POLITECNICO DI TORINO

EFFECTIVENESS OF DIGITAL BACK-PROPAGATION AND SYMBOL-RATE OPTIMIZATION IN COHERENT WDM OPTICAL SYSTEMS

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MOTIVATION

- In long-haul system, maximum reach is limited by non-linear effects
- Symbol Rate Optimization (SRO) has been shown to be effective in non-linearity mitigation
  - Recent experiments and theoretical analysis have demonstrated the potential advantage of Multi-Carrier (MC) systems
- Digital Back Propagation (DBP) at receiver is another technique to mitigate non-linearity
- These techniques are based on quite different mechanisms:

How do they combine their effectiveness?

Can they be synergistic?

OUTLINE

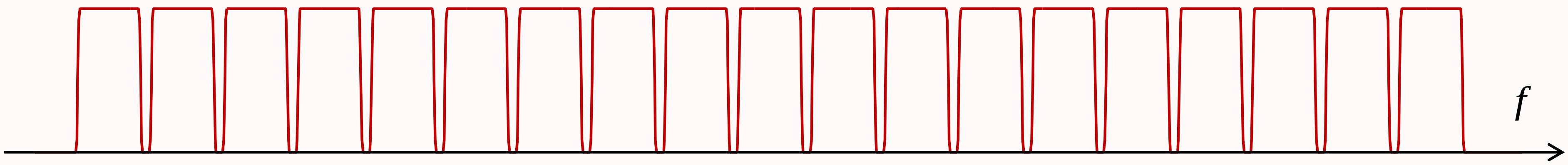
- Theoretical analysis
  - Application of the EGN-model to evaluate the effectiveness of SRO, DBP and of their joint use
- Experimental analysis
  - Application of DBP to a Multi-Carrier experiment
- Conclusions

THEORETICAL ANALYSIS: THE EGN MODEL

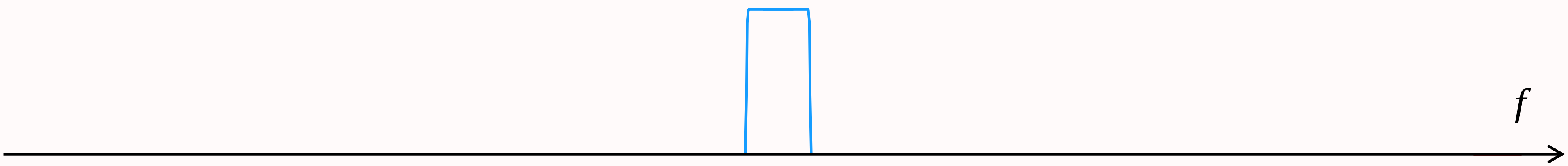
- The Enhanced GN-model allows for precise evaluation of Non-Linear Interference (NLI)
  - Properly account NLI dependence on modulation format and symbol rate
    - A Symbol Rate Optimization (SRO) can be applied to minimize NLI
  - Neither the GN-model nor advanced XPM models were able to demonstrate SRO
- EGN-model also allows to evaluate ultimate limits of DBP

A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini, F. Forghieri, "EGN model of non-linear fiber propagation," Optics Express, vol. 22, no. 13, pp. 16335-16362, June 2014.

IDEAL DBP LIMITS



G_{NLI}



$G_{NLI,SCI}$

$$G_{NLI,DBP} = G_{NLI} - G_{NLI,SCI} \Rightarrow OSNR_{NL} = \frac{P_{ch}}{P_{ASE} + P_{NLI,DBP}}$$

OPTIMUM SYMBOL RATE

- From EGN-model, we can derive an optimum R_S

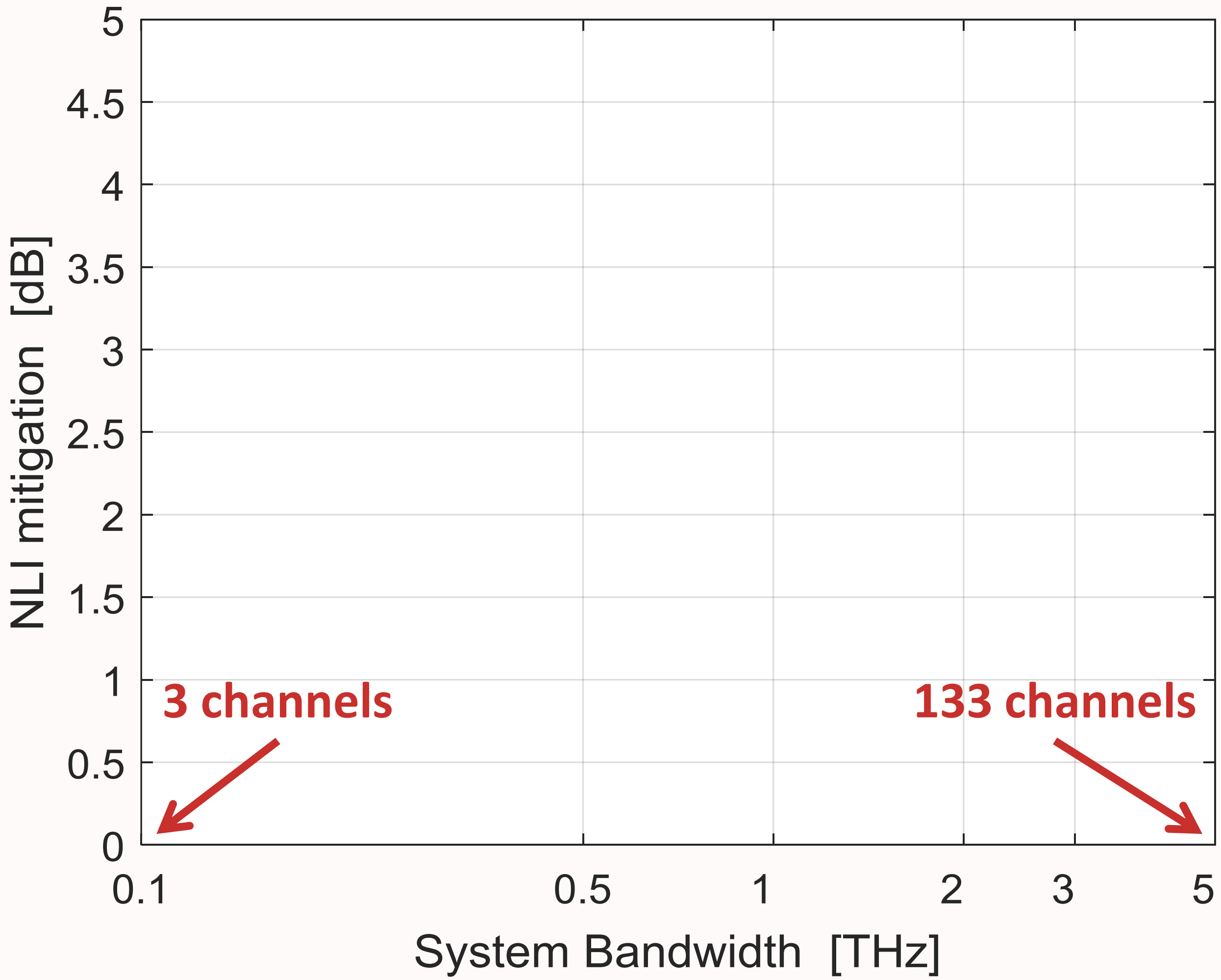
$$R_{S,opt} = \sqrt{\frac{2}{\pi |\beta_2| N_{span} L_{span}}}$$

- Link parameters
  - SMF fiber
  - L_{span}=100 km
  - N_{span}=50

  → $R_{S,opt}$=2.3 GBaud

- Optimum symbol rate is too small for a practical implementation as a single carrier
- A multi-carrier solution is needed
  - Assuming an aggregate symbol rate R_S= 32 GBaud, we consider each channel split in 14 subcarriers

