Performance Dependence on Channel Baud-Rate of Coherent Single-Carrier WDM Systems

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These slides are annotated with notes

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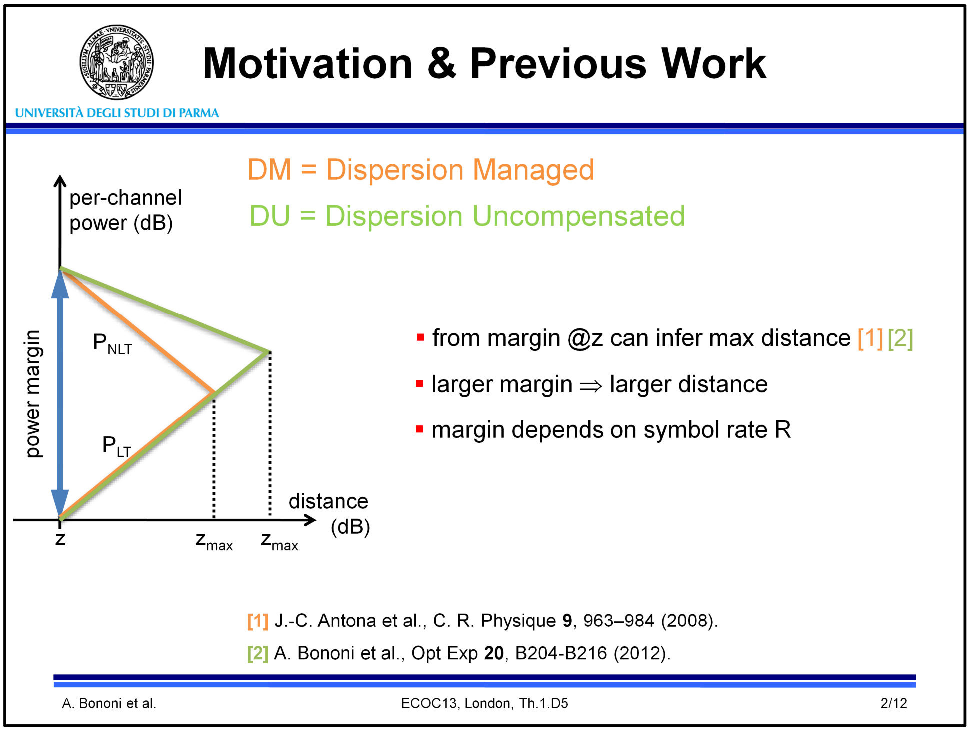
Outline

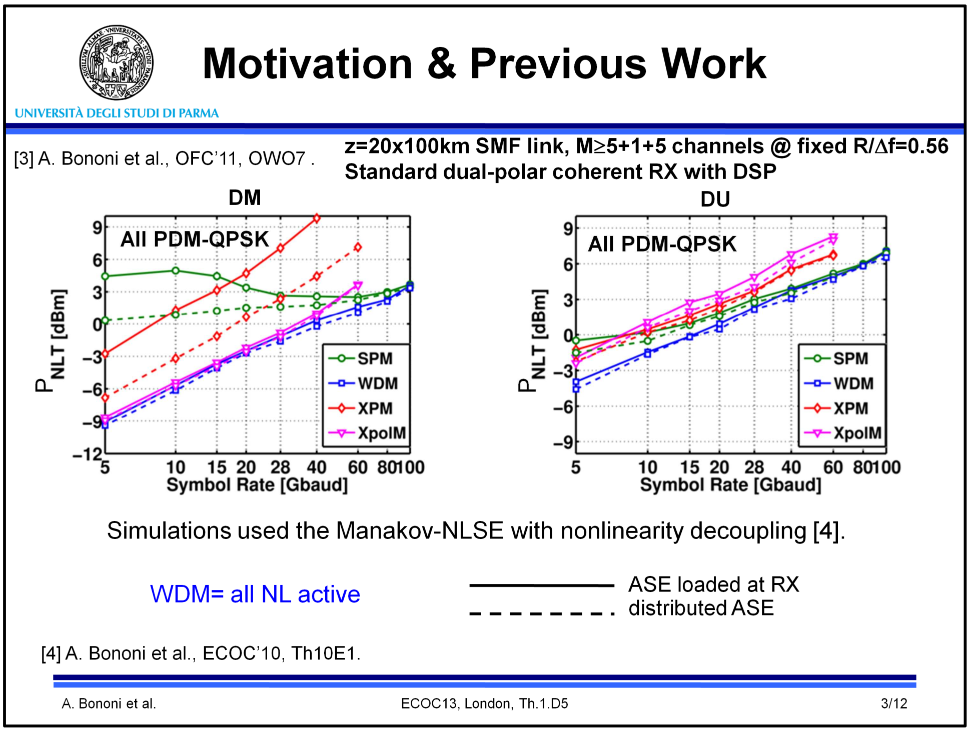
- Motivation and previous work
- nonlinear threshold (NLT) simulations vs. symbol-rate for several modulation formats
  - Dispersion Managed (DM)
  - Dispersion Uncompensated (DU)
- Conclusions



