NON-LINEARITY MITIGATION BY MULTI-SUBCARRIER TRANSMISSION AND JOINT DSP POST-PROCESSING

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MOTIVATION FOR MULTI-SUBCARRIER TRANSMISSION

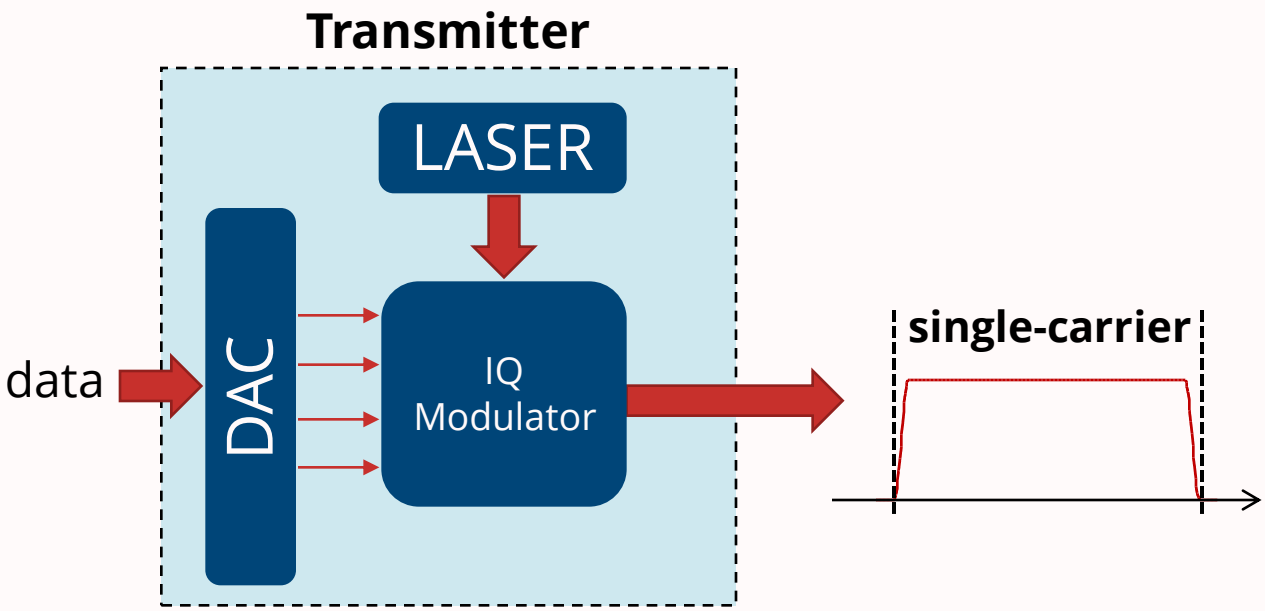
- The **challenges of digital nonlinear mitigation** (most commonly DBP) are mainly two-fold:
  - Intra-channel mitigation is limited in fully loaded WDM transmission;
  - Inter-channel mitigation is still far too complex…

- **Ideally**, we need a way of mitigating nonlinearities that is:
  - **Efficent in fully loaded WDM transmission**;
  - **Feasible to be implemented** (low complexity).

- Let's see what we can do with **multi-subcarrier transmission.**

WHAT IS MULTI-SUBCARRIER TRANSMISSION?

Single-carrier @ **high baudrate** ⇨ Multi-carrier @ **low baudrate**



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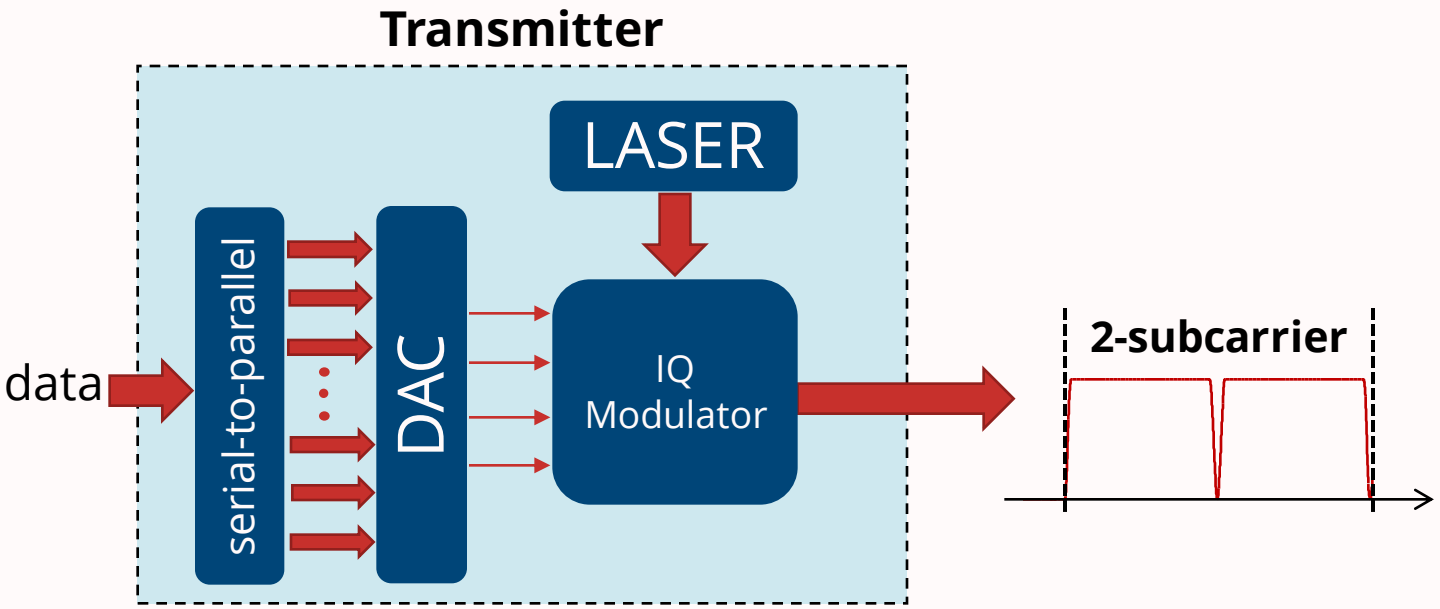

- Note that **only 1 transmitter is required** for multi-subcarrier!

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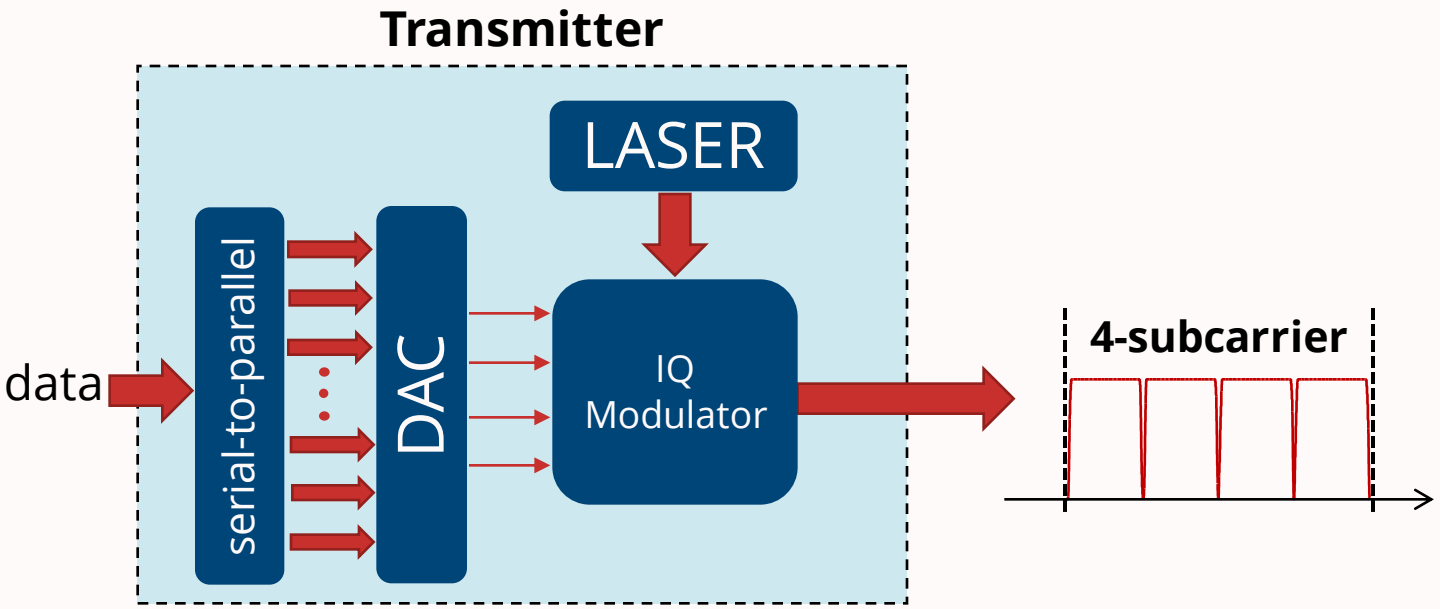

