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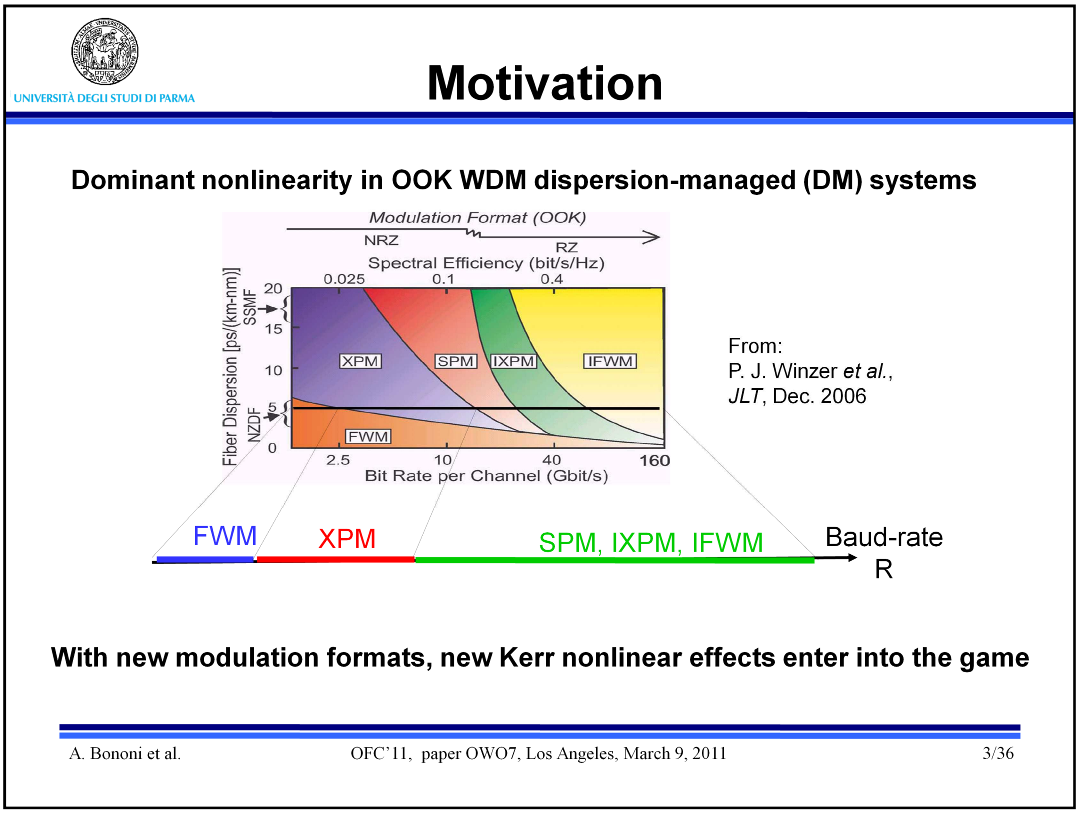
Transmission Limitations due to Fiber Nonlinearity

A. Bononi, N. Rossi, P. Serena
Department of Information Engineering, University of Parma, Parma, Italy

Outline

- Motivation
- Some models of nonlinearity:
  - 1. nonlinear phase and amplitude noise (NLPN,NLAN)
  - 2. cross-nonlinear phase noise (X-NLPN)
  - 3. cross-polarization modulation (XPolM)
- Dominant nonlinearity:
  simulations of NonLinear Threshold (NLT) vs Symbol-rate
- Conclusions



It is well known that the dominant nonlinearity in OOK WDM systems, as the baudrate is increased, is first FWM, then XPM, and then single channel effects, ie SPM, with its variants of single-pulse distortion, interpulse XPM and I-FWM.

With new modulation formats, new Kerr nonlinear effects enter into the game

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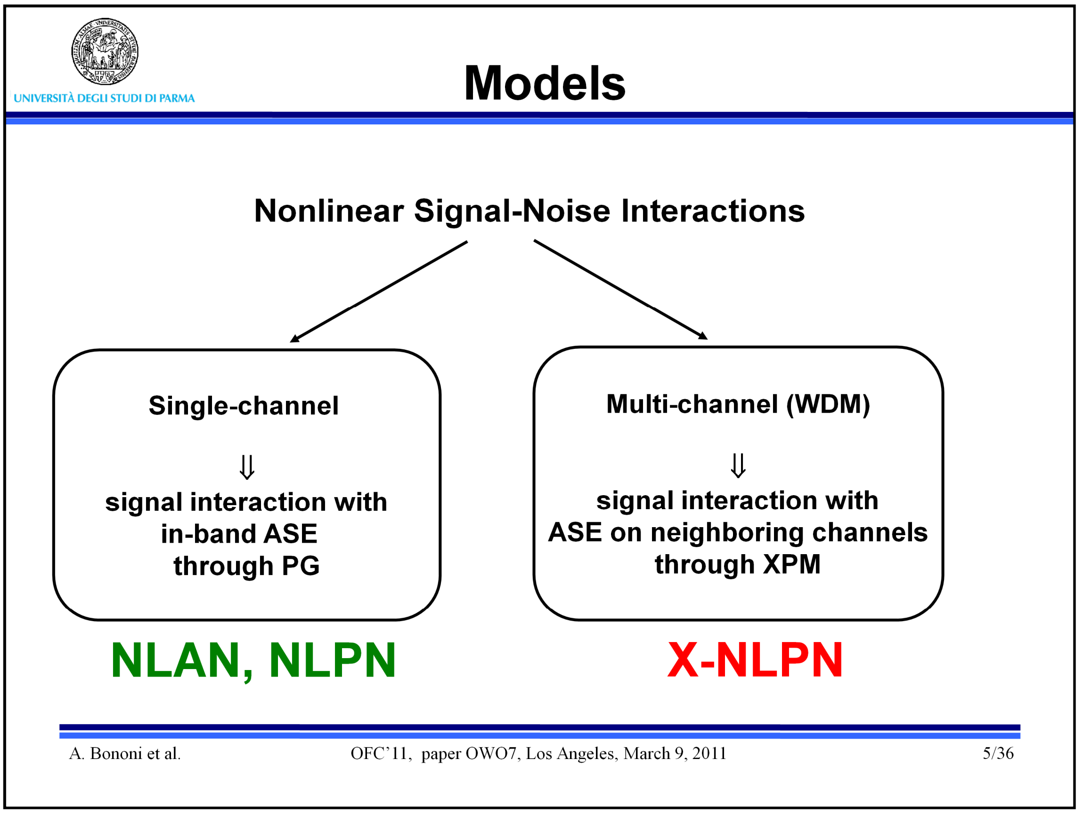
purpose of this section is to discuss such new models of nonlinearity

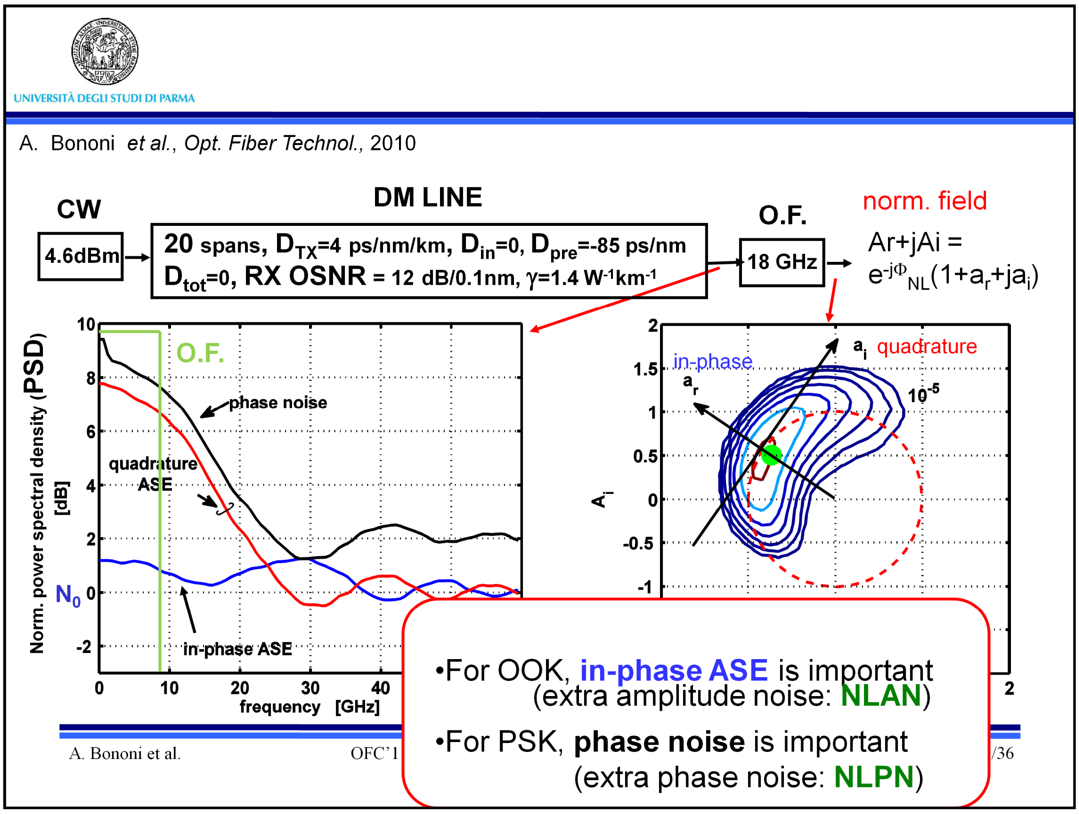


Let's start with nonlinear interactions between signal and noise (NSNI).

NSNI can be classified as

1) single-channel, where we have nonlinear parametric interaction of the reference signal with in-band ASE, producing nonlinear phase and amplitude noise (NLPN, NLAN);
2) multi-channel, where the interaction with the reference signal comes from ASE on neighboring channels through XPM, producing X-NLPN

Let's start with models for single-channel NSNI



To fix the ideas, consider a DM line composed of 20 spans, with nonzero dispersion shifted fiber with dispersion 4 ps/nm/km, full in-line compensation, pre comp of –85 ps/nm and zero net residual dispersion. The transmitted signal is CW with 4.6 launched dBm for a cumulated nonlinear phase of 0.6 pi and a received OSNR of 12 dB/0.1nm.

