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

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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 multispans link based on a typical PSCF
  - Several pumping levels
- Same analysis on a typical low-disperion fiber
  - Effects of predistortion
- Comments and conclusions
Nyquist WDM comb with $\Delta f = R_s$

NLI power on $B_n$

\[ P_{NL} = \frac{256}{27} \frac{B_n}{R_s} v^2 L_{ef} P_{tx}^3 \left( \int_0^{\frac{B_{opt}}{2v}} \frac{\sin^2 \left( 2N_c \pi^2 v^2 \beta_s L_n \right)}{\sin^2 \left( 2\pi^2 v^2 \beta_s L_n \right)} \log \left( \frac{B_{opt}}{2v} \right) dv \right) \]

Generalized FWM efficiency

\[ \rho(v) = \frac{1}{L_{ef}} \int_0^L \left| p_{ch}(z) \exp \left( j4\pi^2 \beta_s v^2 z \right) \right|^2 dz \]

Closed-form expressions in case of counterpropagating undepleted pump

Generalized effective length

\[ L_{ef} = \int_0^L p_{ch}(z) \, dz \]

\[ p_{ch}(z) = e^{-n_c e^{\beta_s v^2 z}} \]

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

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

Given the modulation format and Tx/Rx setups

\[ BER = F_{mod} (OSNR_{NL}) \]

\[ BER_{target} \iff OSNR_{NL,target} \]

\[ OSNR_{NL} = \frac{P_{tx}}{P_{NLI} + P_{ASE}} = \frac{P_{tx}}{P_{NLI} + N_s P_{ASE}^{(1)}} \]

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

Max reach

Optimal power
Validation

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

Validation: PSCF

$\alpha_c = 0.5 \text{ dB}$

$\alpha = 0.185 \text{ dB/km}$

$L_{\text{span}} = 80 \text{ km}$

$D = 20.6 \text{ ps/nm/km}$

$\alpha_c + \alpha_{\text{GFF}} + \alpha_{\text{L}_{\text{span}}} = 20 \text{ dB}$

Properly adjusted in order to have transparency conditions

$G_{\text{HFA}} = G_{\text{RA}} + G_{\text{EDFA}} = 20 \text{ dB}$

$P_{N,HFA} = hB_n (G_{\text{HFA}} - 1) F_{eq}$
Flattened $G_{RA}$ vs. $P_{pump}$

$G_{RA}$ vs. $P_{pump}$

$F_{eq}$ vs. $P_{pump}$

NLI with RA vs. NLI w/o RA

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

Contour plot of $\sigma$
Max reach: theory

![Graph showing Maximum Reach: Theory](image)

Max reach: theory + simulations

![Graph showing Maximum Reach: Theory + Simulations](image)
Max reach vs. $P_{\text{pump}}$: theory + simulations

Validation: NZDSF

\[ P_{N,\text{HFA}} = h f B_n \left( G_{\text{HFA}} - 1 \right) F_{eq} \]
NZDSF: HFA behavior

Flattened $G_{RA}$ vs. $P_{pump}$  

$F_{eq}$ vs. $P_{pump}$

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)

Predistortion ECOC 2012 Paper We.2.C.5
Max reach: theory+simulation

No predistortion

$F_{eq} = -2.1 \, \text{dB}$

$F_{eq} = 1.3 \, \text{dB}$

Theory is a worst-case

Max reach: theory+simulation

10 spans predistortion

$F_{eq} = -2.1 \, \text{dB}$

$F_{eq} = 1.3 \, \text{dB}$

Excellent agreement
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

Acknowledgements

This work was supported by CISCO Systems within a SRA contract

The simulator OptSim™ was supplied by RSoft Design Group (now part of Synopsys)