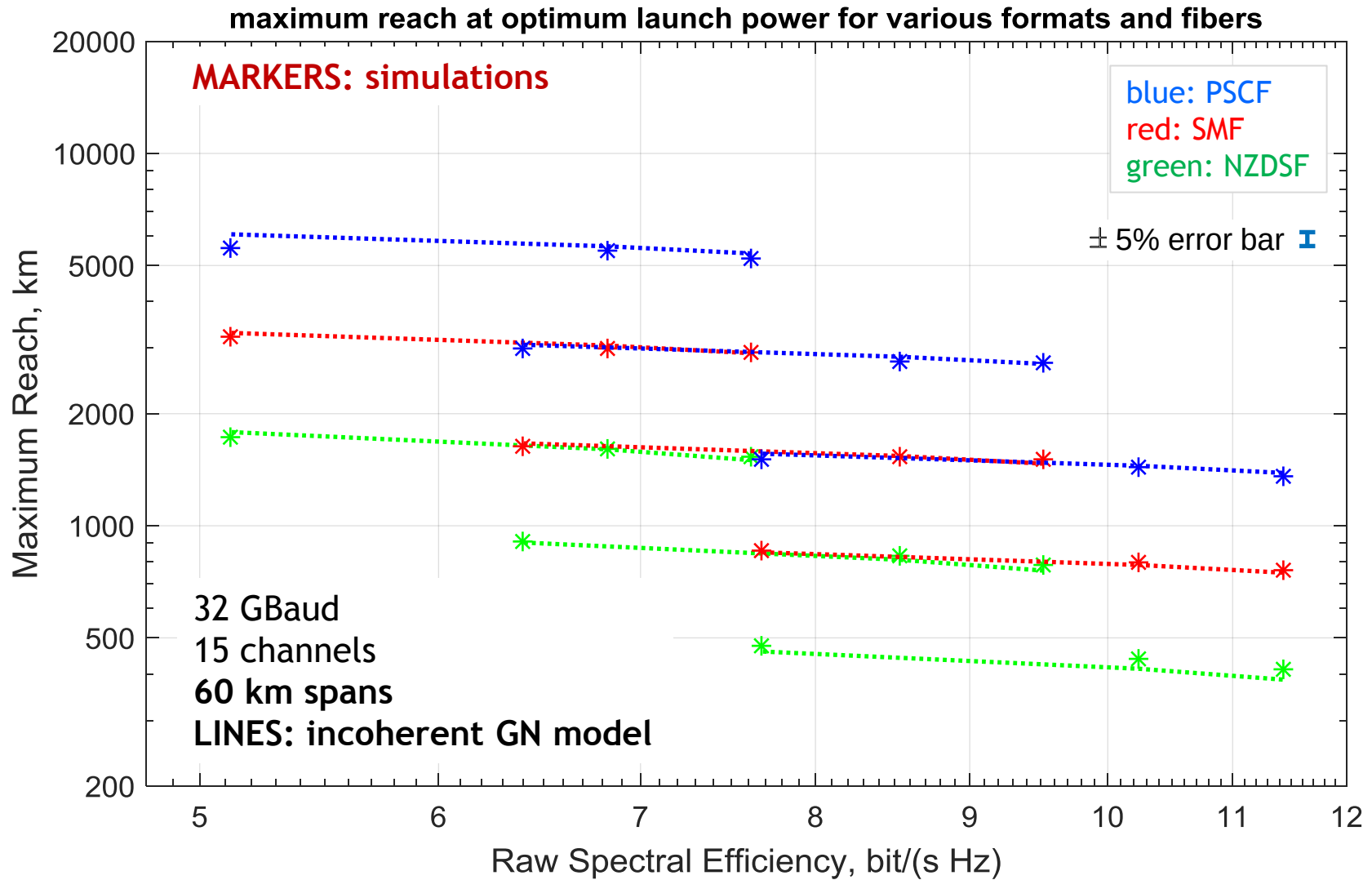












- ▶ 15 channels is a limited number
- ▶ Going to a higher number, max reach estimation becomes more pessimistic
- ▶ You may expect a 5%-10% underestimation of max reach for fully-loaded systems



credit:

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

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

$$\cdot \gamma^2 L_{\text{eff}}^2 \left| \frac{1 - e^{-2\alpha L_s} e^{j4\pi^2 \beta_2 L_s (f_1 - f)(f_2 - f)}}{1 - j2\pi^2 \beta_2 \alpha^{-1} (f_1 - f)(f_2 - f)} \right|^2 df_1 df_2$$

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

$$G_{\text{NLI}}(f) = N_s \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\text{WDM}}(f_1) G_{\text{WDM}}(f_2) G_{\text{WDM}}(f_1 + f_2 - f) \cdot \\ \cdot \frac{\gamma^2 L_{\text{eff}}^2}{1 + 4\pi^4 \beta_2^2 \alpha^{-2} (f_1 - f)^2 (f_2 - f)^2} df_1 df_2$$

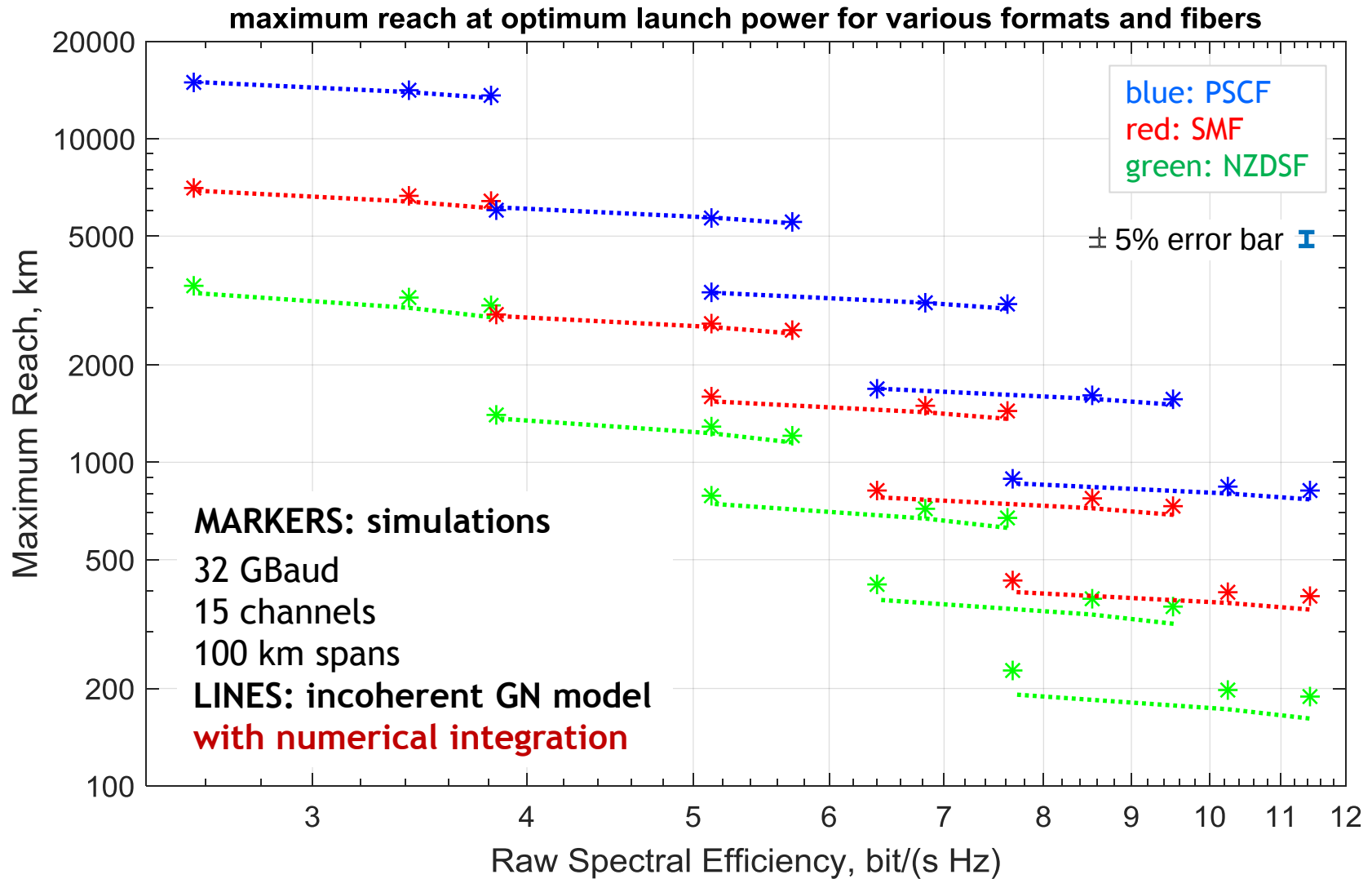
- *it can be integrated analytically !*
(with some approximations)

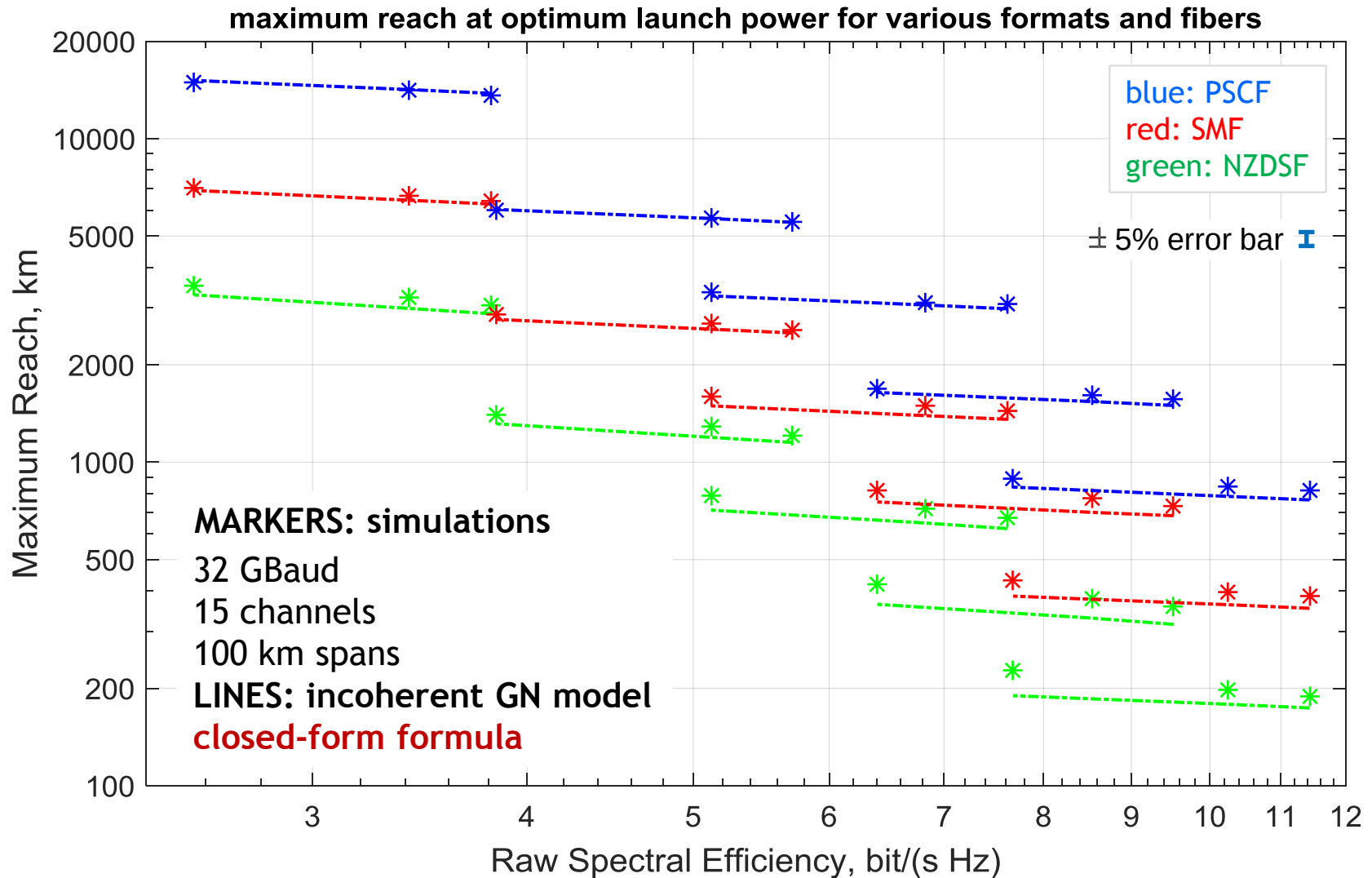
$$P_{\text{NLI}} = N_s \frac{16}{27} \frac{\gamma^2 L_{\text{eff}}^2 P_{\text{ch}}^3}{\pi |\beta_2| \alpha R^2} \text{asinh} \left(\frac{\pi^2}{2\alpha} |\beta_2| R^2 \left[N_{\text{ch}}^2 \right]^{\frac{R_s}{\Delta f}} \right)$$

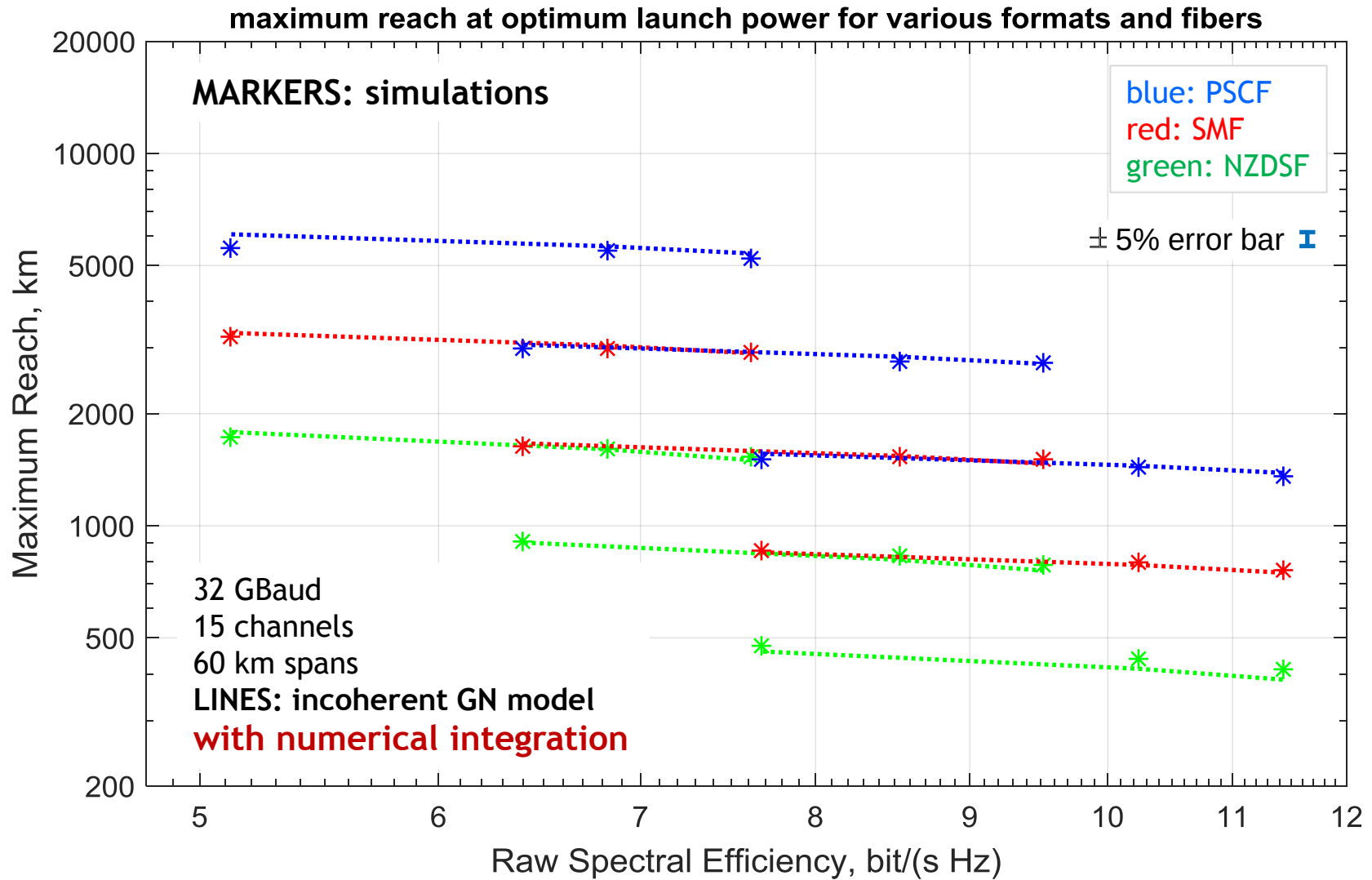
P. Poggiolini "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *J. of Lightwave Technol.*, vol. 30, no. 24, pp. 3857-3879, Dec. 15 2012.

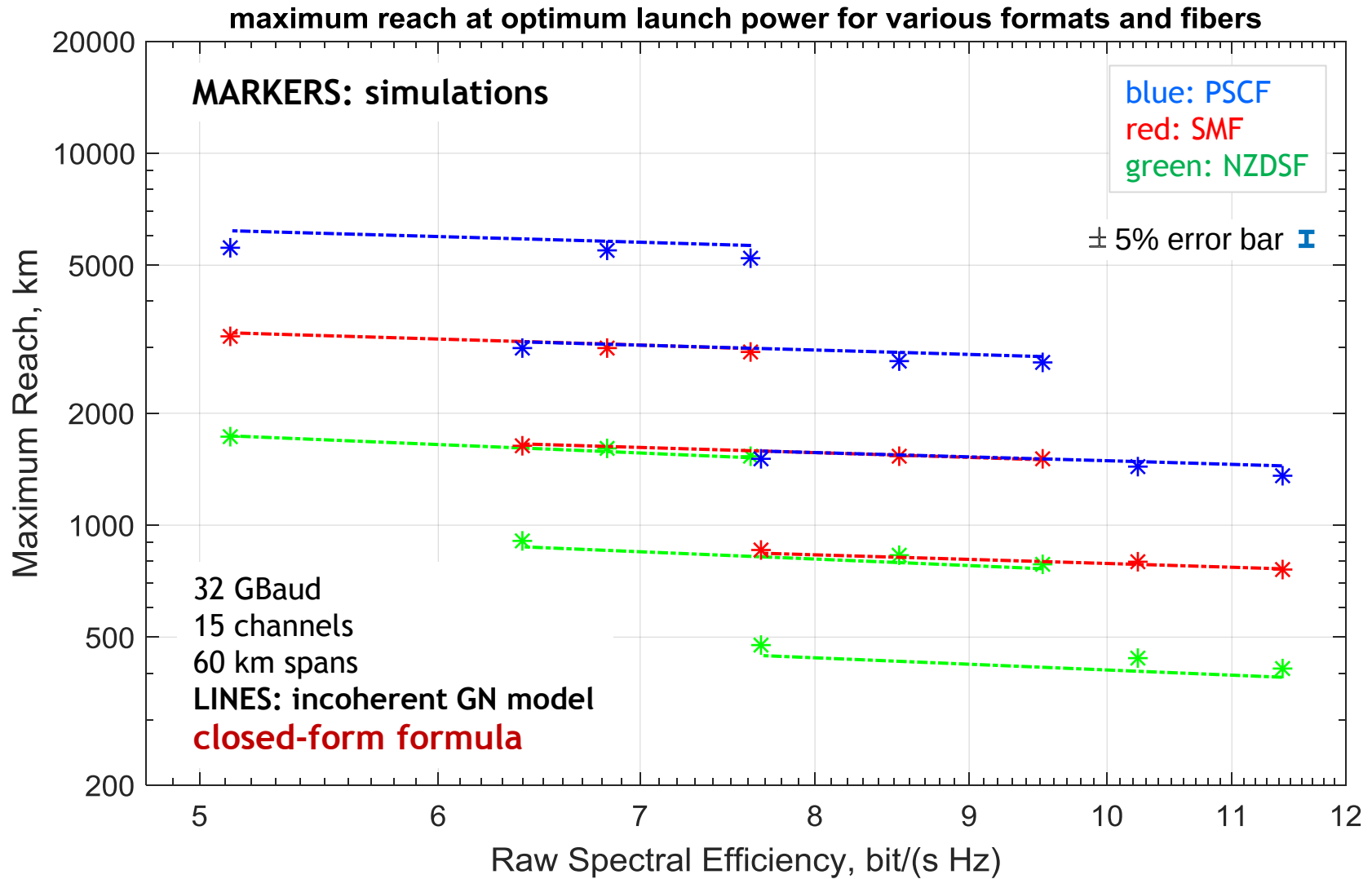
► Other versions address non-uniform spans and all-different channels:

- 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.







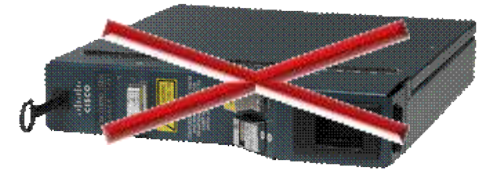


$$P_{\text{NLI}} = N_s \frac{16}{27} \frac{\gamma^2 L_{\text{eff}}^2 P_{\text{ch}}^3}{\pi |\beta_2| \alpha R^2} \text{asinh} \left(\frac{\pi^2}{2\alpha} |\beta_2| R^2 \left[N_{\text{ch}}^2 \right]^{\frac{R_s}{\Delta f}} \right)$$

Various restrictions apply, do not use:

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

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

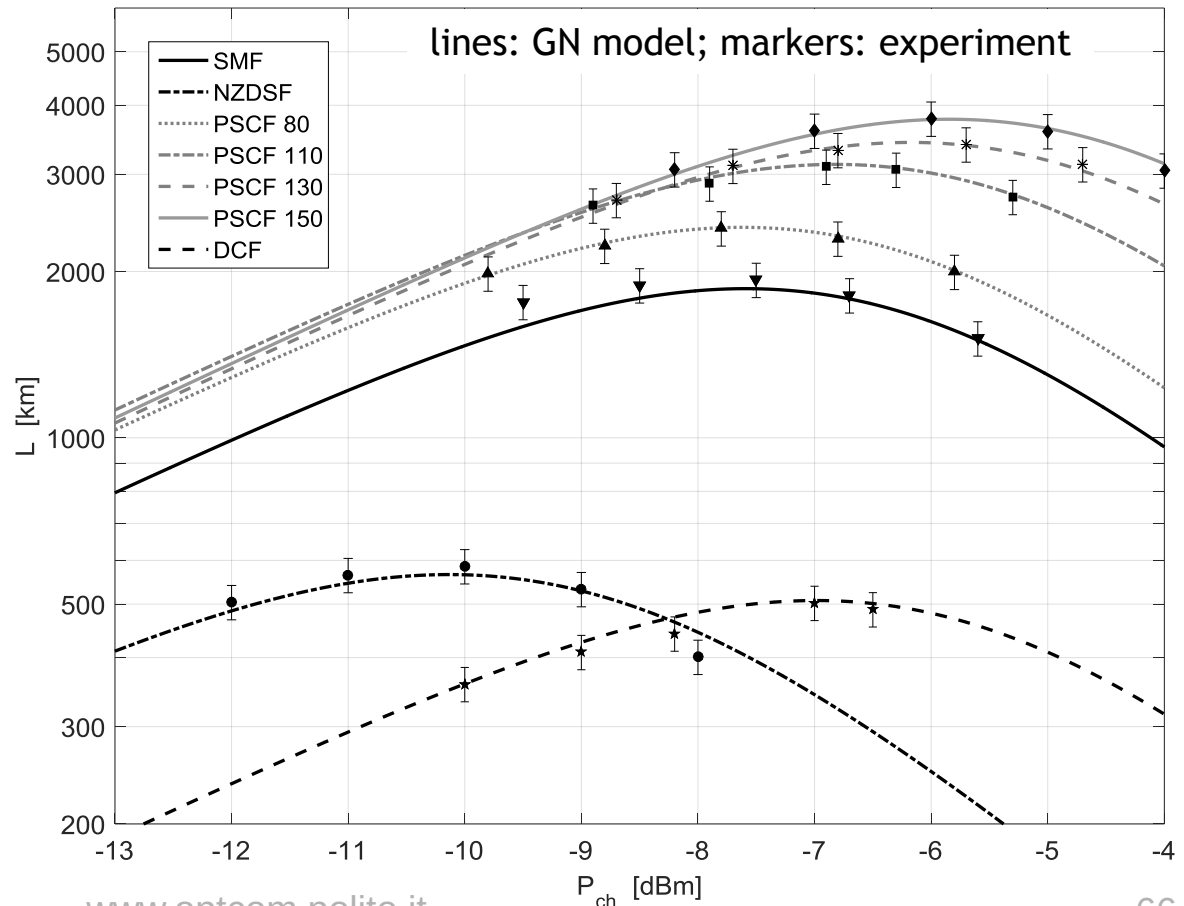


credit: <http://travel-representatives.com/>

- ▶ 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 !!**



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>

**PROBLEM
SOLVED** ✓

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... !

- ▶ 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.

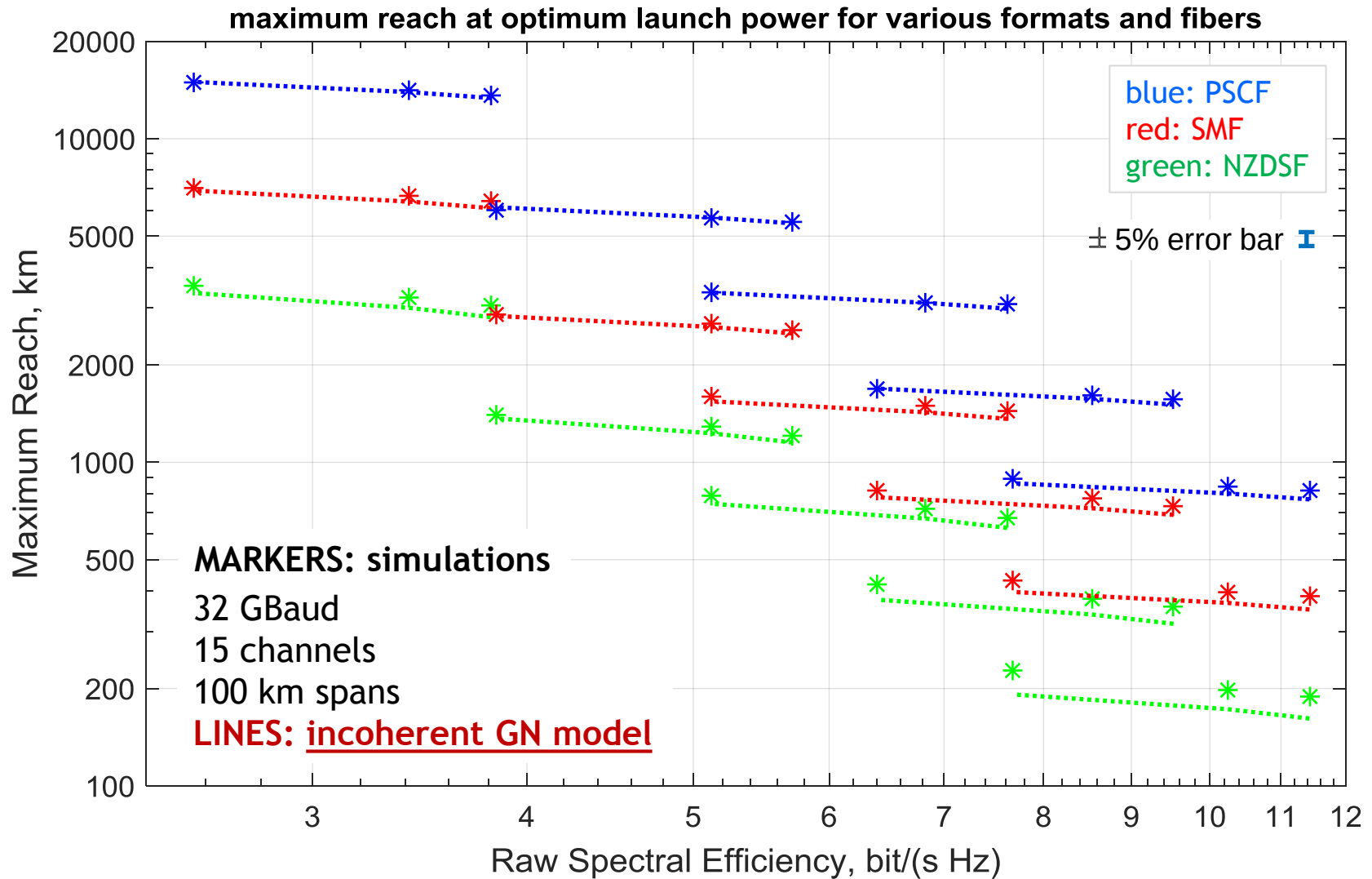
- ▶ It does not allow to study:
 - ▶ pre-dispersion
 - ▶ the effect of low symbol rates on NLI generation
 - ▶ the “finer” effects of formats on NLI generation
 - ▶ etc.

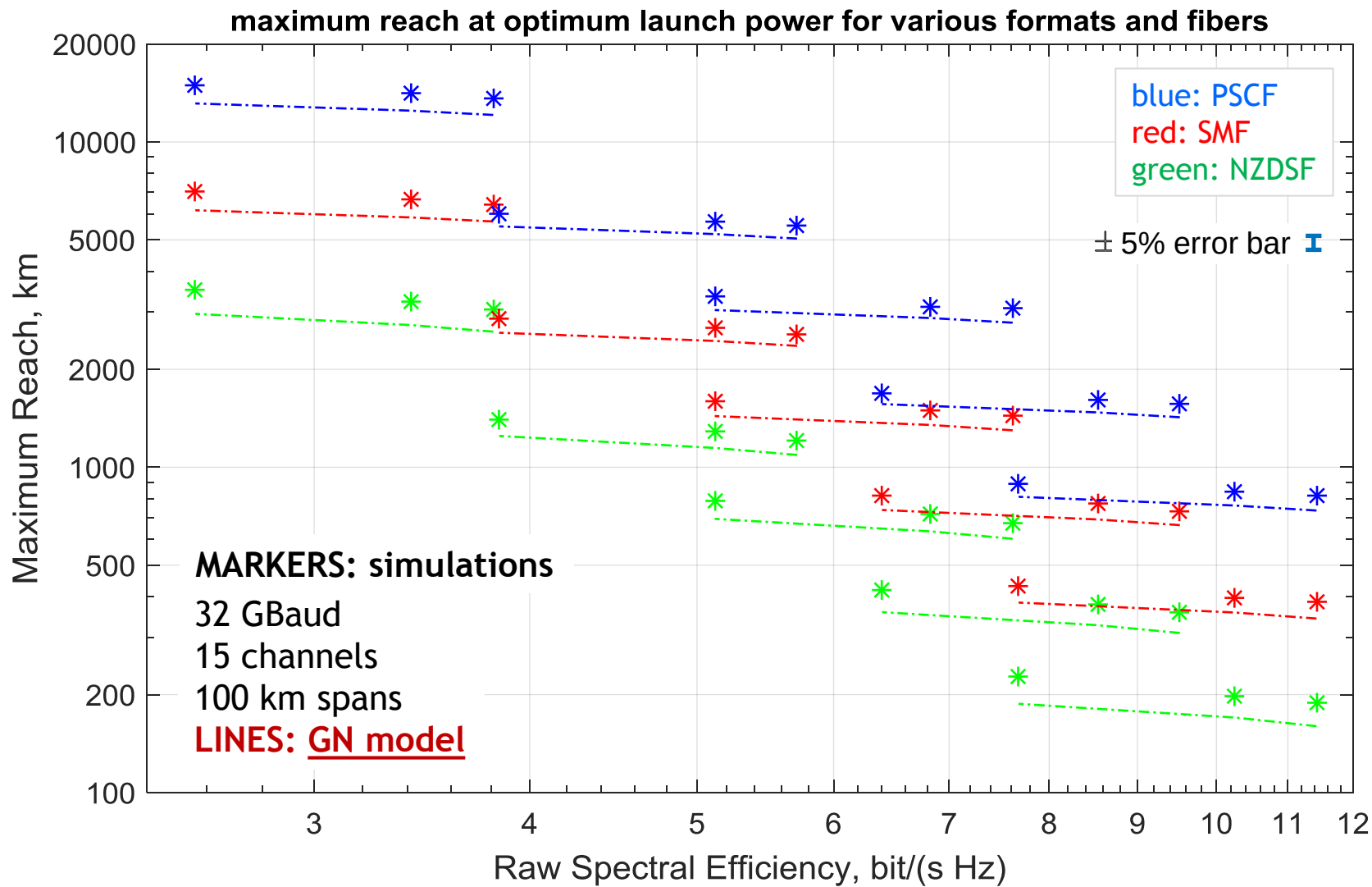
$$G_{\text{NLI}}(f) = \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\text{WDM}}(f_1) G_{\text{WDM}}(f_2) G_{\text{WDM}}(f_1 + f_2 - f) \cdot$$

$$\cdot |\mu(f_1, f_2, f)|^2 df_1 df_2$$

for identical spans with lumped amplification:

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





- ▶ 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

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

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

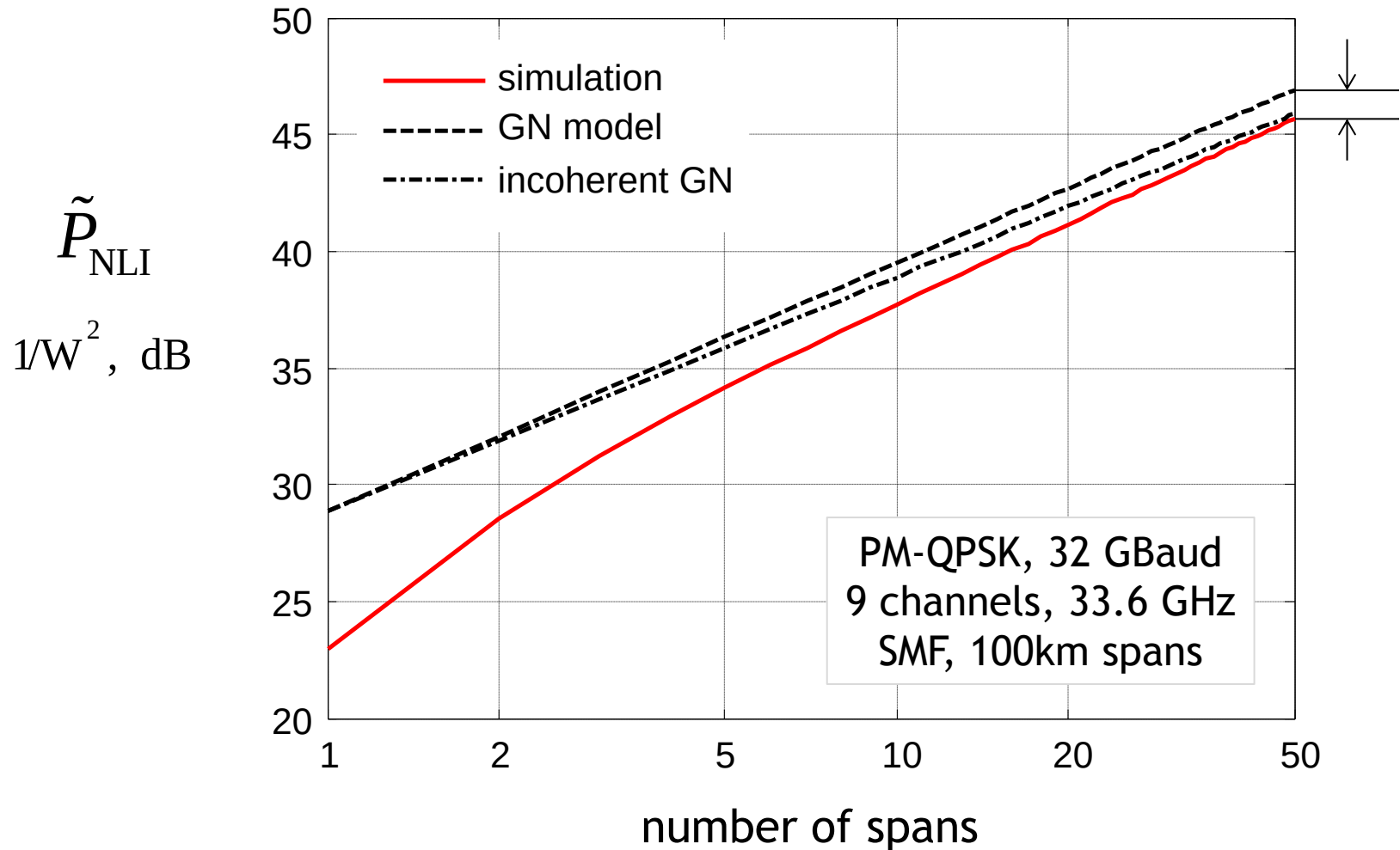
- ▶ 1 dB NLI error → 8% max reach error
- ▶ 3 dB NLI error → 26% max reach error
- ▶ Also, looking at max reach we only test the model “at max reach” but do not know if it is accurate elsewhere along the link

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

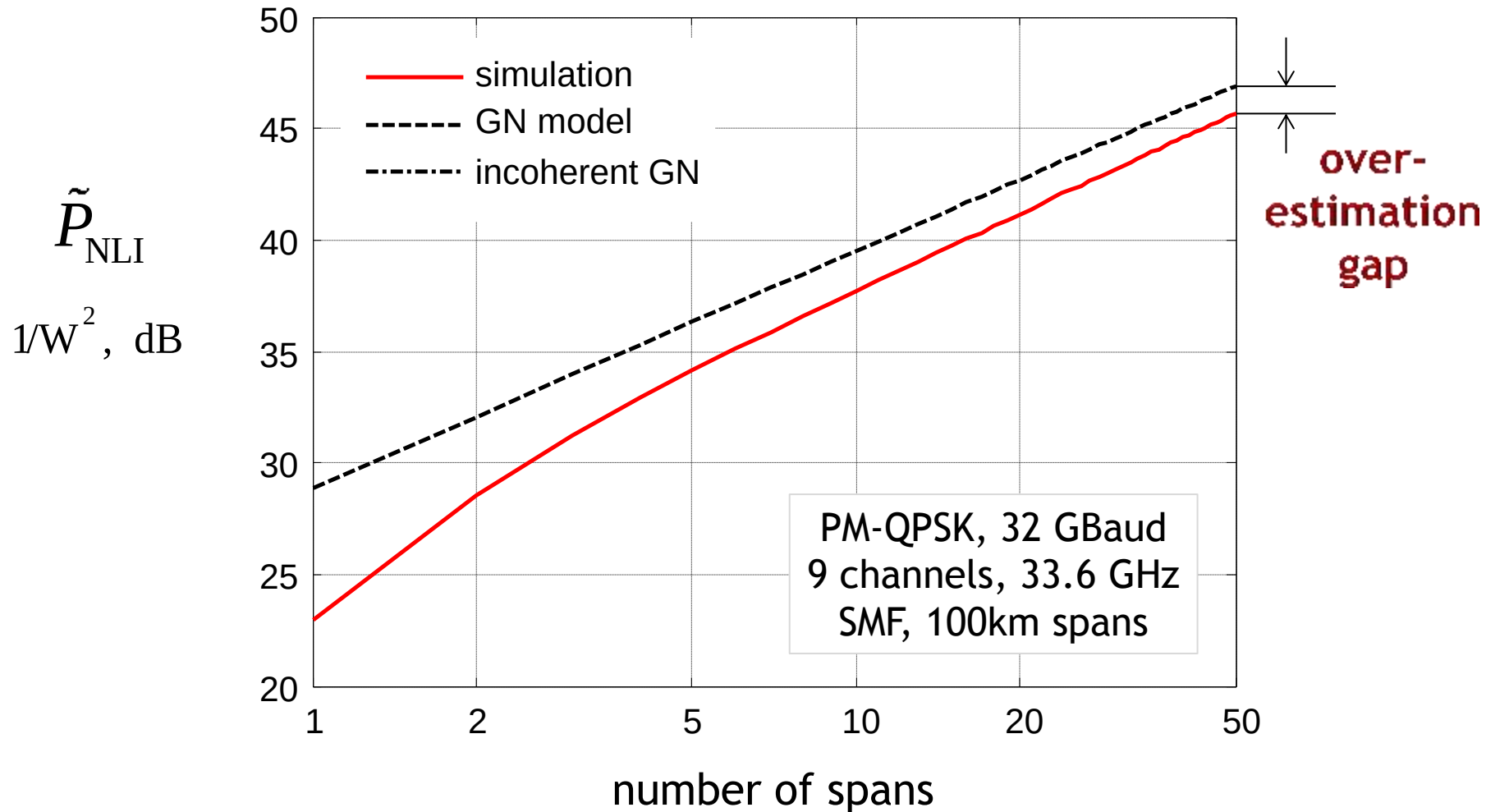
$$P_{\text{NLI}}(n_{\text{span}})$$

- ▶ To have a launch-power-independent quantity you can normalize it:

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



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.