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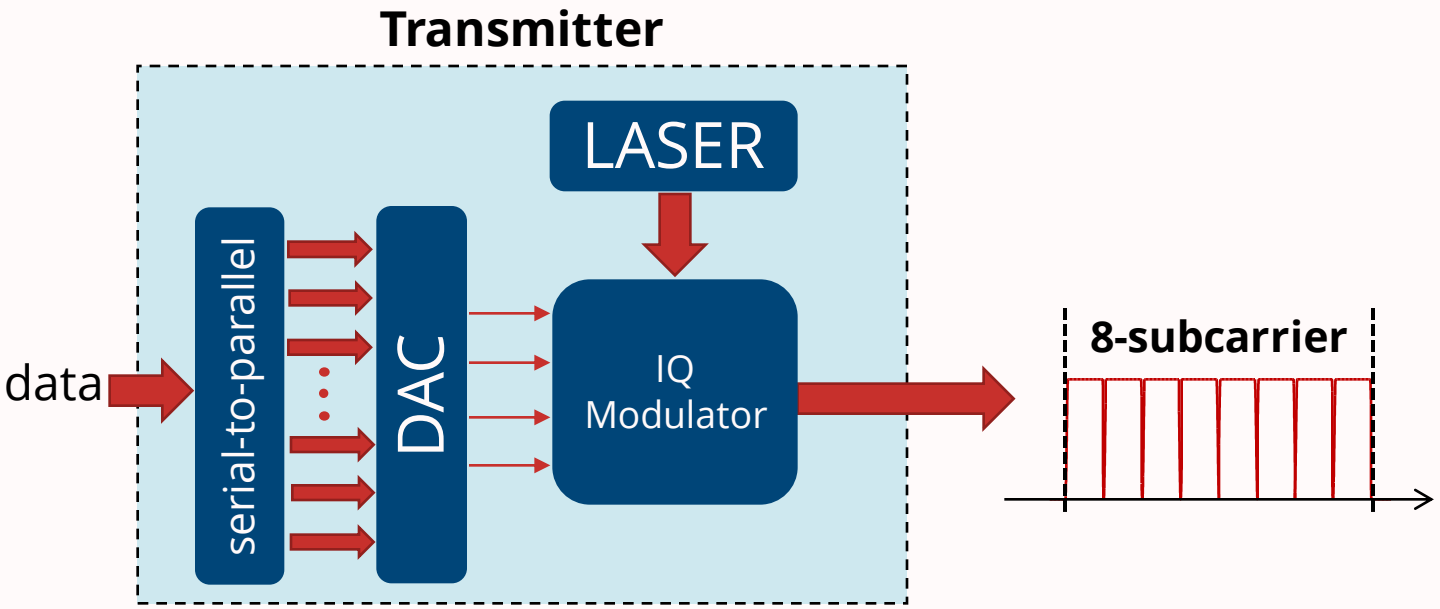

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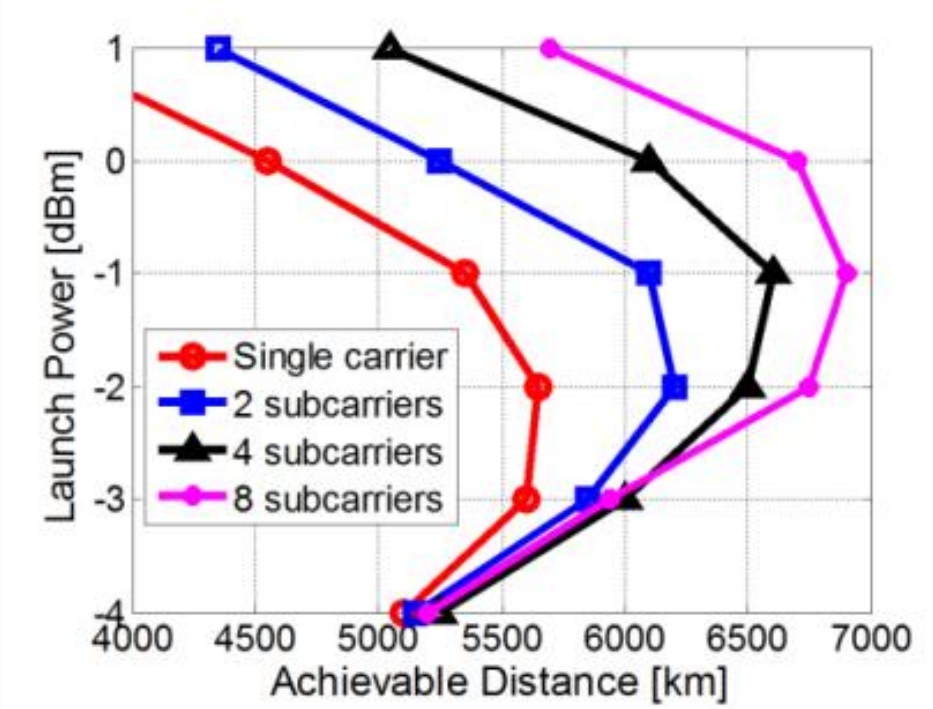
WHAT IS SYMBOL-RATE OPTIMIZATION?

- A recent experimental OFC 2014 paper showed a substantial dependence of performance on the symbol rate:

  Meng Qiu, Qunbi Zhuge, Xian Xu, M. Chagnon, M. Morsy-Osman, and David V. Plant, "Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems," in Proc. OFC 2014, paper Tu3J.2, San Francisco (CA), Mar. 2014.

- a **22% reach increase** was found when using 8x3 Gbaud instead 1x24 Gbaud (PM-QPSK);
- Single-channel transmission.



