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QUALITY OF TRANSMISSION MODELING AND MONITORING

ANDREA CARENA
OPTCOM Optical Communications Group – Politecnico di Torino, Torino - Italy

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OUTLINE

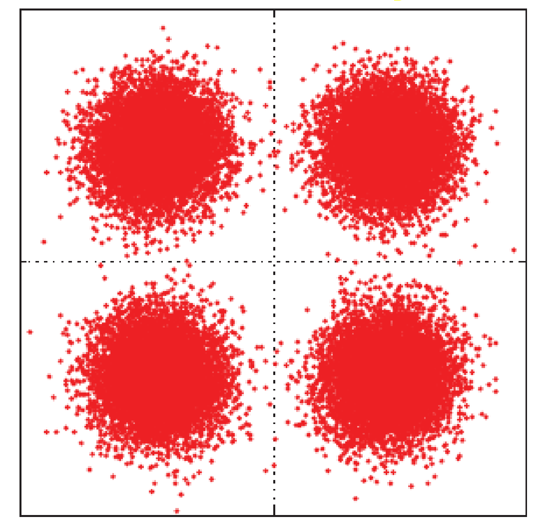
- Modeling
  - Point-to-point links: model evolution
  - Network performance evaluation
  - Static networks vs. dynamic networks: which model?
- Monitoring
  - Taking advantage of DSP processing
- Conclusions

MODELING

NLI AS GAUSSIAN NOISE

SCENARIO:
- **Coherent Detection**
- **Uncompensated links**

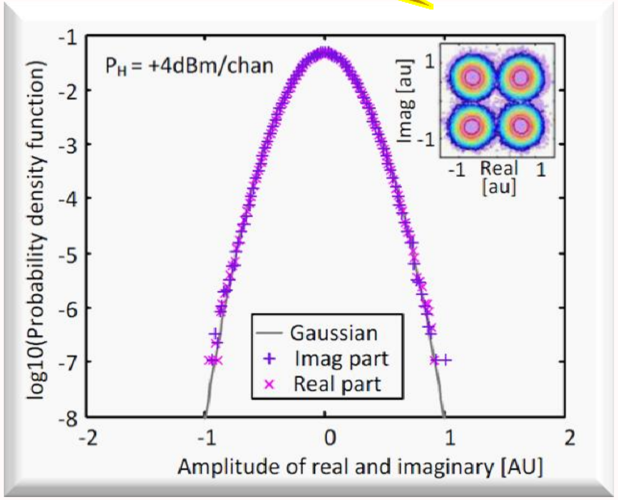
It looks like ASE!



PM-QPSK - 28 GBaud
9 channels
50 GHz spacing
3 dBm per channel
3000 km

simulated without ASE

all noise is due to non-linearity



PM-QPSK
28 GBaud
80 channels
spacing 50 GHz

15x100km spans SMF

4 dBm per channel

ASE "almost" negligible

A. Carena, "Statistical characterization of PM-QPSK signals after propagation in uncompensated fiber links," Proc. ECOC'10, paper P4.07

F. Vacondio, O. Rival, C. Simonneau, E. Grellier, A. Bononi, L. Lorcy, J.-C. Antona and S. Bigo, "On nonlinear distortions of highly dispersive optical coherent systems," Optics Express, Vol. 20, No. 2, Jan 2012.

THE NON-LINEAR OSNR

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

NLI is Gaussian and additive

NLI is uncorrelated with either ASE or the signal

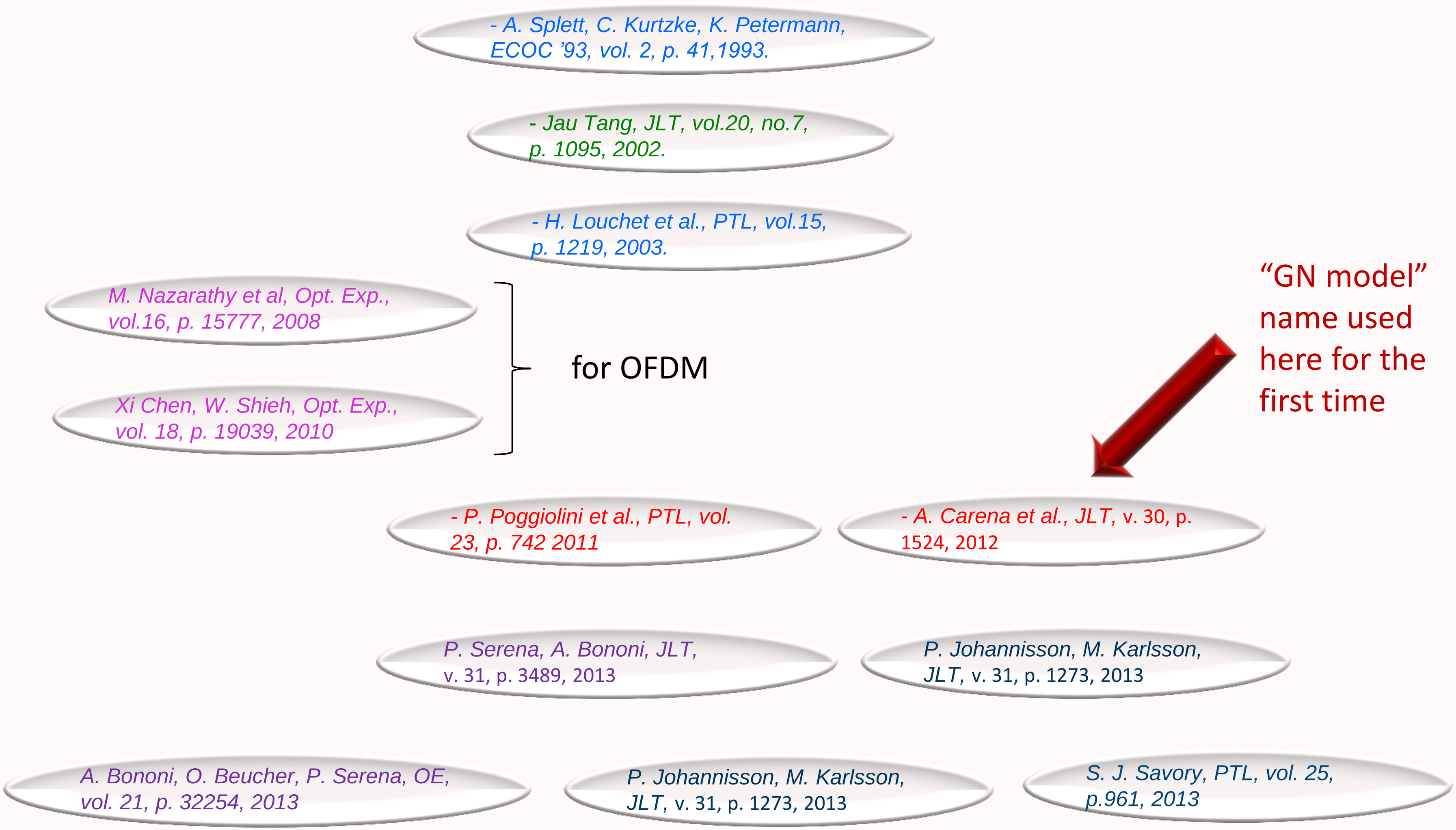
QUALITY OF TRANSMISSION

- In coherently detected systems impacted by Gaussian noise BER is a direct function of OSNR