It is well nown that the design of DM systems is based on Q-Factor contours versus both per-channel power and distance.
Power must be above a liner-threshold P_LT to meet OSNR constraints, and below a nonlinear-threshold P_NLT to cap on nonlinearities.
In DM systems, the slope of both threshold curves is 1dB/dB, so that, if we know the power margin (ie the ratio of nonlinear to linear threshold) at a certain z coordinate, then we can easily infer the maximum distance z_max.

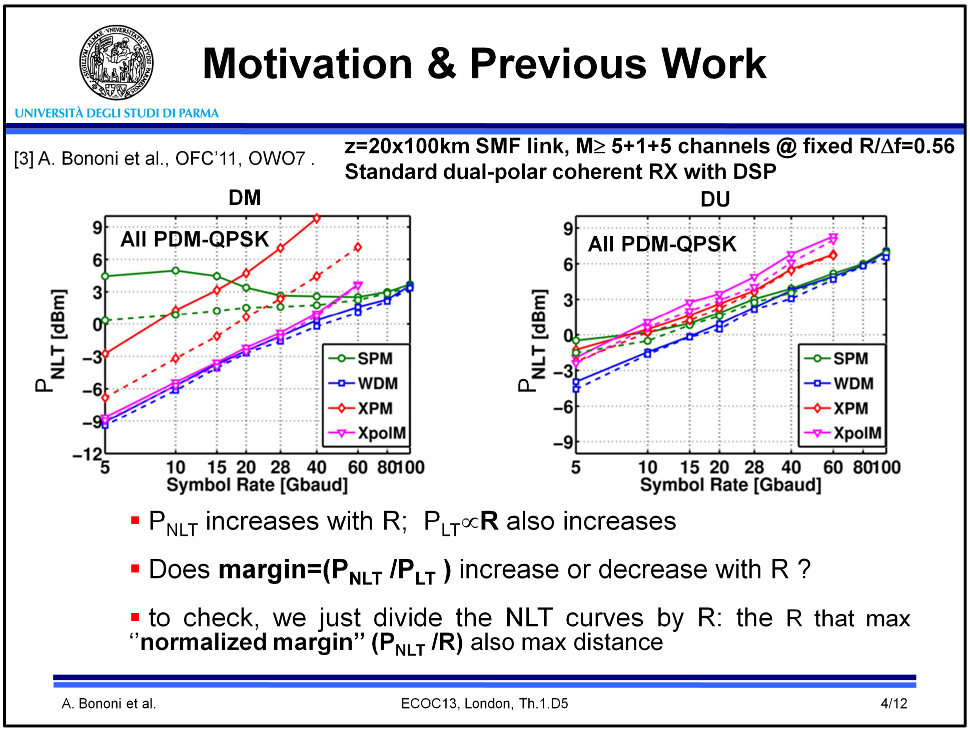
For DU systems the slope of the nonlinear threshold vs distance can be as low as -0.5 dB/dB, hence DU system can reach larger distances.

