Symposium on Challenges to Achieving Capacity in Nonlinear Optical Networks

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Modelling and mitigation of fibre nonlinearity in WDM coherent optical systems

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OPTCOM

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Outline

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- **Modelling of fibre nonlinearity**
  - Modelling approximations
  - The GN/EGN model family
- **Mitigation of fibre nonlinearity**
  - Theoretical limits
  - Practical performance limits

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MODELLING OF FIBRE NONLINEARITY

Non-linear fibre propagation models

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- Any form of analytical description of the non-linear behaviour of the optical fibre
- Example: coupled non-linear Schrödinger equations

$$\boxed{\begin{aligned}\frac{\partial A_x}{\partial z}+\beta_{1x}\frac{\partial A_x}{\partial t}+\frac{i\beta_2}{2}\frac{\partial^2 A_x}{\partial t^2}+\frac{\alpha}{2}A_x&=i\gamma(|A_x|^2+B|A_y|^2)A_x\\ \frac{\partial A_y}{\partial z}+\beta_{1y}\frac{\partial A_y}{\partial t}+\frac{i\beta_2}{2}\frac{\partial^2 A_y}{\partial t^2}+\frac{\alpha}{2}A_y&=i\gamma(|A_y|^2+B|A_x|^2)A_y\end{aligned}}$$

G. P. Agrawal, *Nonlinear Fiber Optics*, 4th edition. Academic Press, 2007, Chapter 6.

  - Numerical integration within a Monte-Carlo simulation environment
- Goal: to find simpler yet accurate models in order to quantify the system impact of the fibre non-linear behaviour

First approximation: the Manakov equation

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$$\begin{cases} \dfrac{\partial A_x(z,t)}{\partial z} = j\dfrac{\beta_2}{2}\dfrac{\partial^2}{\partial t^2}A_x(z,t) - \alpha A_x(z,t) - j\gamma\dfrac{8}{9}\left[\left|A_x(z,t)\right|^2 + \left|A_y(z,t)\right|^2\right]A_x(z,t) \\ \dfrac{\partial A_y(z,t)}{\partial z} = j\dfrac{\beta_2}{2}\dfrac{\partial^2}{\partial t^2}A_y(z,t) - \alpha A_y(z,t) - j\gamma\dfrac{8}{9}\left[\left|A_x(z,t)\right|^2 + \left|A_y(z,t)\right|^2\right]A_y(z,t) \end{cases}$$

- It's based on an analytical average over the random evolution of the state-of-polarization (SOP) along the fibre
- It captures the non-linear effects of one polarization onto the other, but averages over the fast dynamic of SOP variations
- It neglects both linear and nonlinear effects of PMD

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Families of models

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- Examples:
  - time domain
  - frequency domain
  - Volterra-based
  - first order perturbation
  - higher-order perturbation
  - regular perturbation (RP, with variants)
  - logarithmic perturbation (LP, with variants)
  - pulse-collision based
  - more classes and sub-classes based on specific assumptions and approximations…
- In this talk, I will focus on **frequency-domain RP first-order models**

OPTCOM 6

Modelling approximations

- Perturbation approach
- NLI as additive Gaussian noise
- Locally white NLI
- Signal Gaussianity
- Incoherent NLI accumulation
- Single-polarization
- Lossless fibre
- Noiseless propagation
- ….

First-order regular perturbation

- Assumptions:
  - The signal propagates linearly from input to output
  - At each point along the fibre, it excites fibre nonlinearity and creates the NLI disturbance
  - At the end of the fibre, the linearly propagated signal and the NLI are summed (NLI noise can be represented as an additive noise term)

$$s_{WDM}^{NL}(t) = s_{WDM}(t) + \boxed{s_{NLI}(t)}$$

NON-LINEAR INTERFERENCE (NLI)

- In the framework of first-order perturbation analyses, the NLI power is proportional to P_{ch}^3:

$$\boxed{P_{NLI} = \eta P_{ch}^3}$$

  - where η is a coefficient that depends on the fibre parameters and the transmitted signal characteristics.

NLI additive Gaussian noise approximation

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- Assumption:
  - the NLI at the output of the link can be represented as additive Gaussian noise, circular and independent of either the signal or ASE noise
- Key implication: the channel performance can be characterized based on a modified "non-linear" OSNR:

$$\boxed{OSNR_{NL} = \frac{P_{ch}}{P_{ASE} + P_{NLI}}}$$

  - P_{ch} : power of channel under test
  - P_{ASE} : power of ASE noise (e.g. $P_{ASE} = G_{ASE}(f_c) R_s = Fh\nu (G-1) N_{span} R_s$ with EDFA amp.)
  - P_{NLI} is the power of NLI

$$P_{NLI} = \frac{\int_{-\infty}^{+\infty} G_{NLI}(f + f_c) |H_{Rx}(f)|^2 \, df}{\int_{-\infty}^{+\infty} |H_{Rx}(f)|^2 \, df} R_s$$

Locally white NLI noise approximation

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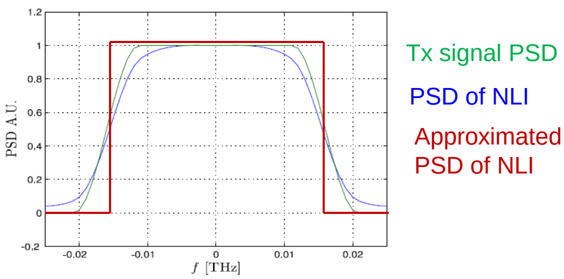
- Assumption:
  - the PSD of NLI is locally flat (over a single channel bandwidth)

$$P_{NLI} \cong \frac{\int_{-\infty}^{+\infty} G_{NLI}(f_c) |H_{Rx}(f)|^2 \, df}{\int_{-\infty}^{+\infty} |H_{Rx}(f)|^2 \, df} R_s = G_{NLI}(f_c) R_s$$

$$OSNR_{NL} = \frac{P_{ch}}{\left[G_{ASE}(f_c) + G_{NLI}(f_c) \right] R_s}$$



- This assumption is acceptable for approximate system performance assessment.
- It should be removed for high-accuracy predictions.