NLI MITIGATION: G_{NLI} REDUCTION



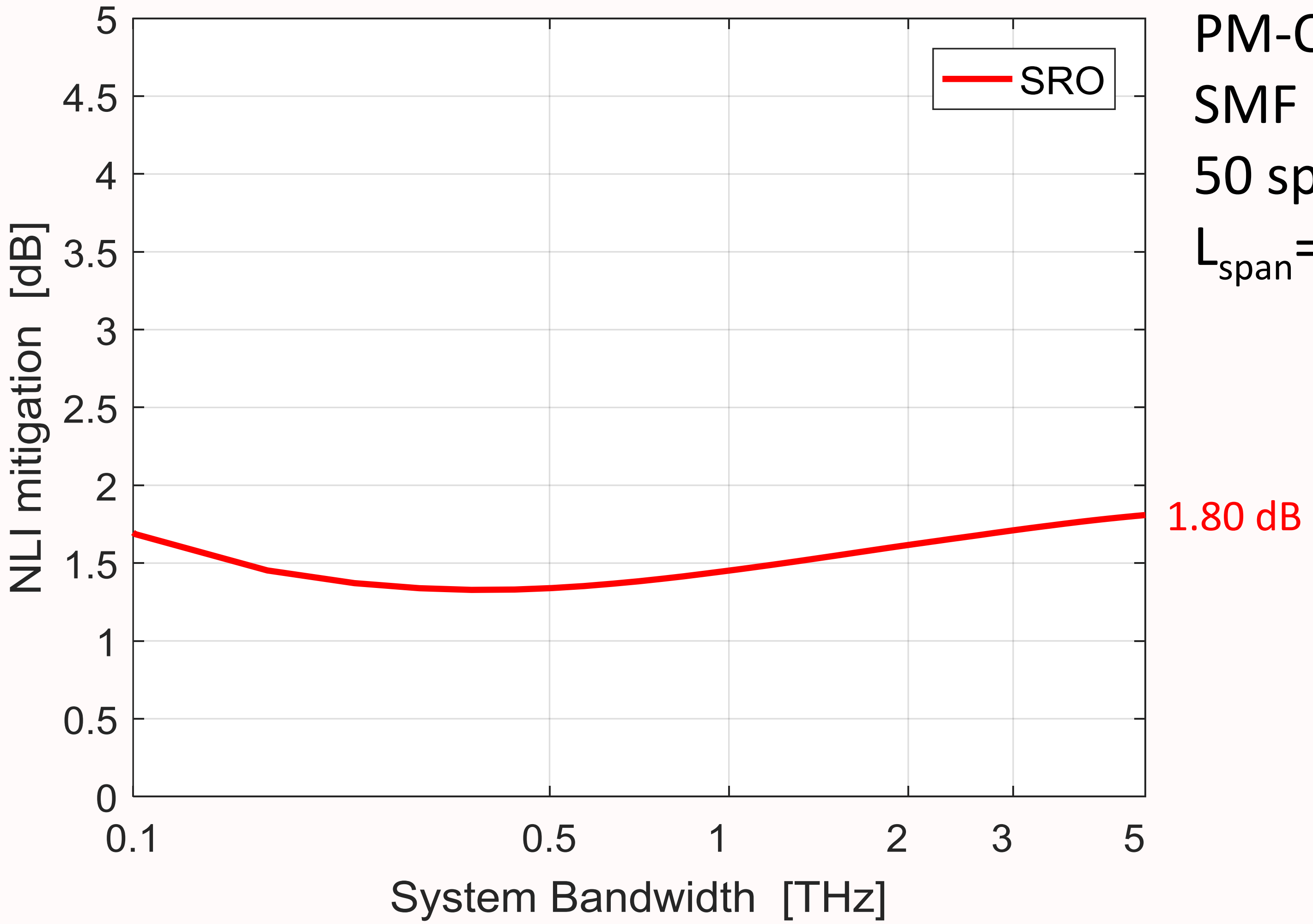
$R_{S,tot}$=32 GBaud

ρ=0.05

Δf=33.6 GHz

N_{sc}=14

NLI MITIGATION: SRO



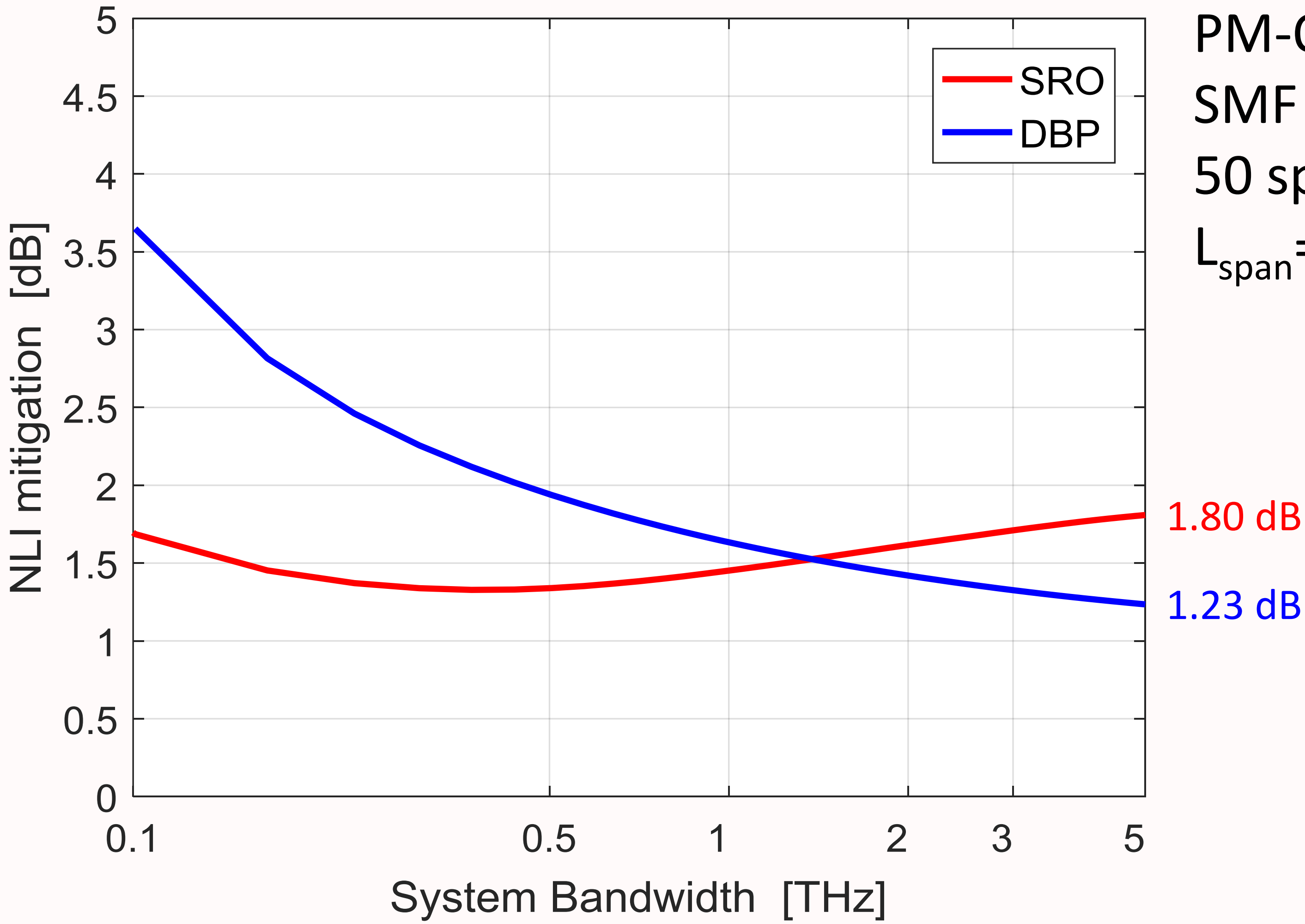
PM-QPSK

SMF

50 spans

L_{span}=100 km

NLI MITIGATION: SRO & DBP



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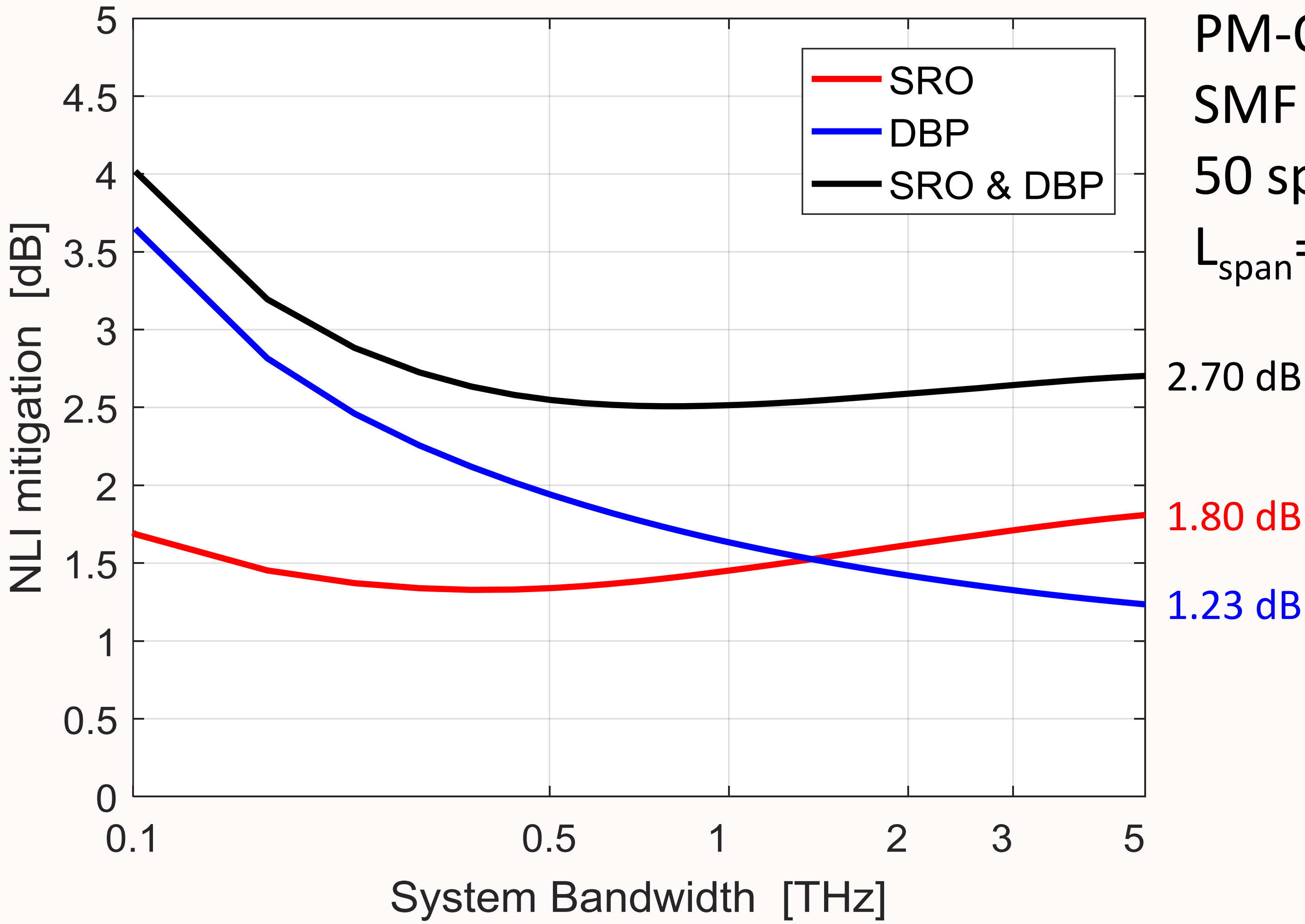
NLI MITIGATION: SRO & DBP



