Evaluation of Non-Linear Interference in Uncompensated Links using Raman Amplification

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ECOC 2012 Paper We.2.C.5

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Motivation and outline

- **Does the NLI theory apply to links with Raman amplification?**
- Summary of NLI theory for Nyquist WDM in presence of distributed amplification
- Validation on a multispan link based on a *typical* PSCF
  - Several pumping levels
- Same analysis on a *typical* low-disperion fiber
  - Effects of predistortion
- Comments and conclusions

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Theory (I)

Nyquist WDM comb with $\Delta f = R_s$

NLI power on B_n

$$P_{NLI} = \frac{256}{27}\frac{B_n}{R_s}\gamma^2 L_{eff}^2 P_{Tx}^3 \frac{\int_0^{\frac{B_{opt}}{2}} \rho(\nu)|\nu| \frac{\sin^2\left(2N_s\pi^2\nu^2\beta_2 L_s\right)}{\sin^2\left(2\pi^2\nu^2\beta_2 L_s\right)} \log\left(\frac{B_{opt}}{2\nu}\right) d\nu}{R_s^2}$$

Generalized FWM efficiency

$$\rho(\nu) = \frac{1}{L_{eff}^2}\left|\int_0^{L_s} p_{ch}(z)\exp\left\{j4\pi^2\beta_2\nu^2 z\right\} dz\right|^2$$

Generalized effective length

$$L_{eff} = \int_0^{L_s} p_{ch}(z)\, dz$$

$$p_{ch}(z) = e^{-\alpha_s z} e^{g_{RA}(z)}$$

$g_{RA}(z)$: Raman gain vs. z

Closed-form expressions in case of counterpropagating undepleted pump

All theoretical details in Th.2.G.1 by Prof. Poggiolini tomorrow at 11.00

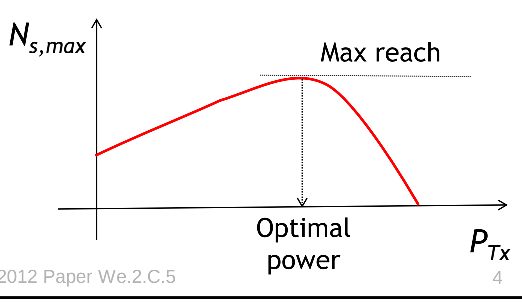
Theory (II)

Given the modulation format and Tx/Rx setups

$$BER = F_{\mathrm{mod}}(OSNR_{NL}) \Rightarrow BER_{\mathrm{target}} \Leftrightarrow OSNR_{NL,\mathrm{target}}$$

$$OSNR_{NL} = \frac{P_{Tx}}{P_{NLI} + P_{ASE}} = \frac{P_{Tx}}{P_{NLI} + N_s P_{ASE}^{(1)}}$$

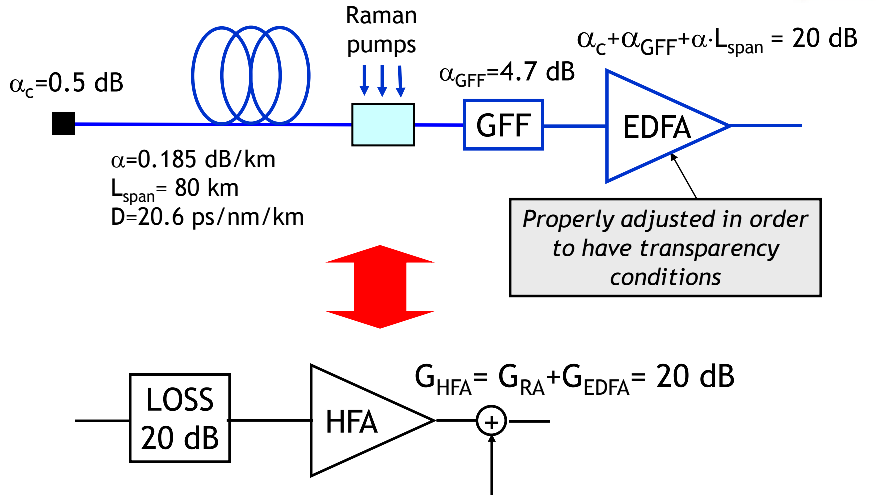
- Given BER_{target} we have $OSNR_{NL,target}$
- We can evaluate the maximum number of spans $N_{s,max}$ vs. P_{Tx}



