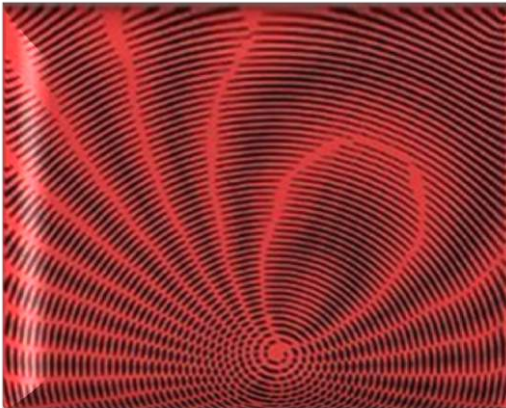


Experimental Demonstration of Fiber Nonlinearity Mitigation in a WDM Multi-Subcarrier Coherent Optical System



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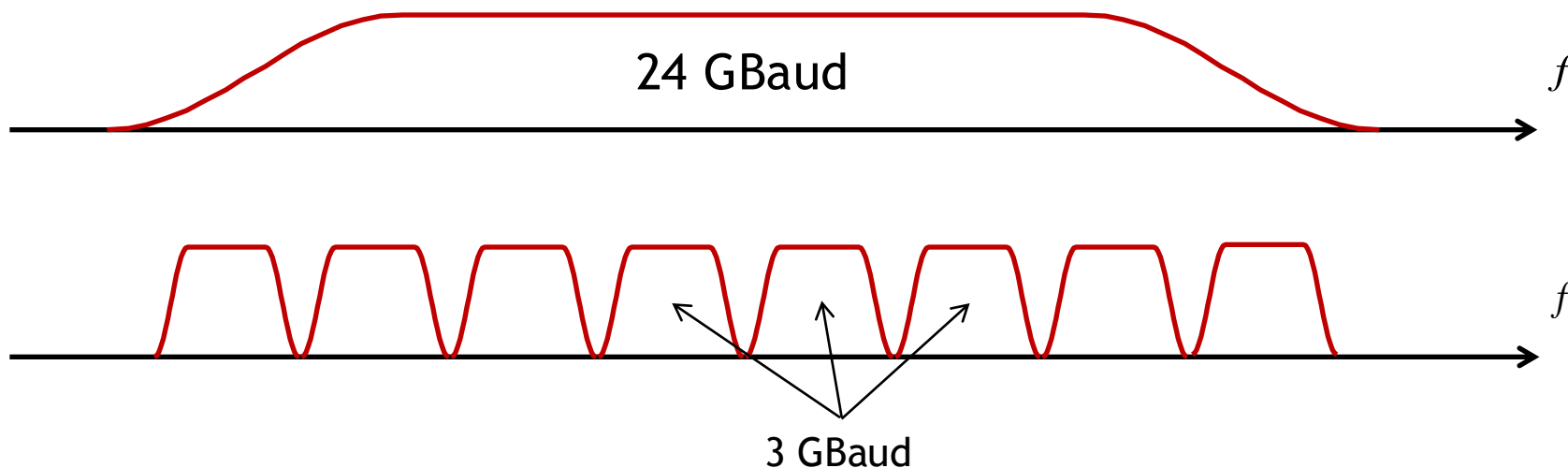
Presenter: Pierluigi Poggiolini

- ▶ One of the currently hottest topics in system research is: *non-linearity mitigation*
- ▶ Many groups are tackling this problem
- ▶ The key requirements are:
 - ▶ *reasonable processing complexity*
 - ▶ *effectiveness must not drop off vs. WDM bandwidth*

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

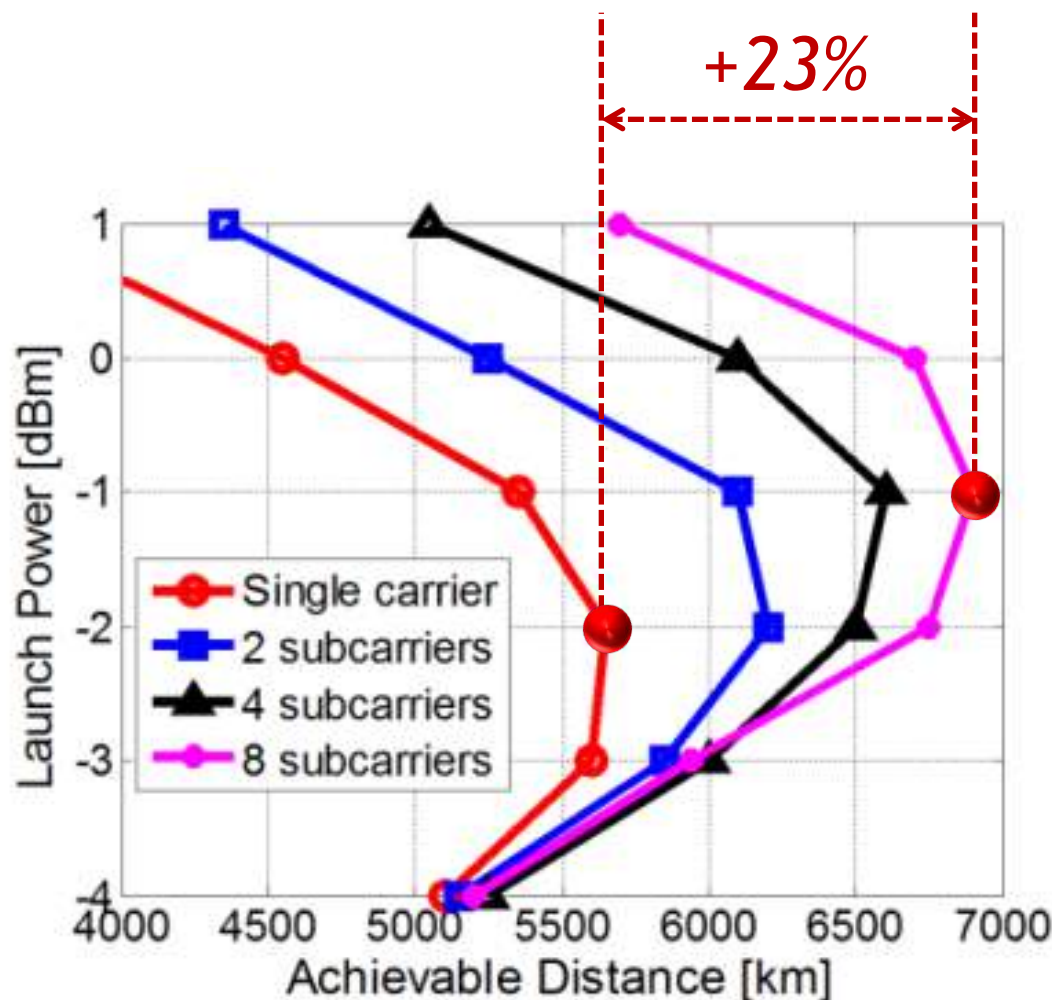
Meng Qiu, Qunbi Zhuge, Xian Xu, M. Chagnon, M. Morsy-Osman, and David V. Plant 'Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems,' in Proc. OFC 2014, paper Tu3J.2, San Francisco (CA), Mar. 2014.

- ▶ a *single* 24 GBaud channel was chopped up into 2, 4, 8 subcarriers



...gains you performance

- ▶ a **23% reach increase** was found when using 8 subcarriers at 3 GBaud vs. a single carrier at 24 GBaud



▶ That paper had simulative/theoretical *precursors*:

- ▶ W. Shieh and Y. Tang, 'Ultrahigh-speed signal transmission over nonlinear and dispersive fiber optic channel: the multicarrier advantage,' IEEE Photonics J., vol. 2, no. 3, pp. 276-283, June 2010.
- ▶ L. B. Du and A. J. Lowery, 'Optimizing the subcarrier granularity of coherent optical communications systems,' Optics Expr., vol. 19, no. 9, pp. 8079, Apr. 2011.
- ▶ A. Bononi, N. Rossi and P. Serena, 'Performance dependence on channel baud-rate of coherent single-carrier WDM systems,' in Proc. of ECOC 2013, paper Th.1.D.5, London (UK), Sept. 2013.
- ▶ Q. Zhuge, B. Chatelain, and D. V. Plant, 'Comparison of intra-channel nonlinearity tolerance between reduced-guard-interval CO-OFDM systems and nyquist single carrier systems,' in Proc. of OFC 2012, paper OTh1B.3, Los Angeles (CA), Mar. 2012.

▶ Simulative/theoretical study - OFC 2015

- ▶ 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, Los Angeles, Mar. 2015.

▶ We found the following:

▶ The effect is very accurately modeled using the **EGN-model**

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

- ▶ neither the GN-model nor advanced XPM models were able to account for it

▶ The EGN model predicted:

max-reach gains of 10% to 20% for PM-QPSK systems

- ▶ simulations fully confirmed the predictions (on 500 GHz WDM systems)

