Evaluation of the Dependence on System Parameters of Non-Linear Interference Accumulation in Multi-Span Links

A. Carena[(1)], P. Poggiolini[(1)], V. Curri[(1)], G. Bosco[(1)], F. Forghieri[(2)]

[(1)] DET, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Torino, Italy

[(2)] Cisco Photonics Italy srl, Via Philips 12, 20900, Monza, Italy.

Motivation

- Non-linear propagation in uncompensated links has been extensively studied
  - The Non-Linear Interference (NLI) can be modeled as an additive Gaussian noise
- Recent experimental evidences indicates a super-linear P_{NLI} accumulation with distance
  - However, contrasting estimates of the P_{NLI} growth have been presented
- We carried out a comprehensive analysis of the dependence of P_{NLI} accumulation on system parameters

Outline

- NLI Theory
  - Analytical formula
  - Understanding the effect
  - Definition of the accumulation exponent (ρ)
- Dependence on System Parameters
  - Reference system description
  - Analytical and simulation results
- Conclusions

NLI Theory

- Several analytical models of the NLI are now available, we based this study on our derivation

$$G_{NLI}(f) = \frac{16}{27}\gamma^2$$

$$\cdot \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} G_{Tx}(f_1)G_{Tx}(f_2)G_{Tx}(f_1+f_2-f)$$

$$\cdot \left| \frac{1-e^{-2\alpha L_S} e^{j4\pi^2|\beta_2|L_S(f_1-f)(f_2-f)}}{2\alpha - j4\pi^2|\beta_2|(f_1-f)(f_2-f)} \right|^2$$

$$\cdot \frac{\sin^2\left(2N_S\pi^2(f_1-f)(f_2-f)|\beta_2|L_S\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)|\beta_2|L_S\right)} df_1 df_2$$

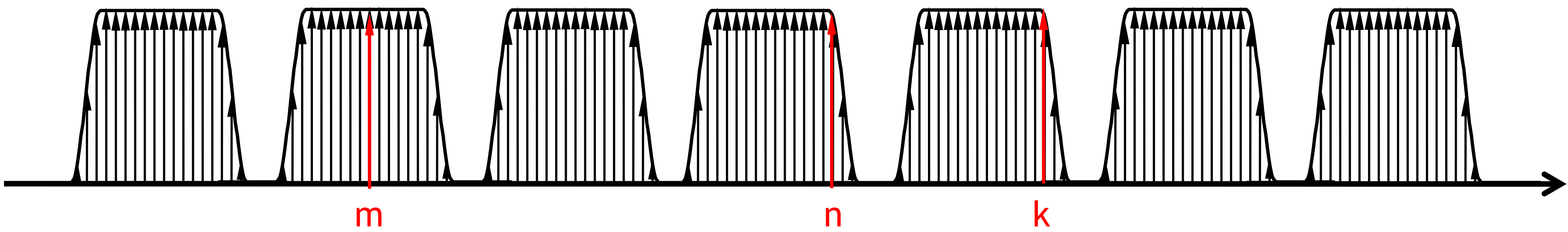
$$P_{NLI} = G_{NLI}(0)\cdot B_n$$

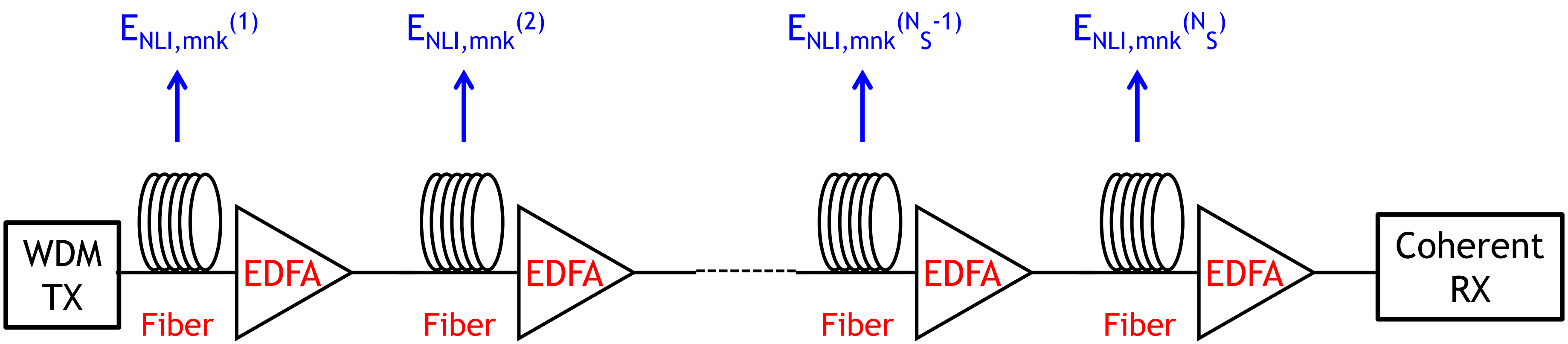
FWM efficiency

Phased-array factor

- A. Carena et. al, "Modeling the impact of nonlinear propagation effects in uncompensated optical coherent transmission links", IEEE/OSA Journal of Lightwave Technology, vol. 30, no. 10, 15 May 2012, pp. 1524-1539.

