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Which is the Dominant Nonlinearity in Long-haul PDM-QPSK Coherent Transmissions?

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Outline

- Motivation, Objectives
- How to Decouple Nonlinearities (NL) in Simulations
- Simulation results of performance when nonlinearities are selectively switched ON/OFF
- Conclusions

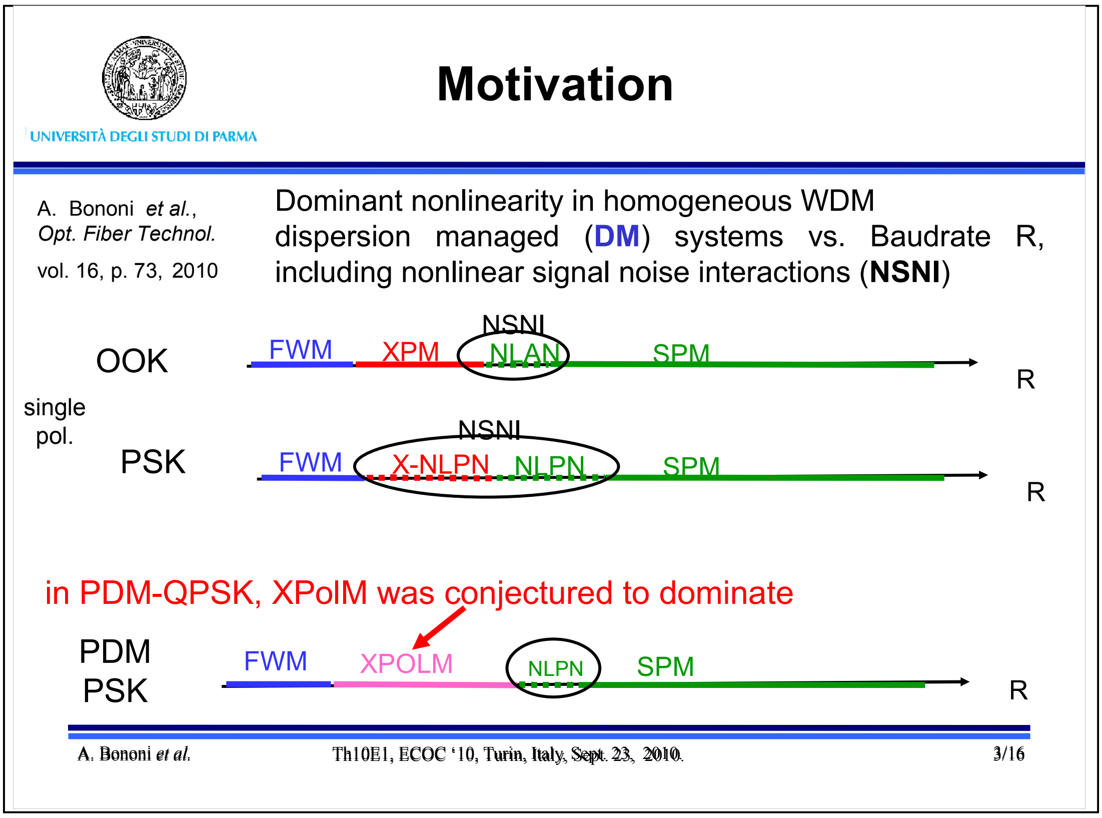
Here is the outline of the talk.

☞ I’ll first provide motivation and objectives of this presentation

☞ then discuss how to decouple nonlinearities in simulation

☞Then I’ll provide simulation results **of performance when nonlinearities are selectively switched on or off**

☞ Finally, I'll draw my conclusions.



We presented last year at ECOC, and later in this OFT paper, a simulation study of the dominant nonlinearity in WDM homogeneous terrestrial DM systems as the signal baud rate was increased, including signal-noise nonllinear interactions, circled in black.