The signal Gaussianity approximation

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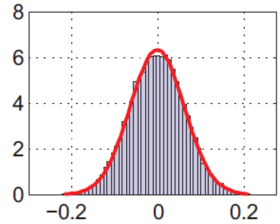
- Assumption:
  - the transmitted signal can be modelled as a stationary circular Gaussian noise, whose PSD is shaped as the PSD of the actually transmitted WDM channels.



500 km of SSMF fiber

- This approximation allows to drastically simplify the model derivation and strongly decreases the model final analytical complexity.

- Using this assumption, the impact of NLI is always overestimated for QAM transmission formats.

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The incoherent NLI accumulation approximation

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- Assumption:
  - the NLI produced in each span adds up incoherently (i.e., in power) at the receiver site.

$$G_{NLI}(f) \approx \sum_{n=1}^{N_{span}} G_{NLI}^{(n)}(f)$$

  - In reality, the NLI contributions should be added together coherently (i.e., at the field level) keeping both their amplitude and phase into account

- The accuracy of this approximation is quite poor at very low span count and at very low channel count.

OPTCOM 12

The EGN-GN model family

Assumption	EGN model	GN model	iGN model
Manakov equation	X	X	X
1st order regular perturbation	X	X	X
Signal Gaussianity		X	X
Incoherent NLI accumulation			X
NLI as additive Gaussian noise	*Approximations that can be applied to all models in order to simplify the computations*		
Locally white NLI			

- **iGN** – P. Poggiolini et al., "Analytical Modeling of Nonlinear Propagation in Uncompensated Optical Transmission Links", IEEE Photon. Technol. Lett. **23**(11), p. 742 (2011).
- **GN** – P. Poggiolini "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *J. Lightwave Technol.* **30**(24), p.3857 (2012).
- **EGN** – A. Carena et al., "EGN model of non-linear fiber propagation," *Opt. Exp.* **22**(13), p. 16335, 2014.

The simplest iGN closed-form solution

- All approximations listed in the previous slide, plus …
  - Equal spans
  - Equal channels (same power, same spectrum with bandwidth ~R_S)

$$\boxed{G_{\rm NLI}\left(f_c\right) = N_{span}\,\frac{16}{27}\,\frac{\gamma^2 L_{\rm eff}^2 P_{\rm ch}^3}{\pi\left|\beta_2\right|\alpha R_s^3}\,\mathrm{asinh}\left(\frac{\pi^2}{2\alpha}\left|\beta_2\right| R_s^2\left[N_{\rm ch}^2\right]^{\frac{R_s}{\Delta f}}\right)}$$

- The model equations become more and more complex, as well as more and more accurate, as the various assumptions are removed

The GN-model reference formula

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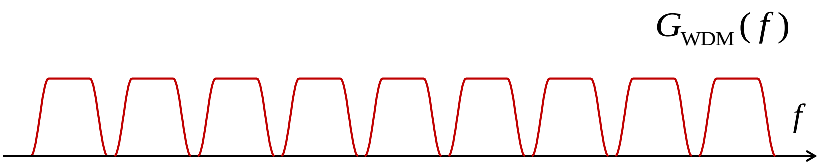
$$\boxed{G_{\mathrm{NLI}}(f)=\frac{16}{27}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_{\mathrm{WDM}}(f_1)G_{\mathrm{WDM}}(f_2)G_{\mathrm{WDM}}(f_1+f_2-f)\cdot\left|\mu(f_1,f_2,f)\right|^2\,\mathrm{d}f_1\mathrm{d}f_2}$$

FWM efficiency of the whole link



- For identical spans with lumped amplification:

$$\left|\mu(f_1,f_2,f)\right|^2=\gamma^2L_{\mathrm{eff}}^2\left|\frac{1-e^{-2\alpha L_s}e^{j4\pi^2\beta_2L_s(f_1-f)(f_2-f)}}{1-j2\pi^2\beta_2\alpha^{-1}(f_1-f)(f_2-f)}\right|^2\frac{\sin^2\left(2N_s\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}{\sin^2\left(2\pi^2(f_1-f)(f_2-f)\beta_2L_s\right)}$$

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The EGN model

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- EGN model stands for “enhanced GN model”
- The EGN model consists of the GN model and of a “correction” term:

$$G_{\mathrm{NLI}}^{\mathrm{EGN}}(f)=G_{\mathrm{NLI}}^{\mathrm{GN}}(f)-G_{\mathrm{NLI}}^{\mathrm{corr}}(f)$$

- For PM-QAM systems the “correction” always decreases NLI
  - this shows the GN-model to be some sort of “upper bound” to NLI

OPTCOM 16

Components of NLI

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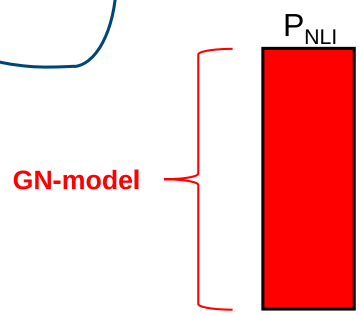
Long-correlated phase and polarization rotation (PPRN) noise

Format-dependent

Short-correlated circular noise

Mainly format-independent



- Negligible for constant-modulus formats
- Increases with the cardinality of the constellation
- Maximum for Gaussian constellation
- Can be partially mitigated by CPE

OPTCOM 17

Components of NLI

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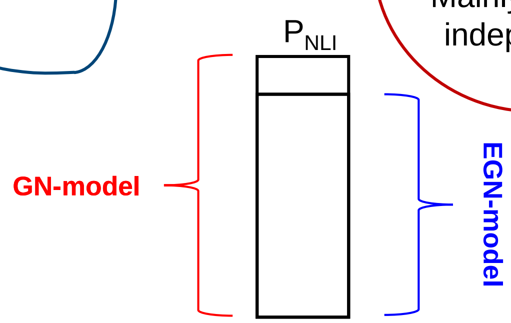
Long-correlated phase and polarization rotation (PPRN) noise

Format-dependent

Short-correlated circular noise

Mainly format-independent



- Negligible for constant-modulus formats
- Increases with the cardinality of the constellation
- Maximum for Gaussian constellation)
- Can be partially mitigated by CPE

