Modeling of WDM systems in Highly and Weakly Dispersive Nonlinear Regimes

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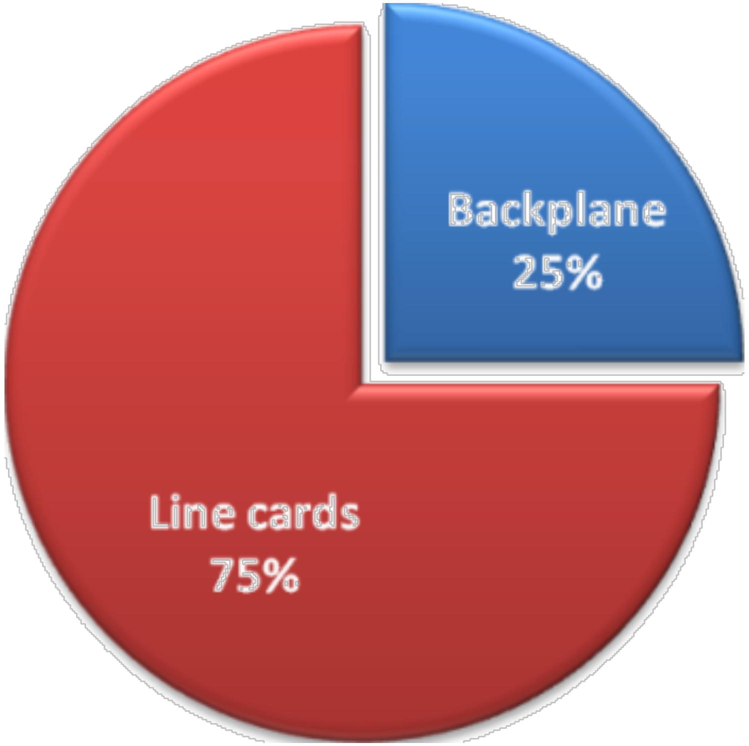
Outline

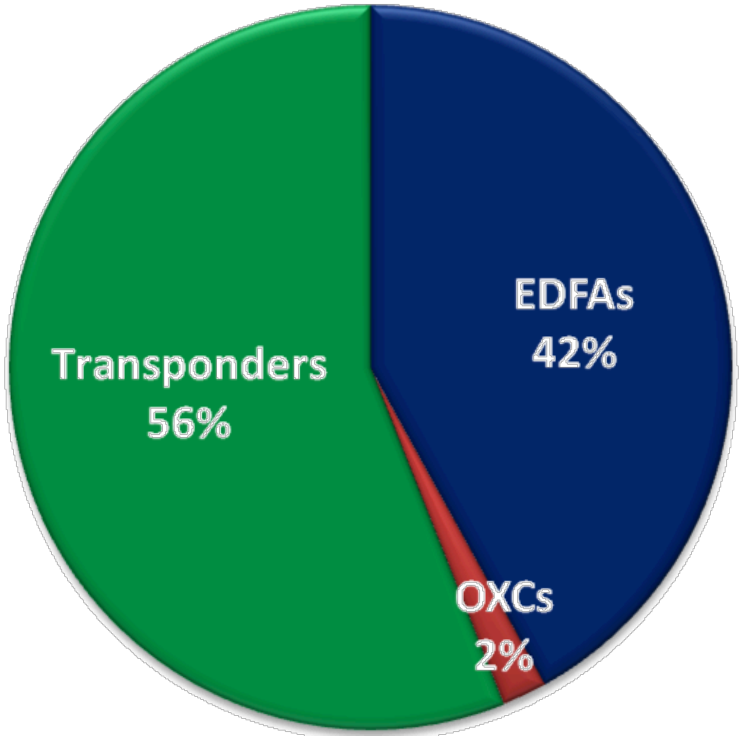
- For network design simple methods to evaluate system performance are necessary taking into account Kerr effect (ITU-T SG15 G.680). The energy saving topic!
- Performance evaluation models in highly dispersive regime
- Importance of Gaussian models
- Here a simple Q factor theoretical approach is adopted for mixed line rate WDM systems, tested with simulations