We found that while NSNI are fundamental in single polarization PSK channels,

in PDM PSK modulations such a signal-noise dependence almost disappears, and we conjectured that this was due to XPolM.

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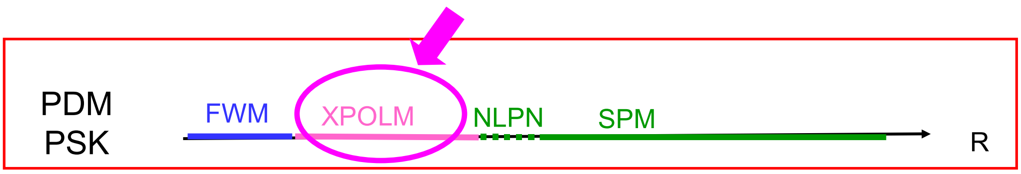
Objectives

- Objectve is thus to indeed verify that at practical baudrates XPolM is Dominant NL in **DM** homogeneous coherent PDM-QPSK systems, and extend study to non-DM (**NDM**) links.
- Goal is NEITHER analytical modeling NOR numerical efficiency, but an exhaustive search through lengthy Monte Carlo simulations of the dominant NL effect.



Hence the objective of this work is to indeed verify that XPolM is the dominant nonlinearity in DM homogeneous
systems at practical baudrates, and to extend the study to NDM systems.

Goal is NOT analytical modeling NOR numerical efficiency, but an exhaustive search through lengthy simulations of the dominant NL effect

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NL Decoupling

Vector Split Step Fourier Method with Manakov NL step

Label	NL Effect	Obtained as
SPM	self-phase modulation	solve single-channel SSFM propagation
XPM	cross-phase modulation	solve system of N coupled SSFM for all WDM channels. Set SPM=OFF, XPolM=OFF
XPolM	cross-polar. modulation	solve system of N coupled SSFM for all WDM channels. Set SPM=OFF, XPM=OFF

WDM Manakov nonlinear step [*M. Winter et al, JLT 2009, pp. 3739-3751*]:

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

σ_0 = 2x2 identity matrix

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

γ = 8/9 of NL coefficient

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

$||s_k||^2 = ||\vec{A}_k||^2$ channel k intensity

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The Dominant NL is found by nonlinearity decoupling

We start from the following expression of the Manakov nonlinear step, as presented by Winter and colleagues, which is used within our vector SSFM.

An is the nth signal field, sigma0 is the 2x2 identity matrix, sigma is the 3x1 vector of Pauli matrices, sk the 3x1 real stokes vector associated with complex signal Ak

and the length of sk is the channel k intensity.

We see here three "operators", corresponding to SPM, to the "average" XPM, and to XPolM.

While SPM and XPM here defined give scalar effects (being multiplied by the identity), all the polarization dependence is lumped in the XpolM operator.

While we know that XPM does in general have a polarization dependence, the XPM defined here s just its "polarization average", and all the rest is lumped in XPolM.

We find this conceptual separation quite convenient.

Now, nonlinearities can be selectively activated by leaving the corresponding operator ON while all others are OFF.

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XPolM: rotation around pivot

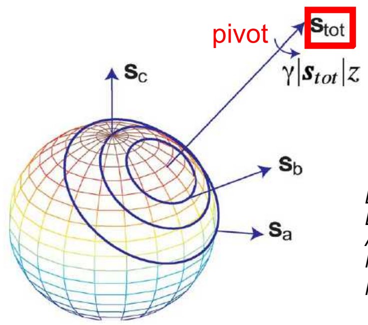
Exact solution of Manakov nonlinear step of length z:

$$\vec{A}_n(z) = e^{\frac{-j\gamma L_{eff}(z)(||\vec{A}_n||^2+3\sum_{k\neq n}||\vec{A}_k||^2)}{2}} \, \boldsymbol{e}^{\frac{-j\gamma L_{eff}(z)}{2}(\boldsymbol{s}_{tot}\cdot\boldsymbol{\sigma})} \vec{A}_n(0)$$

where $L_{eff}(z) = \int_0^z e^{-\alpha s} ds$

$$\boldsymbol{s}_{tot} = \sum_{\substack{All\,channels \\ k}} \boldsymbol{s}_k(0)$$

pivot



L. Mollenauer et al, OL Oct. 95
B. Collings at al, PTL Nov. 00
A. Bononi et al, JLT Sept. 03
M. Karlsson et al, JLT Nov. 06
M. Winter et al, JLT Sept. 09