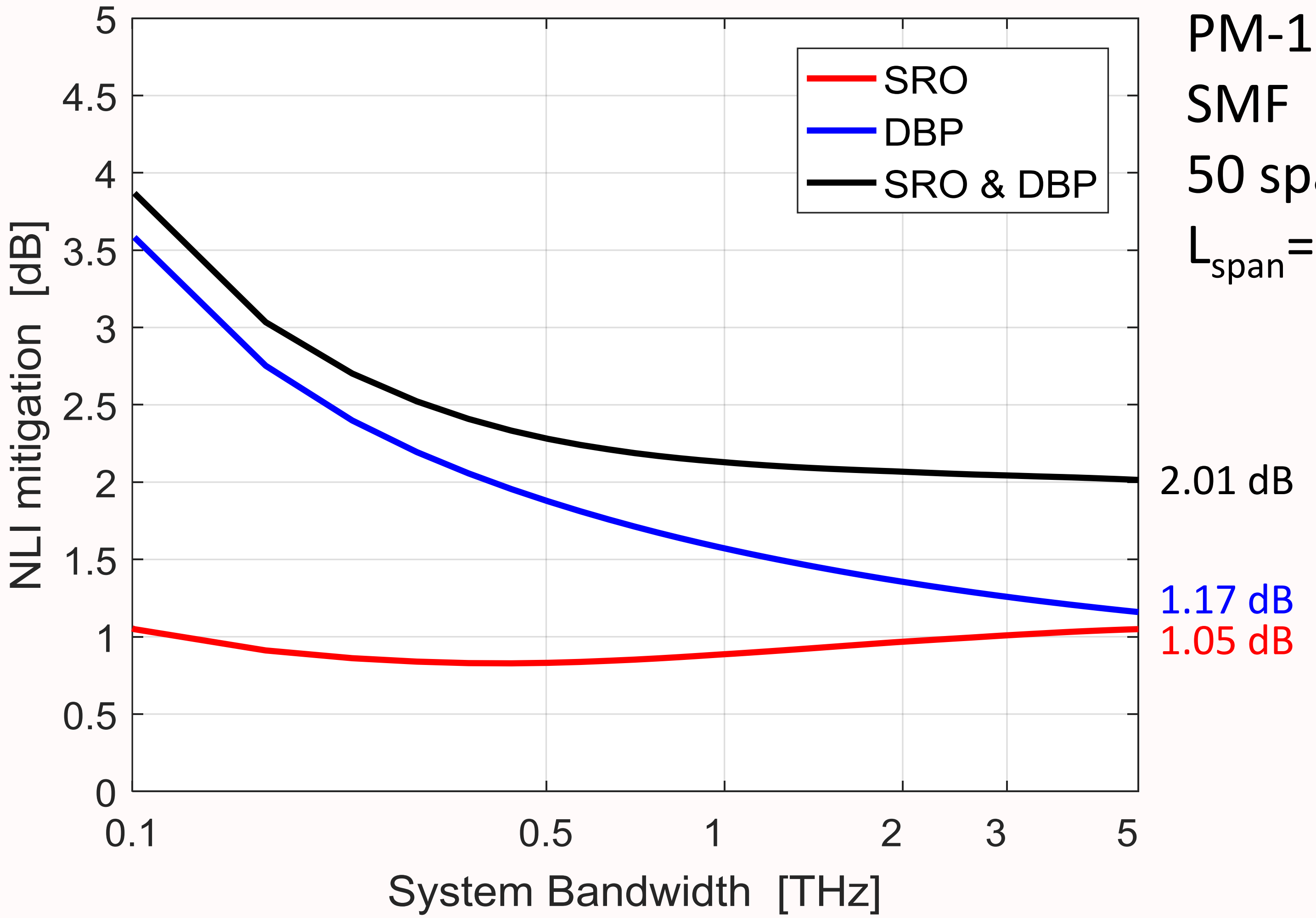
PM-QPSK

SMF

50 spans

L_{span}=100 km

NLI MITIGATION: SRO & DBP



PM-16QAM

SMF

50 spans

L_{span}=100 km

MAXIMUM REACH GAIN

- How does **NLI mitigation** translate into **Maximum Reach Gain**?

$$\text{Maximum Reach Gain [dB]} = \frac{\text{NLI mitigation [dB]}}{3}$$

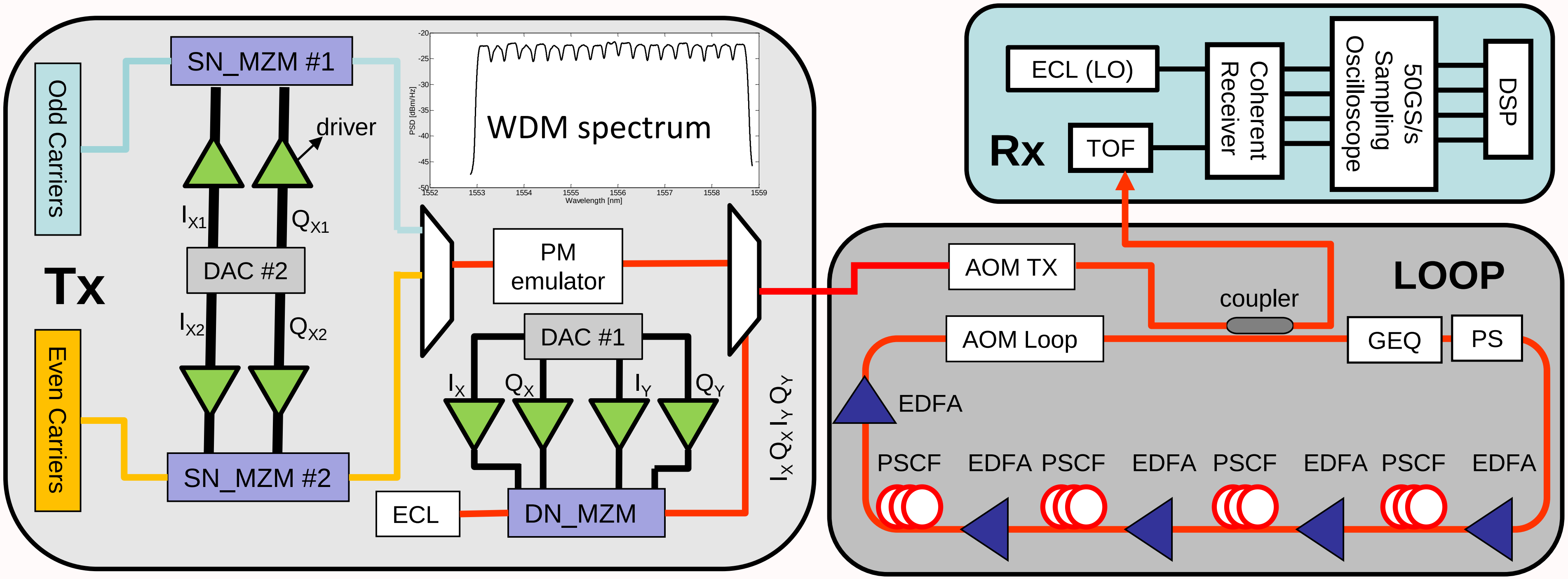
PM-QPSK on C-band

	NLI Mitigation [dB]	MR Gain [dB]	MR Gain [%]
SRO	1.80	0.60	15%
DBP	1.23	0.41	10%
SRO & DBP	2.70	0.90	23%

PM-16QAM on C-band

	NLI Mitigation [dB]	MR Gain [dB]	MR Gain [%]
SRO	1.05	0.35	8%
DBP	1.17	0.38	9%
SRO & DBP	2.01	0.67	17%