Understanding the effect

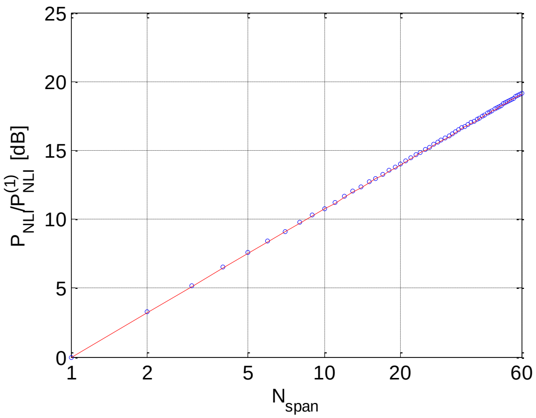




NLI accumulation exponent

- Solving numerically the integral, we observed that the P_{NLI} dependence on N_S can be fitted with high accuracy by the following expression

$$P_{NLI} \cong P_{NLI}^{(1)} \cdot N_S^{\rho}$$



Blue dots: analytical model
Red line: fitting

$P_{NLI}^{(1)}$: amount of NLI generated in the first span

ρ: NLI accumulation exponent

Reference system: Tx & Rx

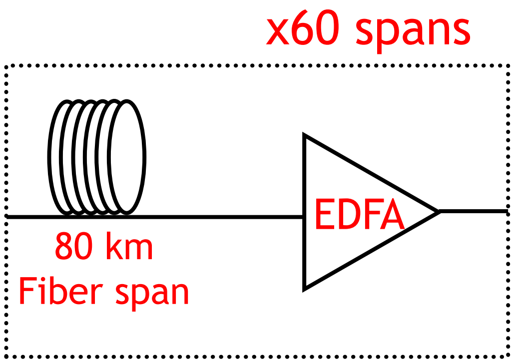
TRANSMITTER

- 256G PM-16QAM
  - R_S=32 Gbaud
- Nyquist-WDM
  - DAC shaping
  - roll-off=0.02
  - Δf=33.6/50.0 GHz

RECEIVER

- Coherent receiver
- Electrical bandwidth
  $B_{elt}=0.5 \cdot R_S=16.0$ GHz
- LMS with training sequence
  - 51 taps
  - $\mu=3 \cdot 10^{-4}$

Reference system: Link



- BER measurements taken up to a of 60 spans
- SMF
  - Attenuation α=0.22 [dB/km]
  - Non-linearity γ=1.3 [1/W/km]
  - Dispersion D=16.7 [ps/nm/km]
- EDFA lumped amplification
  - F= 5 dB
  - Simulations using ASE noise loading at receiver
- Pre-compensation
  - Equal to 10 spans: D_{pre}=16700 ps/nm

P_{NLI} evaluation from simulation

$$BER = \Phi(OSNR)$$

Relationship between BER and OSNR:
we used the back-to-back curve tacking into account actual crosstalk and penalty

$$OSNR = \frac{P_S}{P_{ASE} + P_{NLI}}$$

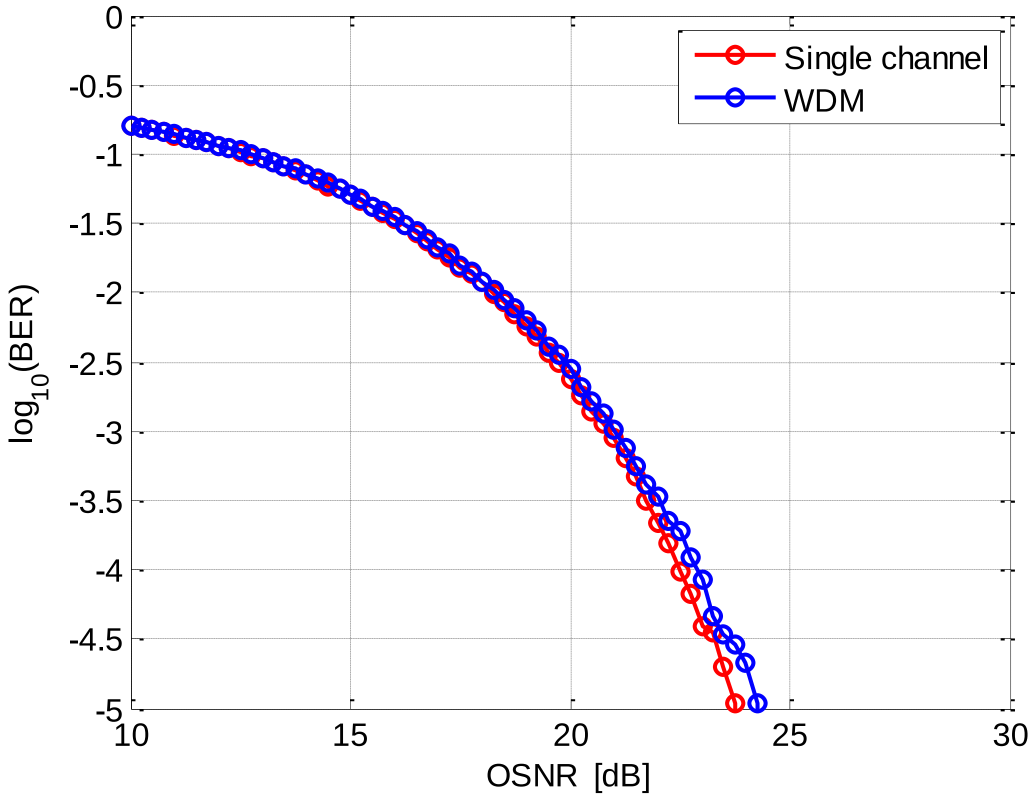
At each measurement point we know P_S and P_{ASE}