What you see on the right is the probability density function (PDF) resolved down to 10^{-5} of the normalized RX optical field at the output of an optical filter of 18 GHz. The average field is marked as a green dot. You note that the RX ASE has a non ellyptical, bean-like PDF which is the signature of single-channel NSNI, so that RX ASE is not Gaussian.

If we factor out the phase rotation of the average field, we can define

a radial or in-phase ASE component, and a tangent or quadrature ASE component......

whose PSD is shown on the left graph, taken upstream of the optical filter.

We alo show the PDF of the phase noise, i.e. of the phase of the field with respect to that of the average field.

For OOK, in-phase ASE (ie amplitude noise) is most important, while for phase modulated formats phase noise is most important.

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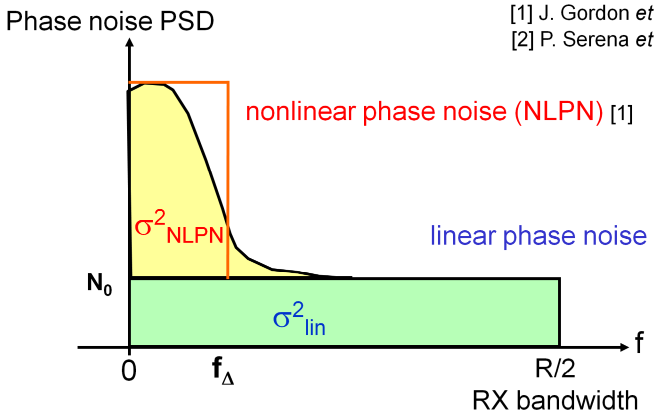
Model 1: NLPN

[1] J. Gordon *et al.*, *Opt. Lett*, Dec. 1990.
[2] P. Serena *et al.*, *JOSA B*, Apr. 2007.



DM with small RDPS [2]: $f_\Delta \cong \frac{1}{2\pi\sqrt{|\beta_2|\frac{1}{\alpha}}}$ (eg SMF, **f_Δ=7GHz**)

NDM: $f_\Delta \cong \frac{1}{\sqrt{2}\pi\sqrt{|\beta_2|L_{NL}}}$ (normally nonlin length L_{NL}>>1/α)

Looking at the phase noise PSD,

we see that the total phase noise variance is the sum of a linear component due to the white ASE PSD at level No, and of a nonlinear phase noise (NLPN) component,

which exists over an effective bandwidth f_delta whose expression for DM systems is reported below,

while for non-DM (NDM) systems it has the following expression....

the difference between DM and NDM is essentially in the use of the nonlinear length L_NL instead of the attenuation length 1/alpha:

since L_NL can be usually up to 2 orders larger than the attenuation length, then f_delta can be 1 order of magnitude smaller in NDM links

than in DM links.

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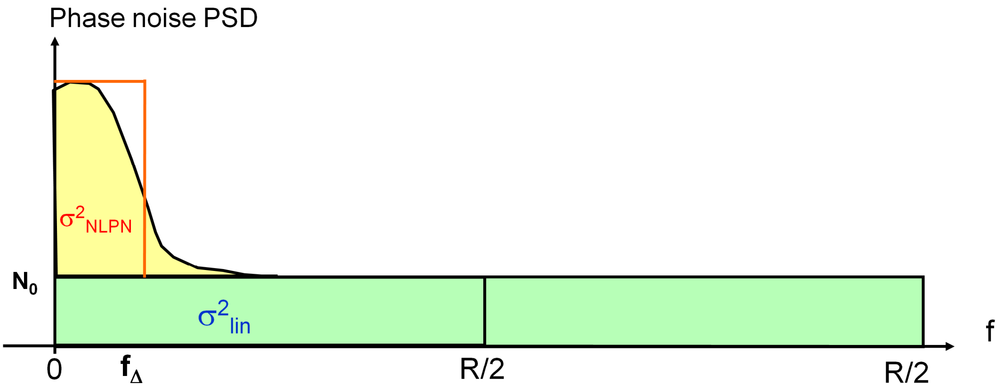
Model 1: NLPN

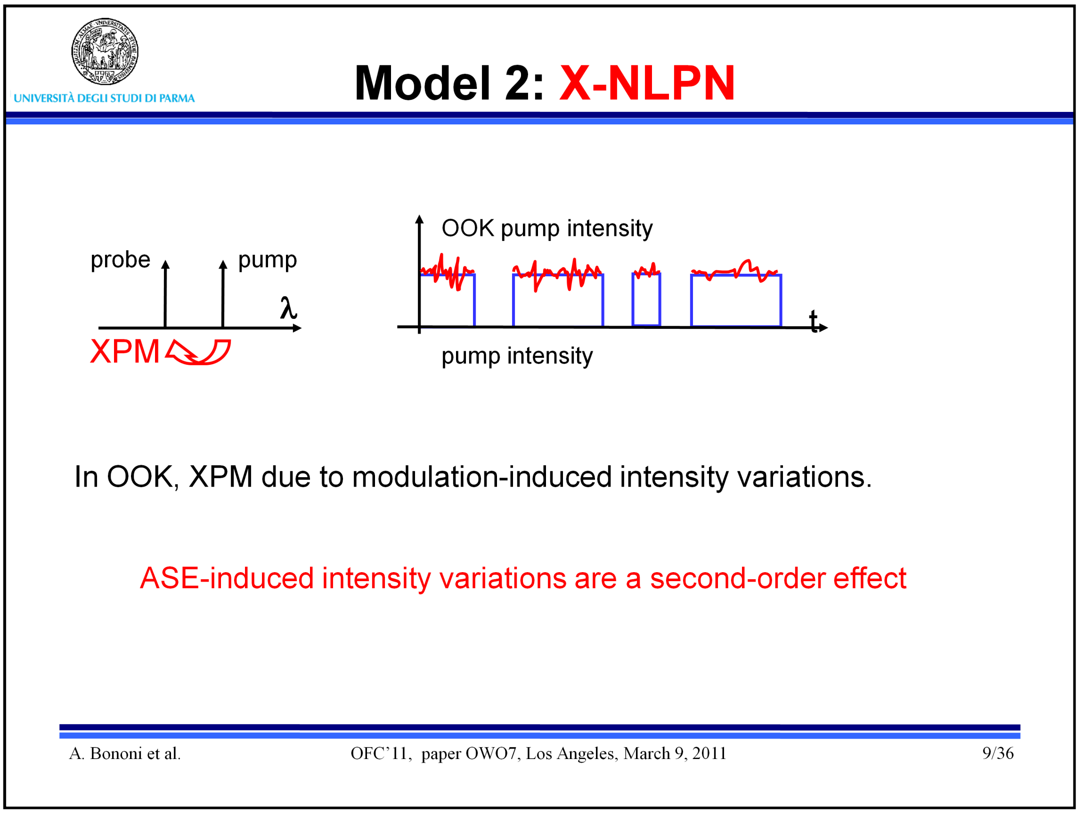


...at increasing symbol rate R, linear phase noise will dominate nonlinear phase noise

since $\mathbf{f}_\Delta$ (NDM) << $\mathbf{f}_\Delta$ (DM), this will occur at << symbol rates R in NDM

...and it is clear that for increasing baudrate and thus optical filter bandwidth, the linear component increases and eventually dominates over NLPN.

The dominance of the linear component will occur at much lower baud-rates in NDM systems, since f_delta is much lower.



Let's move to the multi-channel NSNI.

In OOK, XPM is mainly due to the large modulation-induced intensity variations, while ASE-induced intensity variations are a second-order effect, and have never been considered in analysis.

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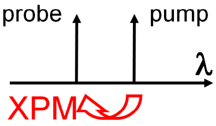
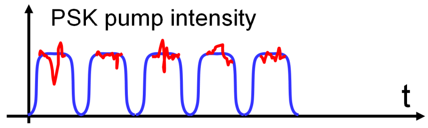
Model 2: X-NLPN

[*] K.-P. Ho, JSTQE, pp 421-427 (2004)





In D(Q)PSK, periodic XPM supressed by differential phase reception:

$$\phi_t = \arg(A_t) - \arg(A_{t-T}) = \varphi_t - \varphi_{t-T}$$

...In coherent RX with **M-power phase estimation**, by "generalized" differential phase reception

$$\begin{aligned} \phi_t &= \arg(A_t) - \frac{1}{4}\arg\left(\frac{1}{2K+1}\sum_{j=-K}^{K} A^4_{t-jT}\right) \\ &\cong \arg(A_t) - \frac{1}{4}\left(\frac{1}{2K+1}\sum_{j=-K}^{K} \arg A^4_{t-jT}\right) = \varphi_t - \frac{1}{2K+1}\sum_{j=-K}^{K} \varphi_{t-jT} \end{aligned}$$

"differential" filtering

K=tap parameter

⇒ ASE-induced intensity variations become a first-order effect: X-NLPN [*]

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however, in phase-modulated channels the XPM induced by the large periodic intensity variations due to pulse shaping is completely suppressed by the differential phase reception in optical delay-demodulation DPSK/DQPSK, and also...

in coherent reception with M-power phase estimation (or Viterbi and Viterbi, V&V) by the generalized differential filter....

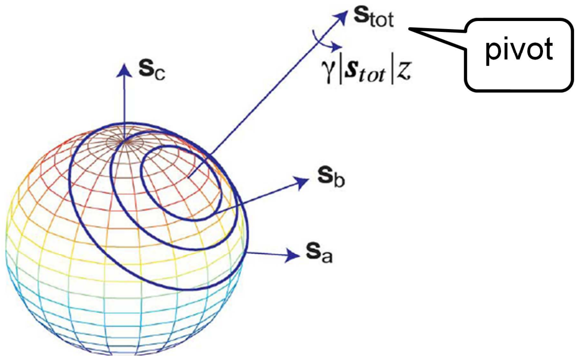
in green you see the differential operation in both cases. K will be called the tap (or smoothing) parameter in V&V (number of taps is 2K+1)

Since the large periodic IM-induced XPM is suppressed, then ASE induced non-periodic intensity variations become a first-order effect: we call it cross-nonlinear phase noise (X-NLPN), which was first analytically treated by Ho in the shown citation.

Model 3: XPolM

According to Manakov equation, Stokes vectors of WDM channels evolve in z by rotating around their **vector Sum (pivot)**, at a speed proportional to its length.