TRANSMISSION EXPERIMENT SETUP



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

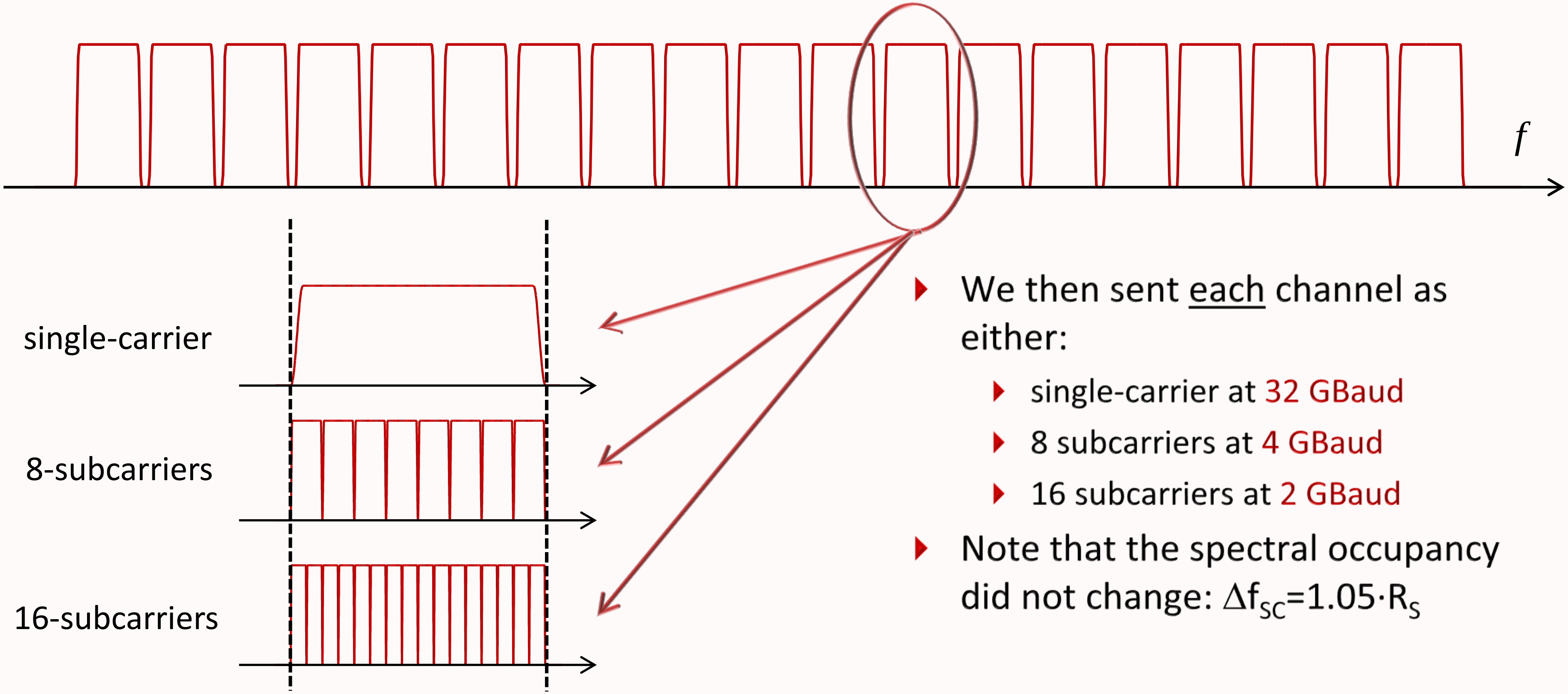
GEQ: Gain Equalizing programmable filter
PS: synchronous Polarization Scrambler
AOM: Acousto-Optic Modulator (used as switch)
TOF: Tunable Optical Filter

PSCF fiber kindly provided by SUMITOMO ELECTRIC

A. Nespola, et al., "Experimental Demonstration of Fiber Nonlinearity Mitigation in a WDM Multi-Subcarrier Coherent Optical System," ECOC, Mo.3.6.3, Valencia, 2015.

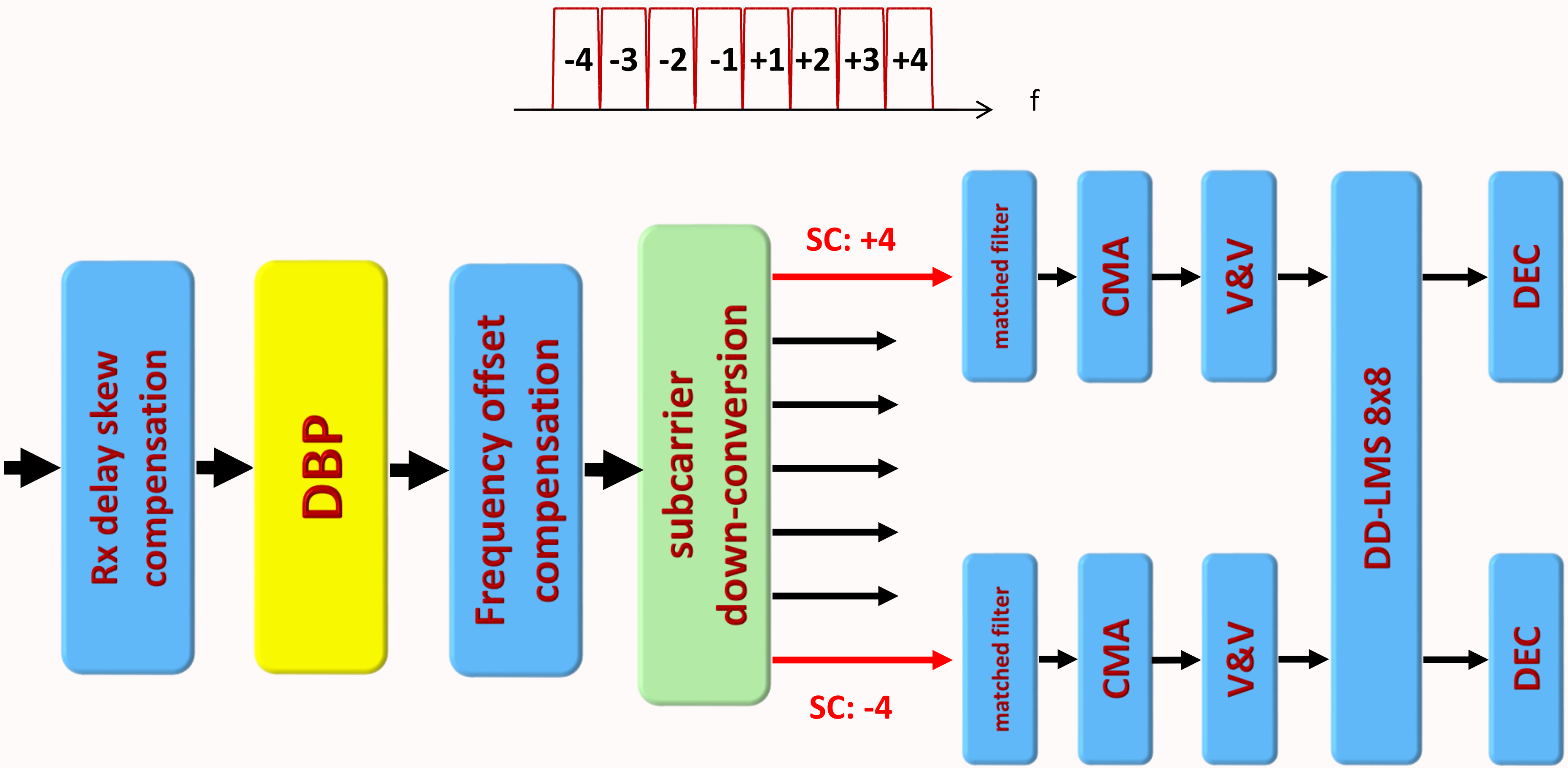
TRANSMISSION EXPERIMENT: SC VS. MC

- We started out with a **19 channel** WDM comb, with channel **spacing 37.5 GHz**, for a total WDM bandwidth of **710 GHz**
- PM-QPSK channels with roll-off=0.05



- 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: $\Delta f_{SC}=1.05 \cdot R_S$