- OSNR can be used as a Quality of Transmission (QoT) parameter

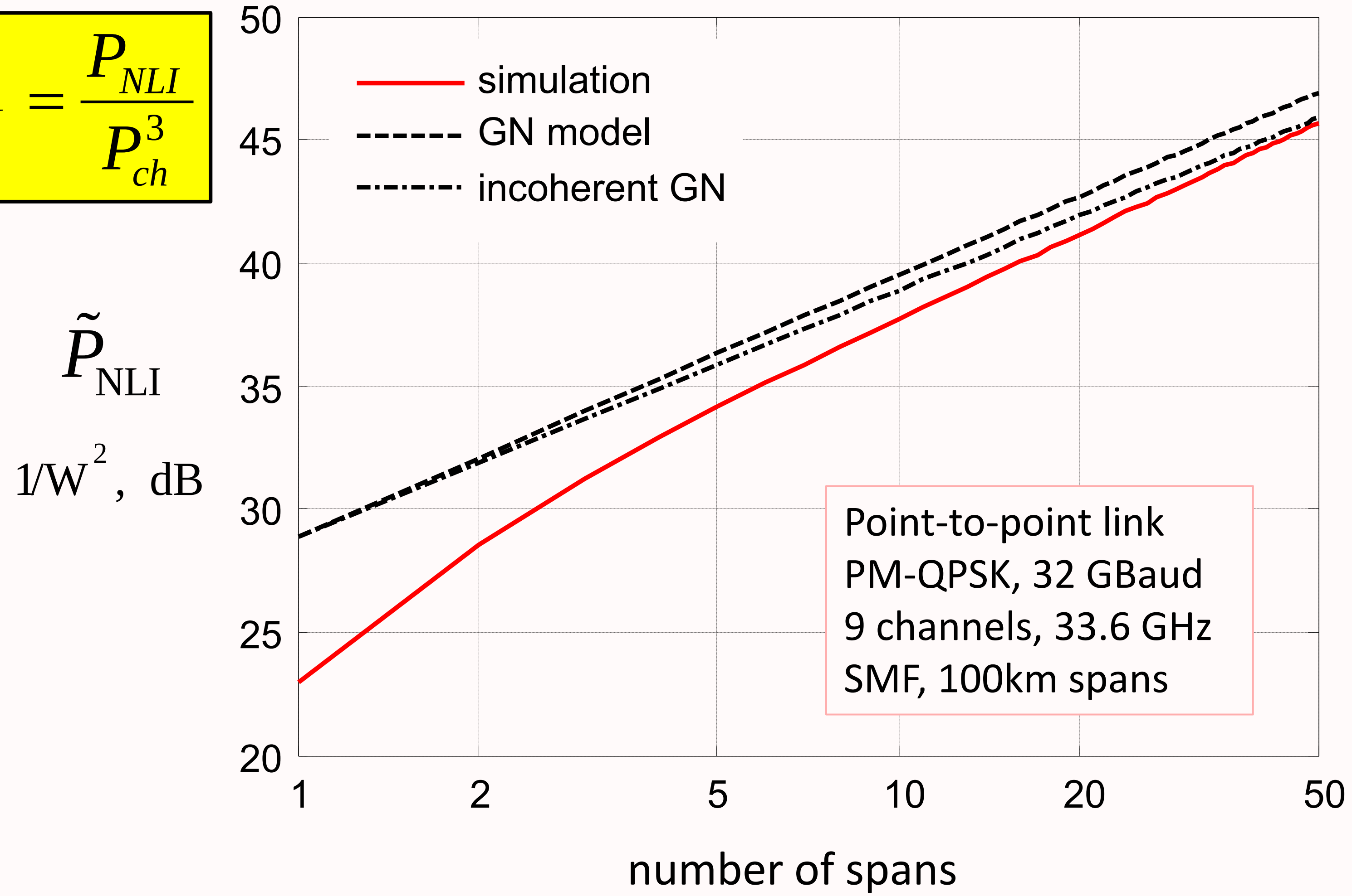
- How to evaluate P_{NLI}?

THE GN-MODEL FAMILY TREE



NLI ACCUMULATION STUDY

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



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.

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.

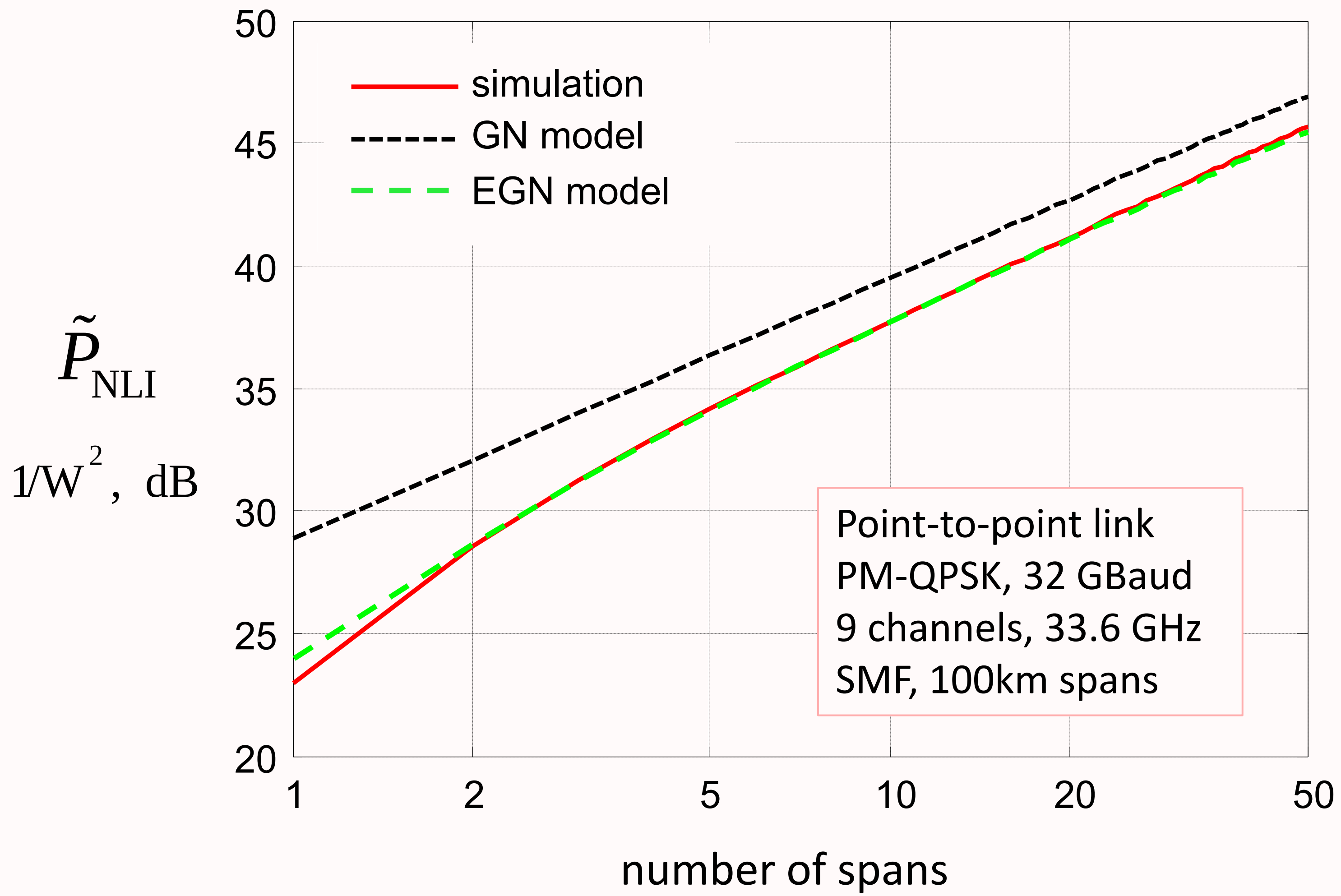
R. Dar, M. Feder, A. Mecozzi, M. Shtaif, *JLT*, vol. 33, p. 1044, 2015

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

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.

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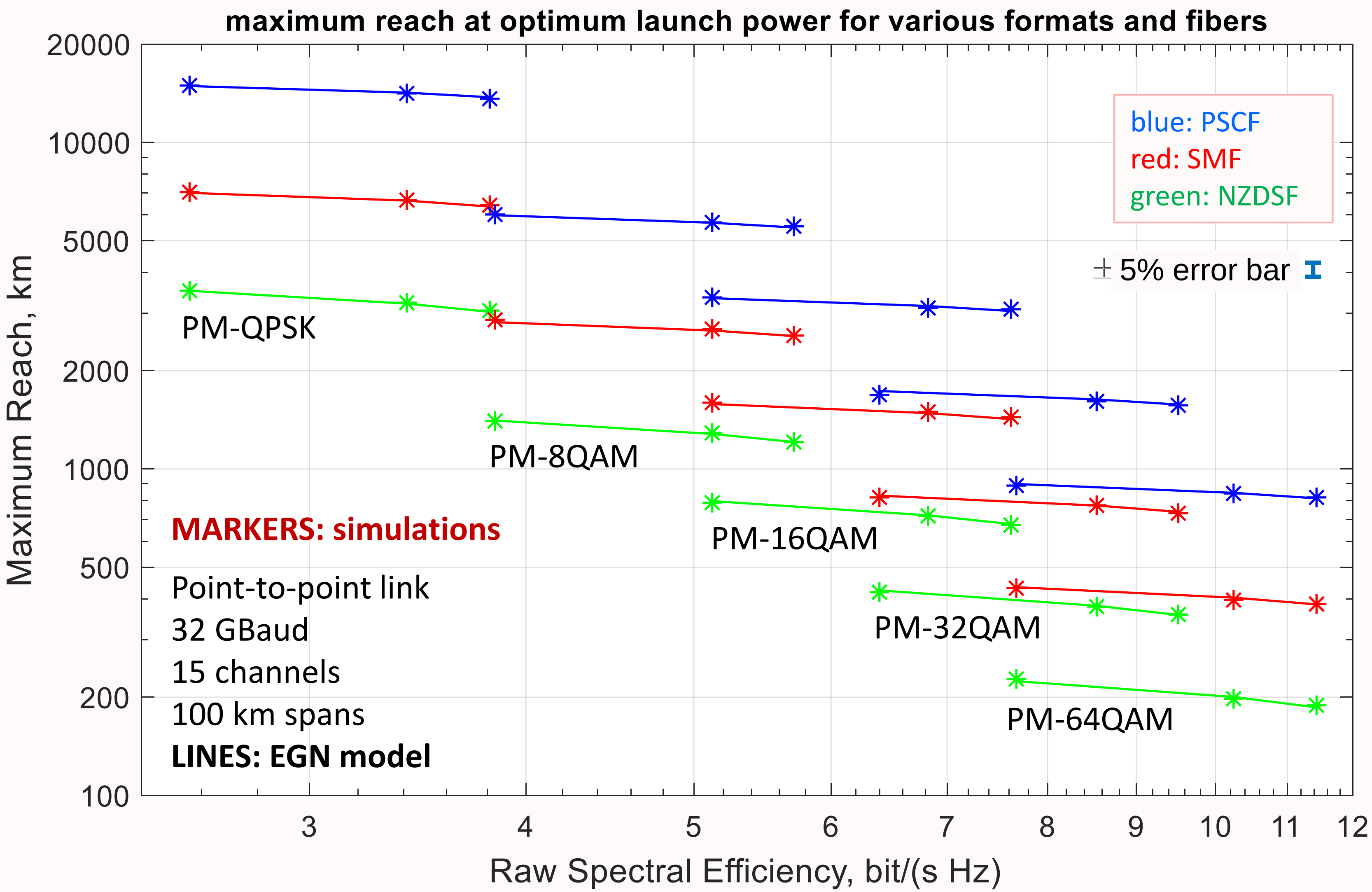
THE BIG PICTURE



