Comparison between different configurations of Hybrid Raman/Erbium-Doped Fiber Amplifiers

A. Carena, V. Curri, P. Poggiolini

ARTIS Software Corporation
San José
California
RnD@artis-software.com
www.artis-software.com

Dipartimento di Elettronica
Politecnico di Torino
Torino - ITALY
OptCom@polito.it
www.optcom.polito.it

Purposes of the Work

- Why Hybrid Raman/Erbium-Doped Fiber Amplifiers ?
- The *Non-Linear Weight*: comparison of HFA configurations.
- Definition of a general multi-span system structure.
- A closed form analysis providing the maximum reachable distance vs. the span length, given a target *OSNR* and *Non-Linear Weight*.
- Description of the design process using the described analysis and simulation results.
- An example: design of 32 x 40 Gbit/s NRZ system in the C bandwidth.

Why Hybrid Amplification?

Pros Raman vs. EDFA

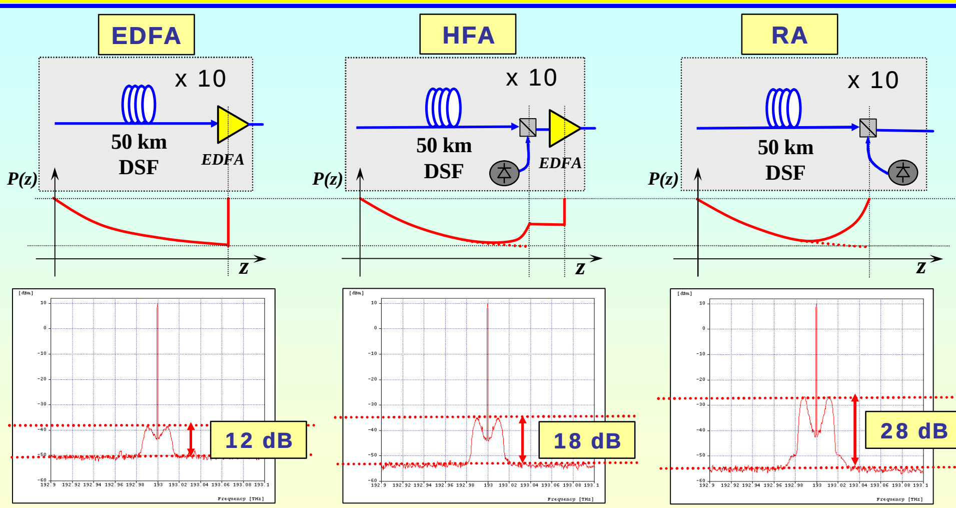
- Distributed amplification
- Lower amount of ASE noise
- Larger bandwidth
- Gain-shape can be designed
- Theoretically available in S, C, L bandwidth
- Allow to enlarge the fiber-span
- Easier upgrade of installed systems

Cons Raman vs. EDFA

- High gain -> high propagating power
- Rayleigh scattering may limit performance
- X-talk signal-pump-signal (in co-prop scheme)
- No saturation working-mode in order to define output power
- Same input power -> Higher impact of non-linearity

HFA

Non-Linear Impact: EDFA vs. RA



Using the same transmitted power (P_{TX}=10 dBm) different configurations of HFA can not be directly compared