We show here the expression of the exact solution of the Manakov nonlinear step with all three nonlinearities ON:

it displays a scalar exponential term, and a Unitary exponential matrix.

The vector Stot is the sum of the stokes vectors of All channels and we call it the pivot. it is well known that the geometric interpretation in stokes space

of the previous complex fields solution is a rigid rotation around the pivot of all the WDM stokes vectors by an angle proportional to the pivot length.

The stokes space representation completely ignores the scalar phase term.

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SPM / XPM / XPolM

Exact solution of Manakov nonlinear step of length z:

$$\vec{A}_n(z) = e^{\frac{-j\gamma L_{eff}(z)(||\vec{A}_n||^2 + 3\sum_{k\neq n}||\vec{A}_k||^2)}{2}} \underline{e}^{\frac{-j\gamma L_{eff}(z)}{2}(\boldsymbol{s}_{tot}\cdot\boldsymbol{\sigma})} \vec{A}_n(0)$$

where $L_{eff}(z) = \int_0^z \mathrm{e}^{-\alpha s} ds$

Solutions with NL Decoupling

$$\begin{aligned}
\vec{A}_{\text{spm}}(z) &= e^{-j\gamma L_{eff}(z)||\vec{A}_n||^2} \vec{A}_n(0) \\
\vec{A}_{\text{xpm}}(z) &= e^{-j\gamma L_{eff}(z)\frac{3}{2}\sum_{k\neq n}||\vec{A}_n||^2} \vec{A}_n(0) \\
\vec{A}_{\text{XpolM}}(z) &= e^{\frac{j\gamma L_{eff}(z)||\vec{A}_n||^2}{2}} \underline{e}^{\frac{-j\gamma L_{eff}(z)}{2}(\boldsymbol{s}_{tot}\cdot\boldsymbol{\sigma})} \vec{A}_n(0)
\end{aligned}$$

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For completeness, we show below (and report in the proceedings) the closed-form solutions of the manakov NL step

actually used in the SSFM for each individual nonlinearity:

SPM and XPM just have scalar phase terms, while XPolM has a unitary exponential matrix and a scalar phase term

due to adding and subtracting the channel of interest in the Manakov equation in order to form the pivot.

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NL Decoupling

Vector Split Step Fourier Method with Manakov NL step

Label	NL Effect	Obtained as
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XPM	cross-phase modulation	solve system of N coupled SSFM for all WDM channels. Set SPM=OFF, XPolM=OFF
XPolM	cross-polar. modulation	solve system of N coupled SSFM for all WDM channels. Set SPM=OFF, XPM=OFF
WDM	All (SPM,XPM,XPolM,FWM) (includes also linear XTalk due to spectral overlap)	solve SSFM with WDM comb treated as a single channel.

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of course, all NL including FWM and Xtalk due to spectral overlap can be simulated by treating the WDM comb as a single channel in the SSFM method.