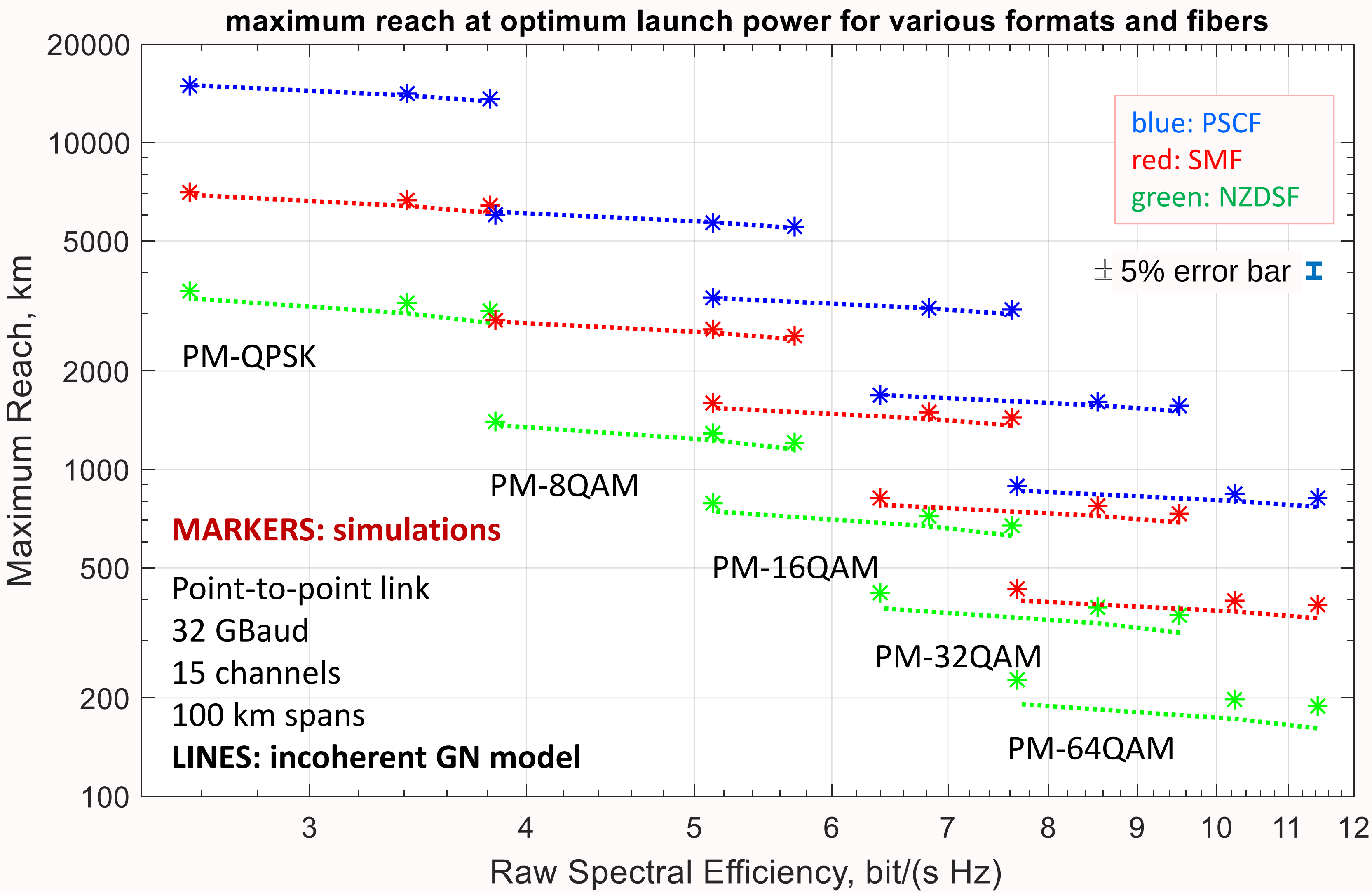
PNLI ERRORS

- How sensitive is OSNR, to NLI estimation errors?

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

- 0.5dB NLI error → 4% OSNR error
- 1.0 dB NLI error → 8% OSNR error
- 2.0 dB NLI error → 17% OSNR error

THE BIG PICTURE



NETWORK PERFORMANCE ANALYSIS

- Application of NLI modeling to physical layer aware network performance analysis
- Comparison of the impact of different models through the Statistical Network Assessment Process (SNAP)

M. Cantono, R. Gaudino, V. Curri, “Data-Rate figure of merit for physical layer in fixed-grid reconfigurable optical networks,” Proc. OFC 2016, paper Tu.3.F.3

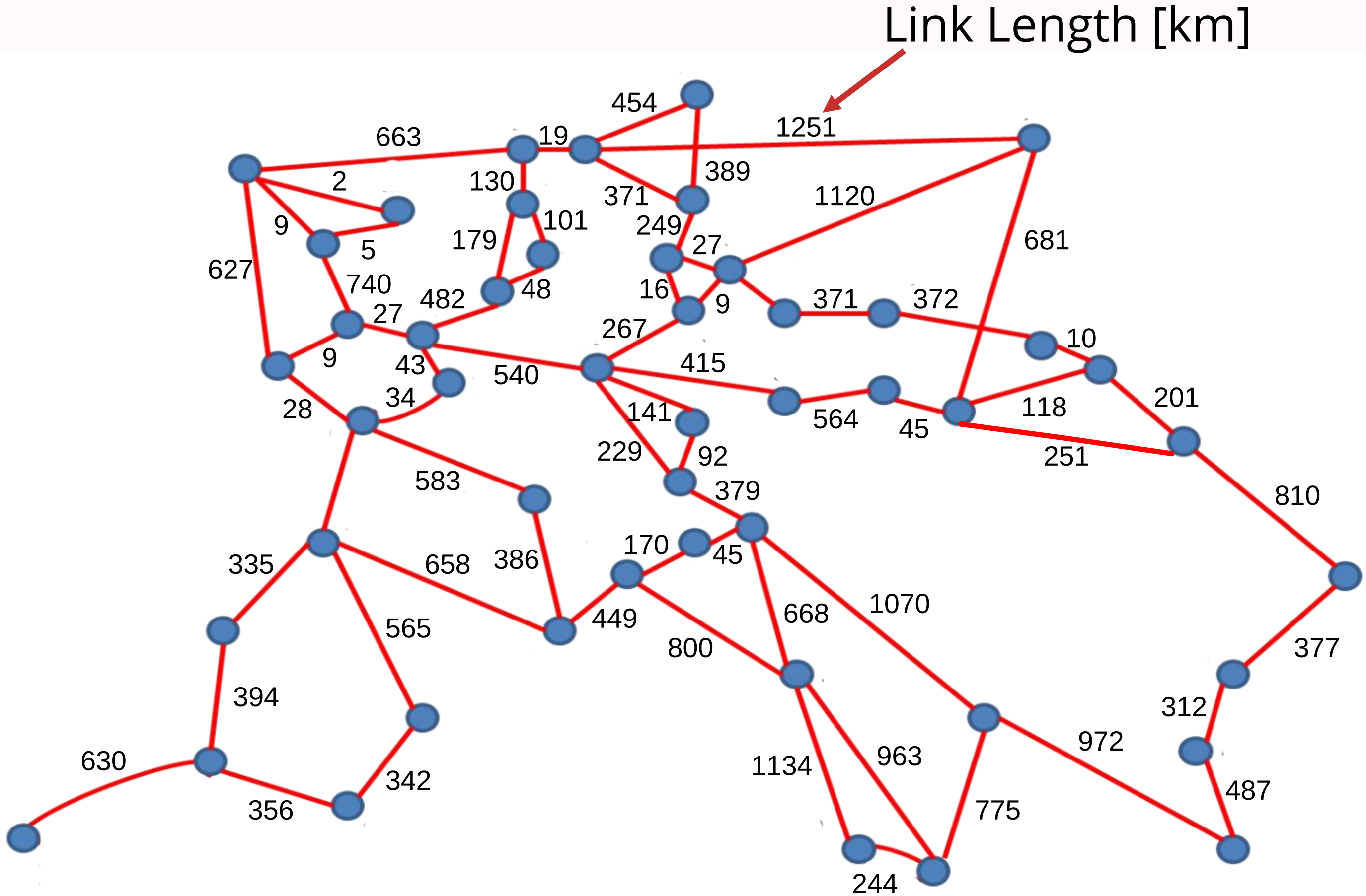
ECOC 2016 PAPERS

V. Curri, “Elastic all-optical networks: a new paradigm enabled by physical layer. How to optimize networks performances,” Proc. ECOC 2016, paper Tu.2.B.5.