▶ The optimum symbol rates were very low: **1 to 3 Gbaud** over SMF/PSCF

- ▶ **provided simple analytical formula**

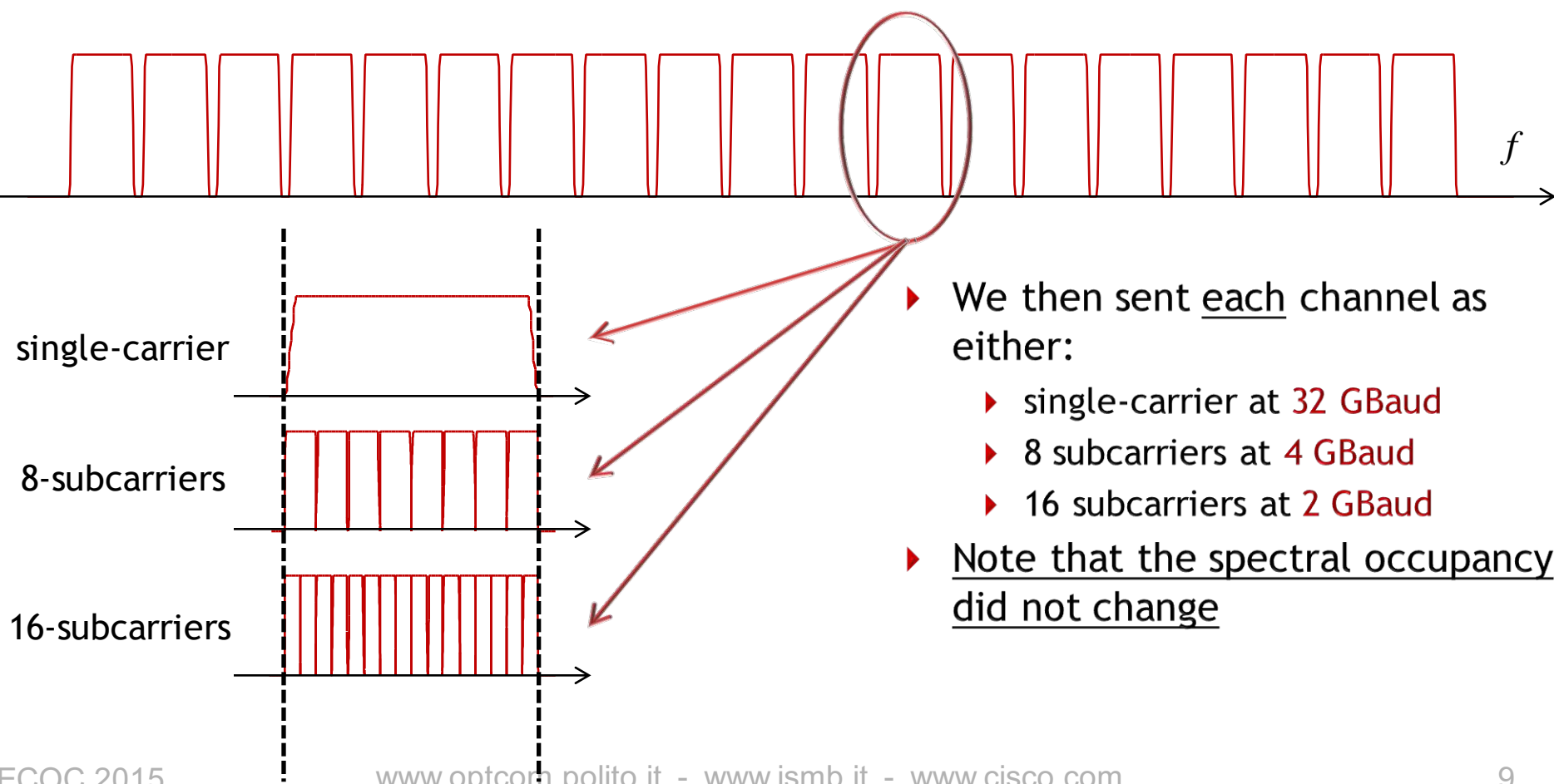
- ▶ Simulation and modeling results are important but nothing can replace experiments...
- ▶ The already mentioned OFC 2014 experimental paper:
Meng Qiu, Qunbi Zhuge, Xian Xu, M. Chagnon, M. Morsy-Osman, and David V. Plant 'Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems,' in Proc. OFC 2014, paper Tu3J.2, San Francisco (CA), Mar. 2014
showed a 23% reach increase
- ▶ On the other hand, a massive WDM experiment, based on 64 channels at 32 GBaud (split into subcarriers),
J. Fickers, et al., 'Multicarrier Offset-QAM for Long-Haul Coherent Optical Communications,' *J. of Lighth. Technol.*, Vol. 32, n. 4, p. 4671, Dec. 2014.
showed essentially no gain
- ▶ OFC 2015 post-deadline
Fatih Yaman, et al., "First Quasi-Single-Mode Transmission over Transoceanic Distance using **Few-mode Fibers**," Proc. OFC, post-deadline paper Th5C.7, Los Angeles, Mar. 2015.
inconclusive (subcarriers improve DSP performance)

The jury's still out on SRO...

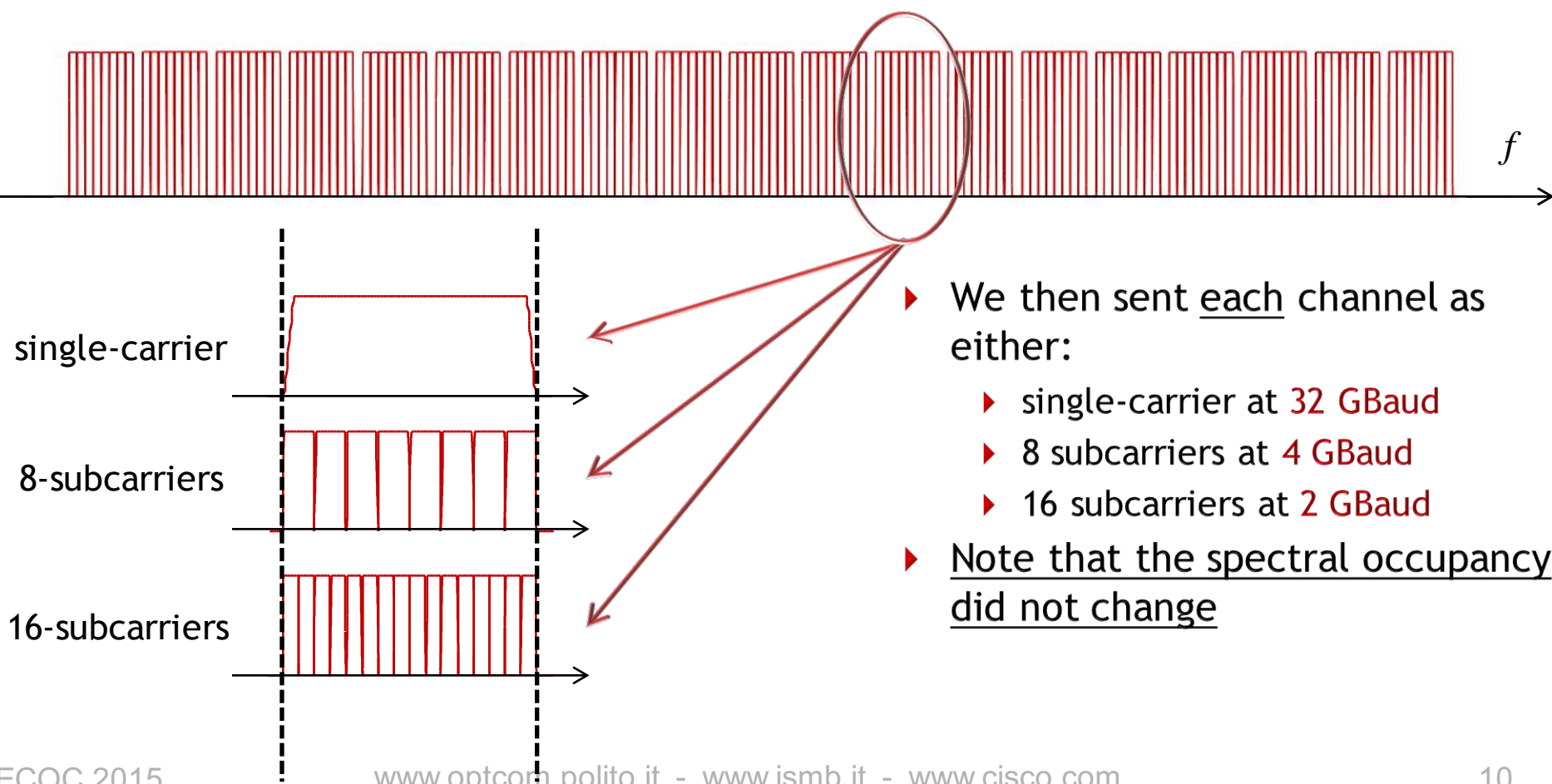


https://www.google.es/search?q=the+jury+is+still+out&biw=1524&bih=638&source=lnms&tbm=isch&sa=X&ved=0CAcQ_AUoAWoVCzMlnZ-slueWyAIVAVcUCh2QFAVw#imgsrc=XsXPsgOI-asKVM%3A

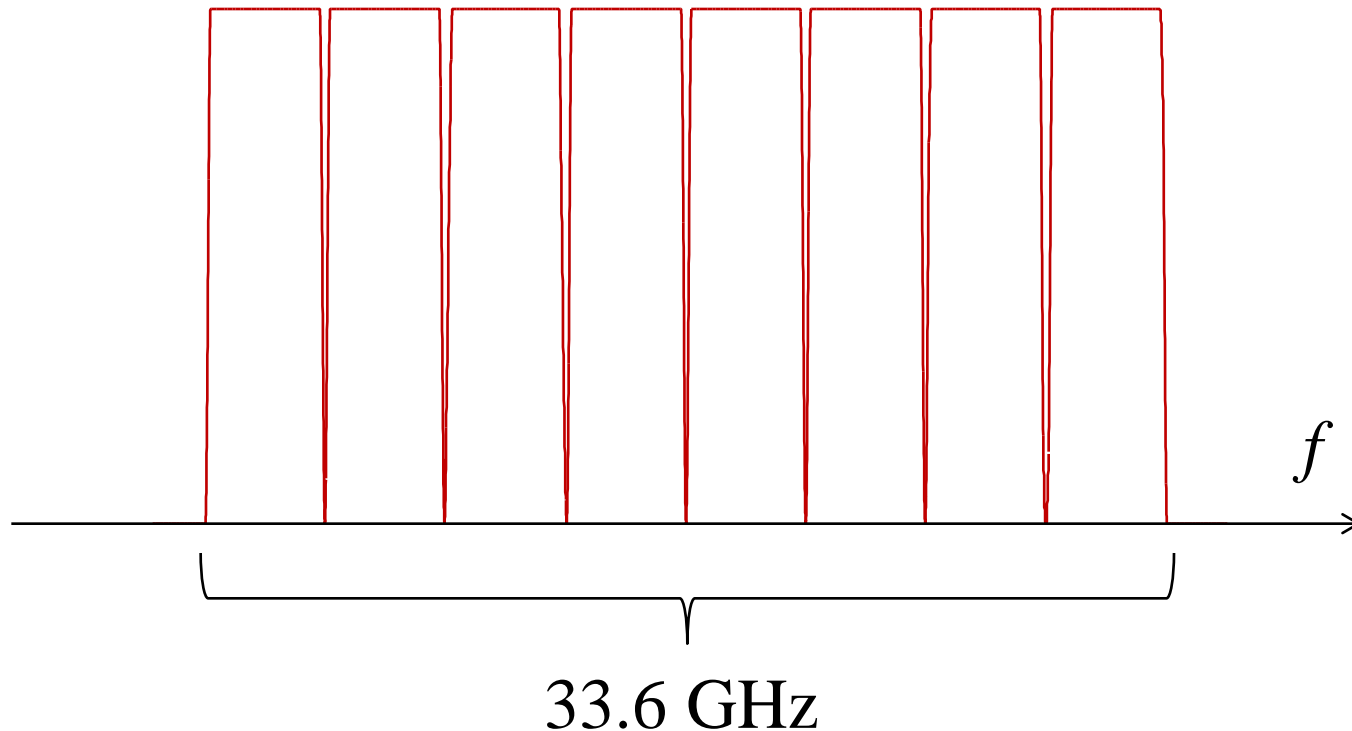
- ▶ We started out with a **19 channel WDM comb**, with channel spacing **37.5 GHz**, for a total WDM bandwidth of **710 GHz**