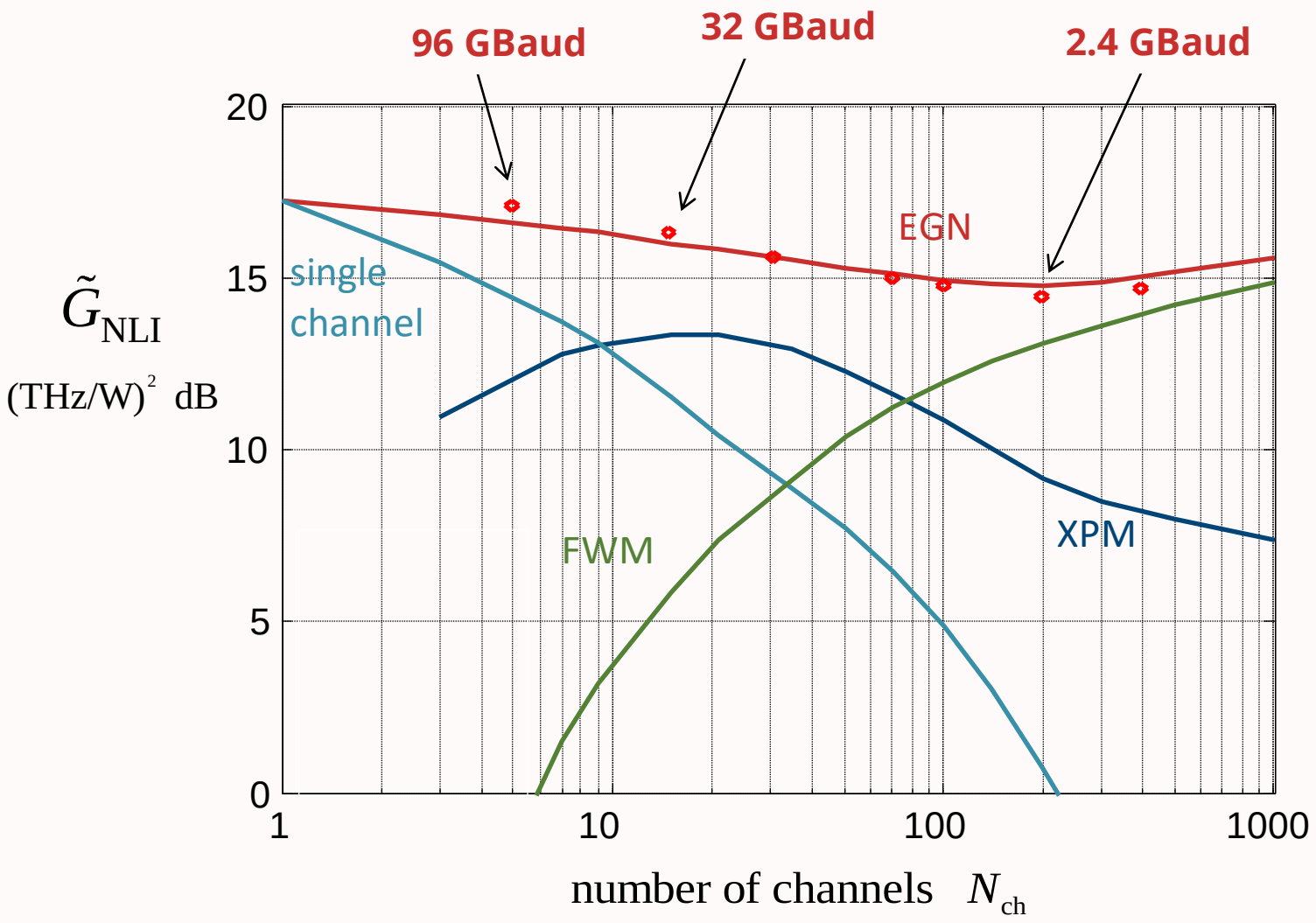
THE ONGOING DEBATE ABOUT SRO

- The discussion about SRO has led to **controversial results**:

- **SRO is clearly observed:**
  - M. Qiu *et al*, "Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems," paper Tu3J.2, OFC 2014.
  - H. Nakashima *et al*, "Experimental Investigation on Nonlinear Tolerance of Subcarrier Multiplexed Signals with Spectrum Optimization," paper ID: 0391, ECOC 2015.
  - P. Poggiolini et al, "Analytical and Experimental Results on System Maximum Reach Increase Through Symbol Rate Optimization," JLT, vol. 34, no. 8, 2016.

- **SRO is inexistent or negligible:**
  - J. Fickers *et al*, "Multicarrier Offset-QAM for Long-Haul Coherent Optical Communications," JLT, vol. 32, no. 24, 2014.
  - A. Carbo *et al*, "Experimental Analysis of Non Linear Tolerance Dependency of Multicarrier Modulations versus Bandwidth Efficiency," paper ID: 0408, ECOC 2015.
  - A. Carbo *et al*, "Experimental Analysis of Non Linear Tolerance Dependency of Multicarrier Modulations versus Number of WDM Channels," paper Tu3A.6, OFC 2016.

SIMULATION/ANALYTICAL EVIDENCE OF SRO



◇ simulations

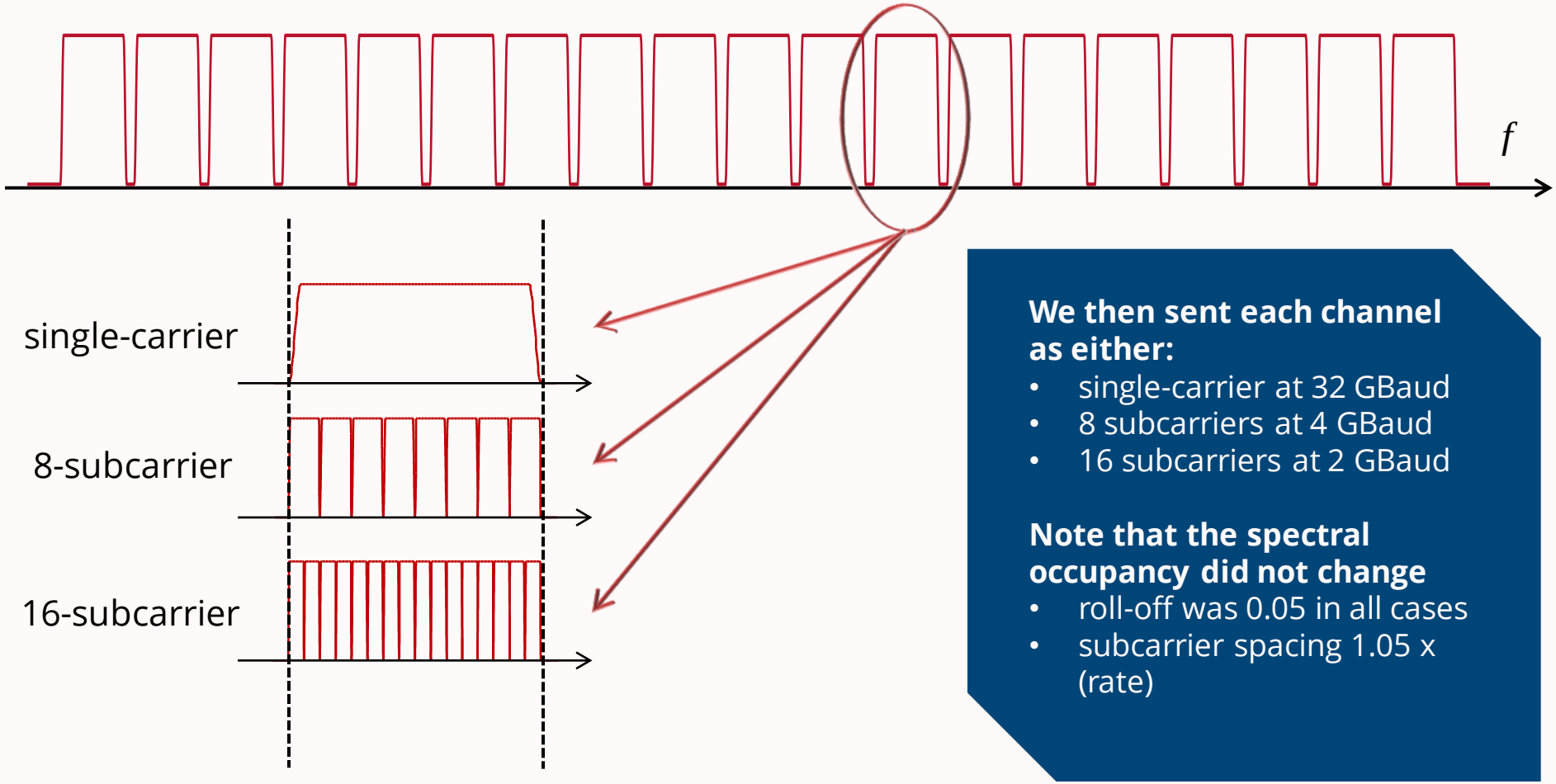
SSMF:

- **50 spans;**
- **B_{WDM} = 504 GHz;**
- **1.92 Tb/s;**
- PM-QPSK;
- spacing 1.05×R_s;
- 100 km spans.

P. Poggiolini, Y. Jiang, A. Carena, G. Bosco, F. Forghieri, "Analytical results on system maximum reach increase through symbol rate optimization," Proc. OFC, paper Th3D.6, 2015.