Power Consumption in Core Networks

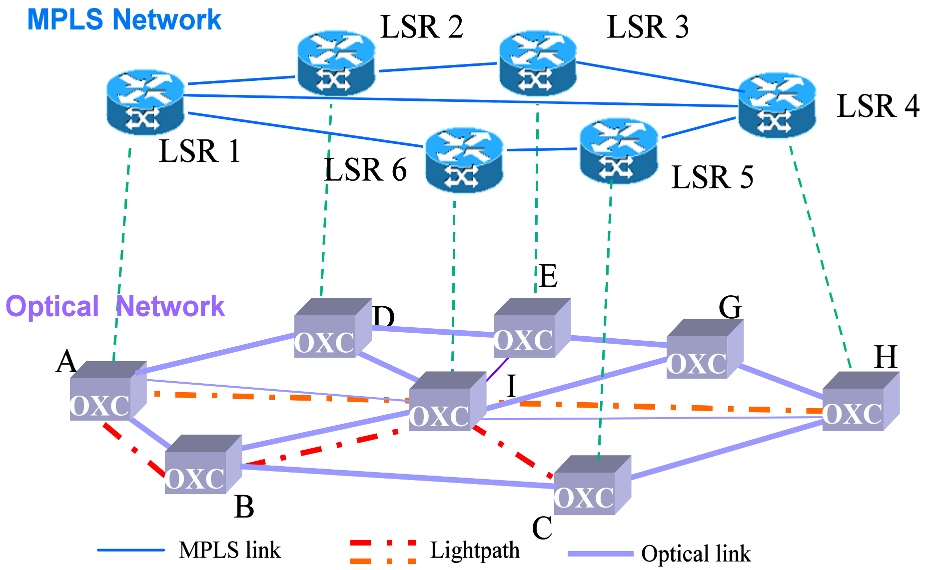
IP network layer

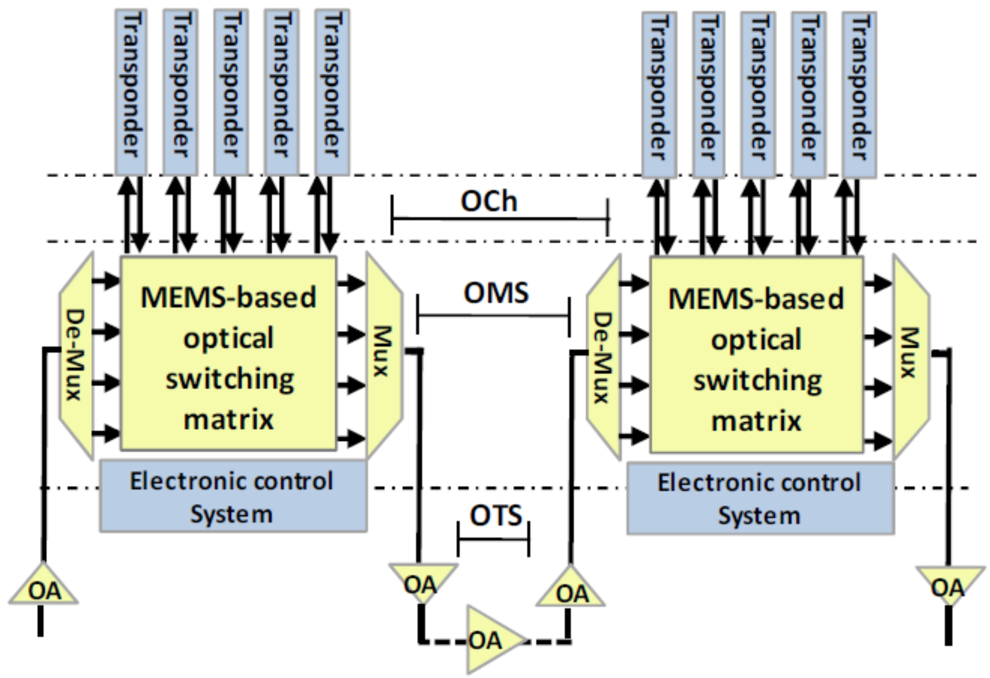


WDM network layer



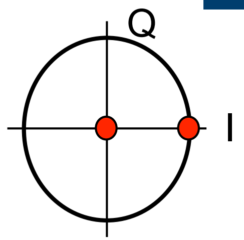
Network Model





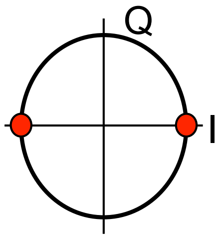
Routing vs Optical paths?

Modulation formats



IM-DD

- ☺ Sistema consolidato
- ☺ Semplici TX e RX
- ☹ Forti limitazioni a sostenere bit rate elevati

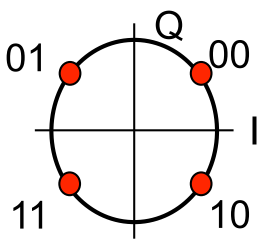


PSK

- ☺ Limite quantico si riduce a 18 fotoni/bit e 3 dB in più
- ☹ Ricezione coerente con PLL ottico

DPSK

- ☺ Non necessita di rivelazione coerente
- ☹ Aumenta la complessità del TX e RX rispetto L'IM-DD



QPSK

- ☺ Efficienza spettrale doppia → tolleranza alla CD e PMD
- ☹ Ricezione coerente con PLL ottico

DQPSK

- ☺ Efficienza spettrale doppia
- ☺ Non necessita di rivelazione coerente
- ☹ Aumenta la complessità del TX e RX rispetto al DPSK

WDM systems

- Nx100 Gb/s, mx400 Gb/s
- Managed dispersion compensation (in-line) vs unmanaged dispersion compensation (all at the End)
- Coherent detection (100 Gb/s Polmux-QPSP)
- Mixed line rate

$$Q = \frac{\langle \Im_1 \rangle - \langle \Im_0 \rangle}{\sigma_1 + \sigma_0}$$

Theoretical Overview: Highly Dispersive Regime (HDR)

- Gaussian Noise model for WDM

  Poggiolini, J. Lightwave Technol. **31** 446 (2013).