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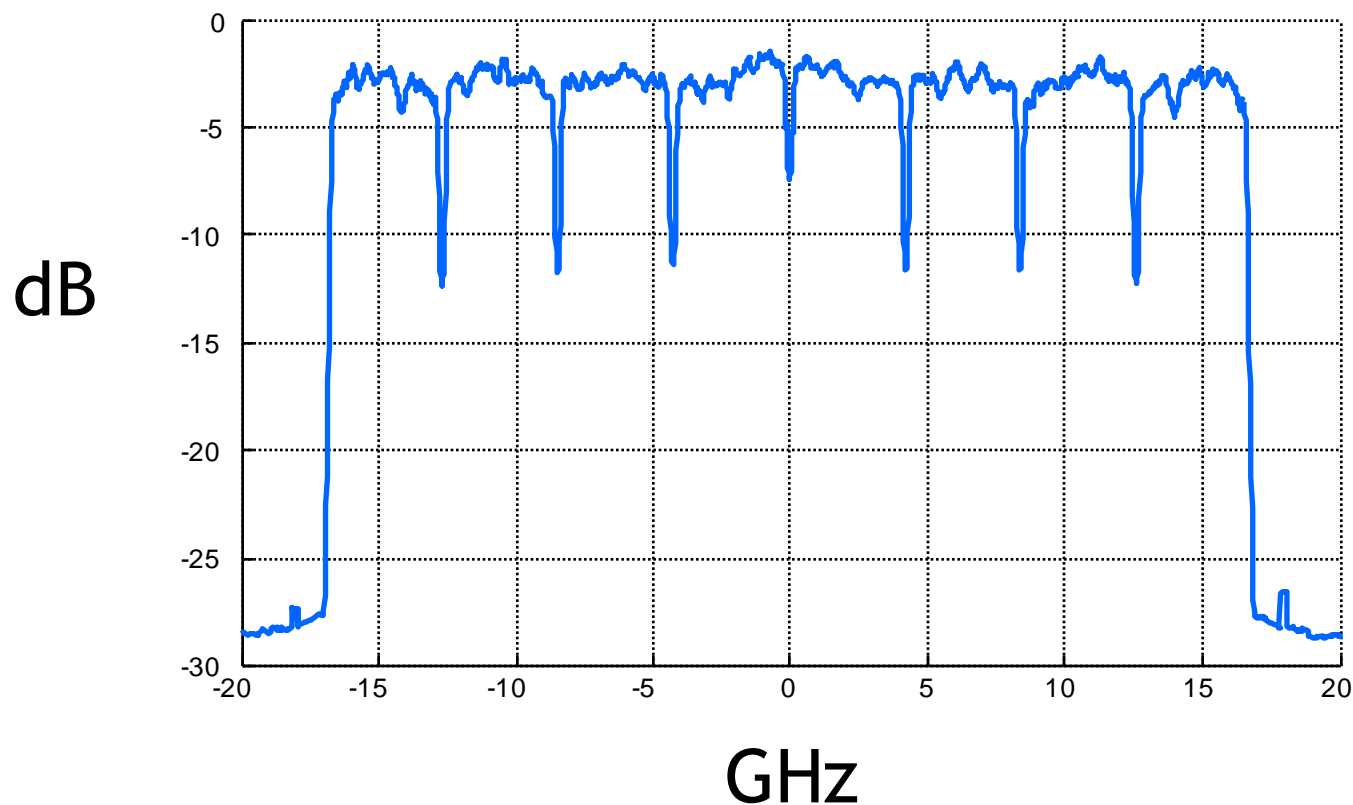


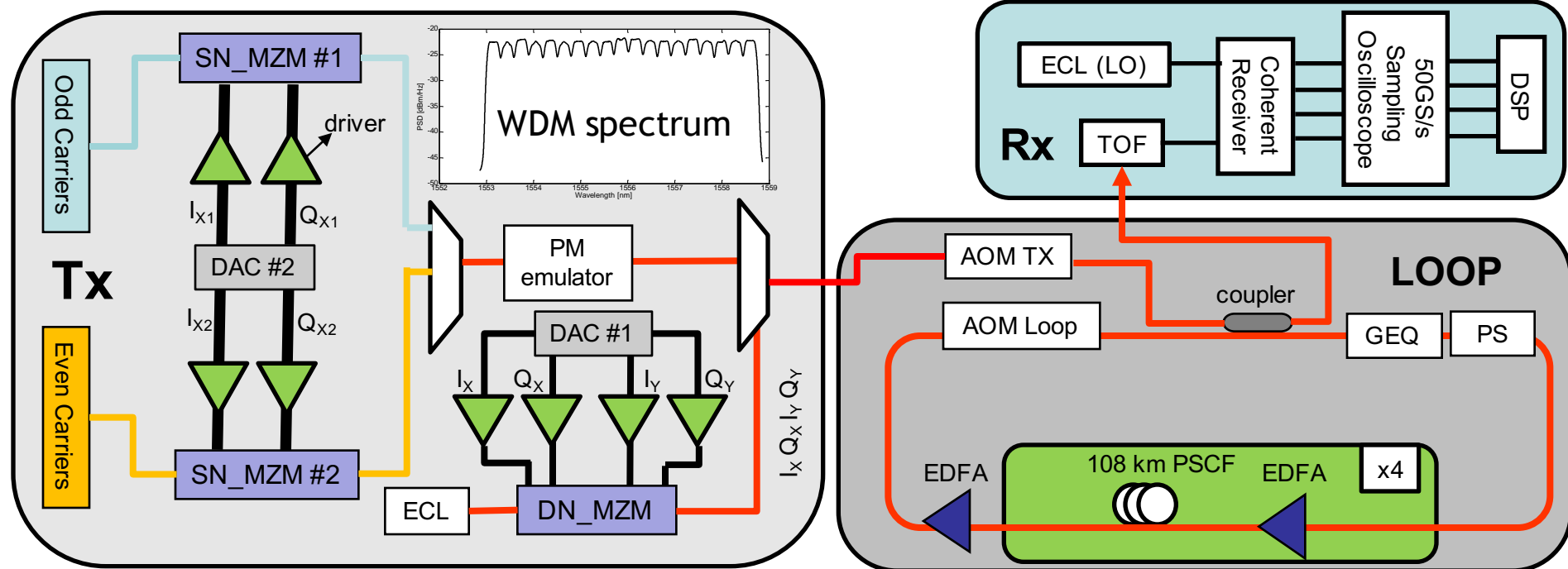
- ▶ the 8-subcarrier DAC-generated spectrum for **one** channel



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

- ▶ the 8-subcarrier DAC-generated **electrical** spectrum for one channel



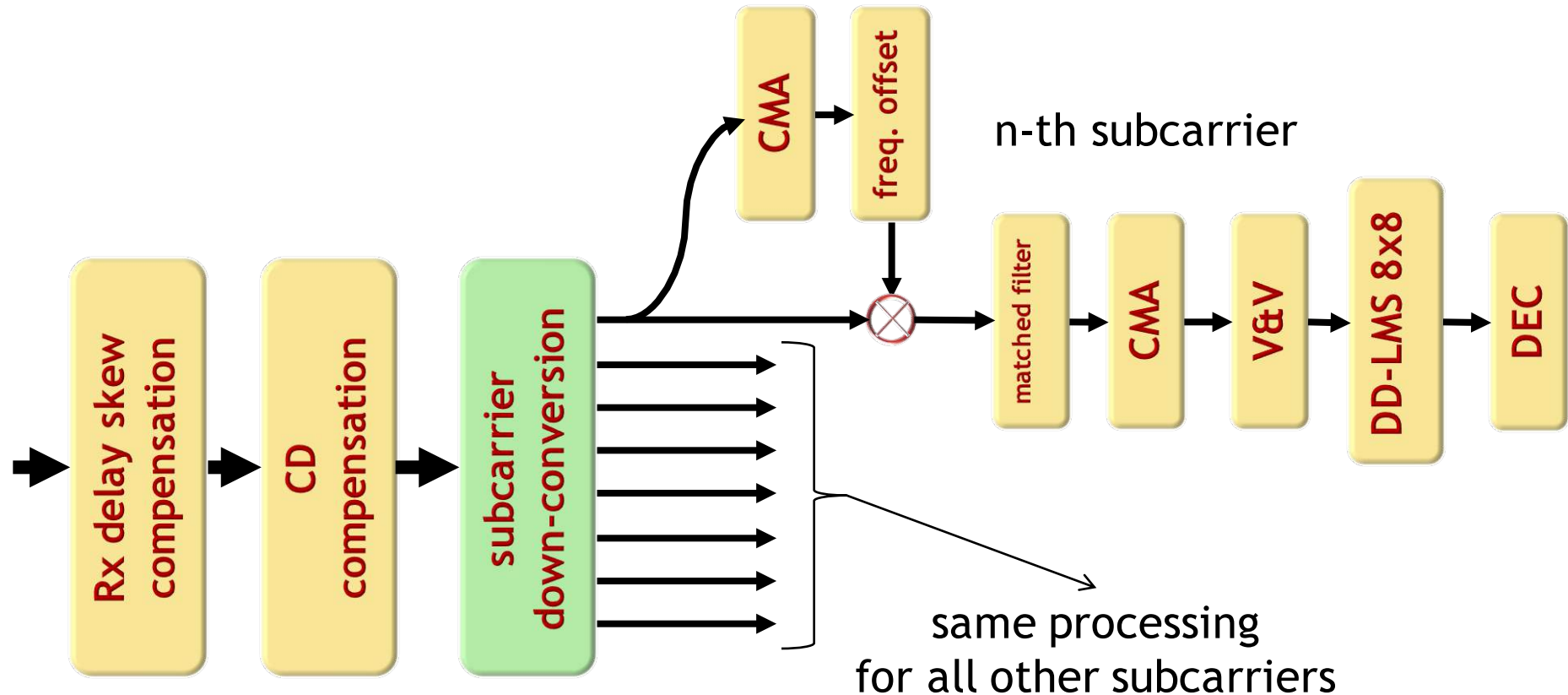


SN_MZM: single-nested Mach-Zehnder mod.
DN_MZM: double-nested Mach-Zehnder mod.