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.

- ▶ 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 (4th and 6th) are taken into account, then *the GN model tendency to NLI overestimation can be completely removed*

- ▶ *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

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

- ▶ *EGN model* stands for “enhanced GN model”
- ▶ The EGN model consists of the GN model and of a “correction” term:

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

- ▶ *For PM-QAM systems the “correction” always decreases NLI*
 - ▶ this shows the GN-model to be some sort of “upper bound” to NLI

- *If the constellation is Gaussian, then*

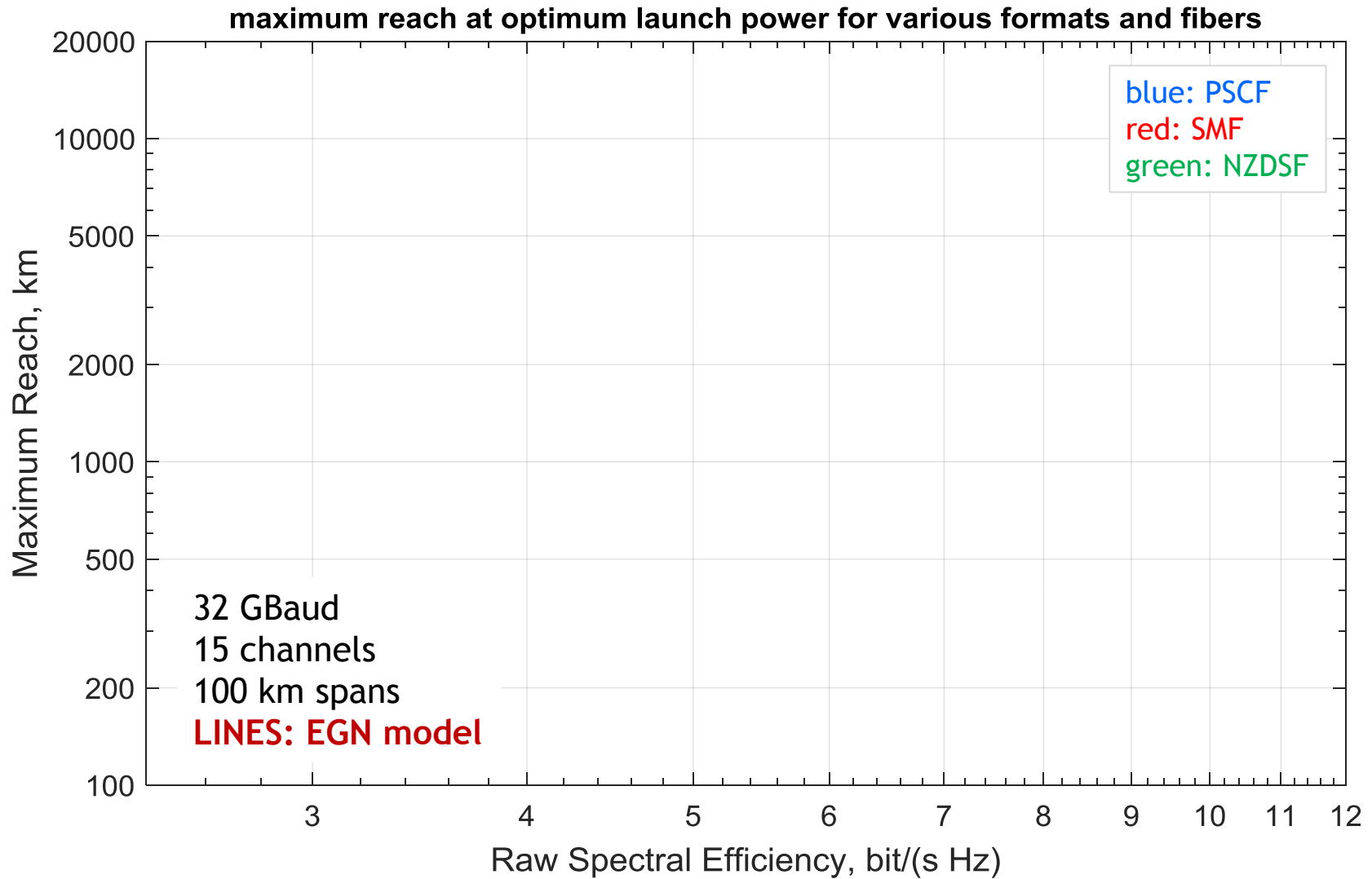
$$G_{\text{NLI}}^{\text{EGN}}(f) = G_{\text{NLI}}^{\text{GN}}(f) - \cancel{G_{\text{NLI}}^{\text{GRT}}(f)}$$

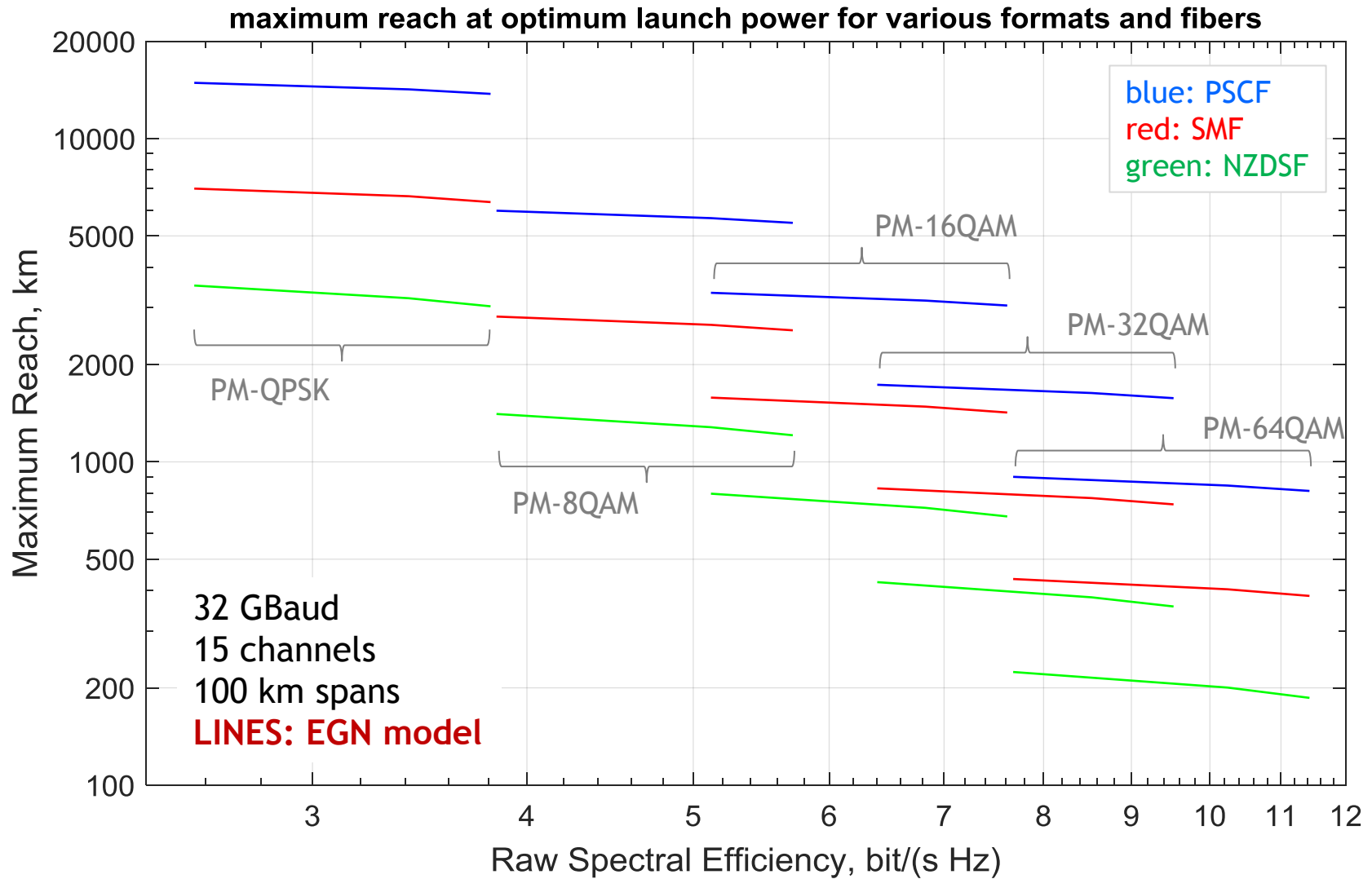
- This might have interesting implications for probabilistic shaping

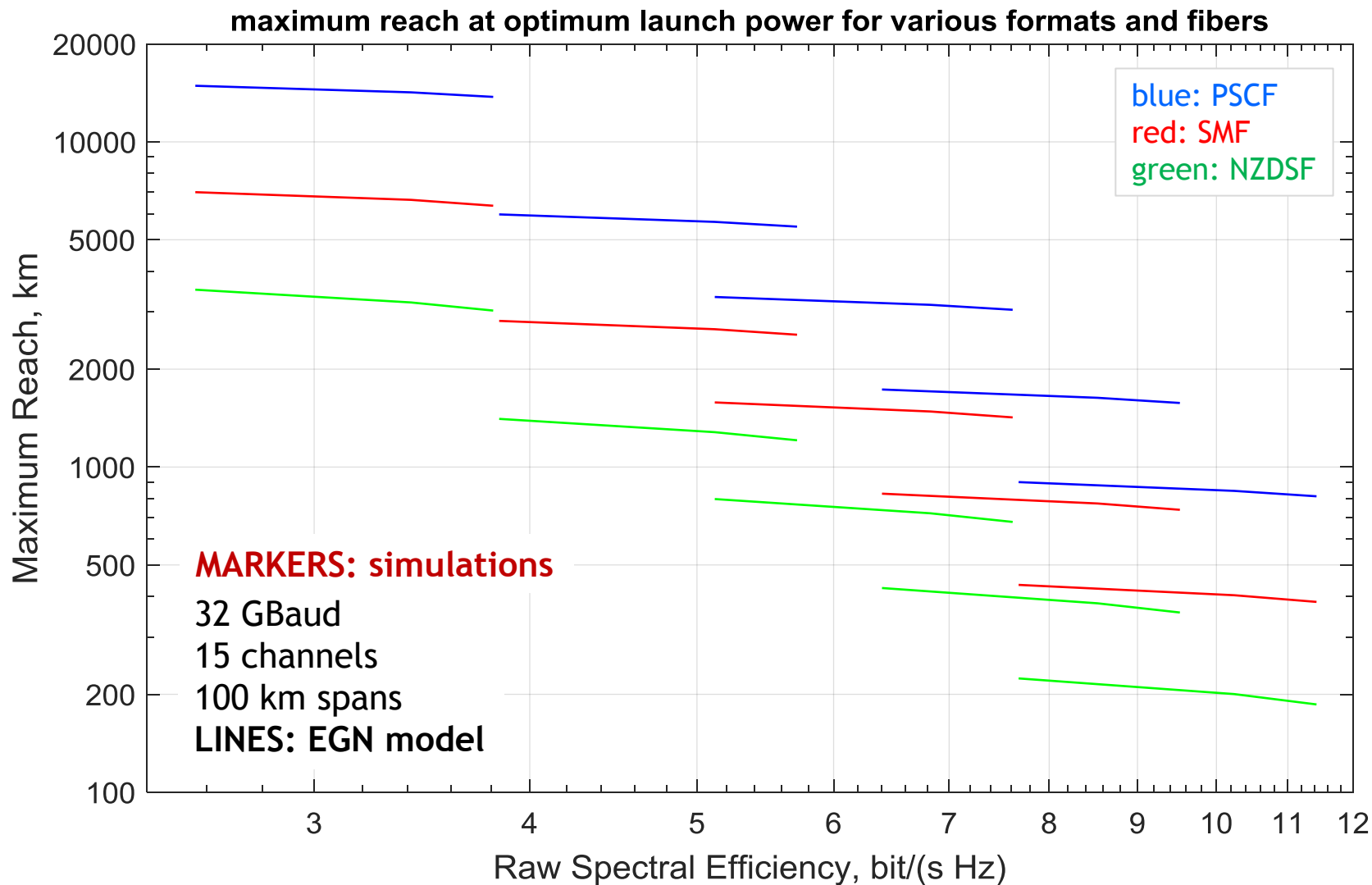
$$G_{\text{NLI}}^{\text{EGN}}(f) = G_{\text{NLI}}^{\text{GN}}(f) - G_{\text{NLI}}^{\text{corr}}(f)$$

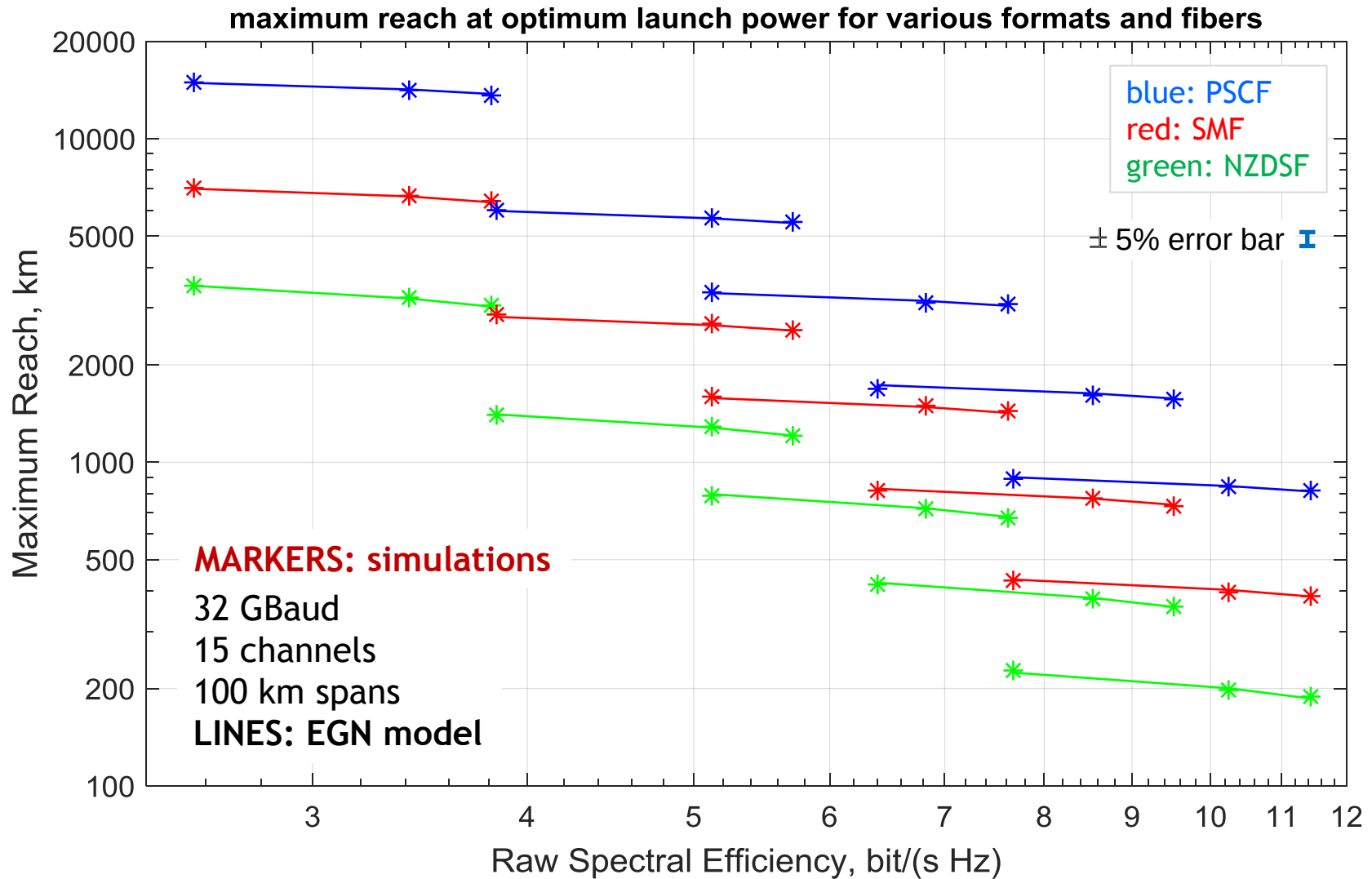


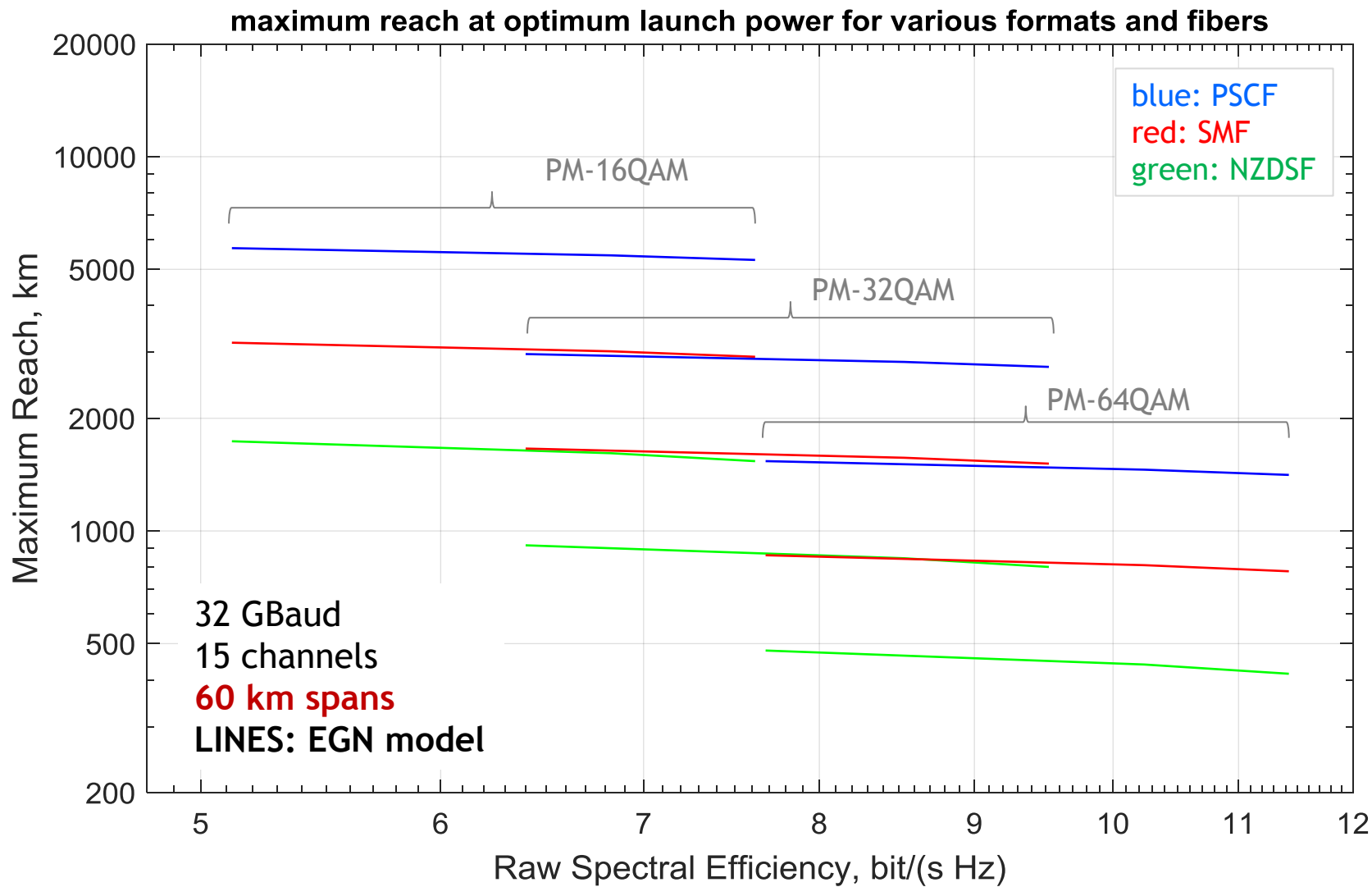
credit: http://www.dtvisiontech.com/2015_12_01_archive.html

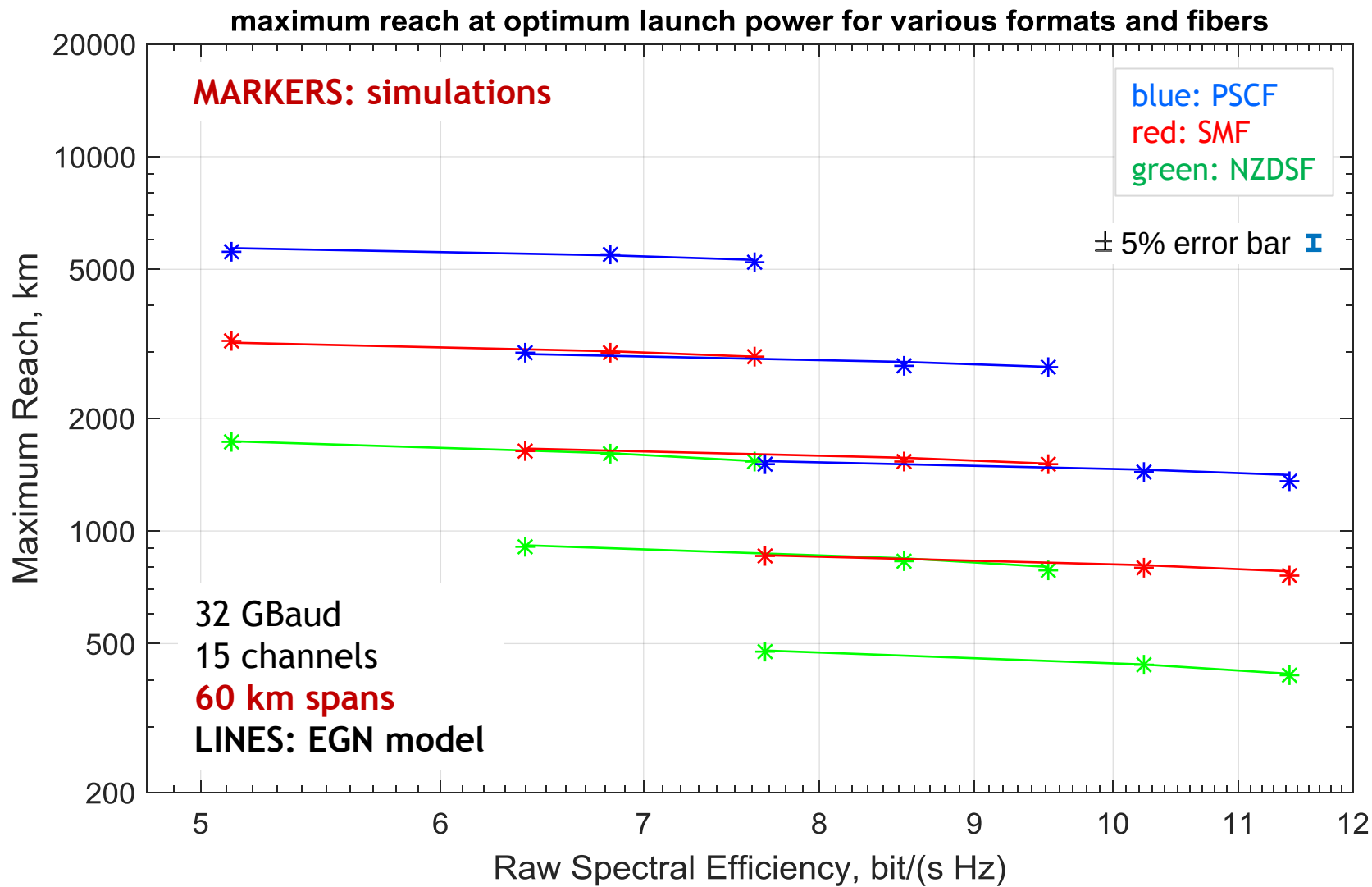










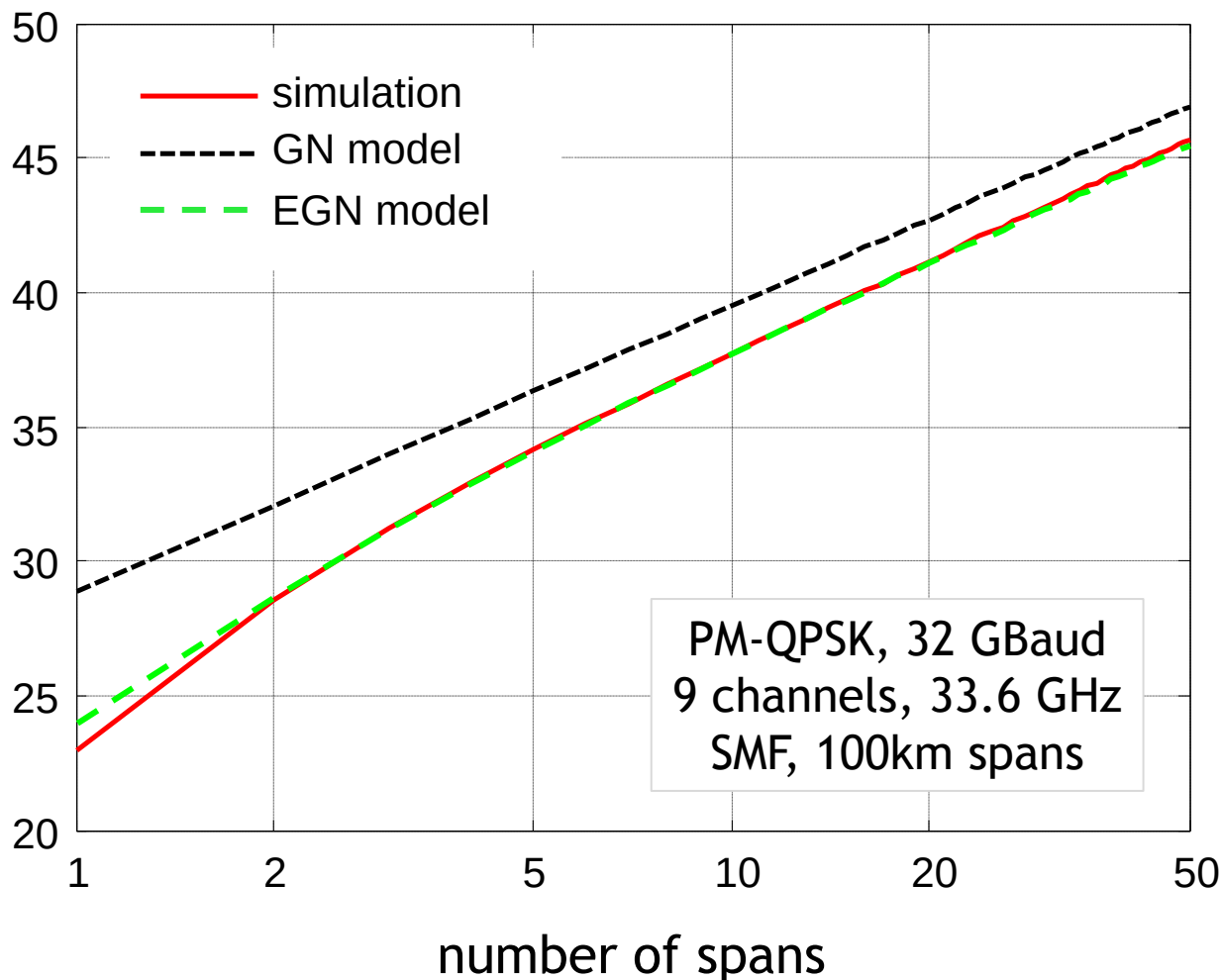


- ▶ But maximum reach is not very sensitive...
- ▶ Let's look at the more sensitive probe:

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

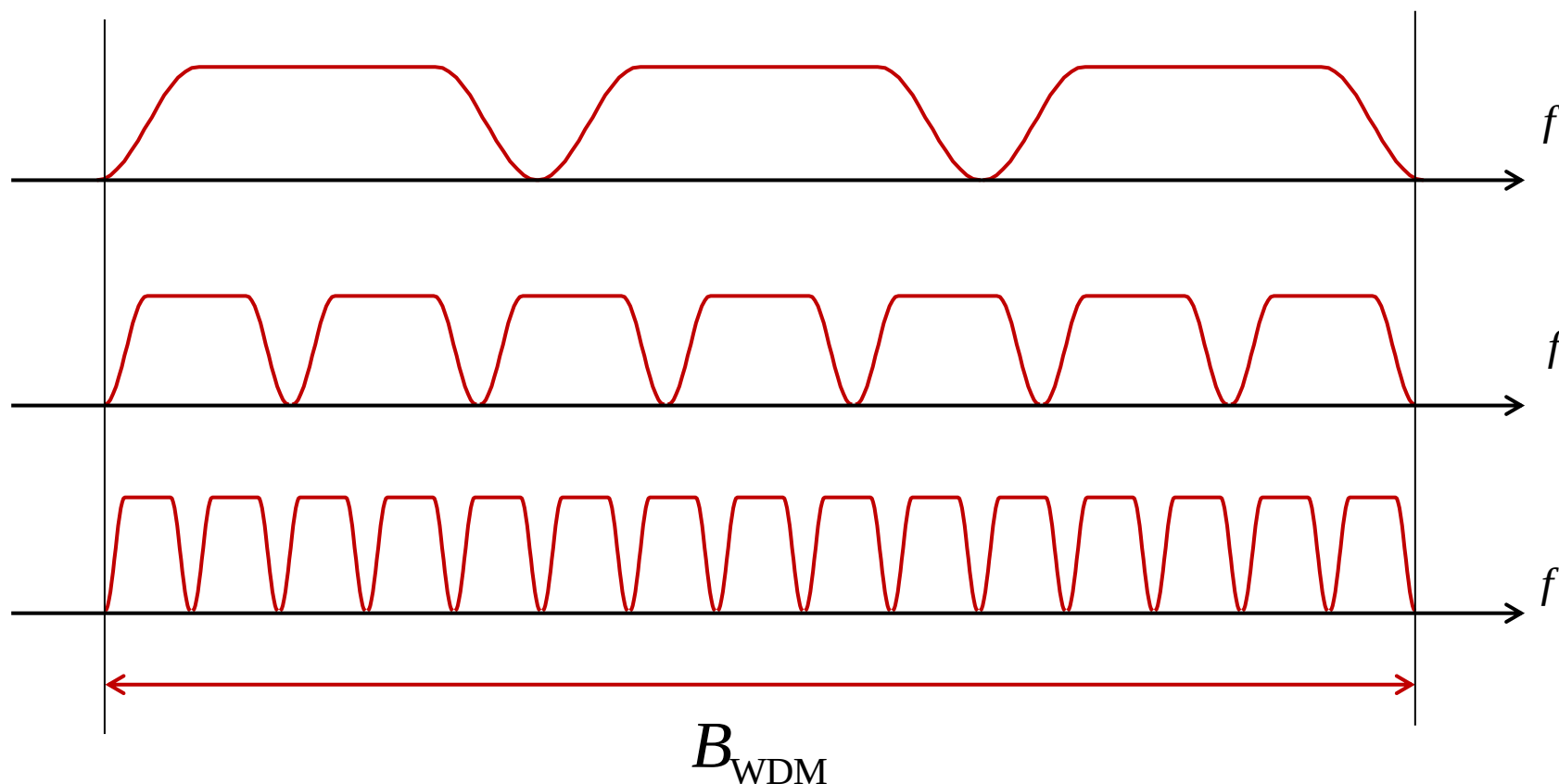
$$\tilde{P}_{\text{NLI}}$$

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



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.

- ▶ 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



Constraint: identical total throughput

Which quantity to analyze ?