$||s_k||^2$ stokes length prop. to channel power



L. Mollenauer et al, Opt. Lett. Oct. 95
B. Collings et al, PTL Nov. 00
C.J. Xie et al, Opt. Lett. 03

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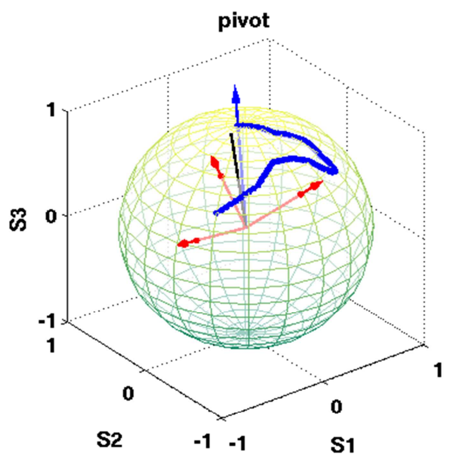
Model 3: XPolM



SOP motion in z is a series of rotations around a pivot with data-driven **random orientation and length**

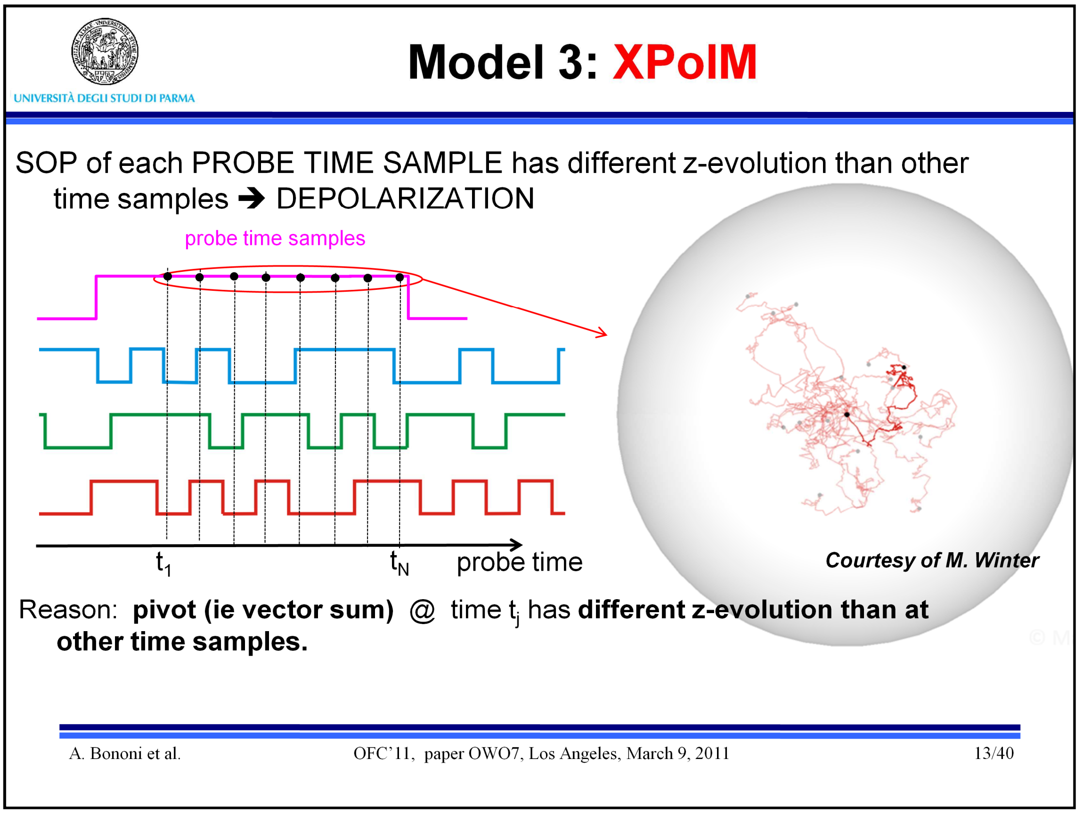
A. Bononi et al, JLT Sep. 03
M. R. Phillips et al, JLT Nov. 06
M. Karlsson et al, JLT Nov. 06
M. Winter et al, JLT Sep. 09
C.J. Xie, OFC'10, OWE1

A. Bononi et al. OFC'11, paper OWO7, Los Angeles, March 9, 2011 12/36

Since the Stokes vectors have their power and direction possibly modulated by the data, the SOP motion in z is a series of rotations around a pivot with data-driven random orientation and length.

However, this picture actually refers to a single time chunk of our (probe) channel of interest.....

what about the SOP motion of its neighboring time chunks?



Here we see the SOP trajectories of several contiguous time chunks of our channel of interest, measured in a NDM system (courtesy of M. Winter):

we see wiggled trajectories, apparently random motions, which lead the end SOP points away from the input SOP and scatter them thus causing depolarization.

The reason of such depolarization is that the pivot (ie, the Stokes vector sum) at time chunk j has a different z-evolution than at other time chunks, since it senses the modulated stokes vectors at different times and in different order than at other times, because of dispersion-induced channel walkoff.

As bad as this picture may seem, it is the best one can hope for.

In fact, in absence of walkoff, the trajectory of each time chunk is a long arc of rotation around a fixed pivot, and such arcs are different for time chunks that encompass different channel data. So overall, OVER THE TYPICALLY LONG MEASUREMENT TIME of the coherent receiver, the depolarization in absence of walkoff is much much larger.

Walkoff instead makes trajectories bend and twist so that the end SOP is not too far from the input SOP.

Even with an infinite walkoff we still have such a diffusion process, ie, the depolarization does not disappear with walkoff.

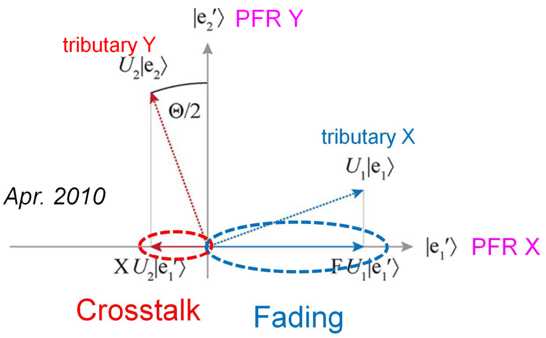
This is a fundamental difference between XPolM and XPM.

Model 3: XPolM

XPolM harmful only for polarization-sensitive RX

For PDM signals, coherent RX tracks (CMA) the average polarization frame of reference (PFR).
Fast (symbol-time) misalignements induced by XPolM (angle Θ/2) not tracked

M. Winter et al, PTL Apr. 2010

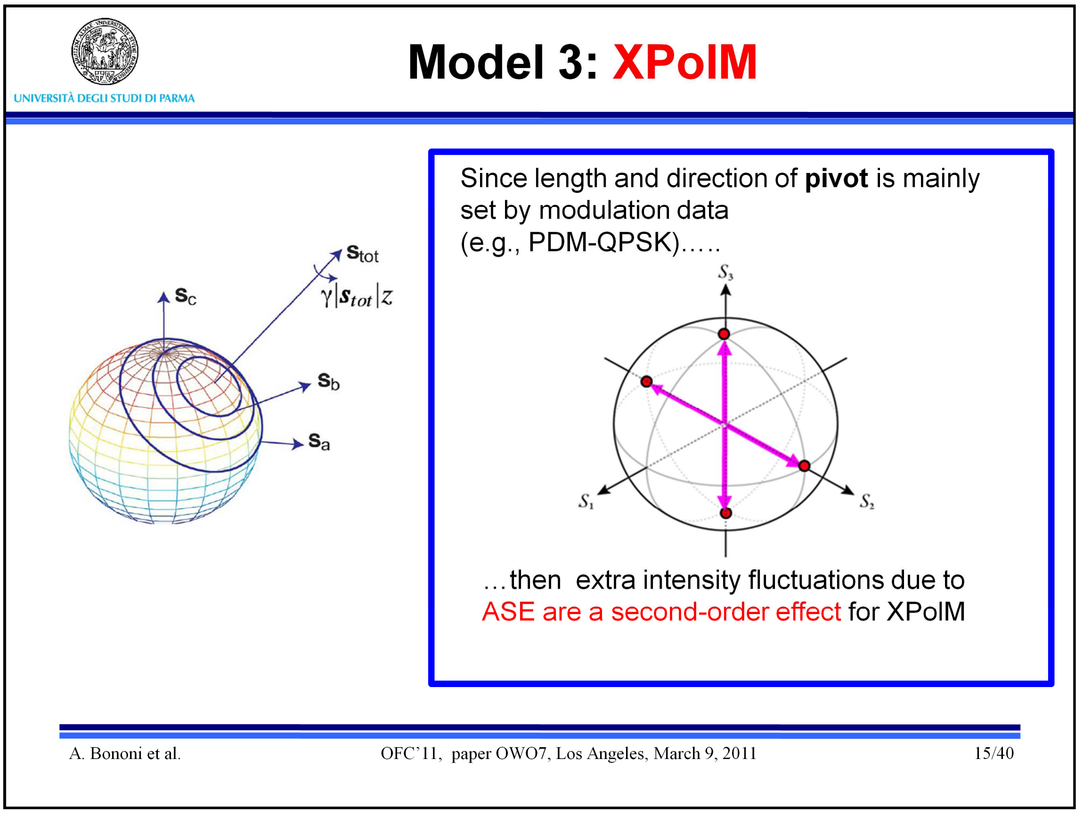


You never heard of XPolM previously, since the OOK receiver is polarization insensitive.

XPolM is actually harmful only for polarization sensitive receivers.

For instance, for PDM signals, the coherent receiver tracks (through the butterly equalizer typically driven by the CMA algorithm) the average polarization frame of reference (magenta vertical and horizontal axes).

The fast misalignments (speeds of the order of the symbol time) produced by XPolM, indicated here by the angle theta/2, are therefore not tracked by the CMA, and thus produce, for instance when trying to retrieve the tributary X, a fading of the desired component, as well as a crosstalk from the orthogonal PDM tributary (this last one is in fact the dominant source of penalty due to XPolM, see the analysis in the shown citation by Winter and co-workers).



A final note on XPolM: since length and direction of pivot is mainly set by the modulation data (e.g. stokes direction is modulated with PDM-QPSK pumps as shown in the inset, or stokes intensity is modulated with OOK pumps), then obviously the extra intensity fluctuations due to ASE are a second order effect in setting the pivot motion and thus for XPolM penalties.