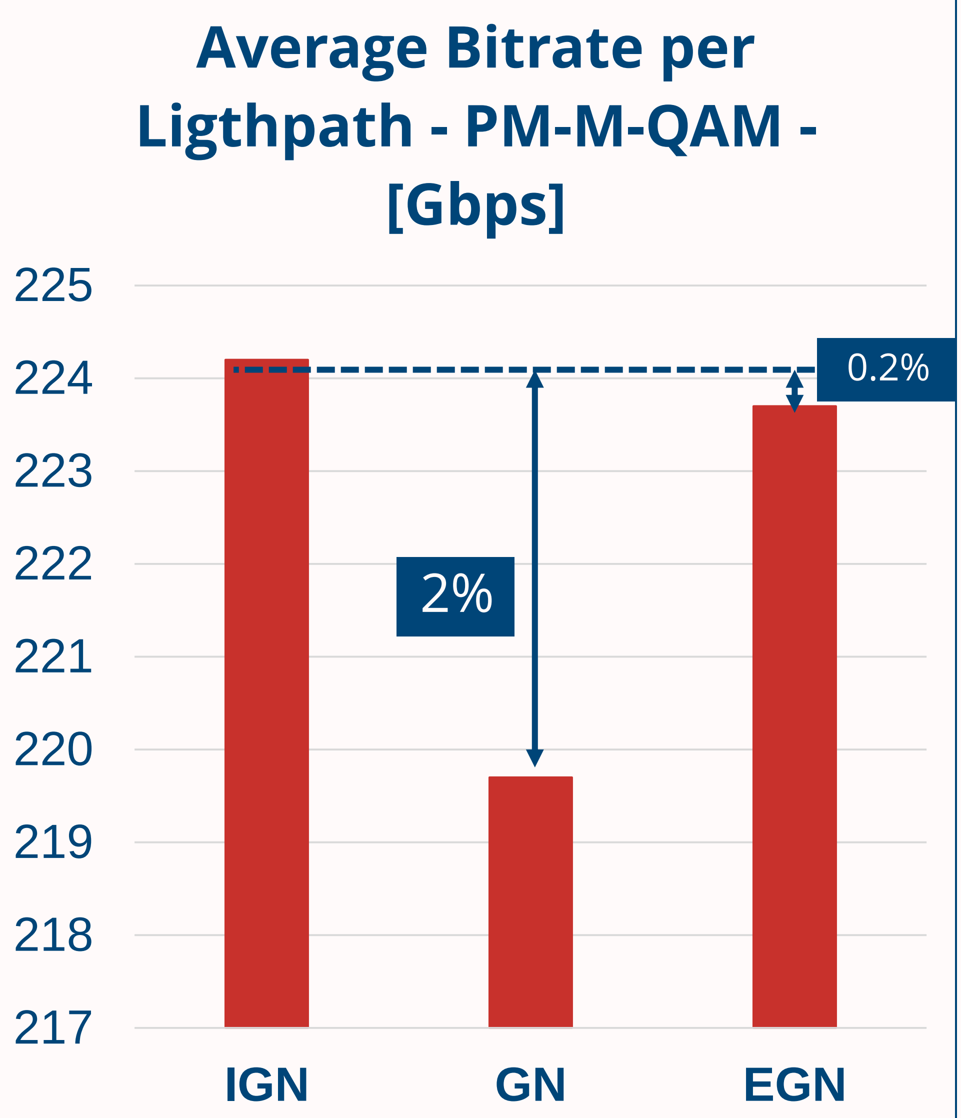
M. Cantono, R. gaudino, P. Poggiolini, V. Curri, “Comparing networking benefits of digital back-propagation vs. lightpath regeneration,” Proc. ECOC 2016, paper Tu.3.D.4.

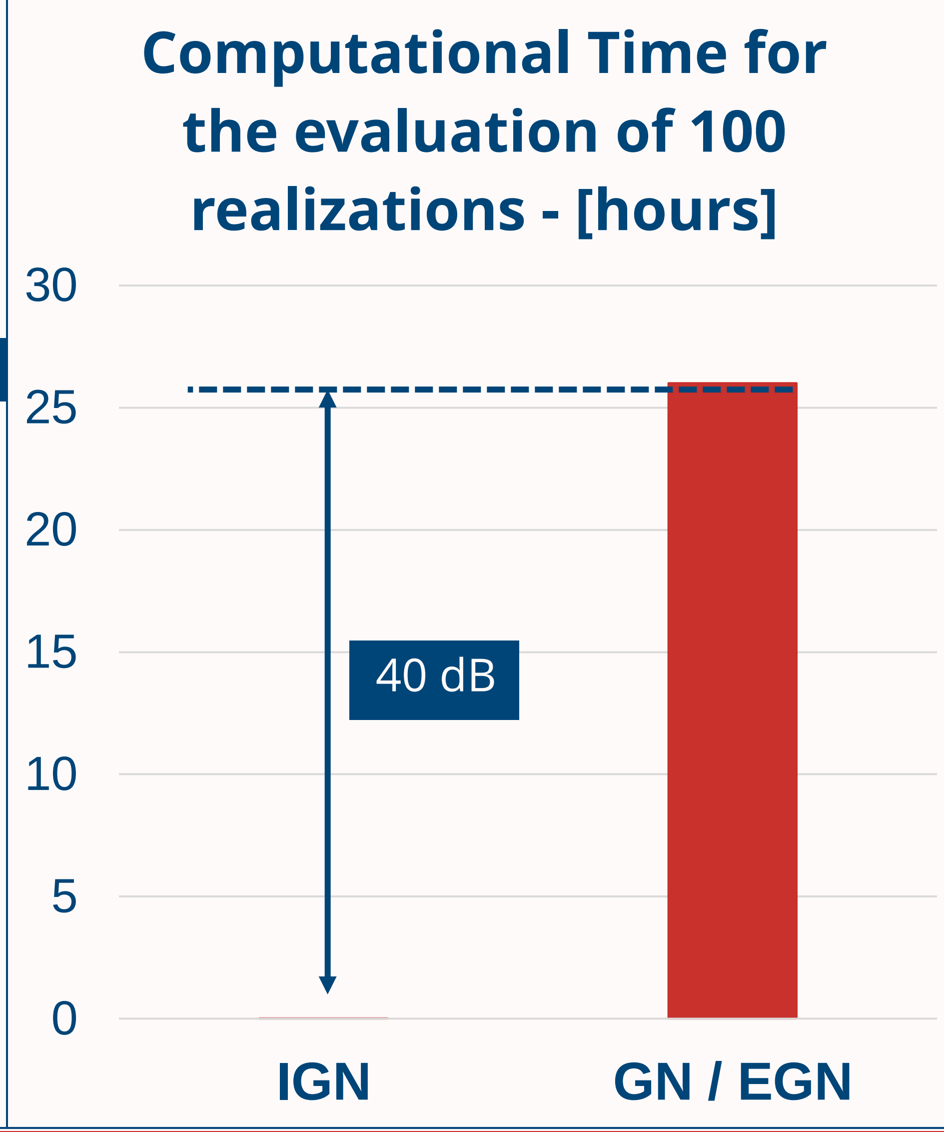
SCENARIO – PAN EUROPEAN TOPOLOGY

- 49 Nodes
- 68 Bidirectional Links
- Standard Single Mode Fiber (SSMF)
  - α_{dB}=0.2 dB/km
  - A_{eff} = 80 um^2
  - n_2=2.50E-20 m^2/W
  - γ = 1.27 1/W/km
  - D = 16.7 ps/nm/km
- Node Loss = 10 dB
- 80 DWDM channels at 32 GBaud gross (25GBaud net) symbol rate