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

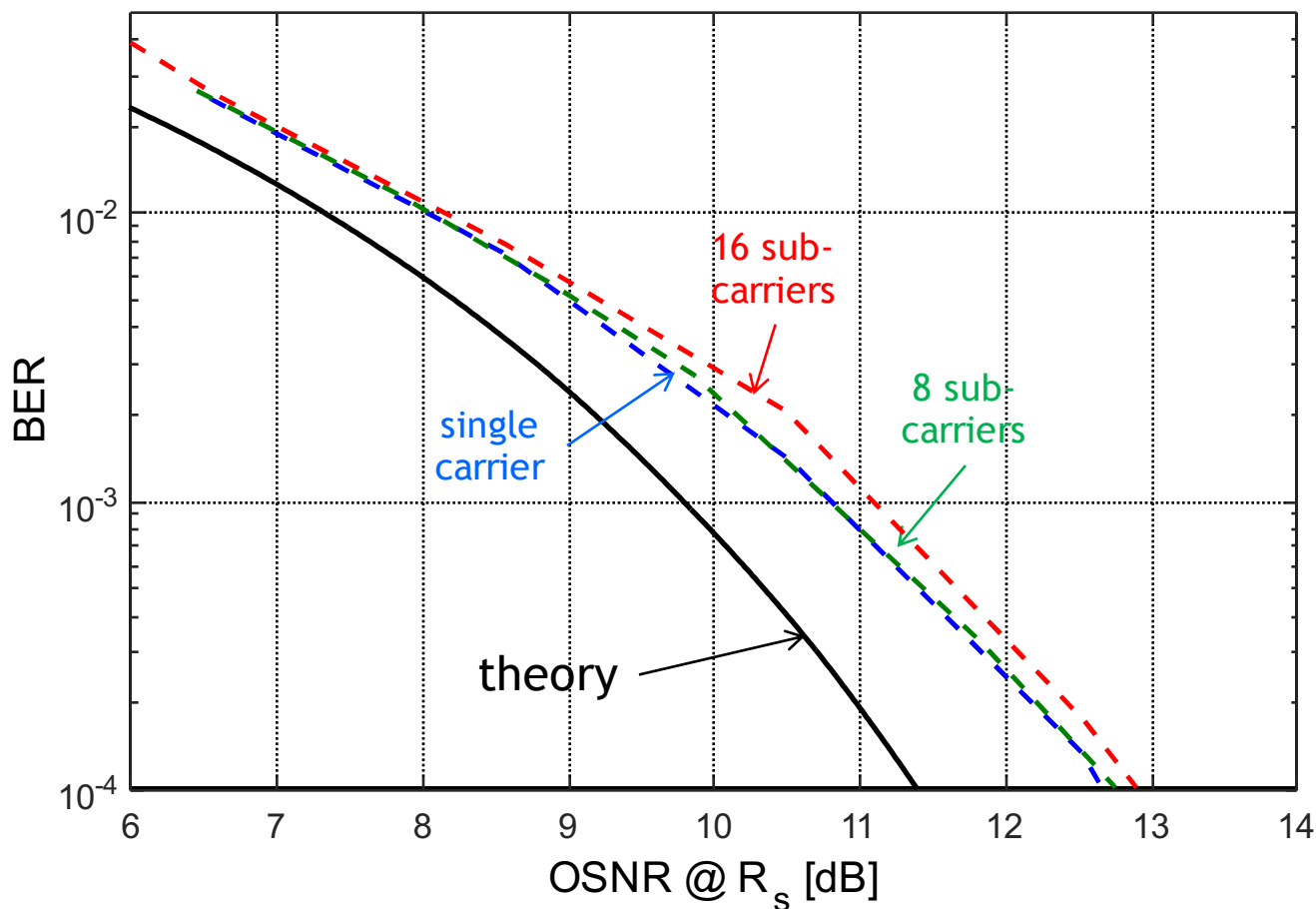
PSCF fiber kindly
provided by



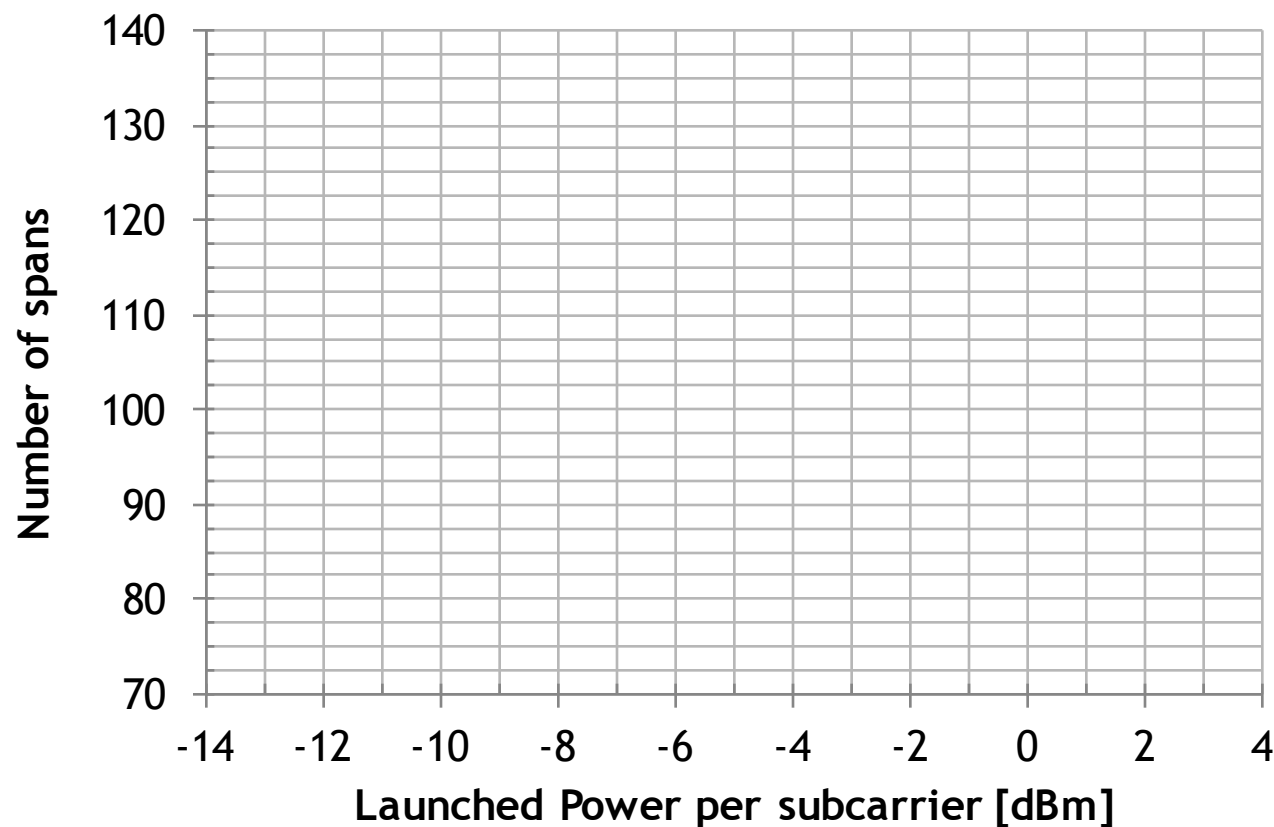


- ▶ the 8x8 (real) LMS is necessary to correct for I/Q delay skew at the transmitter modulator (otherwise 4x4 is enough)