OPTCOM 18

Components of NLI

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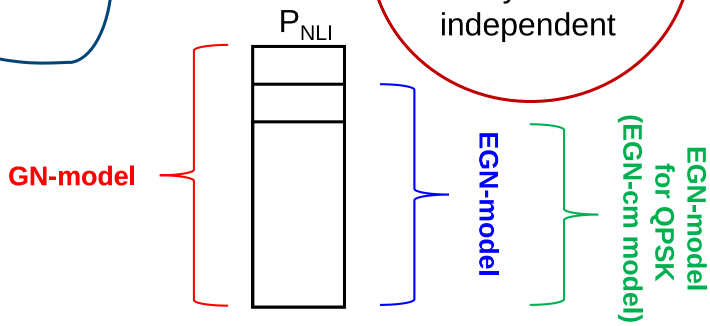
Long-correlated phase and polarization rotation (PPRN) noise

Format-dependent

Short-correlated circular noise

Mainly format-independent

- Negligible for constant-modulus formats
- Increases with the cardinality of the constellation
- Maximum for Gaussian constellation)
- Can be partially mitigated by CPE



OPTCOM 19

Components of NLI

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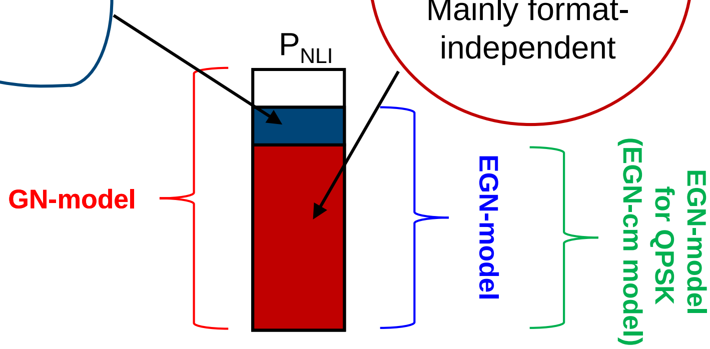
Long-correlated phase and polarization rotation (PPRN) noise

Format-dependent

Short-correlated circular noise

Mainly format-independent

- Negligible for constant-modulus formats
- Increases with the cardinality of the constellation
- Maximum for Gaussian constellation)
- Can be partially mitigated by CPE



OPTCOM 20

Practical implication

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If all the long-correlated phase noise is ideally taken out, then:

any PM-QAM system is well described by the EGN model, calculated as if PM-QPSK was transmitted (EGN-cm model)

A. Nespola et al, "Independence of the Impact of Inter-Channel Non-Linear Effects on Modulation Format and System Implications," Proc. of ECOC 2016, paper W.1.D.3, Amsterdam (The Netherlands), Sep. 2016.

P. Poggiolini et al., "Non-Linearity Modeling at Ultra-High Symbol Rates," Proc. Of OFC 2018, San Diego (USA), Mar. 2018.

32 Gbaud - 48 channels - SMF - 100km spans

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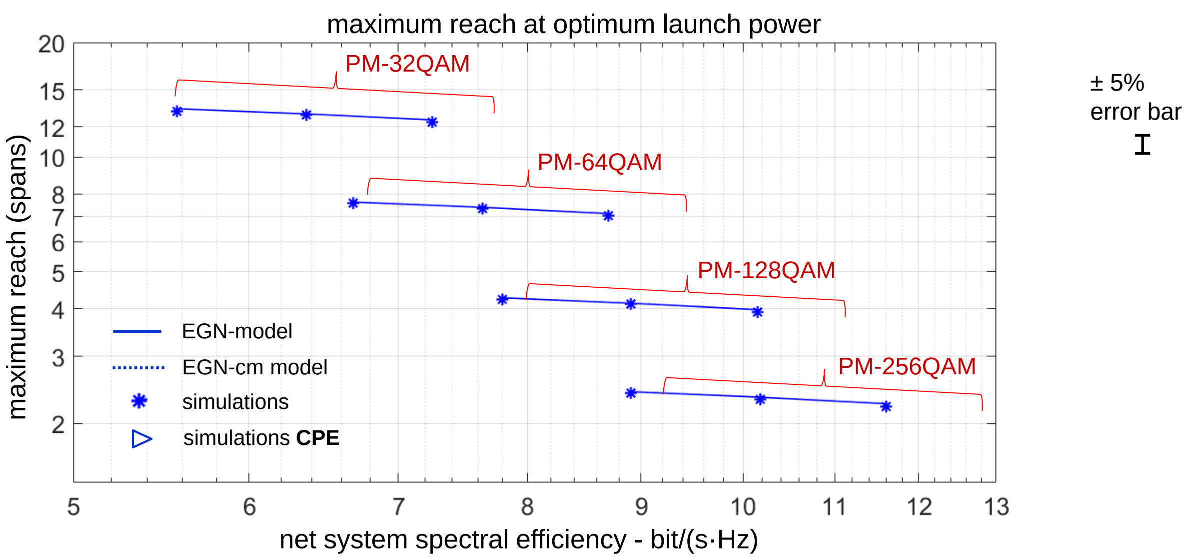
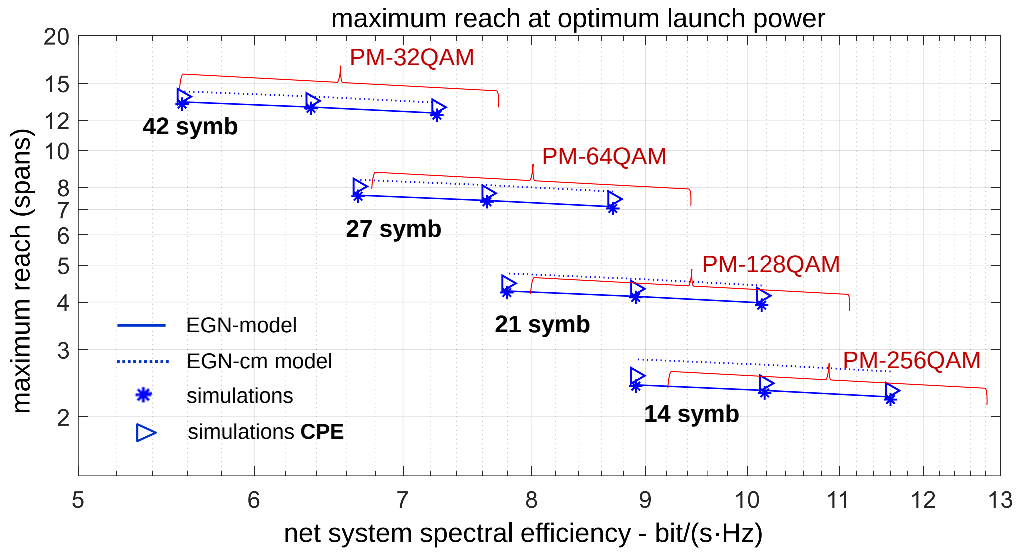


