Limits of DSP Non-Linearity Compensation in Coherent-Detection Uncompensated Optical Links

Gabriella Bosco, Pierluigi Poggiolini, Andrea Carena, Vittorio Curri

Politecnico di Torino

Fabrizio Forghieri

Cisco Photonics Italy

FOTONICA 2013 - paper C2.2

Motivations

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

  → Electronic compensation of non-linear effects

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, “The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems,” J. Lightw. Technol., vol. 30, no.24, pp.3857-3879, Dec. 2012.)

Analytical model

- The model is based on the hypothesis that the NLI can be modeled as additive Gaussian noise → the system BER can be directly derived from the equivalent non-linear OSNR:

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

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

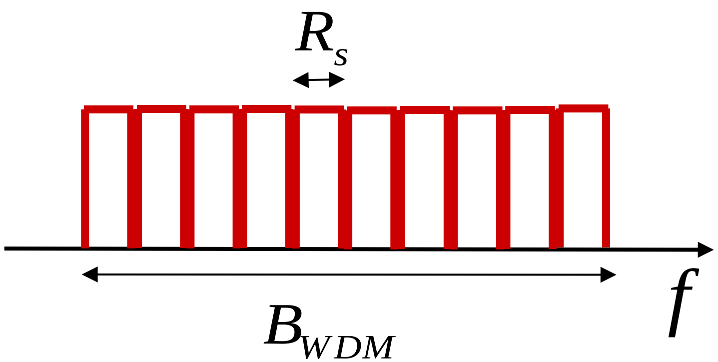
$$P_{NLI} \simeq N_{span}\left(\eta_{NLI} P_{Tx}^{3}\right) B_n$$

- 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

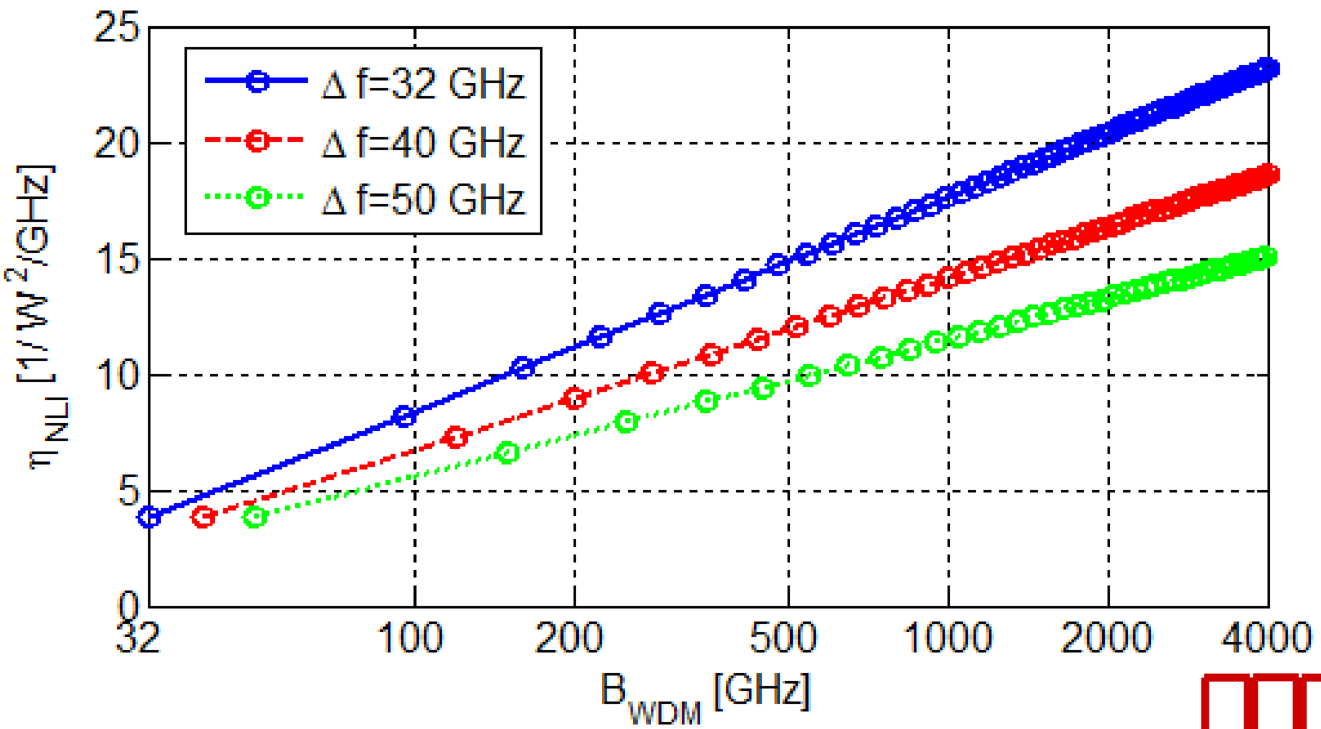
- WDM system based on 32-Gbaud sub-channels
  (the following analysis is independent of the modulation format)