RECEIVER DSP

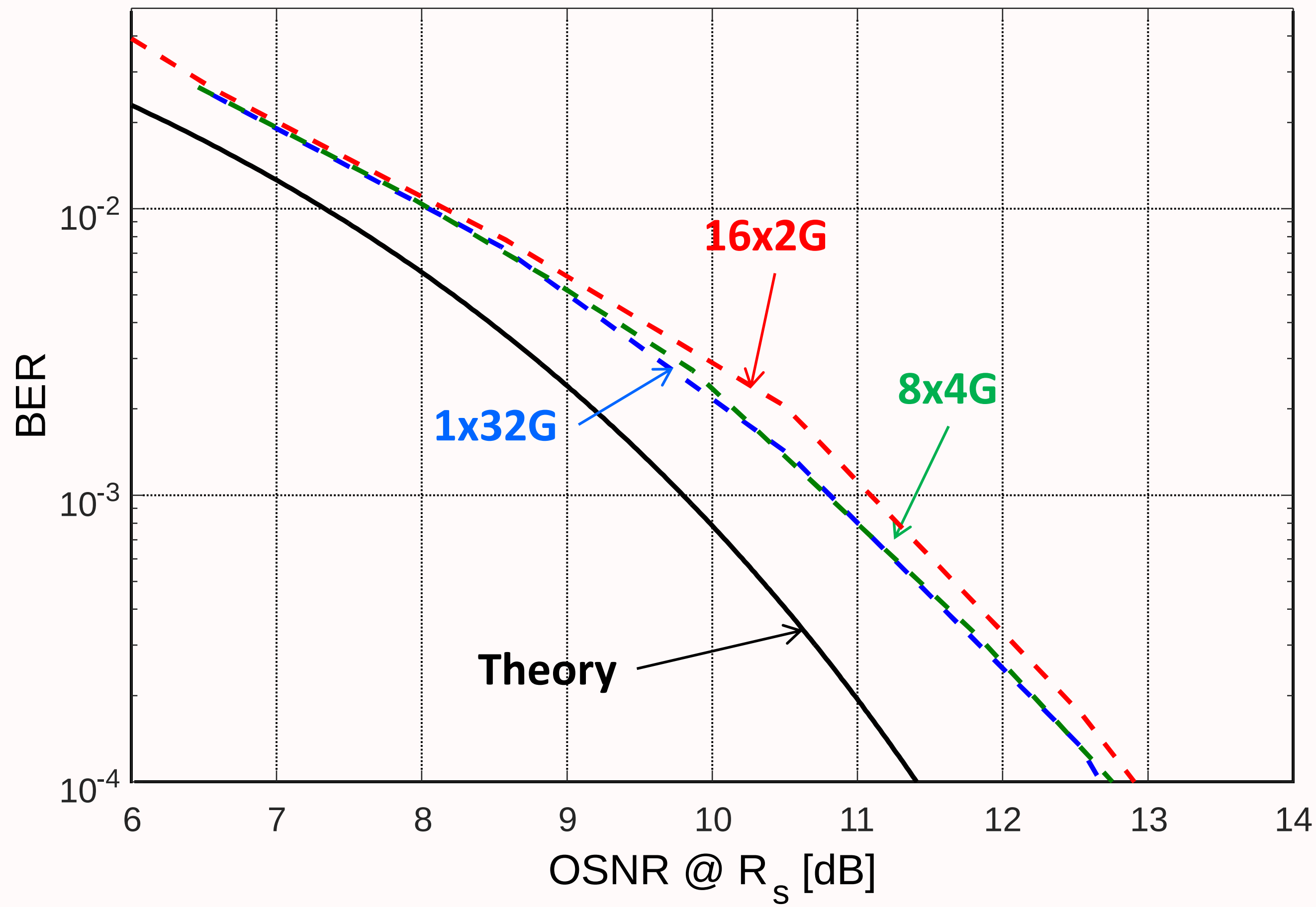


- The 8x8 (real) LMS is necessary to correct for I/Q delay skew at the transmitter modulator (otherwise 4x4 is enough)

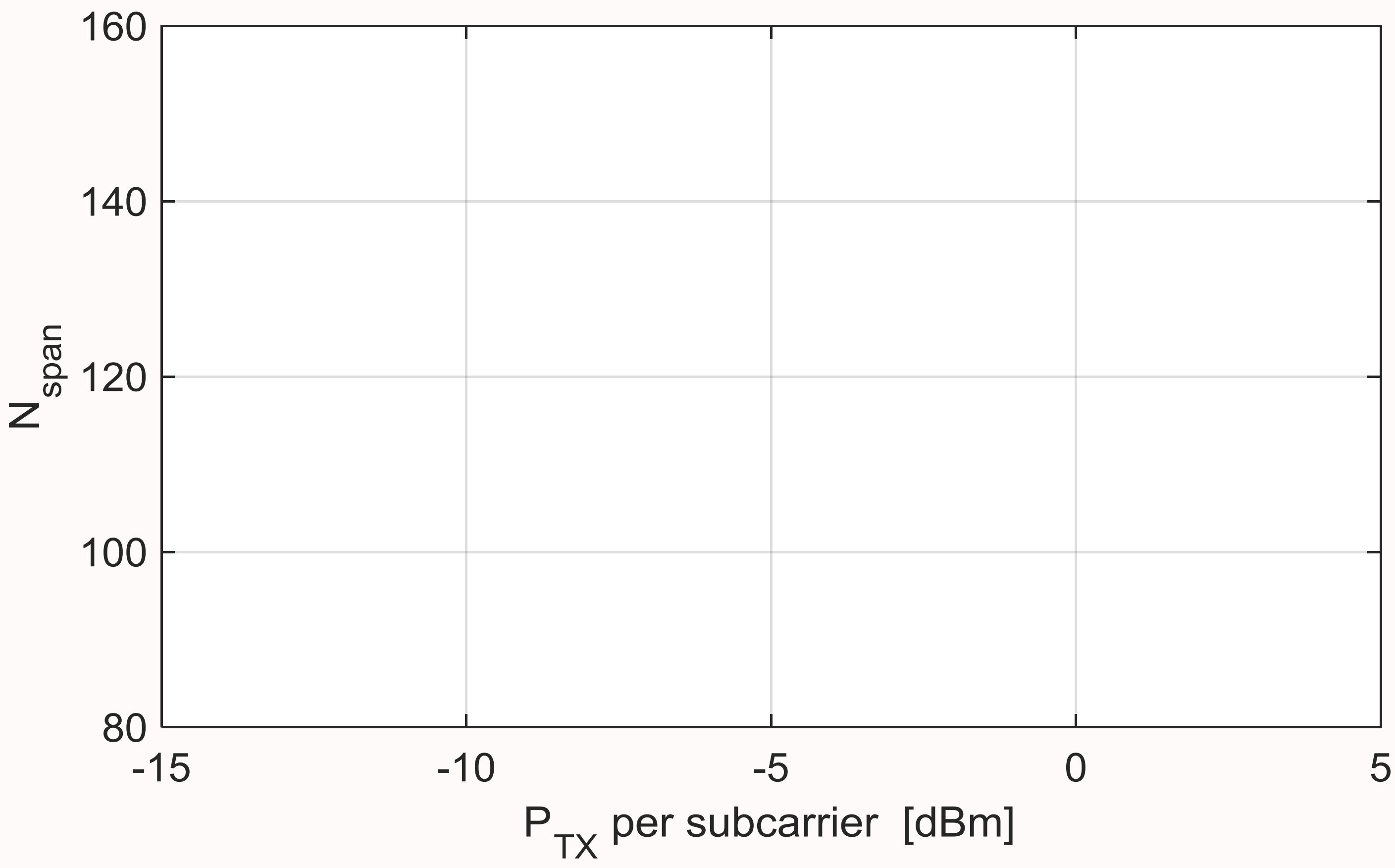
G. Bosco, et al., "Impact of the Transmitter IQ-Skew in Multi-Subcarrier Coherent Optical Systems," OFC, W4A.5, Anaheim, 2016.