32 Gbaud - 48 channels - SMF - 100km spans

POLITECNICO DI TORINO



± 5% error bar

256 Gbaud - 6 channels - SMF - 100km spans

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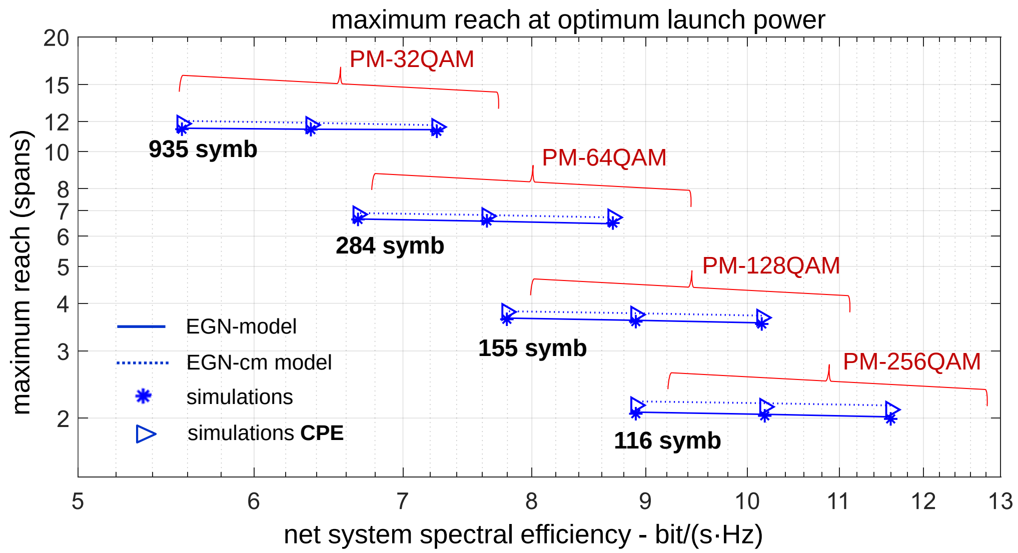

± 5% error bar

Going towards high symbol rates …

- NLPN decreases, as shown by the EGN-cm model
- Mitigating it is easier
- Overall, its impact decreases

P. Poggiolini et al., “Non-Linearity Modeling at Ultra-High Symbol Rates,” Proc. Of OFC 2018, San Diego (USA), Mar. 2018.

MITIGATION OF FIBER NONLINEARITY

NLI mitigation techniques

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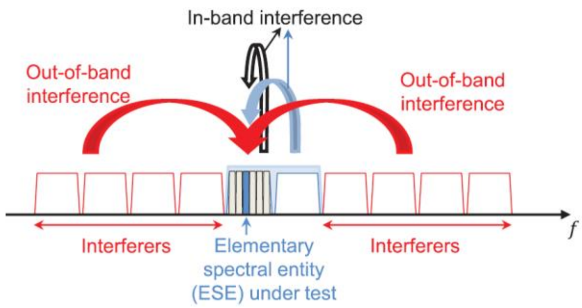
- Several nonlinearity mitigation techniques have been proposed to reduce the power of the NLI noise.
- The effectiveness of nonlinearity mitigation depends on the nature of the NLI, which can be divided into two main classes:
  - ***In-band interference***, which includes the NLI generated within the electronic bandwidth of the transceiver
  - ***Out-of-band interference***, which includes the NLI generated by the interaction with WDM channels that are note accessible to transmitter and receiver.



NLI mitigation techniques

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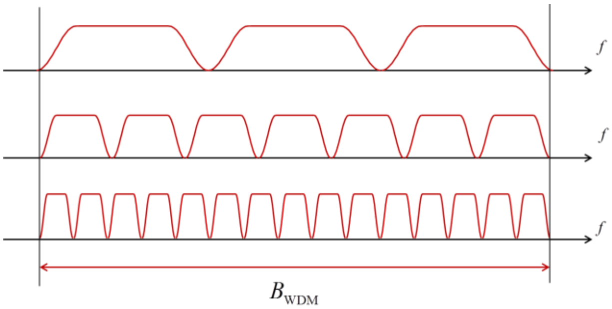
- **In-band NLI** can be mitigated by means of:
  - digital backpropagation (DBP)
  - nonlinear Fourier transform (NFT) transmission techniques
- **Out-of-band NLI that involves the channel under test** can be modelled as time-varying ISI and can be partially mitigated using several techniques (such as MAP or ML decoding).
- **Out-of-band NLI generated solely by out-of-band channels** is typically treated as non-removable noise.
- Mitigation of the impact of NLI can be also obtained using different approaches that optimize one or more transmission parameters, among which:
  - symbol-rate optimization (SRO)
  - dispersion pre-compensation
  - constellation or pulse shaping

Ideal gains of SRO and DBP

The analyzed set-up

- **What is the symbol rate which minimizes NLI ?...**
  …having fixed:
  - the total WDM bandwidth (B_{WDM}=504 GHz, 1.5 THz, 2.5 THz, 5 THz)
  - the modulation format and roll-off (PM-QPSK or PM-16QAM, ρ=0.05)
  - the relative frequency spacing (Δf=1.05 R_s)
- EDFA-only amplification (F=5 dB)
- SSMF fiber (100-km span length)



Normalized NLI power spectral density

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- The total NLI power (P_{NLI}) at the output of the transmission link is estimated either with the EGN model or by numerical simulations based on the split-step Fourier method.
- Systems at different symbol rate are compared in terms of the **normalized NLI power spectral density (PSD)**

$$\boxed{\tilde{G}_{NLI} = \frac{P_{NLI}}{R_s G_{ch}^3}}$$

Transmitted signal PSD

which is independent of the transmitted power per channel.

- Same value of $\tilde{G}_{NLI}$ means same maximum reach.