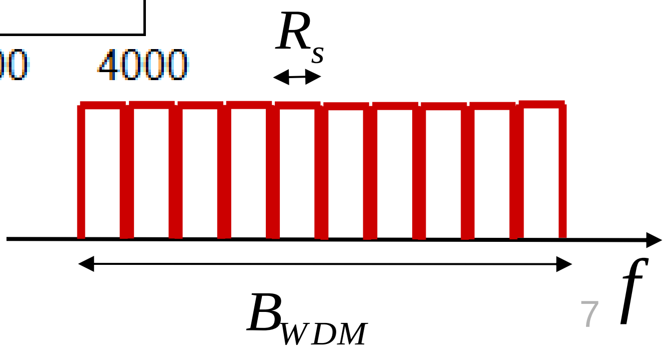
- Fiber parameters (PSCF):
  - L_{span}= 100 km
  - D = 21.5 ps/nm/km
  - α = 0.18 dB/km
  - γ = 0.9 1/W/km

- EDFA-only amplification
  - F=5 dB

- Three different setups have been analyzed:
  - standard spacing Δf = 50 GHz
  - tight Nyquist spacing equal to symbol rate, i.e. 32 GHz
  - intermediate spacing Δf = 40 GHz

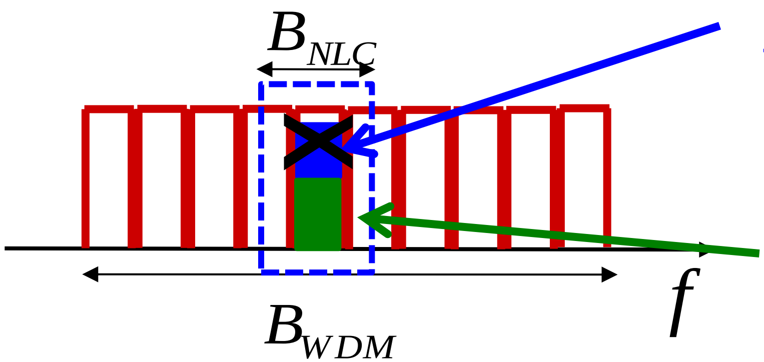
- Using the analytical model, it is possible to obtain the following plots for the increase of the amount of η_{NLI} falling on the center channel vs. the bandwidth of the WDM comb:





Hypotheses

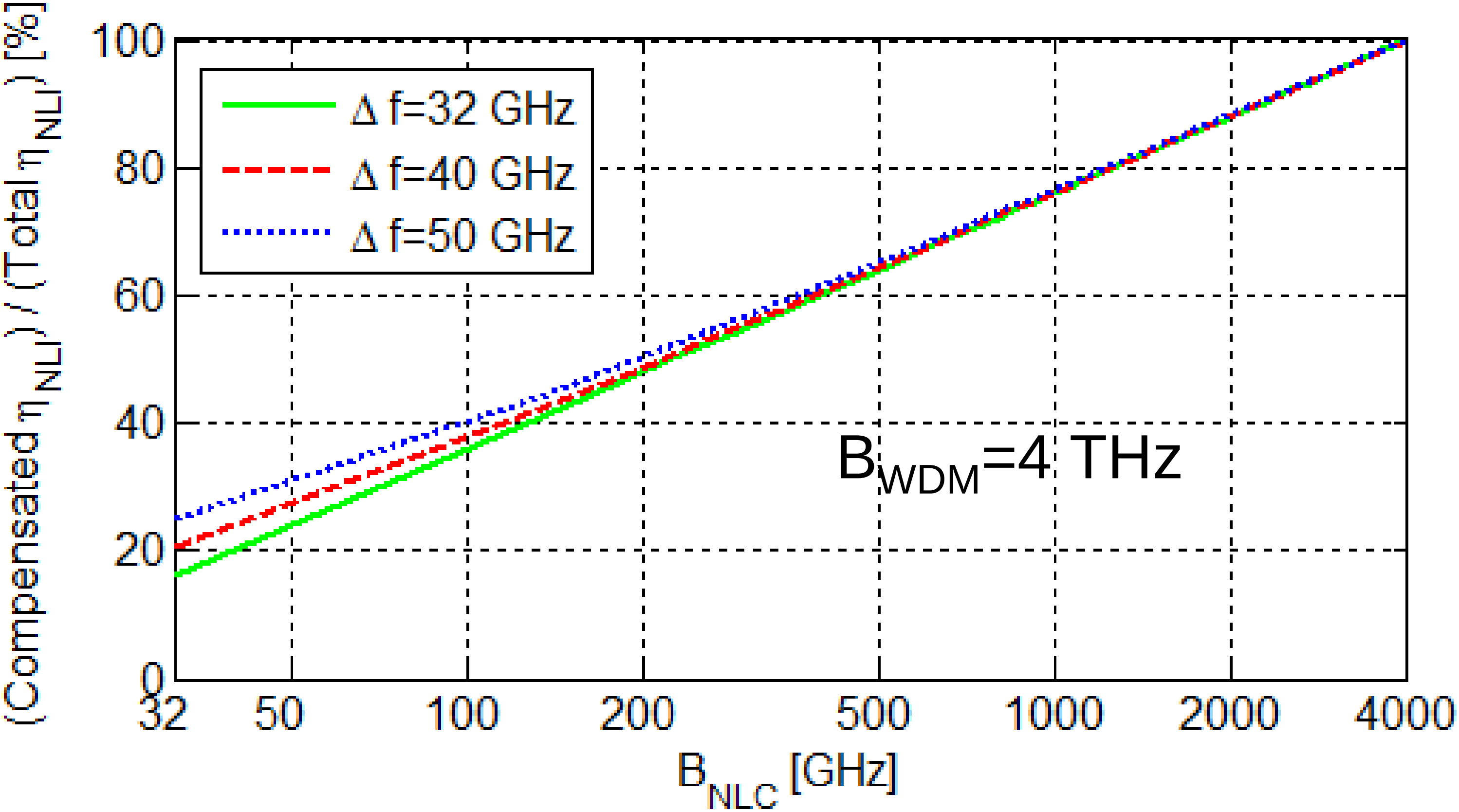
- The compensation algorithm used at the Rx is applied over a bandwidth B_{NLC}, which is a portion of the total bandwidth B_{WDM} of the WDM comb.



- 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 system performance.