- Single-channel Time domain approach

  Mecozzi, Matera, Settembre, Tabacchiera, Opt. Expr. (2011), sing. Ch.
  Mecozzi Matera, Opt. Lett. **19** 3903 (2011). Polmux

- WDM time-domin approach

  Mecozzi, Essiambre, J. L.T (2012) stat. independence of frequencies

- Discrete –Time channel model

  Secondini, Forestieri, Prati J. L.T (2013) Modulation format

- Time domain approach: Limits of Gaussian approach

  Dar, Feder, Mecozzi,Shtaif, Optics express 2013, stat. dependence of frequencies

Theory (1): HDR

Matera, ECOC 2013, single channel:

$$Q = \frac{\sqrt{P_{AV}}}{\sqrt{\xi R_b N_{ASE} N + \rho \gamma^2 P_{AV}^3 L_{NLI}{}^2}}$$

P_{AV} input signal average power, $N_0 = \hbar \omega_0 (G-1) n_{sp}$

R_b boud rate, ξ depends on modulation-detection format

L_{NLI} Nonlinear Interaction Length, obtained by the variance of the photodiode current; f(pulse duration, loss, GVD, boud time); see:

DQPSK and DPSK: Mecozzi, Matera, Settembre, Tabacchiera, Opt. Expr. (2011.

N Fiber spans, ρ takes into account Polmux

Theory (2): HDR

WDM approach

Mecozzi, Essiambre, J. L.T (2012) stat. independence of frequencies

$$Q = \frac{\sqrt{P_{AV}}}{\sqrt{\xi R_b N_{ASE} N + \rho \gamma^2 P_{AV}^3 L_{NLI}{}^2 + \frac{4\gamma^2 P_{Av}^3 L S_B}{|\beta_2| R_b^2}}}$$

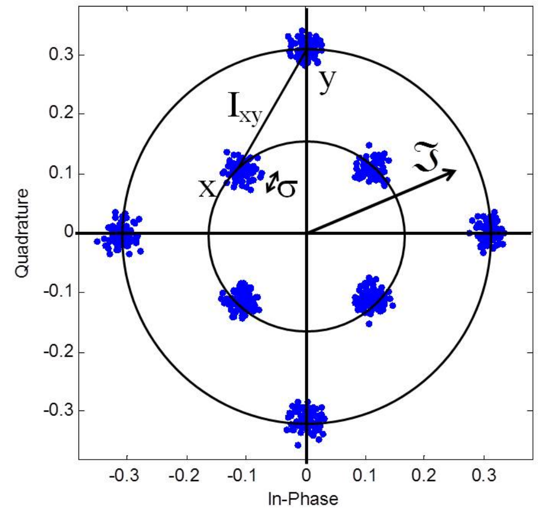
$$\sigma_{WDM}^2 = \frac{4\gamma^2 P_{Av}^3 L S_B}{|\beta_2| R_b^2} \qquad S_B \approx \frac{\kappa R_b}{\pi \Delta f}\left[\ln(m/2) + 0.57\right]$$