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

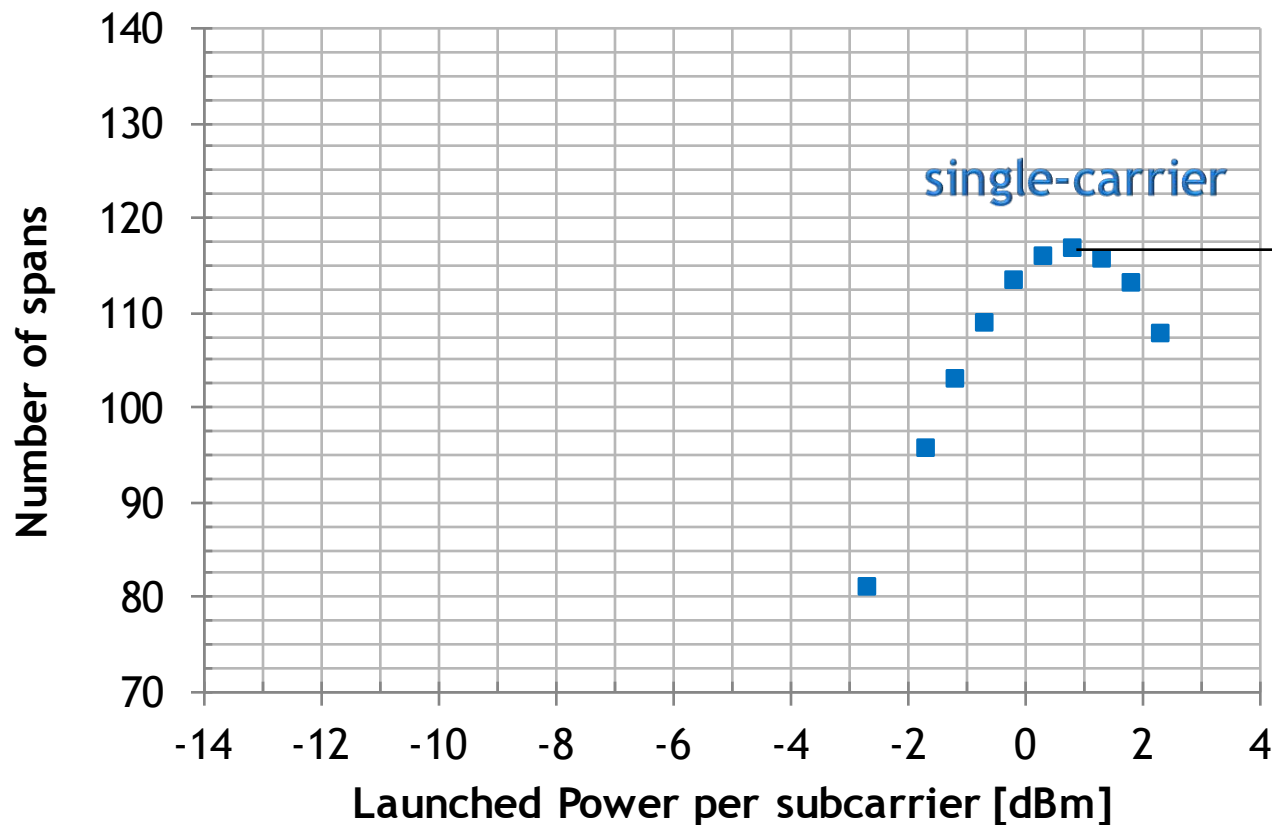


Reach curves at BER 10^{-2}



► markers: experiment

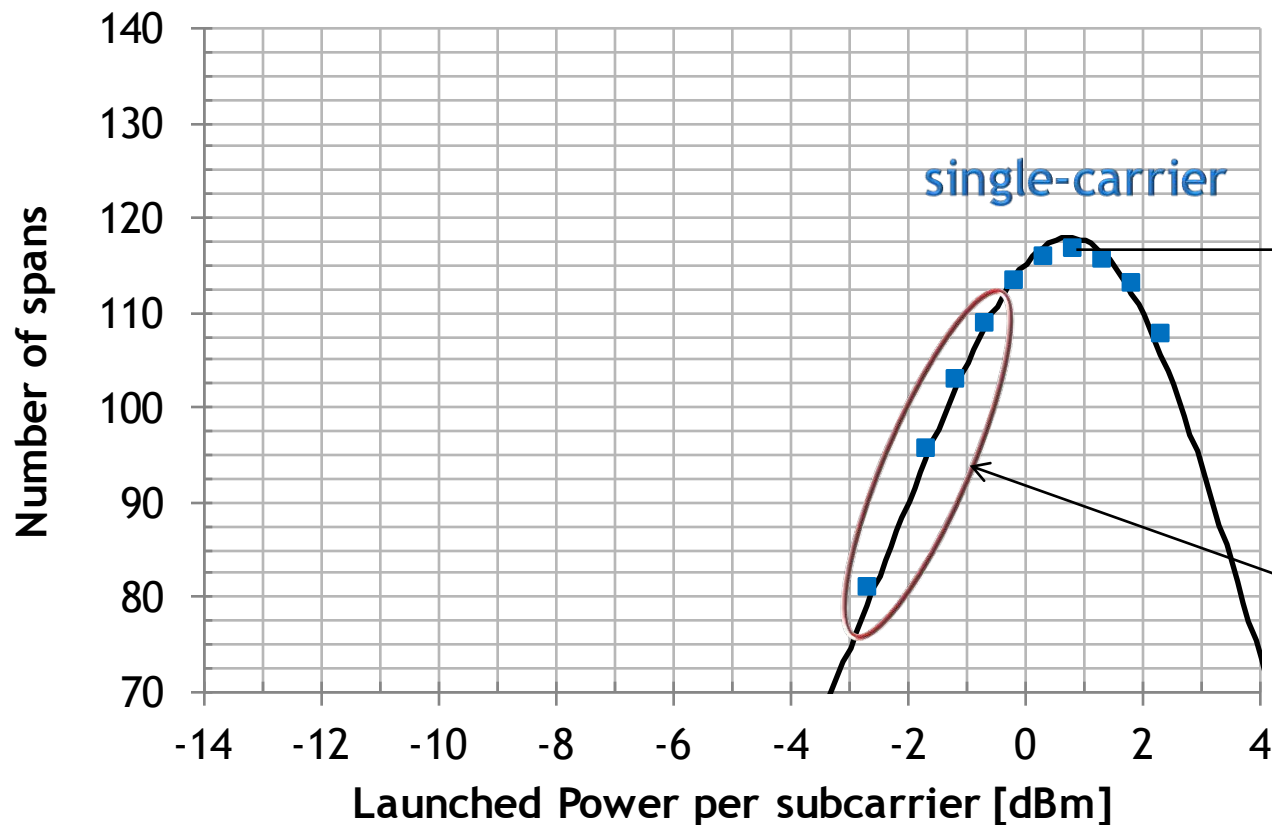
Reach curves at BER 10^{-2}



12620 km

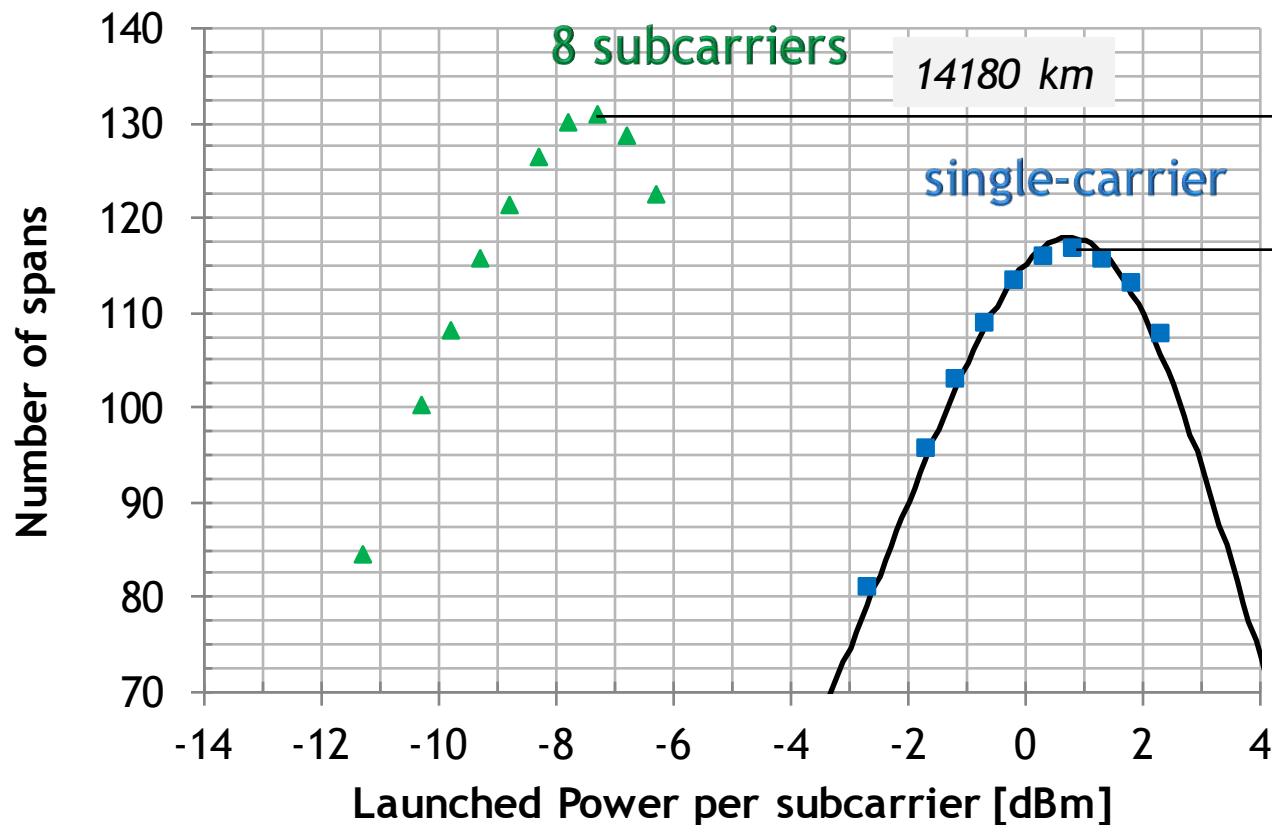
► markers: experiment

Reach curves at BER 10^{-2}



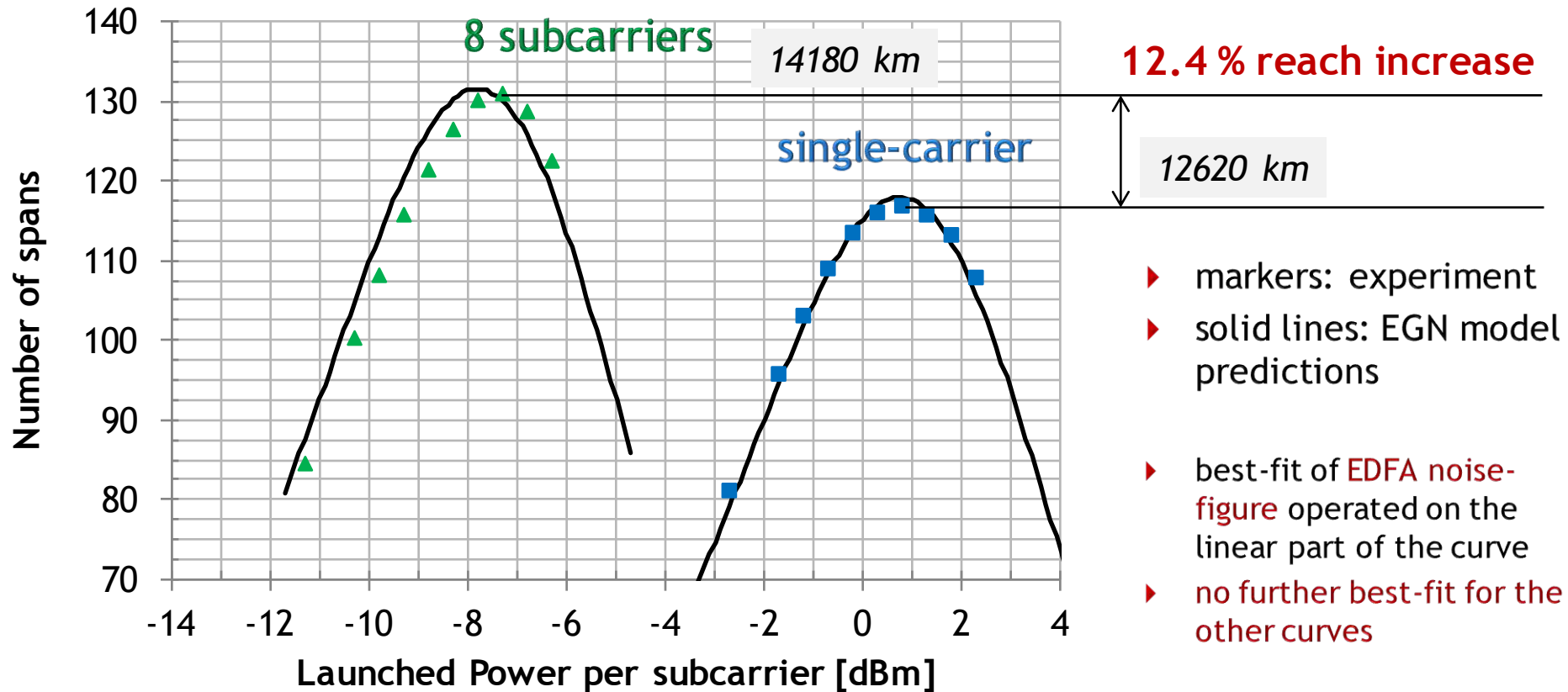
- ▶ markers: experiment