$$P_{NLI} = \frac{P_S}{OSNR} - P_{ASE}$$

This procedure is applied to each analyzed case

$$P_{NLI} = f(N_{ch}, \Delta f, R_S, D, \alpha, \gamma, L_{span}, N_{span})$$

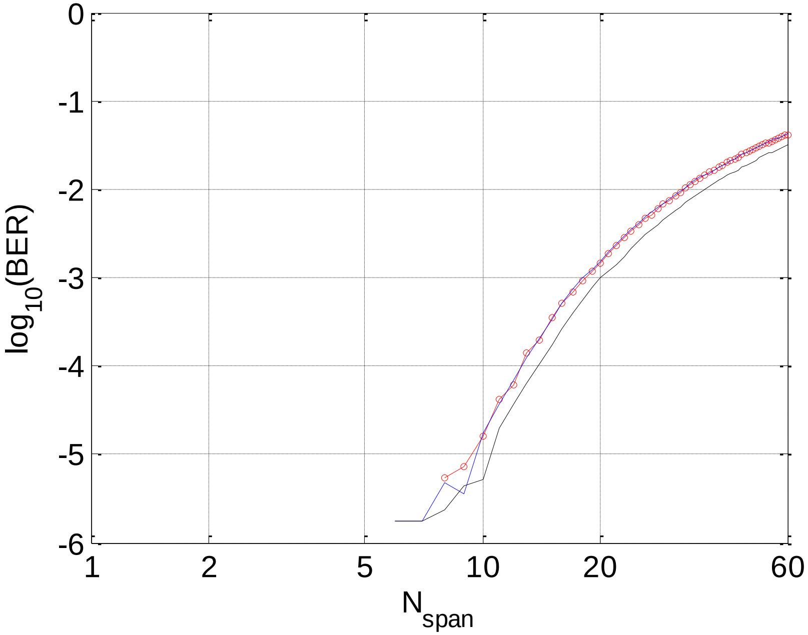
P_{NLI} obtained is compared with values derived using the model

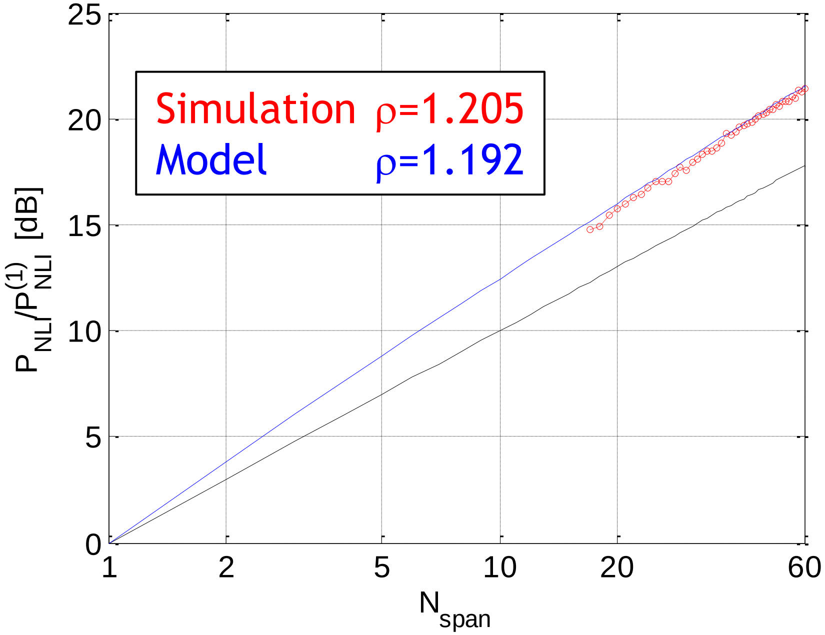


Single channel
WDM
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
10
15
20
25
30
OSNR [dB]
$\log_{10}$(BER)