SRO prediction by EGN model

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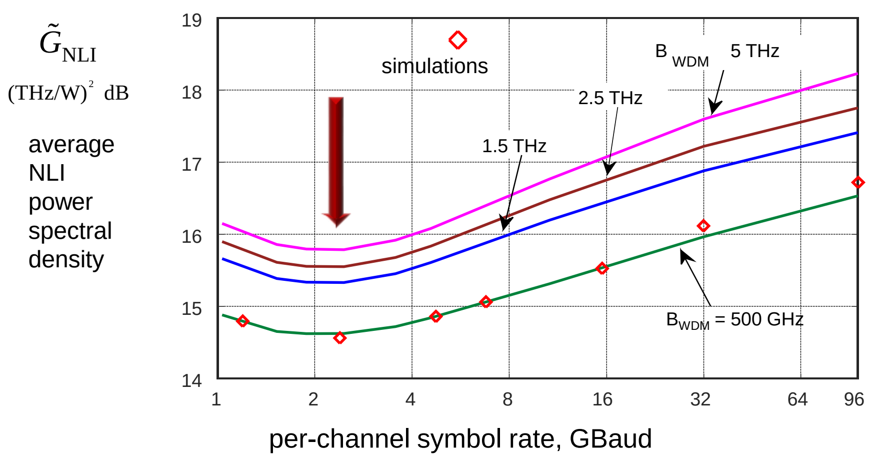
- **PM-QPSK,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**



All curves drawn using the FULL EGN model

$$\boxed{R_{opt} = \sqrt{\frac{2}{\pi |\beta_2| N_{span} L_{span}}}}$$

SRO prediction by EGN model

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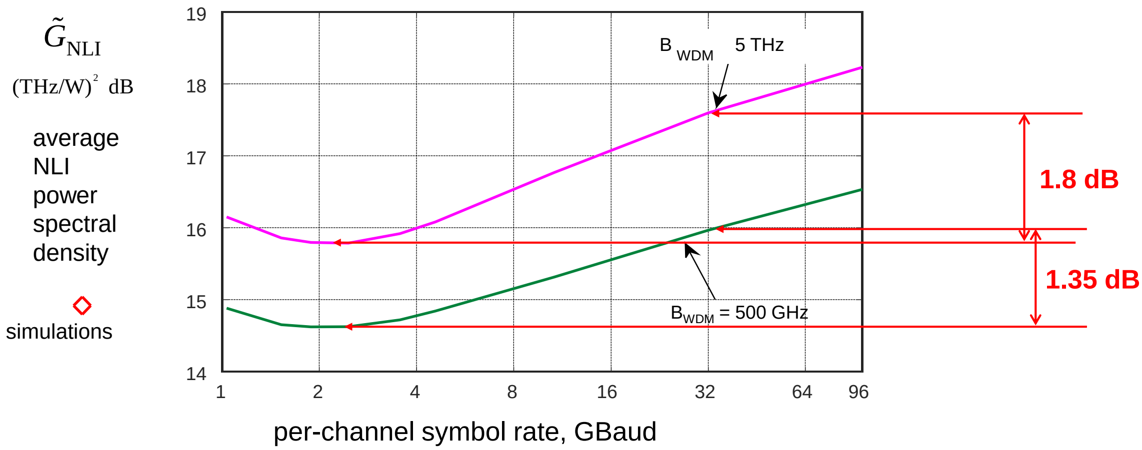
- **PM-QPSK,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**



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NLI mitigation

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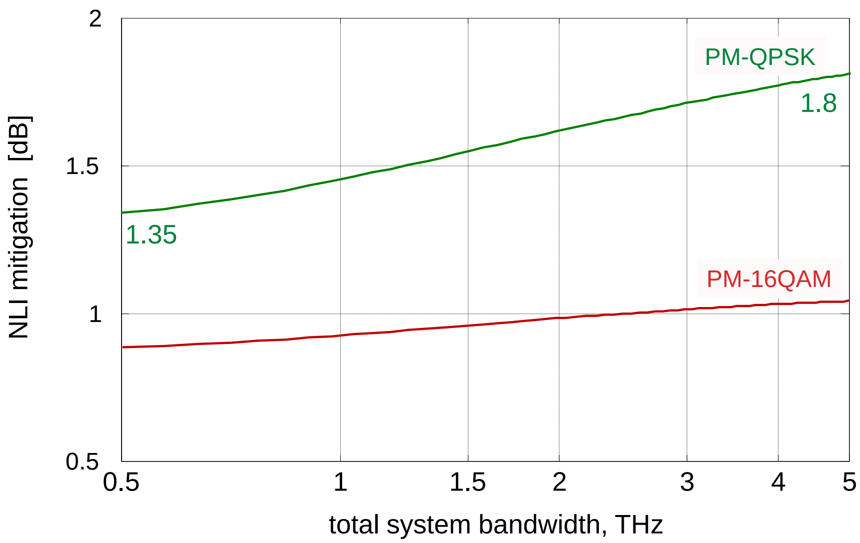


All curves drawn using the FULL EGN model

SRO between 32 GBaud and the optimum rate (2.4 Gbaud)

OPTCOM 34

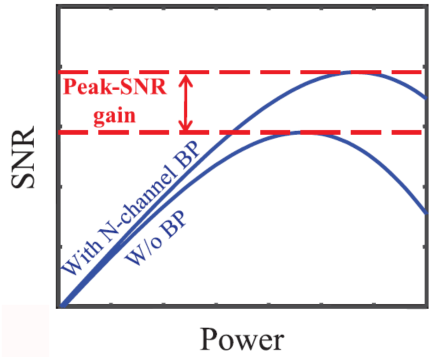
Max reach and peak-SNR

- How does **NLI mitigation** translate into **max reach or peak-SNR gains?**

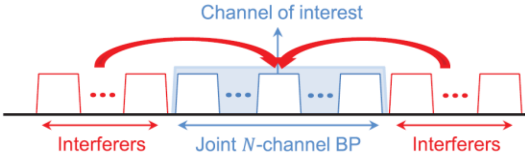
$$\Delta SNR_{peak,\mathrm{dB}} = -\frac{1}{3}\Delta\tilde{G}_{\mathrm{NLI,dB}}$$

$$\Delta L_{\mathrm{max,dB}} \approx -\frac{1}{3}\Delta\tilde{G}_{\mathrm{NLI,dB}}$$