- ▶ solid lines: EGN model predictions
- ▶ best-fit of **EDFA noise-figure** operated on the linear part of the curve
- ▶ **no further best-fit for the other curves**

Reach curves at BER 10^{-2}

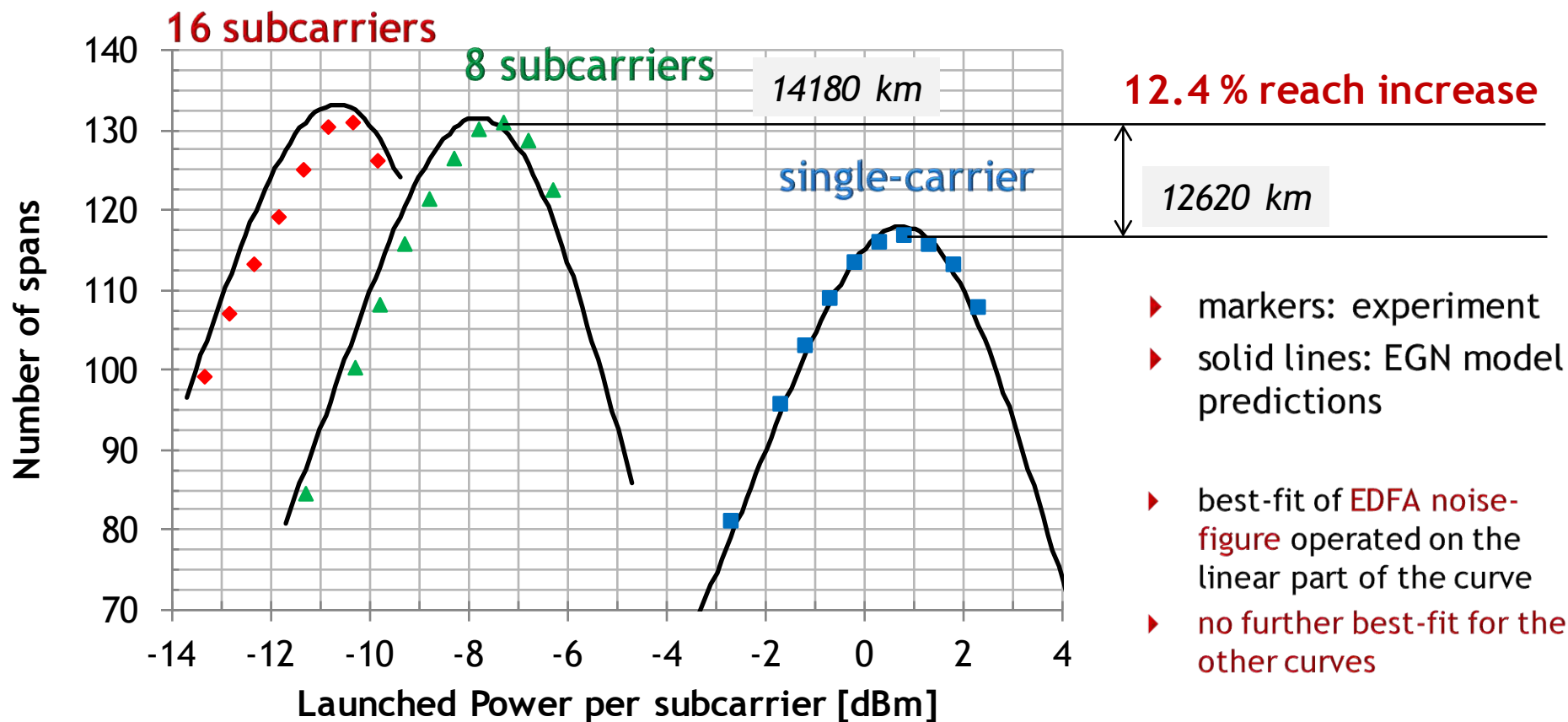


- ▶ markers: experiment
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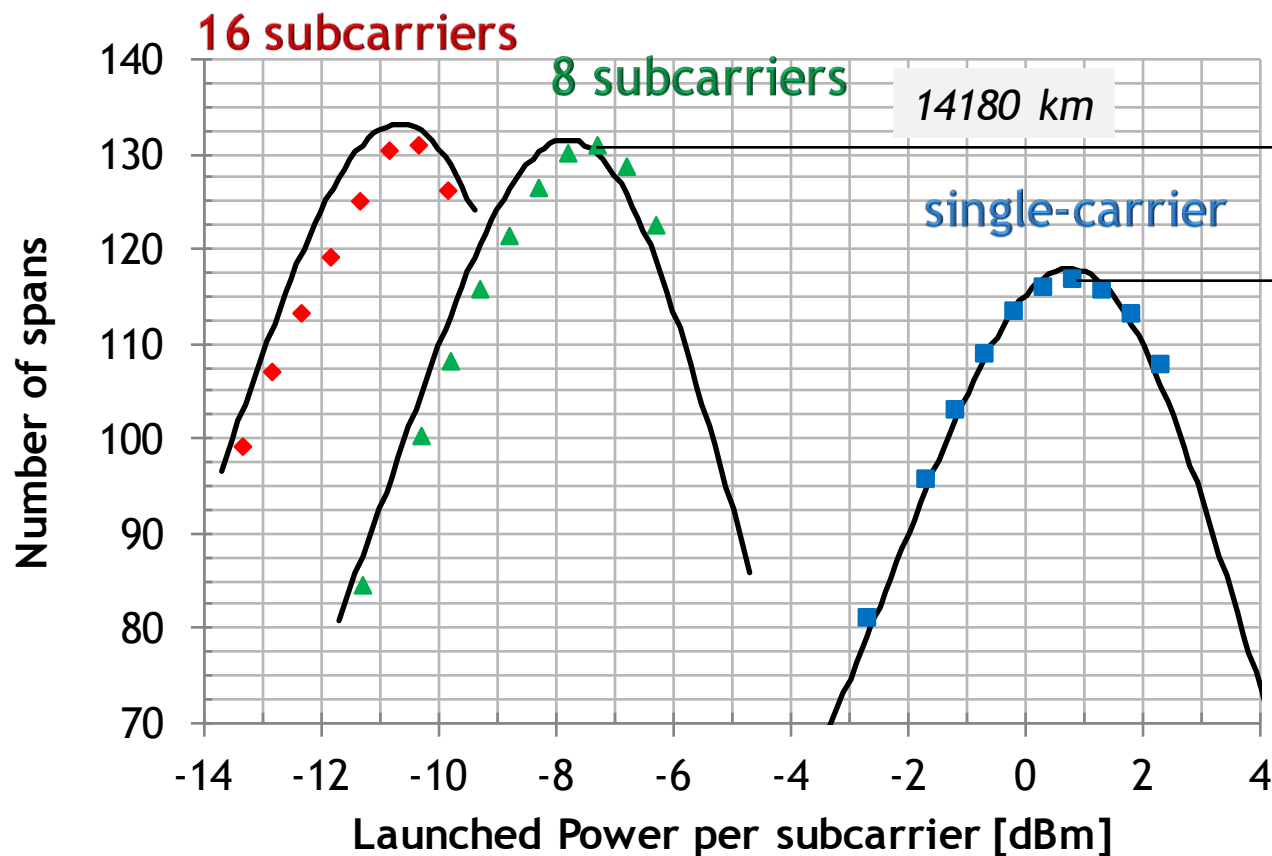
Reach curves at BER 10^{-2}