Percentage of NL compensation

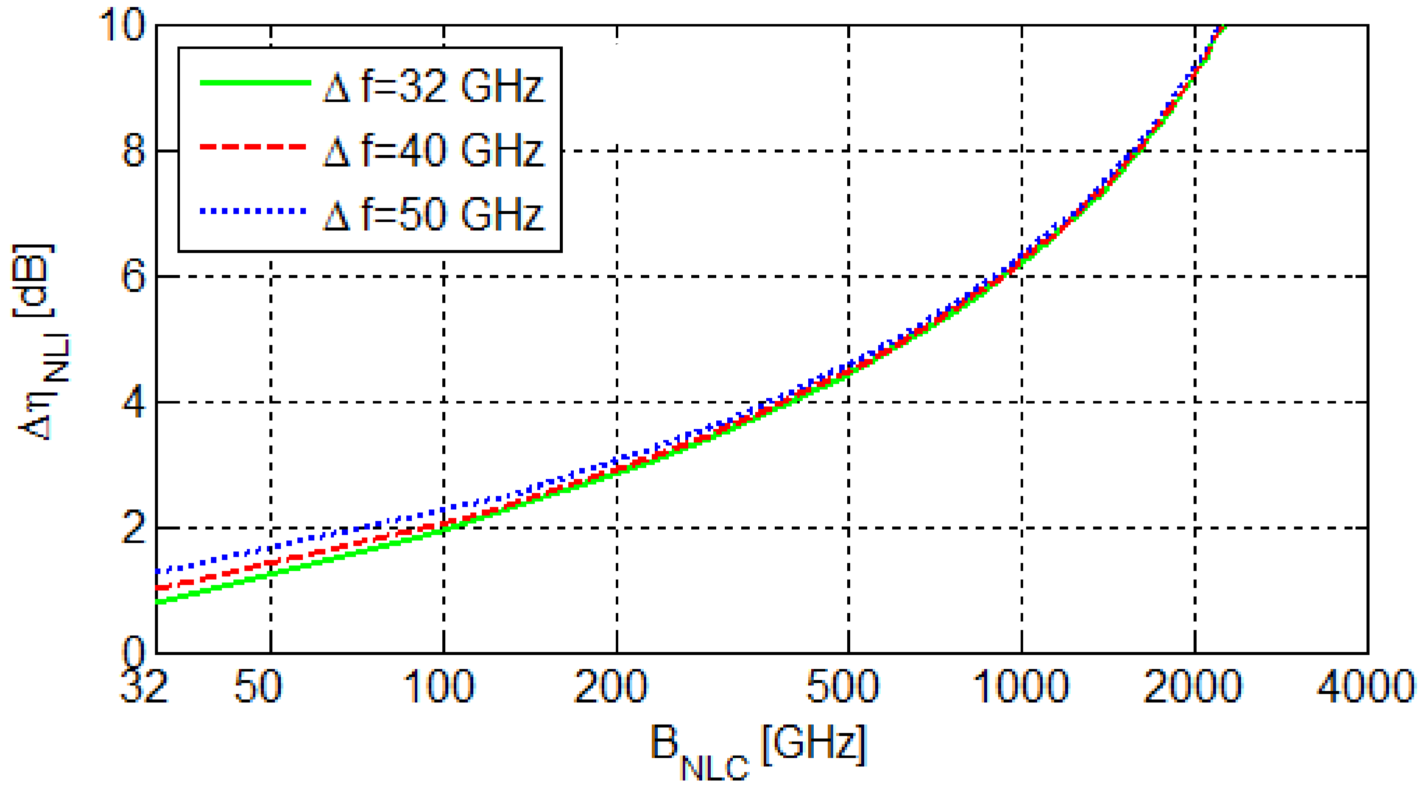
- Percentage of non-linearity compensation, i.e. ratio between the η_{NLI} compensated for at the Rx and the total η_{NLI} produced by the whole WDM comb:



Total reduction of η_{NLI}

- Alternative way of displaying results:

$$\Delta\eta_{NLI}[\text{dB}] = 10\log_{10}\left(\frac{\text{Total }\ \eta_{NLI}}{\text{Residual }\ \eta_{NLI}}\right)$$



Gain in terms of 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} is equal to:

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

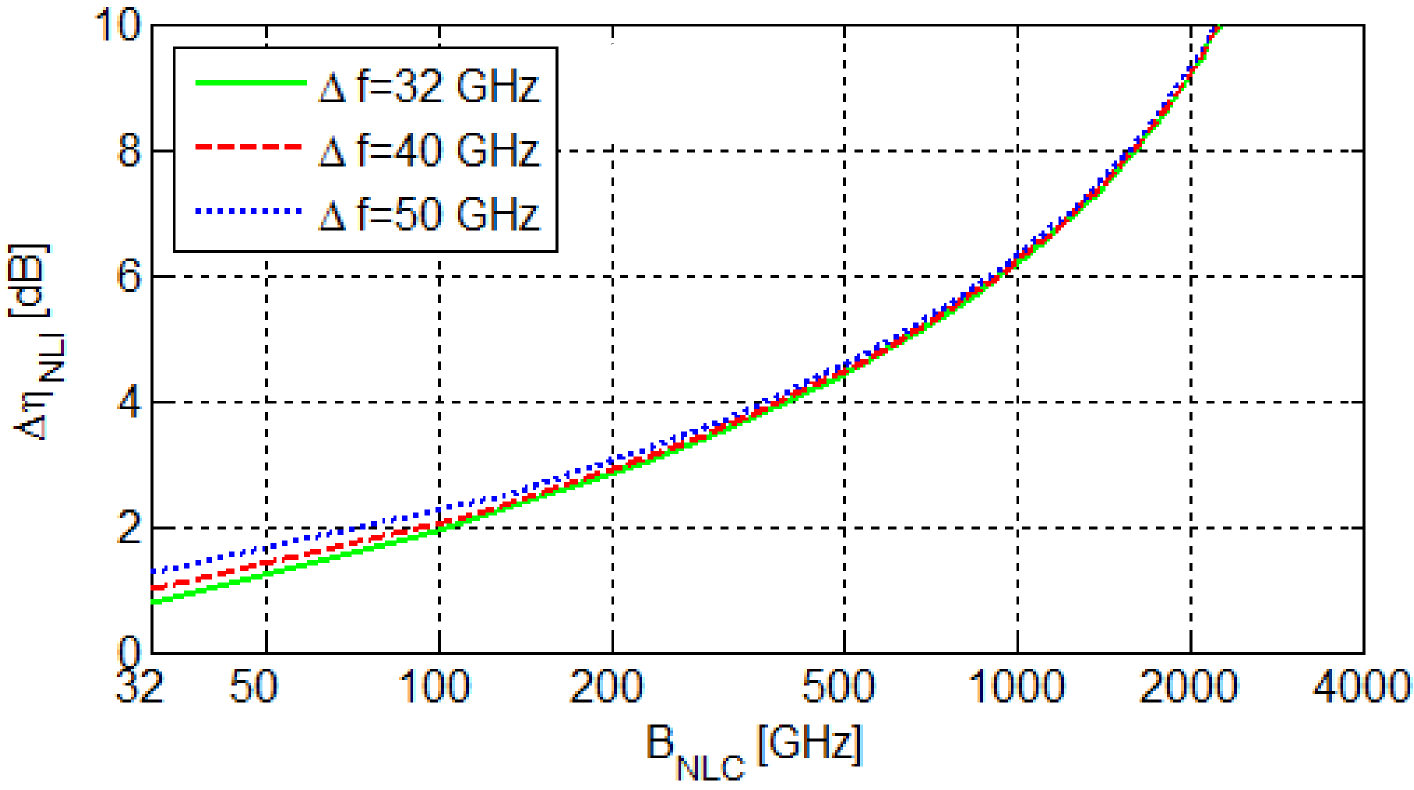
- 1-dB reduction of η_{NLI} corresponds to 1/3-dB increase in maximum reach:

$$\Delta N_{span}^{\max}[\mathrm{dB}] = \frac{1}{3} \Delta \eta_{NLI} [\mathrm{dB}]$$