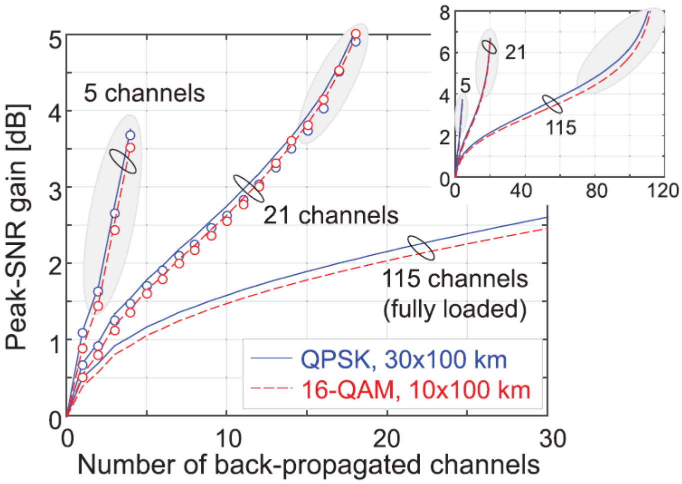
- 1.8 dB mitigation → 15% max reach gain
- 1.35 dB mitigation → 11% max reach gain



Prediction of DBP gain



R. Dar and P. Winzer, "Nonlinear Interference Mitigation: Methods and Potential Gain," *J. Lightw. Technol*. **35**(4), p. 903 (2017).



Backward Propagation vs. SRO – PM-QPSK

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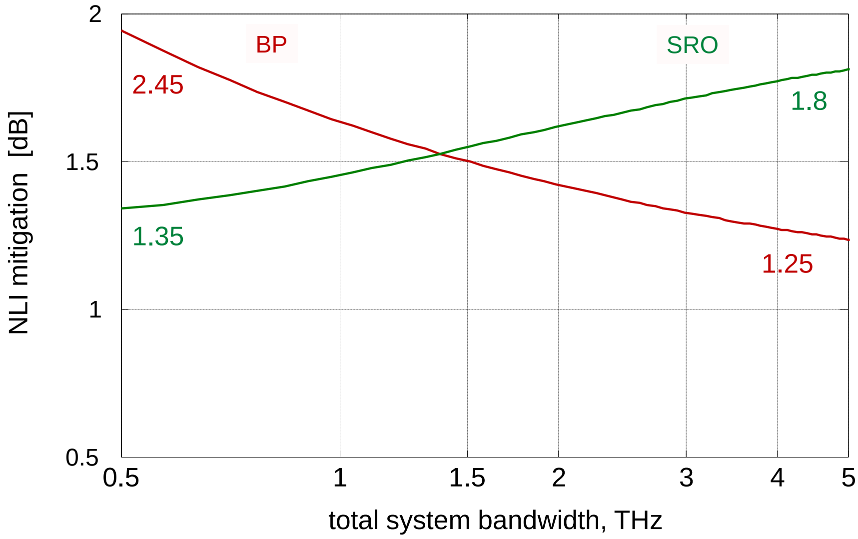

PM-QPSK, roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**

All curves drawn using the FULL EGN model

SRO: between 32 GBaud and the optimum rate (2.4 Gbaud)

BP: ***ideal*** backward propagation over the 32 GBaud center channel

Backward Propagation vs. SRO – PM-16QAM

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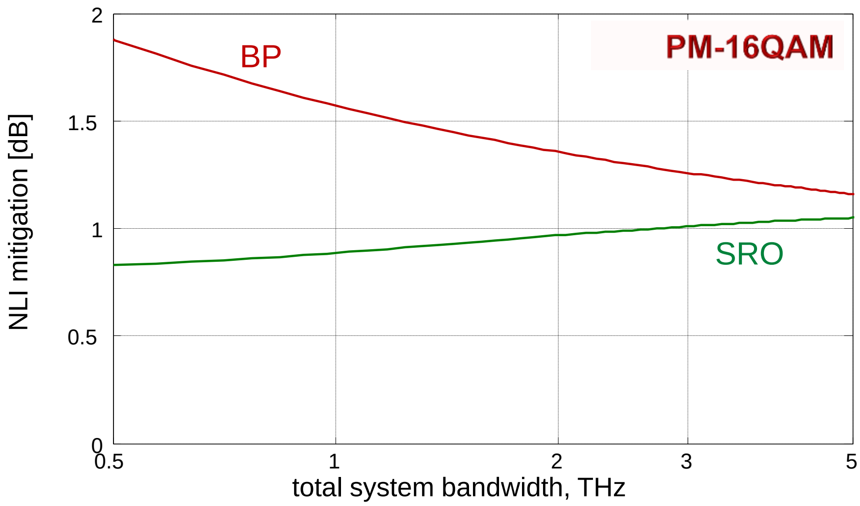
- **PM-16QAM,** roll-off 0.05, spacing 1.05 x (symb rate), **SMF, 100 km spans, 50 spans**



SRO: between 32 GBaud and the optimum rate (2.4 Gbaud)

BP: ***ideal*** backward propagation over the 32 GBaud center channel

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Practical limitations of SRO and DBP

How to exploit symbol-rate optimization gain?

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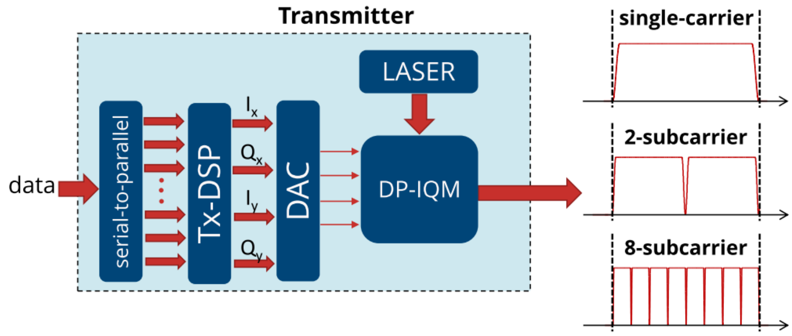
- Optimum symbol rate values in the range 2-4 Gbaud
- It would be extremely inefficient to use a separate transceiver for each low-symbol-rate signal
  - To reach the transmission speed of commercially available 32-Gbaud systems, 16× more transceivers (including laser sources) at 2 Gbaud would be required