Validation

- Simulation of PM-16QAM at 32 Gsymbol/s
- $\Delta f = R_s$
- Nyquist WDM formed with ideal DAC
- $BER_{target} = 10^{-3}$ <-> $OSNR_{NL,target}$ = 23 dB
- 11 channels
- Two types of *typical* fibers
  - PSCF (D = 20.6 ps/nm/km)
  - NZDSF (D = 3.8 ps/nm/km)
- *Loss*: 20 dB/span
- 3-pump counterpropagating Raman with different pump levels

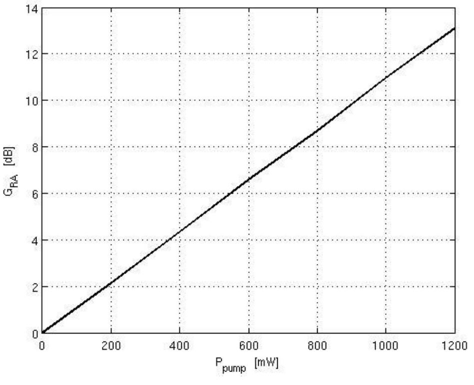
Validation: PSCF



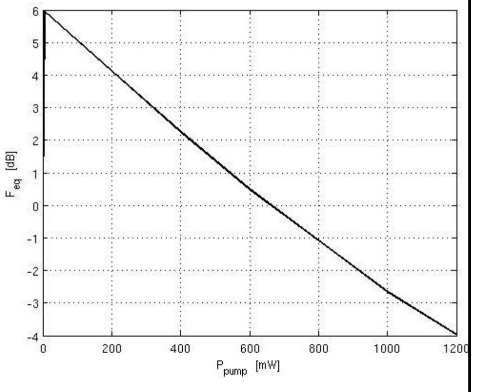
$$P_{N,HFA} = hfB_n(G_{HFA}-1)F_{eq}$$

PSCF: HFA behavior

Flattened G_{RA} vs. P_{pump}



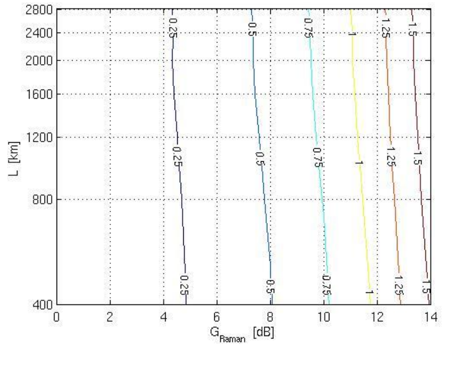
F_{eq} vs. P_{pump}

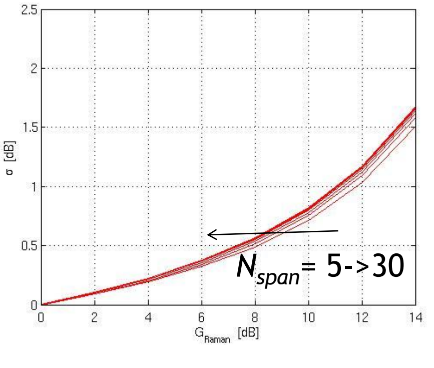


NLI with RA vs. NLI w/o RA

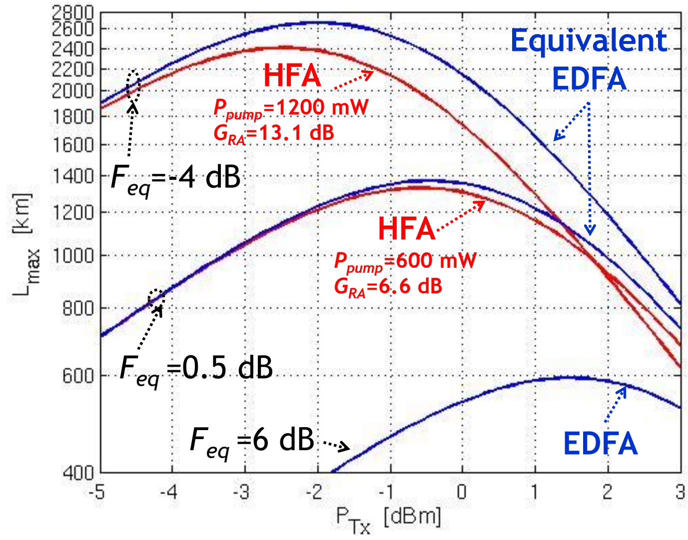
Theoretical eveluation of $\sigma = \frac{P_{NLI}}{P_{NLI,EDFA}}$