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Let's now move to a quantitative analysis of the dominant nonlinearity through simulations of the NLT vs baudrate

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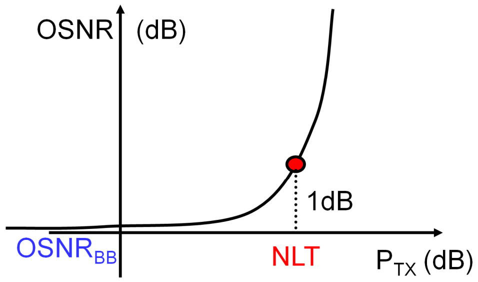
NLT Simulations

A key parameter for any long-haul line and modulation format is the nonlinear threshold (NLT) at 1dB of OSNR penalty at BER=10^{-3}



We will show estimates by simulation of NLT vs. symbol-rate for some modulation formats in optimized DM/NDM lines.

[1] J. K. Fischer *et al., JLT*, Aug. 2009.
[2] A. Bononi *et al.*, *Opt. Fiber Technol.*, 2010
[3] A. Bononi *et al.*, *ECOC* 2010, Th10E1

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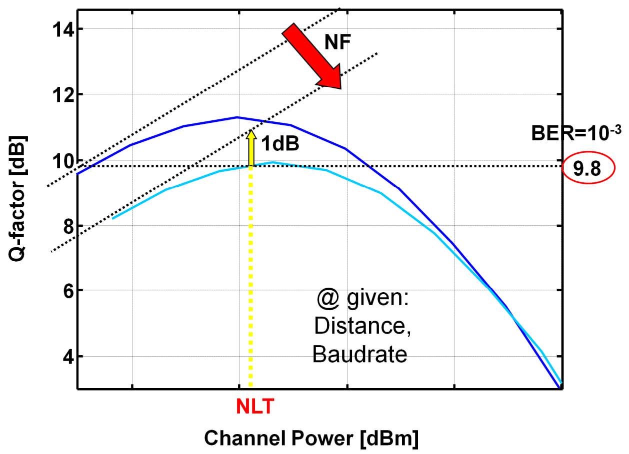
NLT Simulations



@ given distance & symbol-rate, NLT found by varying ampli noise figure NF.....

...... till 1 dB of penalty from back-back @ BER=10^{-3} is found

...this implies repeating several Q measurements and interpolating

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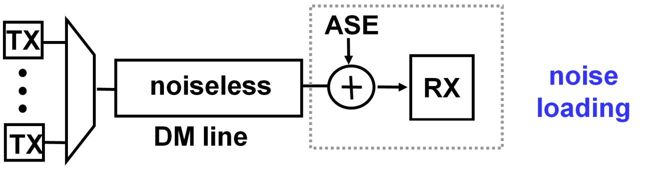
NLT Simulations

- Goal here is NEITHER analytical modeling NOR numerical efficiency, but an exhaustive search through lengthy Monte Carlo simulations of the dominant NL effect.

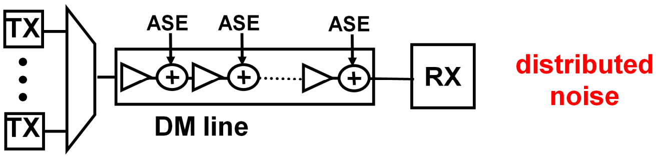
- Dominant NL established from estimation of NLT vs symbol-rate for each NL effect acting individually

Toggling ON/OFF Nonlinear Signal-Noise Interactions

NSNI OFF:



NSNI ON:



Toggling nonlin ON/OFF

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WDM Manakov nonlinear step in vector SSFM [*M. Winter et al, JLT 2009*]:

SPM XPM XPolM

$$\frac{\partial \vec{A}_n}{\partial z} = -i\gamma\left(\left(||\vec{A}_n||^2 + \frac{3}{2}\sum_{k\neq n}||\vec{A}_k||^2\right)\sigma_0 + \frac{1}{2}\sum_{k\neq n}(\mathbf{s}_k \cdot \boldsymbol{\sigma})\right)\vec{A}_n$$

σ_0 = 2x2 identity matrix

$\boldsymbol{\sigma}$ = 3x1 vector of Pauli matrices

$\mathbf{s}_k = \vec{A}_k^{\dagger}\boldsymbol{\sigma}\vec{A}_k$ = 3x1 Stokes vector associated with 2x1 Jones vector A_k

Label	NL Effect	Remarks
SPM	self-phase modulation	**scalar phase modulation**
XPM	cross-phase modulation	**scalar phase modulation**
XPolM	cross-polar. modulation	**includes all polarization effects**

The individual effects of SPM, scalar XPM, and XPolM can be toggled ON/OFF by enabling/disabling the corresponding operators in the WDM Manakov nonlinear step in our vector split-step Fourier method propagator.

Note that XPM is here defined (note the 3/2 coefficient) as the polarization-averaged coefficient, so that it produces a scalar phase modulation like SPM, while all polarization-dependent effects have been lumped into a single operator, which is called XPolM, as suggested by Winter in the given citation.

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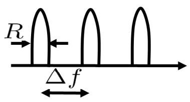
Simulation Details

- Channel spacing scaled with symbol rate



- Number of WDM channels: scaled with symbol rate [1]
- Used purely random symbols, not PRBS.
  Monte-Carlo simulations stopped after counting about 100 errors. [1,2]

[1] A. Bononi *et al.*, *Opt.FiberTechnol.*, 2010.
[2] J.-C. Antona *et al.*, *ECOC '08*, paper We.1.E.3.

NOTE: the number of WDM channels used in the PDM-QPSK NLT results in the published proceedings is smaller than the number shown in this presentation. Please refer to slide 38 for the values actually used.

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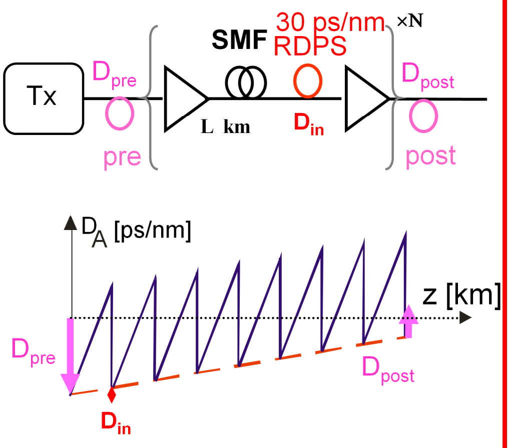
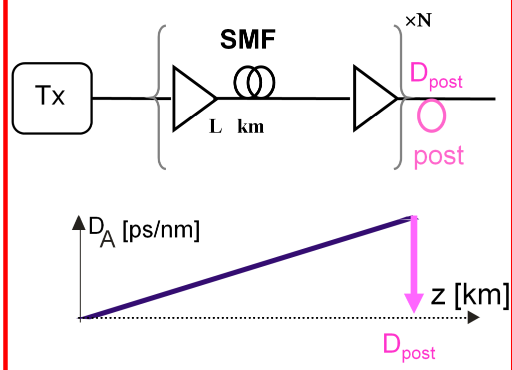
Links

DM



D_{pre}, D_{post} optimized (even w/ coherent RX).
No disp. slope. No NL in DCFs. No PMD

NDM



D_{post} makes D_{total}=0 (even w/ coherent RX).
No disp. slope. No NL in DCFs. No PMD

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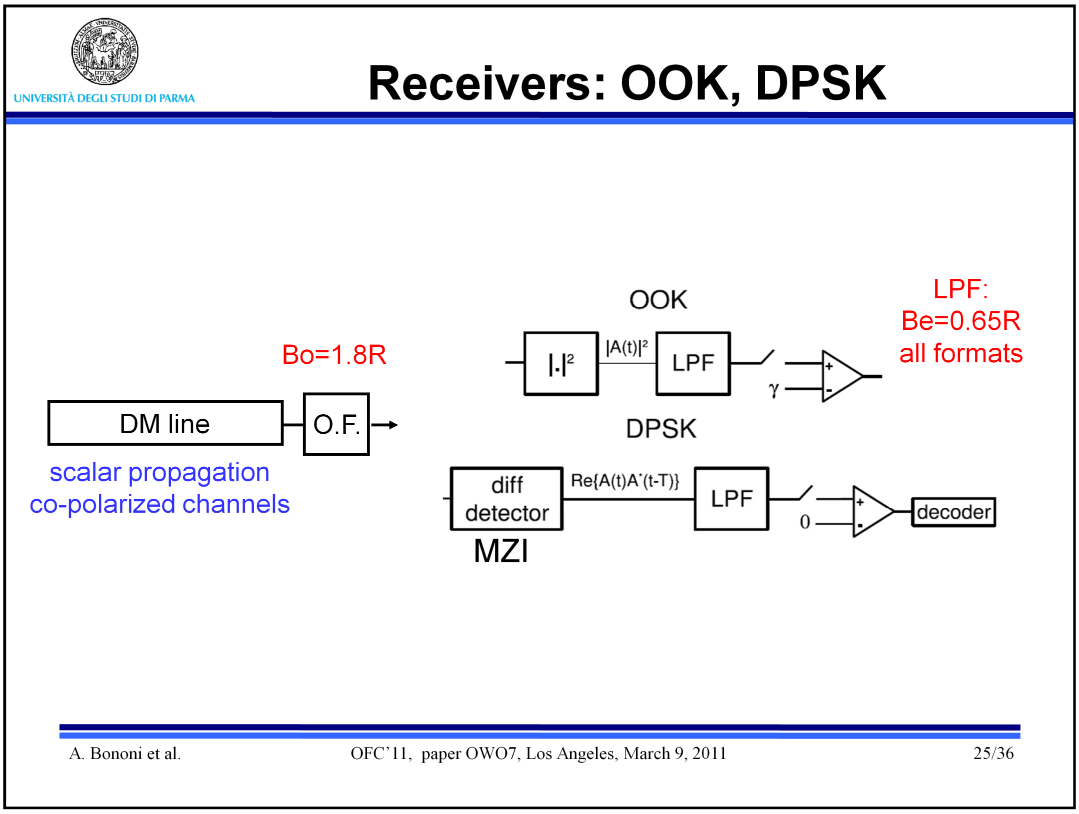
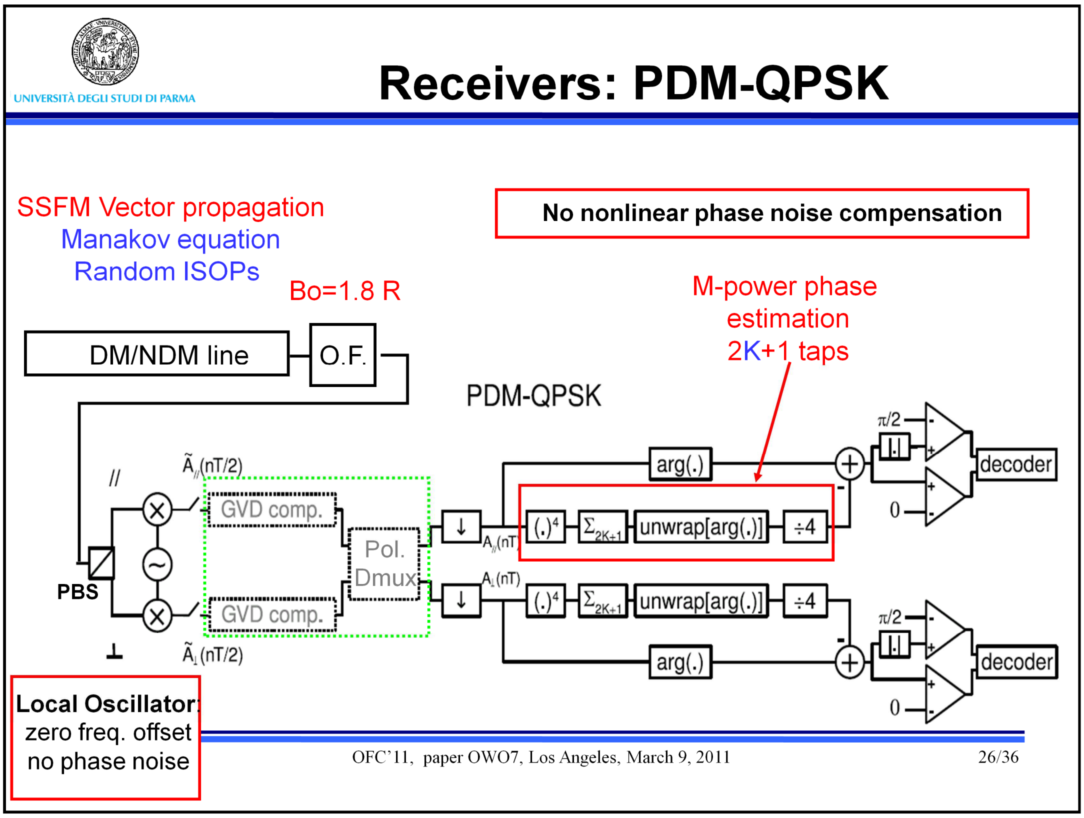
Modulation formats