⬇

Sub-carrier multiplexing

- A high symbol-rate signal is electrically decomposed into a given number of subcarriers, each of which operating at a lower symbol-rate (multiplexing in the digital domain)

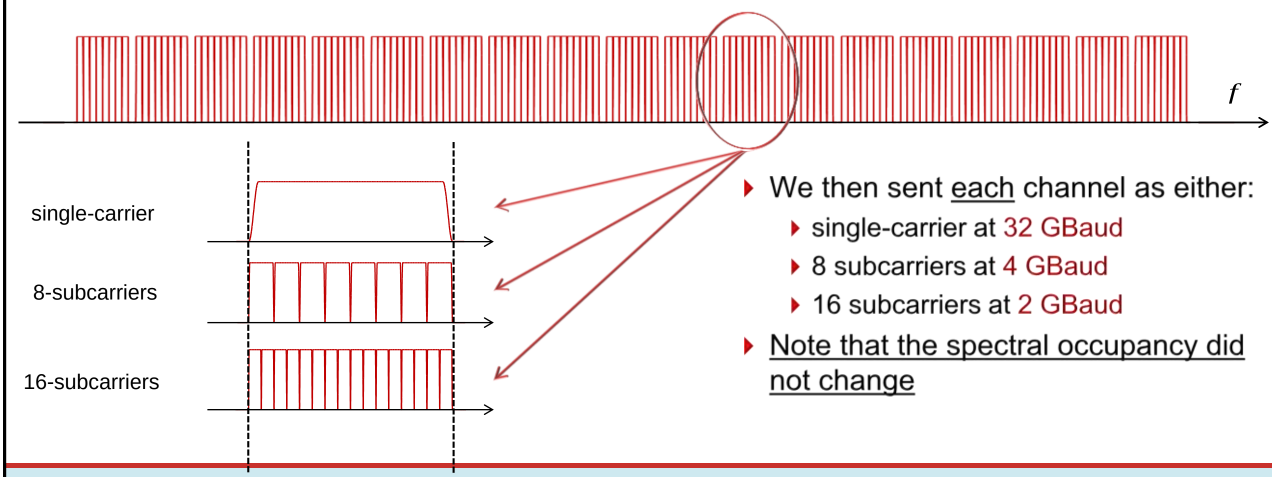
Subcarrier multiplexing



- A. Nespola et al., "Experimental demonstration of fiber nonlinearity mitigation in a WDM multi-subcarrier coherent optical system," ECOC 2015, Sep. 2015.

The experiment

- We started out with a **19 channel** WDM comb, with channel **spacing 37.5 GHz**, for a total WDM bandwidth of **710 GHz**



- We then sent each channel as either:
  - single-carrier at 32 GBaud
  - 8 subcarriers at 4 GBaud
  - 16 subcarriers at 2 GBaud
- Note that the spectral occupancy did not change

System schematic

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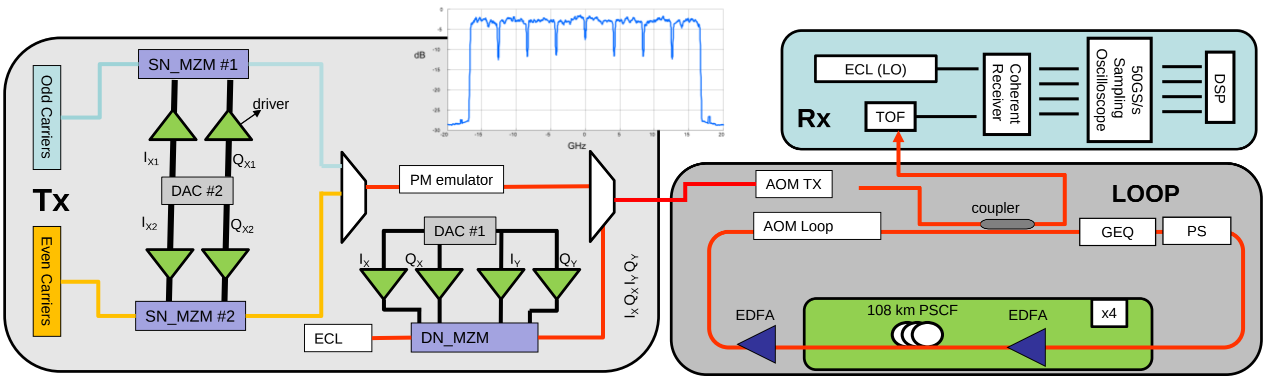

SN_MZM: single-nested Mach-Zehnder mod.
DN_MZM: double-nested Mach-Zehnder mod.

GEQ: Gain EQualizing programmable filter
PS: synchronous Polarization Scrambler
AOM: Acousto-Optic Modulator (used as switch)
TOF: Tunable Optical Filter

Back-to-back characterization

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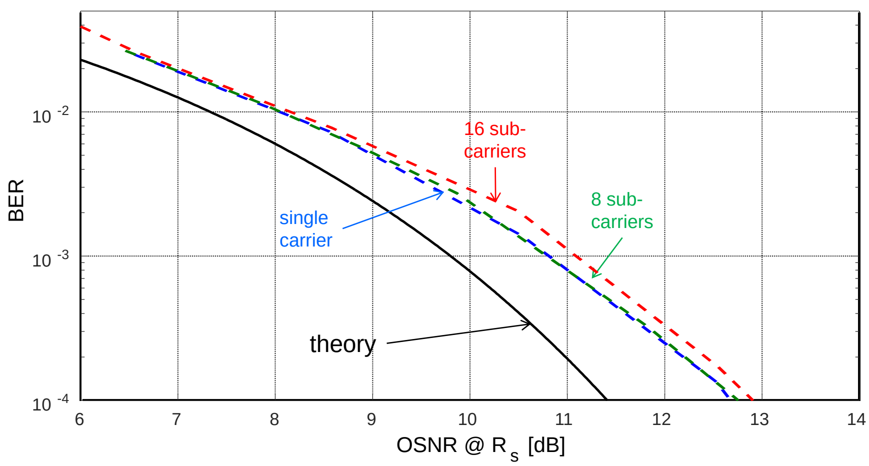
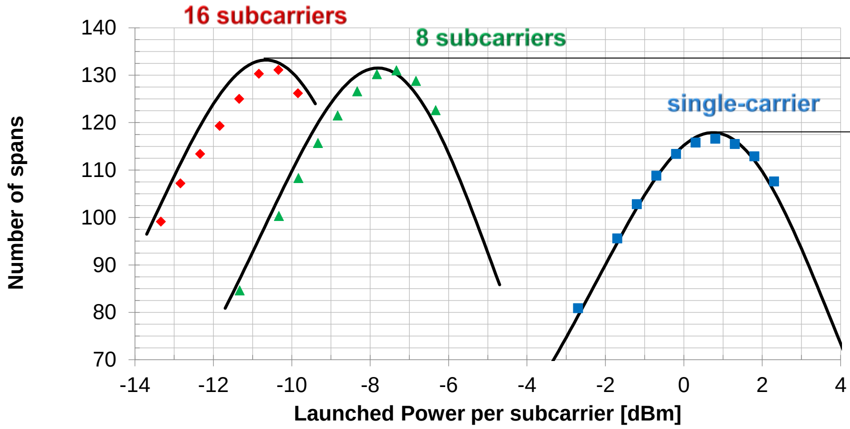
- To perform a meaningful comparative test over the long-haul, it is important that the btb is the same