In both DU and DM cases, though, a larger margin implies a larger distance.
Margin depends on several parameters, and here we concentrate on its dependence on channel symbol-rate.



At OFC'11 we presented nonlinear threshold curves versus symbol rate R for both DM and DU cases.
All channels were PDM-QPSK, the system was 2000km long with 100km spans of SMF, we had 5+1+5 channels (NLT was measured on the central channel) and the spacing Df was scaled with R such that the bandwidth efficiency R/Df was 0.56.
We had a standard dual-polarization coherent receiver with DSP.
Simulations were run with the manakov-NLSE with nonlinearity decoupling. Hence we could find NLTs due to each individual nonlinear effect.
For instance, green curves show single channel (SPM) effects, red curves the scalar XPM (due to intensity fluctuations), and magenta the XPolM (accounting for all polarization effects). Finally blue curves labeled WDM account for all NL effects together.
We also ran both simulations with ASE noise loading (solid lines) and with distributed noise (dashed) and the difference between solid and dashed lines gives an idea of the nonlinear signal-noise interactions.

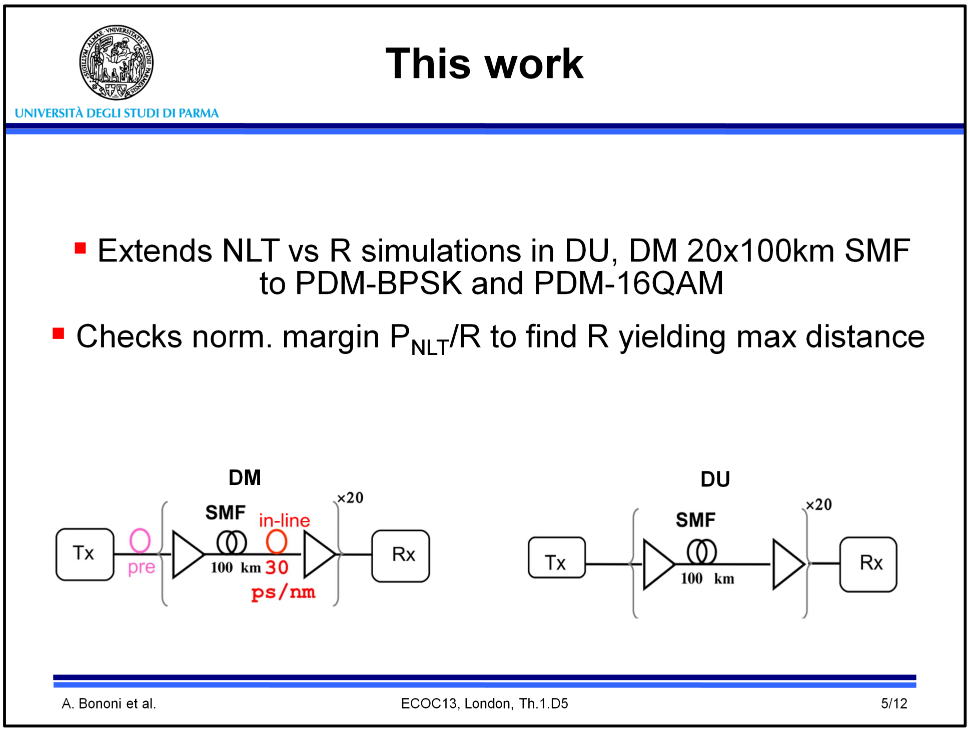
We showed that in DU systems signal-noise interactions are negligible, and that also in DM systems the overall WDM curve does not show signal-noise interactions because it is dominated by XPolM which is determined by data-induced polarization modulation.



in both DM and DU cases the overall WDM NLT curves are increasing. Also the LT is increasing proportionally to R.

hence the question is:
does the margin ie the ratio of nonlinear to linear threshold increase or decrease with R?

to check, all we have to do is divide the NLT curves by R:
the symbol rate that maximizes the "normalized margin" NLT/R also maximizes the distance.