BACK-TO-BACK CHARACTERIZATION

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

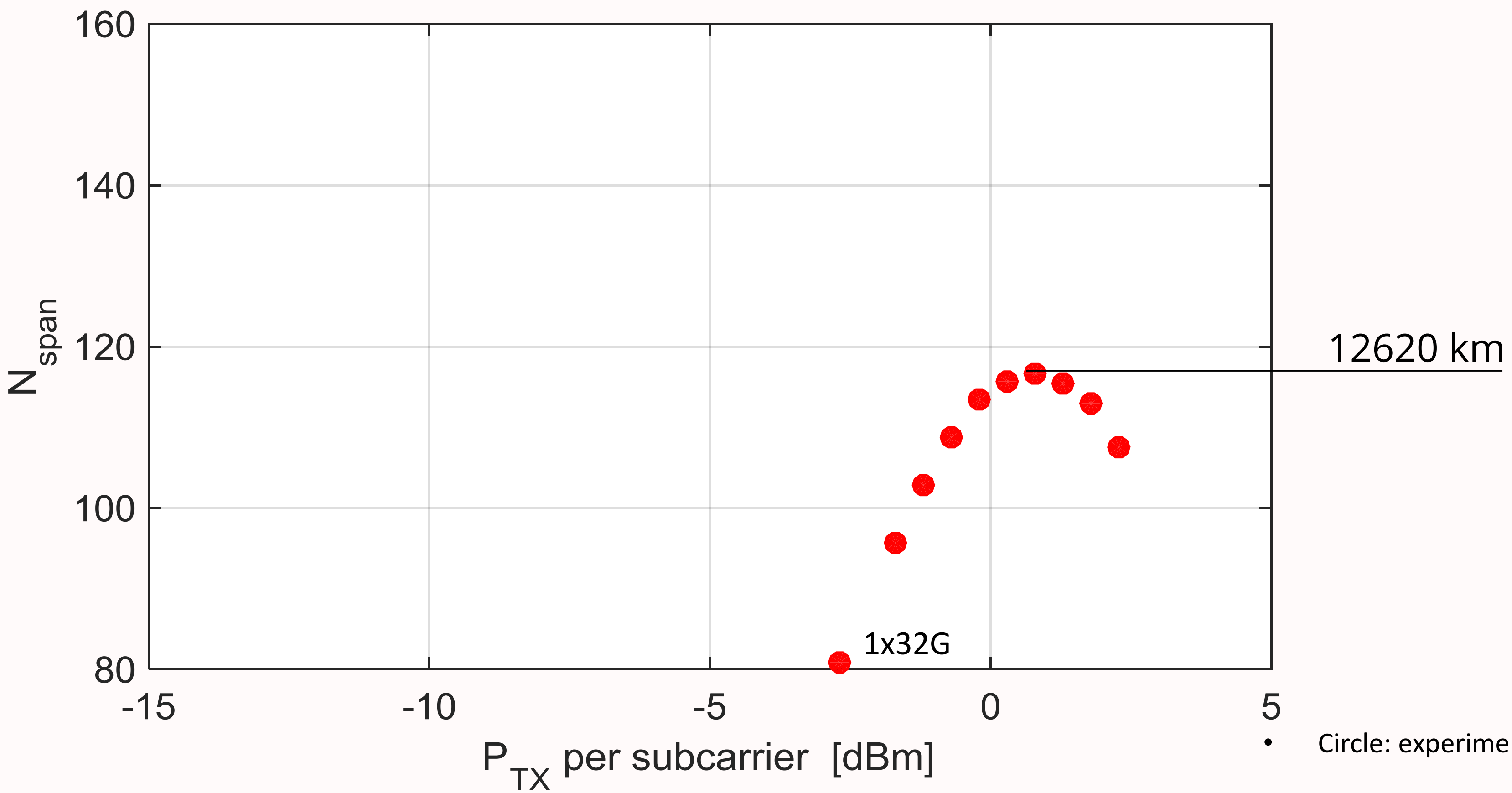


MAXIMUM REACH AT BER=10^{-2}



MAXIMUM REACH AT BER=10^{-2}

Single carrier at 32 GBaud

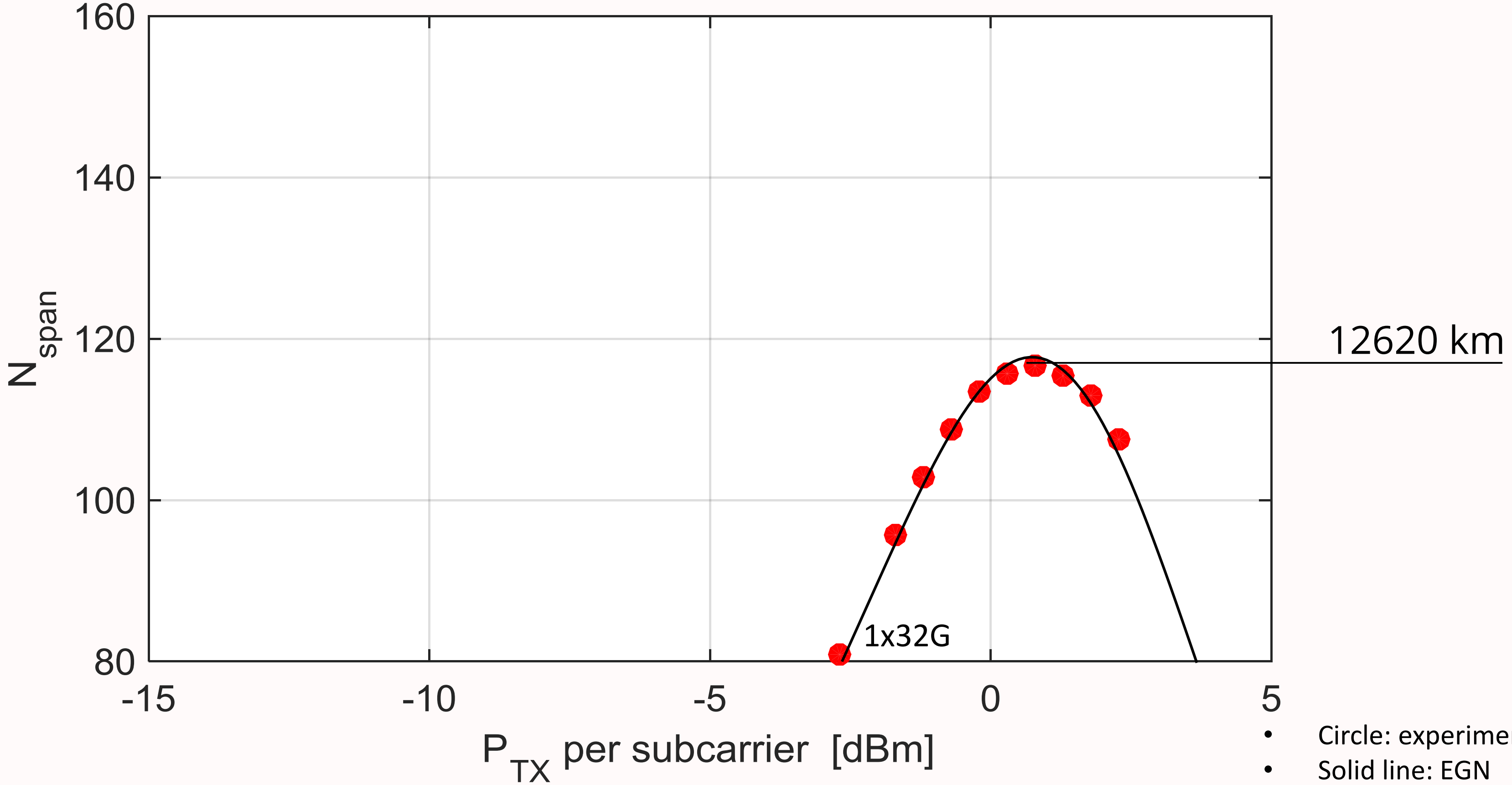


- Circle: experiment

MAXIMUM REACH AT BER=10^{-2}

Best-fit of EDFA noise-figure operated on the linear region: NF=5.2 dB
No further best-fit for ALL other EGN curves

$$\mathrm{OSNR}_{NL} = \frac{P_{ch} - P_{NLI,signal}}{P_{ASE} + P_{NLI,signal+ASE}}$$

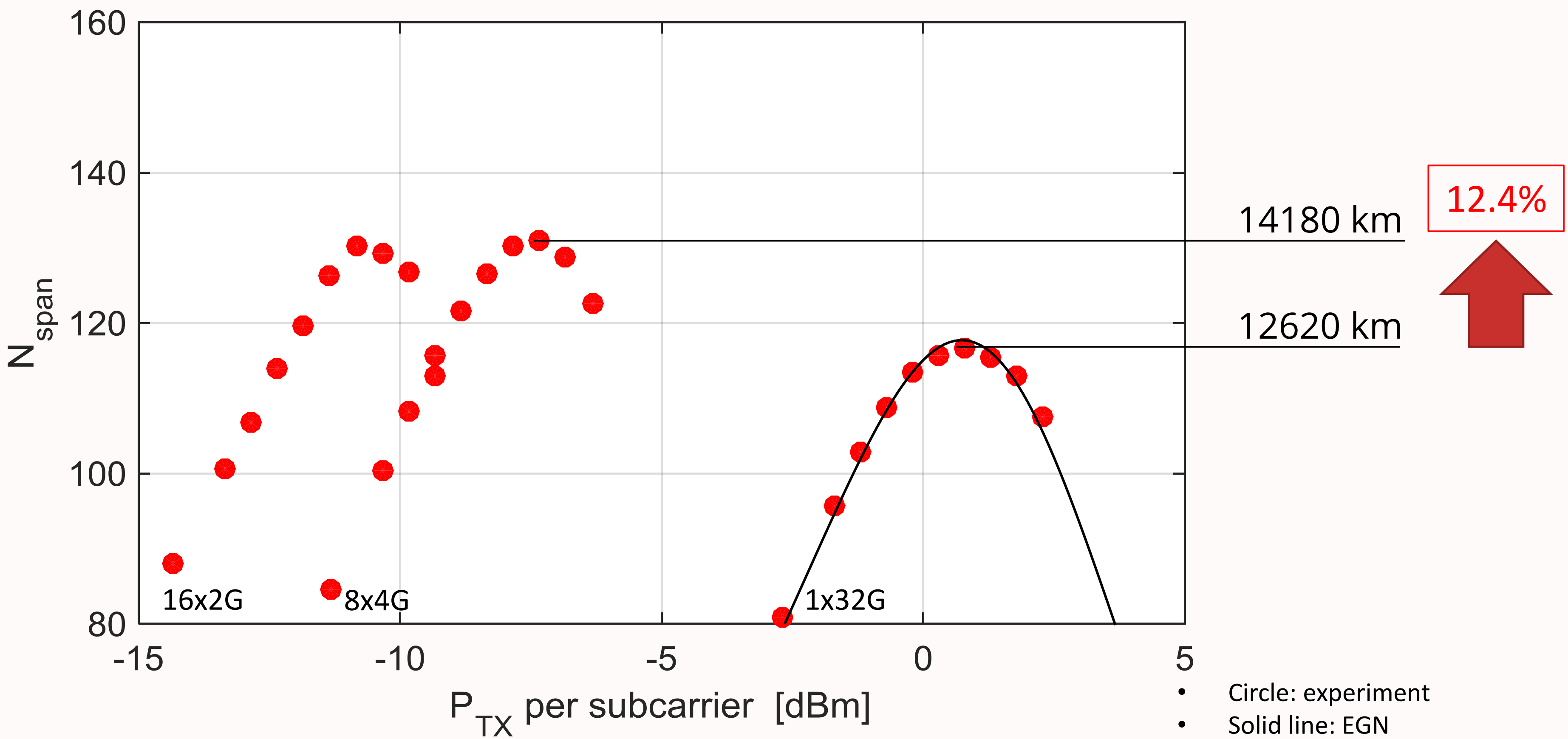


- Circle: experiment
- Solid line: EGN

P. Poggiolini et al., "Impact of Low-OSNR Operation on the Performance of Advanced Coherent Optical Transmission Systems", ECOC, Mo.4.3.2, Cannes, 2014.