Non-Linear Weight

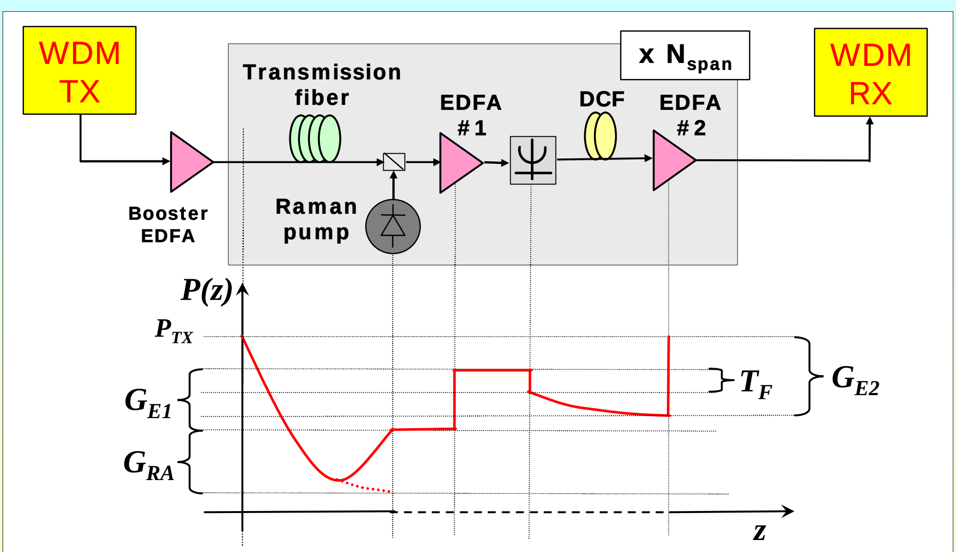
Non-linear weight definition

$$K_{NL} = \int_0^{L_{link}} g(z) P(z)\,dz \quad [rad/ch]$$

It is the overall non-linear phase-shift that one channel experiences along the system.

It allows to compare systems based on the same modulation format, number of channels and channel spacing, and using the same fiber.
Total link lengths may be different as well as the span lengths.

The Analyzed Set-Up



Optimization Parameters

Transparency condition

$$G_{TOT} = G_{RA,dB} + G_{E1,dB} + G_{E2,dB} = a_{S,dB} L_{span} + T_{F,dB} + a_{DCF,dB} L_{DCF}$$

G_{TOT} is defined but individual gains are undetermined

Definition of gain values through parameters k_1 and k_2 is the goal of the process

$$k_2 = \frac{G_{RA,dB} + G_{E1,dB}}{G_{TOT}}$$

Sets the amount of gain of the HFA made by RA+EDFA#1 and of EDFA#2 . Controls the input power of the DCF.

$$k_1 = \frac{G_{RA,dB}}{G_{RA,dB} + G_{E1,dB}} = \frac{G_{RA,dB}}{k_2 G_{TOT}}$$

Defines individual gains of RA and EDFA#1 .

OSNR as a Function of k_{NL}

$OSNR$ at the end of the considered optical link

$$OSNR = \frac{P_{TX}}{hfB_O N_{span}\left[\left(n_{eq,RA} + n_{sp,E1}\frac{G_{E1}-1}{G_{E1}G_{RA}}\right)\exp\left(+a_S L_{span}\right) + n_{sp,E2}\left(G_{E2}-1\right)\right]}$$

We use the *Non-Linear Weight* in order to compare configurations with different parameters: individual gains, span length, total length.

$$P_{TX} = \frac{k_{NL}}{N_{span}[g\, L_{eff} + g_{DCF}\exp(-a_S L_{span})\, G_{RA} G_{E1} T_F L_{eff,DCF}]}$$

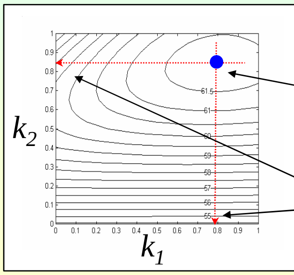
Parameter $OSNR_1$

$$OSNR = \frac{k_{NL} P_1}{N_{span}^2 N_1} = \frac{k_{NL}}{N_{span}^2} OSNR_1$$

Value of P_{TX} which makes $k_{NL} = 1$ after only one span (P_1)

Amount of noise entering the system every span (N_1)

For each L_{span}



$OSNR_1^{opt} = \max\{OSNR_1\}$

$(k_1, k_2)_{opt}$ → G_{RA}^{opt}, G_{E1}^{opt}, G_{E2}^{opt}

Maximum Reachable Distance

L_{span} → $OSNR_1^{opt}$ → G_{RA}^{opt}, G_{E1}^{opt}, G_{E2}^{opt}

$$L_{\max} = \text{int}\left\{\sqrt{\frac{k_{NL}^{\max}}{OSNR_{\min}} OSNR_1^{opt}}\right\} L_{span}$$

$L_{\max} = f(L_{span})$ given $k_{NL}^{\max}$, $OSNR_{\min}$

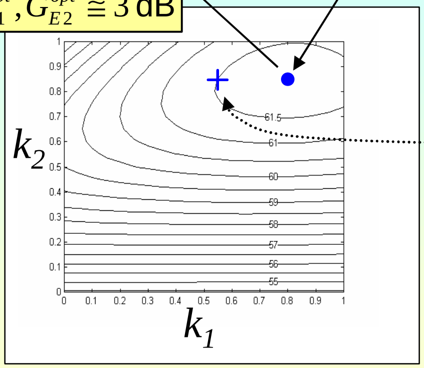
$L_{\max} = f(k_{NL}^{\max})$ given L_{span}, $OSNR_{\min}$