EXPERIMENTAL EVIDENCE OF SRO

- 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

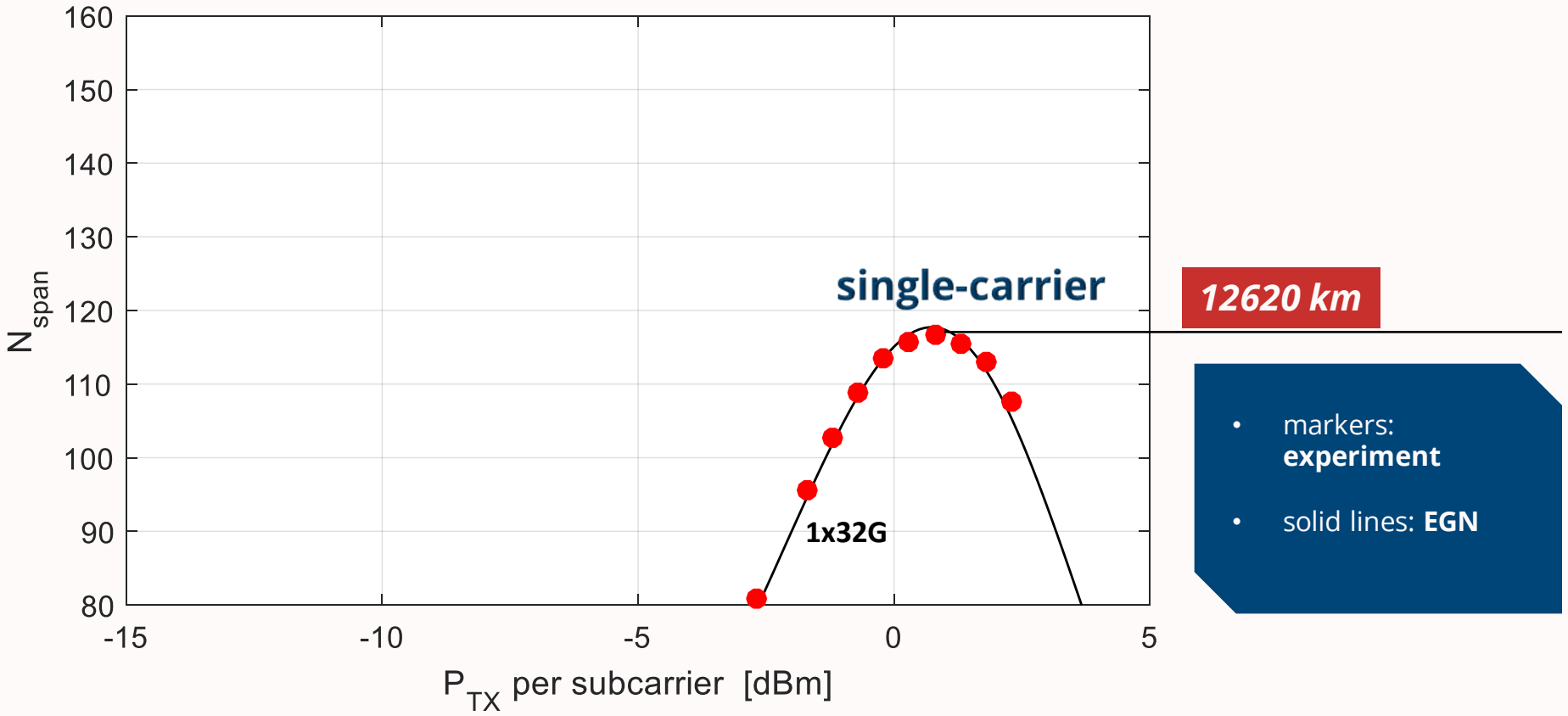
Note that the spectral occupancy did not change

- roll-off was 0.05 in all cases
- subcarrier spacing 1.05 x (rate)

A. Nespola, L. Bertignono, G. Bosco, A. Carena, Y. Jiang, S. M. Bilal, P. Poggiolini, S. Abrate, F. Forghieri, "Experimental Demonstration of Fiber Nonlinearity Mitigation in a WDM Multi-Subcarrier Coherent Optical System," Proc. ECOC, paper ID: 0382, 2015.

COMBINING SRO AND DBP BENEFITS

- **Reach curves at BER 10^{-2} :**



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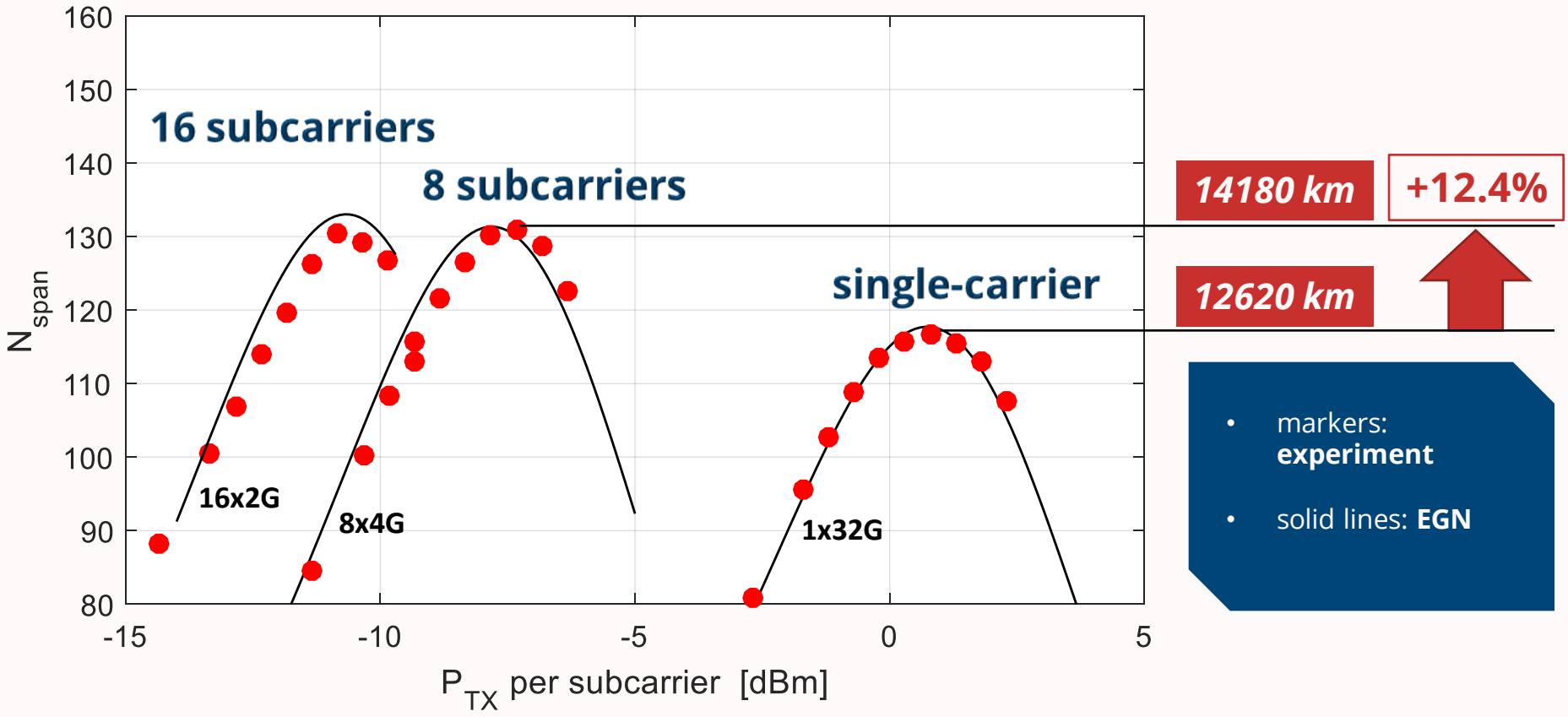