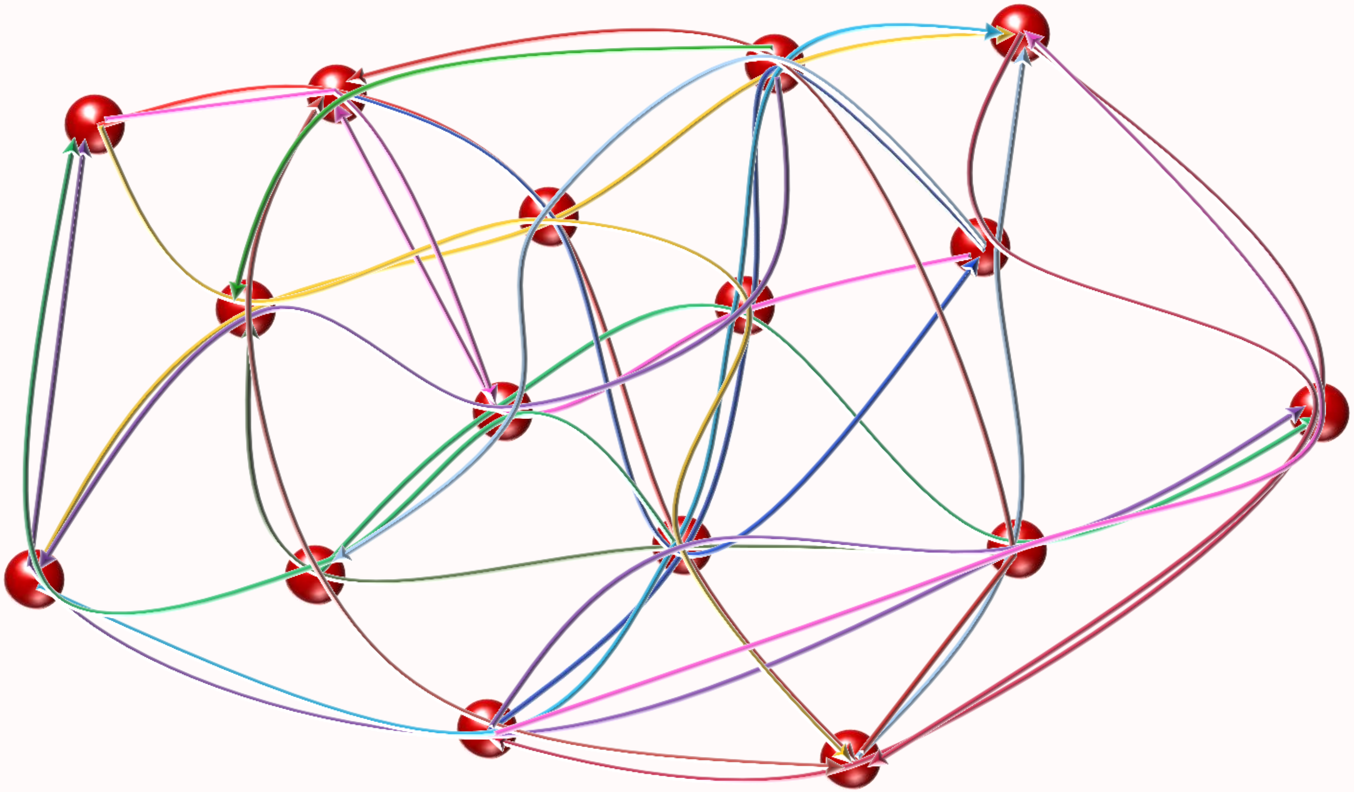


SYSTEM RESULTS – NLI MODELING



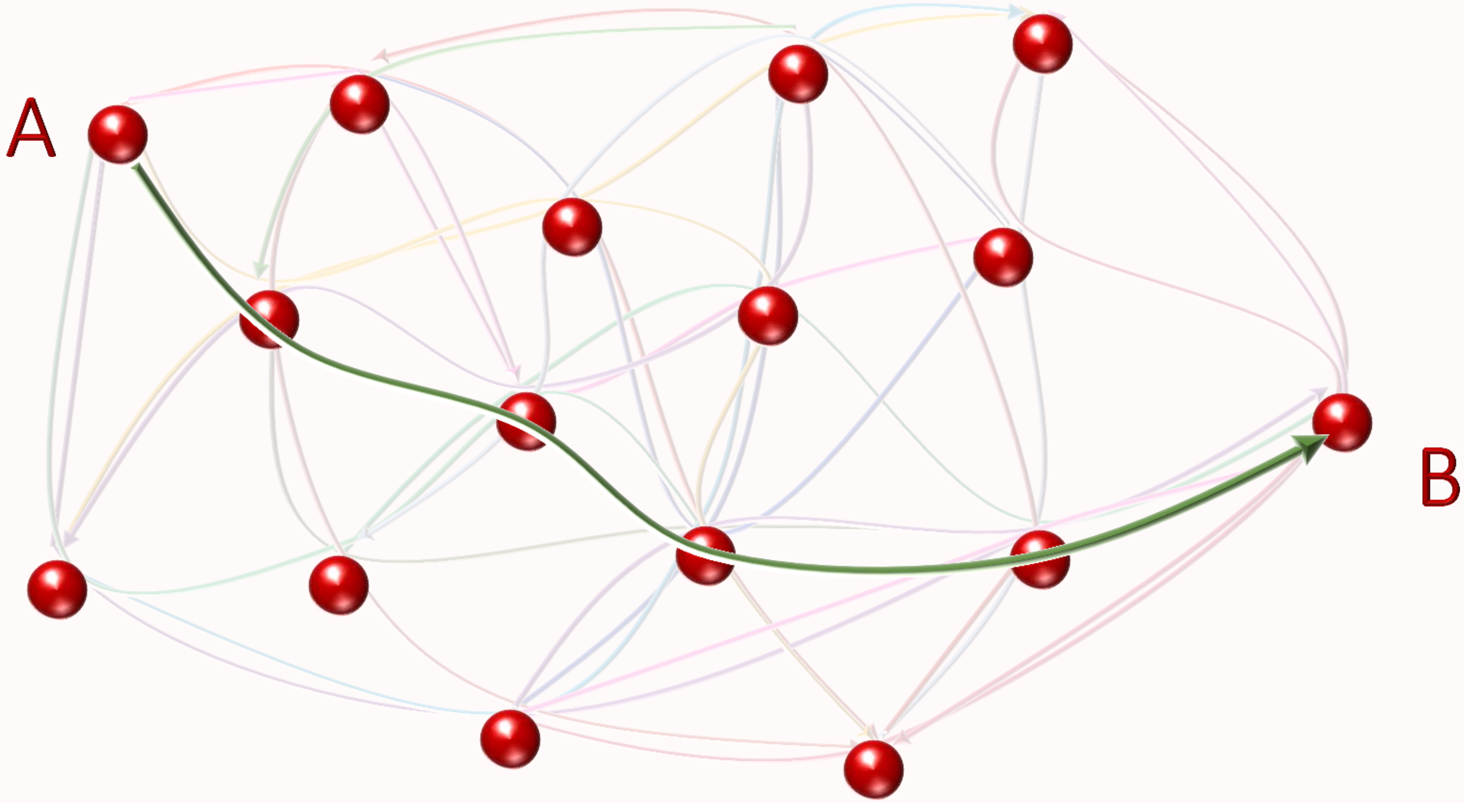


DYNAMIC NETWORK OPERATION



- Is real-time physical-layer awareness possible in a **highly-dynamic reconfigurable** network?