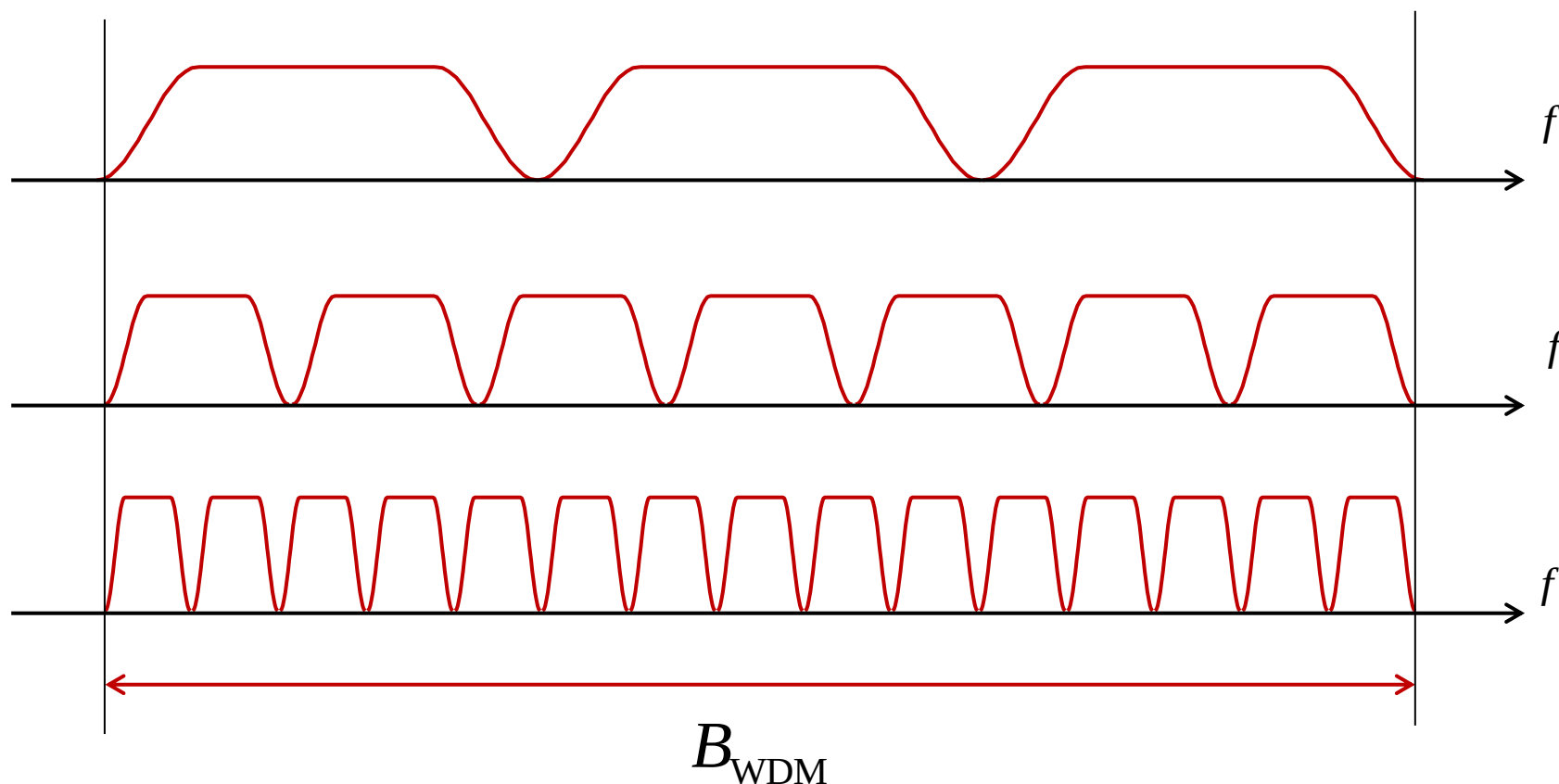
$$\tilde{P}_{\text{NLI}} = P_{\text{NLI}} / P_{\text{ch}}^3$$

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

a constant value

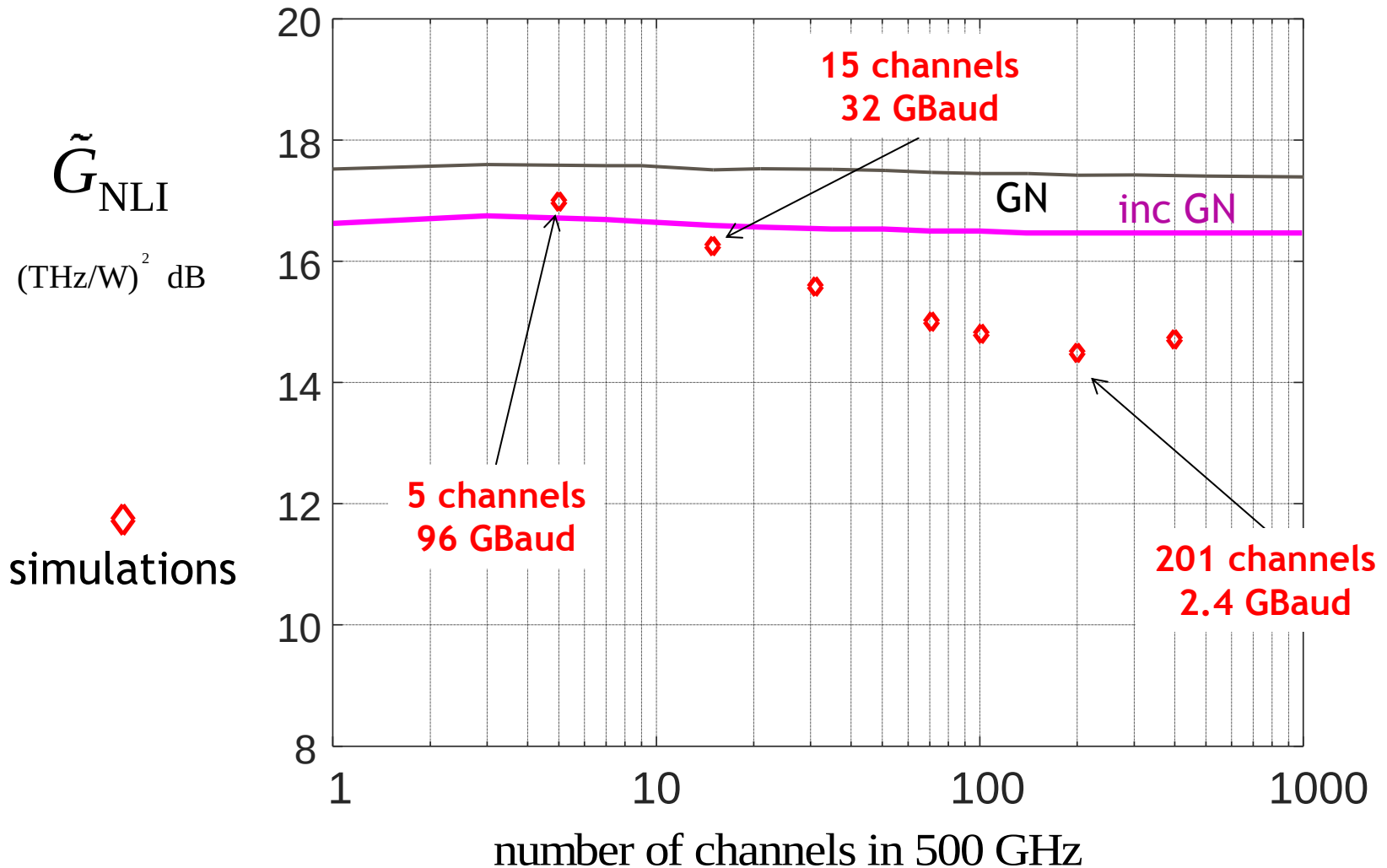
while dividing B_{WDM} into more channels

means same maximum reach

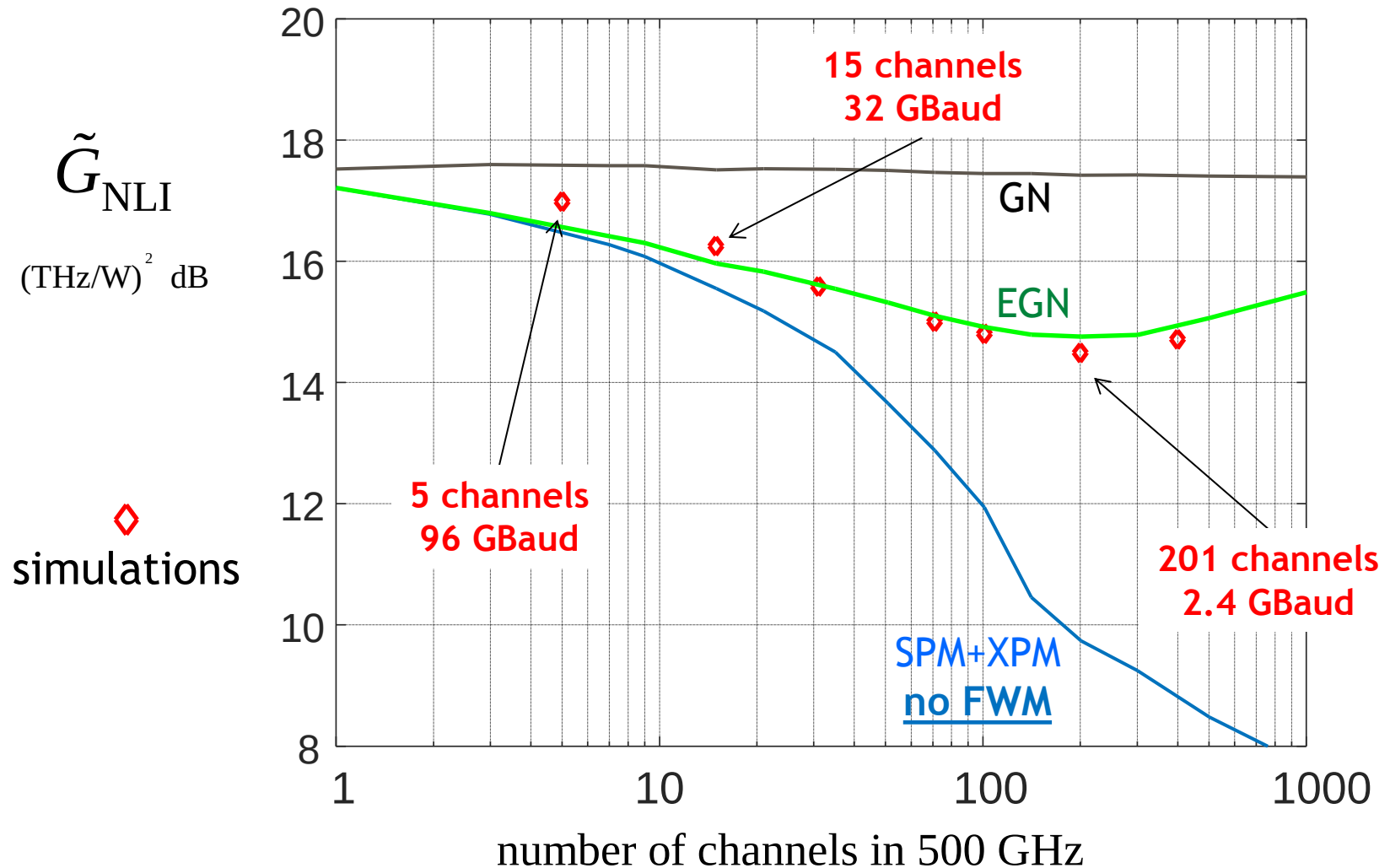


Constraint: identical total throughput

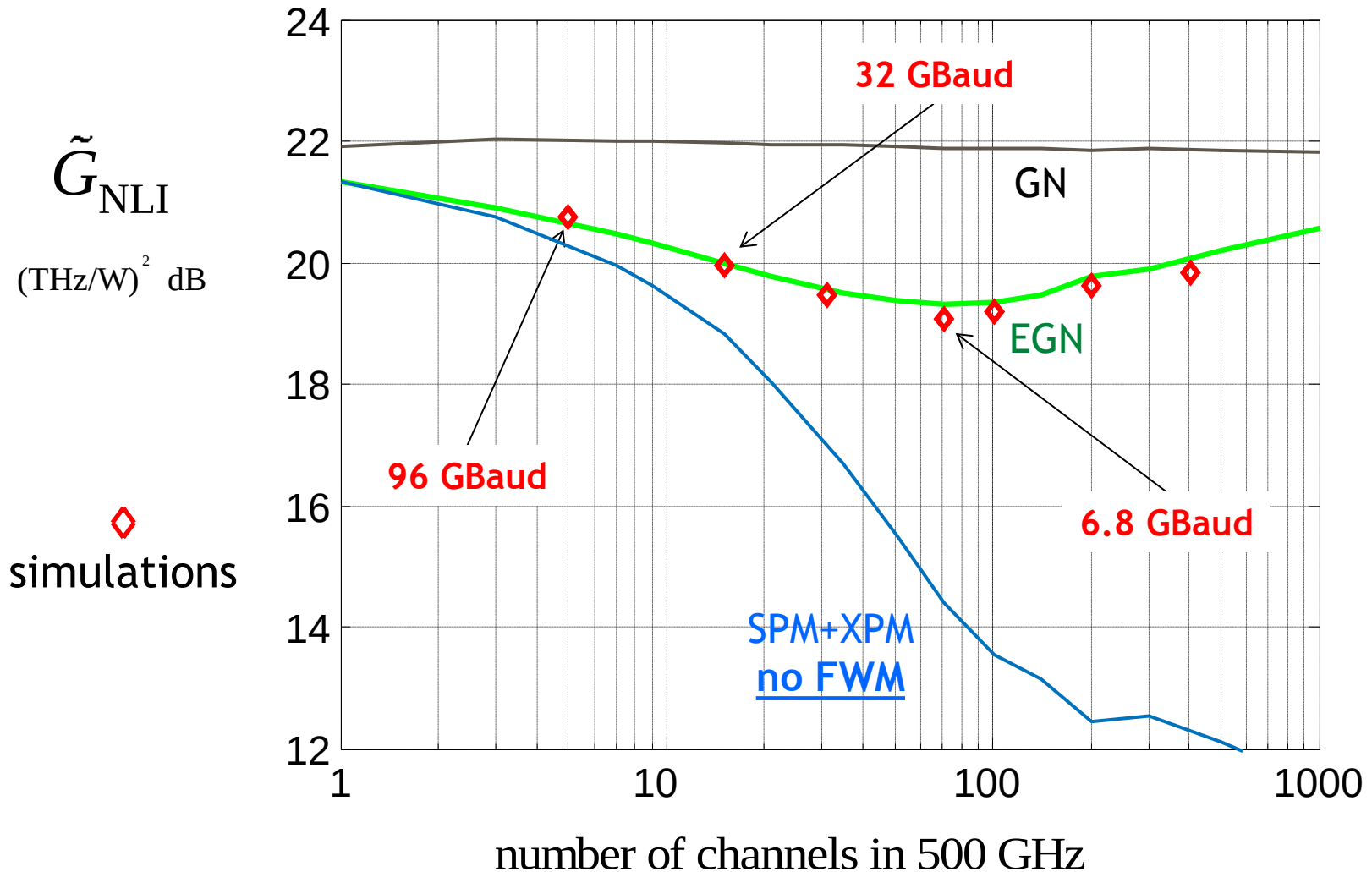
- $B_{\text{WDM}} = 500 \text{ GHz}$, PM-QPSK, 100 km spans, spacing $1.05 \times$ (symb. rate)



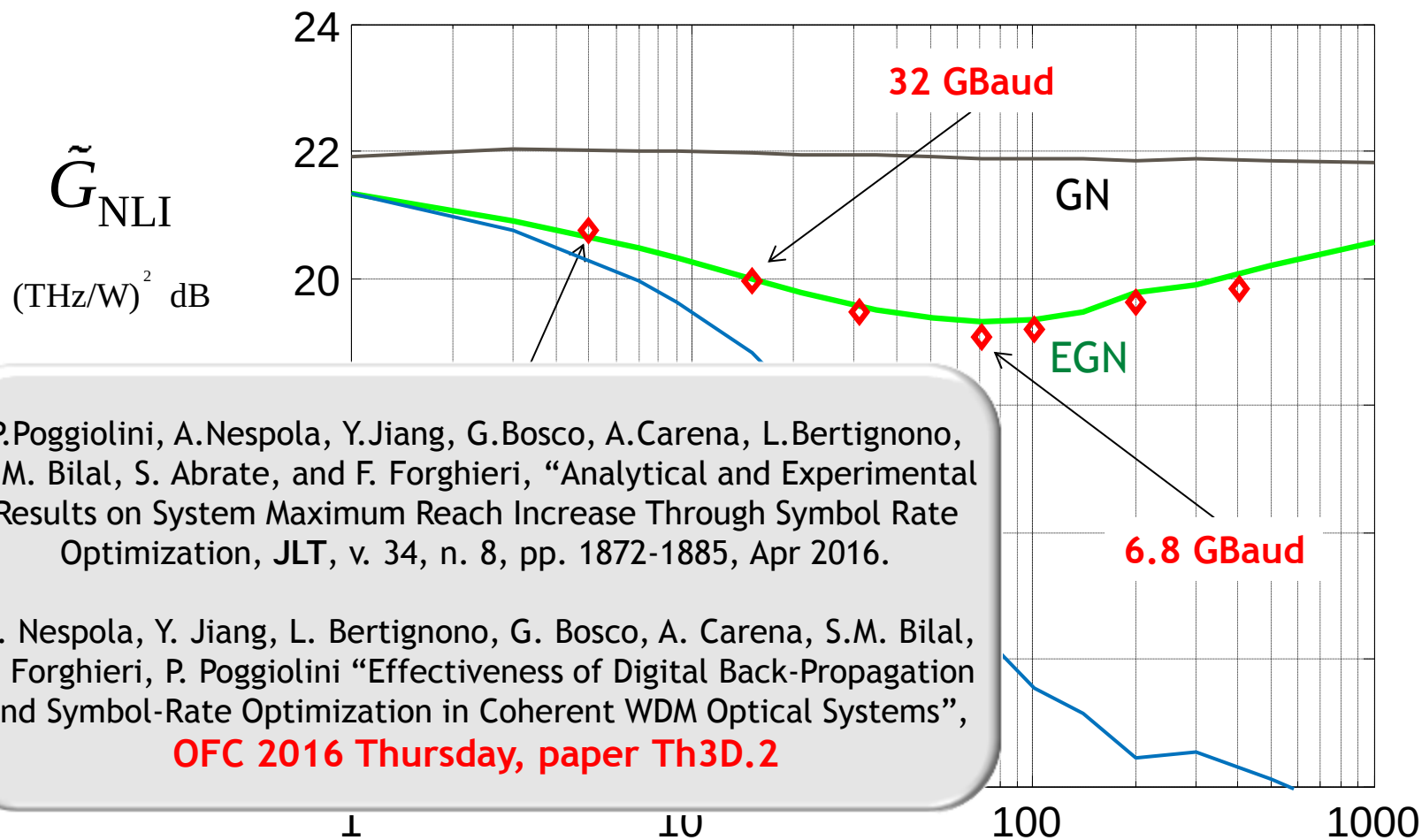
► $B_{\text{WDM}} = 500 \text{ GHz}$, PM-QPSK, 100 km spans, spacing $1.05 \times (\text{symb. rate})$



► $B_{\text{WDM}} = 500 \text{ GHz}$, PM-QPSK, 100 km spans, spacing $1.05 \times (\text{symb. rate})$



► $B_{\text{WDM}} = 500 \text{ GHz}$, PM-QPSK, 100 km spans, spacing $1.05 \times (\text{symb. rate})$



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**

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- ▶ *The EGN model is really very accurate across a very wide range of systems*
- ▶ including low-symbol rate, low dispersion, short systems, 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



- ▶ 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

So that's it !



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well, wait a minute...

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

$$G_{\text{NLI}}^{\text{GN}}(f) = \frac{16}{27} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{\text{WDM}}(f_1) G_{\text{WDM}}(f_2) G_{\text{WDM}}(f_1 + f_2 - f) |\mu(f_1, f_2, f)|^2 df_1 df_2$$

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

SPM

XPM

FWM

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

$$\kappa_m^{\text{SPM}}(f) = \frac{80}{81} R_m^2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_1 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2'.$$

$$|s_m(f_1)|^2 s_m(f_2) s_m^*(f_2') s_m^*(f_1 + f_2 - f) s_m(f_1 + f_2' - f) \cdot \mu(f_1, f_2, f) \mu^*(f_1, f_2', f)$$

$$+ \frac{16}{81} R_m^2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_1 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2'.$$

$$|s_m(f_1 + f_2 - f)|^2 s_m(f_1) s_m(f_2) s_m^*(f_1 + f_2 - f_2') s_m^*(f_2') \cdot \mu(f_1, f_2, f) \mu^*(f_1 + f_2 - f_2', f_2', f)$$

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

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

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

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

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

$$\begin{aligned} & |s_m(f_1)|^2 s_n(f_2) s_n^*(f_2') s_n^*(f_1 + f_2 - f) s_n(f_1 + f_2' - f) \cdot \\ & \mu(f_1, f_2, f) \mu^*(f_1, f_2', f) \end{aligned}$$

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

$$\kappa_{X2}^n(f) = \frac{80}{81} R_m R_n \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2' \cdot$$

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

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

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

$$\kappa_{X3}^n(f) = \frac{16}{81} R_m R_n \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2 \int_{f_m - B_m/2}^{f_m + B_m/2} df_2' \cdot$$

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

$$\mu(f_1, f_2, f) \mu^*(f_1 + f_2 - f_2', f_2', f)$$

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

$$\varsigma_{X4}^n(f) = \frac{16}{81} R_n \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_1' \int_{f_n - B_n/2}^{f_n + B_n/2} df_2' \cdot$$

$$s_n(f_1) s_n(f_2) s_n^*(f_1 + f_2 - f) s_n^*(f_1') s_n^*(f_2') s_n(f_1' + f_2' - f) \cdot$$

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

$$\kappa_{X4}^n(f) = \frac{80}{81} R_n^2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2' \cdot$$

$$|s_n(f_1)|^2 s_n(f_2) s_n^*(f_2') s_n^*(f_1 + f_2 - f) s_n(f_1 + f_2 - f) \cdot$$

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

$$+ \frac{16}{81} R_n^2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2 \int_{f_n - B_n/2}^{f_n + B_n/2} df_2' \cdot$$

$$|s_n(f_1 + f_2 - f)|^2 s_n(f_1) s_n(f_2) s_n^*(f_1 + f_2 - f_2') s_n^*(f_2') \cdot$$

$$\mu(f_1, f_2, f) \mu^*(f_1 + f_2 - f_2', f_2', f)$$

The FWM M1, M2 and M3 corrections

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

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

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

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

when $n = m - 1$, $l_{\min} = 1$, $l_{\max} = n - 1$;

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

$$\kappa_{M1}^l(f) = \frac{80}{81} R_n R_l \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2' \cdot$$

$$|s_n(f_1)|^2 s_l(f_2) s_l^*(f_2') s_l^*(f_1 + f_2 - f) s_l(f_1 + f_2' - f) \cdot$$

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

$$\kappa_{M2}^l(f) = \frac{80}{81} R_n R_l \int_{f_n - B_n/2}^{f_n + B_n/2} df_1 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2' \cdot$$

$$|s_n(f_1)|^2 s_l(f_2) s_l^*(f_2') s_l^*(f_1 + f_2 - f) s_l(f_1 + f_2' - f) \cdot$$

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

$$G_{M3}^{\text{corr}}(f) = \sum_{\substack{n=1 \\ n \neq m, m \pm 1}}^{N_{\text{ch}}} P_n P_l^2 \Phi_l \kappa_{M3}^l(f)$$

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

when n is even, $l = n/2 + 2, n/2 + 3$.

$$\kappa_{M3}^l(f) = \frac{16}{81} R_n R_l \int_{f_l - B_l/2}^{f_l + B_l/2} df_1 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2 \int_{f_l - B_l/2}^{f_l + B_l/2} df_2' \cdot$$

$$|s_n(f_1 + f_2 - f)|^2 s_l(f_1) s_l(f_2) s_l^*(f_2') s_l^*(f_1 + f_2 - f_2') \cdot$$

$$\mu(f_1, f_2, f) \mu^*(f_1 + f_2 - f_2', f_2', f)$$

- ▶ 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:

$$\Phi = 2 - \frac{E\{|a|^4\}}{E\{|a|^2\}} \quad \Psi = -\frac{E\{|a|^6\}}{E\{|a|^2\}} + 9\frac{E\{|a|^4\}}{E\{|a|^2\}} - 12$$

where a is a complex RV representing the QAM constellation points

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

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

and therefore:

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

- ▶ 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.

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

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

- ▶ It is indeed possible to write
“asymptotic” closed-form expressions of the correction term

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

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)

- ▶ 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*

**non-linear phase and
polarization noise**

The EGN model “agnosticism”

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

$$P_{\text{NLI}}$$

- ▶ 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*

- ▶ 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*?

- ▶ 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

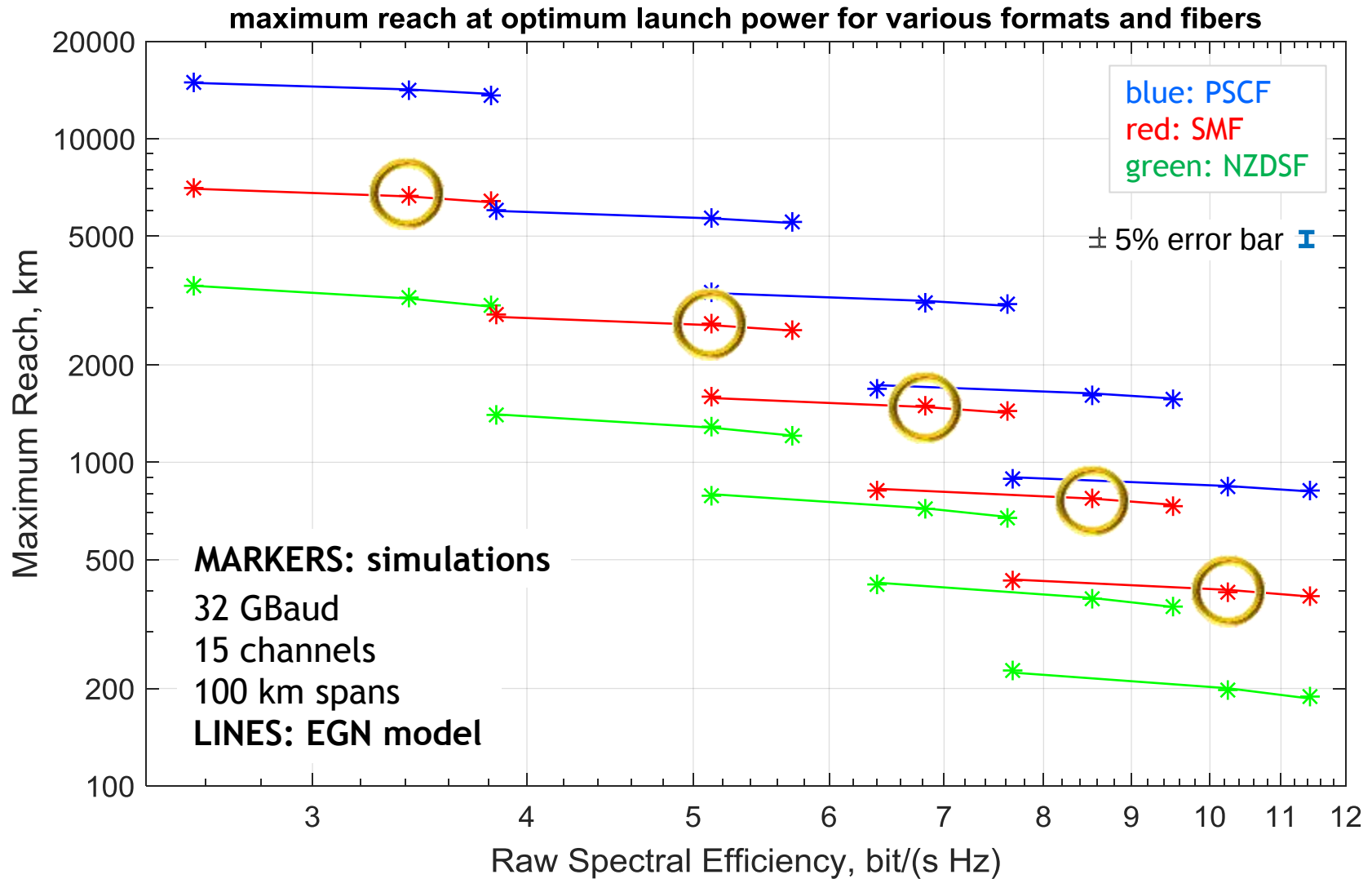
- ▶ Several other papers have addressed phase noise since:
 - ▶ M. Secondini, E. Forestieri, and G. Prati, “Achievable information rate in nonlinear WDM fiber-optic systems with arbitrary modulation formats and dispersion maps,” *J. Lightwave Technol.* 31, 3839-3852 (2013).
 - ▶ R. Dar, M. Feder, A. 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.

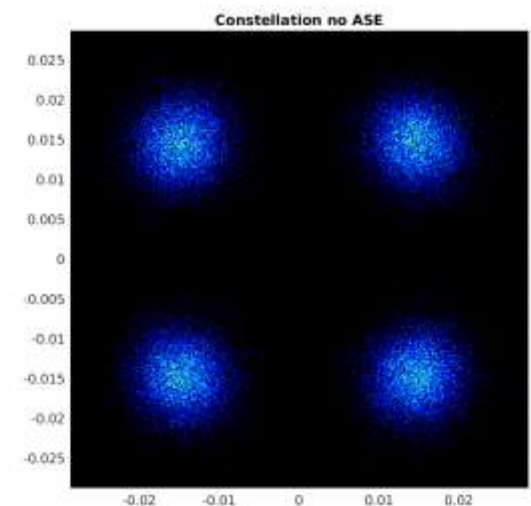
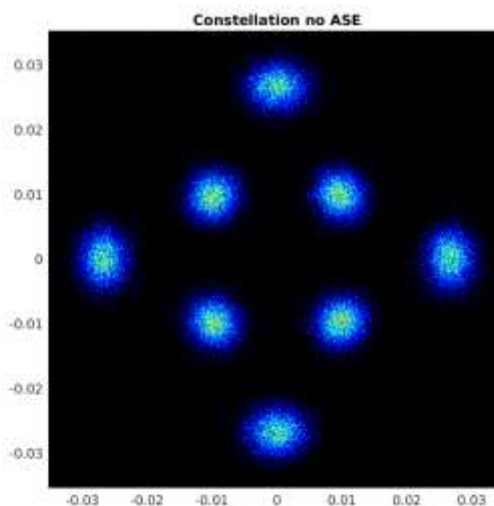
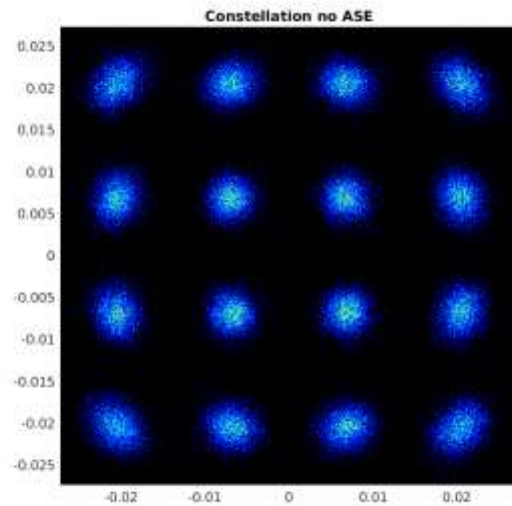
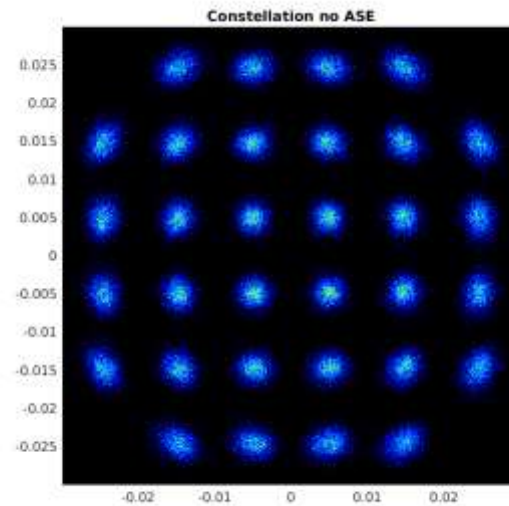
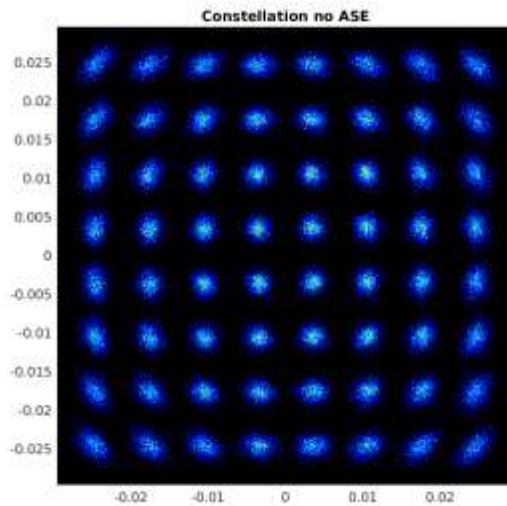
but what is NL phase noise?

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

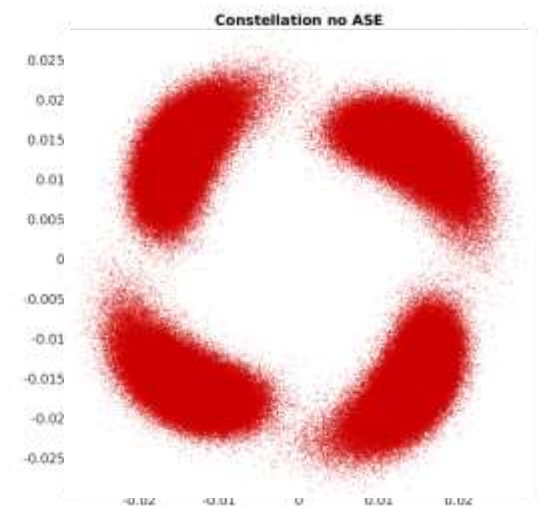
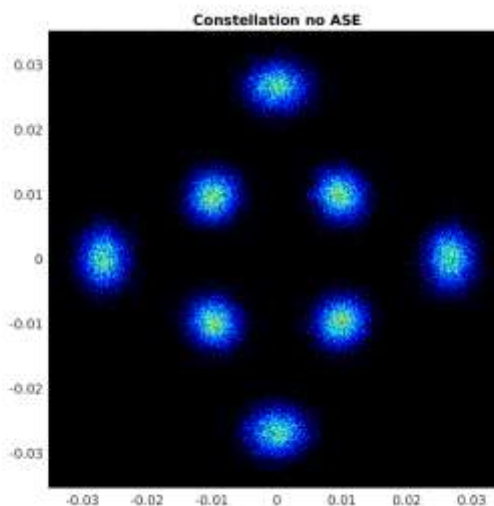
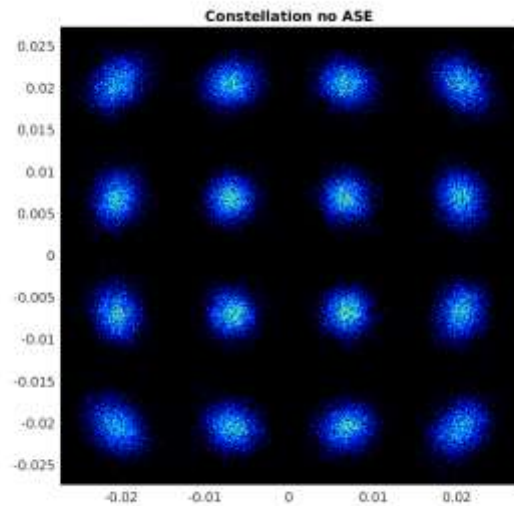
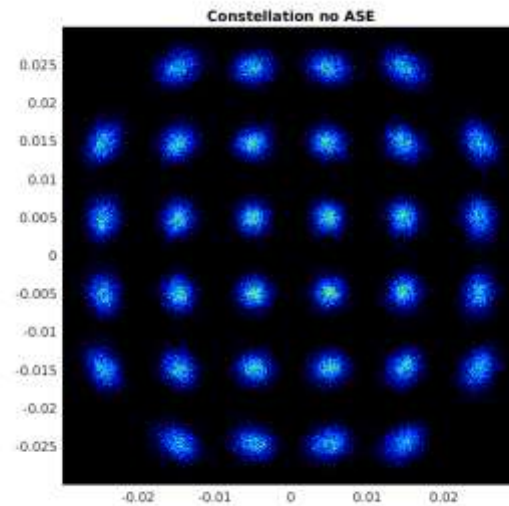
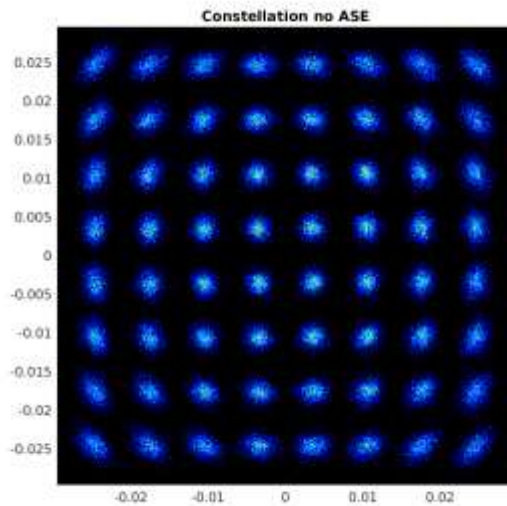


- ▶ This is indeed what you get at very high launch power per channel
 - ▶ [1] S. L.I. Olsson, M. Karlsson, P. A. Andrekson "Nonlinear phase noise mitigation in phase-sensitive amplified transmission systems", Optics Express, vol. 23, p. 11724, May 2015.
- ▶ In typical long-haul systems, however, *phase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