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SRO VS DBP

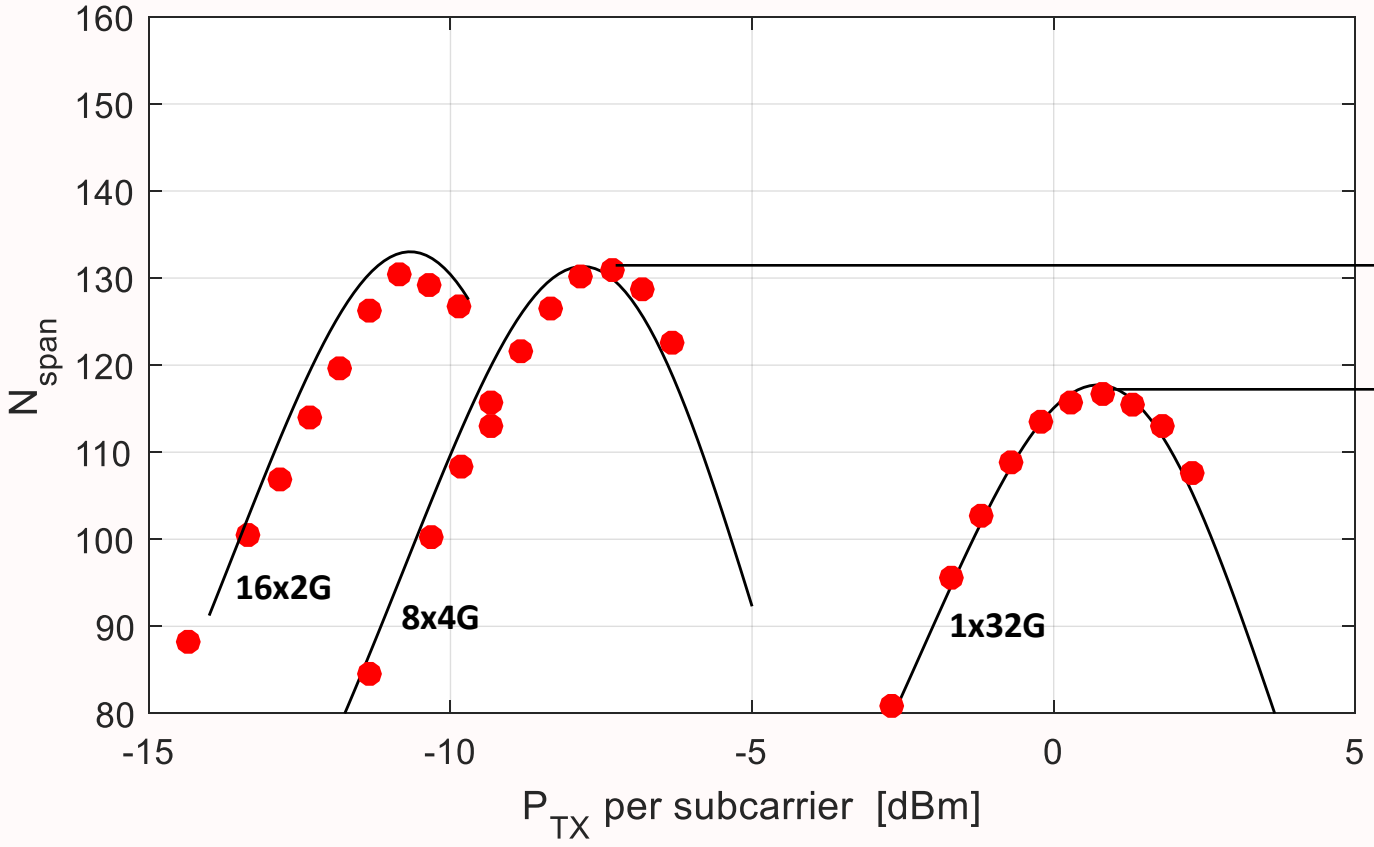
- It looks like SRO is really there!
  - It provides nonlinear mitigation (10-20% in max reach) without requiring additional complexity.

- How does it compare with DBP?

- Can SRO and DBP work synergetically?

COMBINING SRO AND DBP BENEFITS

Max reach after CD compensation only:



14180 km **+12.4%**

12620 km

- markers: **experiment**
- solid lines: **EGN**

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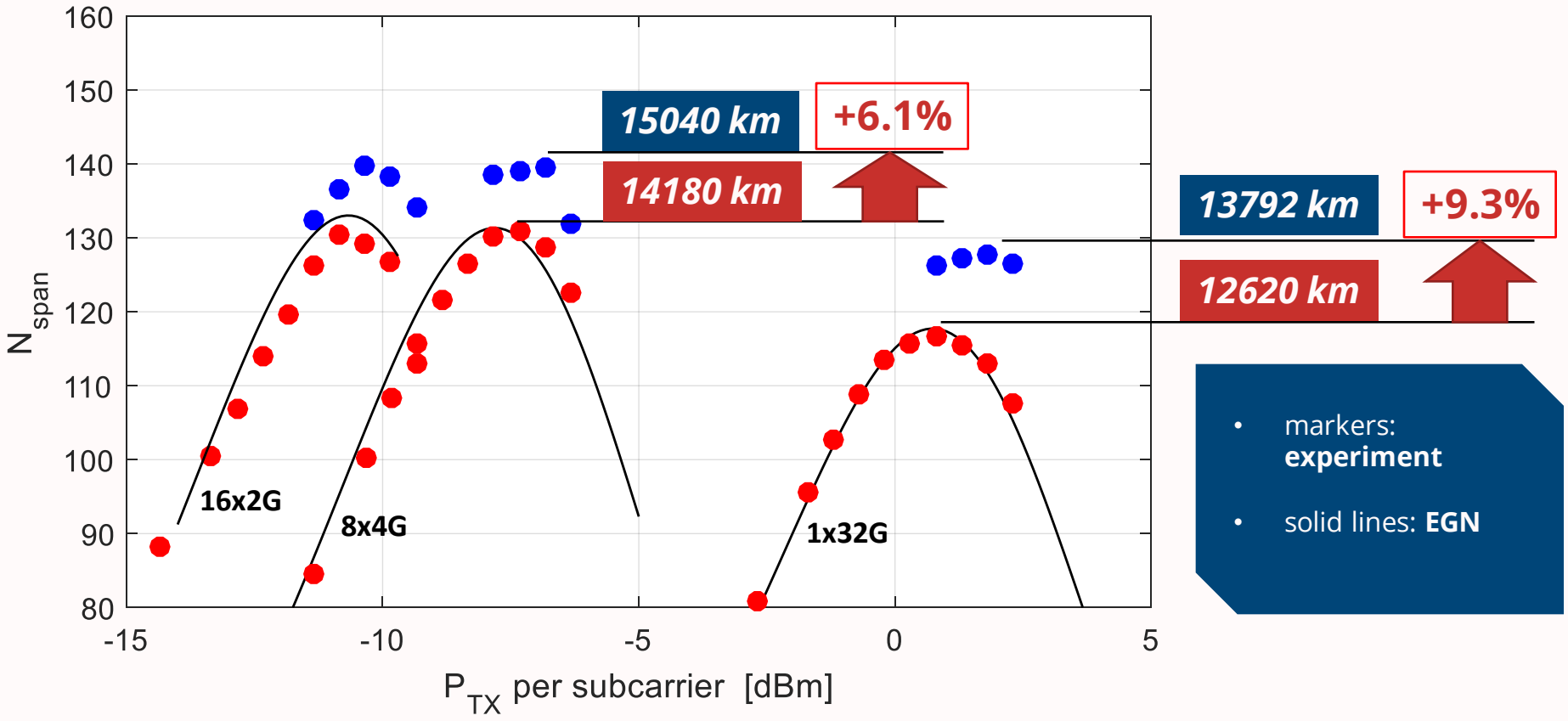
COMBINING SRO AND DBP BENEFITS

DBP with 5 steps per span:



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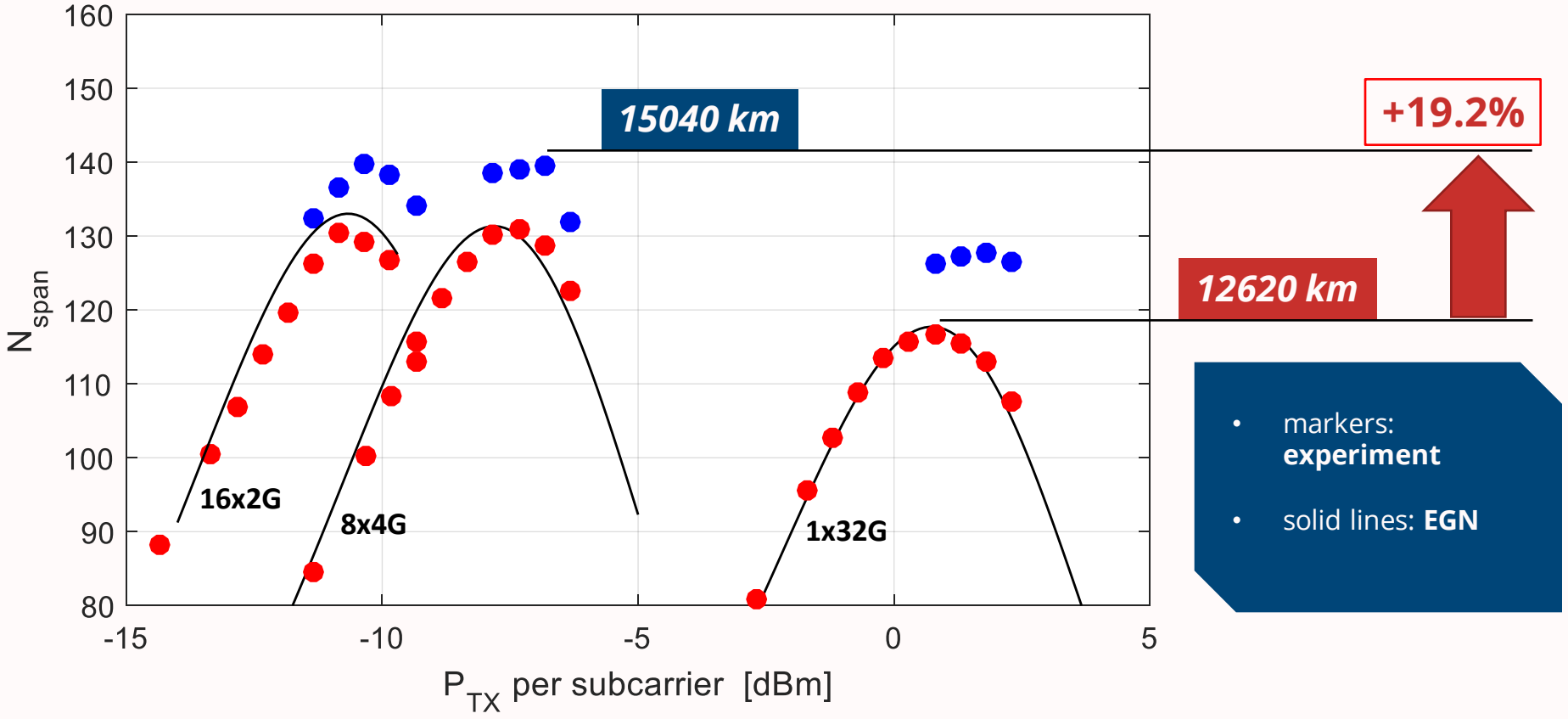

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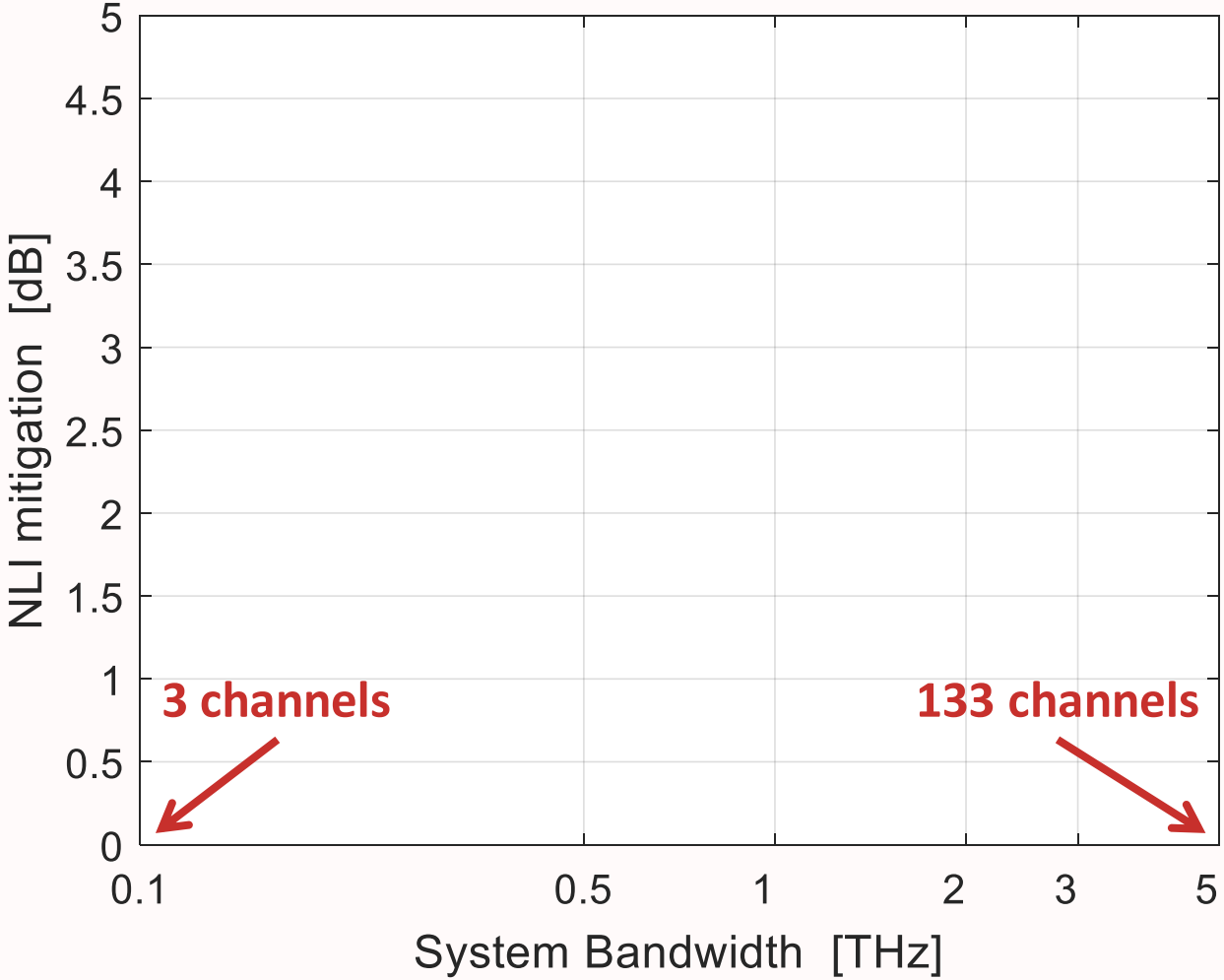
WHAT HAPPENS IN FULLY-LOADED WDM SYSTEMS?



- $R_{S,tot}$ = 32 GBd
- roll-off = 0.05
- Δf = 33.6 GHz
- N_{sc} = 14

P. Poggiolini, A. Nespola, Y. Jiang, G. Bosco, A. Carena, L. Bertignono, S. M. Bilal, S. Abrate, F. Forghieri, "Analytical and Experimental Results on System Maximum Reach Increase Through Symbol Rate Optimization," JLT, vol. 34, no. 8, 2016.