$N_{ch}=1$

P_{TX}=-1 dBm





Red dots: simulations

Blue line: analytical model

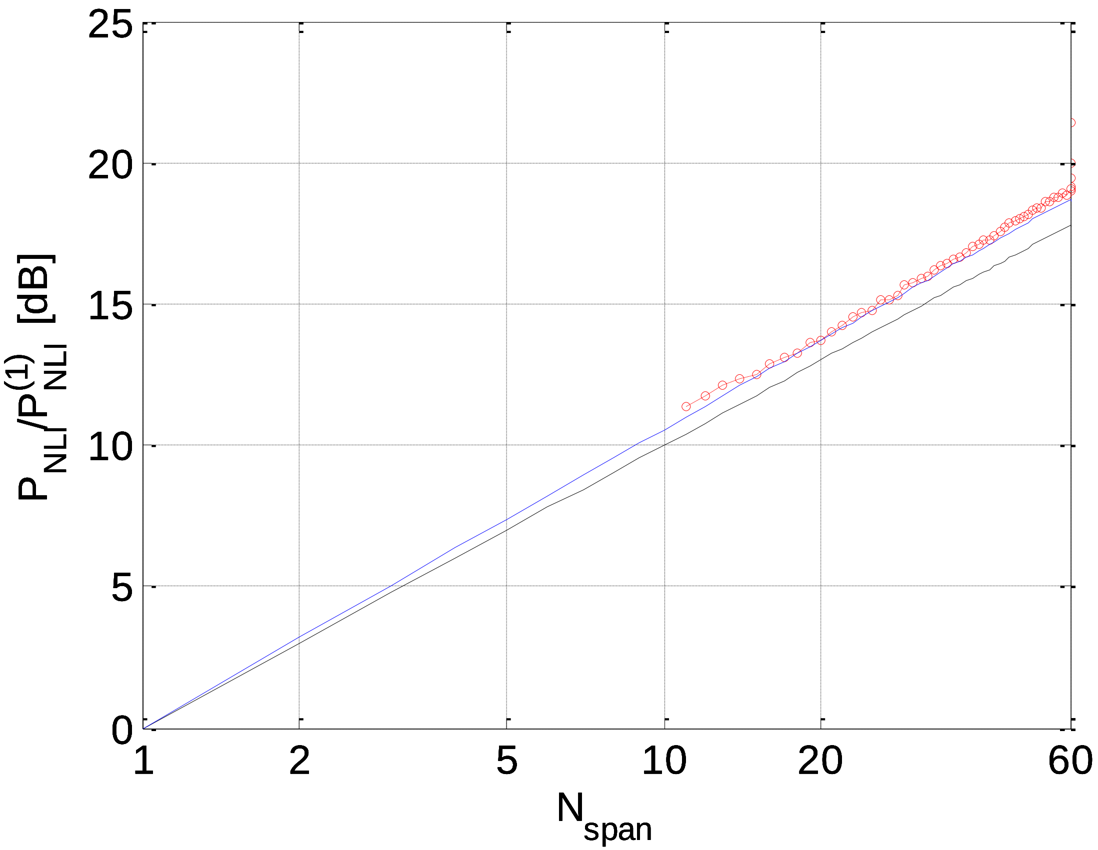
Black line: linear accumulation (ρ=1)

Δf=33.6 GHz

N_{ch}=39

Simulation ρ=1.050

Model ρ=1.053



Red dots: simulations

Blue line: model

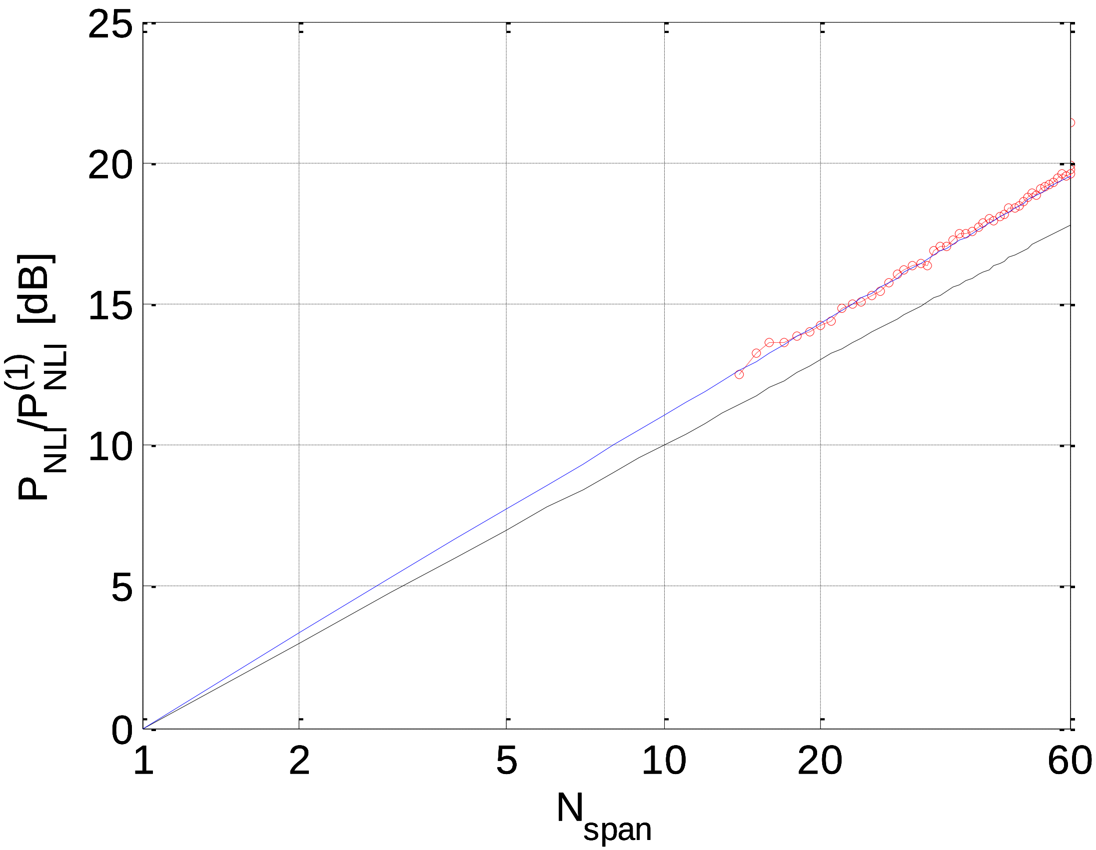
Black line: linear accumulation (ρ=1)