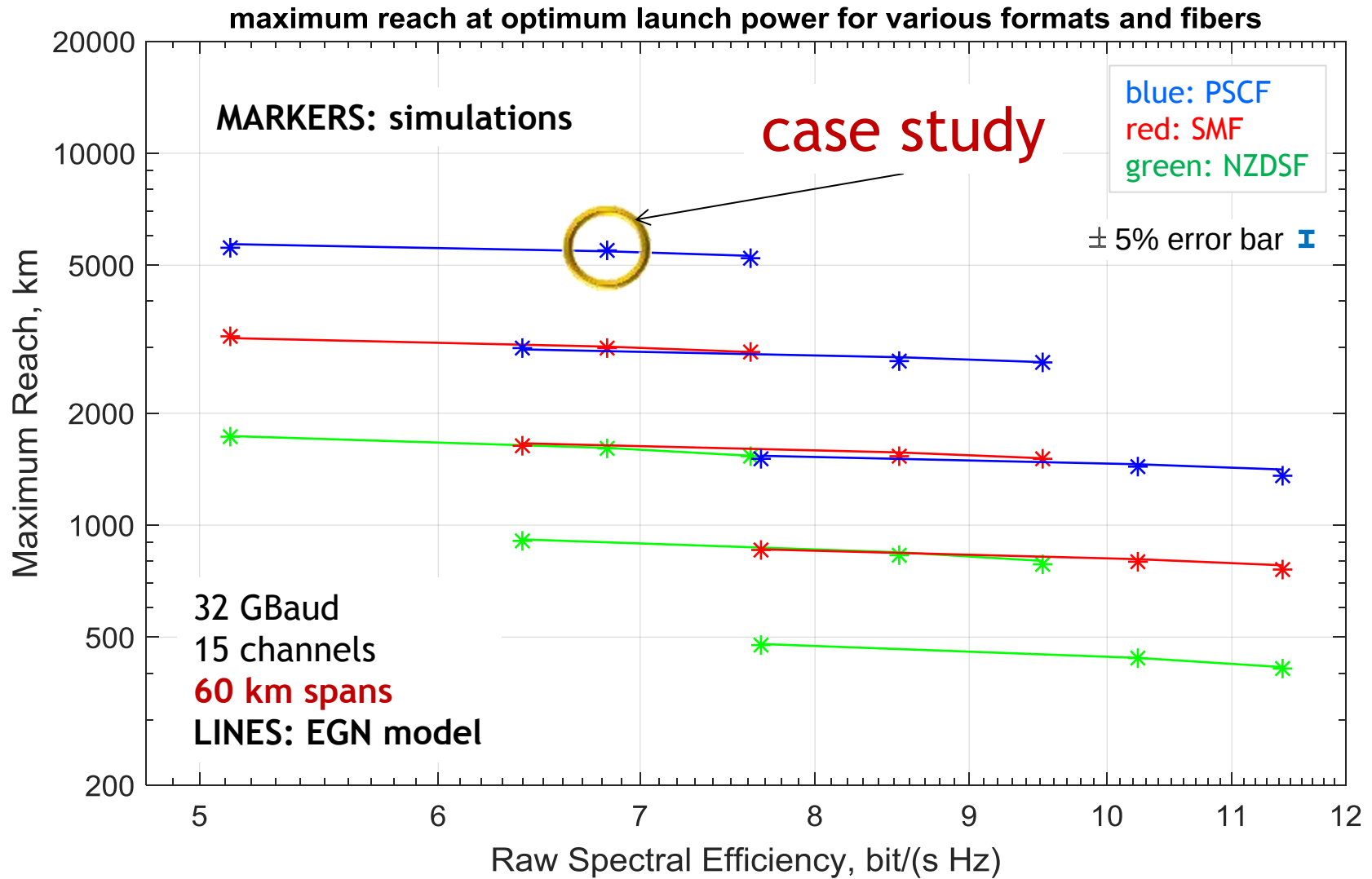




no ASE, at max-reach

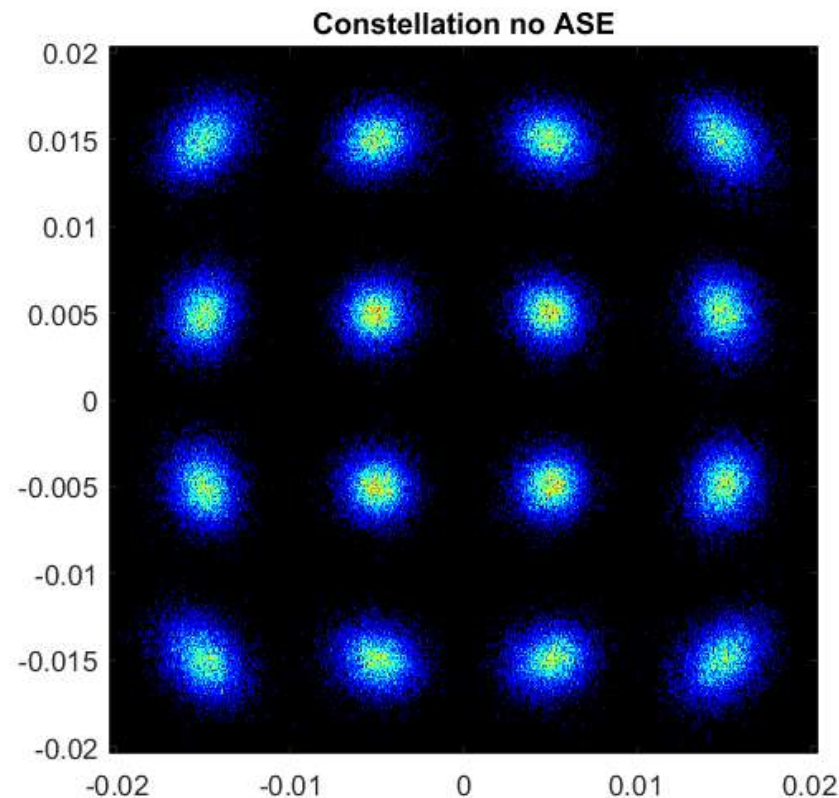


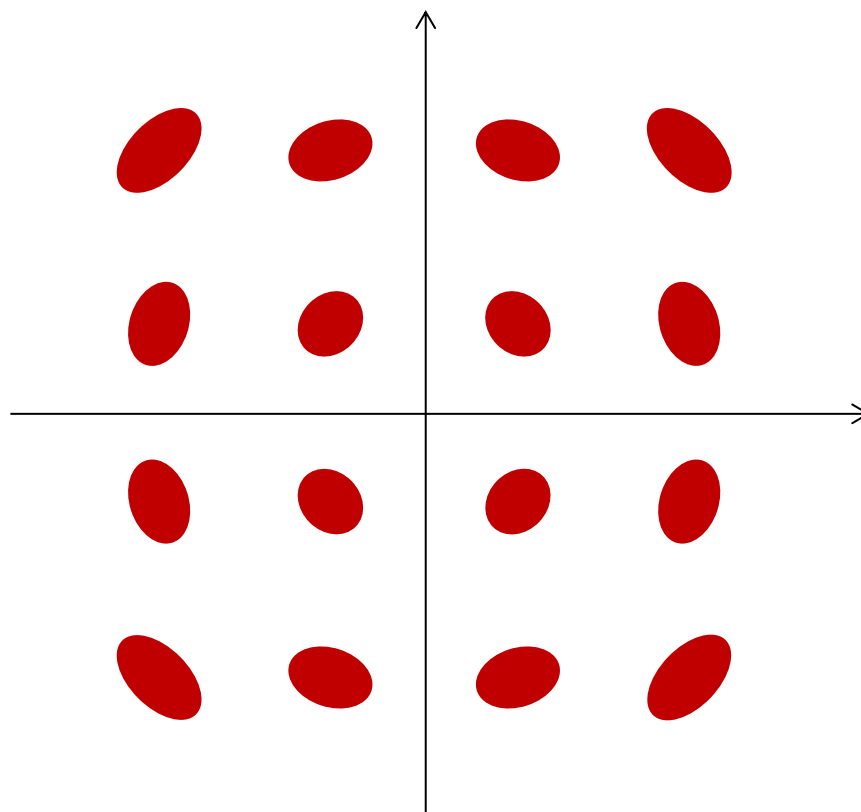
no ASE, at max-reach

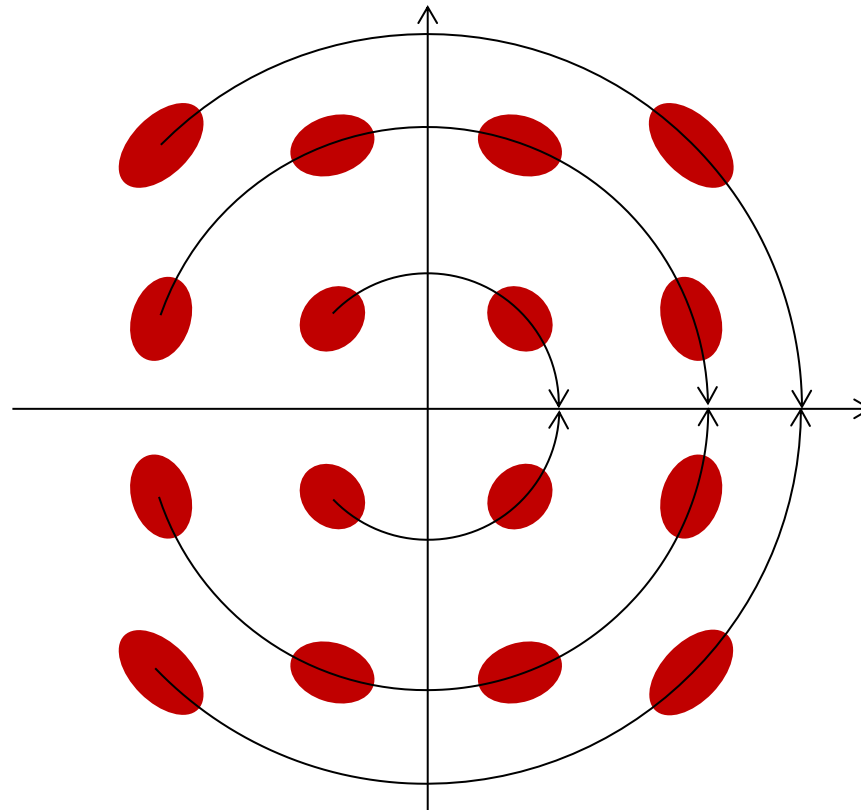


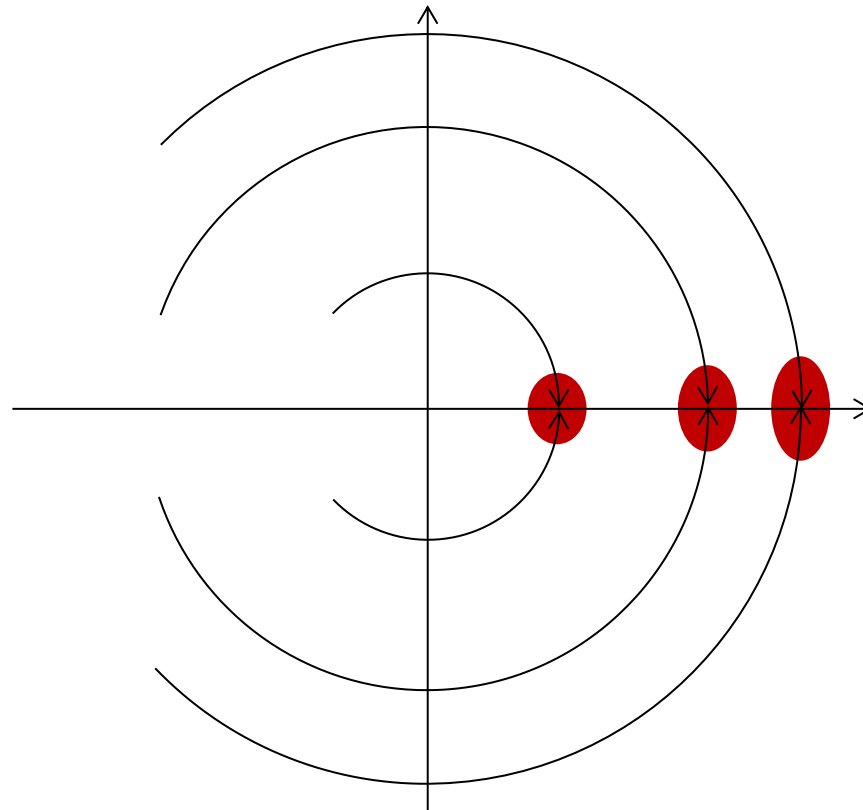
► CASE STUDY:

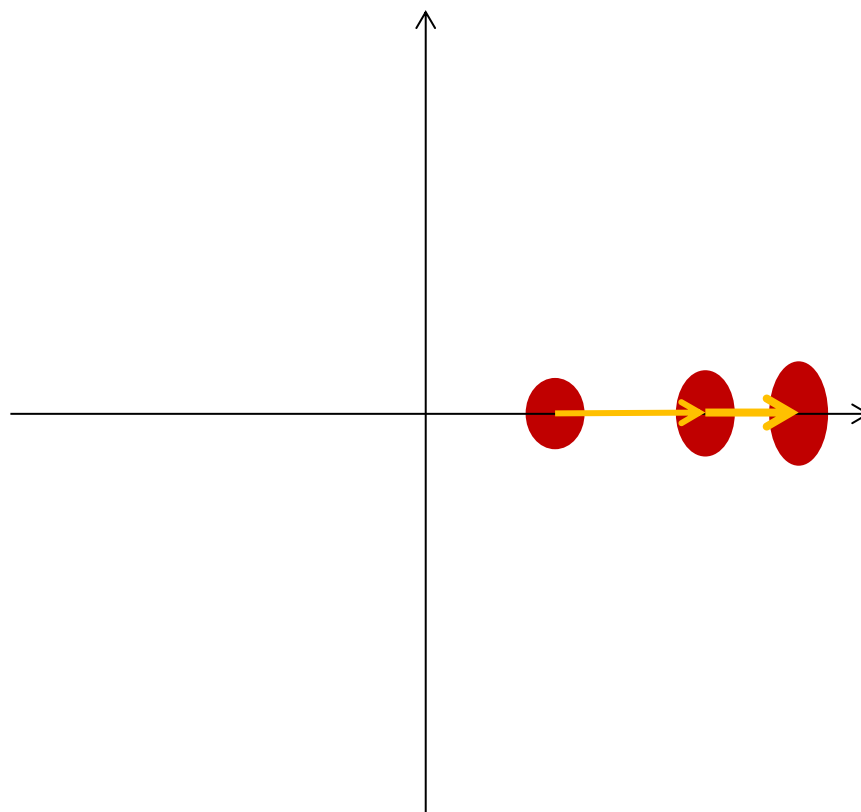
PSCF, 60km spans, PM-16QAM, 15 channels, at 6000 km (about max reach)

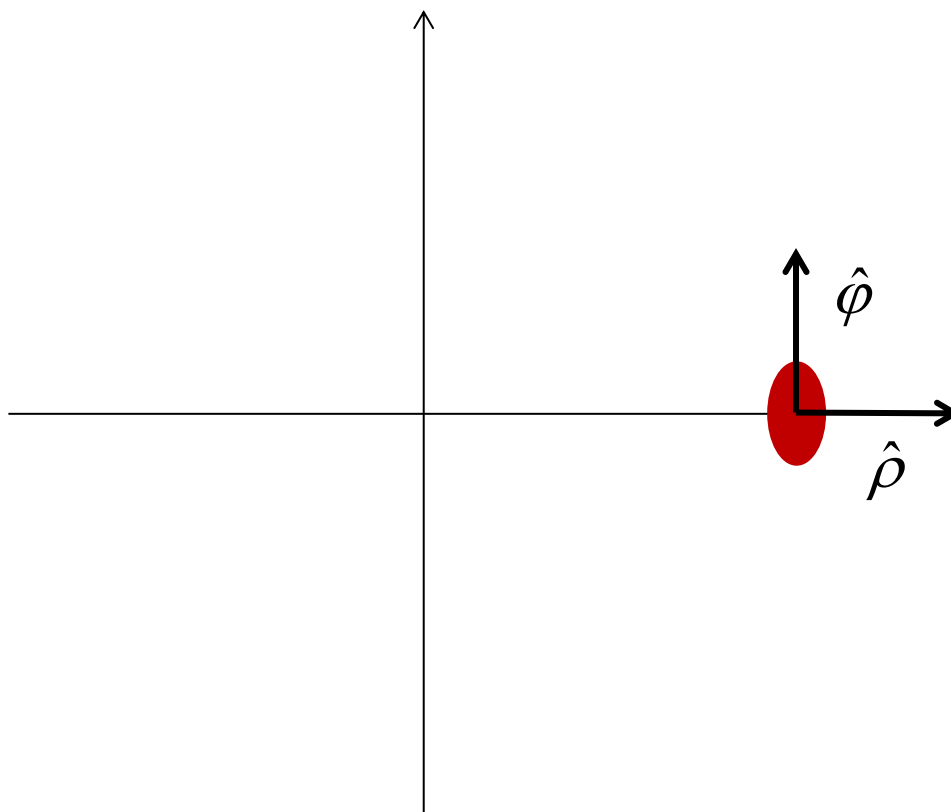




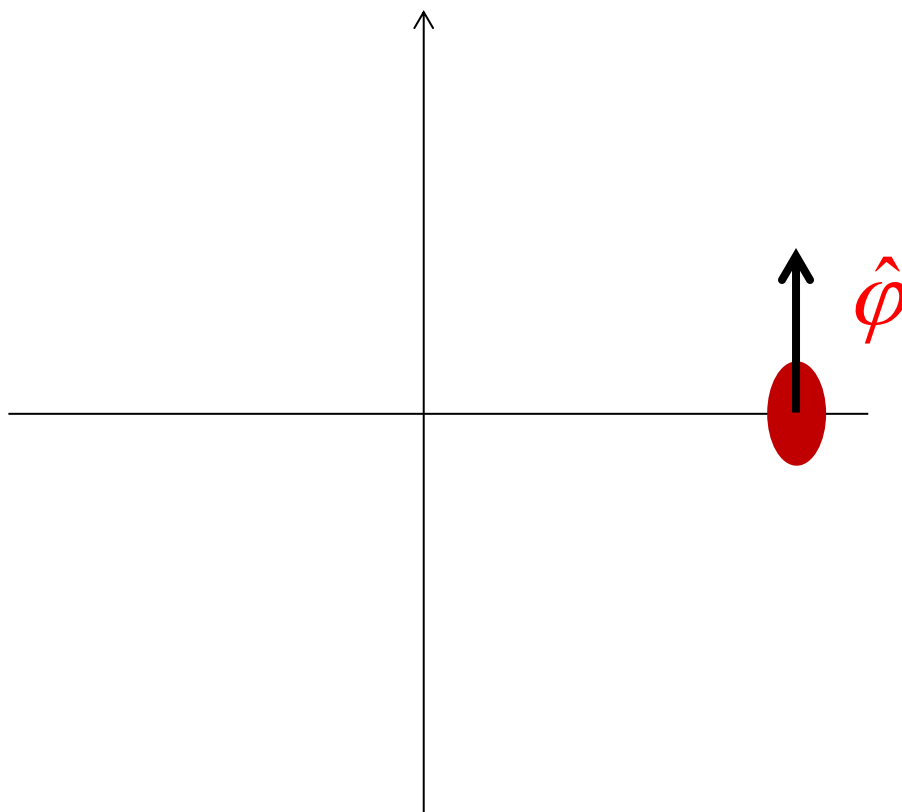




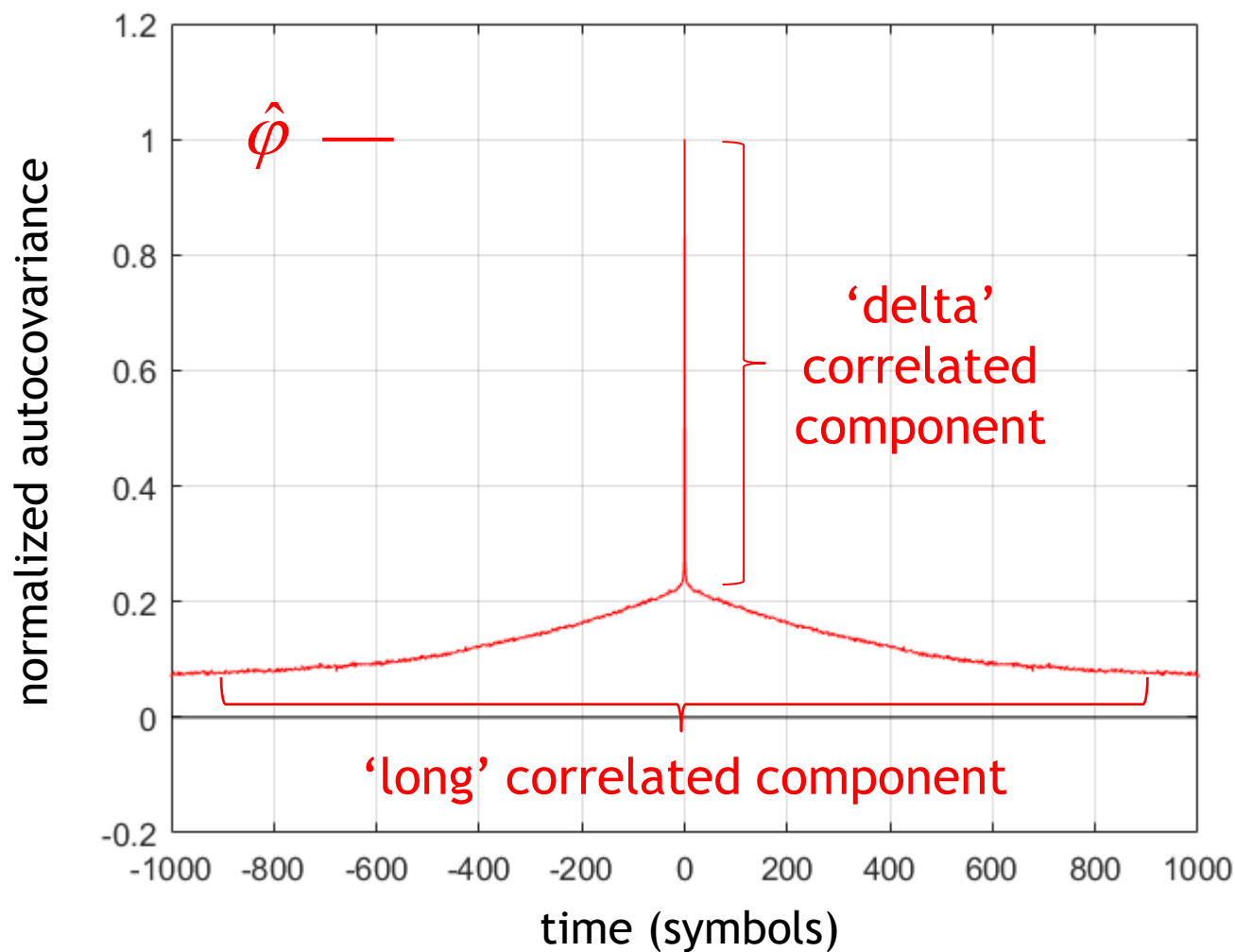


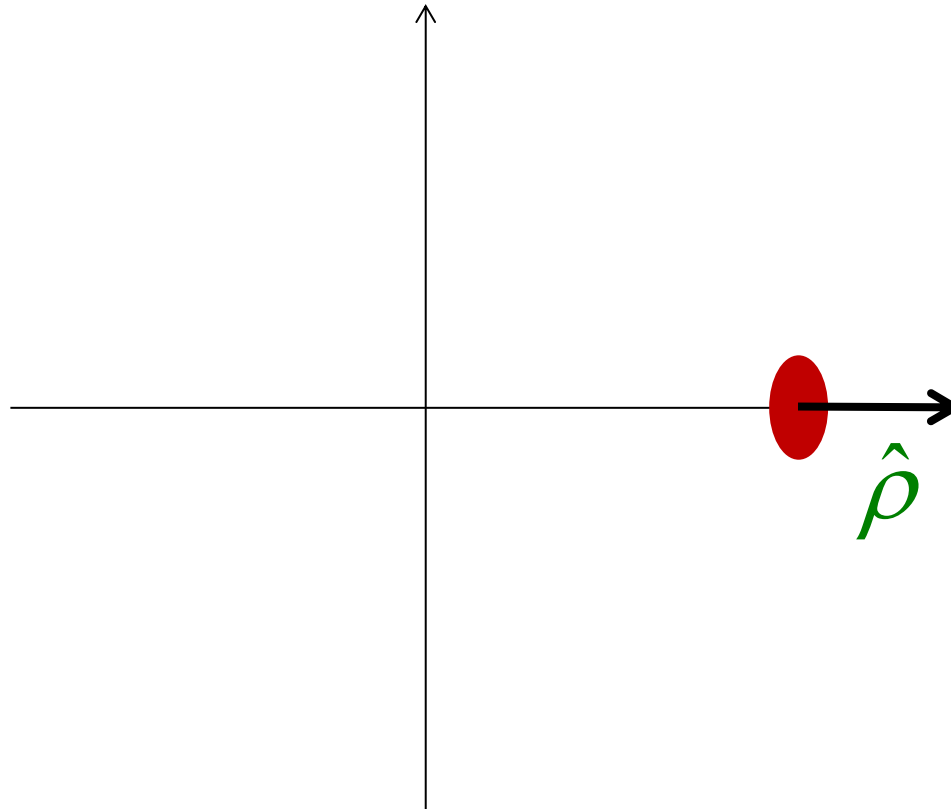


Carsten Schmidt-Langhorst, Robert Elschner, Felix Frey, Robert Emmerich, Colja Schubert, “Experimental Analysis of Nonlinear Interference Noise in Heterogeneous Flex-Grid WDM Transmission”, ECOC 2015, paper Tu.1.4.3, Sept. 2015.

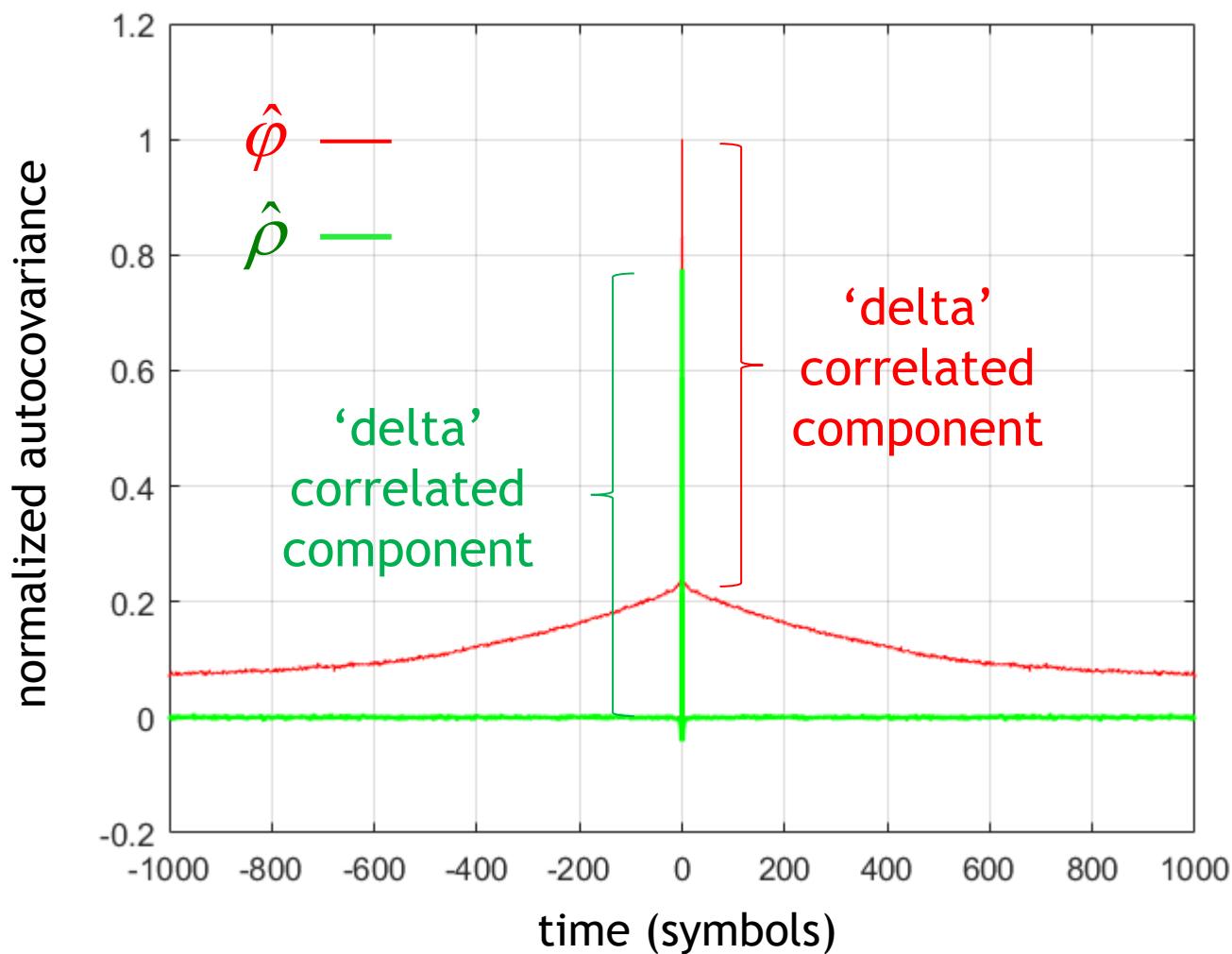


autocovariance





autocovariance



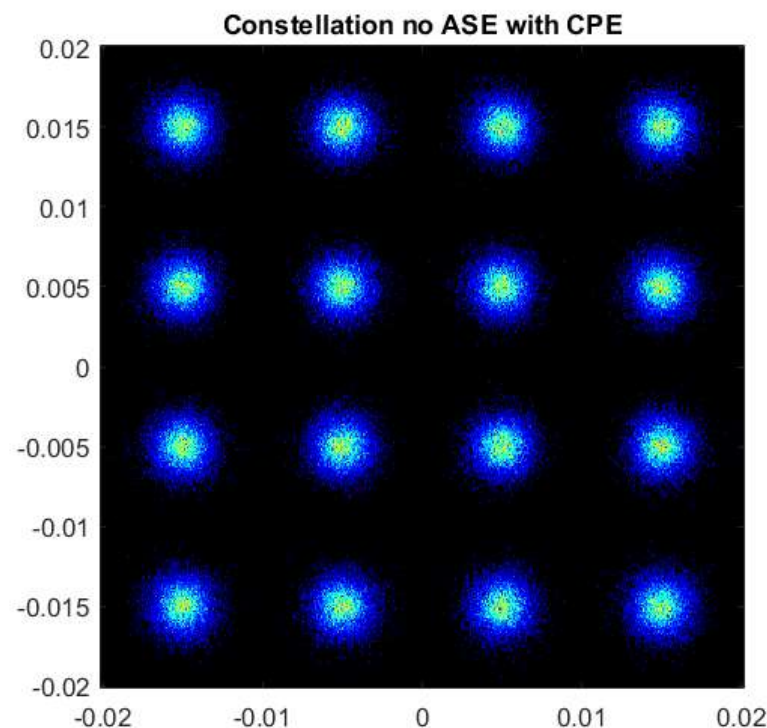
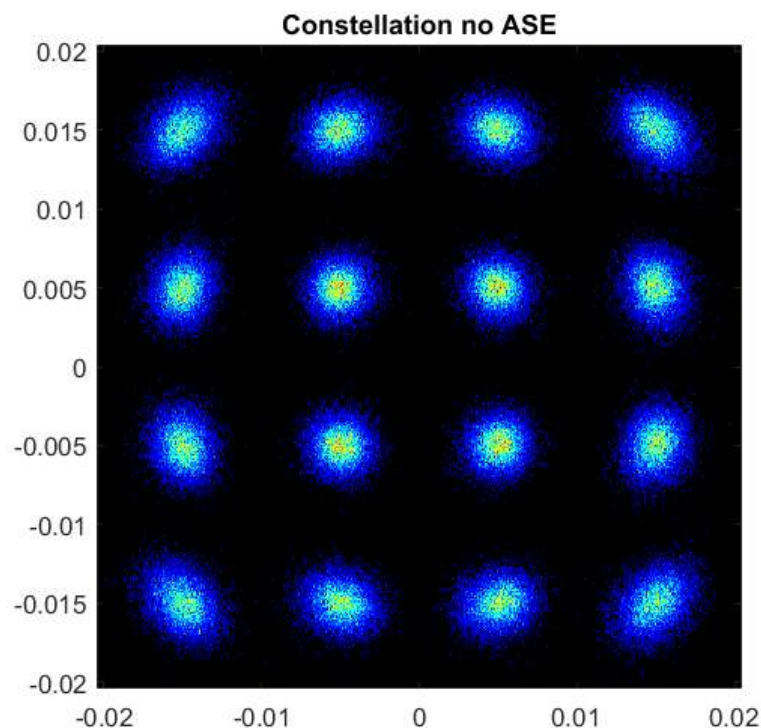
- ▶ To estimate (and then remove) long-correlated phase-noise, we used the PN-receiver as proposed in

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

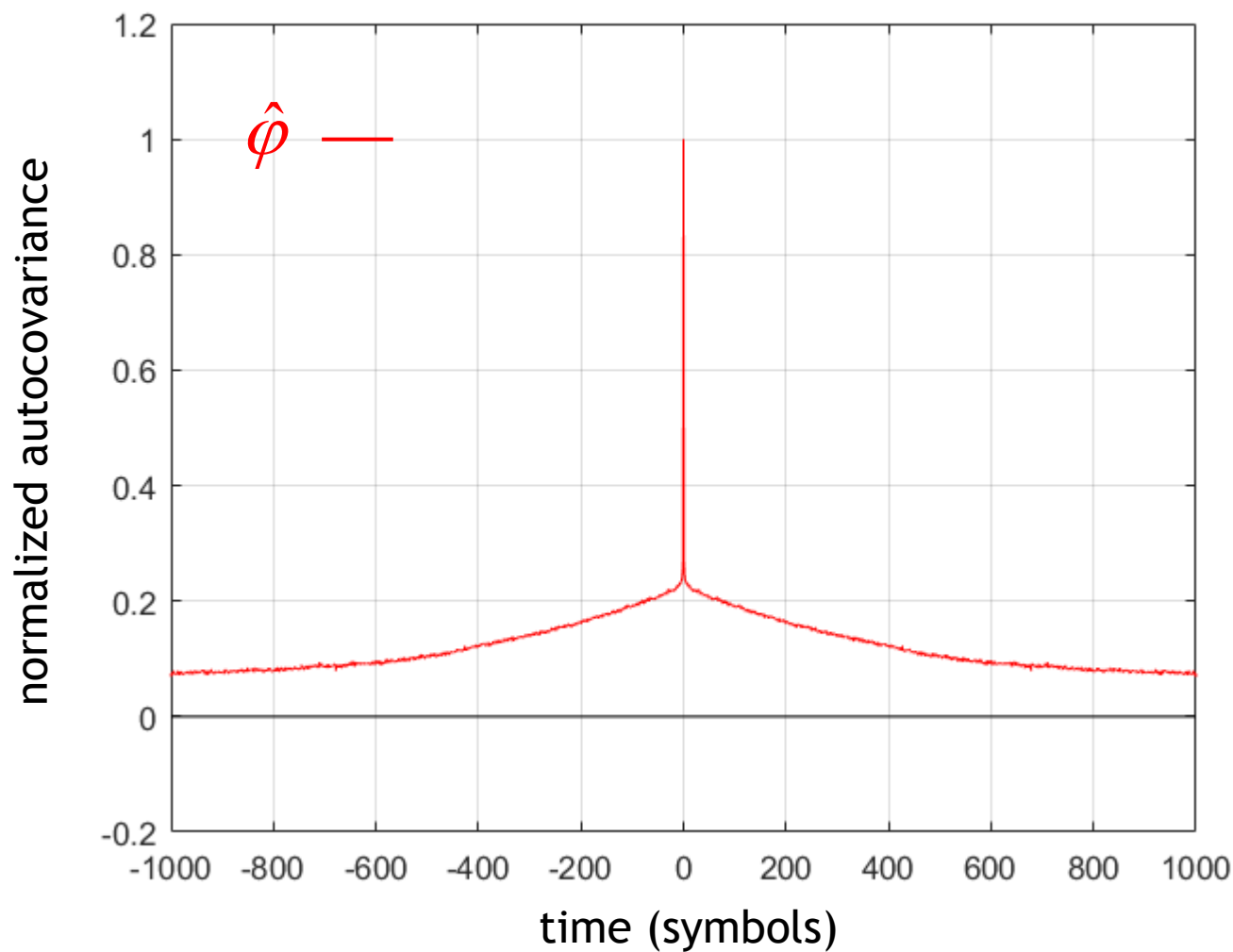
► CASE STUDY:

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

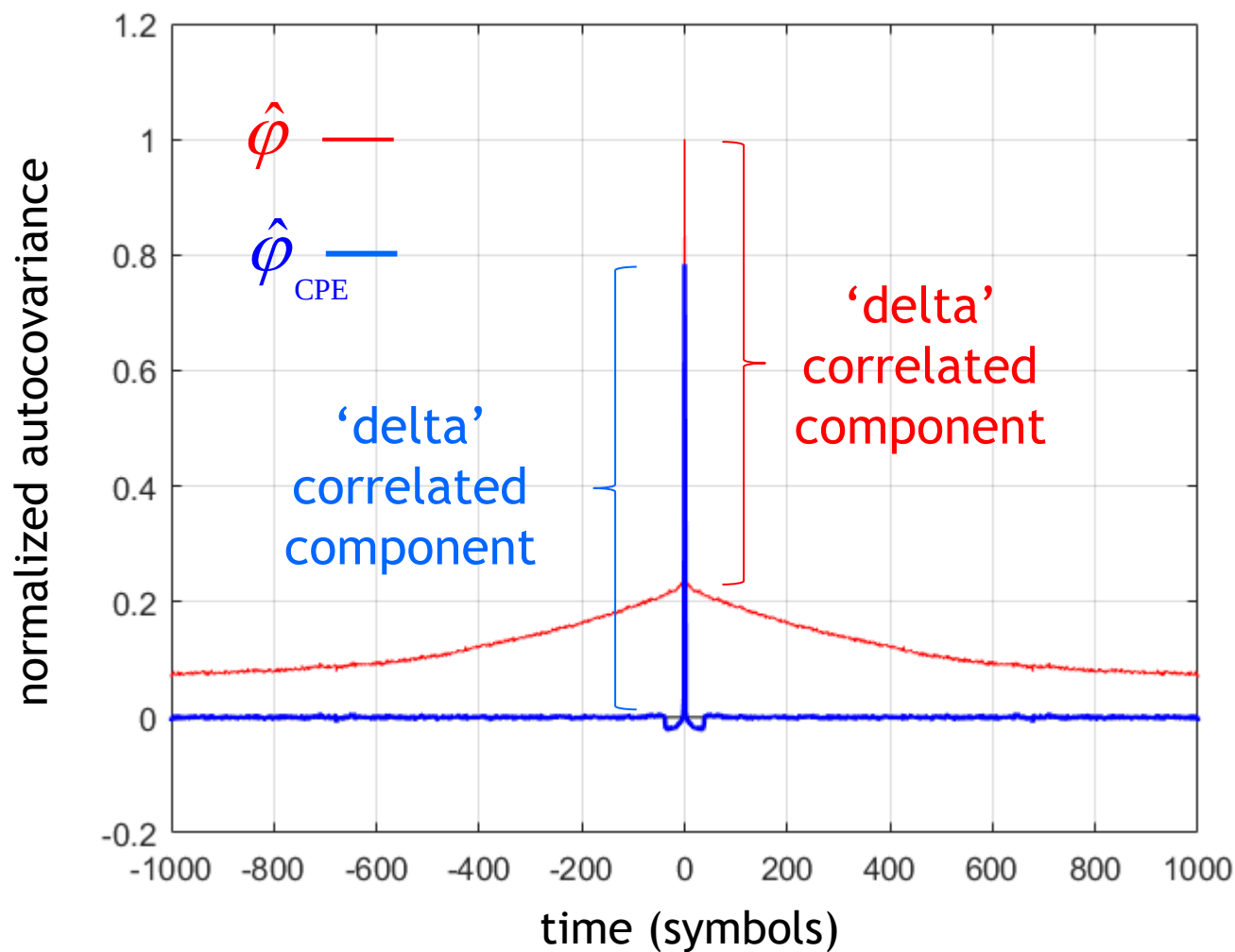


► at least “visually”, phase noise is gone

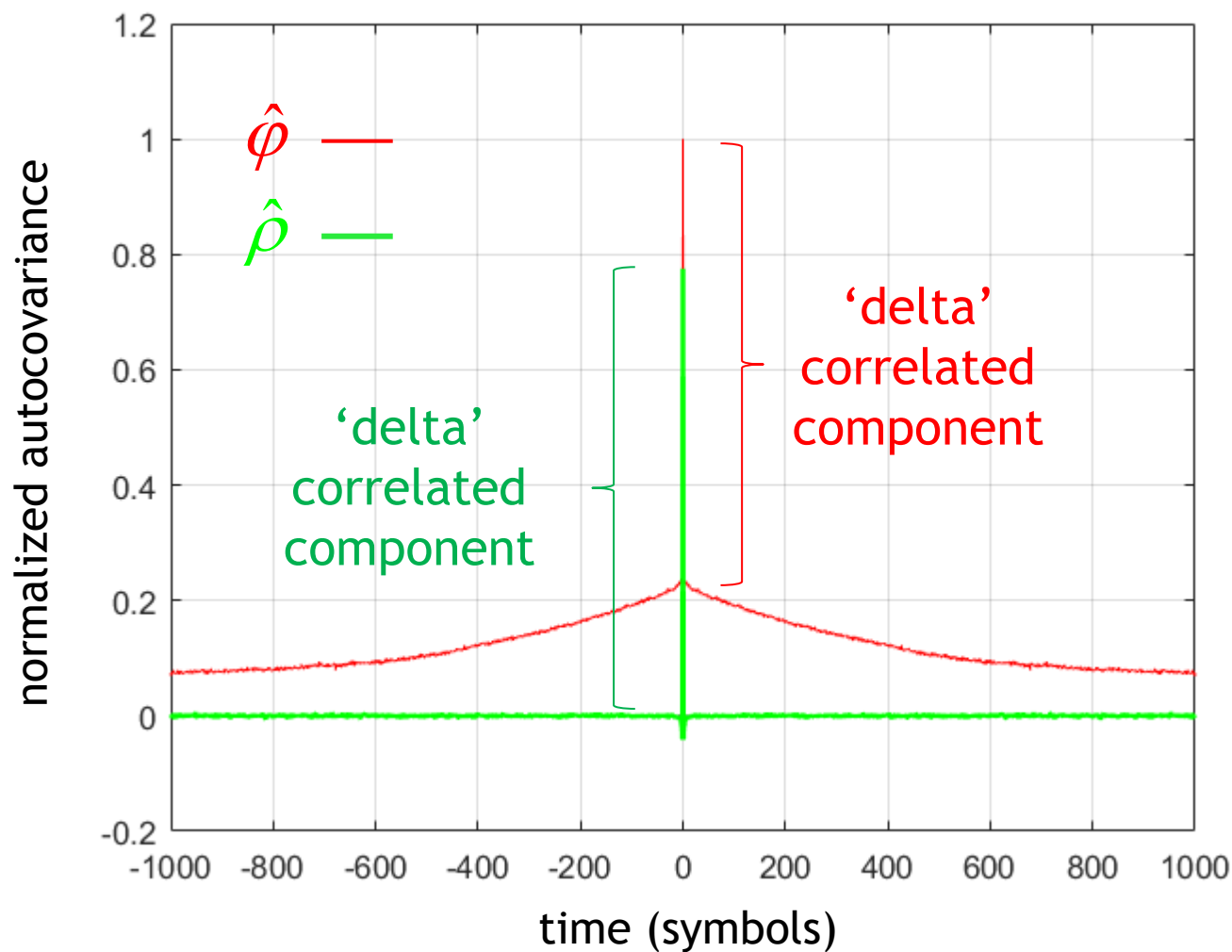
autocovariance

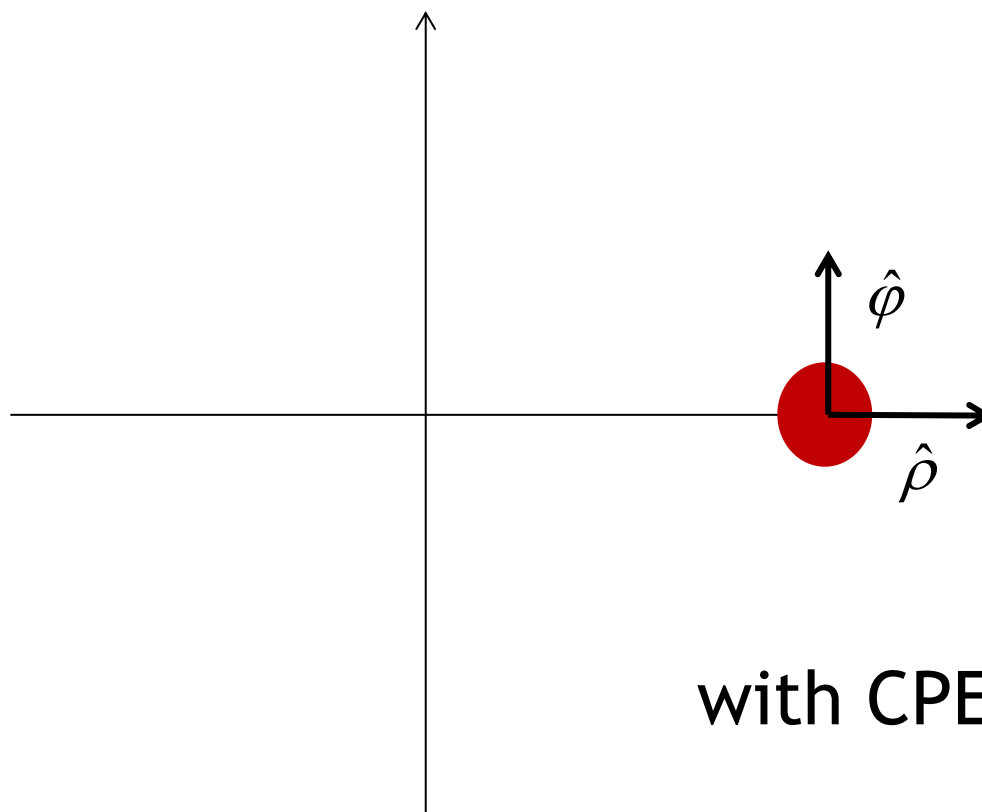


autocovariance



autocovariance

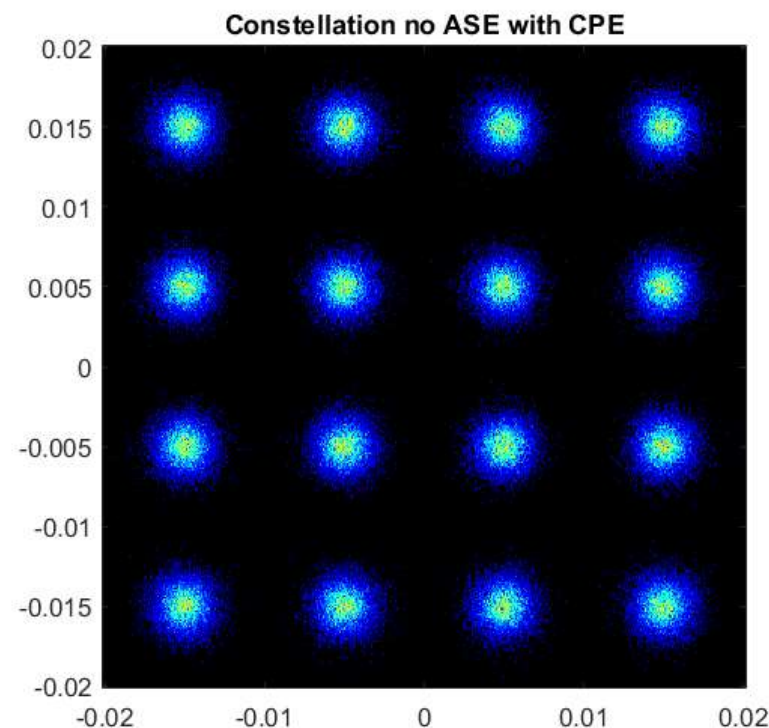
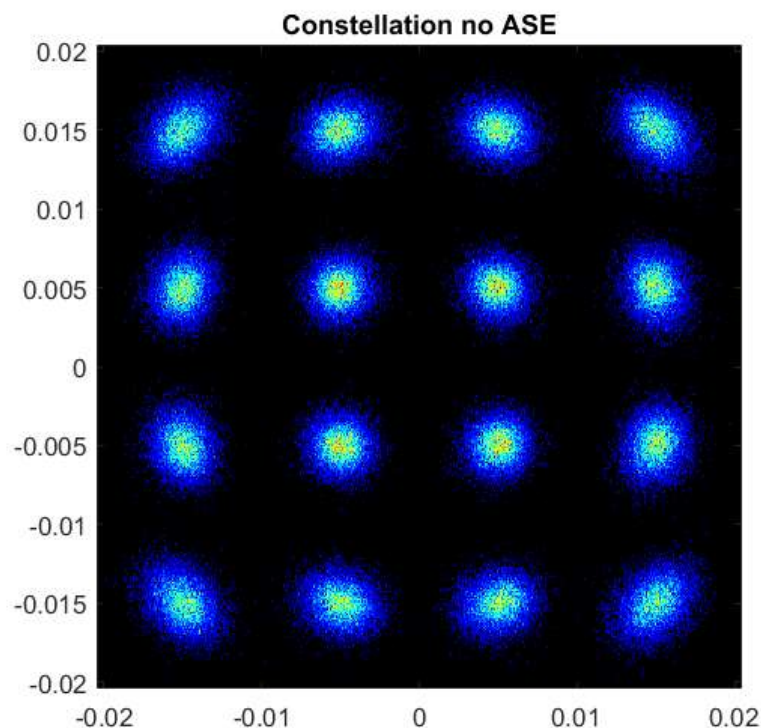




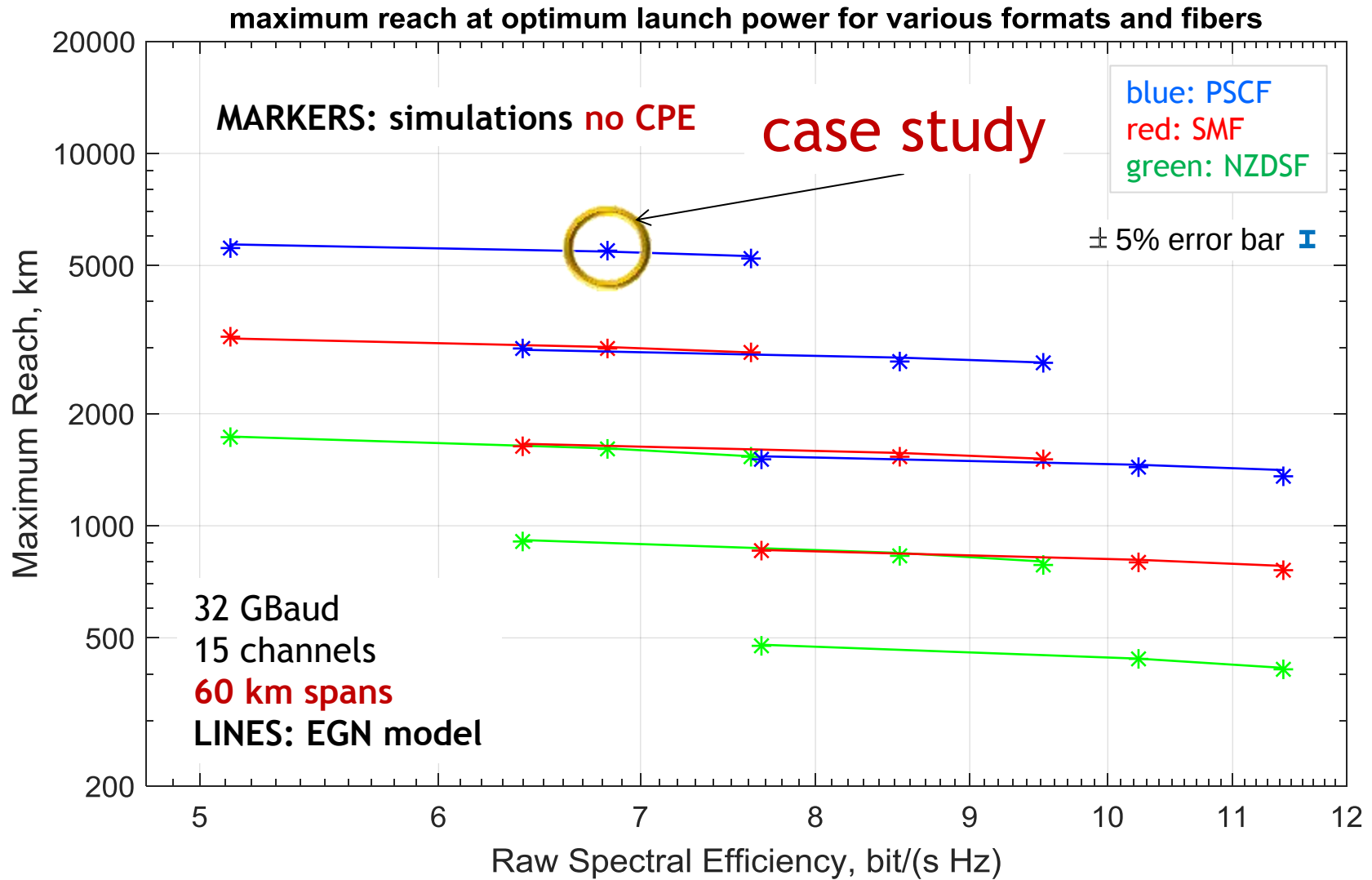
with CPE

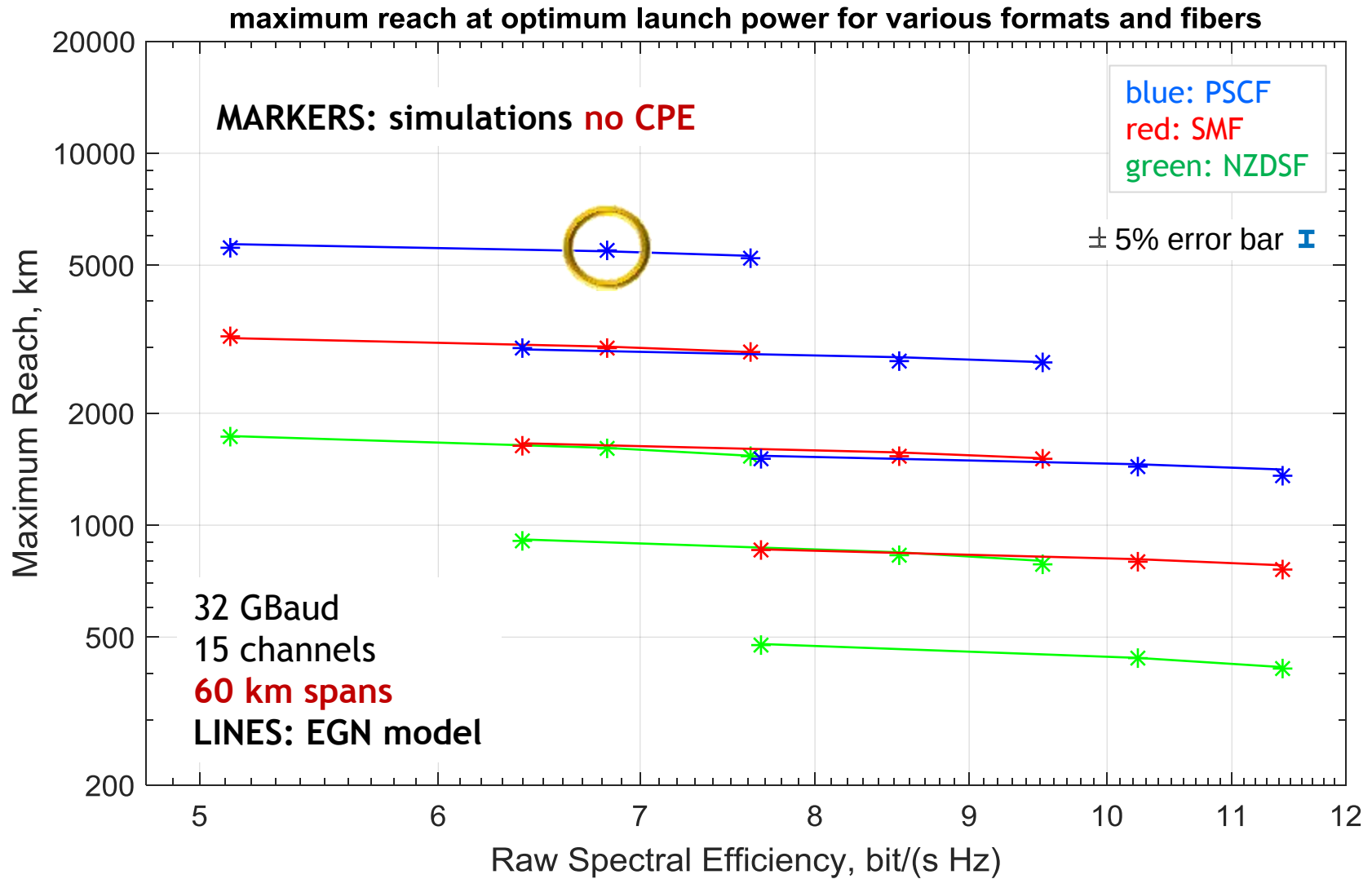
► study case:

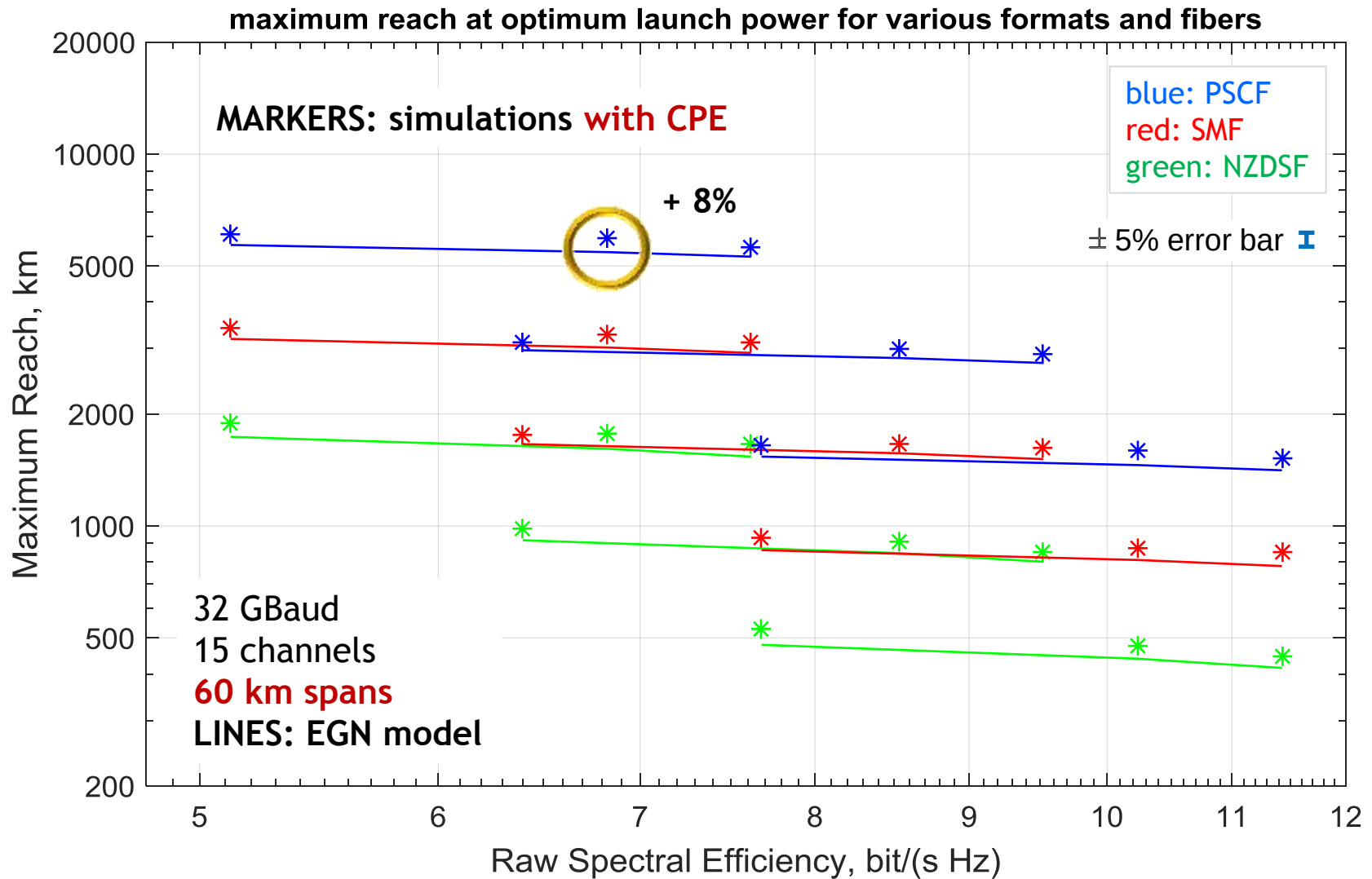
PSCF, 60km spans, PM-16QAM, 15 channels, at 6000 km (about max reach)

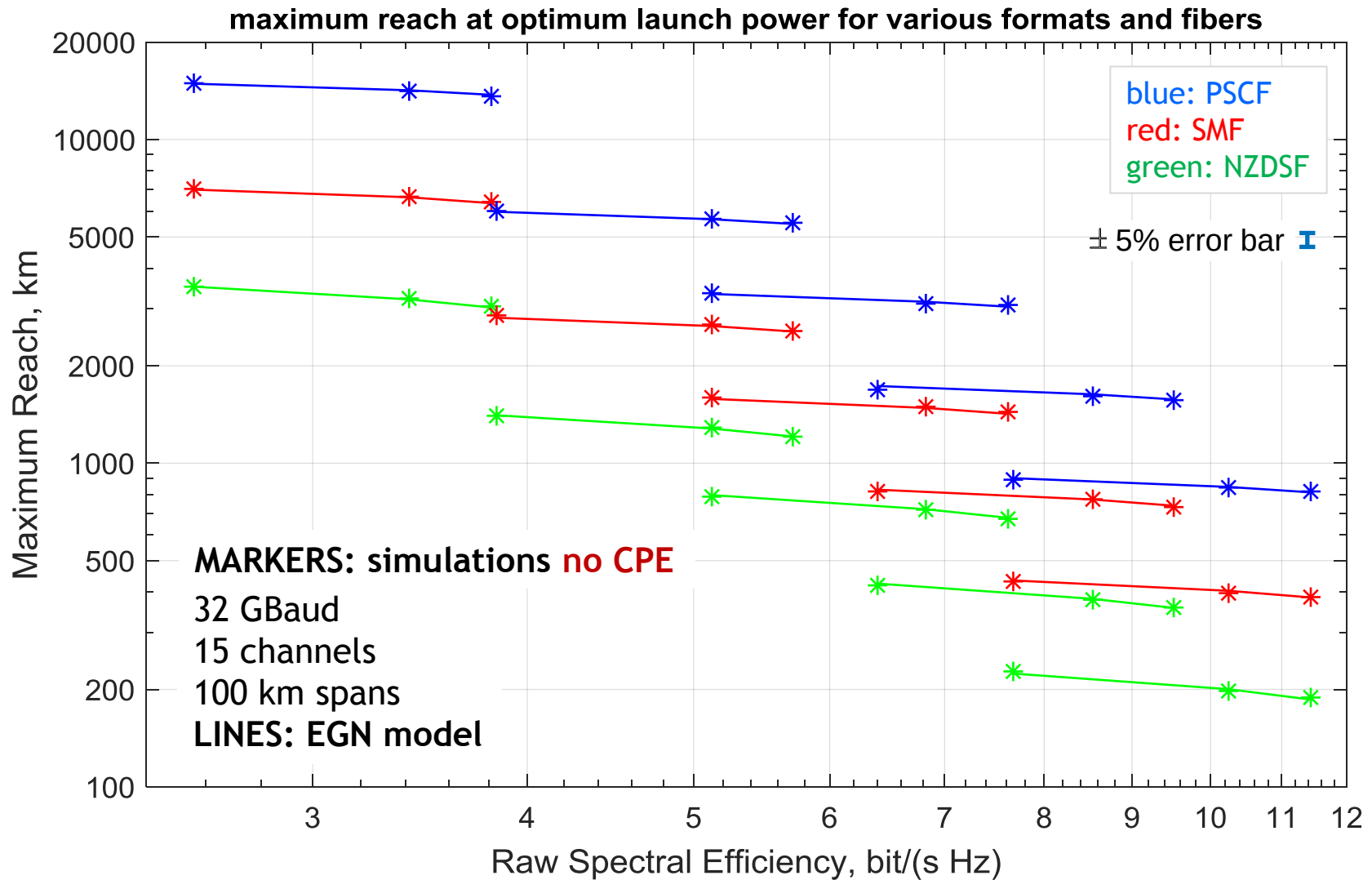


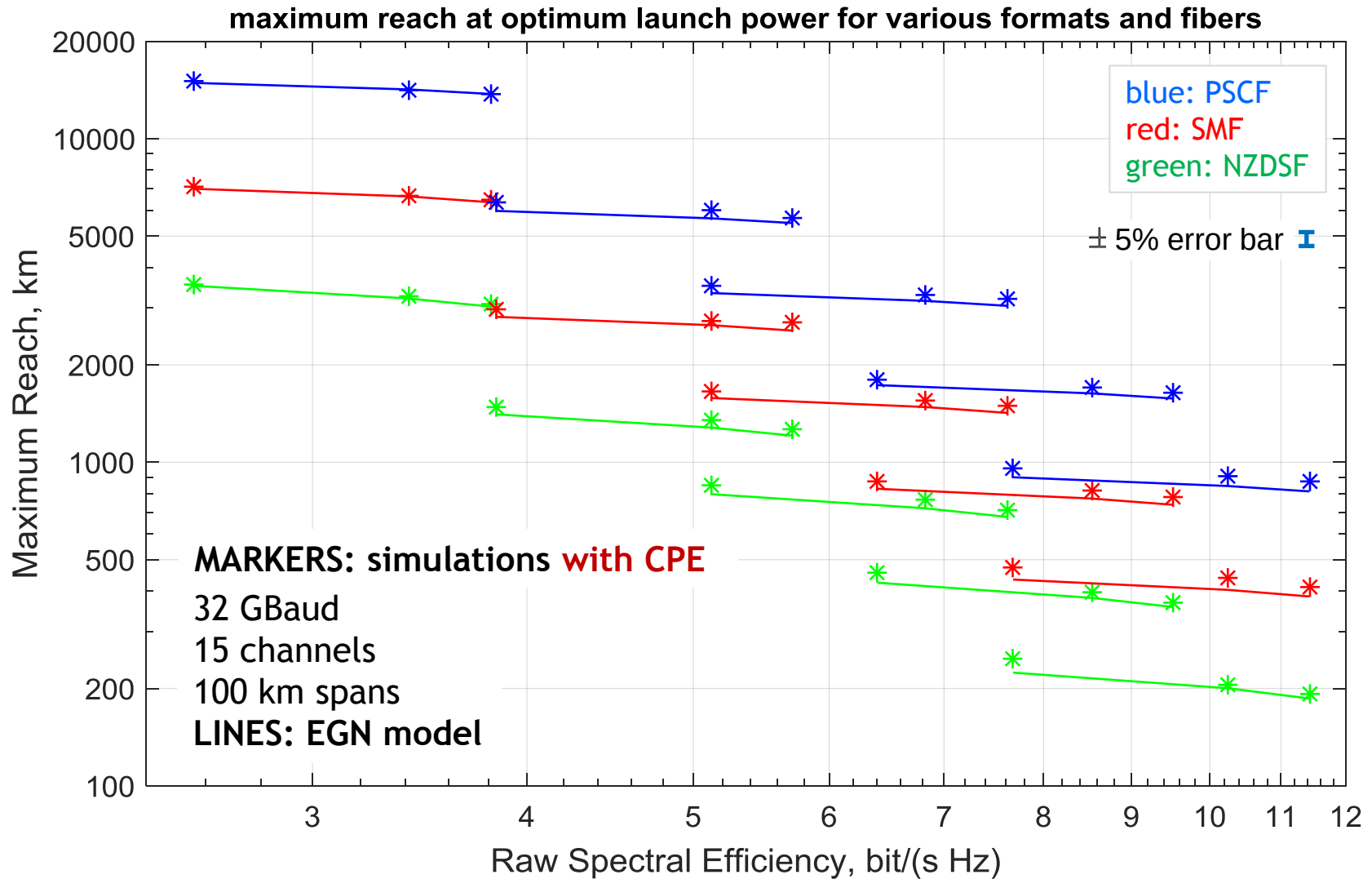
► ... but what is the system impact ?











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

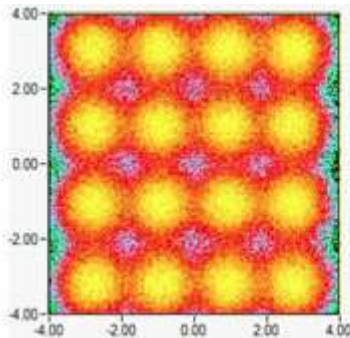
- ▶ The max-reach “CPE” gain is *modest* for 100km spans
 - ▶ average on the on the big picture is 2.5%, peak is 4.7%
 - ▶ less than 1% MR gain for PM-QPSK

- ▶ 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.

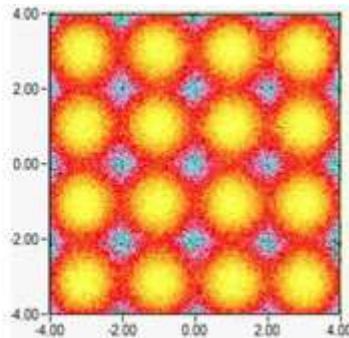
Is the gain already in the systems ?

- 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

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/>



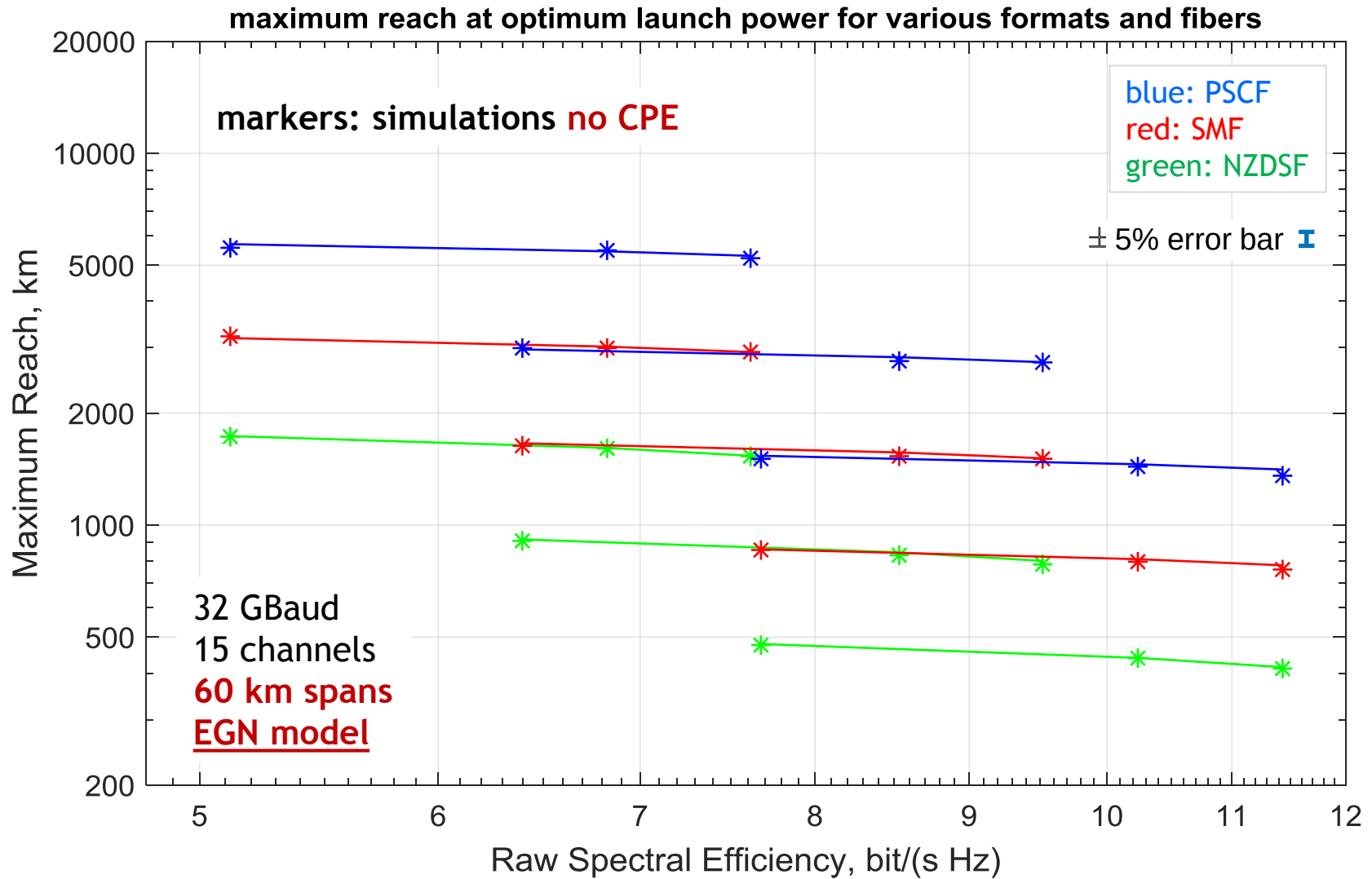
- Can the effect of CPE be *modeled easily* ?

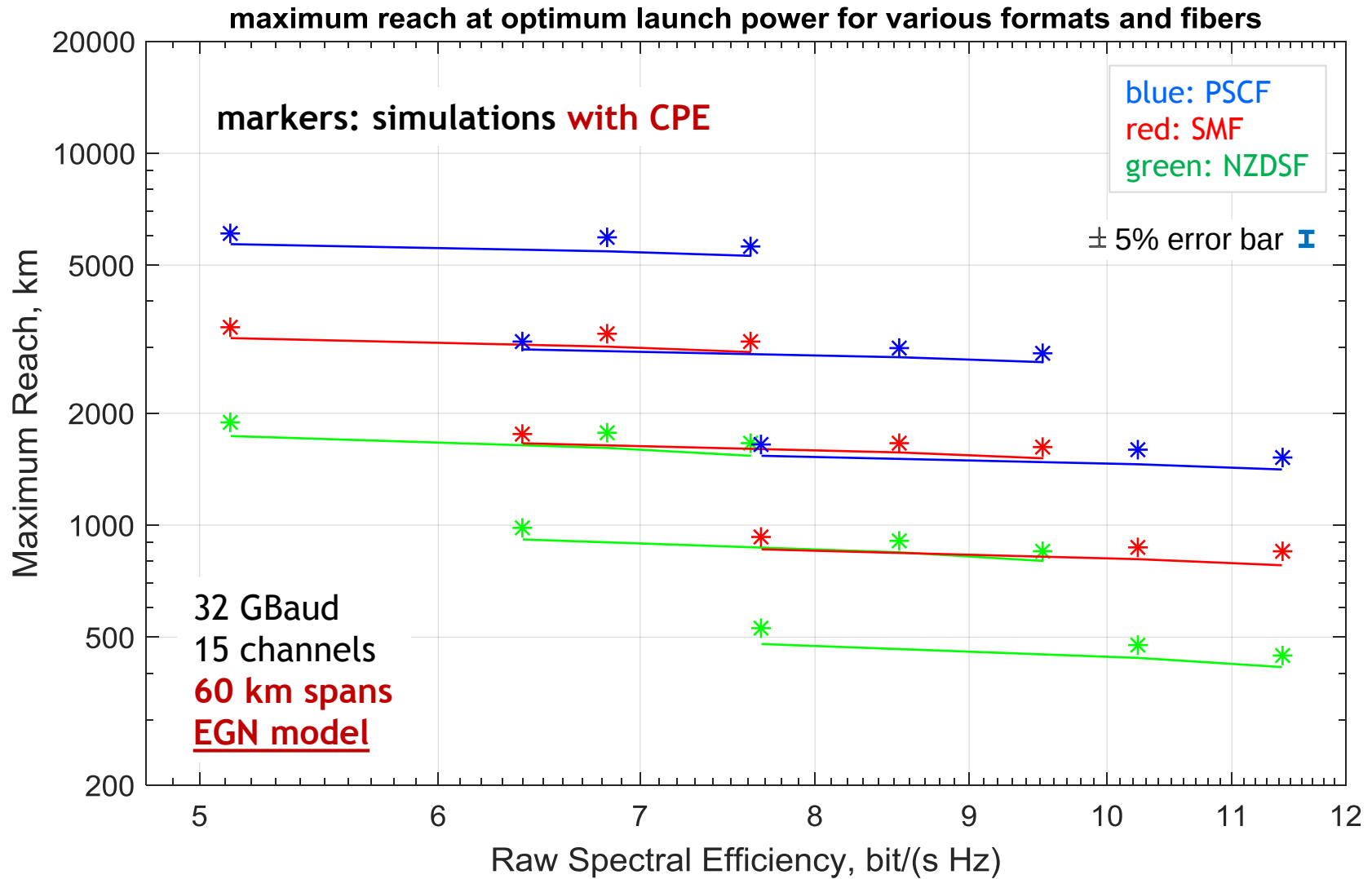
- ▶ Can the effect of the CPE be accounted for *easily* ?
- ▶ Excellent models exist but they add further complexity
 - ▶ see the cited recent papers by
 - ▶ Secondini, Forestieri
 - ▶ Dar, Feder, Mecozzi, Shtaif
- ▶ We tried to find if there was a very simple way of assessing CPE gains, *at least approximately*, which required minimal further complexity

