Non-linearity Compensation Limits in Optical Systems with Coherent Receivers

Gabriella Bosco, Andrea Carena, Pierluigi Poggiolini, Vittorio Curri,

Politecnico di Torino

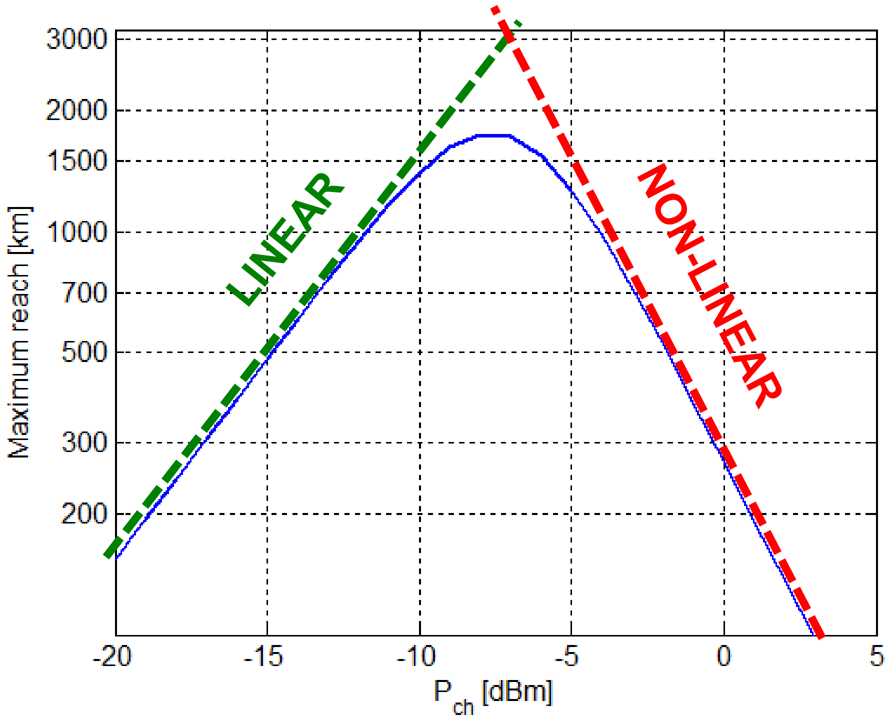
Fabrizio Forghieri

Cisco Photonics Italy

SPPCom 2012 - paper SPW3B6

Motivations

- Coherent detection → almost total compensation of linear transmission impairments with reasonable complexity through Rx DSP
- Main limitation to system reach: fiber nonlinearity



Motivations

- Electronic compensation of non-linear effects → higher computational complexity

Single-wavelength

(frequency range equal to the bandwidth of a single channel)

- Moderate complexity
- Good performance in single-channel transmission
- Low gain in WDM scenarios

WDM

(larger non-linearity compensation bandwidth B_{NLC})

- High complexity
- Potentially good performance also in WDM scenarios

Motivations

- Goal: to assess the ultimate limitations of electronic compensation of non-linear effects in a WDM scenario

- Tool: analytical model for nonlinear propagation in uncompensated optical systems with coherent detection
  (P. Poggiolini et al., PTL, vol. 23, pp.742-744,2011)

Analytical model

- The model is based on the hypothesis that the system BER can be directly derived from the equivalent non-linear OSNR:

$$OSNR_{eq} = \frac{P_{Tx}}{P_{ASE} + P_{NLI}}$$

$$P_{ASE} = N_{span}\left(A_{span} F h \nu\right) B_n$$

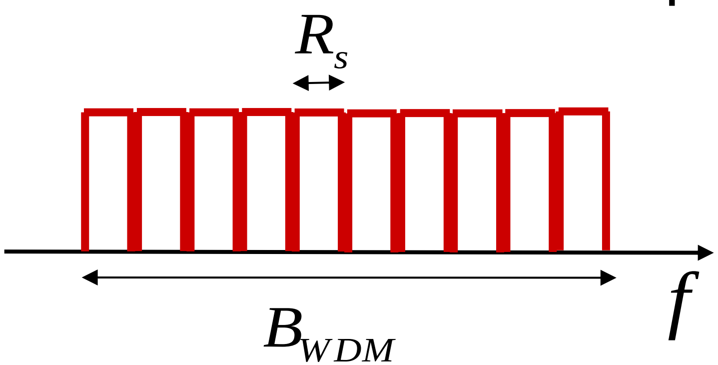
$$P_{NLI} = N_{span}\left(\eta_{NLI} P_{Tx}^3\right) B_n$$