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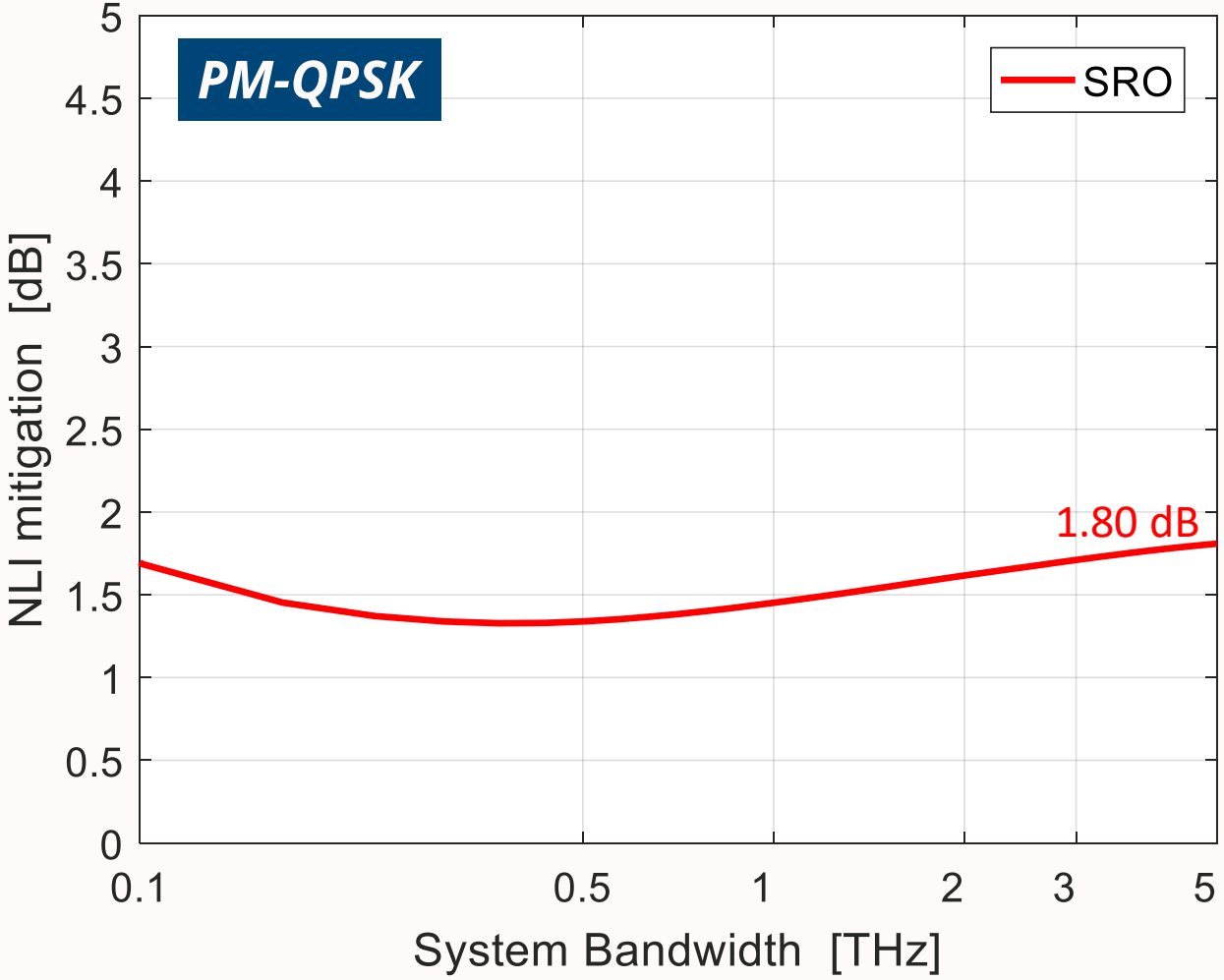

- **PM-QPSK**
- SSMF
- 50 spans
- L_{span} = 100 km

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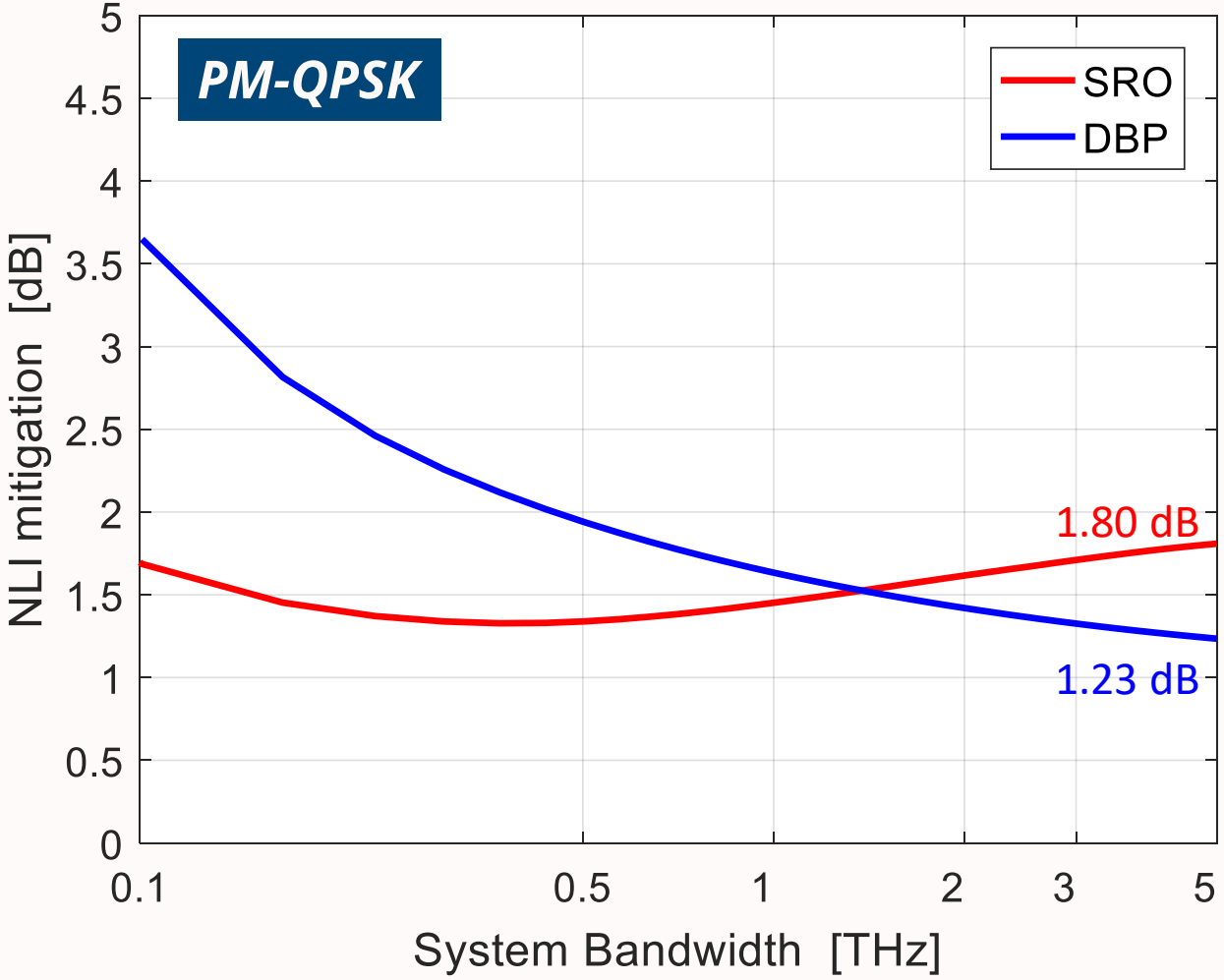