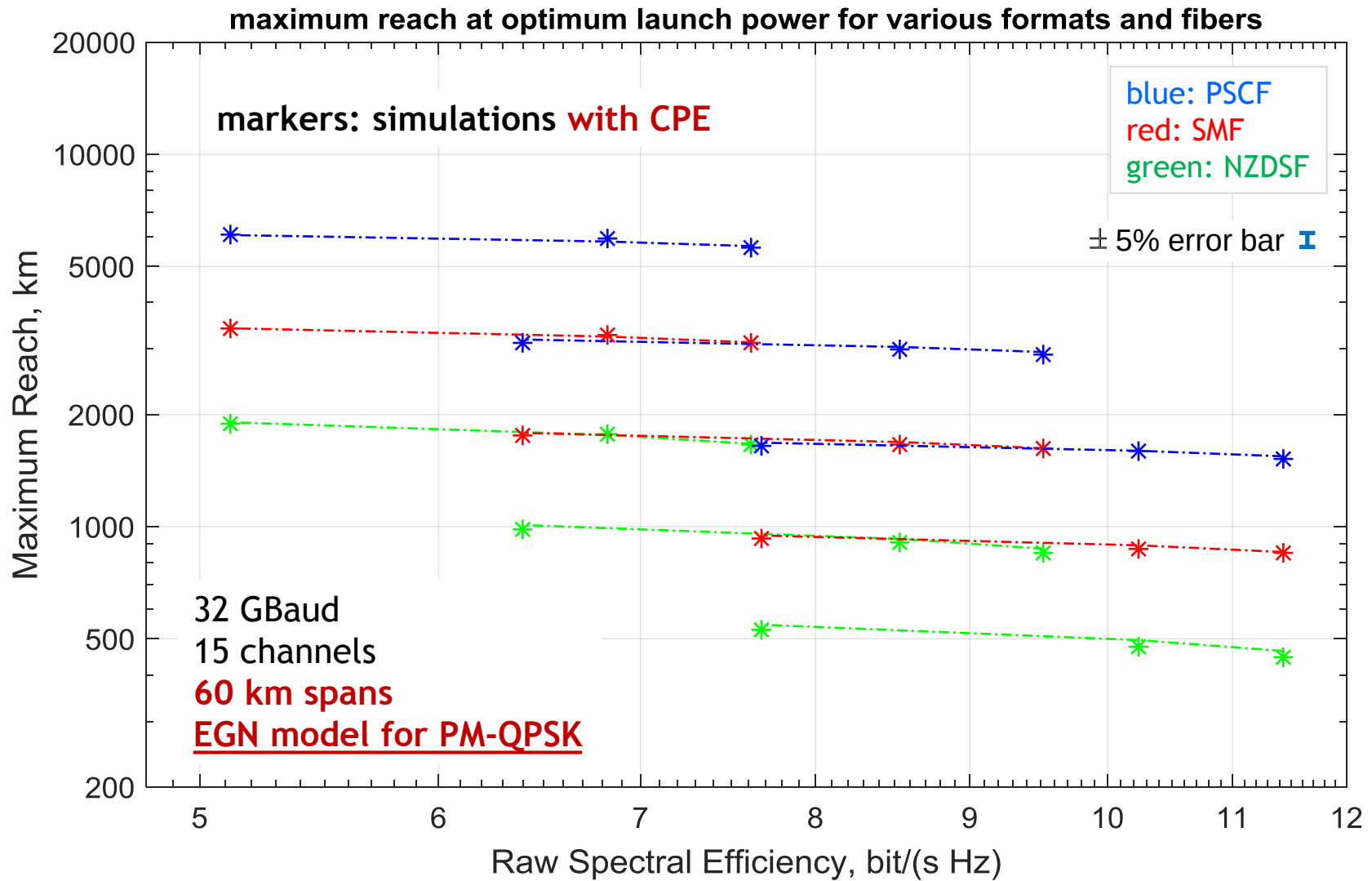
- ▶ Through extensive numerical investigation and with experimental confirmation we have found out that
 - ▶ If all the long-correlated phase noise is ideally taken out, then:

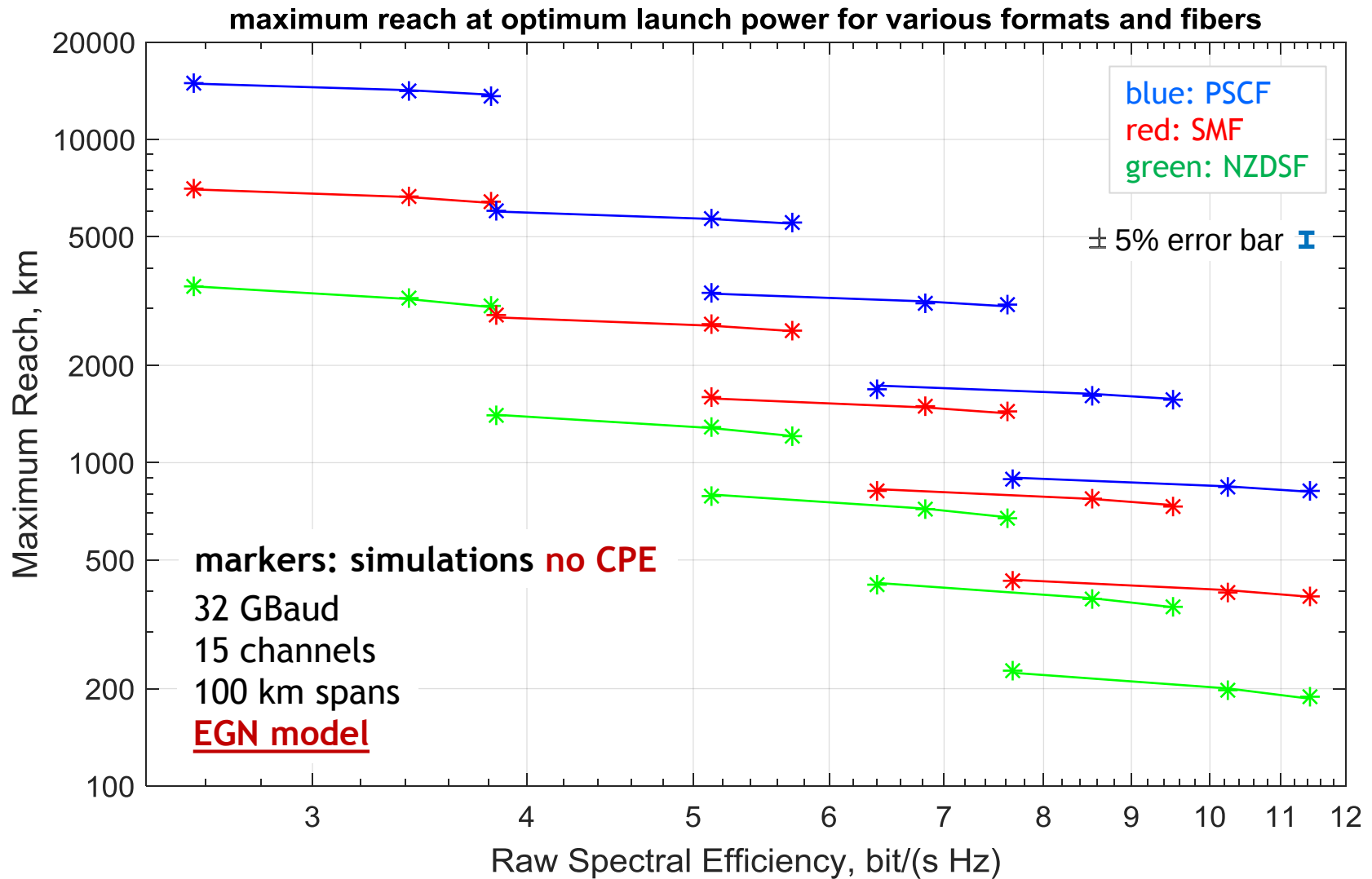
any PM-QAM system is well described by the EGN model, calculated as if PM-QPSK was transmitted

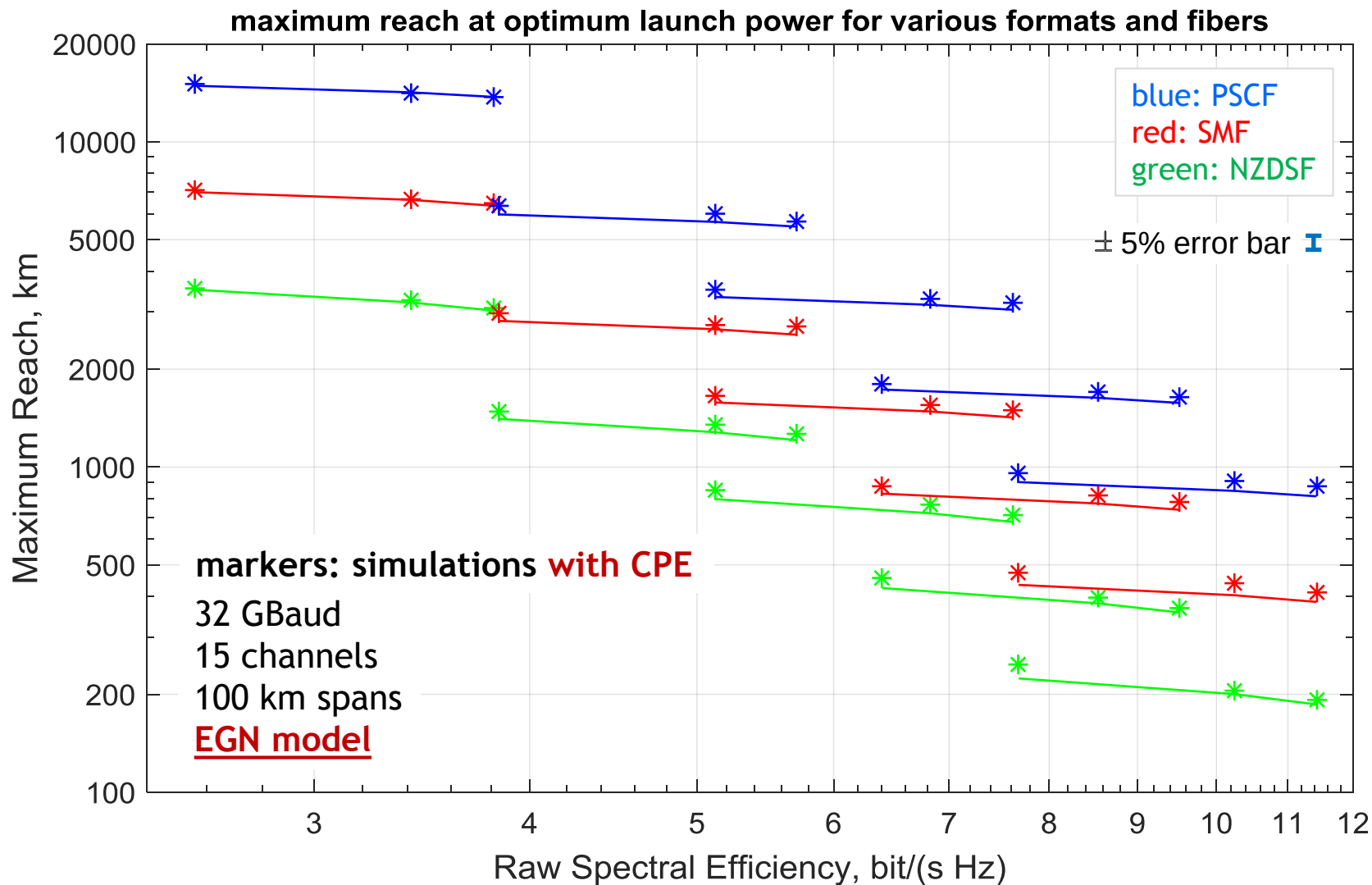
- ▶ No modeling overhead !

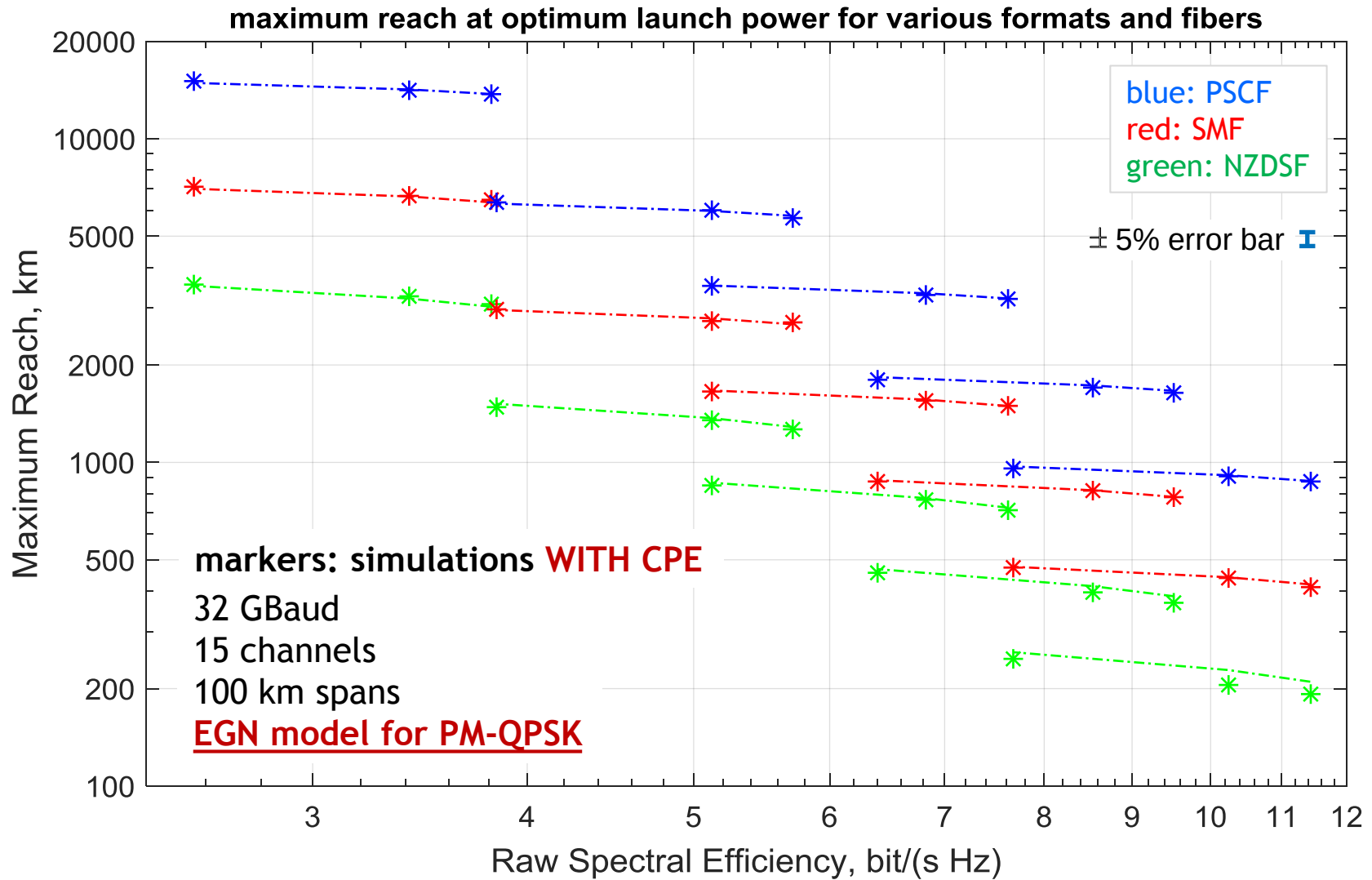


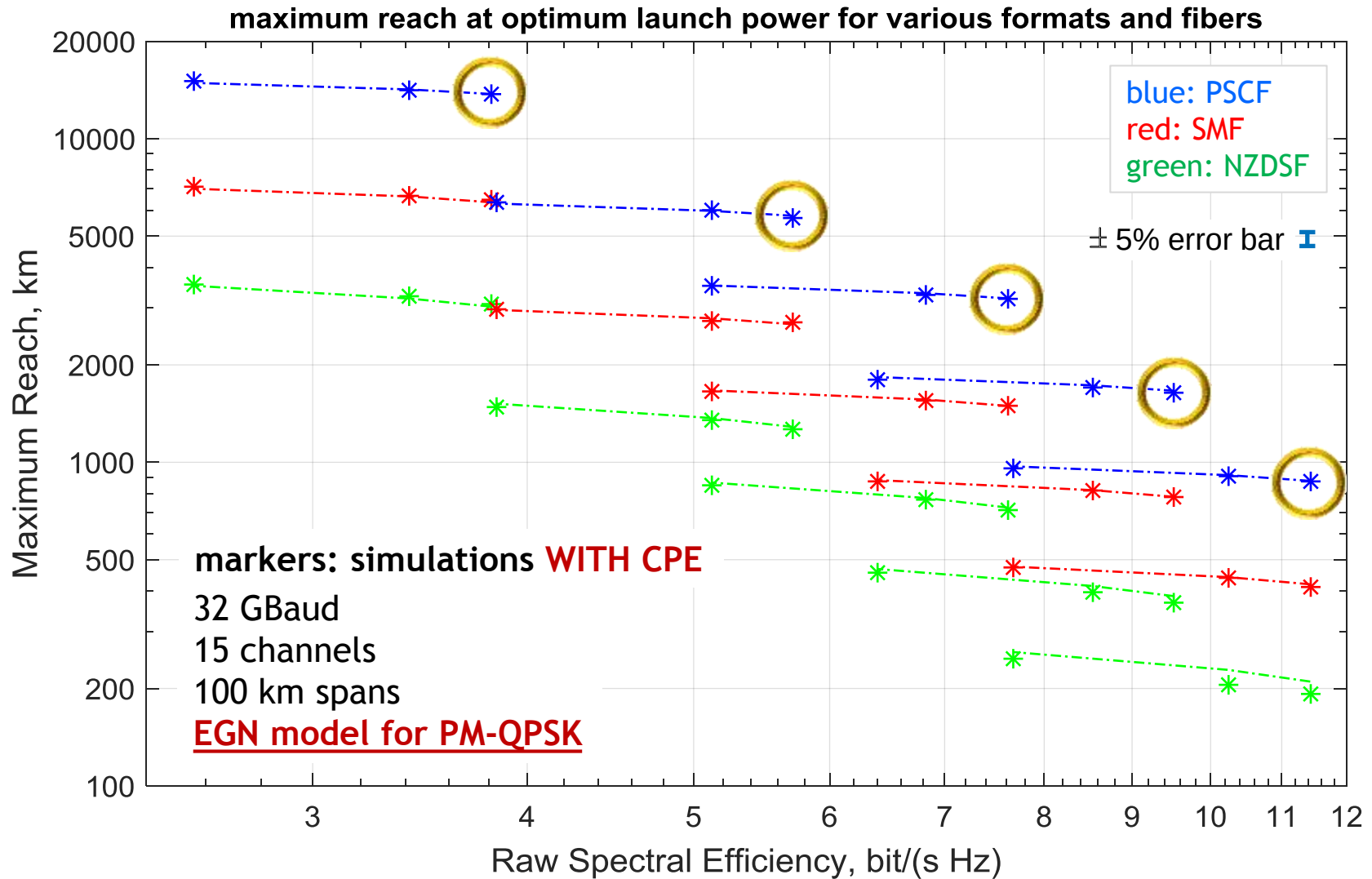












NO CPE

CPE

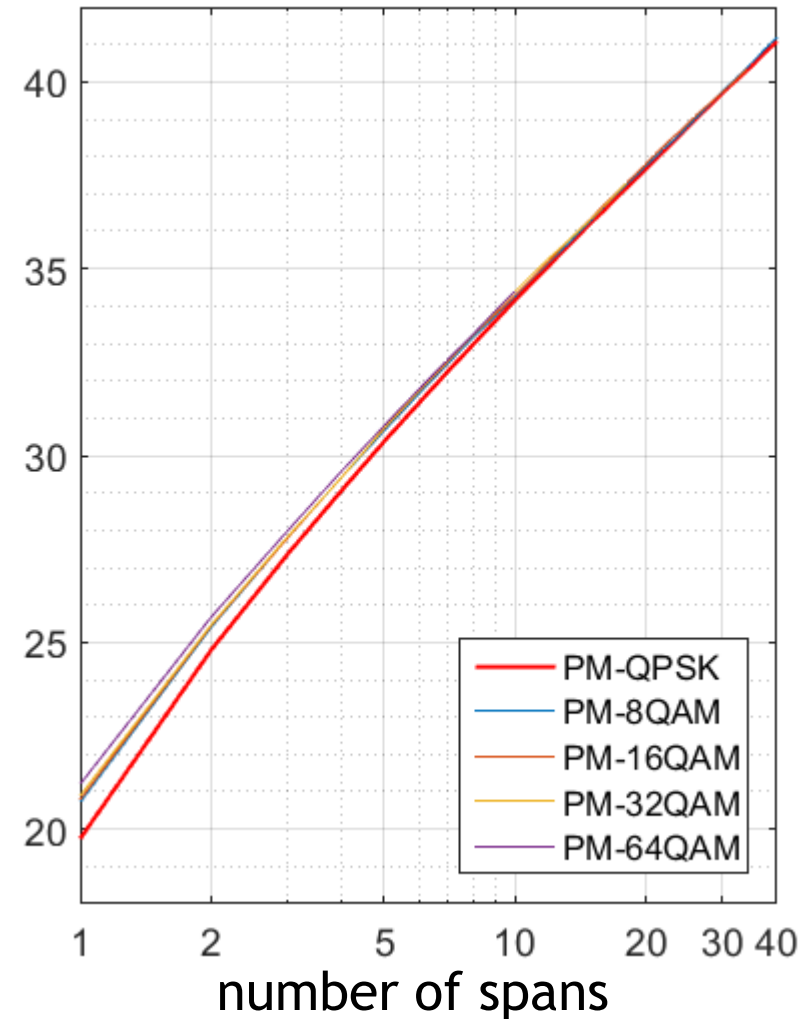
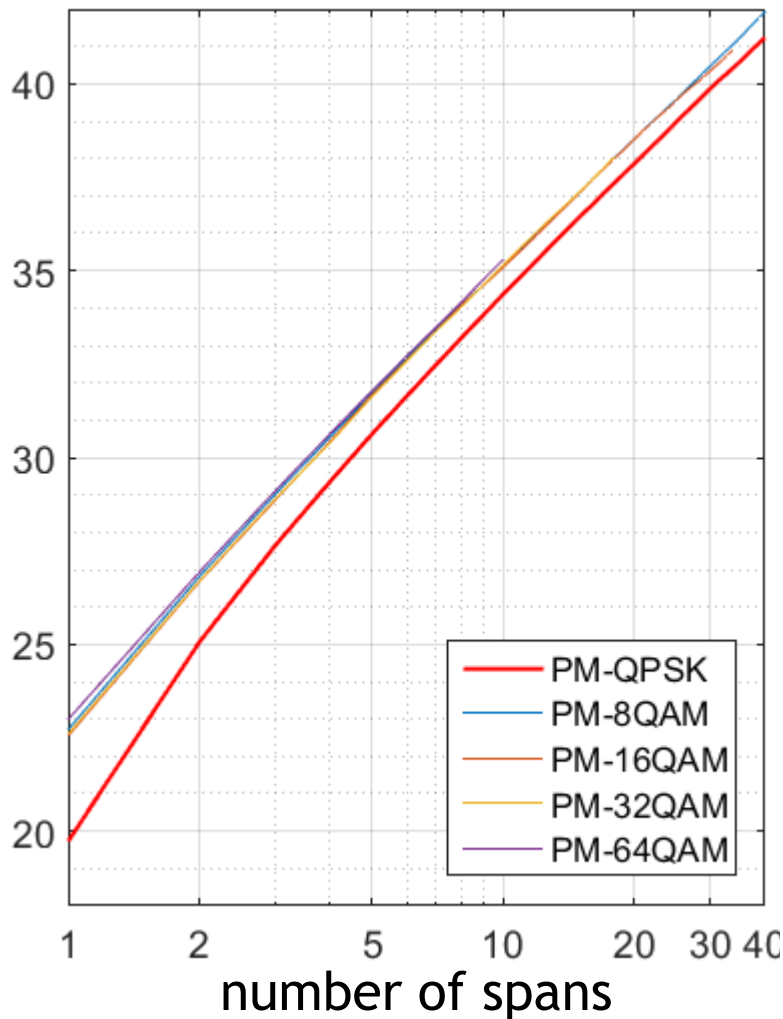
$\tilde{P}_{\text{NLI}}$

$1/W^2$

dB

PSCF
100 km
Spans

See circles
prev. slide





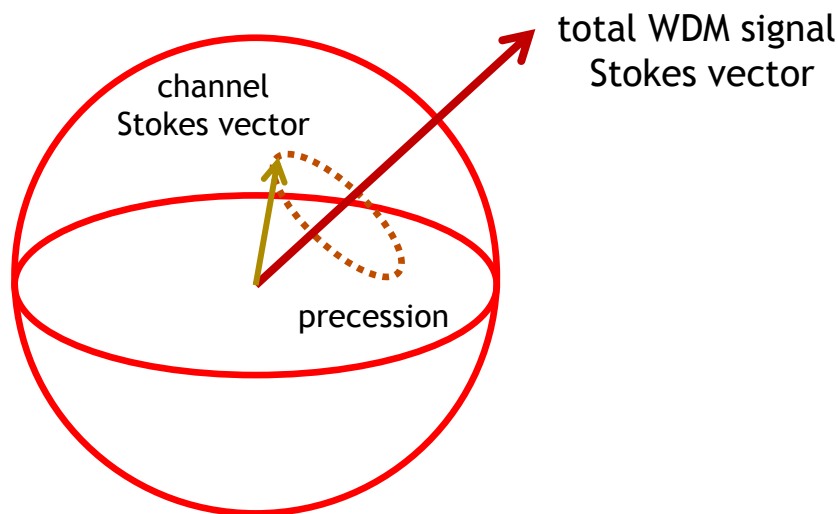
- ▶ When all the long-correlated phase noise is taken out ideally, then:

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

- ▶ 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



- ▶ 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

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

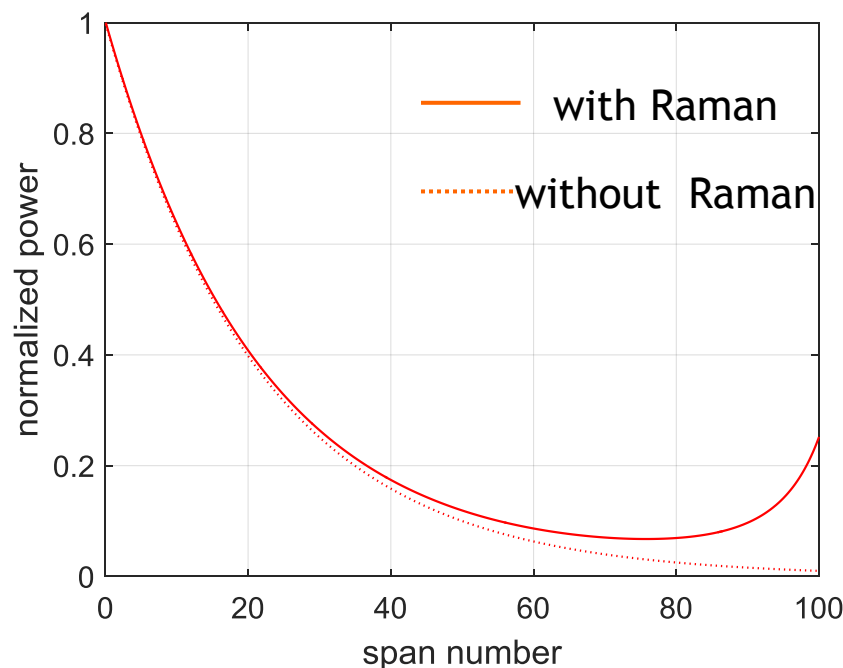
Modeling Raman

- ▶ 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

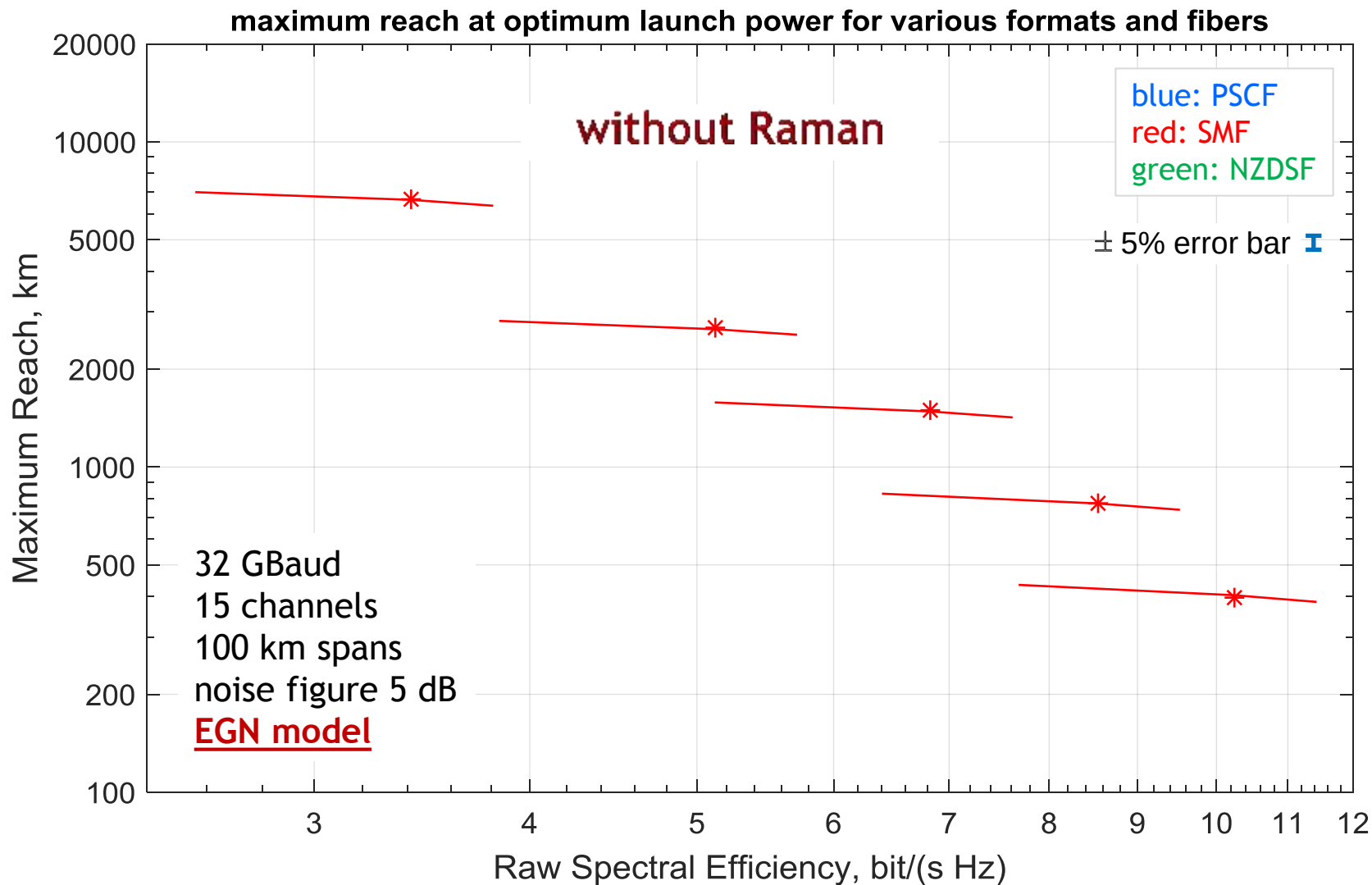
V. Curri, A. Carena, “Merit of Raman pumping in uniform and uncompensated links supporting NyWDM”, JLT, v. 34, n.2, pp. 554-565, Jan. 2016.

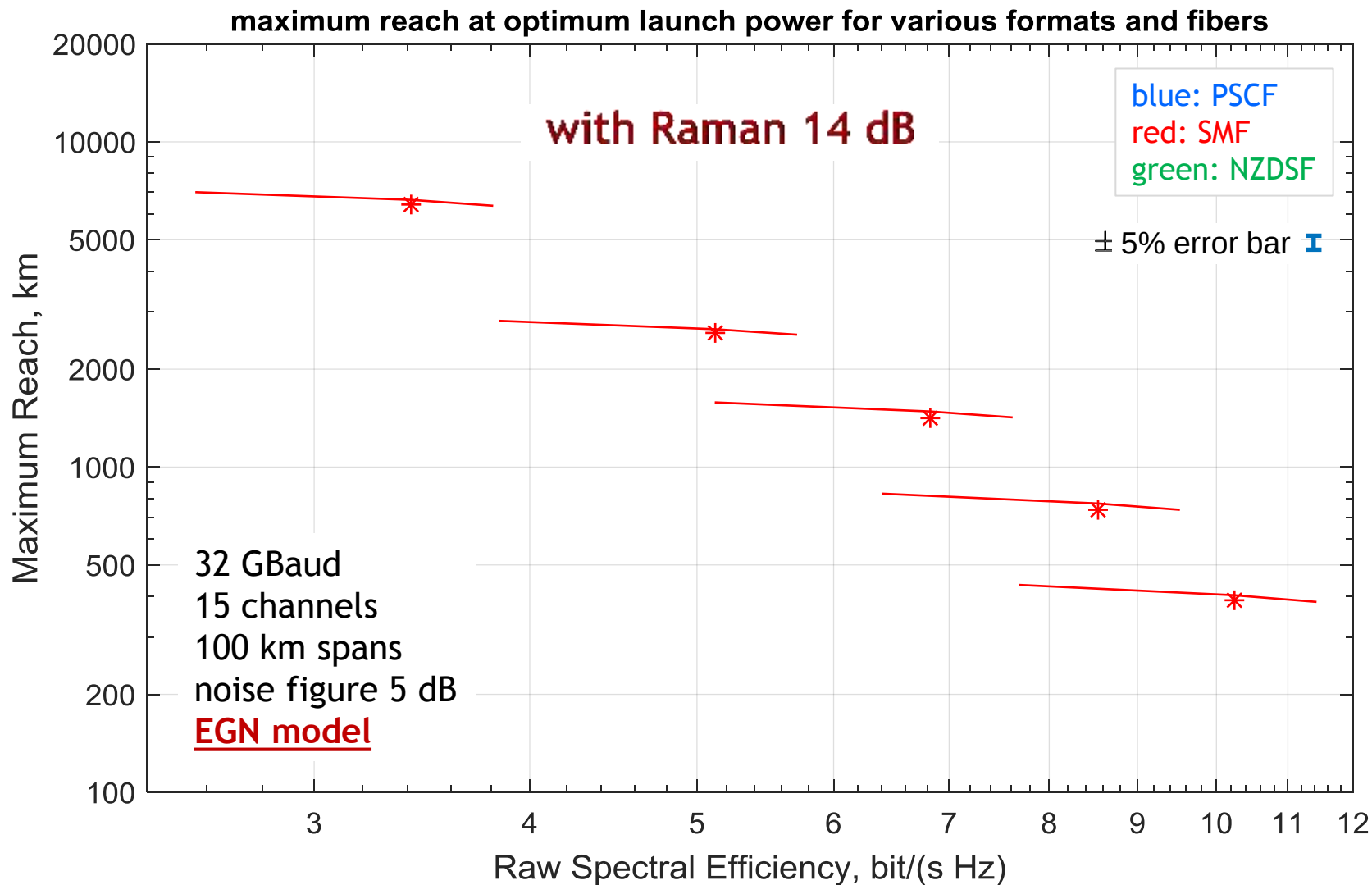
- ▶ We specifically addressed the case of
 - ▶ SMF, 100 km spans, *20 dB span loss*
 - ▶ *14 dB Raman gain*

- ▶ 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 span noise figure (kept it at 5 dB)





- ▶ 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.

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- ▶ The effect of hybrid Raman amplification on NLI generation can be neglected if:

- ▶ Raman is backward-pumped
- ▶ The power at the end of the span is at least 6 dB lower than at the beginning of the span

Modeling inline-ASE and signal depletion

- ▶ 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

- ▶ 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

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:

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

(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

- ▶ *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”)

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



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

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)



- ▶ Signal depletion is significant when :

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

(essentially only PM-QPSK is affected)

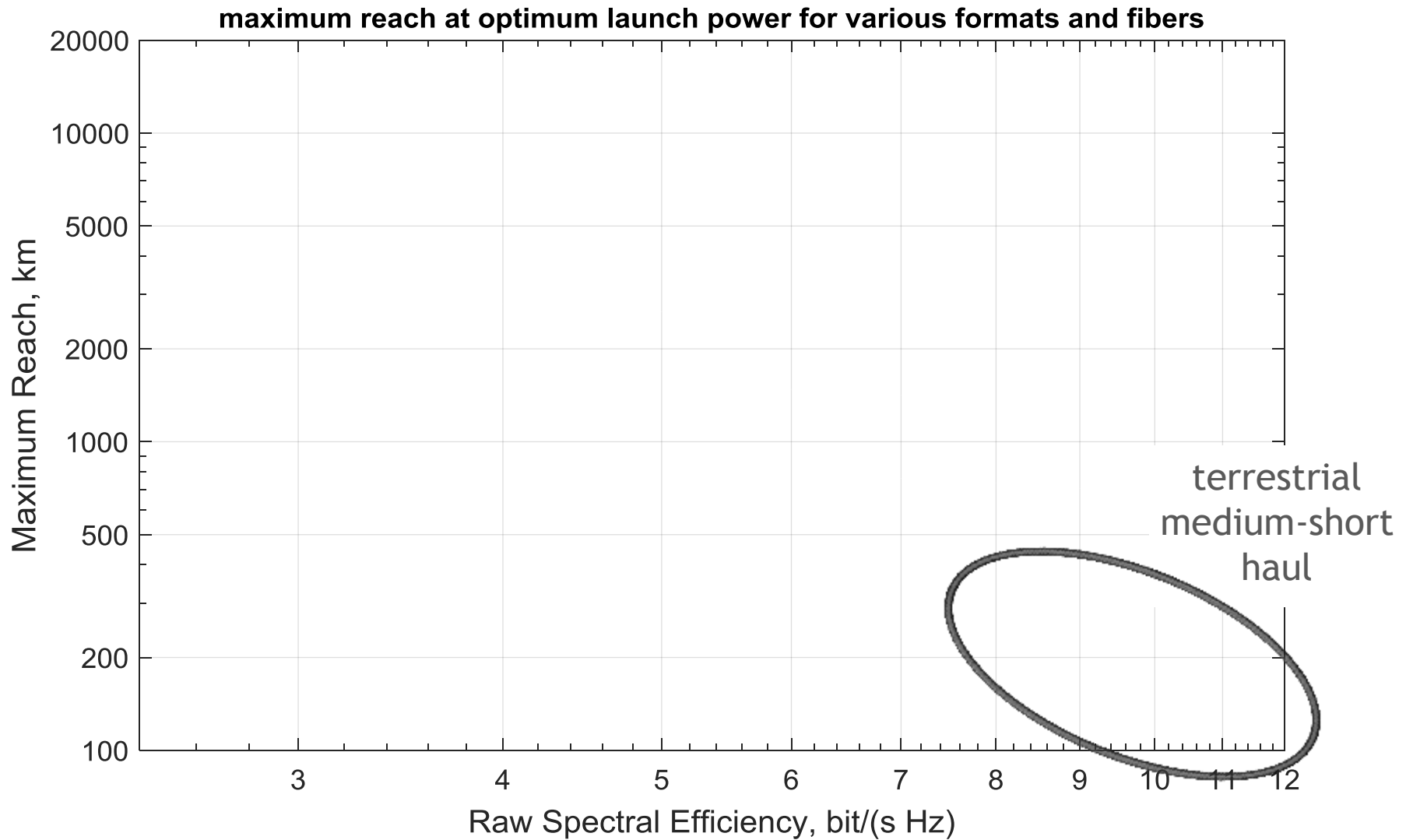
- ▶ A phenomenological correction is possible which turns out to be quite effective

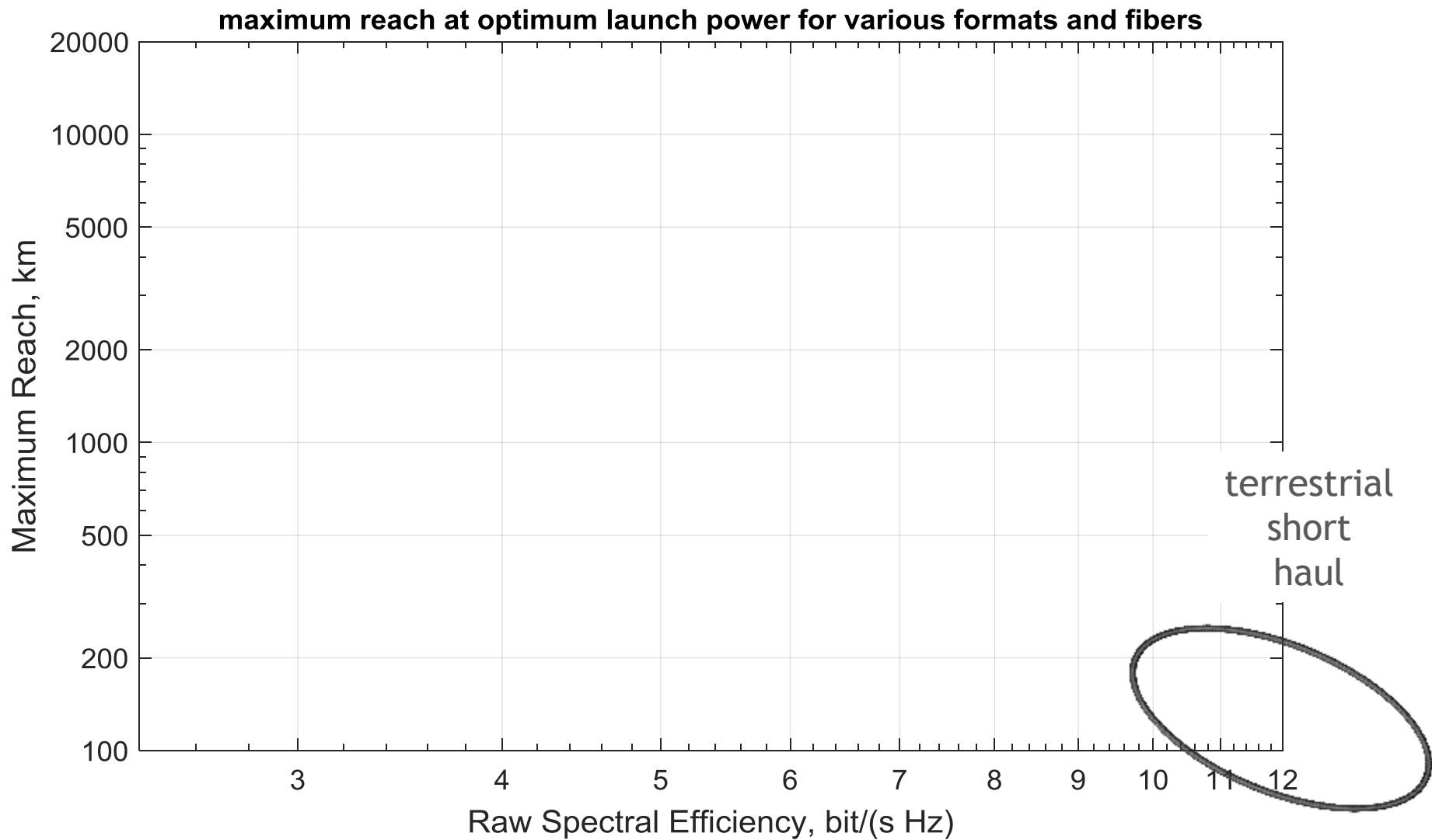


credit: <http://www.examiner.com/article/where-are-we-going-an-exercise-irresponsible-speculation>

- ▶ *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 non-linearity compensation 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.