- P_{Tx} is the launch power per channel
- P_{ASE} is the power of ASE noise introduced by optical amplifiers
- P_{NLI} is the power of nonlinear interference accumulated along the link

- N_{span} is the number of fiber spans and A_{span} is the total span loss
- F is the optical amplifier noise figure
- h is Planck's constant and v is the operation frequency
- B_n is the equivalent noise bandwidth over which the OSNR is evaluated

An analytical expression for η_{NLI}

- η_{NLI} is a non-linearity coefficient which depends on fiber characteristics, number of channels and frequency spacing
- At the Nyquist limit



the power of the non-linear interference (and consequently the value of η_{NLI}) can be analytically evaluated:

$$\eta_{NLI} \approx \left(\frac{2}{3}\right)^3 \gamma^2 L_{eff} \frac{\ln\left(\pi^2 |\beta_2| L_{eff} B_{WDM}^2\right)}{\pi |\beta_2| R_s^3}$$

$$B_{WDM} = N_{ch} \Delta f \qquad L_{eff} = \frac{1 - e^{-2\alpha L_s}}{2\alpha}$$

- β_2 = dispersion coefficient
- γ = non-linearity coeff.
- L_{eff} = fiber effective length
- α = loss coefficient

System set-up

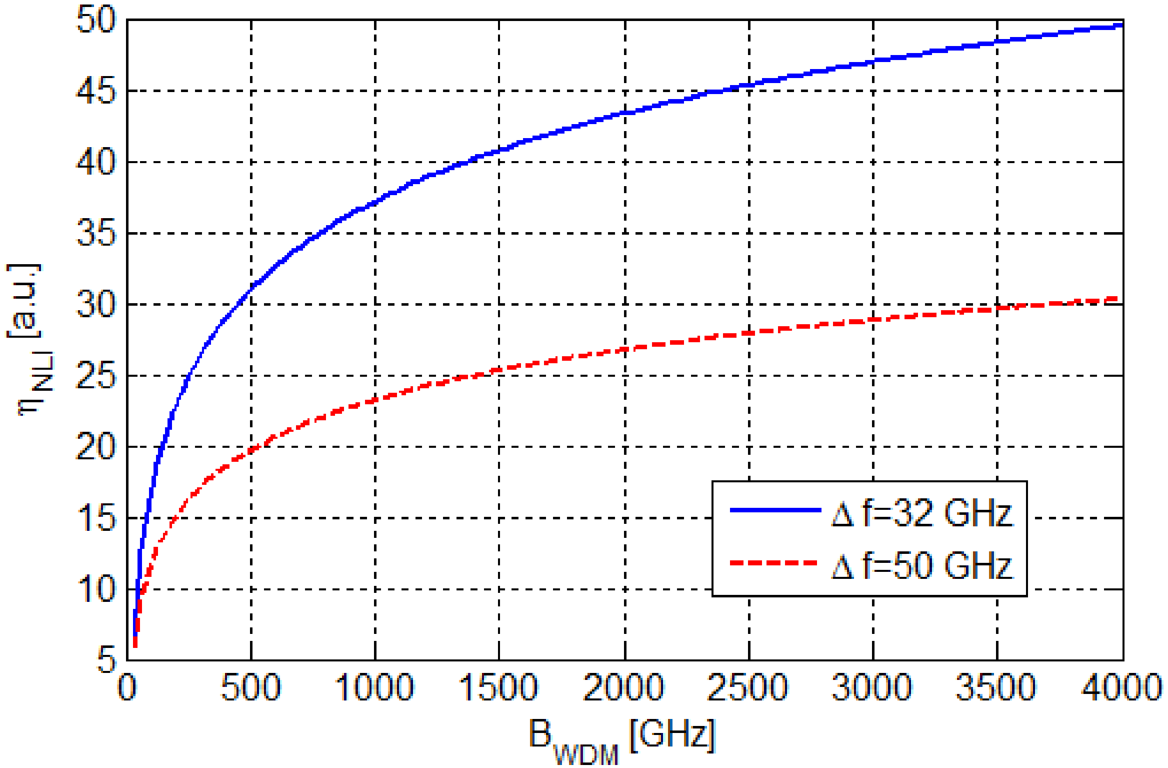
- WDM system based on 32-Gbaud sub-channels
  (the following analysis is independent of the modulation format)

- Fiber parameters (SSMF):
  - L_{span}= 100 km
  - D = 16.7 ps/nm/km
  - α = 0.22 dB/km
  - γ = 1.3 1/W/km

- Two different setups have been analyzed:
  - standard spacing Δf = 50 GHz
  - tight Nyquist spacing equal to symbol rate, i.e. 32 GHz.