Δf=50.0 GHz

N_{ch}=9

Simulation ρ=1.104

Model ρ=1.099

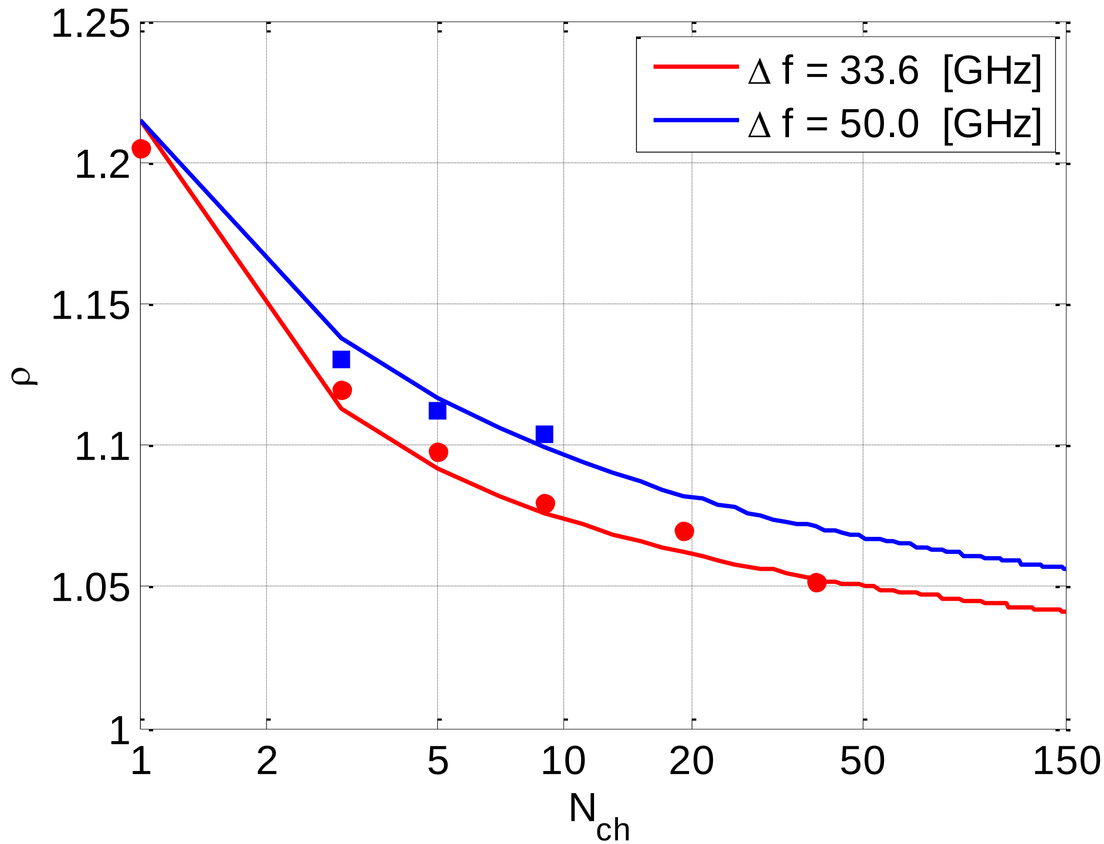


Red dots: simulations

Blue line: model

Black line: linear accumulation (ρ=1)