So in this work we extend the NLT vs R OFC'11 simulations to 2 more modulation formats, namely, BPSK and 16QAM, and
we check the NLT/R curves to find the optimal R that yields the max distance.

The simulated DU and DM systems are shown below: 20 spans, 100km each of standard SMF,
in the DM case we had 30ps/nm of residual in-line dispersion per span and an optimized precompensation.

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Main Simulations Assumptions

Number of channels: **7+1+7** (test only central ch)

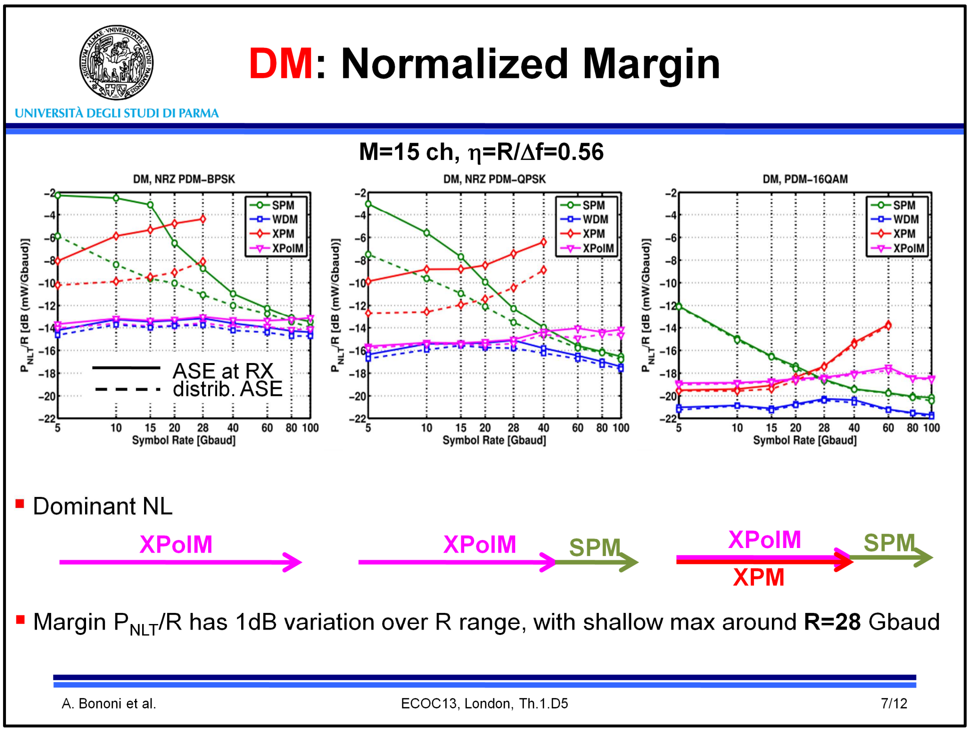
fixed bandwidth efficiency η=R/Δf=0.56 (Δf=50GHz @ R=28G)

Standard DSP coherent RX with PDM equalizer and CPE

SSFM simulation with no PMD
TX/RX lasers with no phase noise, no frequency offset

Monte Carlo error counting (>100 error counts at each BER meas.)
Purely random symbol sequences (not PRBS)

$\mathbf{P_{NLT}}$ **:=** per-channel power giving 1dB OSNR penalty @ BER=10^{-3}