Reach curves at BER 10^{-2}



Reach curves at BER 10^{-2}



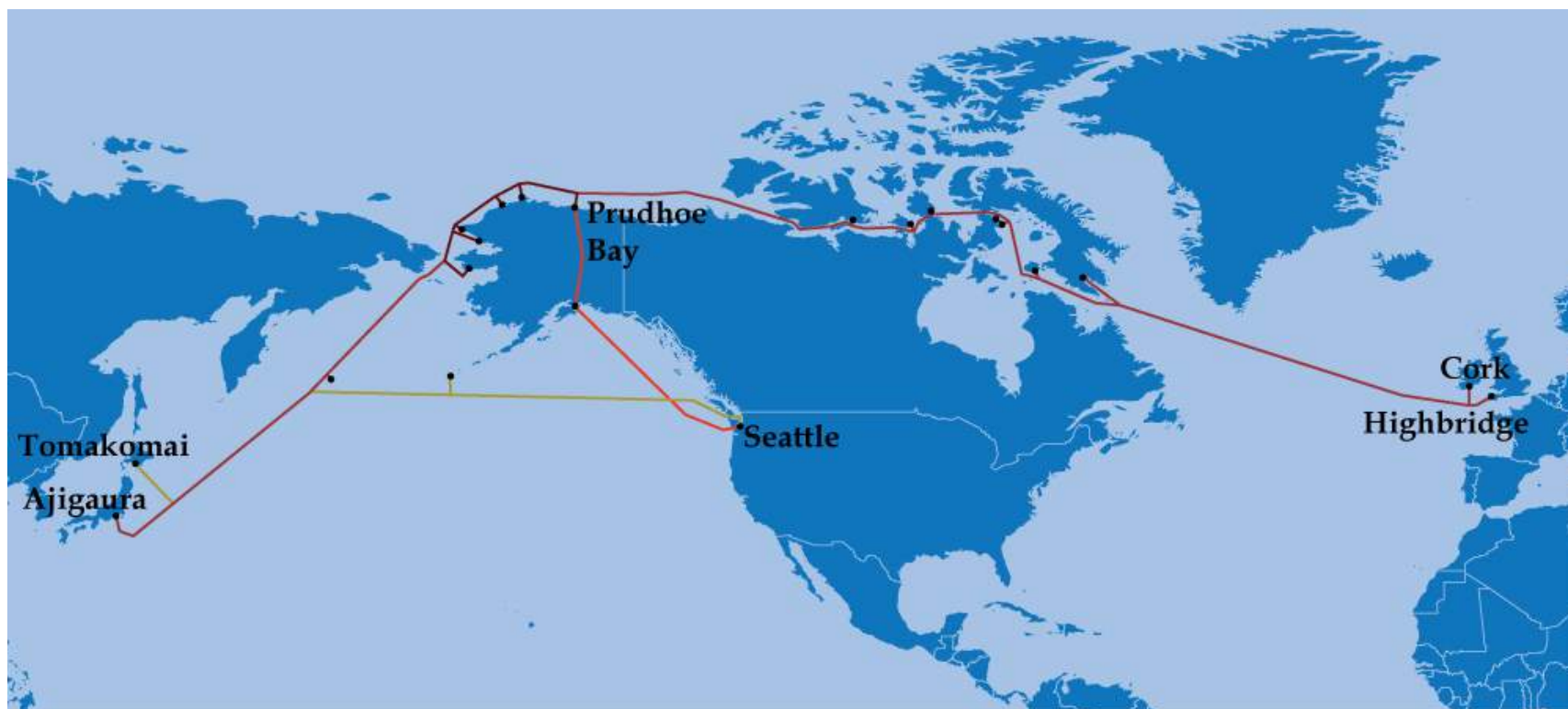
12.4 % reach increase

12620 km

- ▶ markers: experiment
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- ▶ best-fit of **EDFA noise-figure** operated on the linear part of the curve
- ▶ no further best-fit for the other curves

The Arctic Fibre link

- ▶ Tokyo to London submarine cable
- ▶ Projected length between 15,137 km and 15,600 km

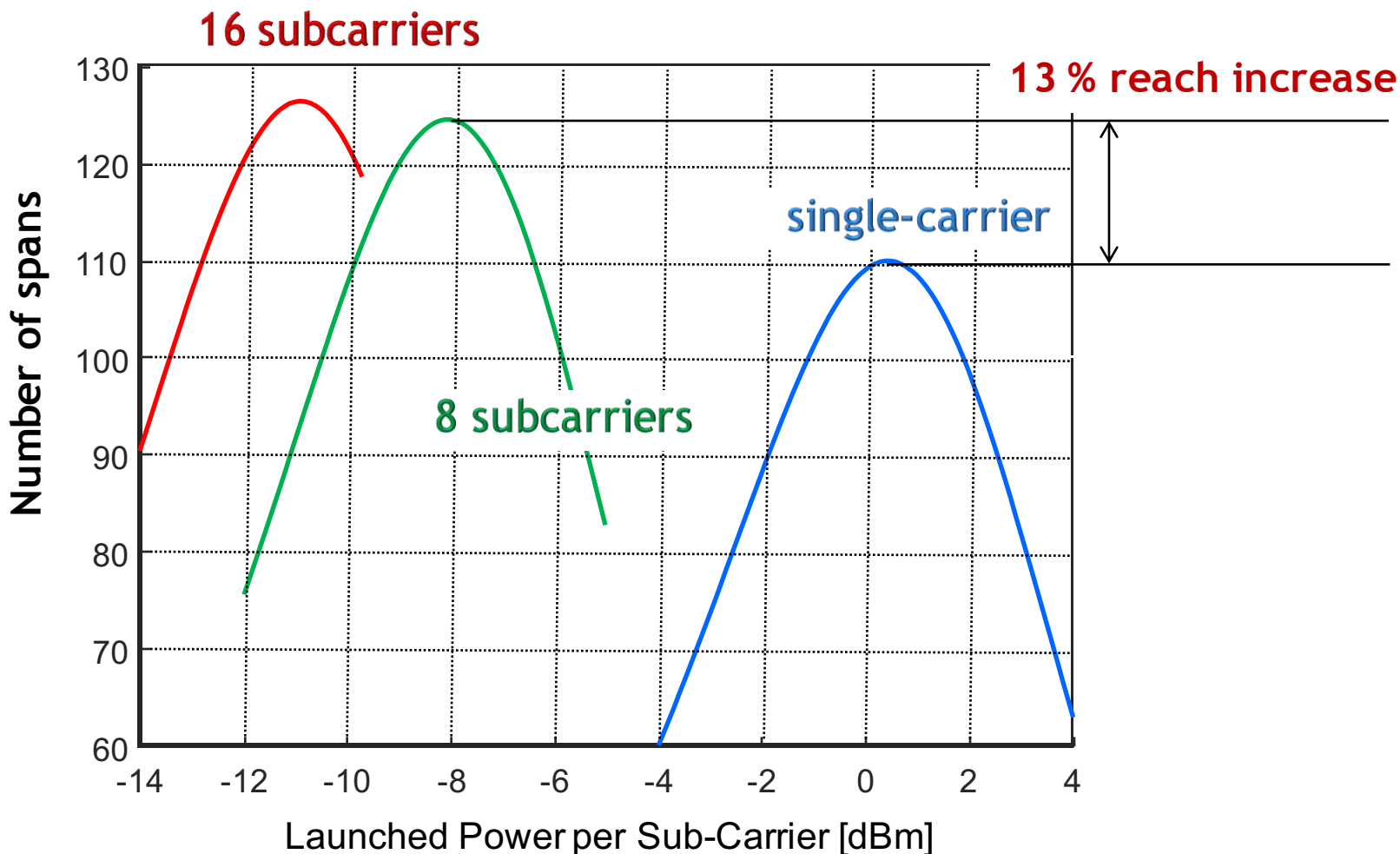


<http://arcticfibre.com/network/routing-map/>

- ▶ This is a single test
 - more experimentation needed
- ▶ Nonetheless:
 - ▶ non-linearity mitigation through SRO appears to really take place
- ▶ This experiment encompassed 700 GHz
 - ▶ how would it fare if it was extended to C-band?
- ▶ The EGN model seems to match well not only simulations, but also the experiment
 - we used it to extrapolate the answer

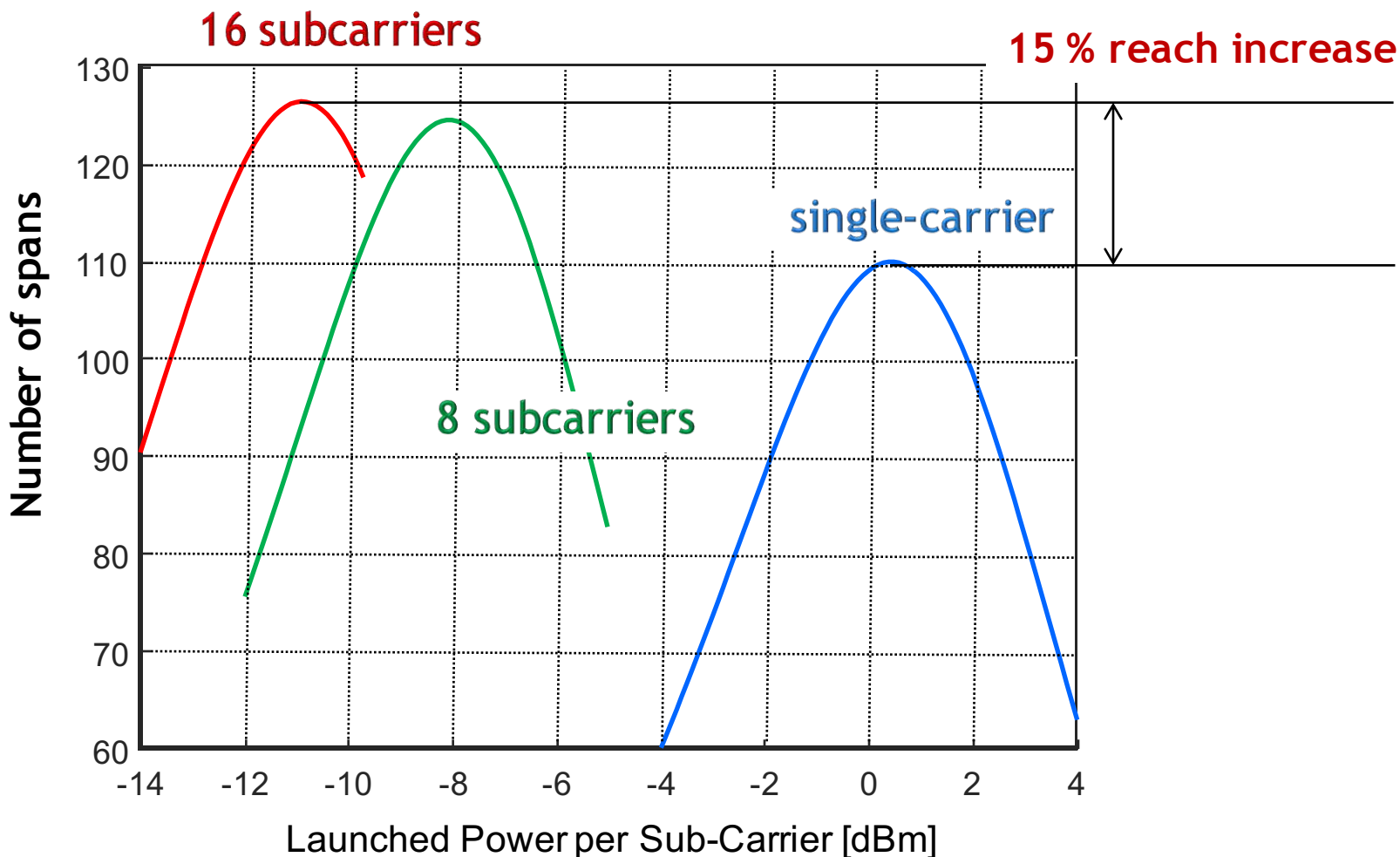
Would it all go away at C-band?