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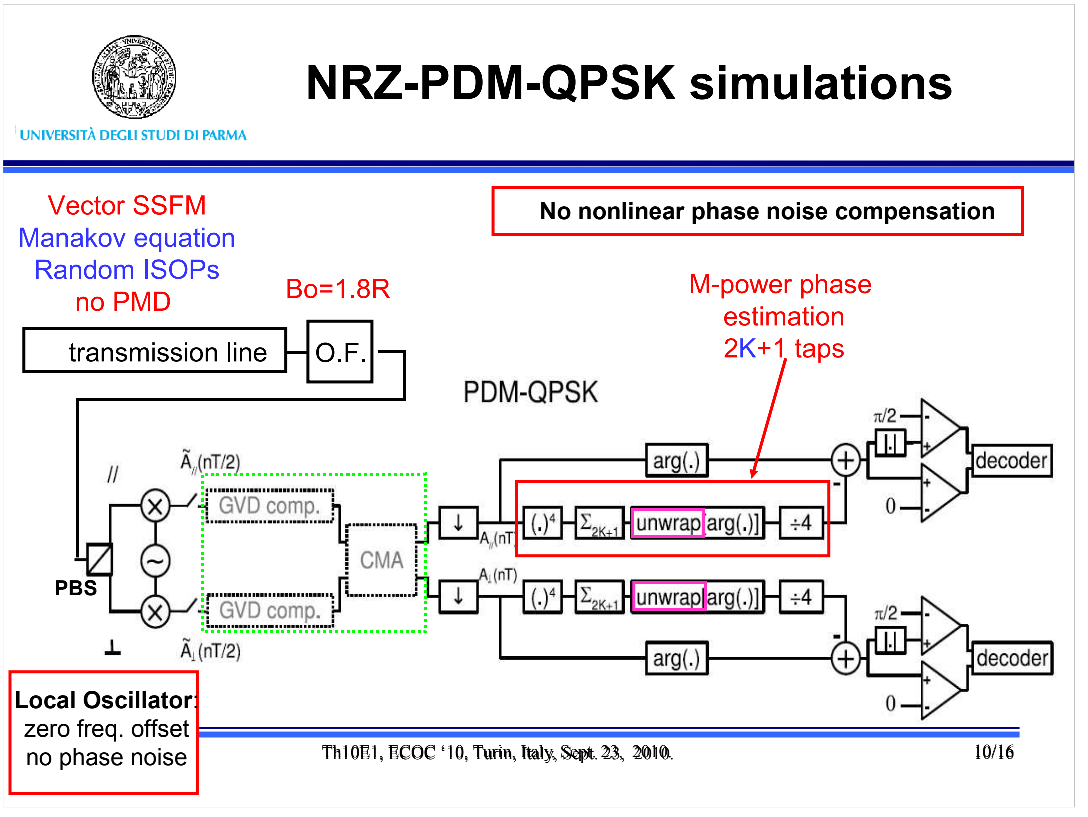
- Simulation Results for PDM-QPSK
- Conclusions

Let's now move to the simulations of the PDM-QPSK system.



The vector SSFM simulation used the Manakov equation with random ISOPs and no PMD in the line.