Δf frequency spacing; κ depends on modulation ring

Bosco, Poggiolini, Curri, Carena, Fotonica 2013, Milan (IT) May 21-23, 2013

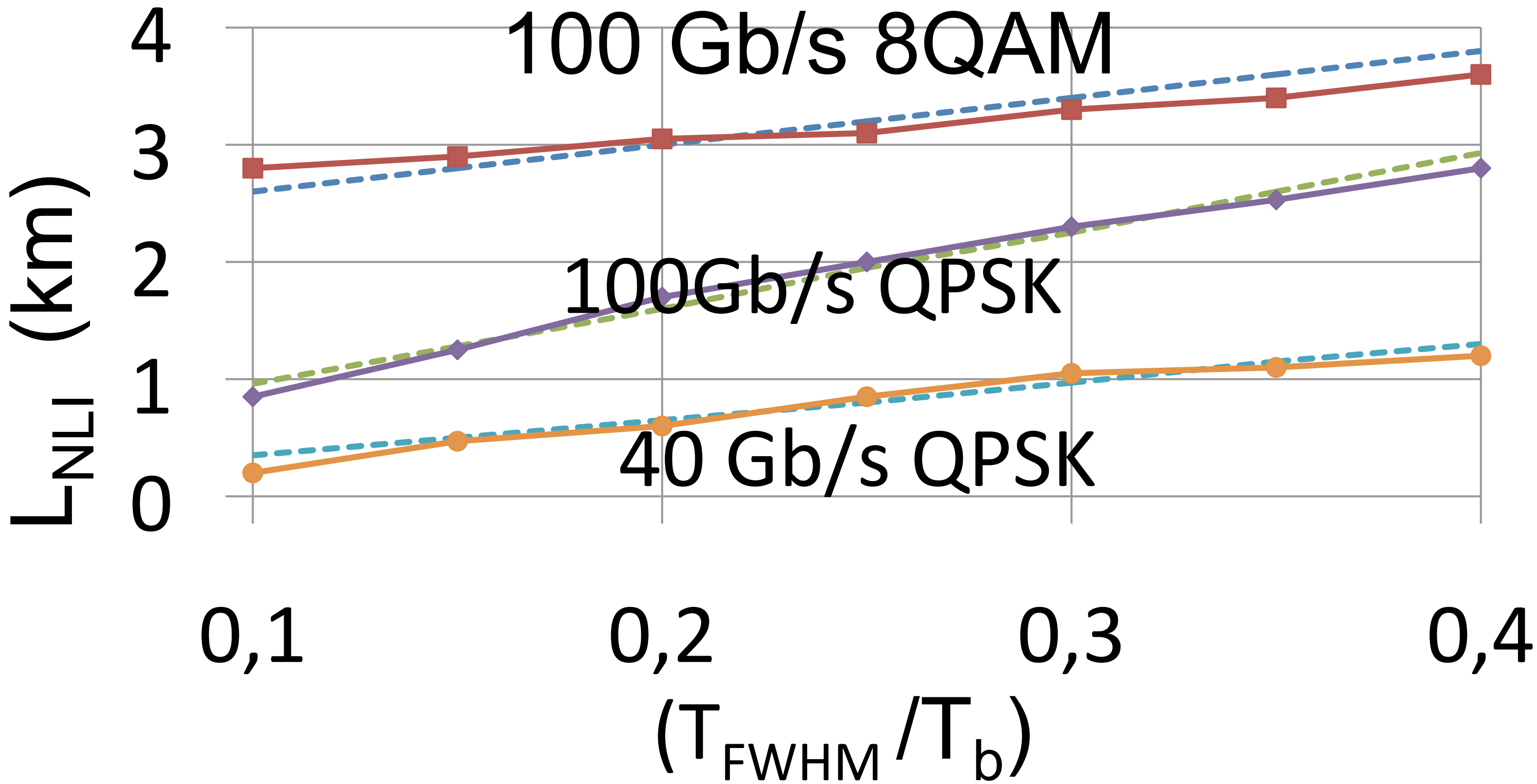
Simulation model

- Split-step method
- IM-DD, DPSK, DQPSK, QPSK, 8QAM
- Polarization multiplexing
- 4096 symbols



γ=1.3 $W^{-1}km^{-1}$, GVD=16 ps/nm/km,
loss=0.25 dB km, Lamp=100 km

NonlinearInteraction Length



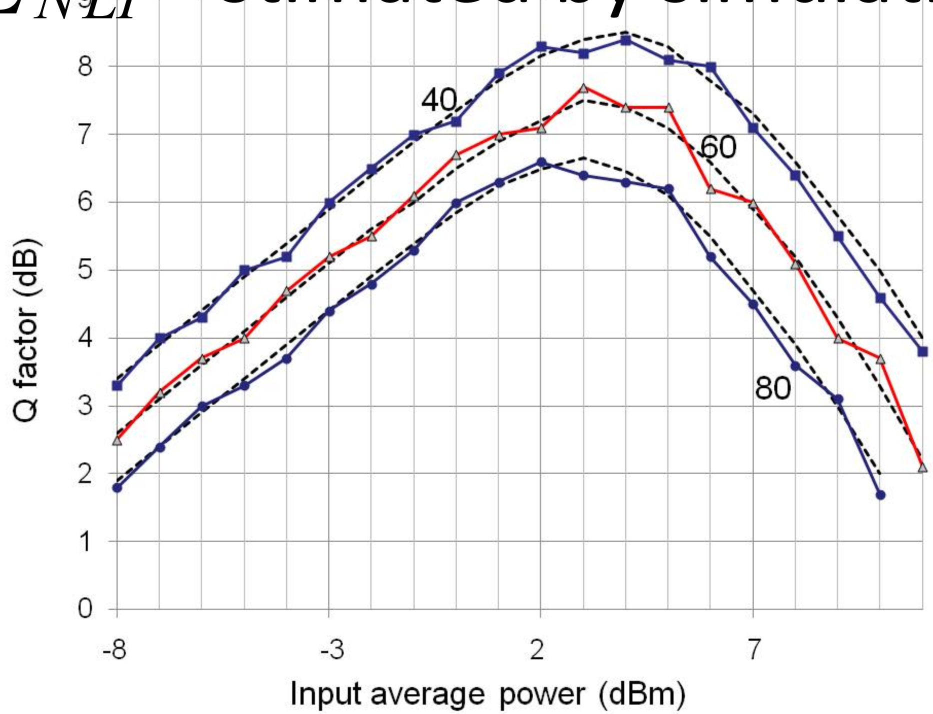
L_{NLI} N for in-line compensation

N^{Γ} for compensation all at the end, $0.5<\Gamma<1$

Weakly dispersive regime?