1. Direct-detection OOK
2. Direct-detection DPSK
3. Coherent PDM-QPSK



The receivers for OOK and D(Q)PSK are standard ones, with optical filter bandwidth 1.8 times the baudrate, electrical filter 0.65 the baudrate, and scalar propagation along the DM line (i.e. in the worst-case of all co-polarized WDM channels).

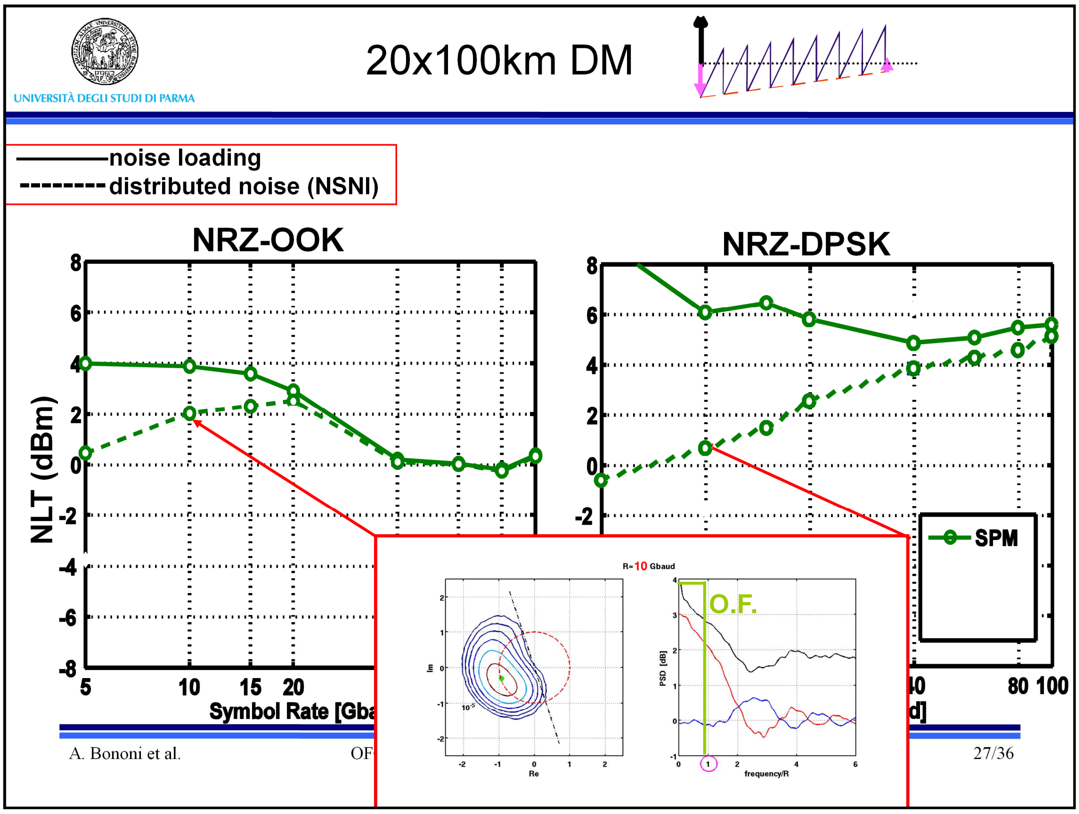


In the coherent PDM-QPSK case, the propagation was vectorial, based on the Manakov equation (with random WDM input SOPs), and PMD was set to zero (if you are interested in the combined action of PMD and PG, please see our ECOC 09 poster P4.12). Optical filter scaled again as 1.8 times the baud rate. Electronic GVD compensation was not implemented since a post-compensation optical fiber was considered (this is equivalent to electrical compensation since local oscillator phase noise was not included and DCF fibers were ideal). Also CMA was not implemented, since the known cumulated linear birefringence was undone at the optical level. This allowed us to concentrate on the action of the feedforward M-power phase estimation, equipped with the unwrapping function to eliminate equivocation.

More assumptions:

-- the local oscillator had zero frequency offset for the reference central channel of the WDM comb

-- the coherent receiver had no electronic nonlinear phase noise compensation.



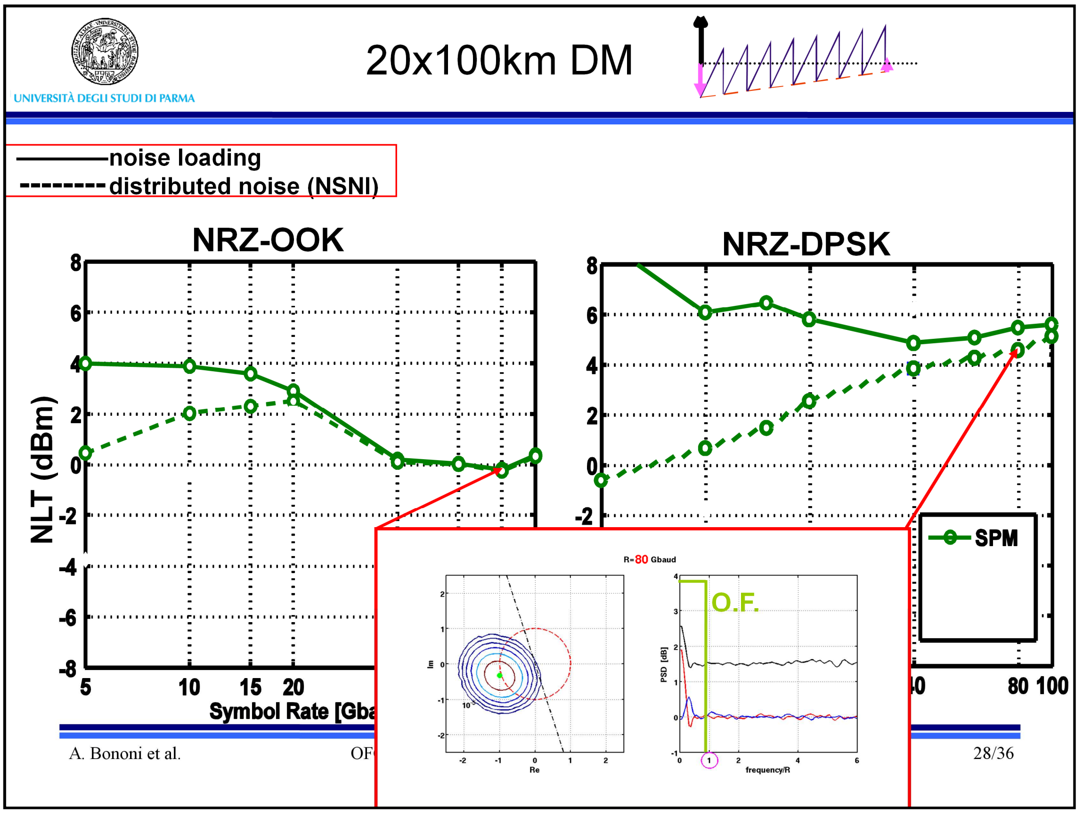
☞ let’s move to the NLT vs baurate results. Pls recall that a high NLT means a weak nonlinearity.

☞ In all plots, solid lines will refer to the noise-loading case that neglects NSNI, while dahed lines to the realistic case of distributed noise which includes NSNI.