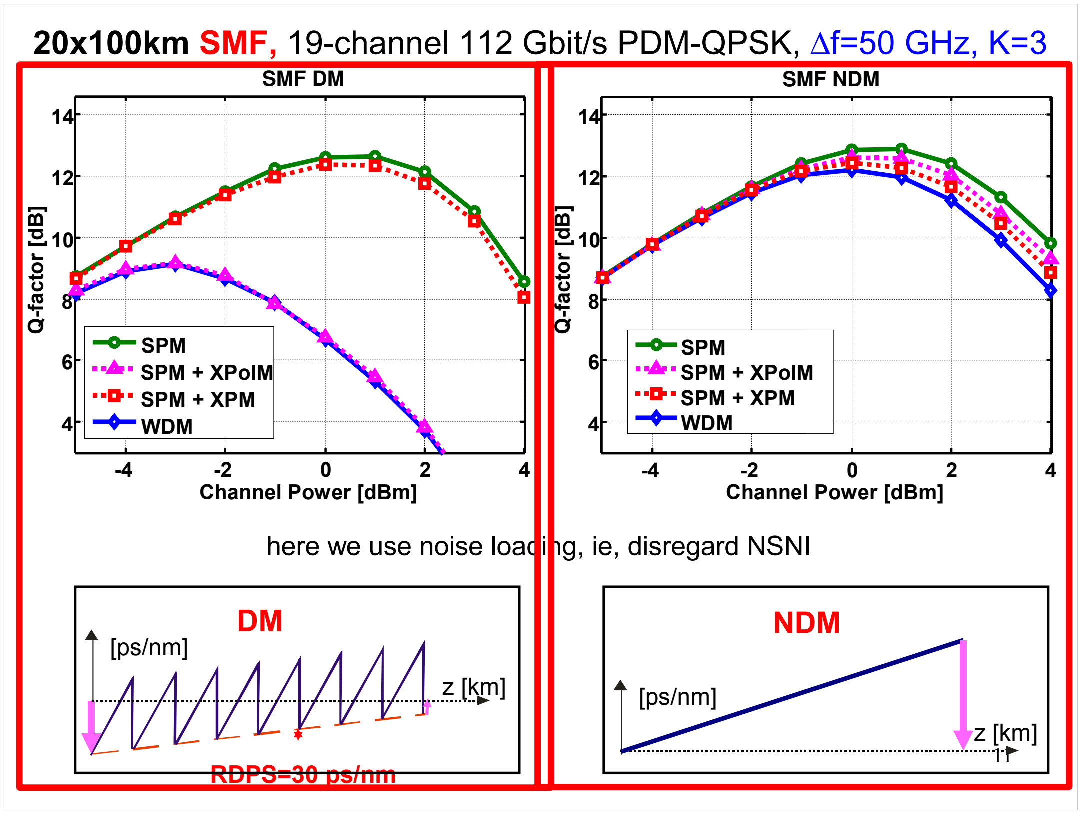
When varying the baudrate, the Optical filter scaled as 1.8 times the baud rate. GVD compensation was simulated with an ideal optical post-compensating fiber.

The receiver is a stanard one with polarization demultiplexing, vitebi&viterbi carrier phase recovery with 2K+1 taps, and final decision.

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.



We now show the Q factor vs transmitted power, the so called bell-curves, for a 2000 km SMF line, with 19 PDM-QPSK channels at 28 Gbaud and 50 GHz channel spacing.

On the left we have the DM case, with a residual dispersion per span RDPS of 30 ps and optimized pre-compensation, while on the right we have the no-DM case.

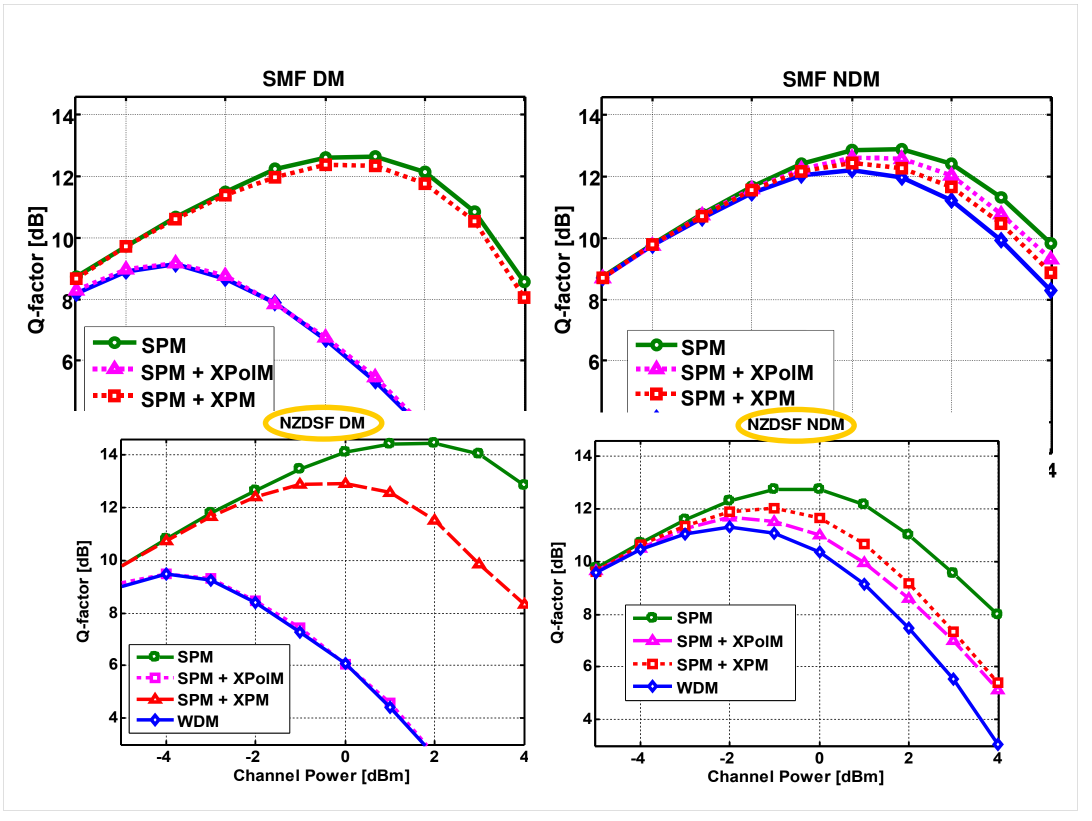
In both cases ASE noise was loaded at the end of the line, thus neglecting NSNI.