MAXIMUM REACH AT BER=10^{-2}

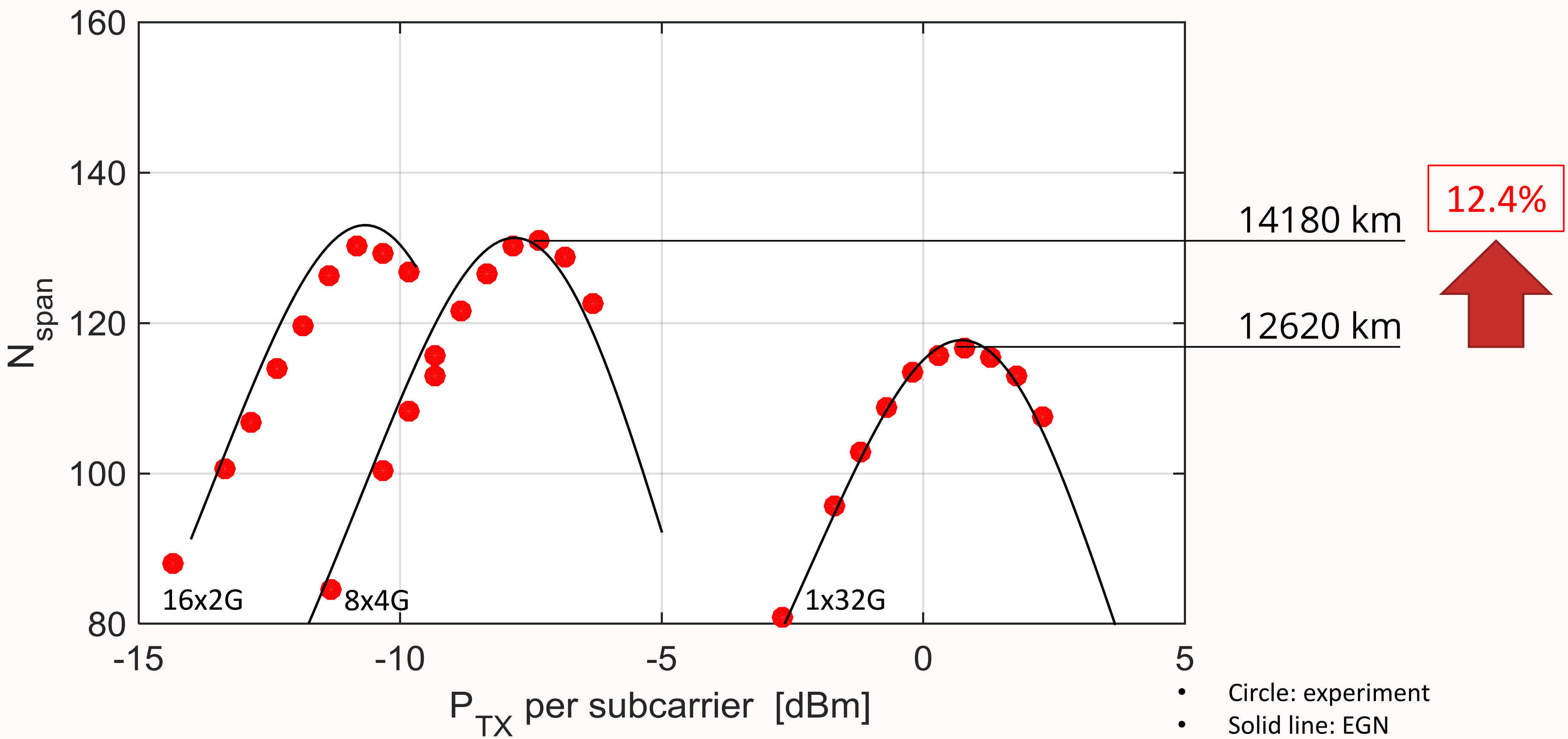
Multi-Carrier: 8x 4 GBaud and 16x2 GBaud



- Circle: experiment
- Solid line: EGN

MAXIMUM REACH AT BER=10^{-2}

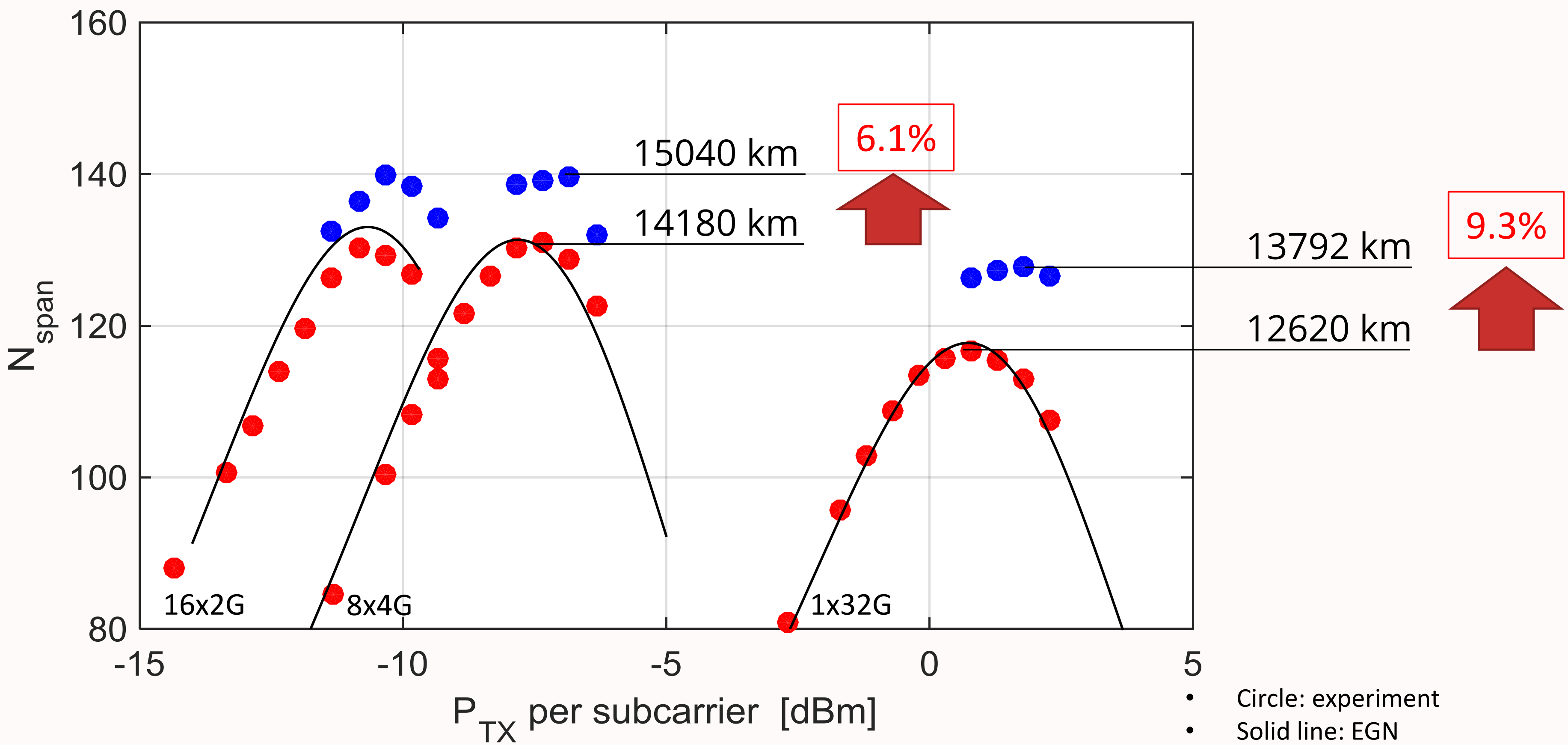
Multi-Carrier: 8x 4 GBaud and 16x2 GBaud