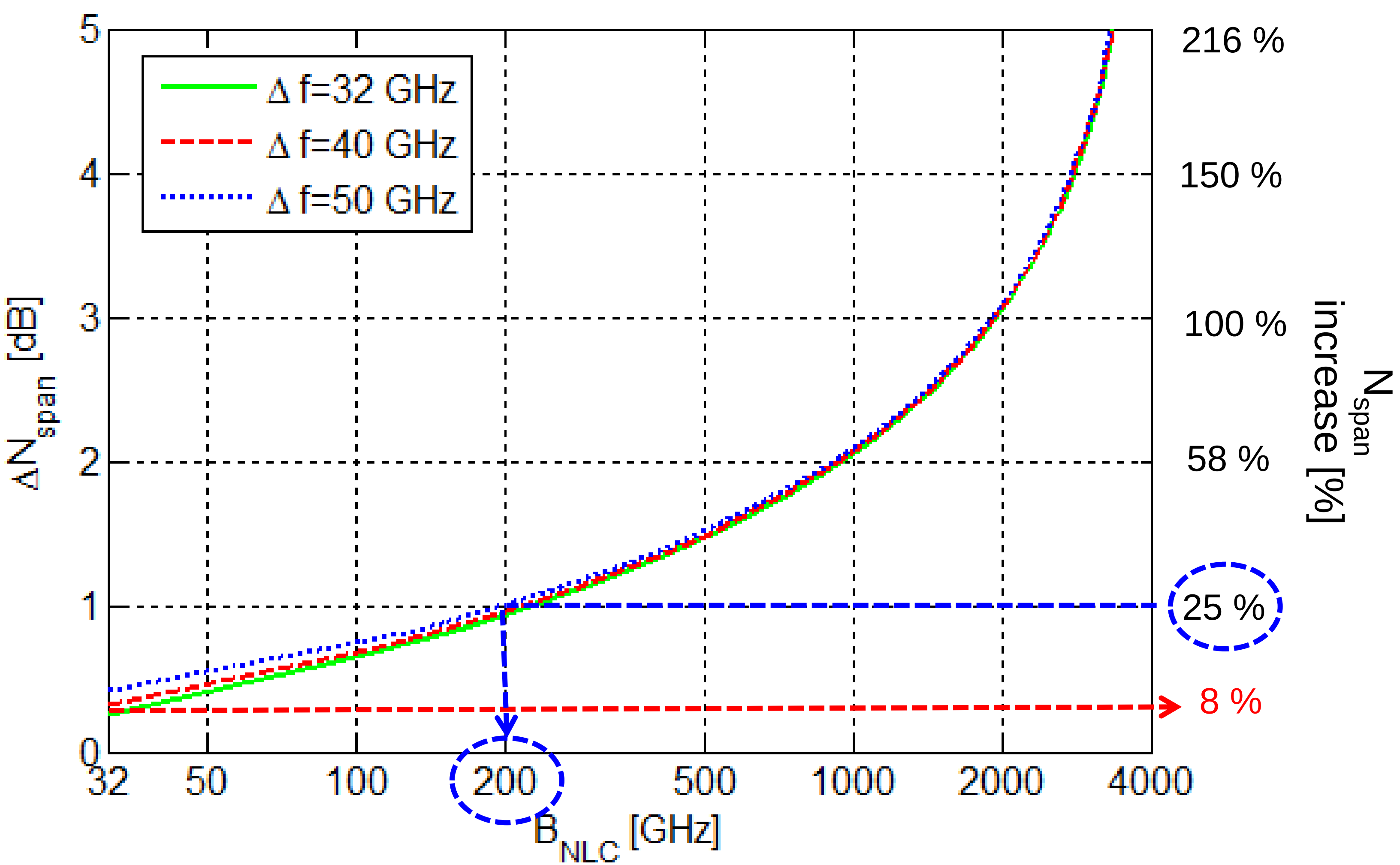
Total reduction of η_{NLI}

- Alternative way of displaying results:

$$\Delta\eta_{NLI}\,[\mathrm{dB}] = 10\log_{10}\left(\frac{\text{Total }\ \eta_{NLI}}{\text{Residual }\ \eta_{NLI}}\right)$$