- At the reference BER=10^{-2}:
  - No penalty from single SC to 8 SCs
  - 0.1-dB penalty from single SC to 16 SCs

Reach curves at BER 10^{-2}



13.5 % reach increase

- markers: experiment
- solid lines: EGN model predictions

- Back-to-back penalty taken into account in the EGN model curves (theoretical reach gain ~14.5 %)

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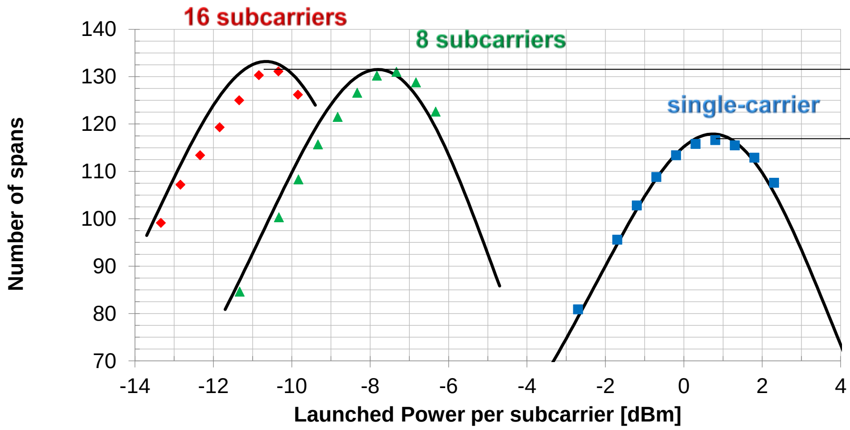
Reach curves at BER 10^{-2}



12.5 % reach increase

- markers: experiment
- solid lines: EGN model predictions

- The gain predicted by the analytical model cannot be fully exploited due to practical implementation issues (higher sensitivity to transceiver impairments and phase noise)

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DBP performance vs. number of steps per span

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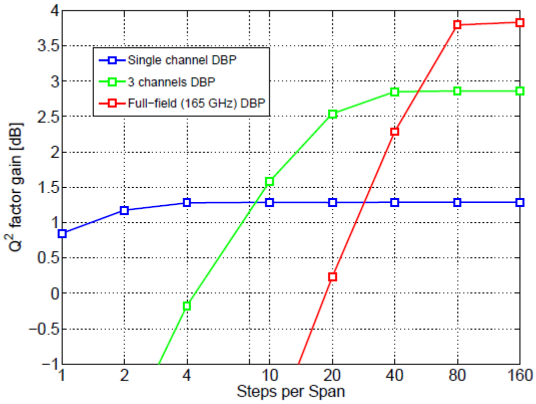
- 5x32 Gbaud PM-16QAM, SMF, 80 km spans, 40 spans



- The number of steps per span must be increased as the DBP bandwidth increases.
- The benefit of back-propagating large bandwidths can be totally lost if a suboptimal step size is used (due to an inaccurate compensation of the NLI).

- G. Liga et al., "On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission," *Opt. Exp.* **22**(24), p. 30053 (2014)

DBP performance vs. PMD

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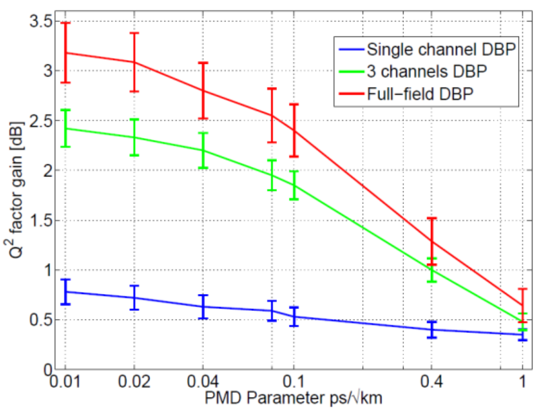
- 5x32 Gbaud PM-16QAM, SMF, 80 km spans, 40 spans



- Multichannel DBP performed with optimal operation parameters.
- For typical values of the PMD parameter the beneficial effects of multichannel DBP reduce significantly as the DBP bandwidth is increased.
- In the presence of PMD, back-propagating larger portions of bandwidth beyond a certain value becomes ineffective to improve the transmission performance.

- G. Liga et al., "On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission," *Opt. Exp.* **22**(24), p. 30053 (2014)

Conclusions

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- The **NLI analytical models** are useful tools to obtain an accurate prediction of the **ultimate performance** achievable by the various mitigation techniques.
- The **actual performance gain** will also depend on several implementation issues that cannot be easily included in the analytical estimations, such as:
  - sub-optimum performance of low-complexity DBP algorithms
  - higher impact of NLPN in digital multi-subcarrier systems

  which reduce the nonlinearity mitigation benefits.

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Symposium on Challenges to Achieving Capacity in Nonlinear Optical Networks

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Modelling and mitigation of fibre nonlinearity in WDM coherent optical systems

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OPTCOM The Wordsworth Hotel, Grasmere 19th June 2018