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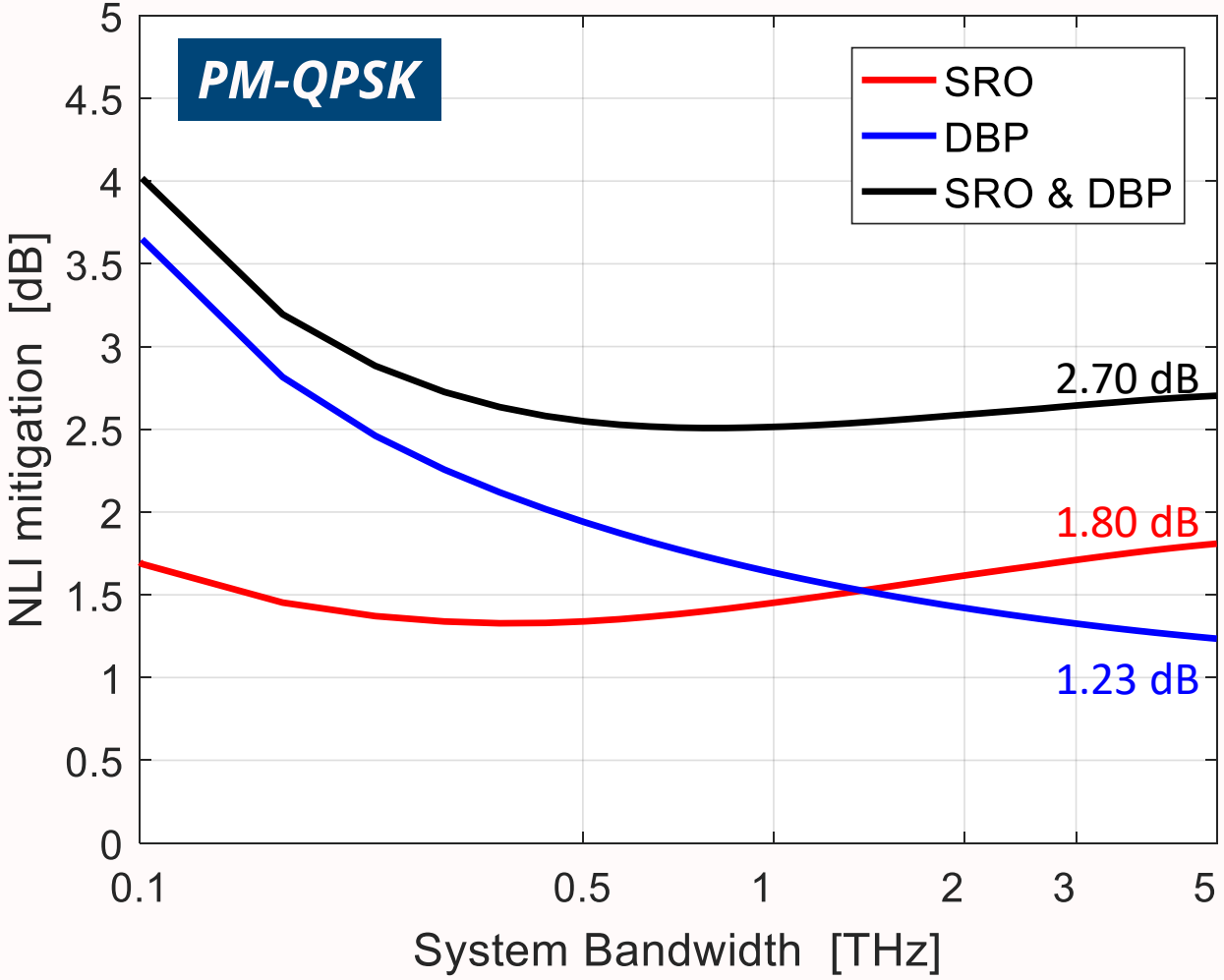

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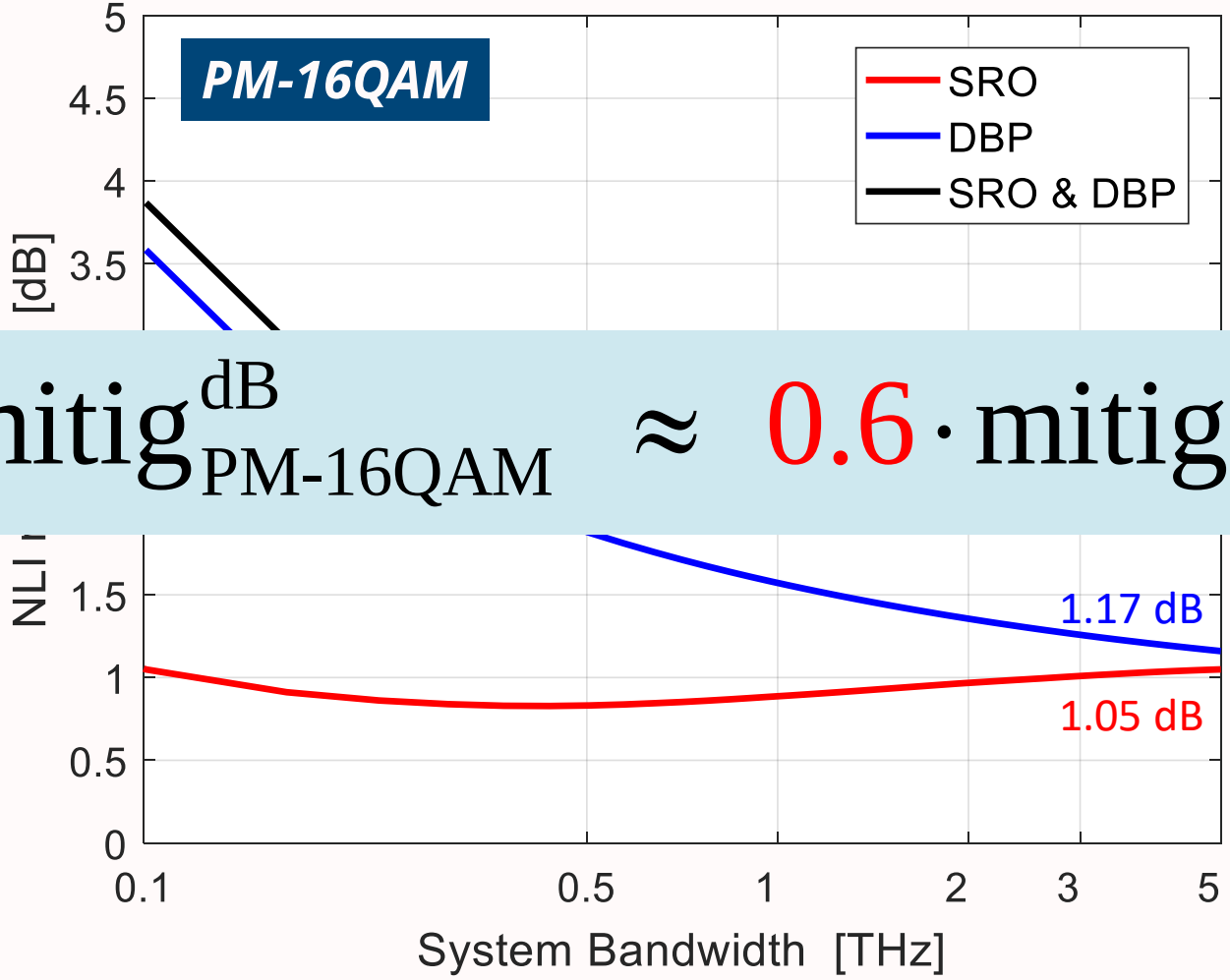

- **PM-16QAM**
- SSMF
- 50 spans
- L_{span} = 100 km

$$\text{mitig}^{\text{dB}}_{\text{PM-16QAM}} \approx 0.6 \cdot \text{mitig}^{\text{dB}}_{\text{PM-QPSK}}$$

GBd

- roll-off = 0.05
- Δf = 33.6 GHz
- N_{sc} = 14

P. Poggiolini, A. Nespola, Y. Jiang, G. Bosco, A. Carena, L. Bertignono, S. M. Bilal, S. Abrate, F. Forghieri, "Analytical and Experimental Results on System Maximum Reach Increase Through Symbol Rate Optimization," JLT, vol. 34, no. 8, 2016.

WHAT ABOUT HIGH-ORDER QAM?

- The EGN model shows that the SRO advantage may be reduced fo[redacted]
  - But, is it inev[redacted]?

Wednesday 9:30:
W.1.D.3: Independence of the Impact of Inter-Channel Non-Linear Effects on Modula[redacted]lications

- If long-co[redacted]lated nonlinear phase [redacted]ise is completely removed, [redacted] [redacted]erference becomes **independe[redacted] of the modulation format**.

- **Effective NLPN removal** should be able to preserve the SRO gain provided by PM-QPSK.

CONCLUSIONS

- For each uncompensated optical link there exists an **optimal symbol-rate** (2-10 GBd);
- SRO provides **zero-overhead nonlinear mitigation**;
- SRO is expected to **hold up for fully-loaded systems**;
- **Joint SRO + DBP** processing enables further mitigation;
- **Nonlinear Phase Noise** is a critical issue for m-QAM.
  - There's a need for improved joint DSP.

ACKNOWLEDGMENTS

THANK YOU!

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