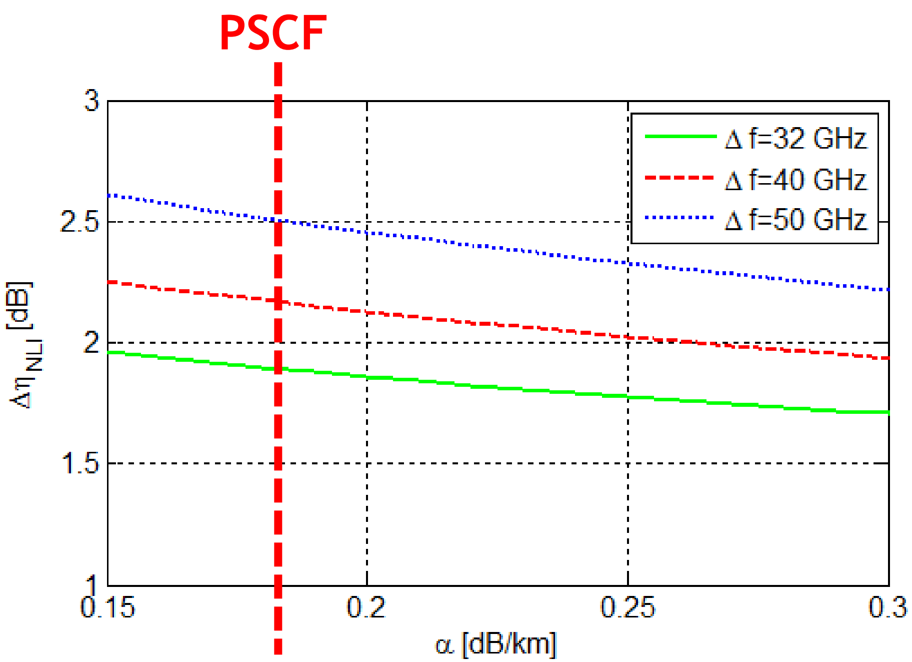


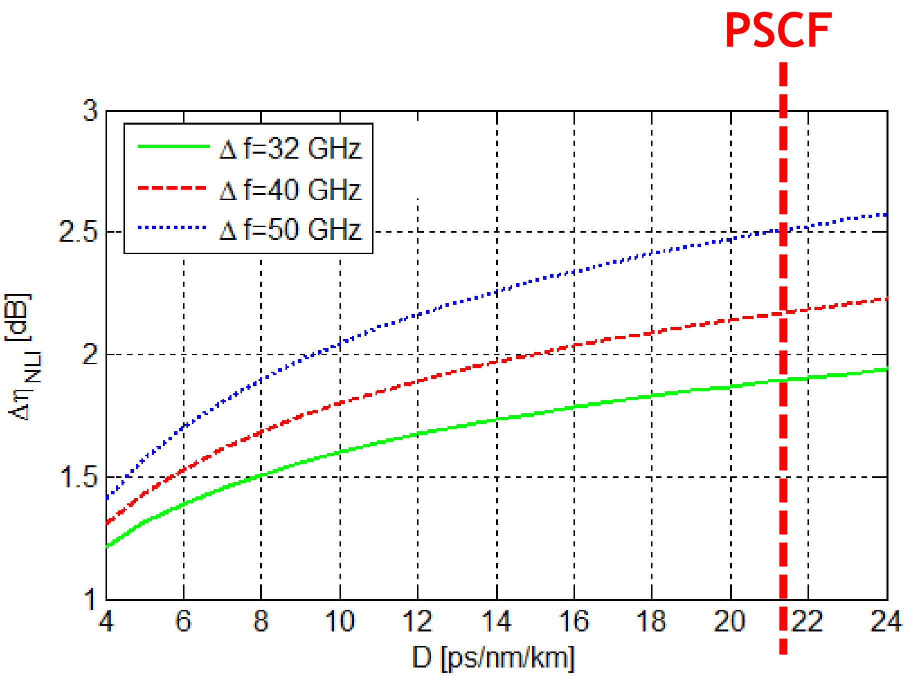
Gain in terms of maximum reach



Other system scenarios

- Evaluation of achievable η_{NLI} reduction as a function of loss coefficient α and dispersion coefficient D
  - The value of $\Delta\eta_{NLI}$ is independent of the nonlinearity coefficient γ
- 32 Gbaud with nonlinearity compensation bandwidth equal to three times the frequency spacing ($B_{NLC} = 3\ \Delta f$).





Conclusions

- When the entire C-band is occupied by the WDM comb, in order to obtain **significant gains** the NL compensation bandwidth should be substantially higher than 100 GHz → **high implementation complexity**.
- Actual implementations with **limited complexity**, like DBP with reduced number of steps per span, in general show a **reduced effectiveness** → the results shown in this work have to be considered as an **upper bound** to the effectiveness of electronic non-linearity compensation.

Thank you!

gabriella.bosco@polito.it

www.optcom.polito.it

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