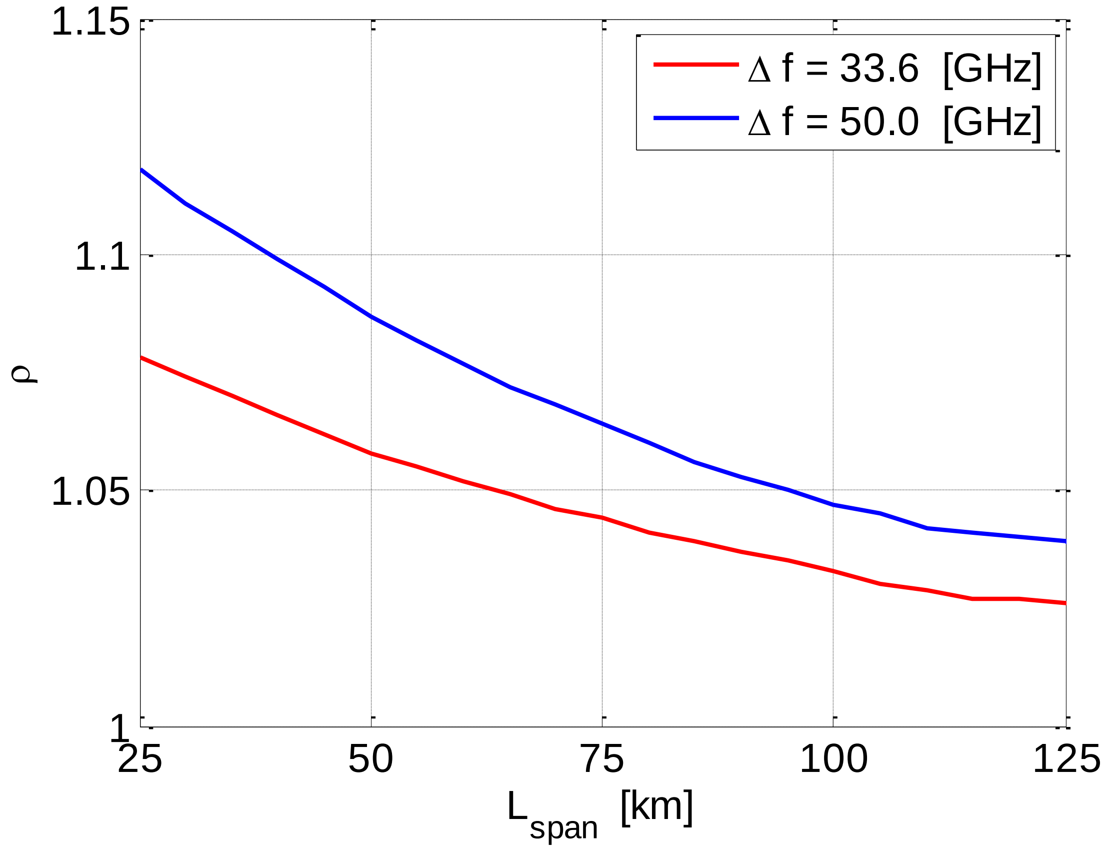
N_{ch} dependence



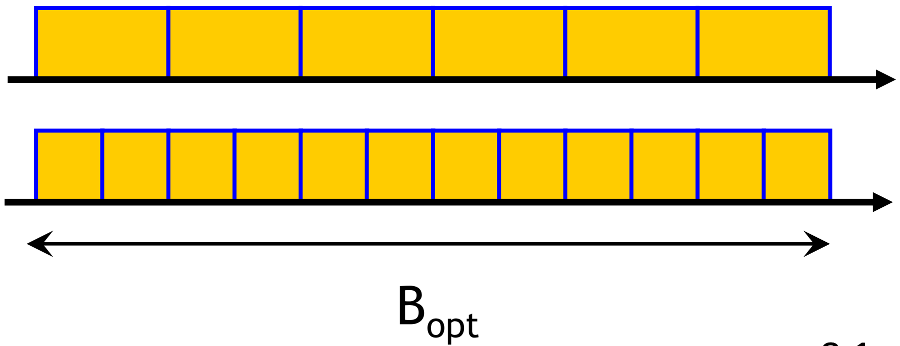
Dots: simulations
Solid lines: model

L_{span} dependence

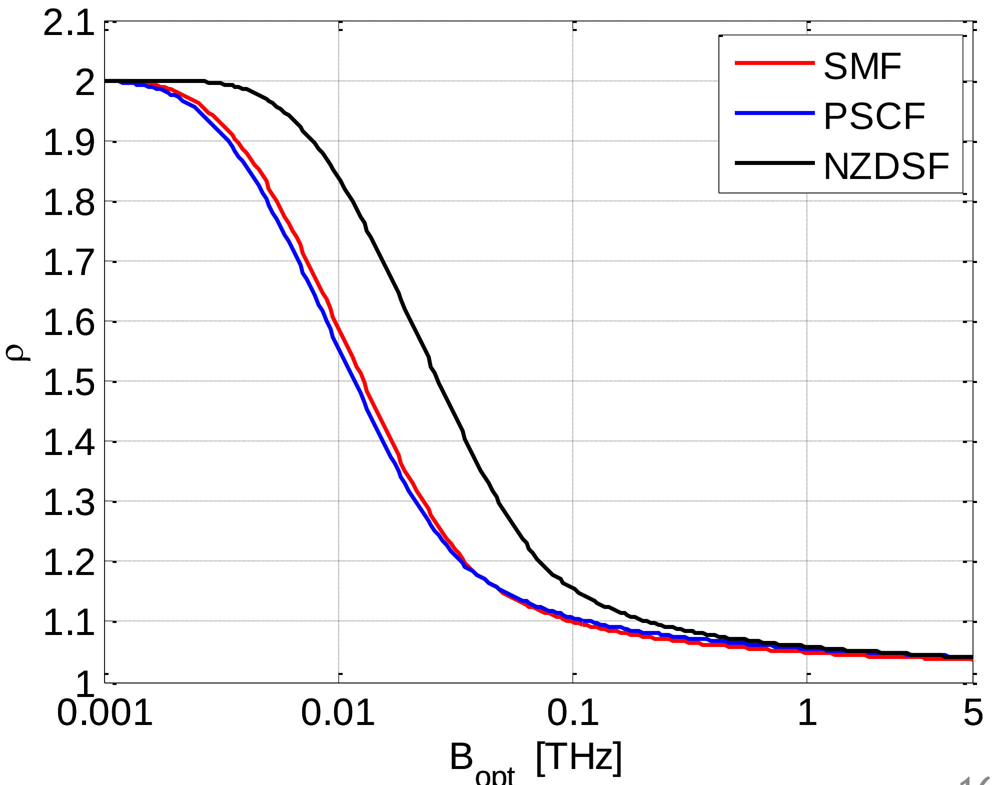
Whole C-band (5 THz)