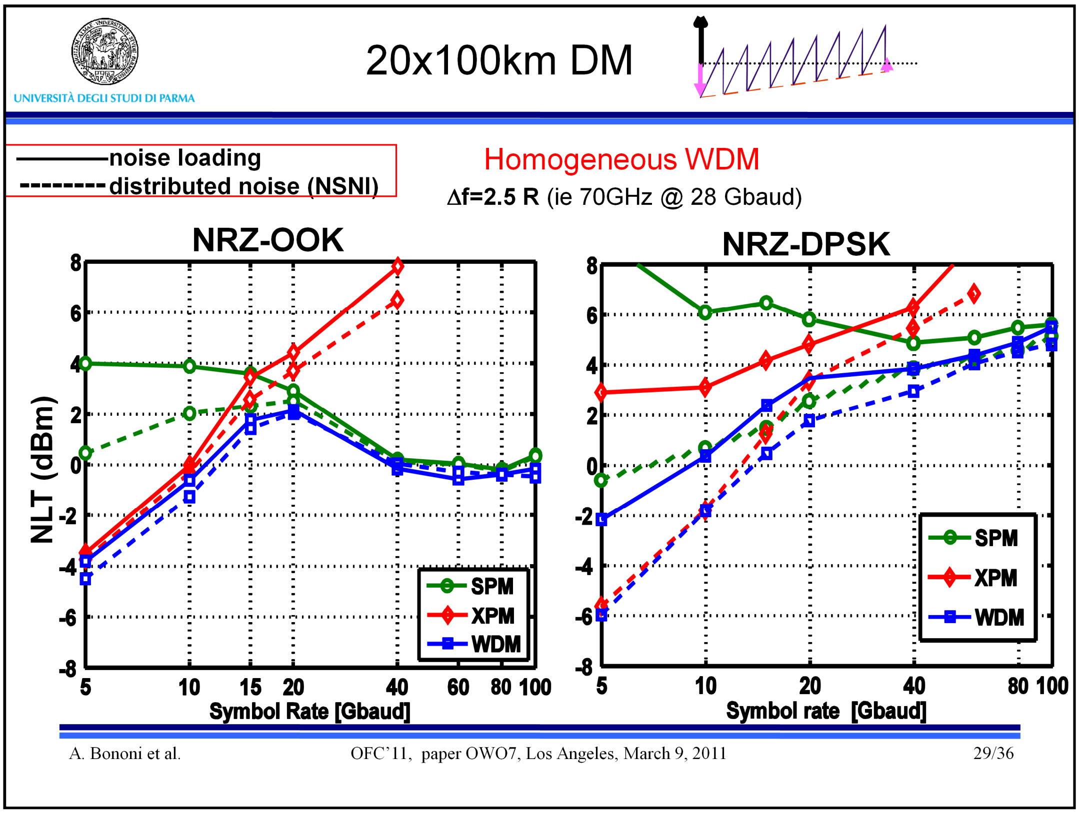
☞ We consider here a DM SMF system, composed of 20 spans of 100km each, and 30 ps/nm residual dispersion per span (RDPS).

☞We start with binary formats, OOK on the left, DPSK on the right. In green I show single-channel results (“SPM” label) both with noise loading (solid) and with distributed ASE (dashed).

☞We see that at lower baudrates the effect of single channel NSNI is quite evident, since the ASE PDFs have significant bending (important for OOK) and NLPN is dominant over the optical filter bandwidth (important for DPSK).



☞ but if we move to higher baudrates, eg 80 Gbaud, then the PG interaction band, f_delta, is a very small portion of the optical filter bandwidth, and thus NSNI vanshes for OOK (no PDF bending) and is reduced for DPSK, although the NLPN is seen to be significant even beyond 100 Gbaud.



☞We next move to the WDM case at a channel spacing 2.5 R, blue lines (WDM comb propagated as a single channel, corresponding to all nonlinearities ON).

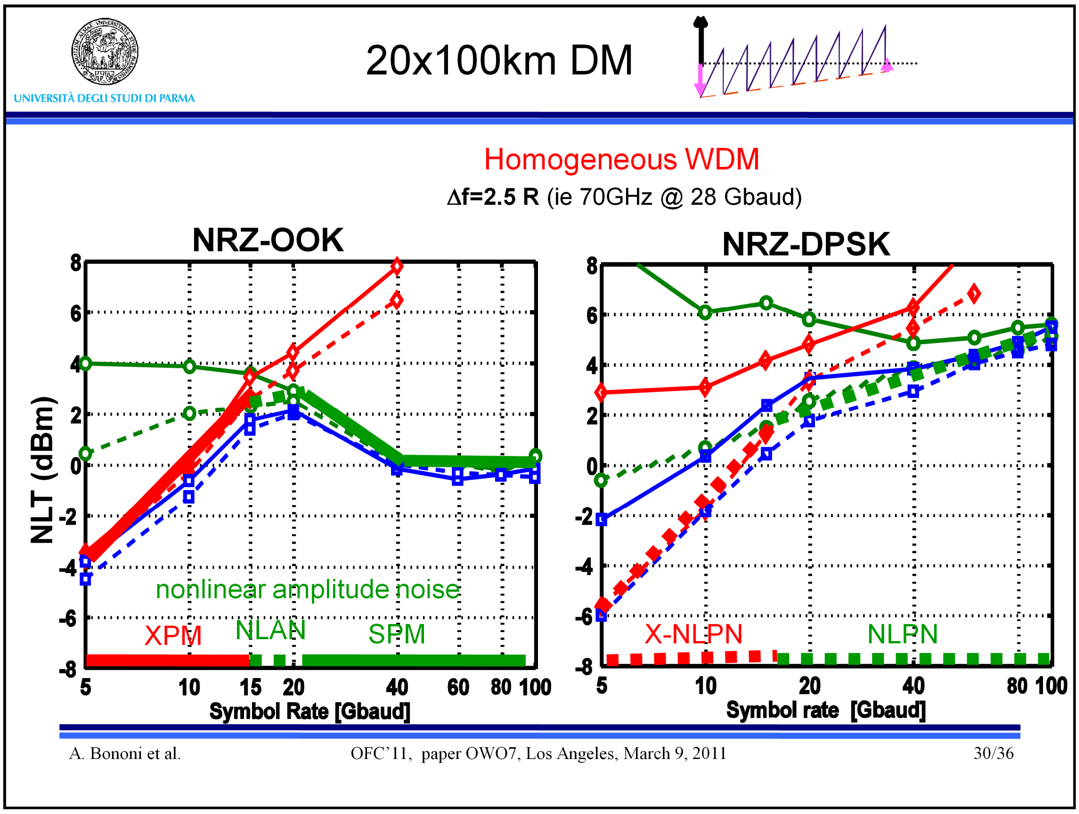
☞ We note that here the NSNI is marginal in OOK, while it is fundamental for DPSK.

☞To investigate the dominant nonlinear effect, we also performed simulations in which XPM is the only nonlinearity, see red curves: we solved the coupled NLSEs for all WDM channels (which automatically excludes FWM and spectral overlap during propagation) and we switched SPM "OFF".

☞We note that in OOK the solid red curve (noiseless XPM) is essentially matching the dotted red curve (XPM+distributed ASE), thus confirming the secondary role of ASE on pumps

☞On the contrary, the red dotted line is dominant in DPSK: it is thus X-NLPN the dominant nonlinearity at lower baudrates.

☞ the offset between the solid red and the solid blue lines in DPSK at lower baudrates cannot be explained by FWM (it would be too small in this SMF line with 30 ps/nm RDPS): a more likely explanation is the linear Xtalk due to spectral overlap, which acts as an intensity noise during propagation and thus causes nonlinear phase noise exactly as ASE would do. Overlap is due both to the unfiltered TX input channels used in this case (note instead that in the PDM-QPSK curves shown in the next slides the channels were filtered at the TX with a Gaussian 2nd order filter of BW 0.9R), and also to the spectral broadening due to XPM during propagation.

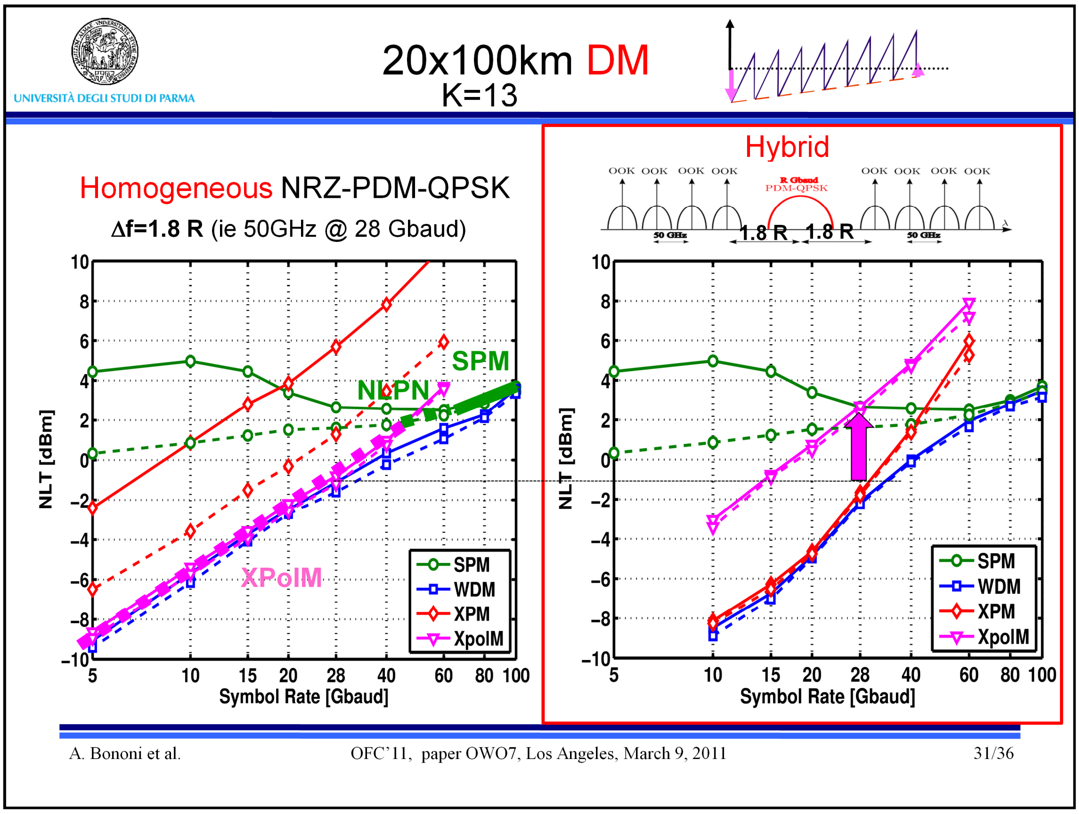


If I had to draw simple conclusions, I would thus state that :

☞ For OOK, noiseless XPM is the dominant nonlinearity at lower baudrates, up to 15 Gbaud, then single-channel NSNI dominates (in the form of "nonlinear amplitude noise" (NLAN), mostly due to PDF bending) between 15 and 20 Gbaud, next noiseless SPM is the dominat effect beyond 20 Gbaud.