L_{NLI} : theoretical calculation does not coincide with simulations but still valid 1/P Q factor behavior

L_{NLI} * stimated by simulation



10 Gb/s IM-DD system in a link composed by N (40, 60, 80), G.652 fibres. The chromatic dispersion is compensated at each span output. Dashed lines theoretical Q factor , solid lines simulations.

General Q factor evaluation for Mixed line Rate

Channels statistically independent

$$\sigma^2_{WDM} = \sum_i \frac{4\gamma^2 P^3_{Avi} L_A N_i S_{Bi}}{|\beta_2| R^2_{bi}} \qquad S^2_{Bi} = \kappa_i \frac{1}{2\pi T \Delta f_i}$$

L_{NLI} is evaluated theoretically in highly dispersive regime, stimated by simulations for weakly dispersive (10 Gb/s)

For exact evaluation…

- To take into account all the SPM and XPM effects the Mecozzi model can be adopted and you may evaluate your system performance at

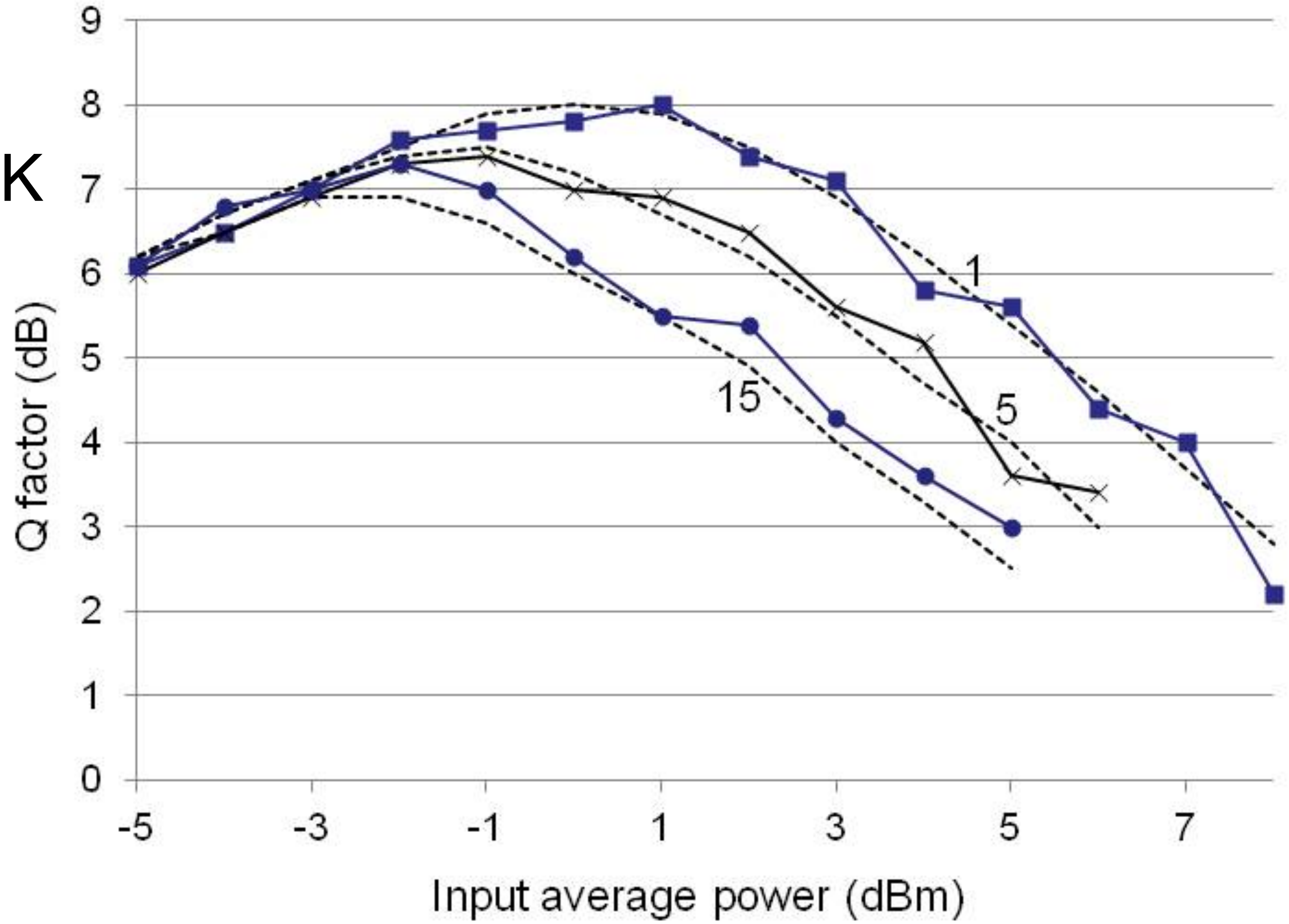
  http://nlinwizard.eng.tau.ac.il

Dar, Feder, Mecozzi,Shtaif, Optics express 2013, stat. dependence of frequencies

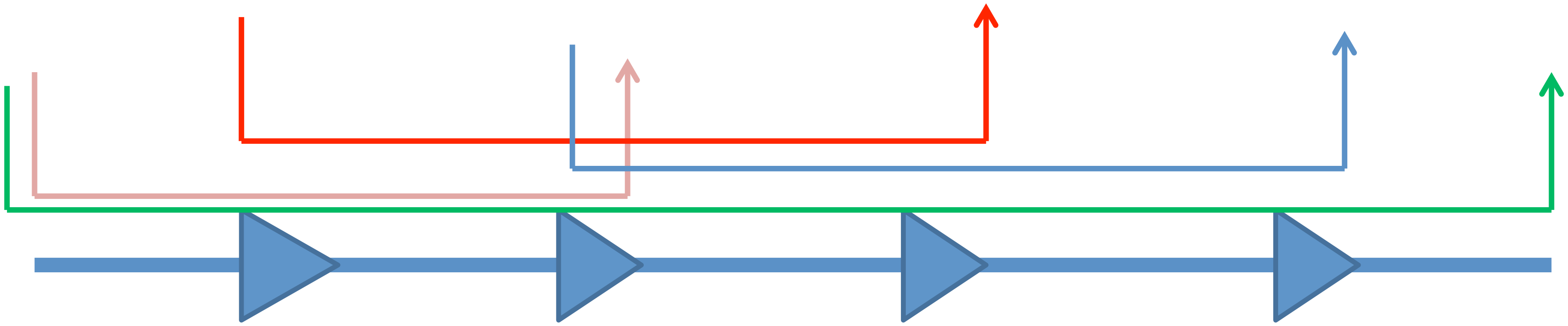
WDM FIXED LINE RATE

100 Gb/s DQPSK

Comp. All at the End

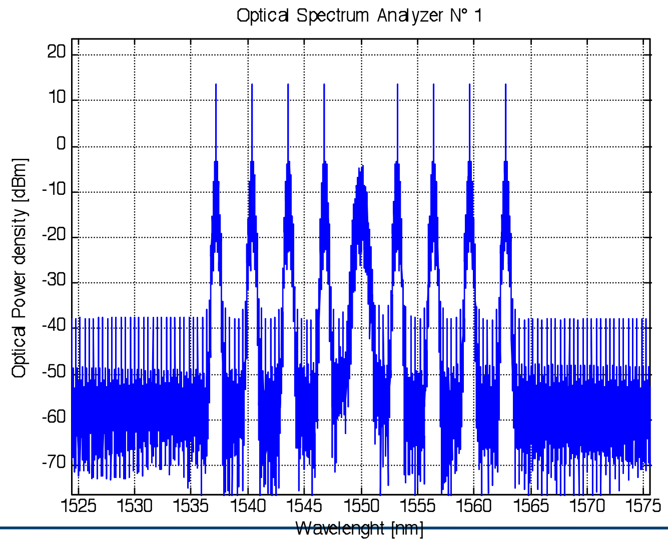


Link characteristics



Link parameters

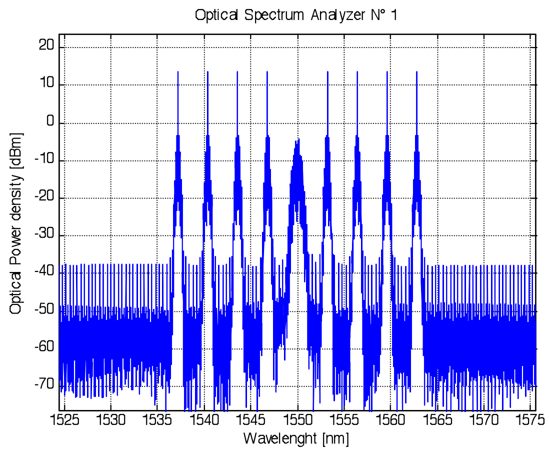
γ=1.3 $W^{-1}km^{-1}$, GVD=16 ps/nm/km,
loss=0.25 dB km, Lamp=100 km