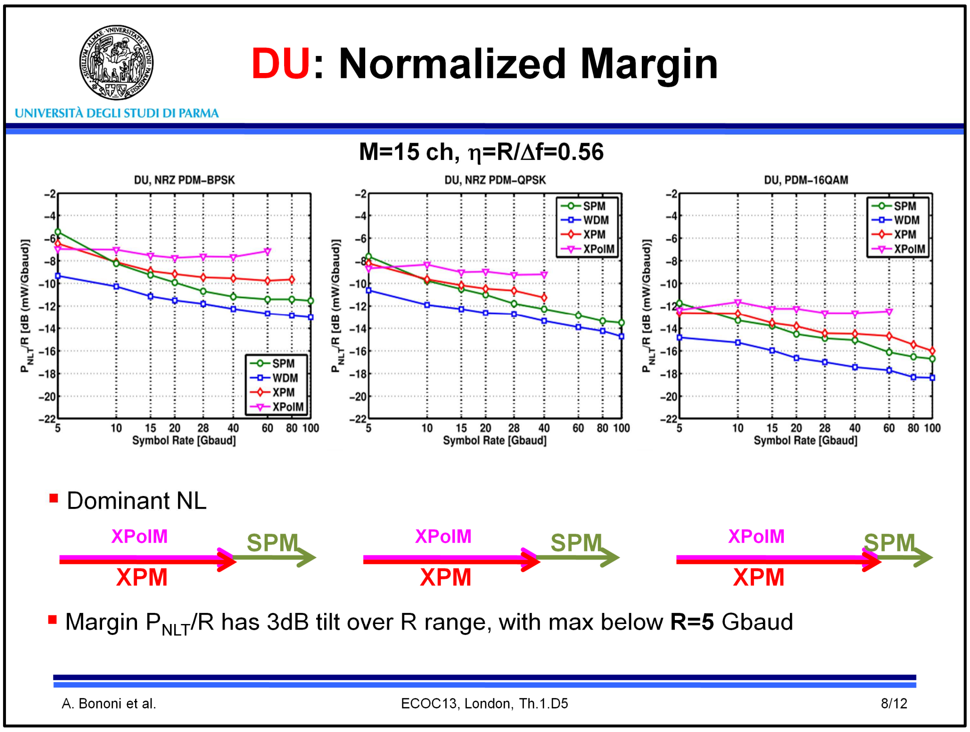


So, let's see the NLT/R curves for the DM case, for our 15 channel WDM system at bandwdth efficiency 0.56:
modulations from left are BPSK, QPSK, 16QAM (central one is essentially the OFC'11 NLT divided by R).

We see that for both BPSK and QPSK the dominant NL effect is XPolM, while for 16QAM also scalar XPM becomes as important as XPolM (and does not show any significant signal-noise interactions).

So in summary, the dominant NL is:
(click animation)

Moreover, the WDM overalll curves are rather flat,
and (click).....



In the DU case we only simulated the noise loading case, since signal-noise interactions are negligible.
Again, left to right we have BPSK, QPSK and 16QAM.

We note that here the scalar XPM (which only depends on intensity fluctuations) becomes very large because of the large PM-IM conversion due to the huge cumulated in-line dispersion.
Hence the dominant NL is
(click)

(click)
We note a tilt of about 3dB of the margin for all formats across the shown R range, with a max below 5Gbaud

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GN Theory

- For **DU systems** a Gaussian Noise theory is available [4]. According to [2,eq. (7),(9)]:

$$\frac{P_{NLT}}{R} = \frac{1}{R\sqrt{4.84 \cdot S_0 a_{NL}}}$$

where S_0= required electrical SNR, and $a_{NL} = \int G_{NLI}(f)df$

with G_{NLI} evaluated using the GN reference formula [4] with the same input spectra as in the SSFM-based NLT simulations.

- The GN model postulates input WDM signal is a stationary Gaussian process.

- If a_{NL} independent of modulation format $\Longrightarrow$ also $\boxed{\sqrt{S_0}\frac{P_{NLT}}{R}}$ independent.