☞ For DPSK, the low baudrates are dominated by multi-channel NSNI (ie X-NLPN) up to around 15 Gbaud, then single-channel NSNI dominates (in the form of NLPN) well beyond 100 Gbaud, after that noiseless SPM would dominate.

☞At lower spectral efficiency, the red XPM curves would shift upards, and so would the low baudrate portion of the blue curves: this would extend the dominance of single-channel NSNI to lower baudrates....



Let's move to the coherent PDM-QPSK case.

Again we consider the same 20 span, 100 km per span DM system as before, with 30 ps/nm RDPS.

In all the PDM-QPSK curves we kept a fixed value K=13 in the V&V phase estimation.

On the left we see the NLT vs symbol rate for a homogeneous system, ie, all channels are PDM-QPSK at the same Baud-rate and with the same power per channel. The channel spacing is here 1.8R, i.e., at R=28 Gbaud the spacing was 50 GHz. For this reason, channel filtering at the transmitter is implemented with a 2nd order Gaussian filter of bandwidth 0.9R.

We note that in the single-channel case we do have nonlinear phase noise, as for DPSK; the red curves show that the "noiseless" XPM (XPM with noise loading, red solid line) is mostly suppressed by the generalized phase differential reception in the M-power phase estimation, while the "noisy" XPM (we call it X-NLPN, red dotted) is the dominant XPM contribution, but we note here a new nonlinear impairment, namely, XPolM, magenta curves.

XPolM is weakly-dependent on nonlinear signal noise interactions (dashed and solid lines coincide), as we noted in slide 15.

From its vicinity to the WDM NLT, we thus conclude that at lower baud rates XPolM is the dominat impairment, followed by NLPN above roughly 40 Gbaud, then followed by "noiseless" SPM at R above 60 Gbaud.

Let's now move to see what changes in a hybrid system, where we have a central PDM-QPSK channel at variable baudrate R, with two lateral islands of 10G OOK legacy channels with intra-OOK channel spacing of 50 GHz. The two islands are spaced apart from the PDM-QPSK carrier by 1.8R.

The power of the OOK channels was here chosen to get BER of 10^-3 for both the PDM-QPSK and the OOK channels in linear propagation.

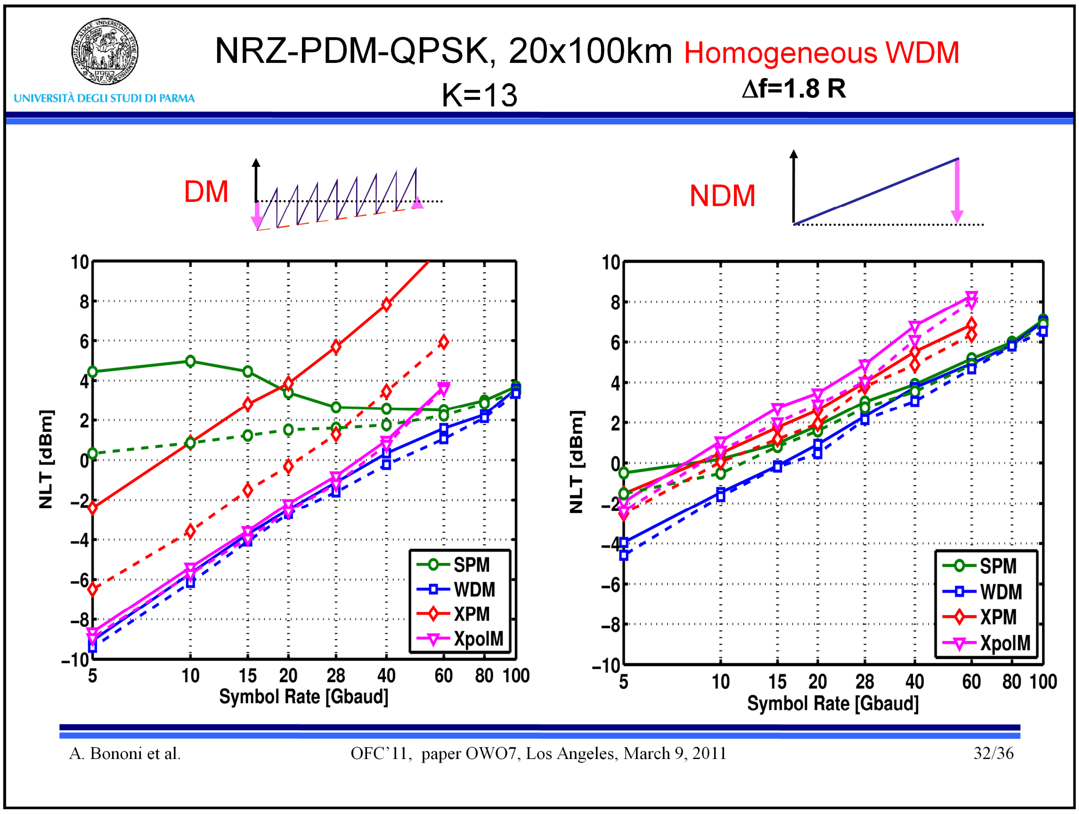
I.e., the OOK channels had rougly 5 dB lower power than the PDM-QPSK channel.

We note that here the roles of XPM and XPolM are reversed, being the scalar XPM by far the dominant impairment at lower rates.

The XPolM NLT in fact improves with respect to the homogeneous case, mostly because the lower OOK power causes a slower rotation around the pivot and thus yields a lower depolarization w.r.t the homogeneous case. However, the intensity variations of the OOK "pumps" is much larger than in the homogeneous case, hence the dramatic decrease of the XPM threshold.

Such XPM NLT essentially is not influenced by the signal-noise nonlinear interactions (solid and dashed curves match), as in the OOK NLT curves of slide 29.

To see the effect of a better, lower value K=3 in the hybrid system dominated by XPM, please refer to slide 37.



Here, for the same 20x100 km homogeneous PDM-QPSK DM system shown before (left), we show on the right chart what changes if we remove pre- and in-line compensation, thus turning the line to NDM.

We note three major facts:

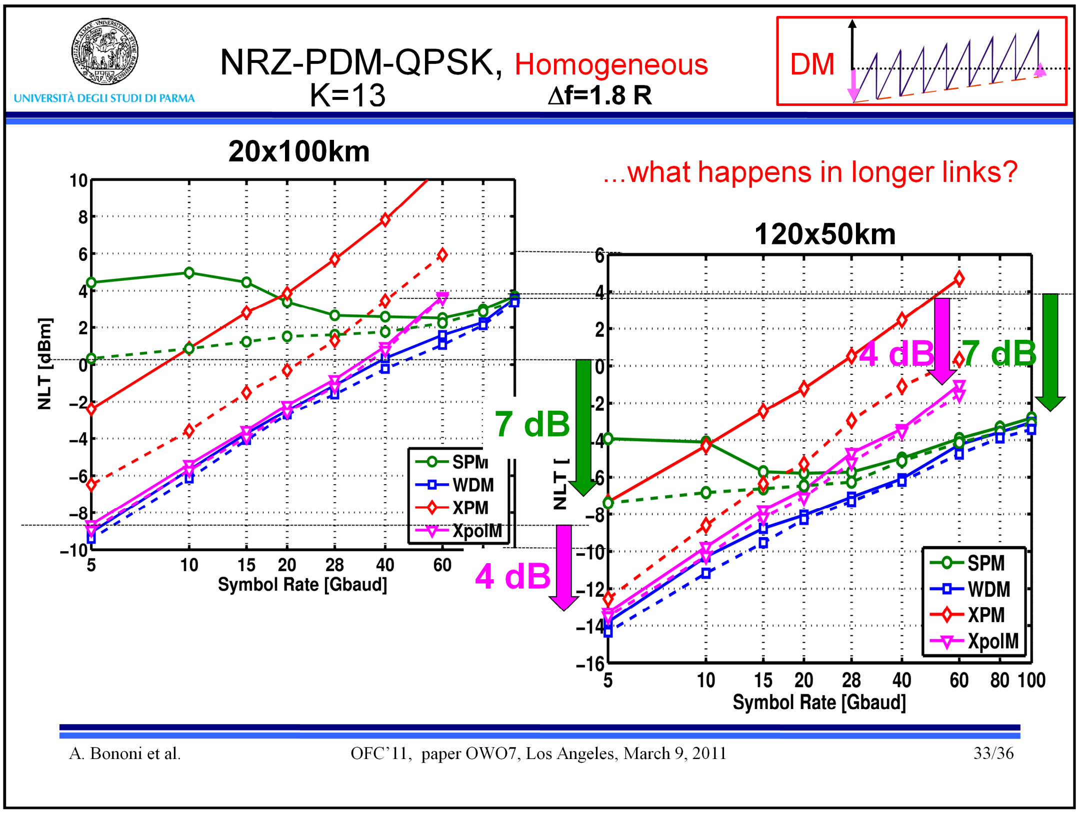
1) the single channel green "SPM" NLT for NDM is worse (lower) at baudrated below about 20 Gbaud, and better (higher) above that.

Hence in single-channel operation, removing in-line compensation improves performance only at higher baudrates.

2) the NLT of the dominant cross-nonlinear effects (XPolM in magenta, X-NLPN in red dashed) get higher because of the increased channel walkoff that weakens both x-effects;

3) nonlinear signal noise interactions have been pushed to much lower baudrates, below the shown range of R, because of the decreased parametric interaction bandwidth f_delta (see slide 8).

Overall, we conclude that, in this 20x100km SMF NDM link, single channel effects are the dominant nonlinearity above 20 Gbaud, with roughly 1 dB of extra penalty due to cross-nonlinearities at 28 Gbaud.



For the DM homogeneous PDM-QPSK system, we now show, by comparison with the already shown NLTs at 20x100km (left chart) what happens as we multiply by a factor 6 (7.7 dB) the number of spans.