► ...on the contrary, it grows some:

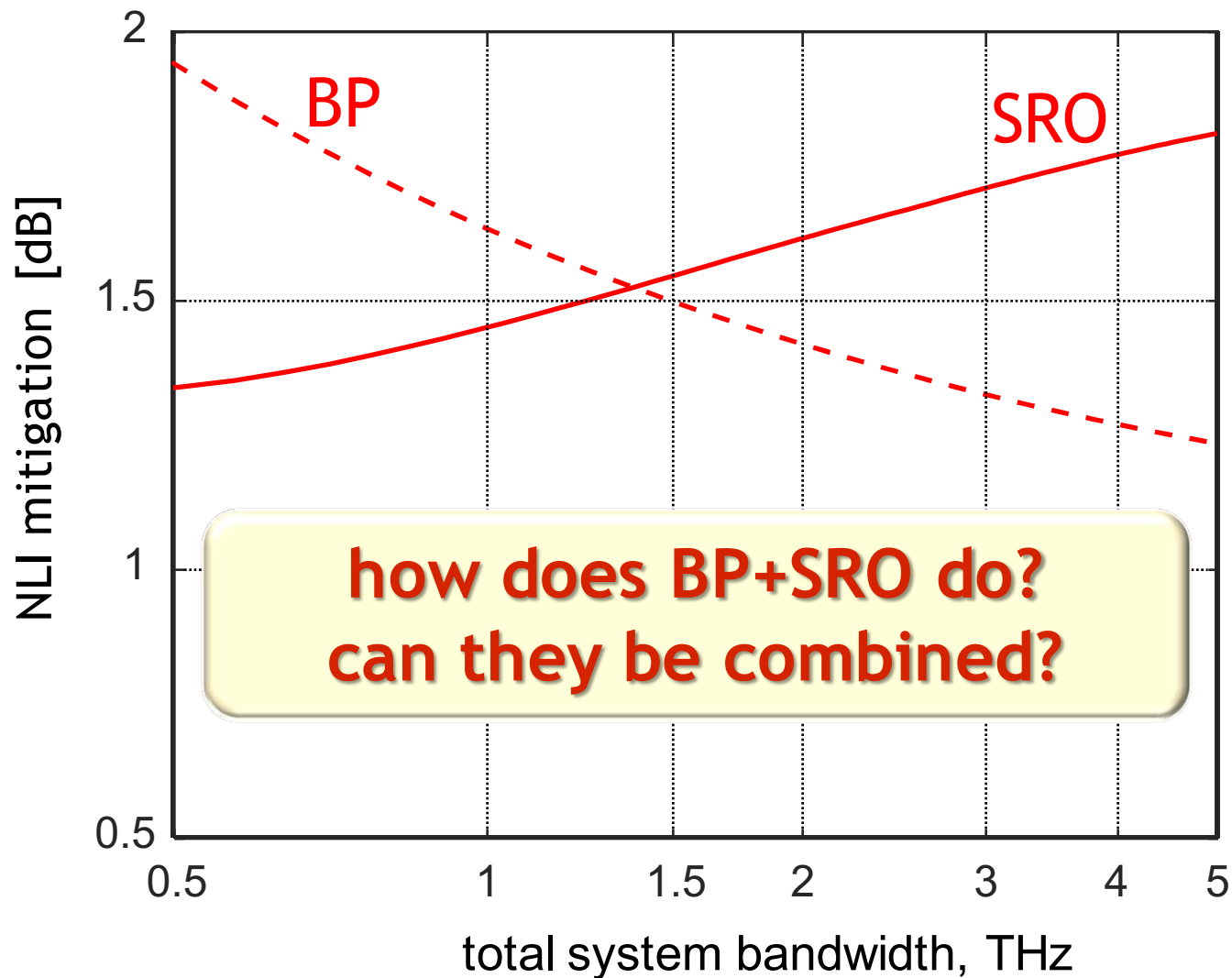


Would it all go away at C-band?

► ...on the contrary, it grows some:



Backward Propagation vs. SRO



- ▶ SMF, 100 km spans
- ▶ 50 spans
- ▶ PM-QPSK
 - ▶ roll-off 0.05
 - ▶ spacing 1.05 x (symb rate)
- ▶ SRO: symbol rate optimization between 32 GBaud and optimum rate (2.4 GBaud)
- ▶ BP: *ideal* backward propagation over the 32 GBaud center channel

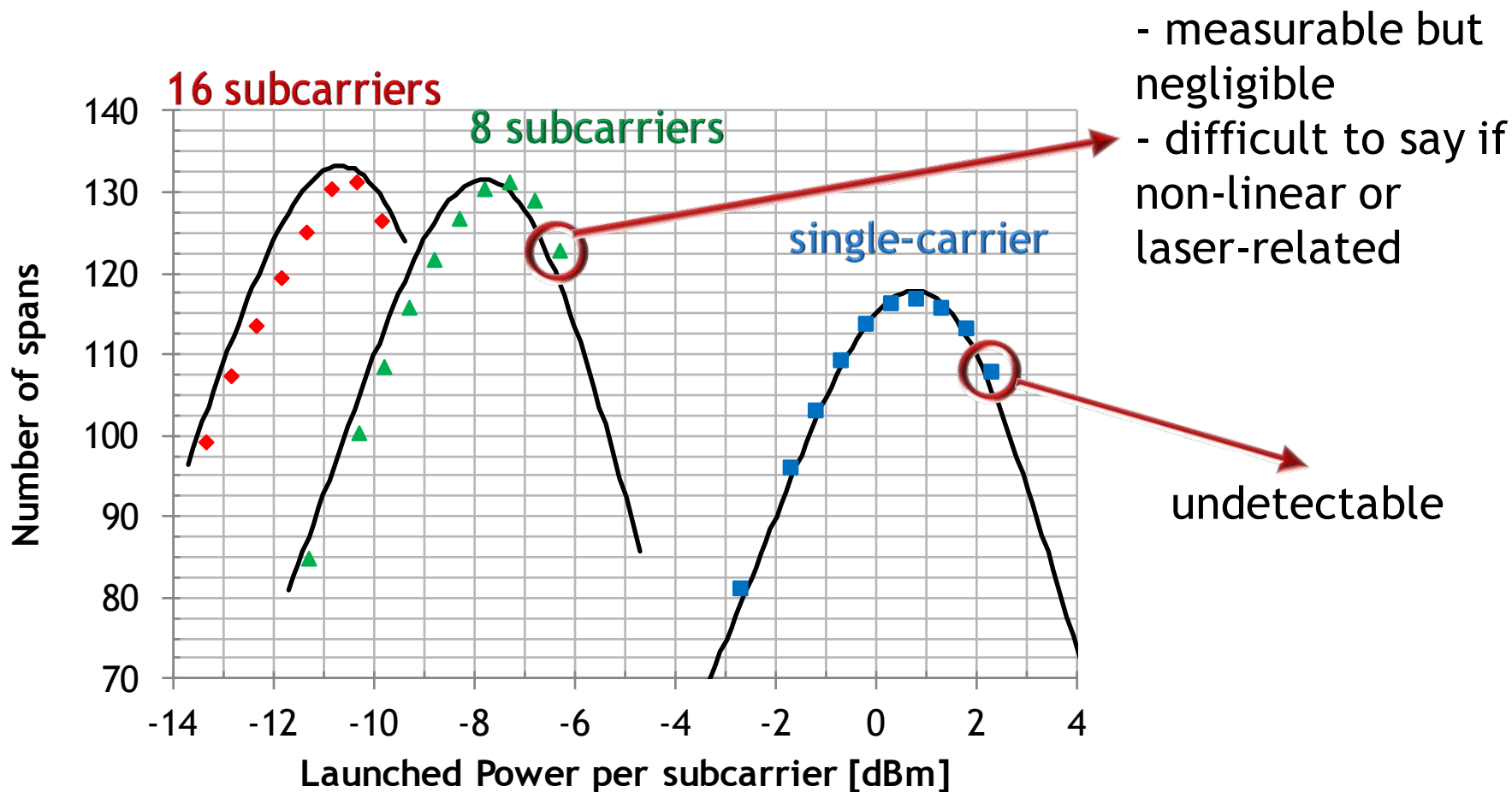
how does SRO compare to BP at C-band? can they be combined ?

Pierluigi Poggiolini, Andrea Carena, Yanchao Jiang,
Gabriella Bosco, Fabrizio Forghieri

“On the Ultimate Potential of Symbol-Rate
Optimization for Increasing System
Maximum Reach”

ECOC: Wednesday 30th
4:45 PM - room Pinedo
We.4.6.2

- ▶ We looked for it at the decision stage
- ▶ We studied it at very high power to detect non-linear phase-noise



- ▶ Our multi-subcarrier ultra-long-haul experiment achieved a **12.5% reach increase** vs. single-carrier
- ▶ **SRO appears to be real !**
- ▶ Its effectiveness **seems to hold up** at large WDM bandwidths (EGN model prediction)
- ▶ More optimized system designs could achieve 15%-20% at C-band (with PM-QPSK)
- ▶ Does SRO compare favorably to backward propagation?
- ▶ Can SRO and backward propagation be combined?
 - ▶ come see **We.4.6.2 Wednesday afternoon** for some answers
- ▶ *This presentation can be downloaded from **www.optcom.polito.it***