$L_{\max} = f(OSNR_{\min})$ given $k_{NL}^{\max}$, L_{span}

Contour plot of $OSNR_1$ in the (k_1,k_2) space

$$(k_1,k_2)_{opt} = (0.80.0.85)$$

$$G_{RA}^{opt} \cong 12\text{ dB}$$
$$G_{E1}^{opt}, G_{E2}^{opt} \cong 3\text{ dB}$$



L_{span}= 50 km - SMF fiber

$OSNR_1$ is less sensitive to a sub-optimal choice of k_2 than of k_1

$$G_{RA}^{sub-opt} \cong 8\text{ dB},\ G_{E1}^{sub-opt} \cong 7\text{ dB}$$
$$G_{E2}^{sub-opt} \cong 3\text{ dB}$$

$$OSNR_1^{opt} - OSNR_1^{sub-opt} < 1\text{ dB}$$

$$L_{max}^{sub-opt} > 0.9 L_{max}^{opt}$$

The Design Process

Max *BER*

Margin

Max K_{NL}

L_{span}

Max G_{RA}

Min *OSNR*

Optimal $OSNR_1$

$$L_{max} = \text{int}\left\{\sqrt{\frac{k_{NL}^{max}}{OSNR_{min}} OSNR_1^{opt}}\right\} L_{span}$$

G_{RA}

G_{E1}

G_{E2}

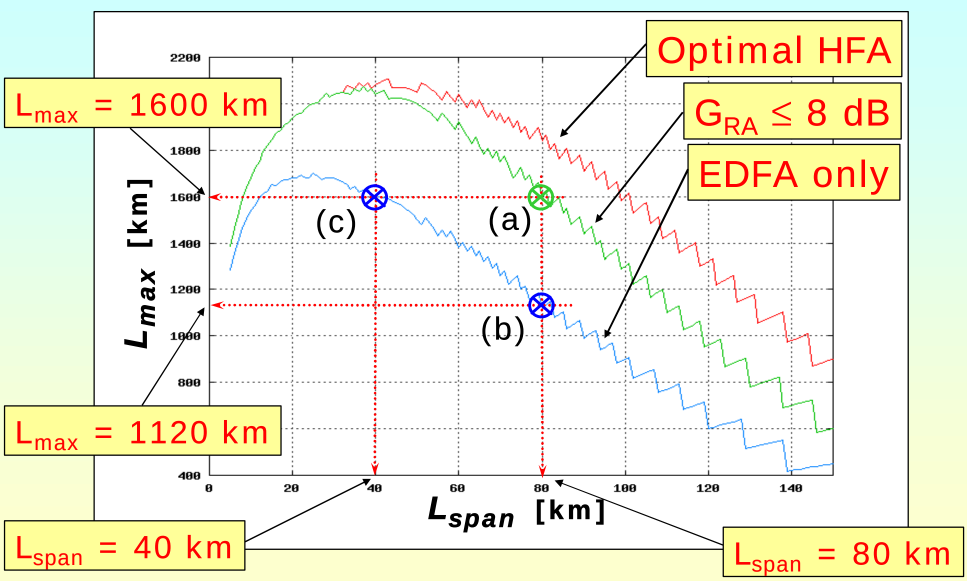
L_{max}

Simulation of the system in order to check the propagation impairments

Example: description

- 32 x 40 Gbit/s NRZ channels, 100 GHz spaced
- Transmission fiber: D=5 ps/nm/km, A_{eff}=55 μm^2
- DCF: D=-100 ps/nm/km, A_{eff}=25 μm^2
- Dispersion perfectly compensated at the receiver
- Raman amplification: two-pump with G_{RA}<8 dB
- EDFAs: flat gain and NF=4.5 dB
- GFF loss: 2 dB
- Target OSNR: 15 dB over 0.5 nm Þ BER $<10^{-9}$ Þ using FEC RS(255,239) Þ 3 dB margin to get BER$<10^{-12}$
- **Goal:** maximum reachable distance with pseudo-linear propagation (k_{NL}=0.25 rad/channel)