Contour plot of σ

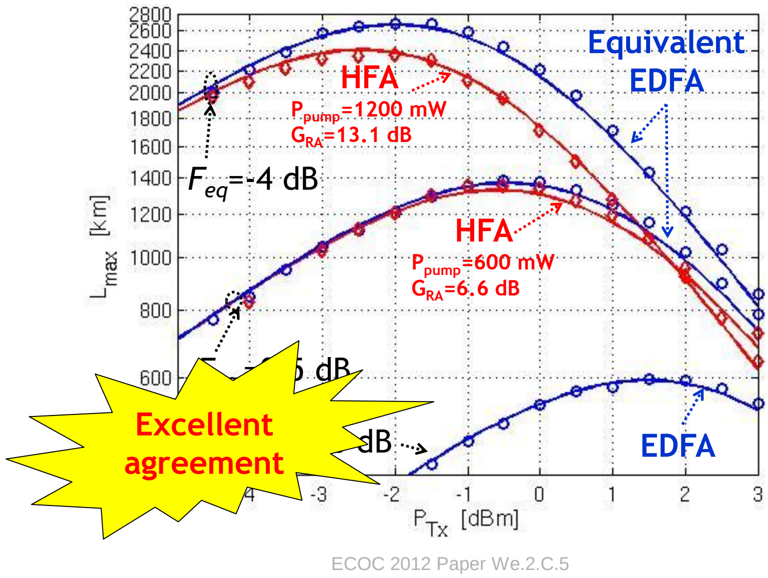




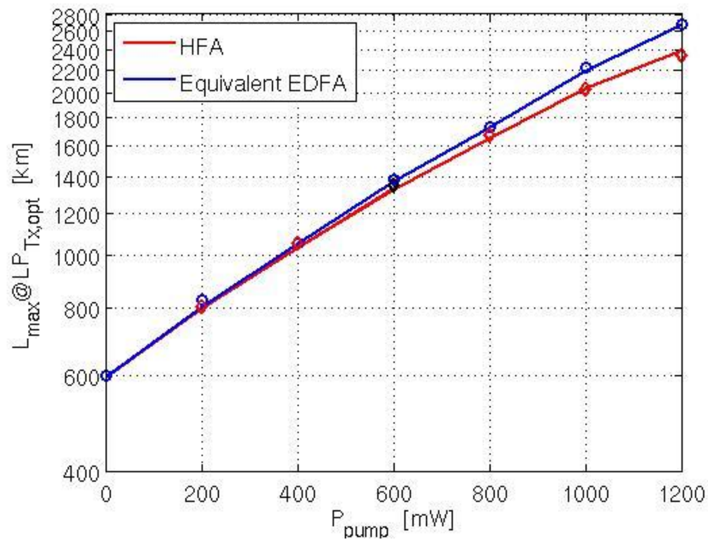
Max reach: theory



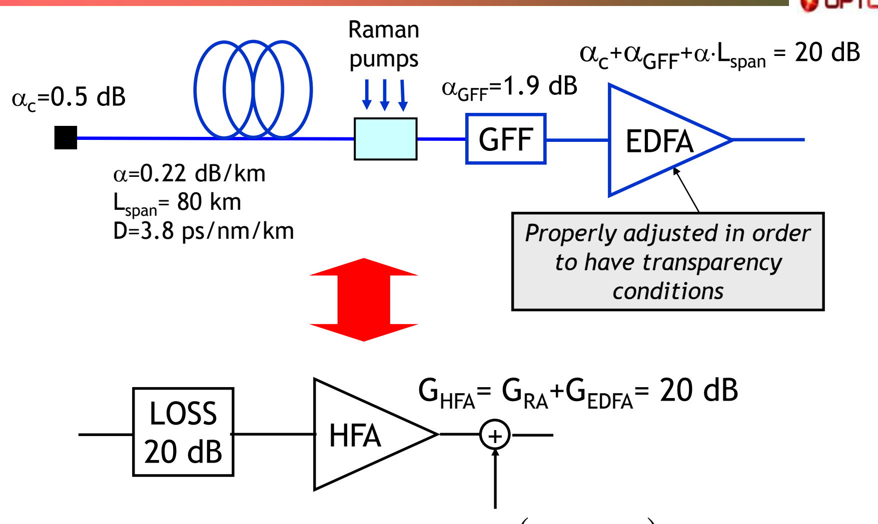
Max reach: theory+simulations



Max reach vs. P_{pump}: theory +simulations



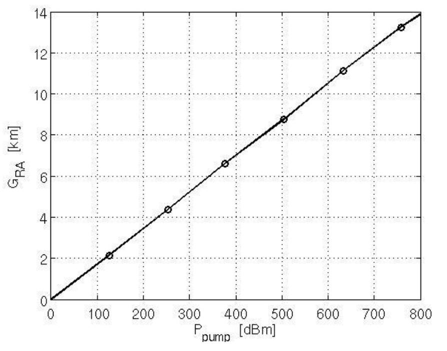
Validation: NZDSF



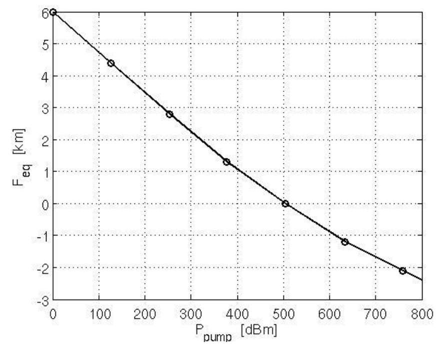
$$P_{N,HFA} = hfB_n(G_{HFA} - 1)F_{eq}$$