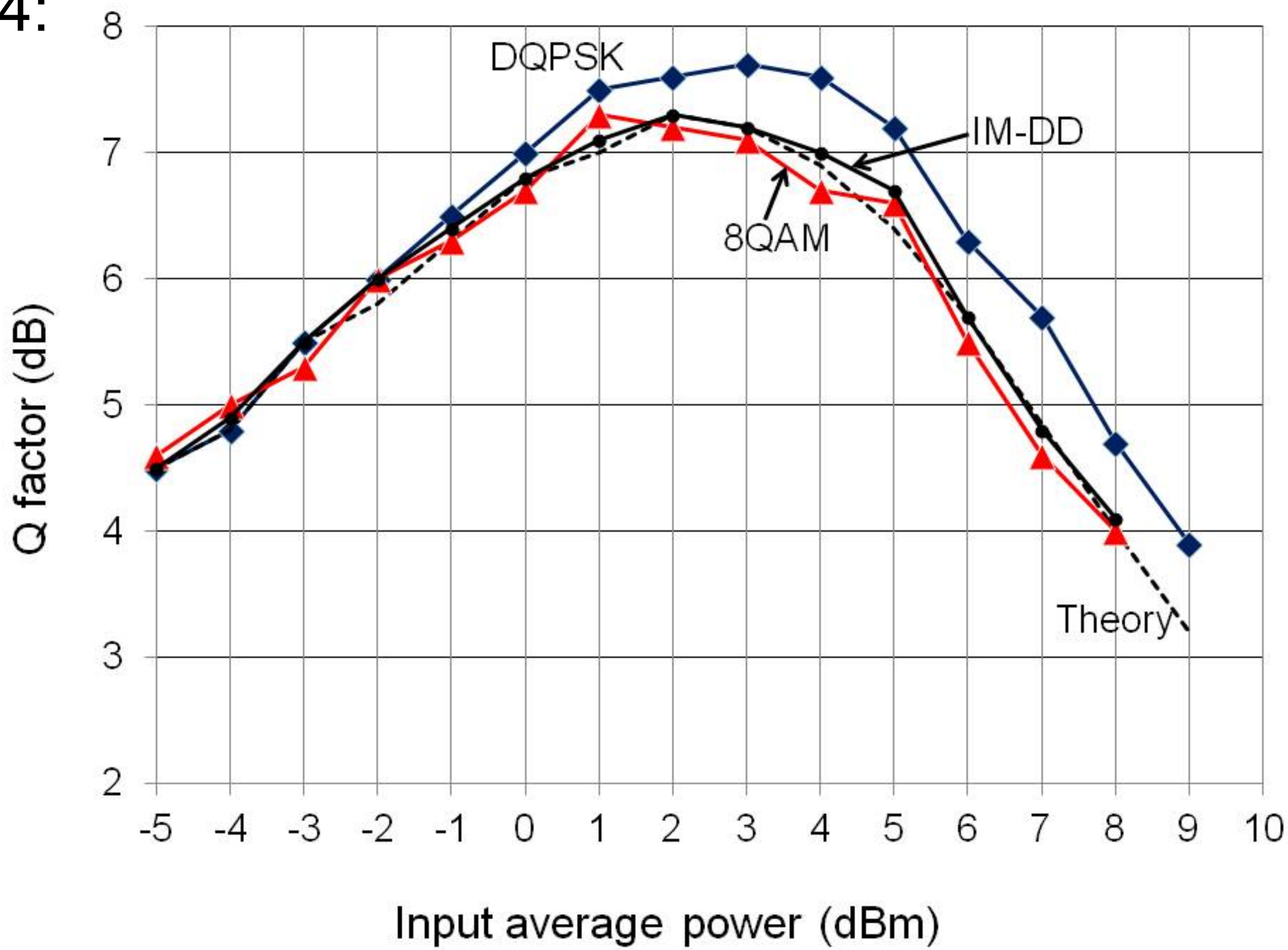


Mixed Line Rate

100 Gb/s 8QAM +4+4:
100 Gb/s DQPSK;
100 Gb/s 8QAM;
10 Gb/s IM-DD

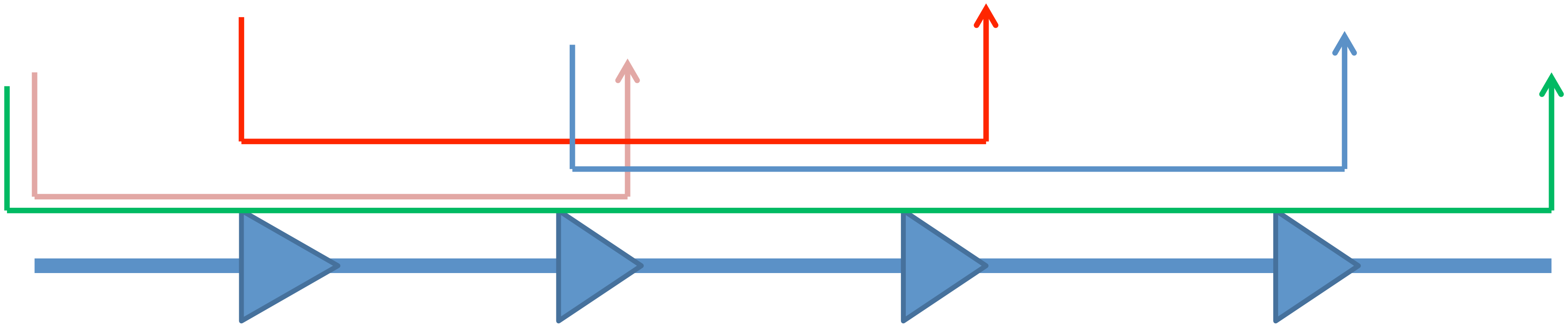
Compensation *all at the end*.