[4] P. Poggiolini, J. Lightw. Technol. 30, 3857 (2012)

[2] A. Bononi et al., Opt Exp **20**, B204-B216 (2012).

With these long, complicated simulations one has always the question “are they correct?”. Fortunately, for DU systems an accurate Gaussian Noise model (see ref 4) is available to double check simulations.

According to the results in [2], the NLT/R can be expressed as one over R times square root of a constant times the electrical SNR times the nonlinear interference coefficient a_NL, which can be calculated from the GN model using the same input signal spectra as those used in Split-Step Fourier simulations.

Now, the GN model postulates the input WDM signal is a stationary Gaussian process: the intuition is that due to the large dispersion, all digital signals will evolve into Gaussian-like processes.

If a_NL were indep of modulation format, then also sqrt(S0) NLT/R would be independent of modulation format: this can be checked from our NLT simulations

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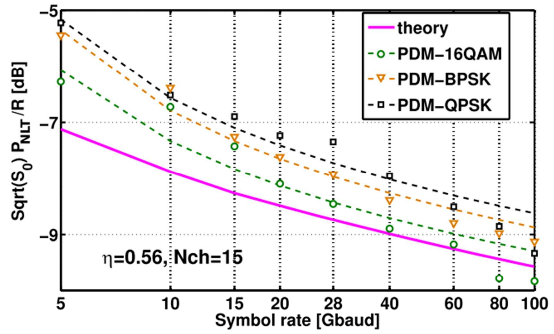
GN theory



- Modulation Format dependence within 2dB from GN theory predictions
- 16QAM closest to GN theory.

- For more work on format dependence, see [5],[6]

[5] P. Serena et al., ECOC'13, Th1D3.
[6] R. Dar et al., arXiv:1307.7401v1 [physics.optics] (2013).

here is the plot of sqrt(S0) times NLT/R versus symbol rate.
GN theory in magenta, simulation results in symbols.
We note that the modulation format dependence is within 2dB from the GN theory and 16QAM is closest to the GN theory.

For more work on the modulation format dependence please refer to the recent references [5],[6]

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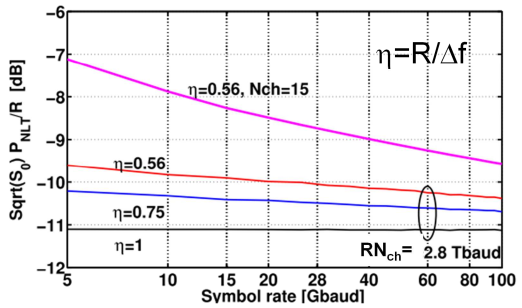
GN theory



<1dB tilt of P_{NLT}/R [dB] in practical WDM DU systems. Can prove that [2]

$$N_{max}^{dB} = \frac{2}{3+\epsilon}\left(\frac{P_{NLT}}{R}\right)^{dB} + k$$

Hence even smaller tilt of max distance [dB] (Cfr [6])

[2] A. Bononi et al., Opt Exp **20**, B204 (2012).

[6] P. Poggiolini et al., Photon. Technol. Lett **23**, 15 (2011).

Simulations are necessarily limited to a few WDM channels for feasibility (each NLT curve took weeks to complete).
But what happens at practically larger channel counts, and at other bandwidth efficiency eta values?
The GN model can answer these questions.
We fixed here the baud-rate times number of channel product to 2.8Tbaud and plotted at fixed eta the normalized “margin”:
we note a tilt of less than 1dB even in the worst case eta=0.56.
How does that translate into a tilt of maximum distance?
It is proven in [2] that the max distance tilt is less than 2/3 the tilt of the margin. these predictions are in line with findings in ref [6] on maximum distance.

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Conclusion

- In both DM and DU pol-mux digital coherent WDM systems we conclude for all tested modulation formats that per-channel symbol rate has little influence on maximum distance.