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R. Dar, P. Winzer “On the Limits of Digital Back-Propagation in Fully Loaded WDM Systems,” PTL, in pre-print, available on IEEE Xplore.
- ▶ Looking at the potential impact of *probabilistic shaping* (“*Gaussian Constellations*”)
- ▶ *Transporting all the above to SDM... ???*

Conclusion...

- ▶ 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

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

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

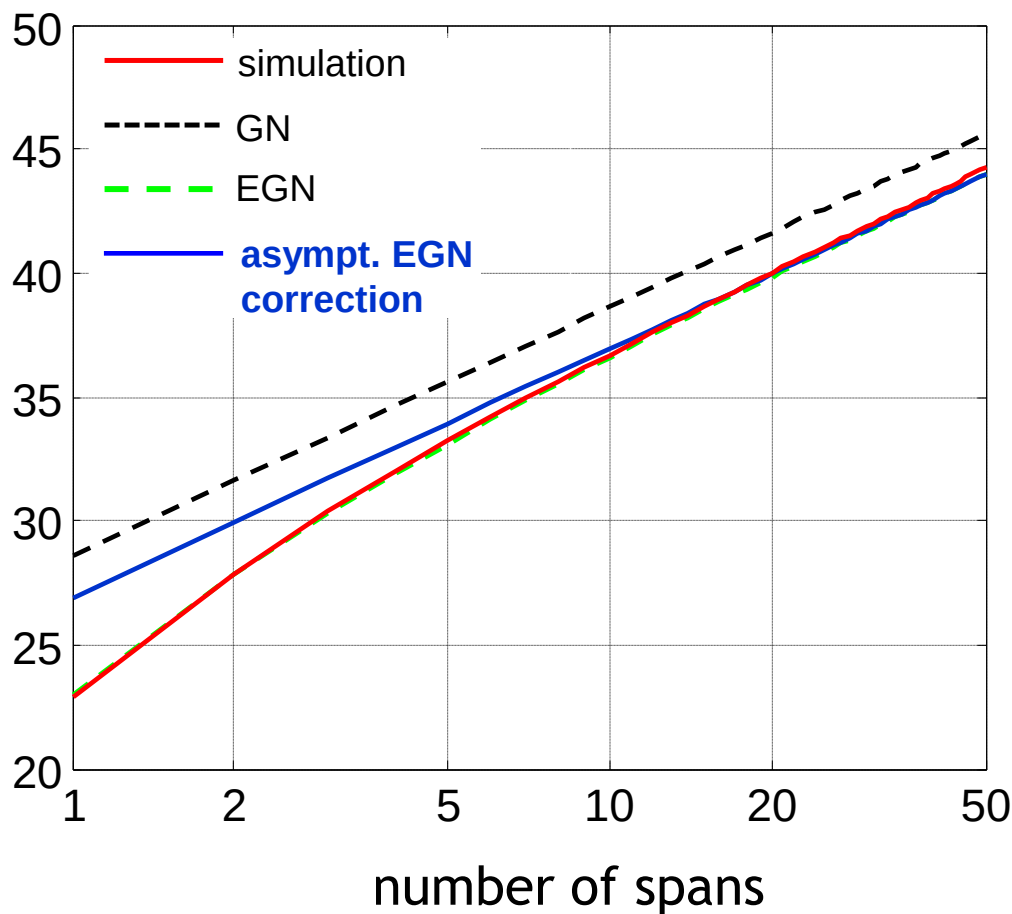
- ▶ It is possible to write “*asymptotic*” closed-form expressions of the correction term

- ▶ 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

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

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

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



The (simple) asymptotic formula

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

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

note:

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

- ▶ This version assumes all identical channels but it can be generalized:

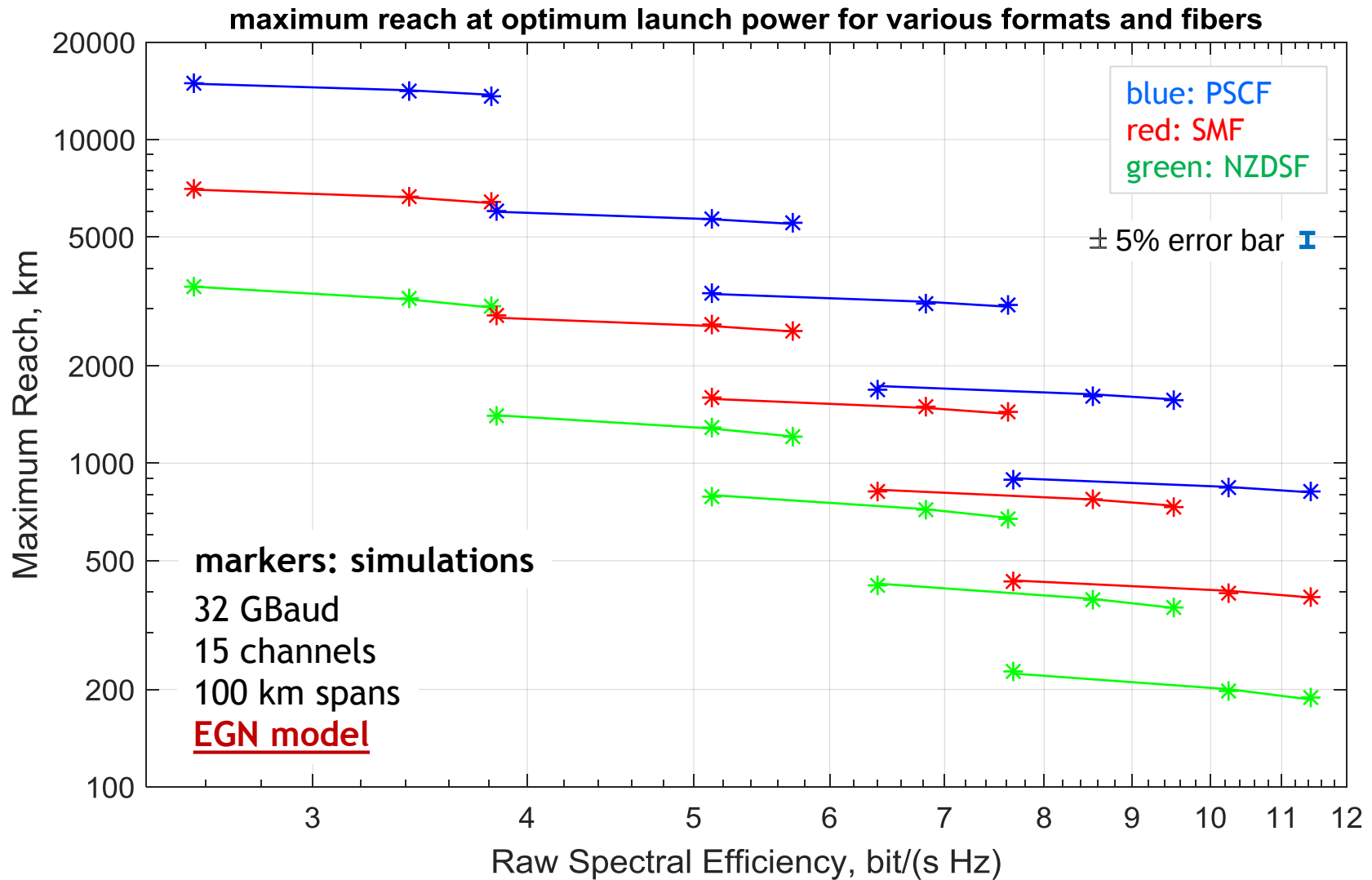
Xiang Zhou and Chongjin Xie Editors, *Enabling Technologies for High Spectral-efficiency Coherent Optical Communication Networks*, John Wiley & Sons, Chapter 7, by P. Poggiolini, Y. Jiang, A. Carena, F. Forghieri, ISBN 9781118714768

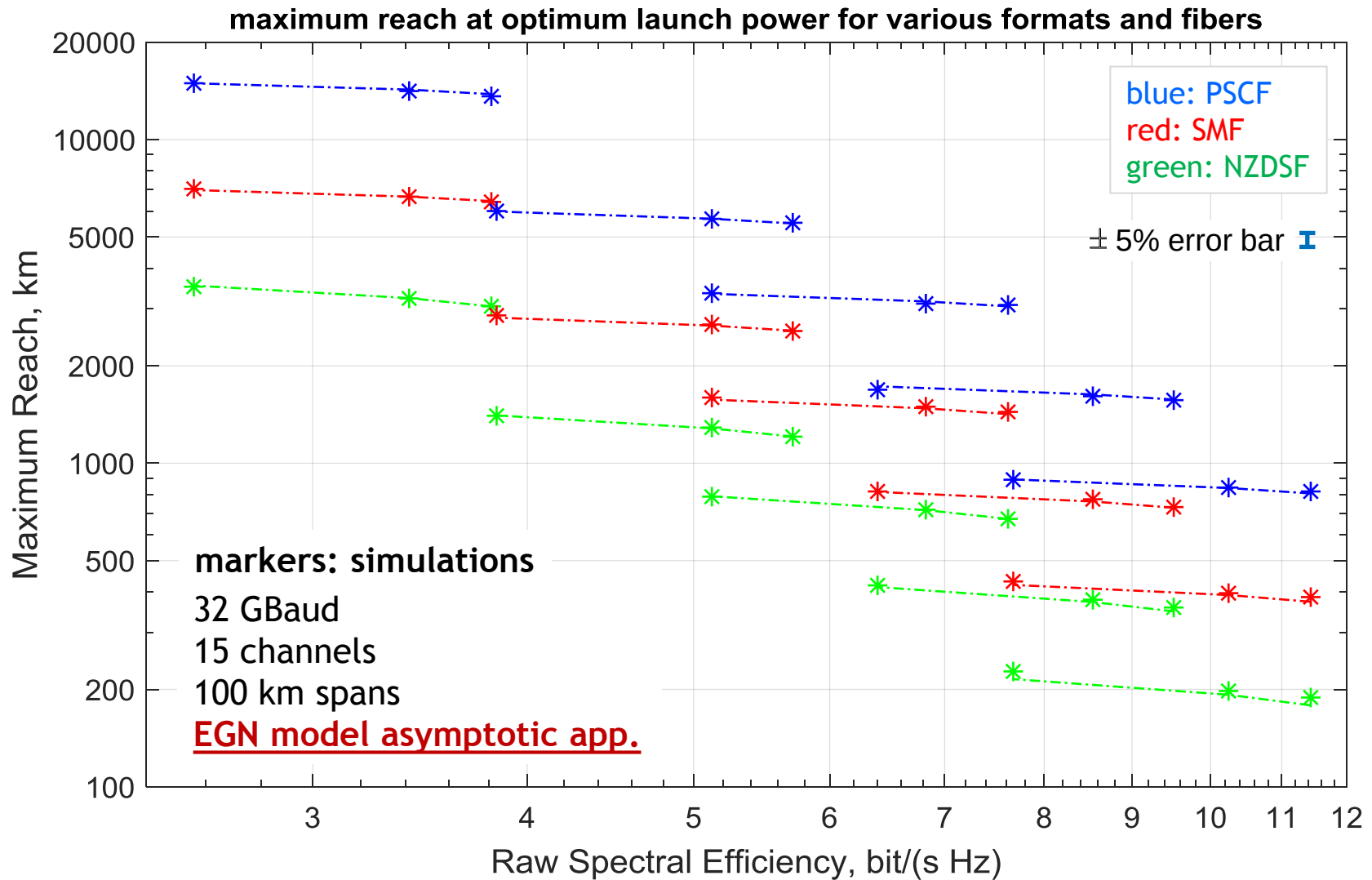
- ▶ *Limitations: loses accuracy at very low symbol rates*

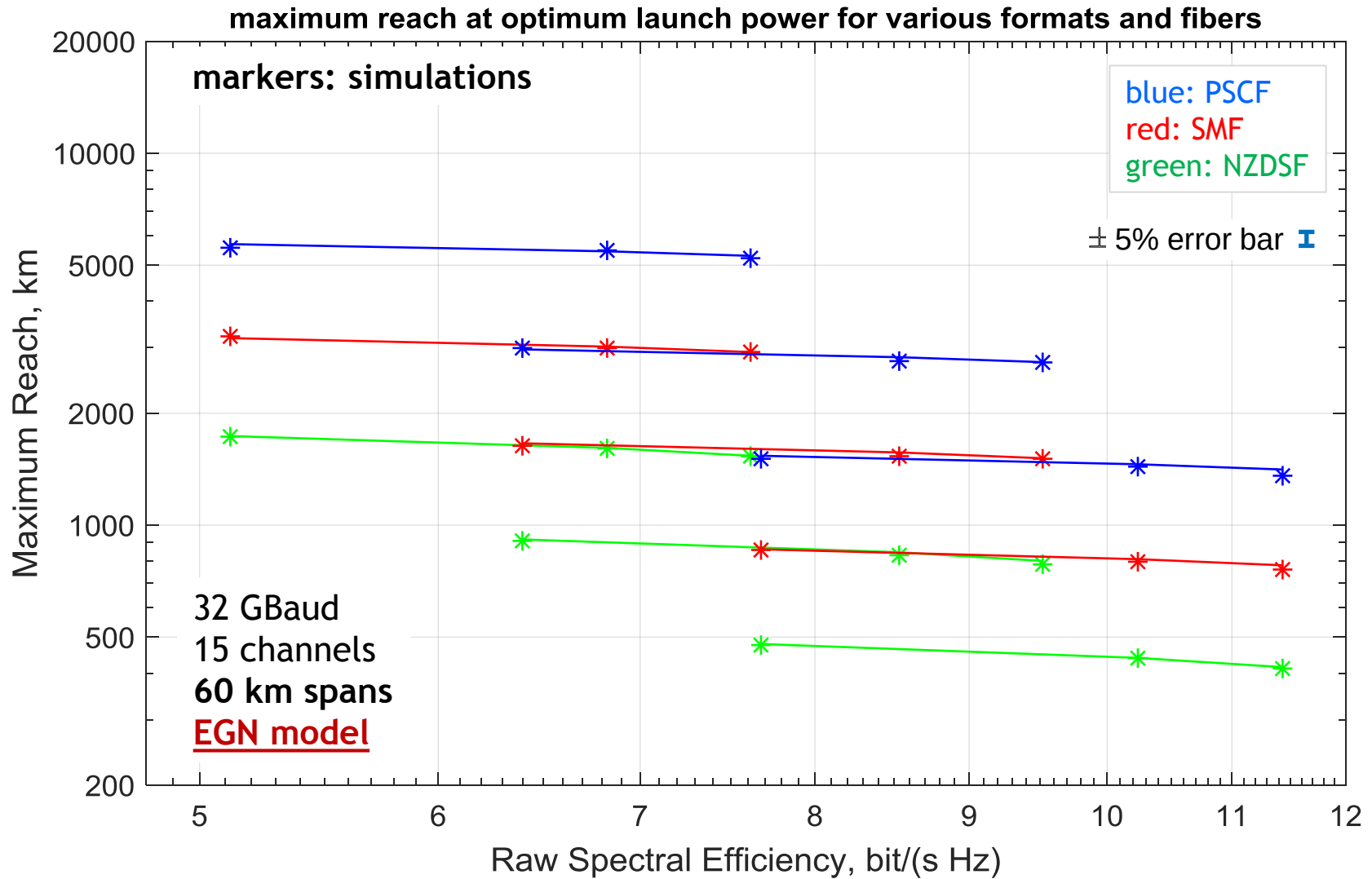
- ▶ use it only when:

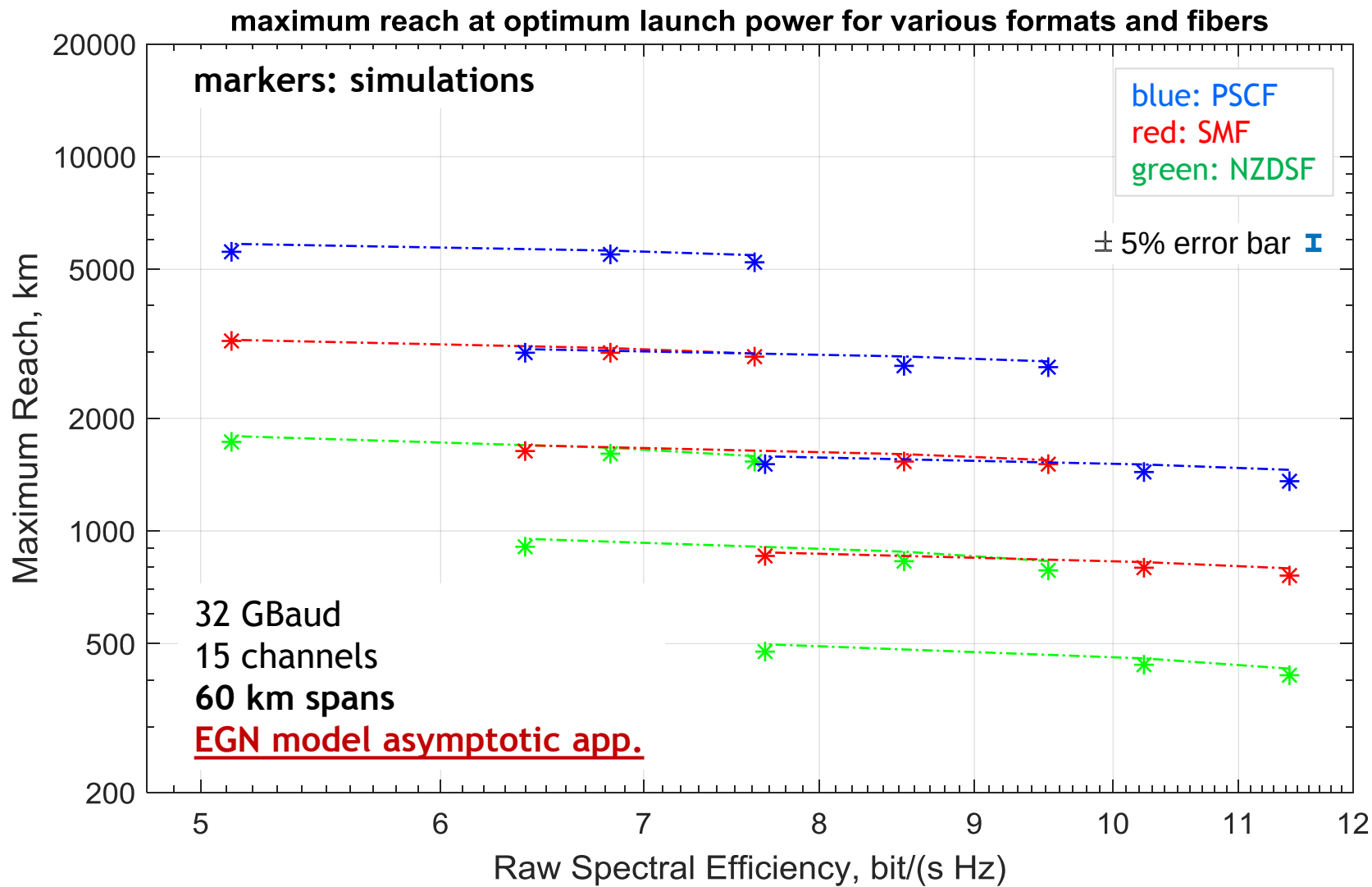
$$R \gg \sqrt{2 / (\pi |\beta_2| L_s N_s)}$$

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







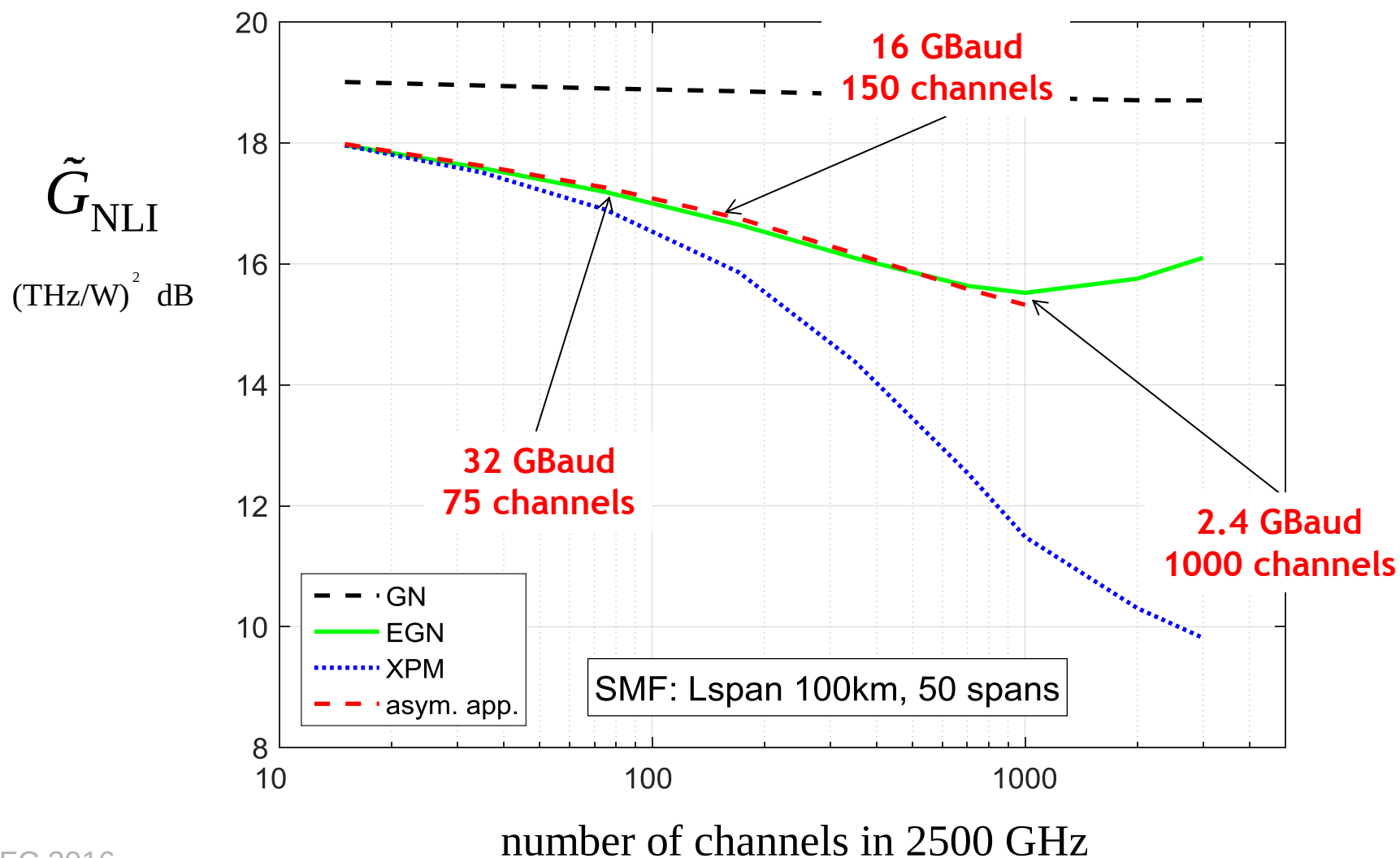


- ▶ A more complex but still closed-form formula is available which is *valid down to the optimum symbol rate*

$$\begin{aligned}
 G_{\text{NLI}}^{\text{corr}} \approx & \Phi \frac{80}{81} R_s^{-2} \gamma^2 P_{\text{ch}}^3 \frac{L_{\text{eff}}^2}{\pi L_s \Delta f} N_s \left\{ HN([N_{\text{ch}} - 1]/2) + \frac{\Delta f}{R_s} \left(1 - \frac{R_{\text{opt}}}{R_s} \right) \right. \\
 & + \frac{\pi}{2} \sum_{n_{\text{ch}}=1}^{(N_{\text{ch}}-1)/2} \sum_{n=1}^{N_p} \frac{\Delta f}{N_s} \frac{1}{1 + \frac{n^2 \pi^2}{(\alpha L_s)^2}} \frac{1}{2n\pi^2} \frac{\left(1 + \frac{2n_{\text{ch}} \Delta f}{n N_s R_s} \right)}{1 - \left(\frac{R_s}{2n_{\text{ch}} \Delta f} \right)^2} \cdot \\
 & \left. \left[\text{sinint} \left((2N_s - 1) \frac{n\pi R_s}{2n_{\text{ch}} \Delta f} \right) + \text{sinint} \left(\frac{n\pi R_s}{2n_{\text{ch}} \Delta f} \right) \right]^2 \right\} \\
 N_p = & \lfloor n_{\text{ch}} \pi \beta_2 L_s R_s \Delta f \rfloor \quad R_{\text{opt}} = \sqrt{2 / (\pi |\beta_2| L_{\text{span}} N_{\text{span}})}
 \end{aligned}$$

Test at 2.4 THz of bandwidth

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

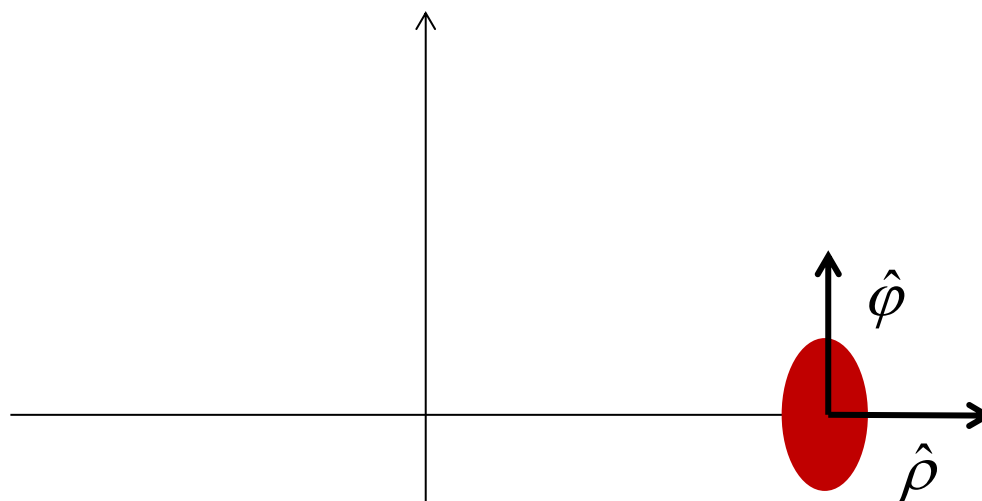


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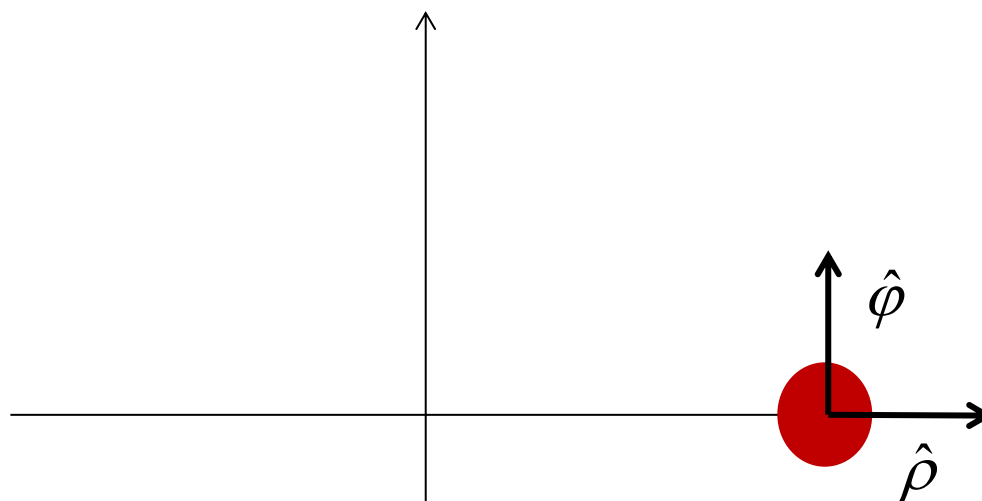


- ▶ The asymptotic EGN correction formula(s) are promising low-complexity solutions for max-reach studies
- ▶ Being “asymptotic” in the number of spans, they *should be used with caution* in short-reach systems (< 300 km)

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

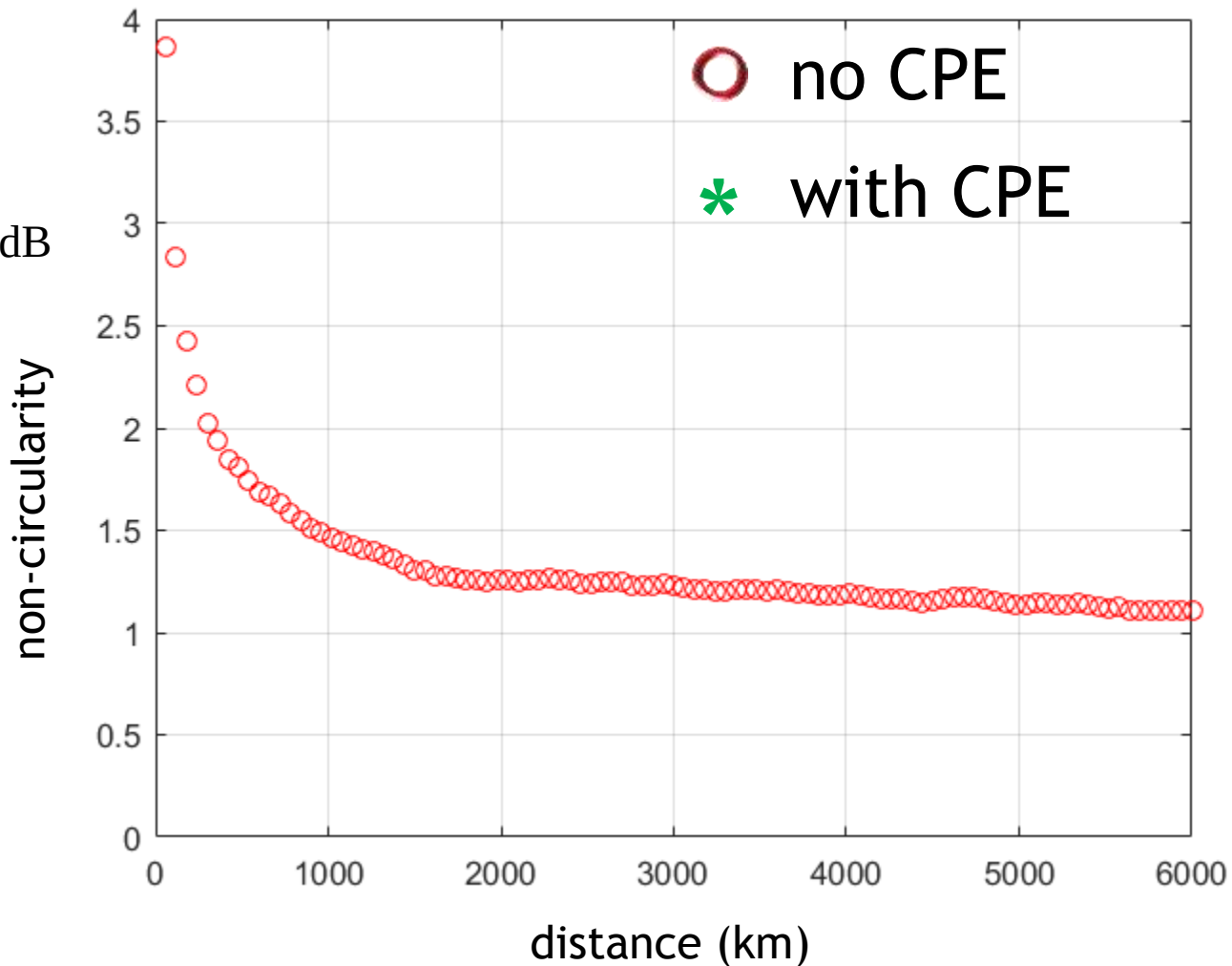


“non-circularity”: $\left(\frac{\sigma_{\hat{\phi}}^2}{\sigma_{\hat{\rho}}^2} \right)_{\text{dB}}$

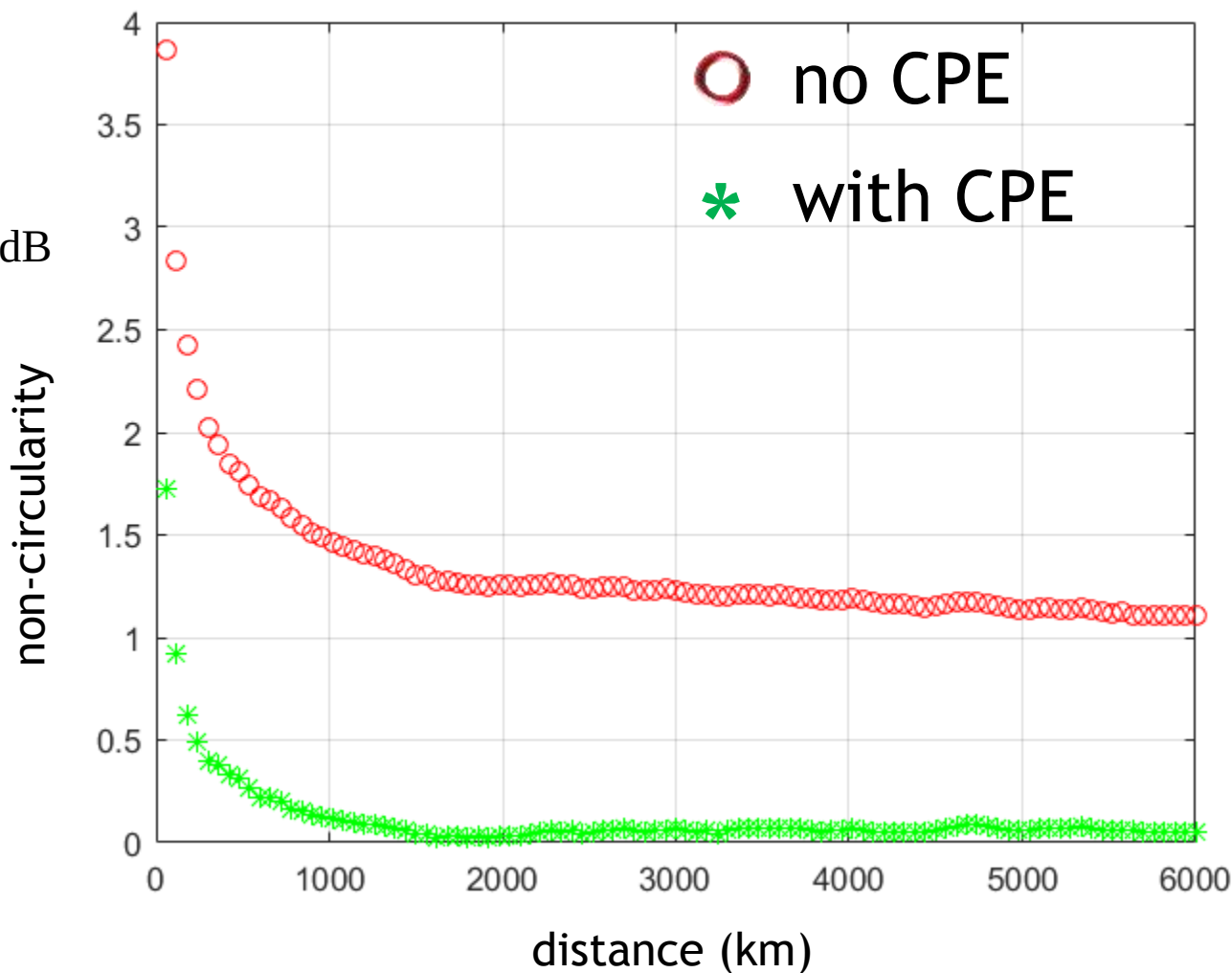


$$\left(\frac{\sigma_{\hat{\phi}}^2}{\sigma_{\hat{\rho}}^2} \right)_{\text{dB}} = 0$$

$$\left(\frac{\sigma_{\hat{\phi}}^2}{\sigma_{\hat{\rho}}^2} \right)_{\text{dB}}$$