- Circle: experiment
- Solid line: EGN

MAXIMUM REACH AT BER=10^{-2}

DBP with 5 steps per span

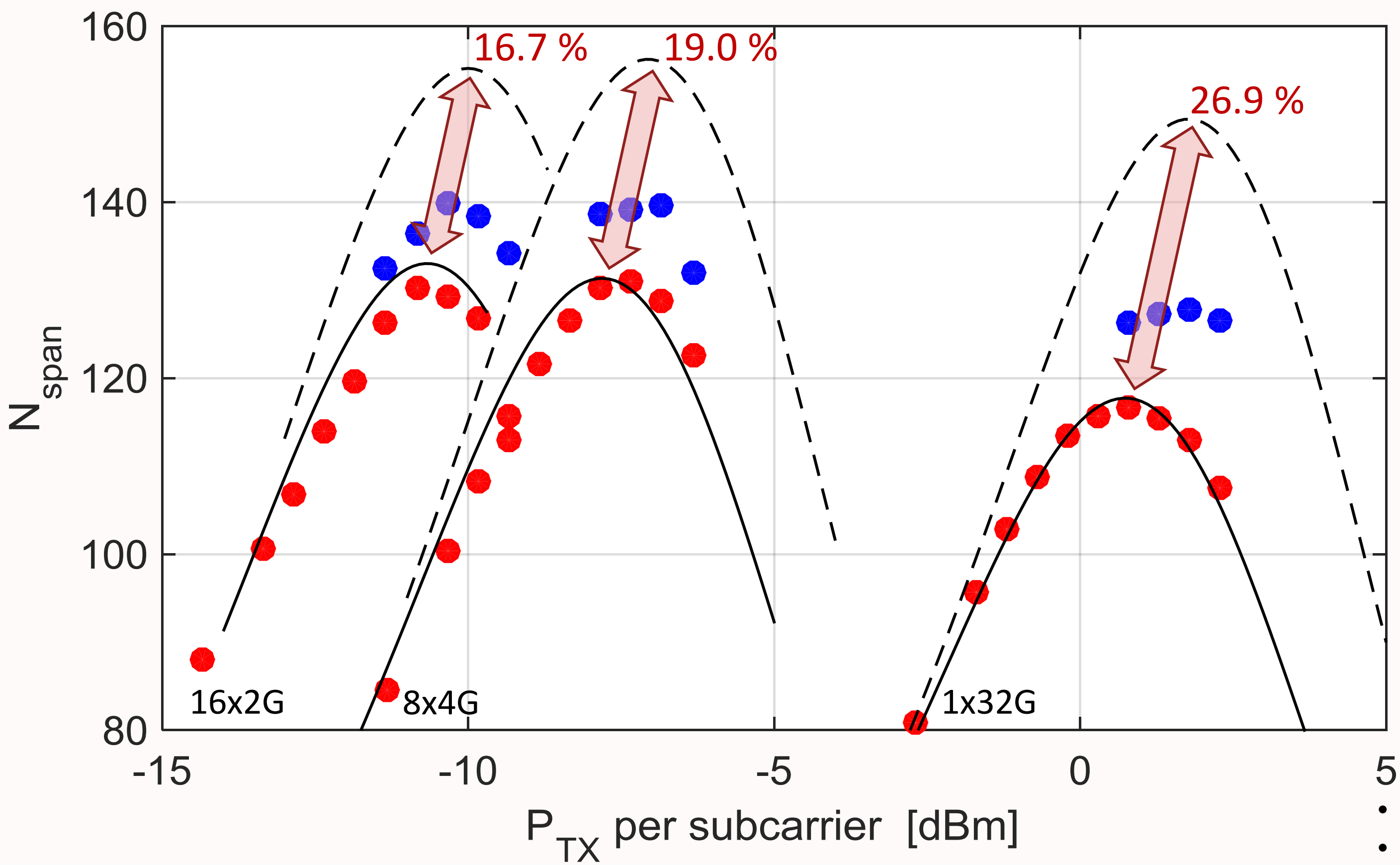


- Circle: experiment
- Solid line: EGN

MAXIMUM REACH AT BER=10^{-2}

EGN predictions with DBP

$$\mathrm{OSNR}_{NL} = \frac{P_{ch} - P_{NLI,signal}}{P_{ASE} + P_{NLI,signal+ASE} - P_{NLI,SCI}}$$

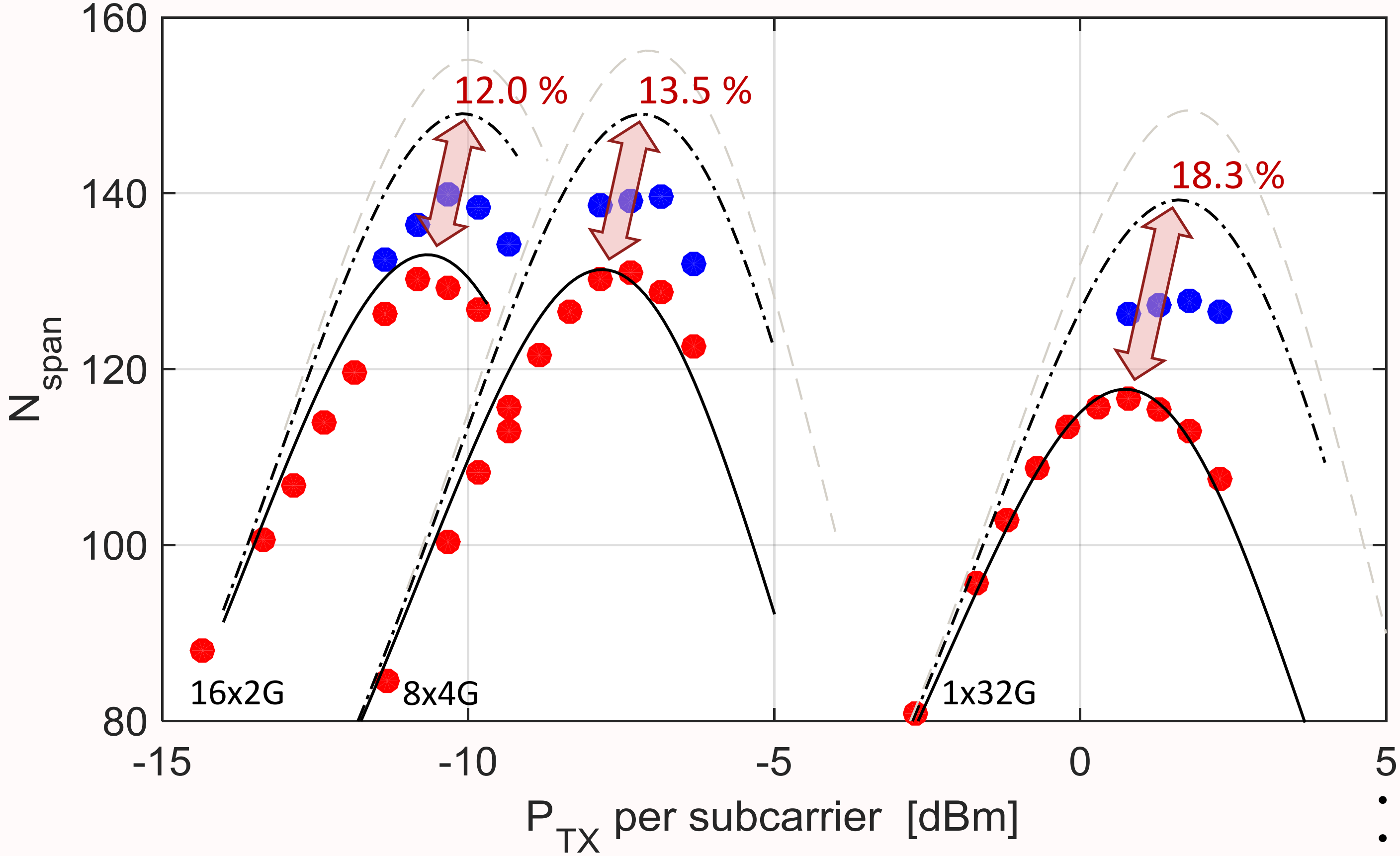


- Circle: experiment
- Solid line: EGN
- Dashed line: EGN wDBP

MAXIMUM REACH AT BER=10^{-2}

EGN predictions with DBP and ASE corrections

$$OSNR_{NL} = \frac{P_{ch} - P_{NLI,signal}}{P_{ASE} + P_{NLI,signal+ASE} - P_{NLI,SCI} + P_{NLI,ASE+DBP}}$$



- Circle: experiment
- Solid line: EGN
- Dashed line: EGN wDBP
- Dash-dotted: EGN wDBP + ASEc

CONCLUSIONS

- Theoretical analysis combining SRO and DBP shows that the two techniques are potentially synergistic
- Our ULH experiment confirm some advantages of combining SRO and DBP
- SRO deliver all the expected NLI mitigation
- DBP underperform its expected benefit
  - DBP is vulnerable when applied in low-OSNR conditions
  - Polarization effects also hinder DBP effectiveness
- In higher-OSNR systems, like PM-16QAM, DBP may result more effective

THANK YOU!

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This work was supported by Cisco within a SRA contract.