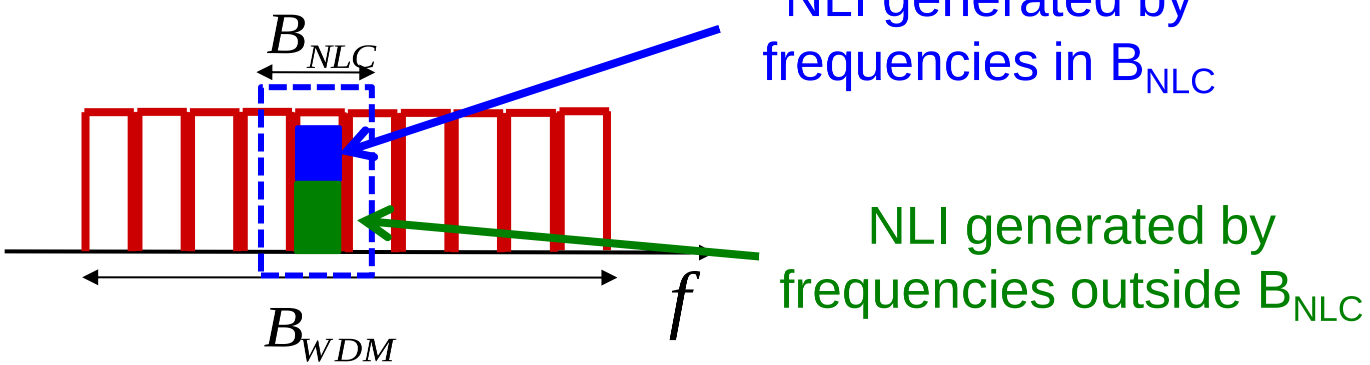
η_{NLI} vs. B_{WDM}

- Using the analytical model, it is possible to obtain the following plots for the increase of the amount of η_{NLI} falling on the center channel vs. the bandwidth of the WDM comb:



Hypotheses

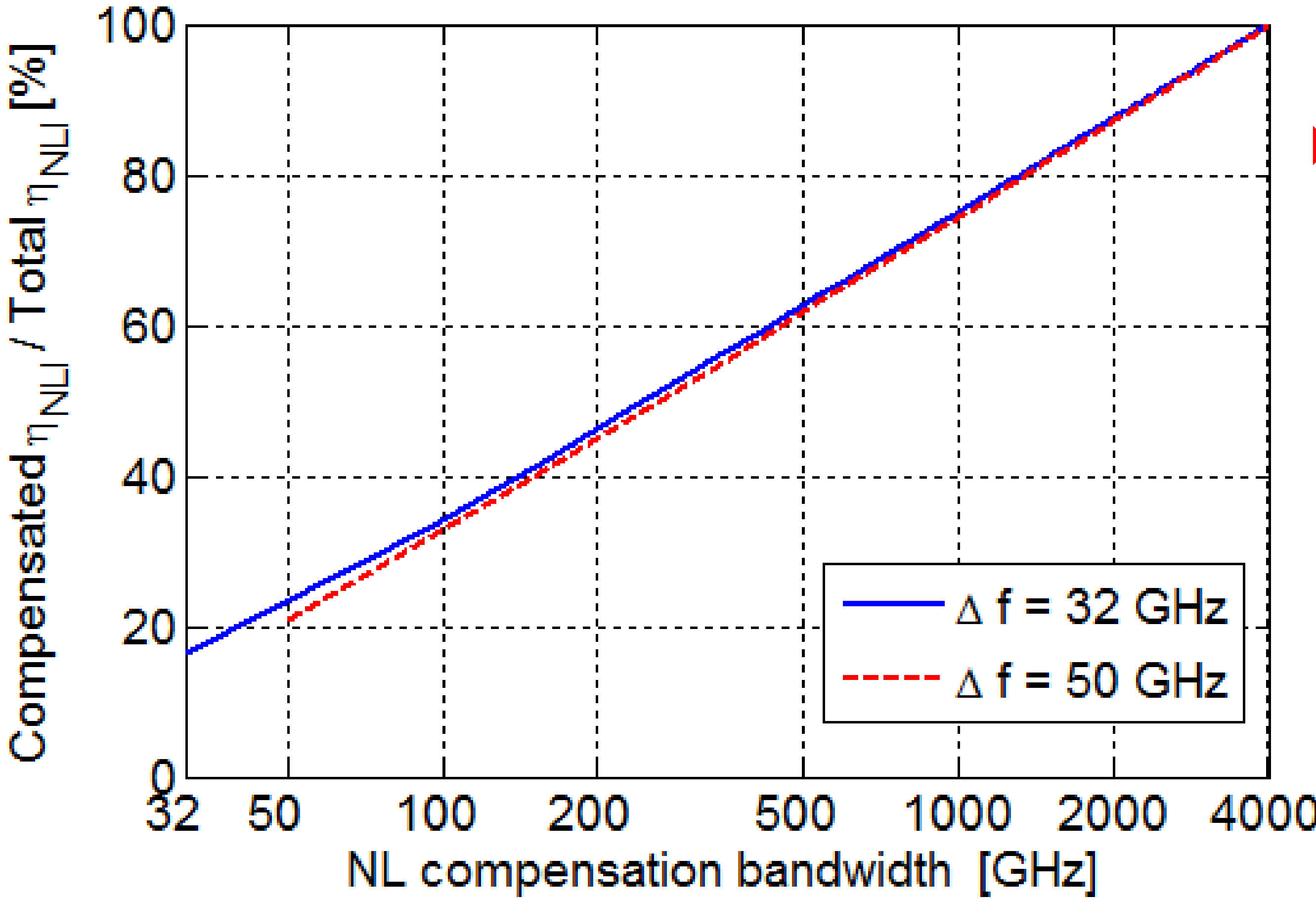
- The compensation algorithm used at the Rx is applied over a bandwidth B_{NLC}, which is a portion of the total bandwidth B_{WDM} of the WDM comb.



- The compensation algorithm is able to completely cancel the amount of η_{NLI} generated by the WDM signal components falling inside B_{NLC}.
- The amount of non-linear noise is thus reduced, with a consequent potential gain in terms of optimum launch power, span budget and maximum reach.

Percentage of NL compensation

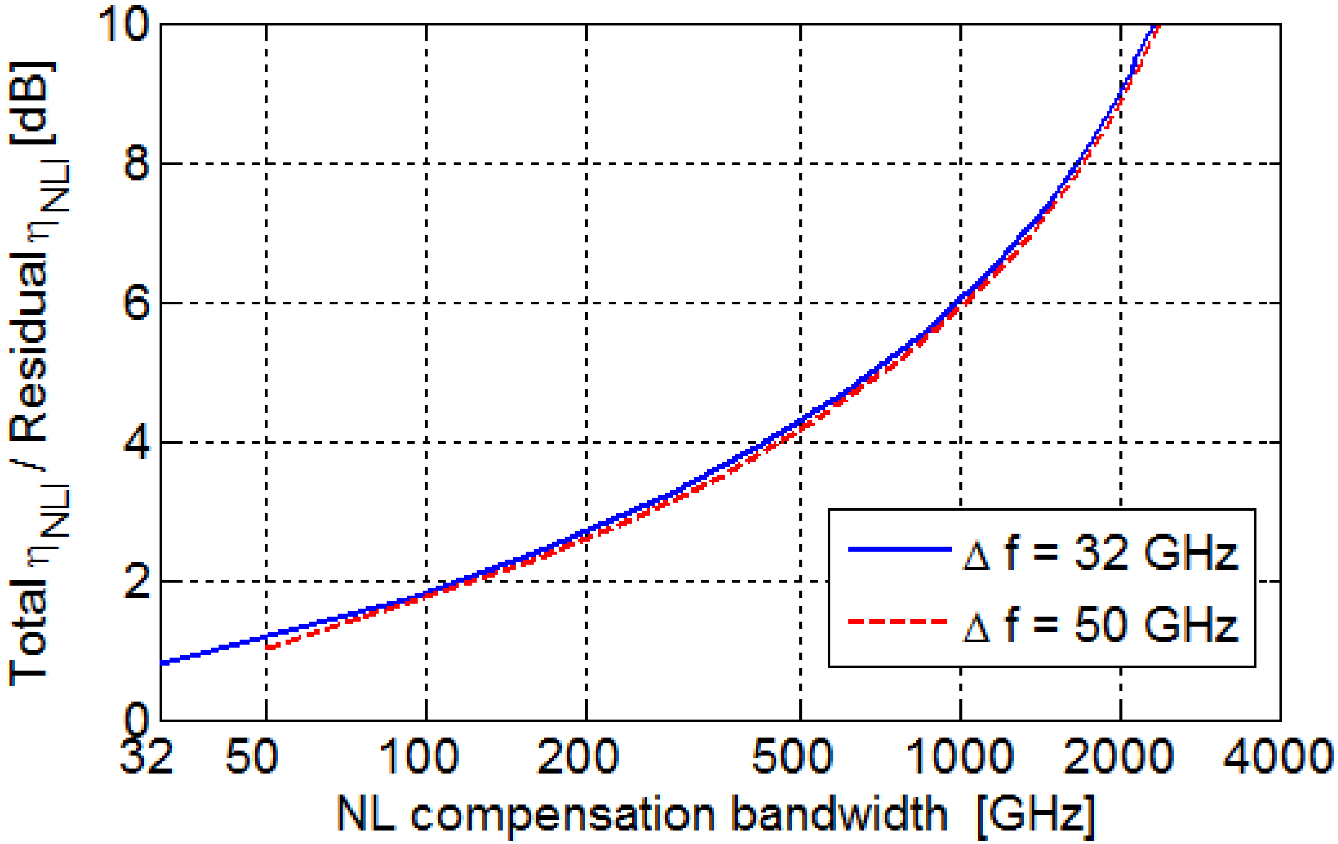
- Percentage of non-linearity compensation, i.e. ratio between the η_{NLI} compensated for at the Rx and the total η_{NLI} produced by the whole WDM comb:



- B_{WDM}=4 THz

Gain in η_{NLI}

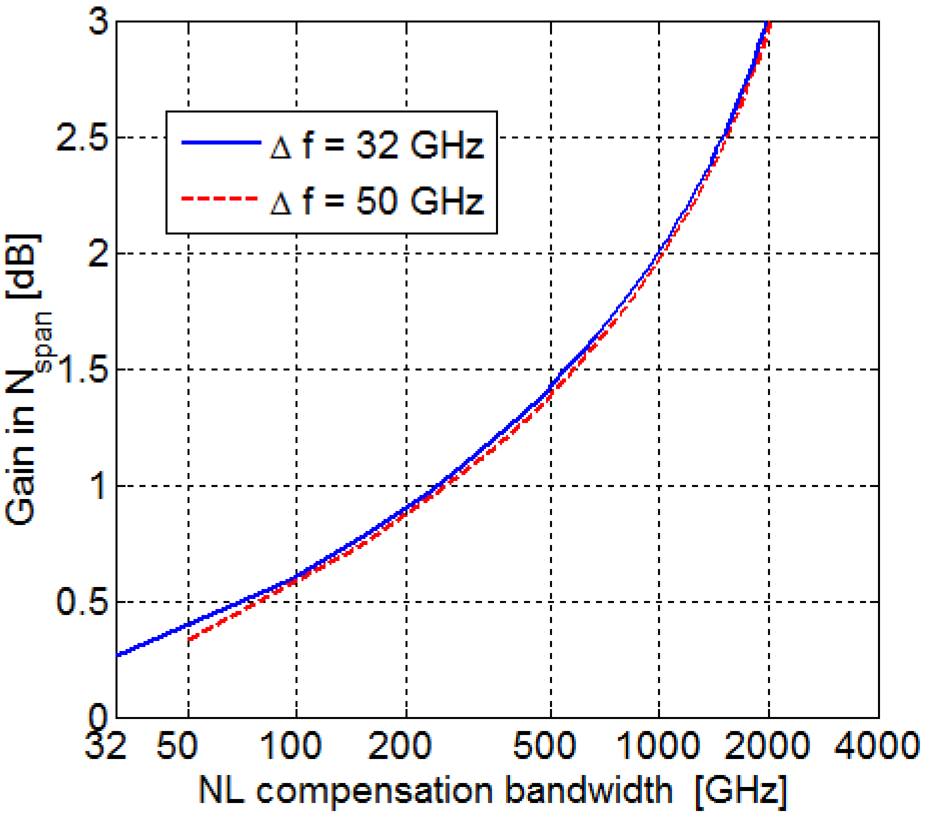
- The gain in η_{NLI} is defined as the ratio between the total η_{NLI} and the residual η_{NLI} after compensation:



Gain in maximum reach

- Fixing the span budget A_{span} and the value of reference BER (i.e. reference $OSNR_{eq}$), the relationship between the maximum distance (corresponding to the optimum launch power) and the value of η_{NLI} can be analytically evaluated at the Nyquist limit:

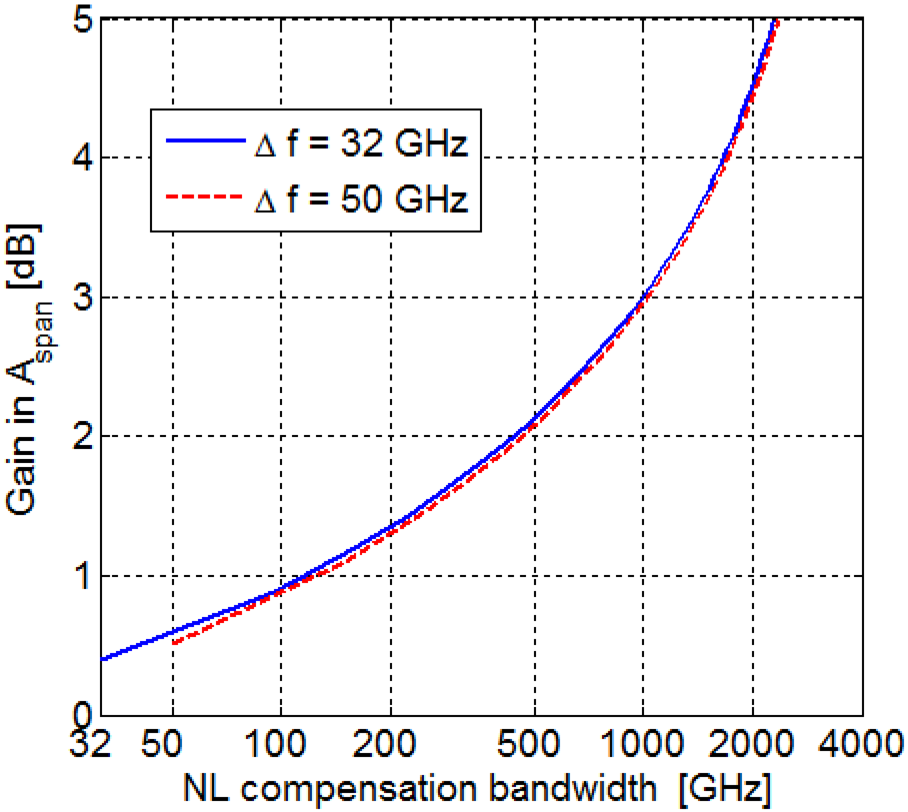
$$N_{span}^{max} = \left[\frac{4/27}{\left(A_{span} F h \nu\right)^2 \left(B_n OSNR_{eq}\right)^3 \eta_{NLI}} \right]^{\frac{1}{3}} \propto \eta_{NLI}^{-\frac{1}{3}}$$



Gain in span budget

- Fixing the number of spans N_{span} and the value of reference BER (i.e. reference $OSNR_{eq}$), the relationship between the maximum span loss (corresponding to the optimum launch power) and the value of η_{NLI} can be analytically evaluated

$$A_{span}^{max} = \left[\frac{4/27}{(Fh\nu)^2 \left(N_{span} B_n OSNR_{eq} \right)^3 \eta_{NLI}} \right]^{\frac{1}{2}} \propto \eta_{NLI}^{-\frac{1}{2}}$$



Conclusions

- Our analysis suggests that only marginal improvement could be achieved by multi-carrier NL compensation approaches, even assuming an unrealistically large Rx bandwidth.

- Note that actual implementations with limited complexity, like digital back-propagation with reduced number of steps per span, in general show a reduced effectiveness, thus the results shown in this work have to be considered as an upper bound which can be tighter or looser depending on practical implementations.

Acknowledgments

This work was partially supported by CISCO Systems within a SRA contract.

This work was supported by the European Union within the EURO-FOS project, a Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme.

Thank you!

gabriella.bosco@polito.it
www.optcom.polito.it