FUB Ricerca e Innovazione

Link characteristics



Ideal Add drop, 30 channels, 1000 km

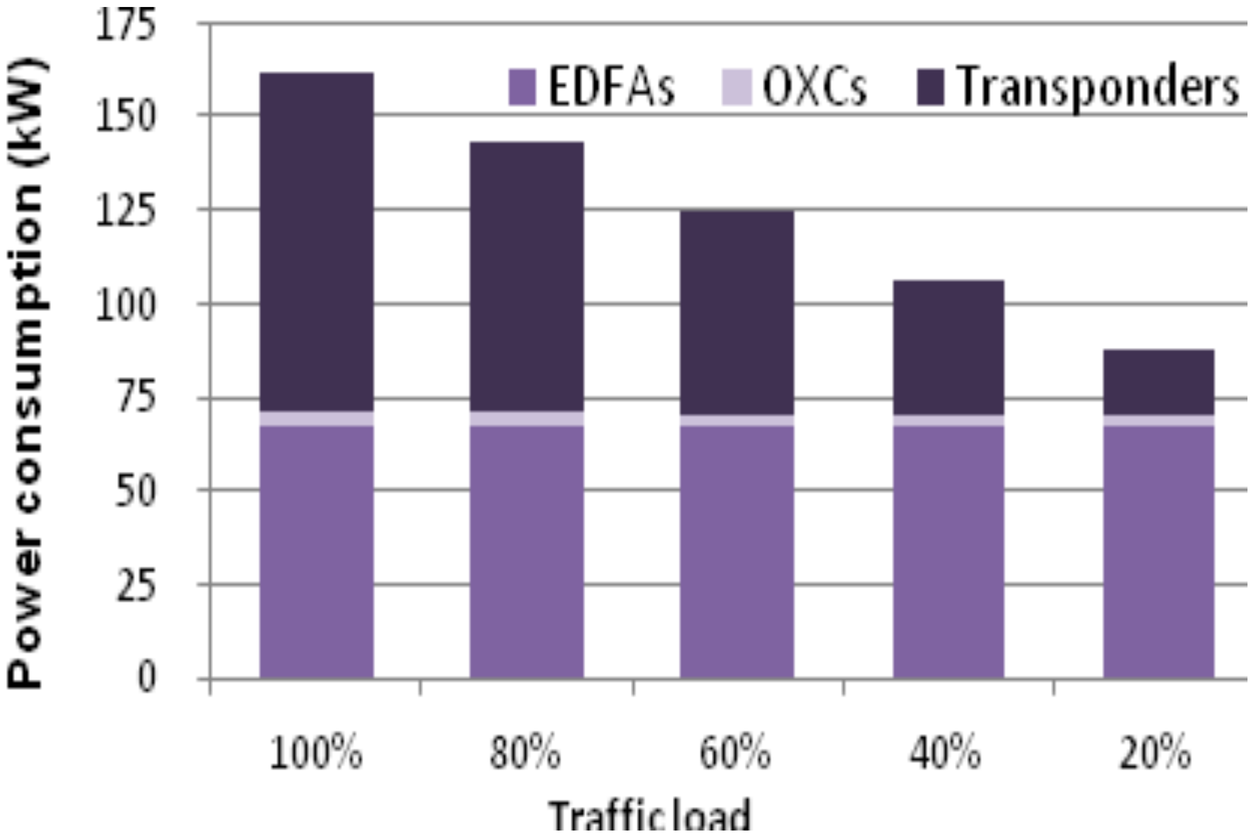
IM-DD, DQPSK, QPSK, 8QAM; RZ gaussian pulse

γ=1.3 $W^{-1}km^{-1}$, GVD=16 ps/nm/km,
loss=0.25 dB km, Lamp=100 km

WDM link performance

System	(ps) τ_{FWHM}	(km) L_{NLI-0}	path	P_{Av} (dBm)	Freq. posit.	Qth	Qsim
6x40 Gb/s IM-DD	5	0.96	1-6	2	1,2,3,4 ,5,8	6.3	6.5
9x10 Gb/s IM-DD	25	0.13	1-10	0	6,7,91 0,11 12,13 17,18	6.2	6.8
3x40 Gb/s DPSK	5	0.86	4-10	2	14,15, 16	6.2	6.5
4x100 Gb/s 8QAM	7.5	3.46	3-7	4	19,20 21,22	6.5	6.8
4x100 Gb/s DQPSK	5	2.5	3-9	4	23,24 25,26	6.1	6.6
4x100 Gb/s QPSK	5	2.6	3-10	4	27,28 29,30	6	6.5

Power Consumption



Conclusions

- Proposed a simple approximated analytical approach to evaluate the performance of MLR WDM links
- Main limitations for mixed IM-PM systems (some dB)
- Useful for Network design: i.e. Wavelength assign and energy saving
- Further investigation on short links