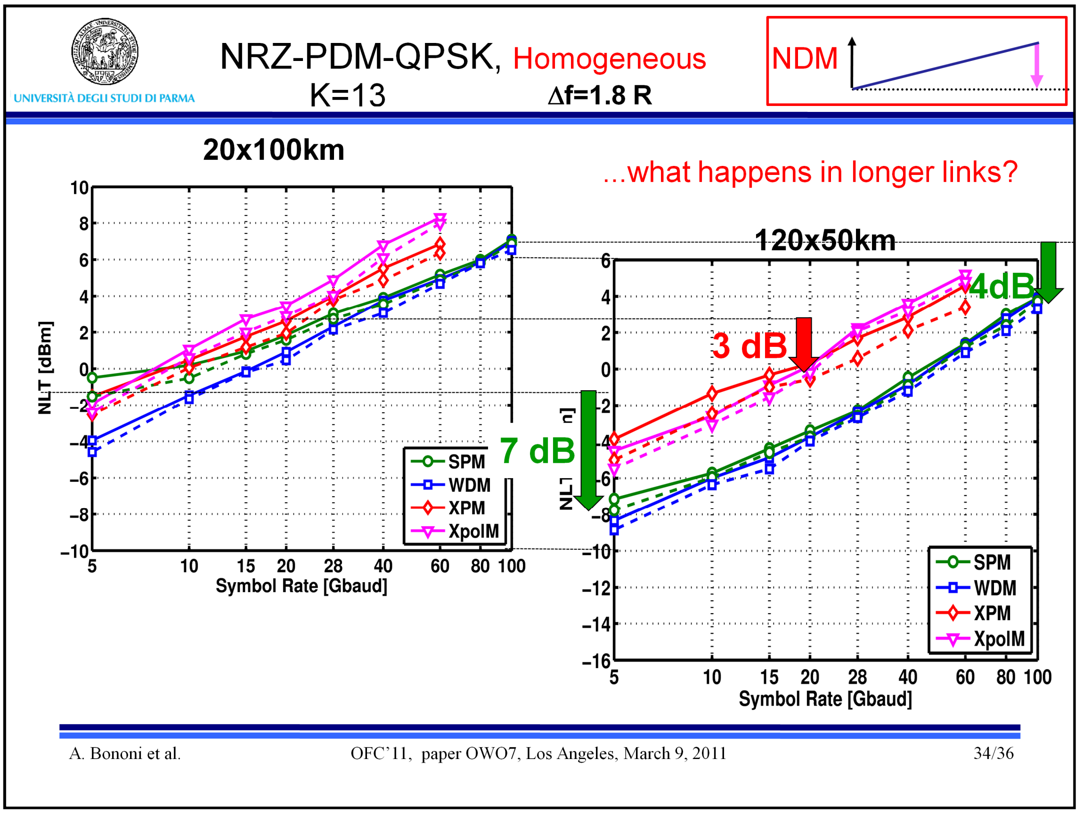
We note that single channel NLTs sink more or less uniformly over the shown range by about 7 dBs (7.7 would be expected if the links remained 100 km long: with smaller 50 km, the RDPS of 30 ps/nm is larger in percentage of the cumulated dispersion per span, resulting in a slightly weaker nonlinearity).

However, the dominant cross-channel NLTs sink less, by about 4 dBs.

The net result is that the high-baudrate range of dominance of single channel effects stretches towards lower values of R.

In other words, the DM link is "single-channel like" over a larger baudrate range.

Such an effect is much more evident in NDM links, as the next slide shows.....



Here we see that the NDM 120 span link has a non-uniform sinking of single-channel NLTs (green), from 7 dBs at 5 Gbaud up to about 4 dB at higher rates. Also, the cross-channel NLTs sink more or less uniformly by about 3 dBs.

The net result is that now the link appears almost entirely dominated by single channel effects.

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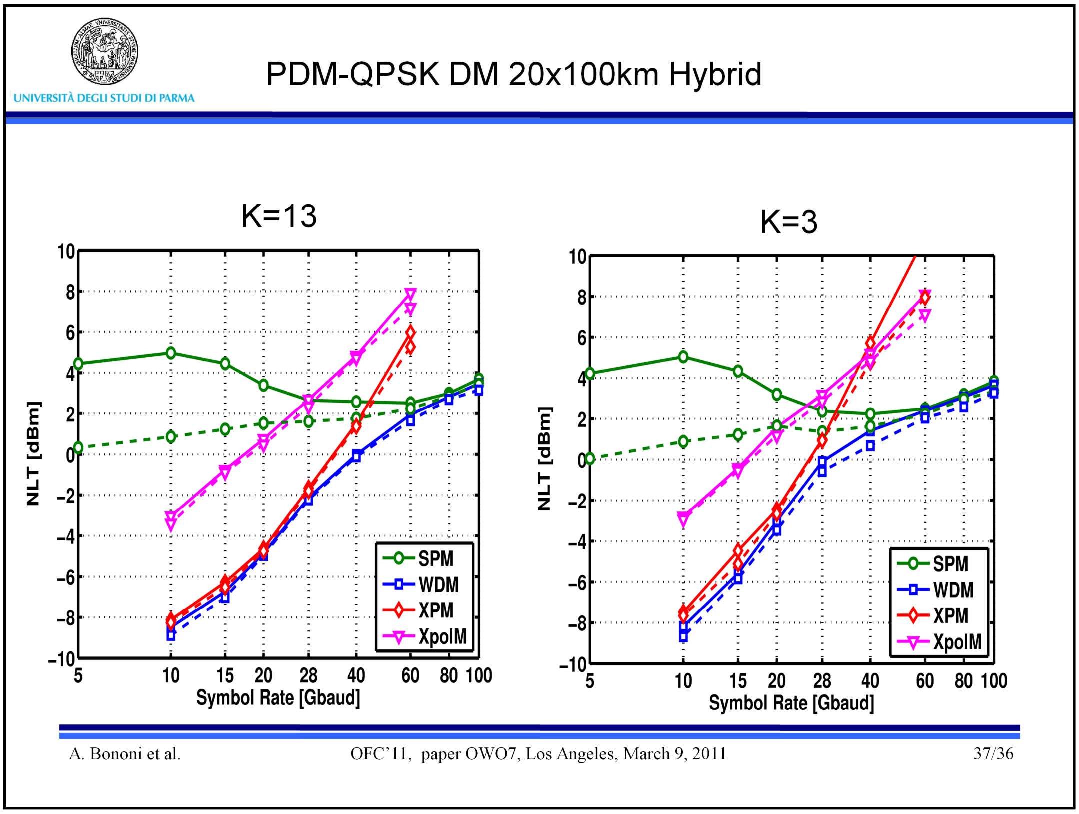
Conclusions

- Shown a simulation-based methodology to find dominant nonlinearity
- In NDM, single-channel NL is dominant, especially for longer links.
- NLT for XPolM was just the AVG: outage probability is also of interest for non-ergodic polarization-impaired channels [1]
- With coherent RX and long-enough equalizer (CMA)...

...PMD helps reduce XPolM [2,3,4,5]

[1] M. Winter *et al.*, *ECOC '10*, paper Th.10.E.3
[2] M. Winter *et al.*, *JLT Sep. '09*
[3] P. Serena *et al.*, *ECOC '09*, paper Th.10.4.3.
[4] C. Xia *et al.*, *ECOC '10*, paper Th.10.E.5.
[5] P. Serena *et al.*, "Intra- vs Inter-channel PMD in linearly compensated coherent PDM-QPSK nonlinear transmissions", *JLT, 2011, submitted*

Thank you.
Questions?

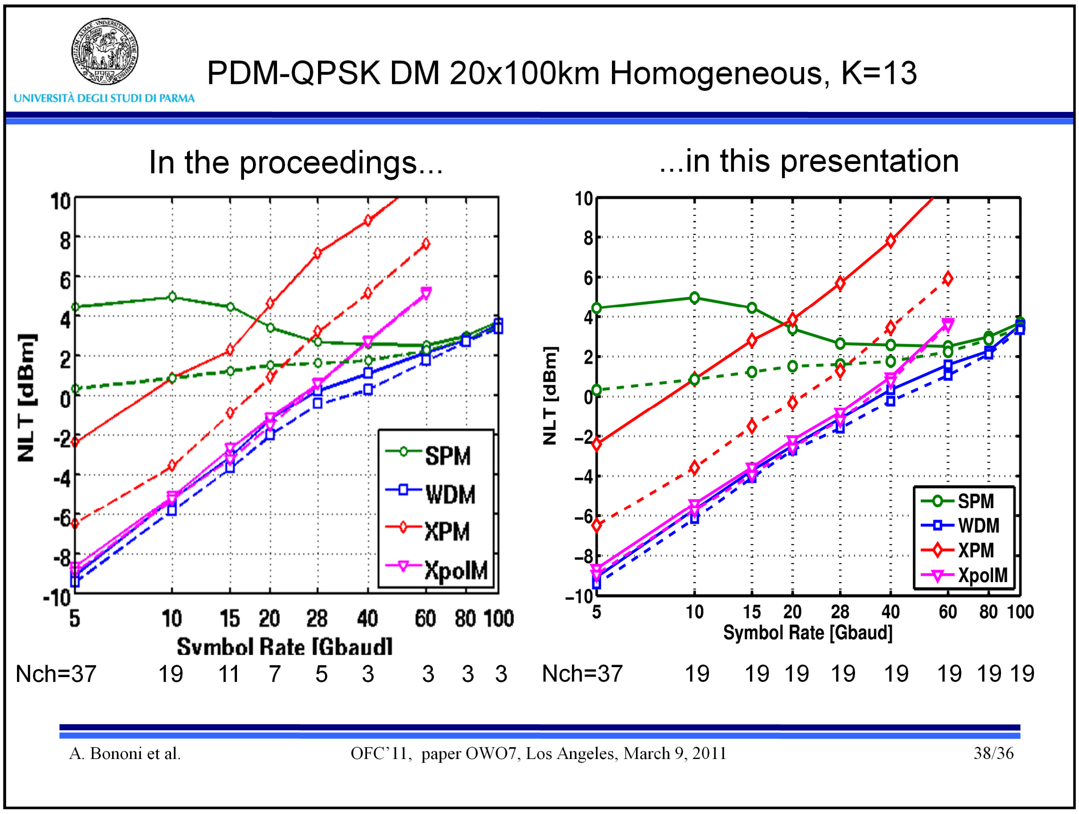


One possible objection to the previous results for hybrid PDM-QPSK/OOK systems is that the used

value of the M-power estimation parameter K=13 is too large when XPM is dominant.

We repeated the NLT measurement in the case of K=3, obtaining the results shown on the right.

XPM clearly improves a lot, but still remains by far the dominat impairment.



The number of WDM channels used in the published OFC'11 proceedings for PDM QPSK, and also in this presentation

for OOK and DPSK, is shown in the left plot, at the bottom. This scaling of Nch with baudrate R was known

to be roughly sufficient to reproduce XPM impairments [see Bononi et al, OFT 2010].

However XPolM requires more channels. Hence in this presentation the PDM-QPSK NLT curves have been

recalculated at the increased number of channels shown on the right.