L_{max} vs. L_{span}

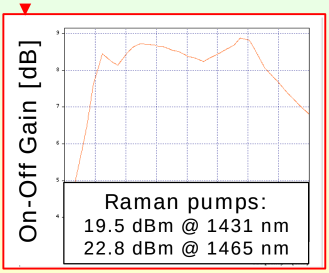


Simulated Systems Using OptSim

HFA, $G_{RA} \leq 8$ dB

(a)

P_{TX} = -5.6 dBm/ch
L_{span} = 80 km
L_{TOT} = 1600 km
G_{RA} = 8 dB
G_{E1} = 8 dB
G_{E2} = 4 dB



EDFA only

(b)

P_{TX} = -2.9 dBm/ch
L_{span} = 80 km
L_{TOT} = 1120 km
G_{E1} = 12 dB
G_{E2} = 8 dB

(c)

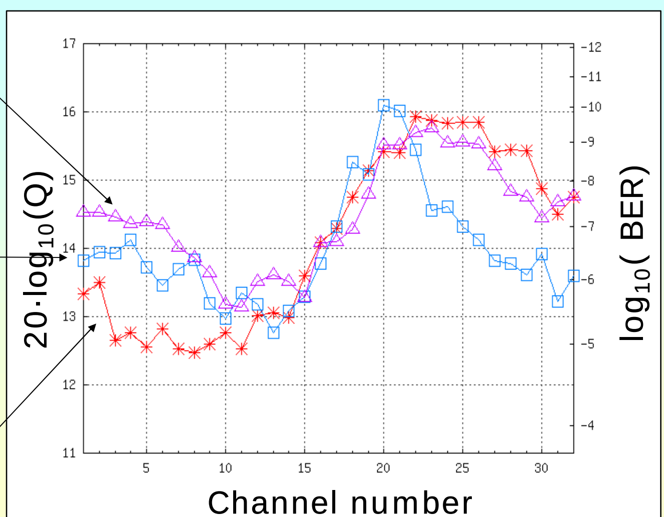
P_{TX} = -7.1 dBm/ch
L_{span} = 40 km
L_{TOT} = 1600 km
G_{E1} = 8.8 dB
G_{E2} = 2.2 dB

Simulation Results: Comparison

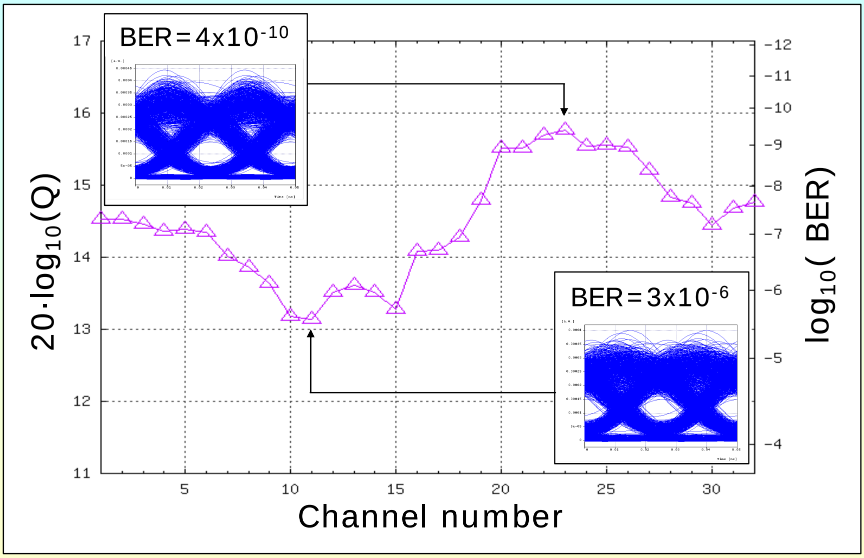
HFA
20 x 80 km

EDFA
40 x 40 km

EDFA
14 x 80 km



Simulation Results: HFA System



Conclusions

- It has been derived a closed-form analysis giving the maximum reachable distance using the optimal HFA.
- A design process for HFAs has been described for DWDM systems.
- The design process has been applied to a 32 x 40 Gbit/s NRZ system.
- Results demonstrate:
  - non-linear weight is a good parameter for comparison of different system configurations;
  - use of HFAs enlarge the maximum reachable distance.
- Further investigation: simultaneous optimization of HFA and dispersion map.