The green curves show the single channel performance (where only SPM is present); blue curves indicate the WDM performance with all nonlinearities ON.

In the DM case,

The red curve shows SPM+XPM, while the purple curve the SPM+XPolM, and we see that essentally the whole WDM penalty is accounted for by XPolM.

In the NDM case the cross channel NL are much reduced because of the increased walkoff, and we see that XPM and XpolM have about the same impact on performance.



We repeated the measurement for an NZDSF line with dispersion reduced by a factor of 4,

and again XPolM is the dominant effect even though XPM is larger than before;

in the NDM case again XPM and XPolM are of equal size, although they are both stronger than before

because of the decreased walkoff.

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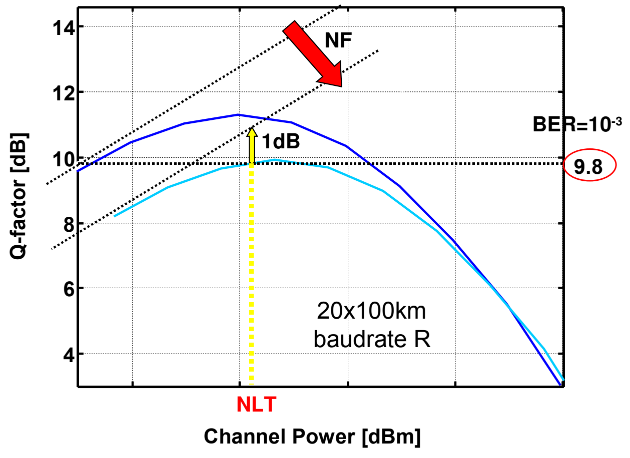
NLT Simulations



nonlinear threshold (NLT):
channel TX power
at 1dB penalty
w.r.t BB at BER=10^{-3}

We measured NLT for a wide range of R, while scaling channel spacing as $\Delta f=2.5R$
($\Delta f=25$ GHz at 10 Gbaud
$\Delta f=70$ GHz at 28 Gbaud)