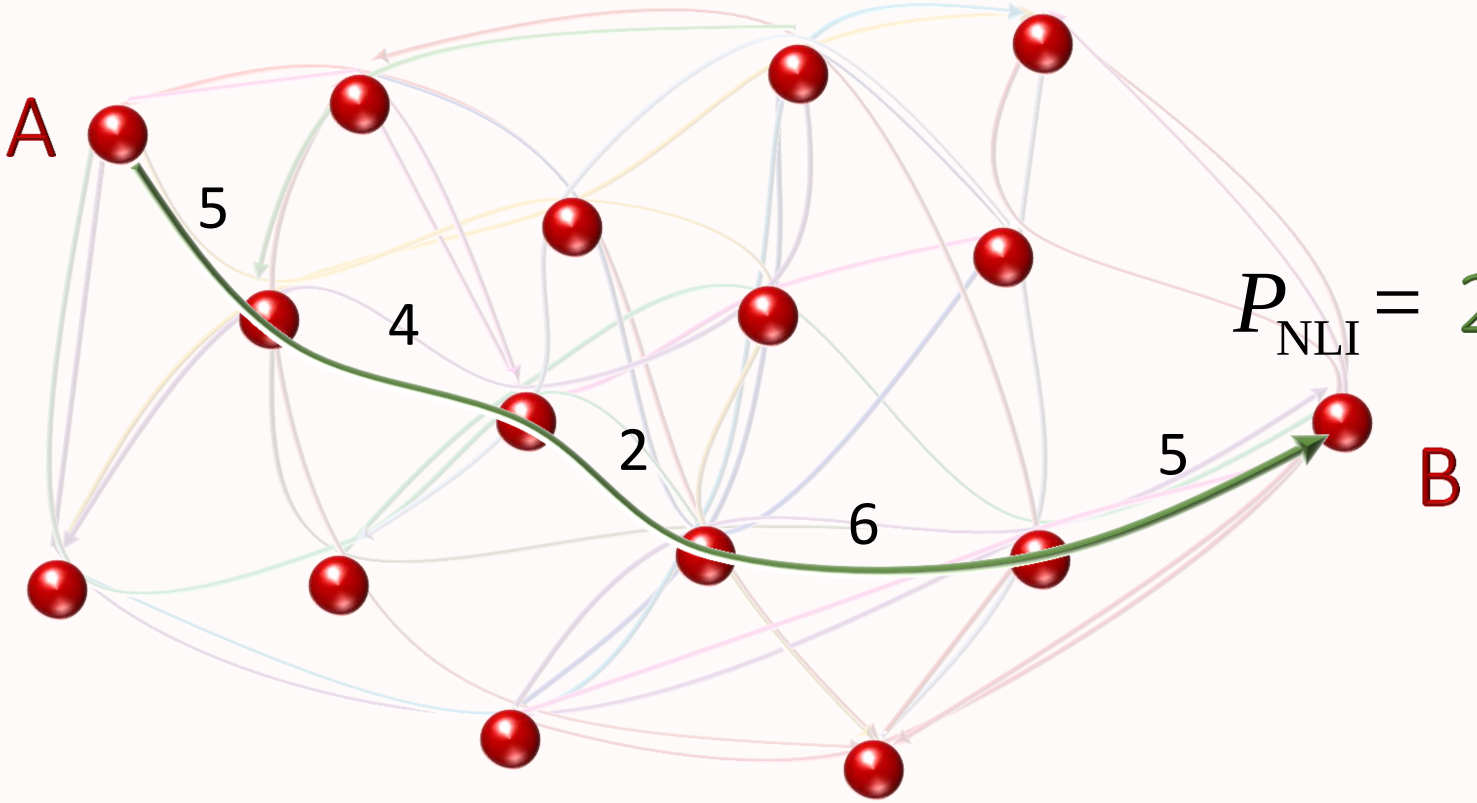
SETTING UP A LIGHTPATH



KEEP IT SIMPLE

- First, you want a model that does not need too many information
- Second, you want a model that is “additive” in non-linear degradation
  - You want that total non-linear degradation is simply the sum of those of each span
- The **incoherent GN model** is the candidate
  - It also satisfy speed and accuracy requirements

THE INCOHERENT ADAVANTAGE



$P_{\mathrm{NLI}} = 22$

THE LINK CALCULATOR

- Closed-form approximate formula for NLI of the n-th span
- Different symbol rate and launch power in each channel
- Uneven channel spacing
- Assuming incoherent noise accumulation
- With some further minor approximations

$$G_{\mathrm{NLI}}(f_{\mathrm{ch},i}) = \frac{16}{27}\gamma_{n_s}^2 L_{\mathrm{eff},n_s}^2 \cdot \sum_{n=1}^{N_{\mathrm{ch}}} G_{\mathrm{ch},n} G_{\mathrm{ch},n} G_{\mathrm{ch},i} \cdot (2-\delta_{ni})\psi_{n,i}$$

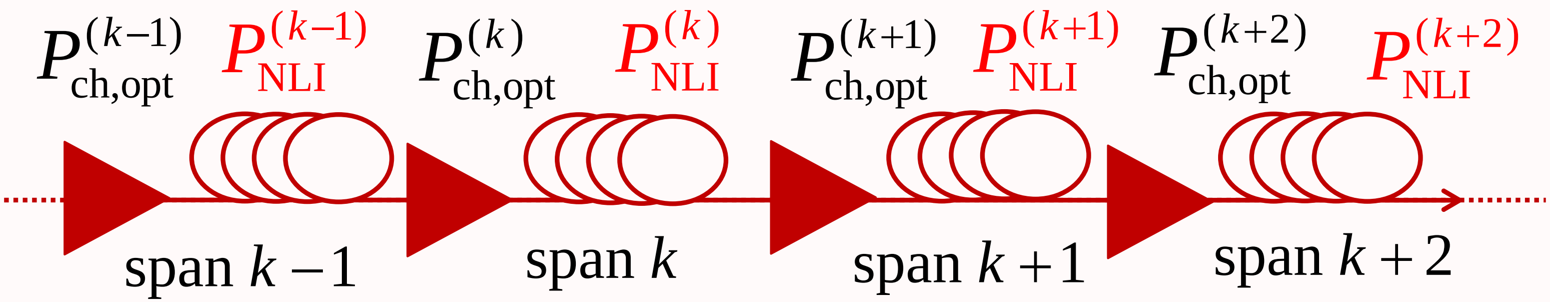
$$\psi_{n,i} \approx \frac{\operatorname{asinh}\left(\pi^2(2\alpha)^{-1}|\beta_2|\left[f_{\mathrm{ch},n}-f_{\mathrm{ch},i}+B_{\mathrm{ch},n}/2\right]B_{\mathrm{ch},i}\right)}{4\pi(2\alpha)^{-1}|\beta_2|} - \frac{\operatorname{asinh}\left(\pi^2(2\alpha)^{-1}|\beta_2|\left[f_{\mathrm{ch},n}-f_{\mathrm{ch},i}-B_{\mathrm{ch},n}/2\right]B_{\mathrm{ch},i}\right)}{4\pi(2\alpha)^{-1}|\beta_2|}, \quad n \neq i$$

$$\psi_{i,i} \approx \frac{\operatorname{asinh}\left(\frac{\pi^2}{2}|\beta_2|[2\alpha]^{-1}B_{\mathrm{ch},i}^2\right)}{2\pi|\beta_2|[2\alpha]^{-1}}$$

One span in matlab: a ms or less…

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. (JLT),* vol. 32, no. 4, pp. 694-721, Feb. 2014.

Local Optimization – Global Optimization



$$\text{OSNR} = \left[\sum_{k=1}^{N_{\text{span}}} \frac{1}{\text{OSNR}_k} \right]^{-1}$$

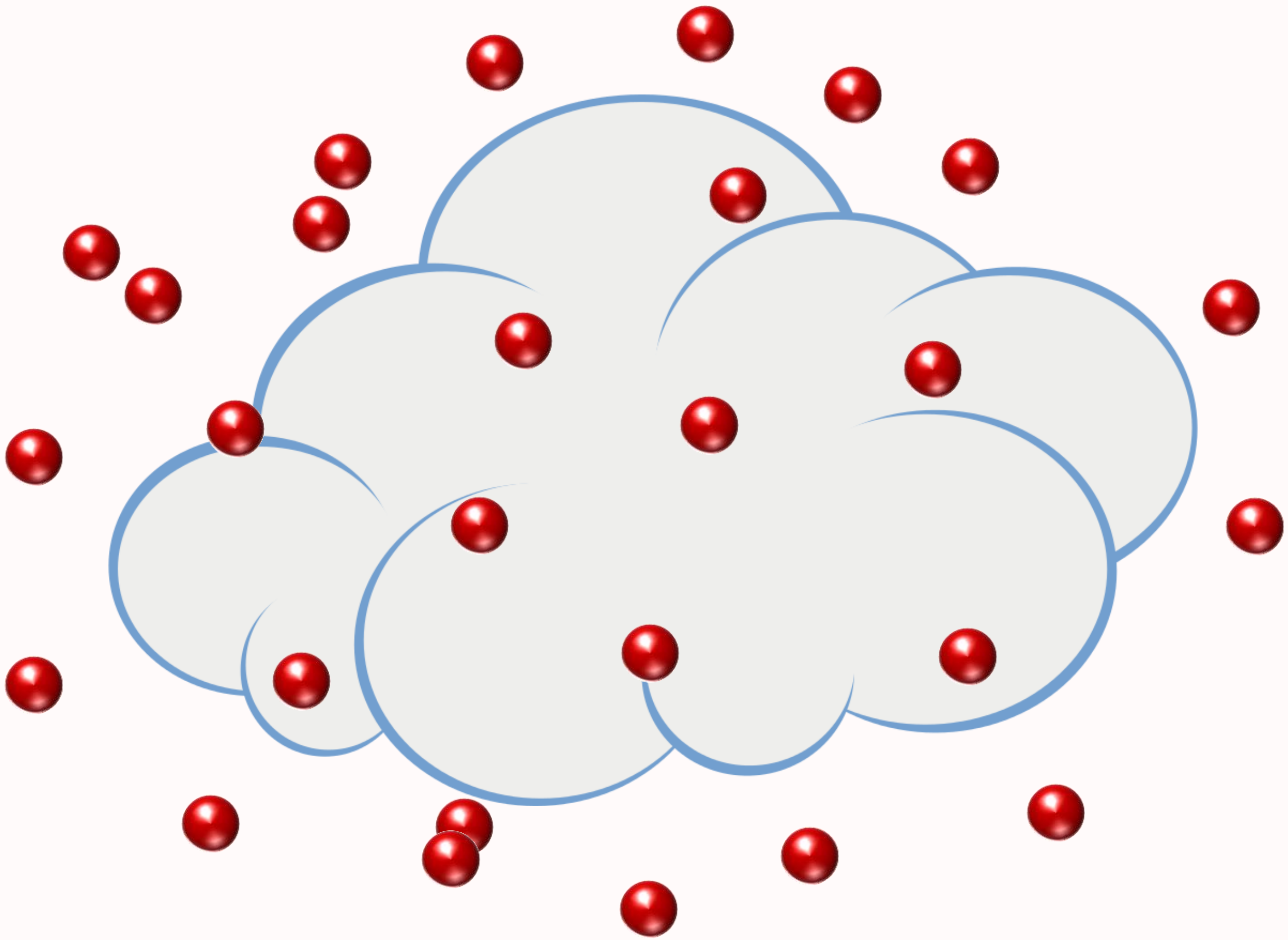
- OSNR_k is due to NLI and ASE produced exclusively in the k-th span
- Maximizing each OSNR_k will maximize the overall OSNR
- $P_{\text{ch,opt}}$ can be optimized on span per span basis

P. Poggiolini, G. Bosco, A. Carena, R. Cigliutti, V. Curri, F. Forghieri, R. Pastorelli, S. Piciaccia, "The LOGON strategy for low-complexity control plane implementation in new generation flexble networks," Proc. OFC 2013, paper OW1H.3.