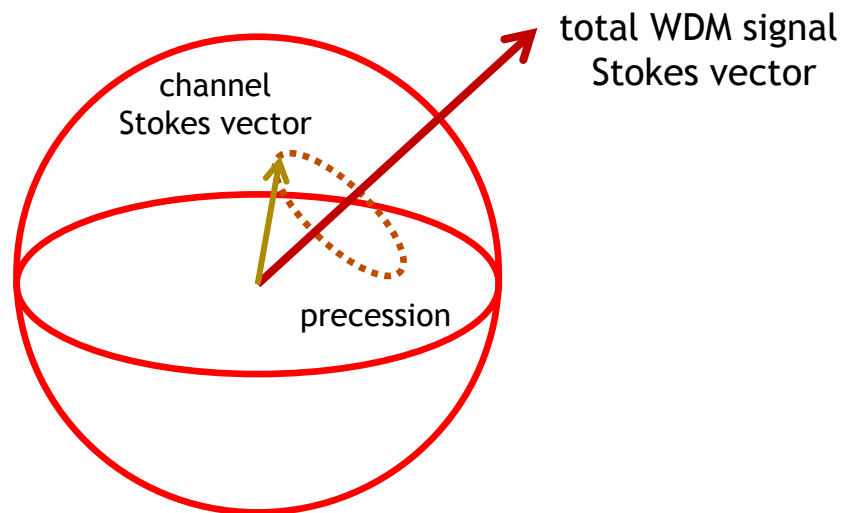
$$\left(\frac{\sigma_{\hat{\phi}}^2}{\sigma_{\hat{\rho}}^2} \right)_{\text{dB}}$$



More details on 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



- ▶ 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*

- ▶ 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:

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

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

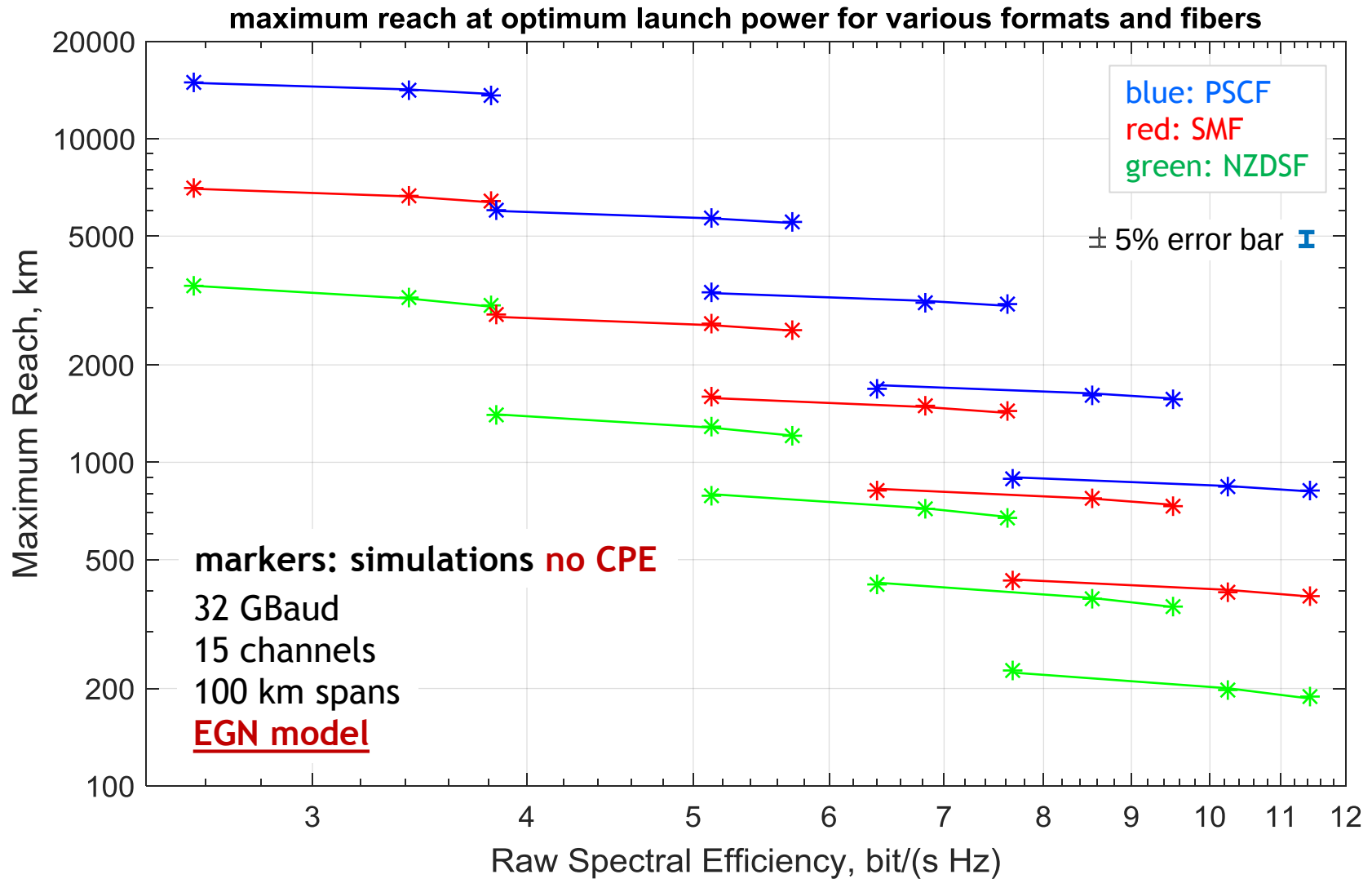
PolN-induced
phase noise

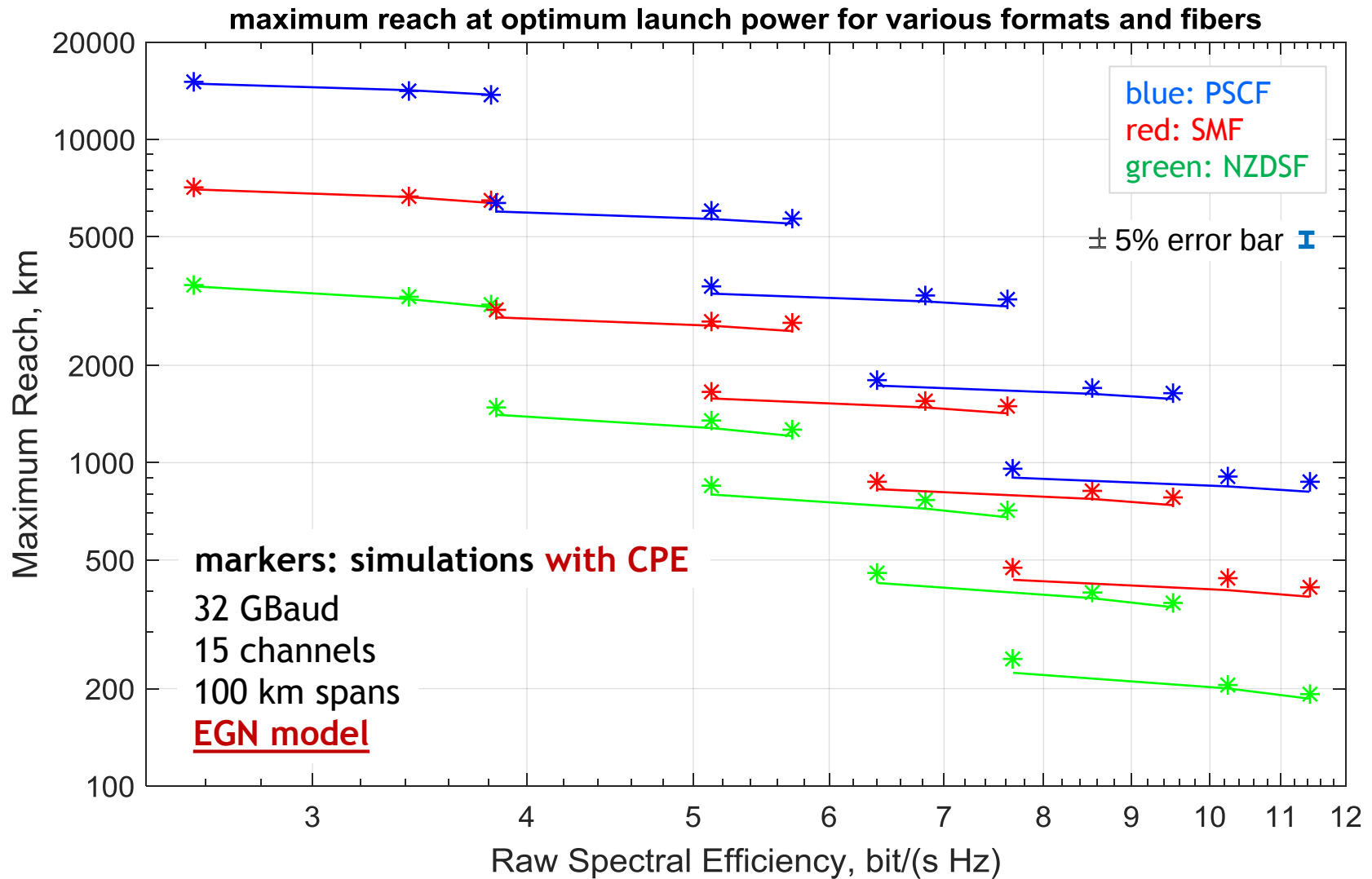
if the Rx CPE works independently
on the two polarizations, it already
removes long-correlated PolN, too.

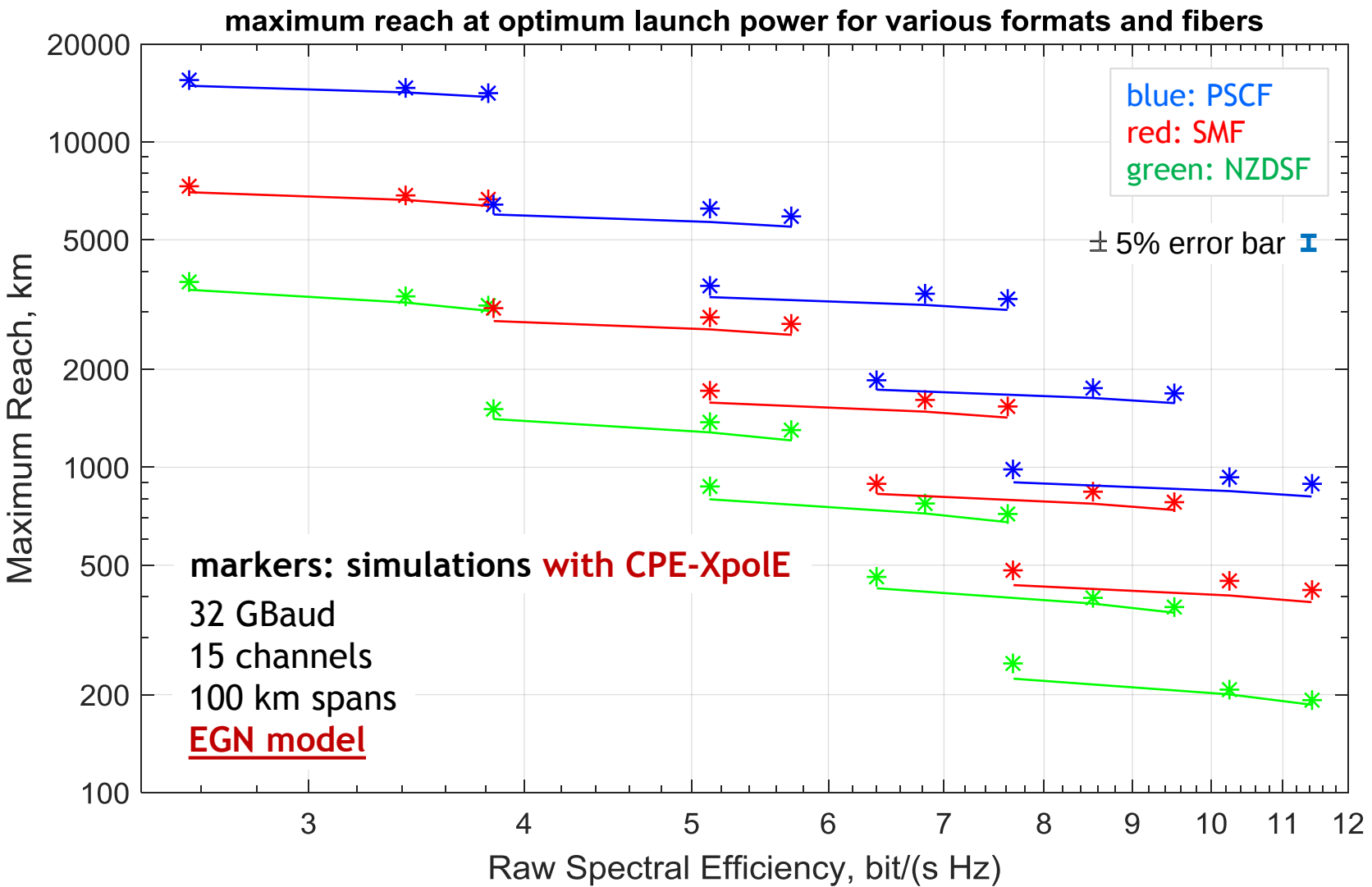
In our simulations this was the case.

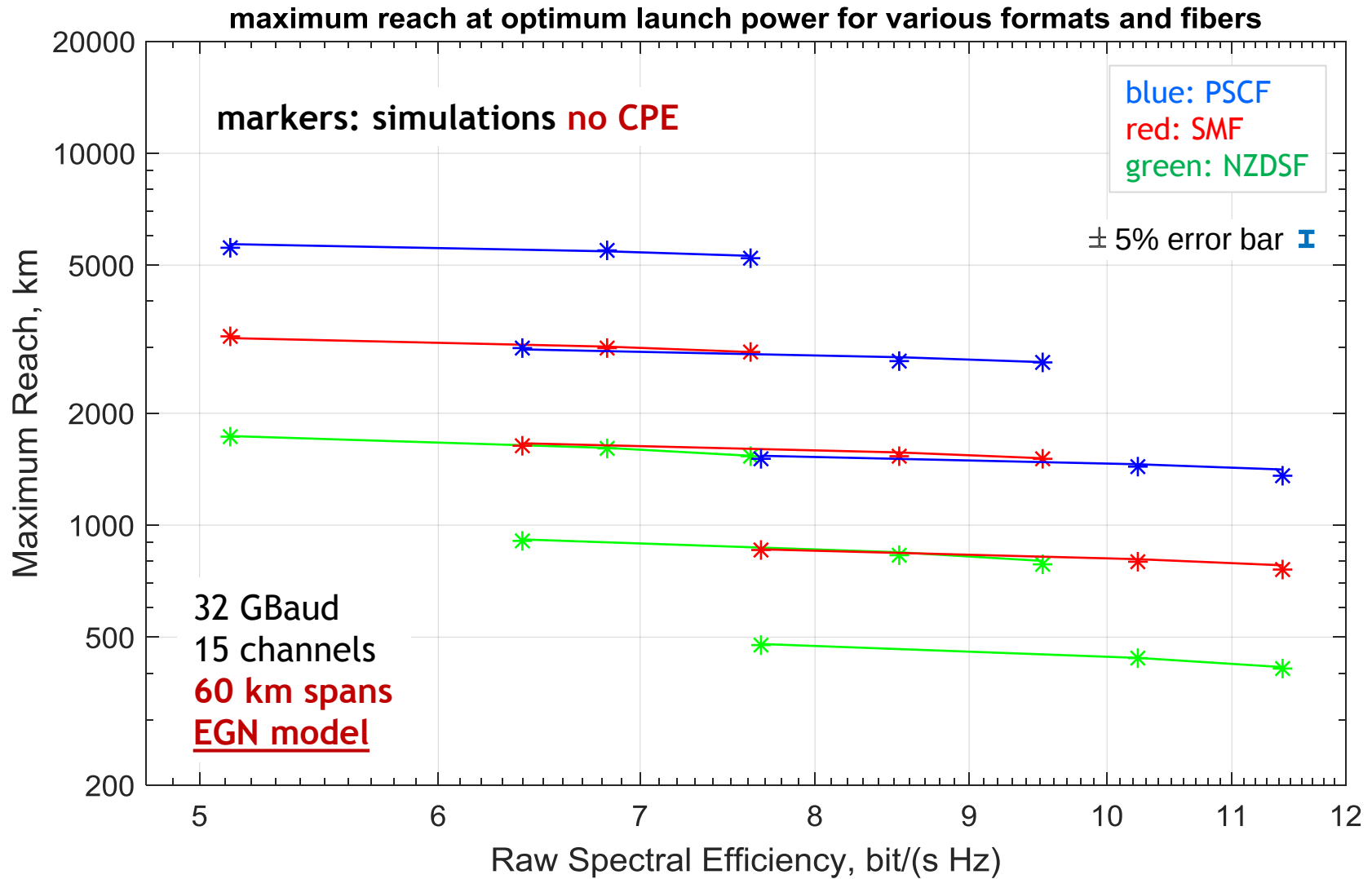
crosstalk
between the
two constellations

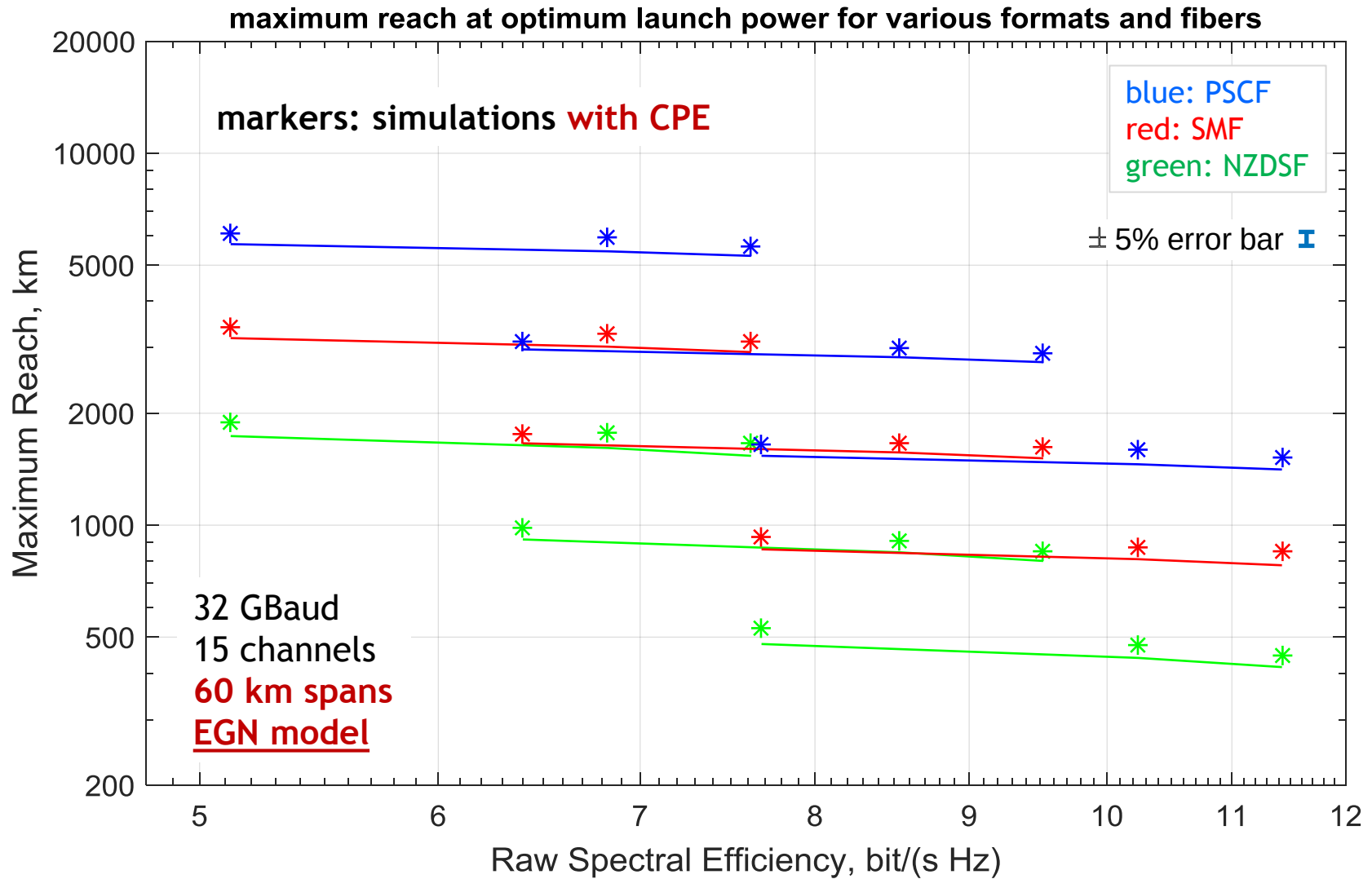
requires an “ad hoc” algorithm to
estimate and remove its
long-correlated (LC) part

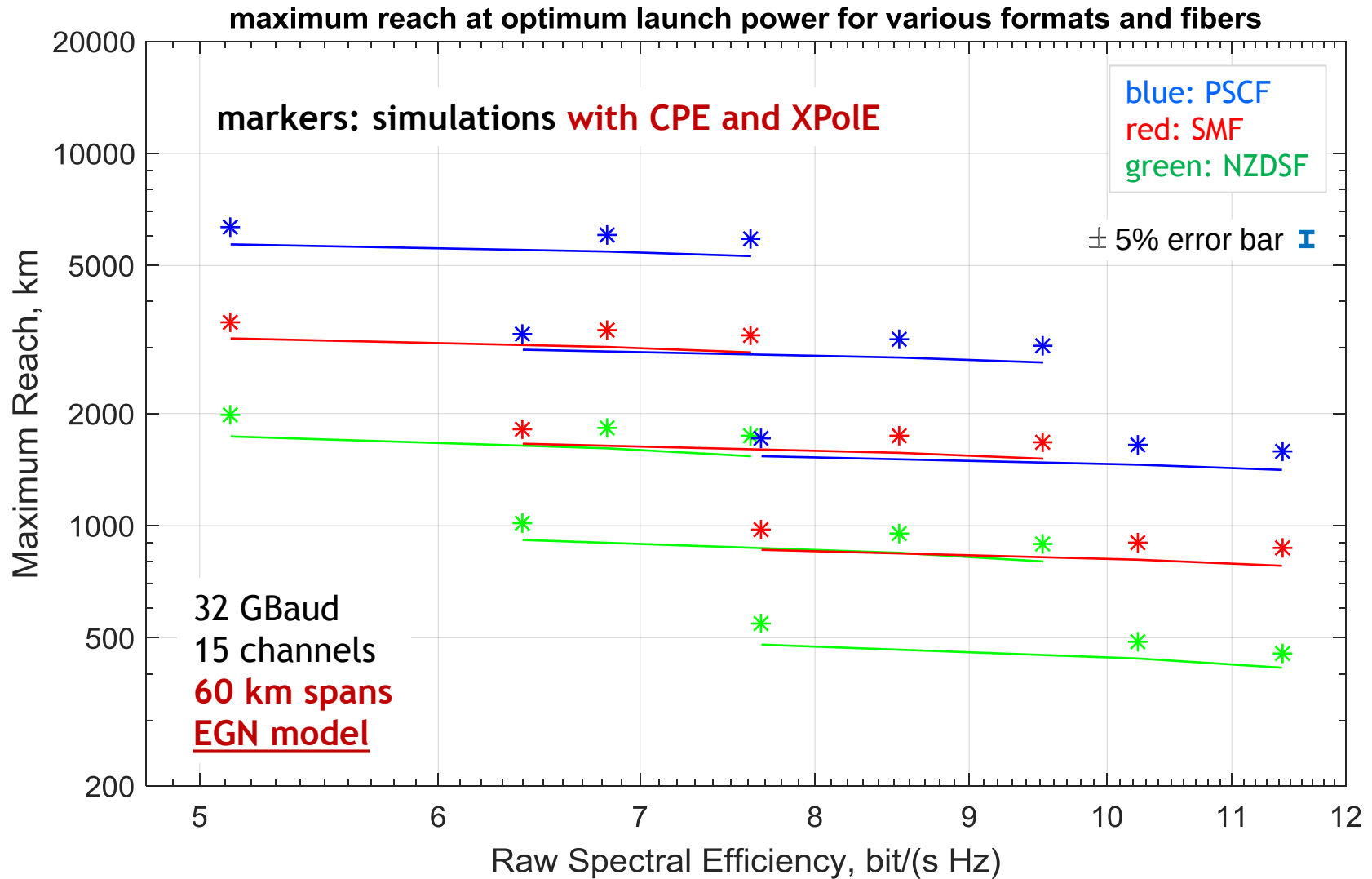












- ▶ The *further MR gain on top of CPE* is substantial for 60 km spans
 - ▶ average on “the big picture” is 3.7%, peak is 5.5%
- ▶ The *further MR gain on top of CPE* is somewhat less for 100km spans, but comparable
 - ▶ average on “the big picture” is 2.4%, peak is 5.5%
- ▶ In existing systems, the 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*

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- ▶ 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/>

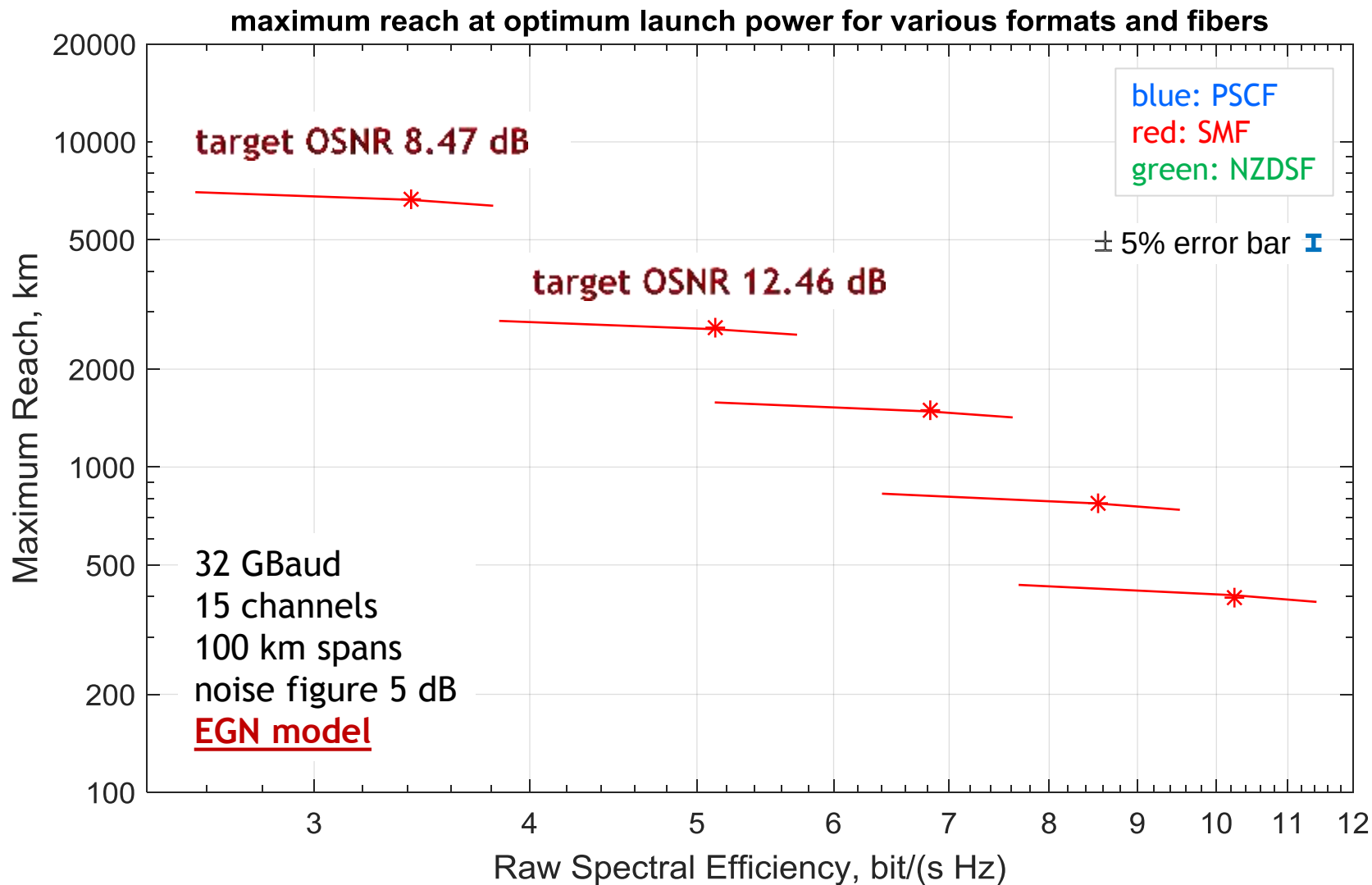
More details on in-line ASE

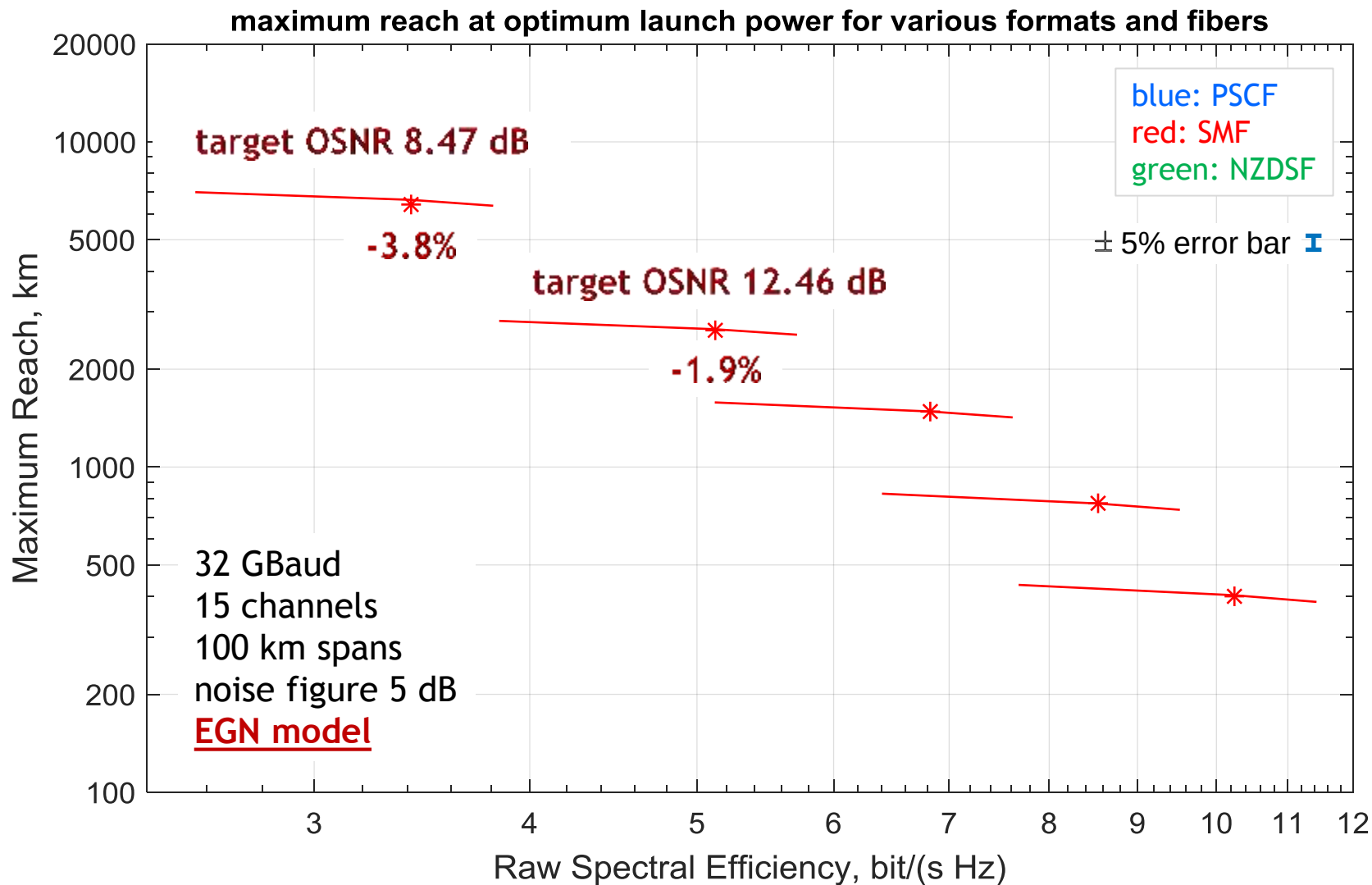
- ▶ ASE noise is actually injected into the system at every span
- ▶ Models typically neglect its contribution to NLI generation
- ▶ *But ASE does create further NLI*

- ▶ 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





- ▶ 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

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

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

(essentially only PM-QPSK is affected)

- ▶ Exact models for ASE are now available but are complex

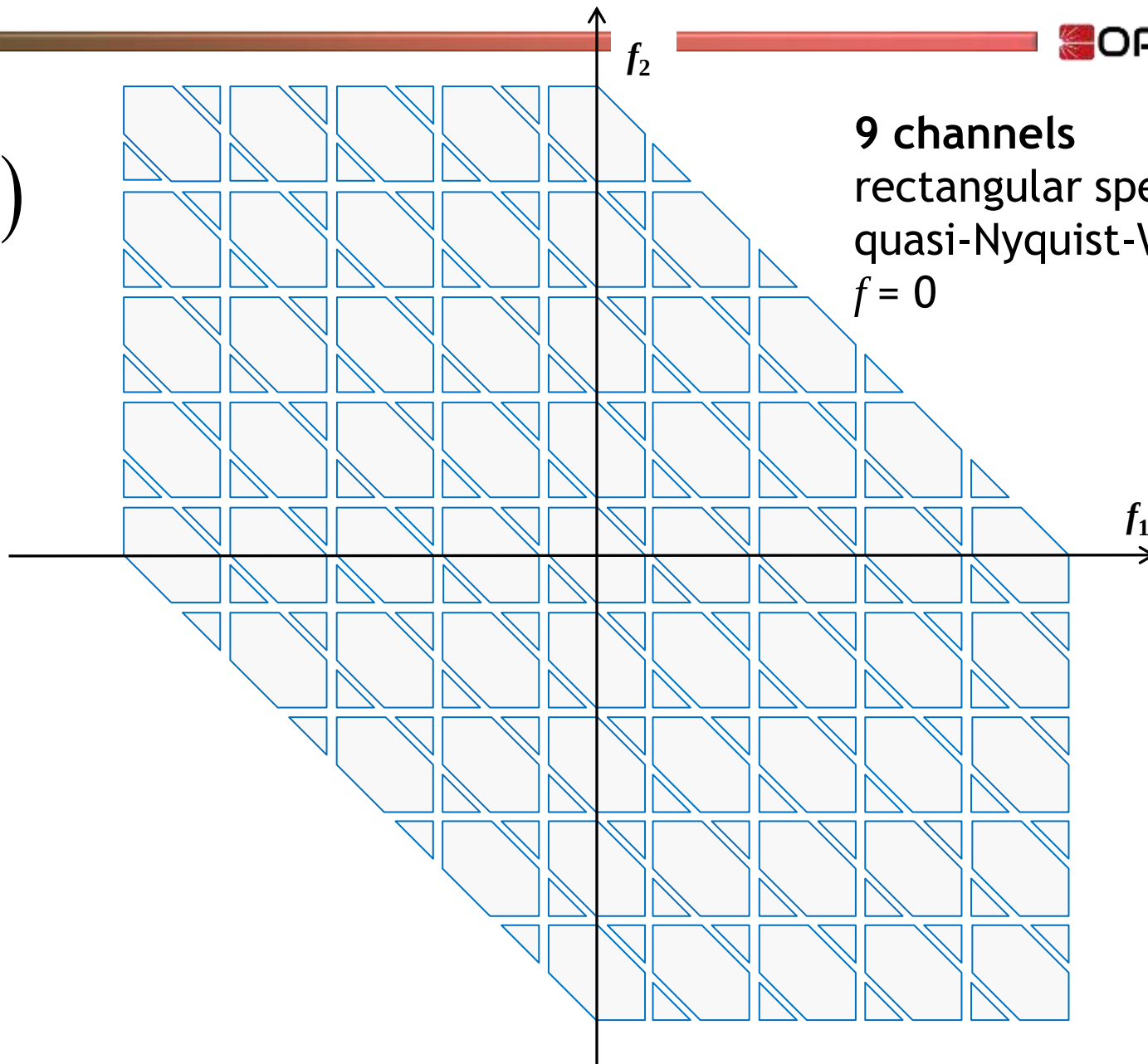
Very accurate analytical treatment in the context of the EGN model

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”

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



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

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

the correction
exists in
all colored islands