Nyquist limit - $\Delta f = R_S$



Fiber	D [ps/nm/km]	α [dB/km]	γ [1/W/km]
SMF	16.7	0.22	1.3
PSCF	20.1	0.18	0.9
NZDSF	3.8	0.22	1.5



Conclusions

- The noise accumulation exponent depends on:
  - fiber dispersion and span length
  - the overall system bandwidth
- In all practical conditions ρ is only slightly higher than 1
- For standard fibers, if the full-C band is used the accumulation exponent is very close to 1 (linear growth)

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Europe's Research Network on Photonic Systems

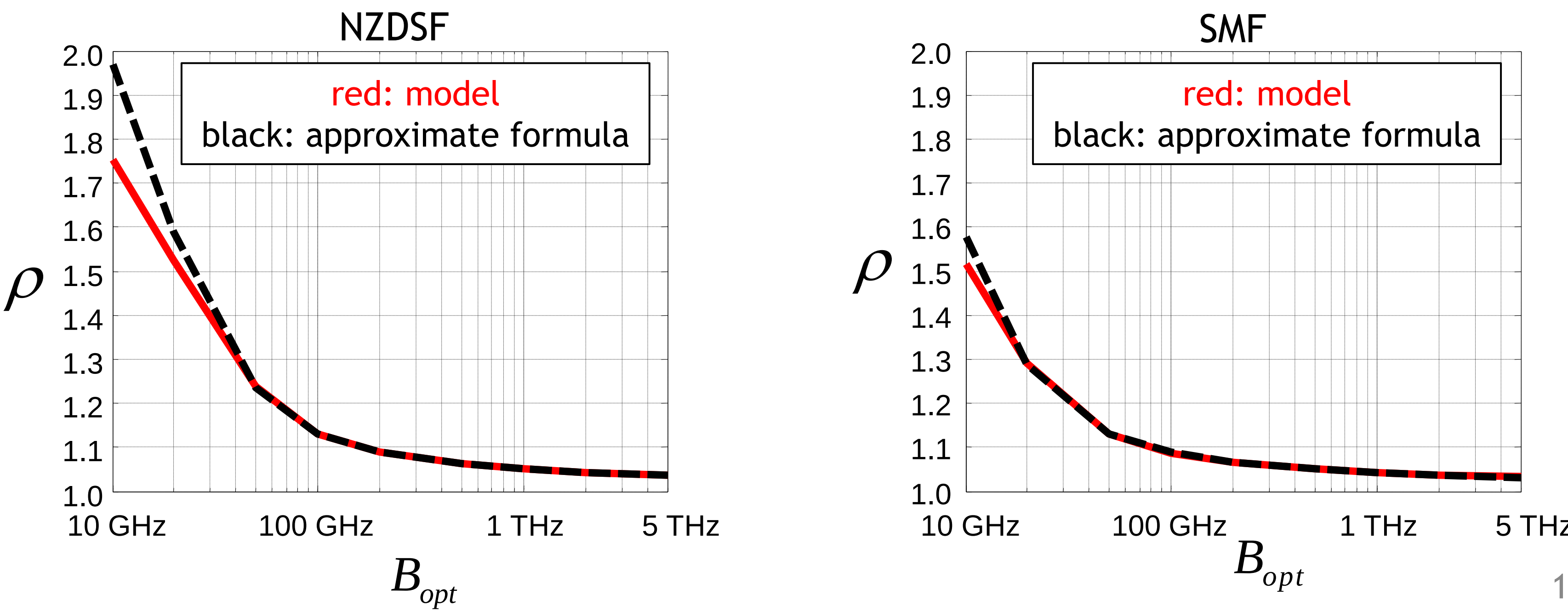
andrea.carena@polito.it - www.optcom.polito.it

An approximate formula

- We use again the same approximate formula:

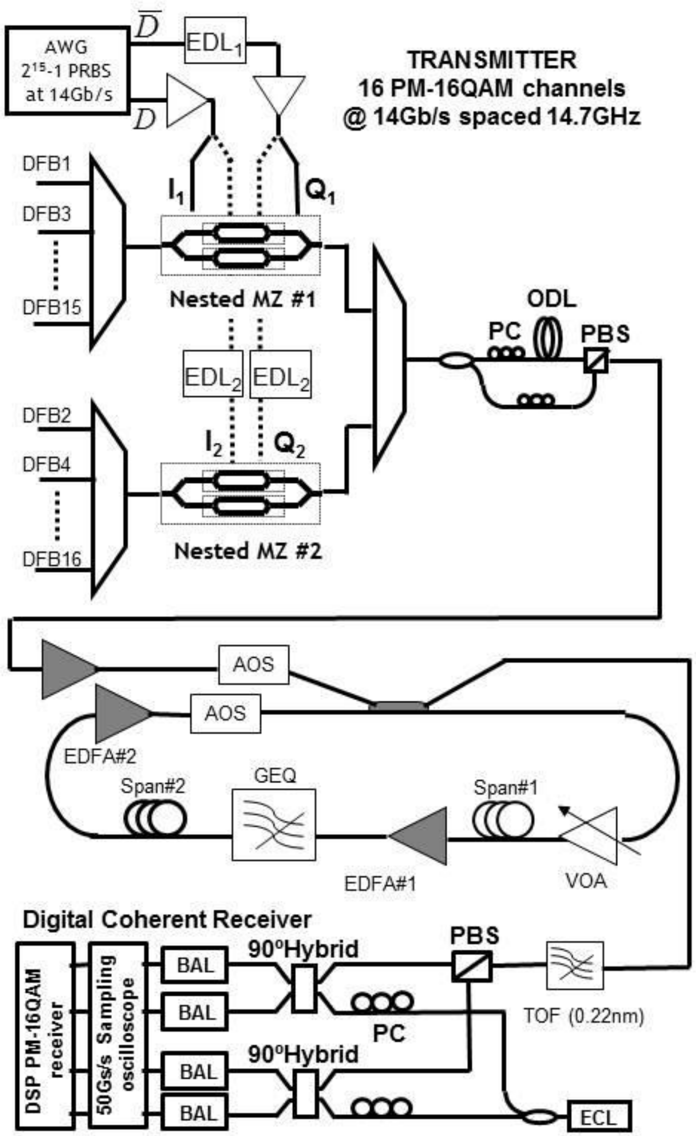
$$\rho = 1 + \frac{3}{10} \cdot \log\left(1 + \frac{6}{L_S} \frac{L_{eff,a}}{\operatorname{asinh}\left(\frac{23}{5} \beta_2 L_{eff,a} B_{opt}^2\right)}\right)$$

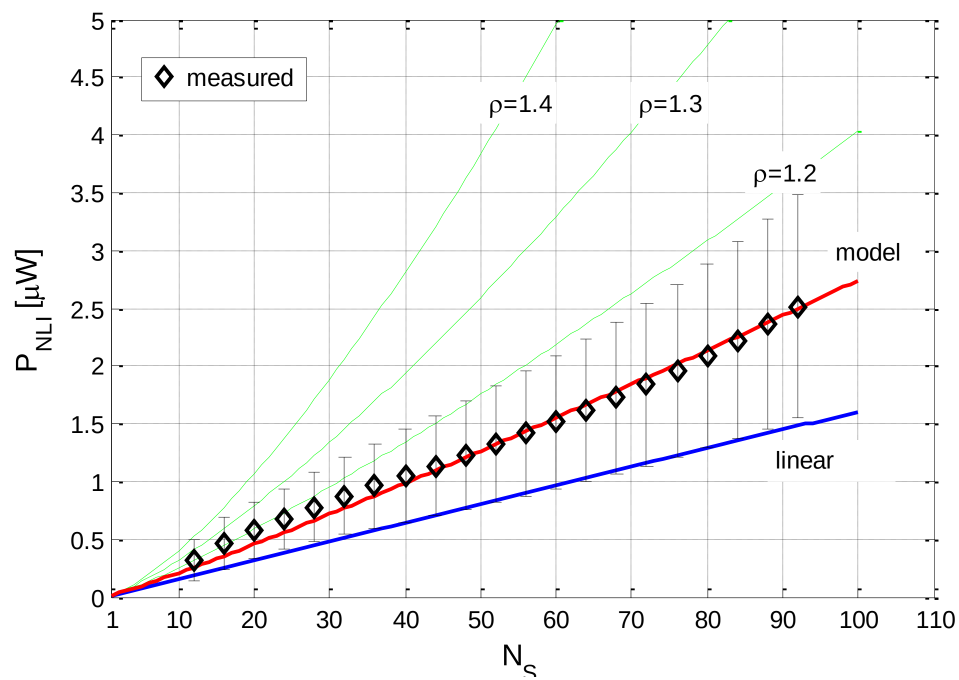
- The formula is very accurate down to very small B_{opt}



- P. Poggiolini, "The GN model of non-linear propagation in uncompensated coherent optical systems", accepted for pubblication on IEEE/OSA Journal of Lightwave Technology, available on IEEE Xplore early access.

Experimental validation





- G. Bosco et. al, "Experimental investigation of nonlinear interference accumulation in uncompensated links", IEEE Photonics Technology Letters, vol. 24, no. 14, 15 July 2012, pp. 1230-1232.