NZDSF: HFA behavior

Flattened G_{RA} vs. P_{pump}

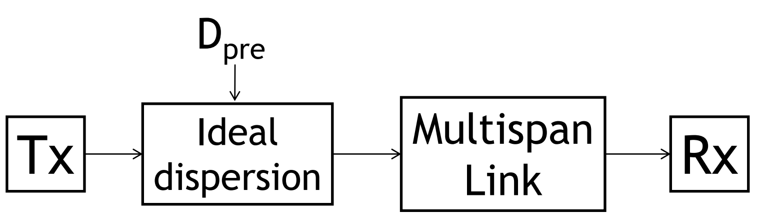


F_{eq} vs. P_{pump}



Predistortion

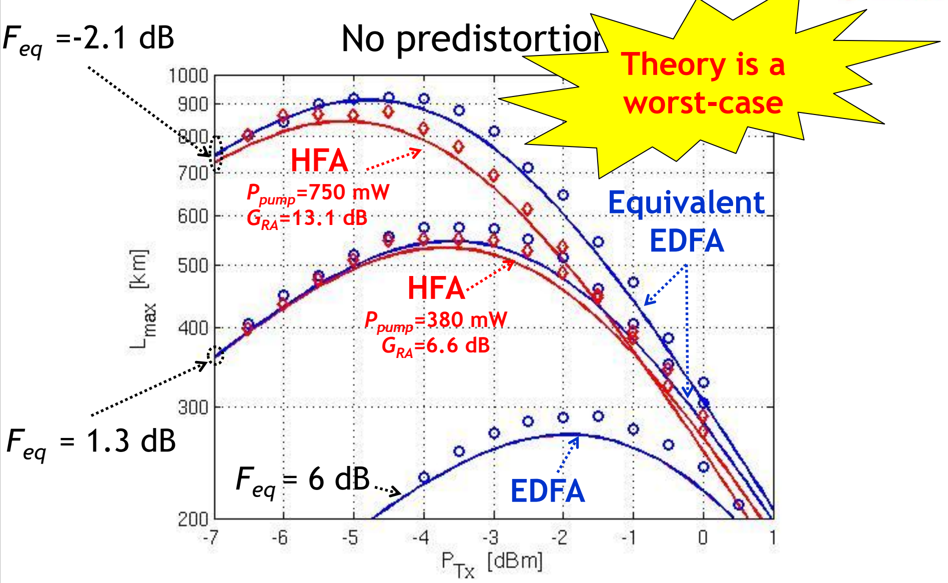
- In low dispersion fibers, “lack of Gaussianity” in first spans may induce lower NLI generation
- We tested possible presence of predistortion



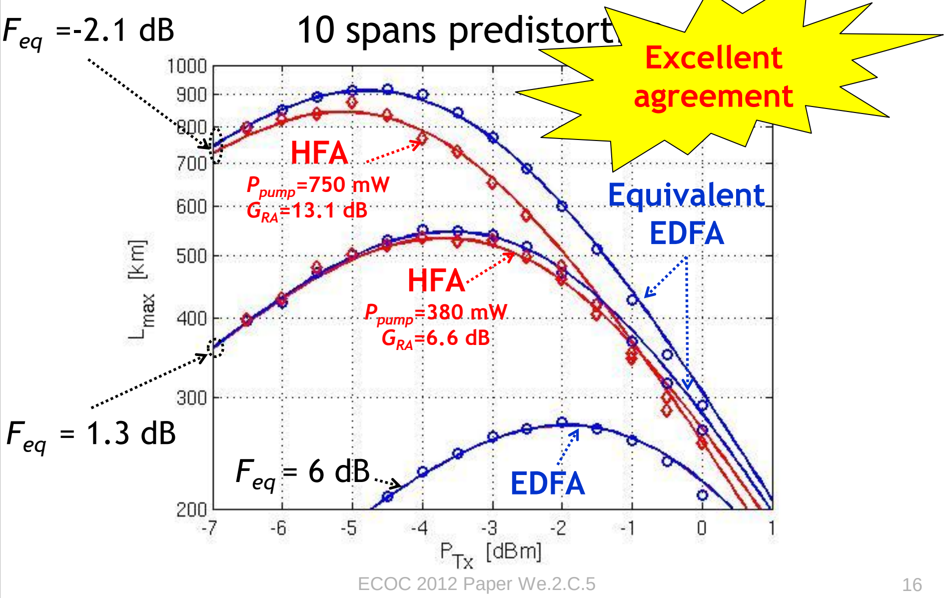
Predistortion OFF: D_{pre} = 0 ps/nm

Predistortion ON : D_{pre} = 380 ps/nm (10 spans)

Max reach: theory+simulation



Max reach: theory+simulation



Comments and conclusions

- NLI model is reliable also for systems using Raman amplification
- Raman amplification induces a limited NLI enhancement
- Model is validated by simulation for a link based on a typical PSCF
  - Several Raman pumping schemes were analyzed
  - Excellent agreement theory vs. simulation
- Validation was done also on a typical NZDSF
  - Excellent agreement in case of predistorion, otherwise NLI gives a worst case evaluation

Acknoledgemets

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