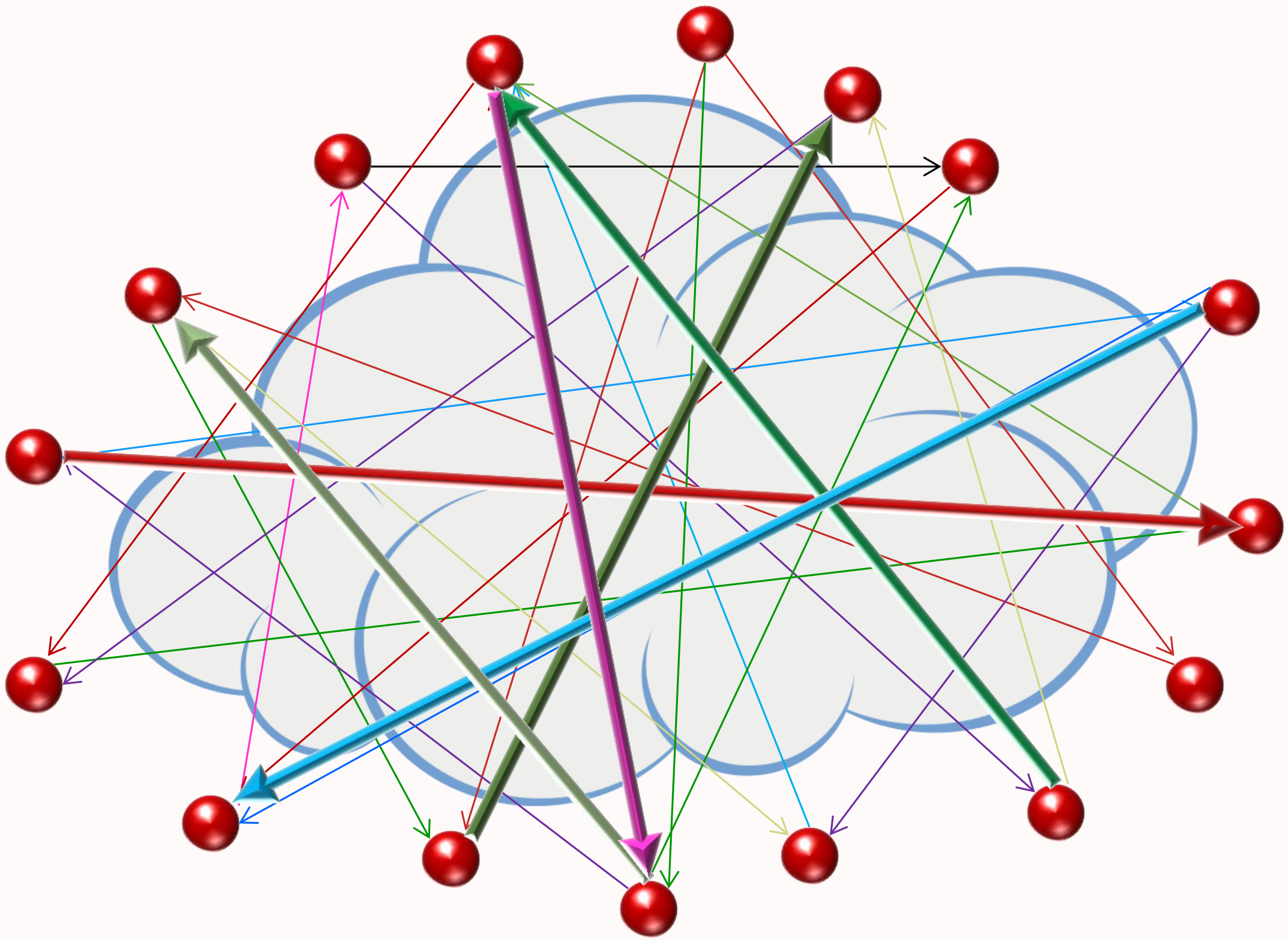
SUPER-OPTIMIZATION

- The simple incoherent GN model helps but is not enough…
- Assume you have super-optimized your network, but it’s a dynamic network and you want to create a new lightpath
  - There are chances that the new lightpath is going to disrupt pre-existing lightpaths

A SOLUTION: THE OPTICAL ETHER

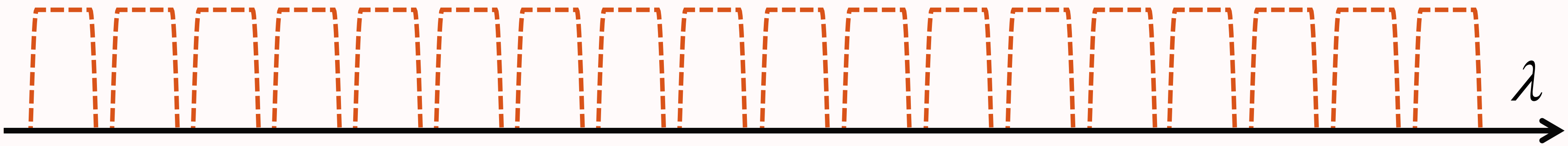


THE OPTICAL ETHER



ENSURING THE OPTICAL ETHER

- It can be done like this:
  - Assume that the whole C-band is fully saturated at all times

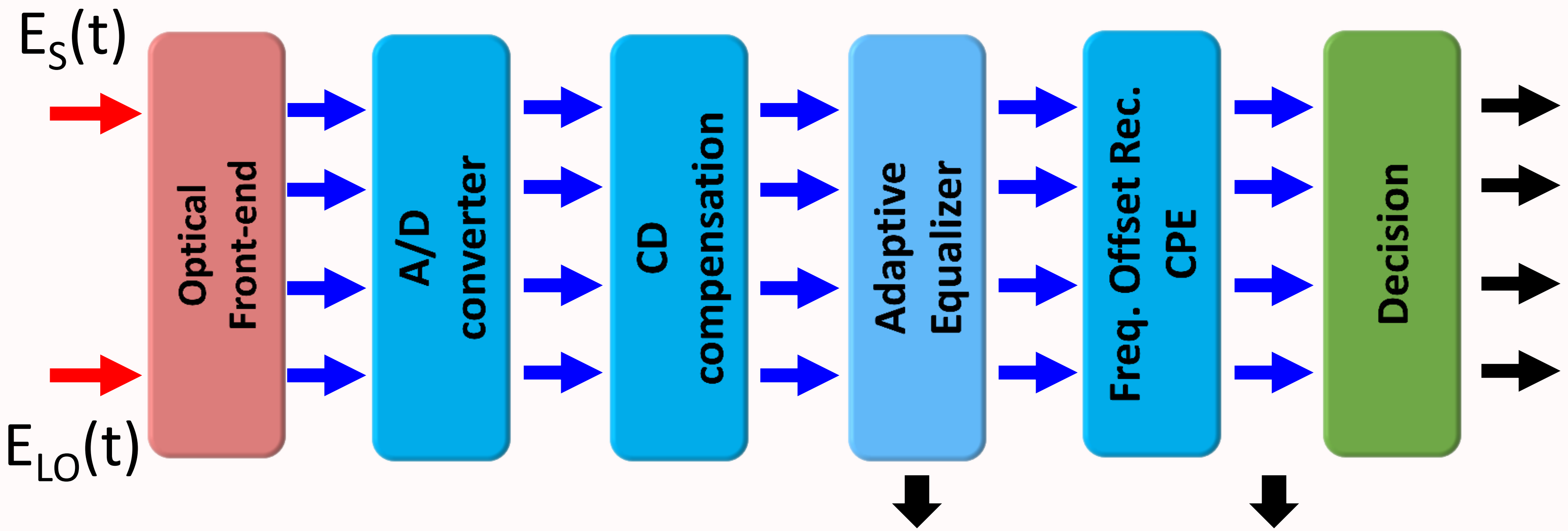


  - The model formulas tell us the optimum launch power $P_{\mathrm{ch,opt}}$ into each span (uniform) as if all channels were there
  - The model also calculates P_{NLI} as if all channels were really there!
  - Both P_{NLI} and $P_{\mathrm{ch,opt}}$ can be pre-computed once and for all
  - All routing and regeneration decision are made as if all channels were already lit and non-linearity was the maximum possible
- DRAWBACK: you won't squeeze all the potential throughput out of the network
- ADVANTAGE: you achieve maximum flexibility

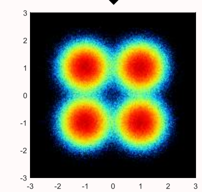
MONITORING

DSP ENABLES MONITORING

- DSP algorithms provide intrinsic monitor functionality



$$\mathbf{W}(n) = \begin{bmatrix} w_{xx}(n) & w_{xy}(n) \\ w_{yx}(n) & w_{yy}(n) \end{bmatrix}$$

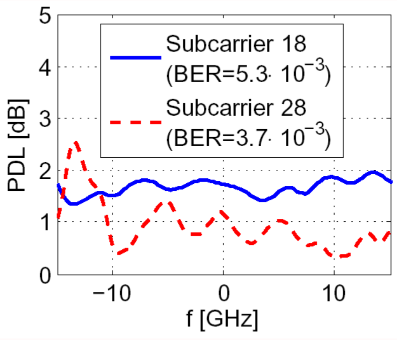


LINK MONITORING

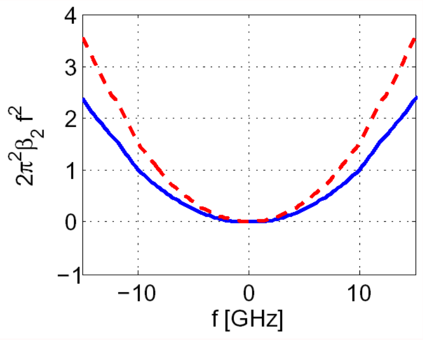
$$\mathbf{W}(f) = H(f) \cdot e^{+j2\pi^2\beta_2 f^2}\mathbf{U}(f)\mathbf{P}(f)$$

- **P** is a Hermitian matrix accounting for the inverse channel PDL
- **U** is a unitary matrix accounting for the inverse channel DGD
- The exponential scalar factor is the inverse CD
- H(f) is approximately the inverse of the electro-optical system scalar transfer function

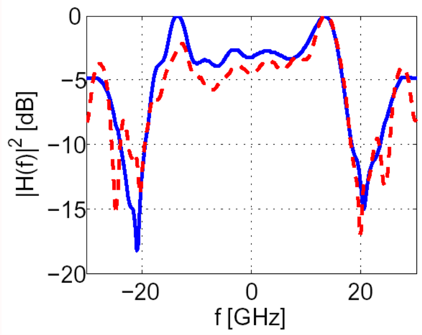
PDL



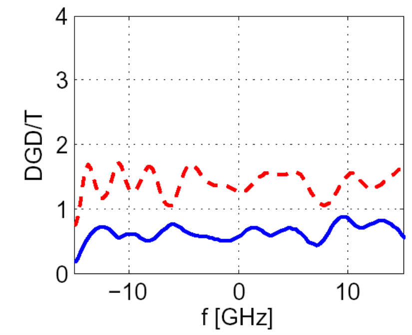
Residual CD



H(f)



DGD



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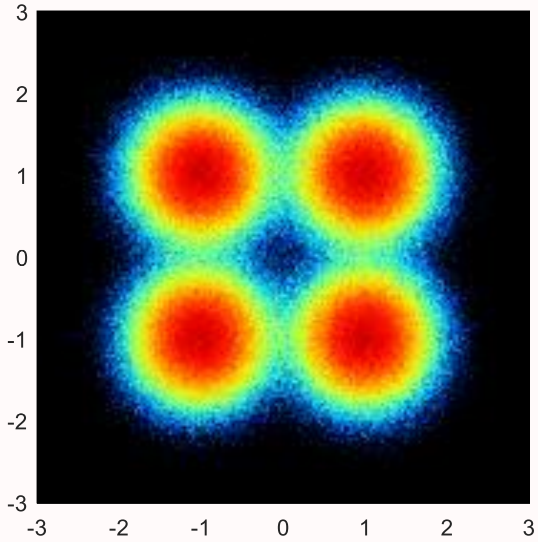
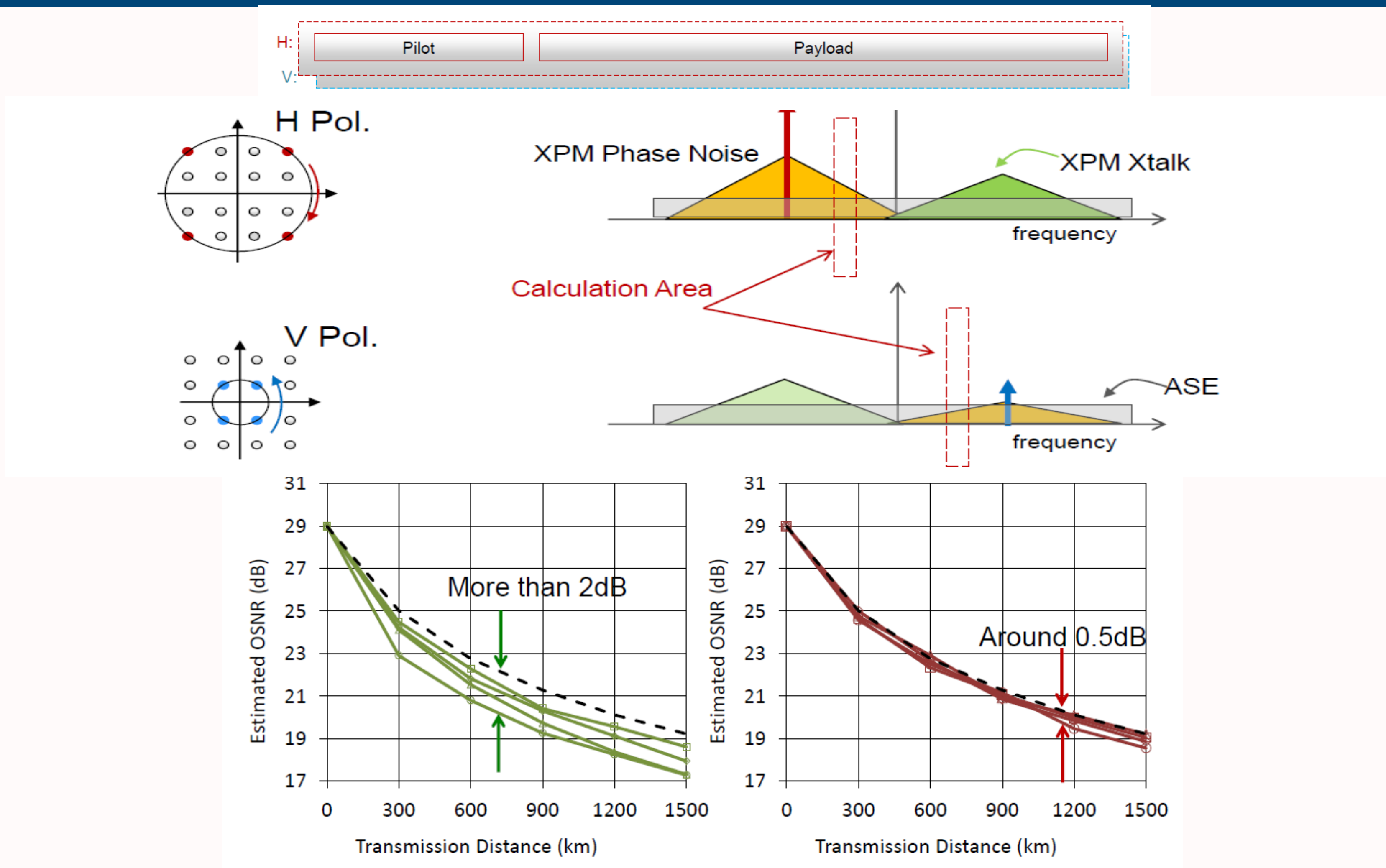
OSNR MONITORING



- The presence of NLI lead to under-estimation of OSNR
  - Both intra-channel and inter-channel noise has similar spectral property as ASE

- «Real» OSNR (due to ASE only) is important
  - To monitor the nonlinear noise degradation on current system

PILOT AIDED OSNR MONITOR



T. Yamauchi, S. Oda, L. Dou, X. Su, T. Hoshida, Y. Aoki, Z. Tao, J. C. Rasmussen, "OSNR System Margin Estimation by Nonlinear Noise Insensitive OSNR Monitor," Proc. ECOC 2016, paper Tu.2.C.1.

CONCLUSIONS

- MODELING
  - **Incoherent GN-model** should be the choice in “networking”
    - Both for performance evaluation and real-time dynamic reconfigurations
  - **LOGO** allow simplified optimization
  - **Optical Ether** can be a solution for dynamic control planes

- MONITORING
  - **Use DSP** to provides monitor functions
  - **Pilot based solutions** can enhance monitoring capabilities

THANK YOU!

andrea.carena@polito.it

Slides will be available at **www.optcom.polito.it**

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