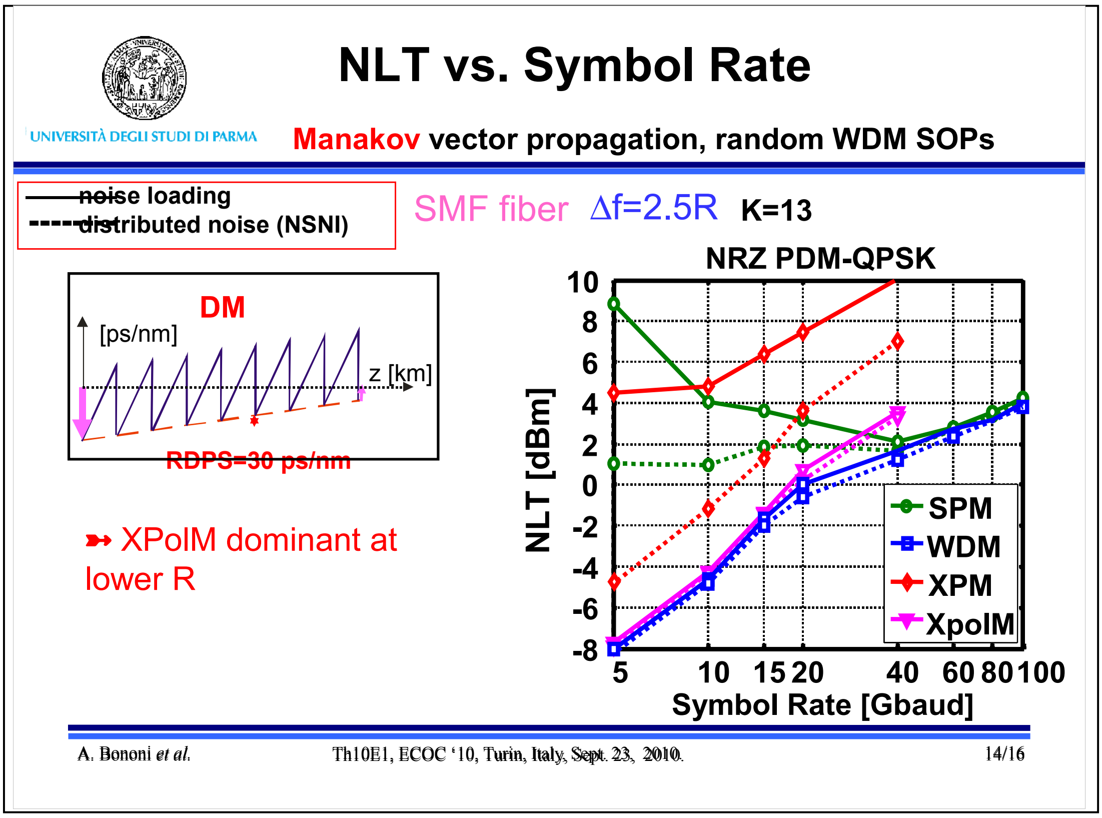
Next we show curves of nonlinear threshold NLT versus baudrate for the same 2000 km SMF line as before.

The NLT is defined as the TX power at 1 dB of penalty w.r.t. the linear case at a reference BER of 10 to the -3,

and is obtained by artificially varying the amplifiers NF until 1 dB of penalty at 10-3 is achieved.

We measured NLT for a wide range of baudrates R, while scaling also channel spacing as 2.5 times the baudrate,

giving 25 GHz at 10 Gbaud, and 70 GHz at 28 Gbaud, thus with a little less NL than the 50 GHz case seen before.



Here we see NLT vs R in the DM case.

Green curves labeled SPM are for single channel: here we performed simulations both with noise loading

(solid lines, ignoring NSNI) and by injecting ASE at each amplifier (distributed noise, ie the realistic case with NSNI).

We see that indeed NSNI are the dominant effects in single channel operation, up to about 40 Gbaud.

Next we see in blue the WDM curves, with all nonlinearities ON:very little dependence on NSNI is observed.

The reason is found by exploring the individual NLT due to XPM only and XPolM only.

In red we see the XPM only NLT, both with noiseless propagation (solid) and with distributed noise (dashed):

the noiseless XPM threshold , solid, is much higher since in this case the intensity is almost periodic and the induced XPM is mostly suppressed by the differential phase receiver.

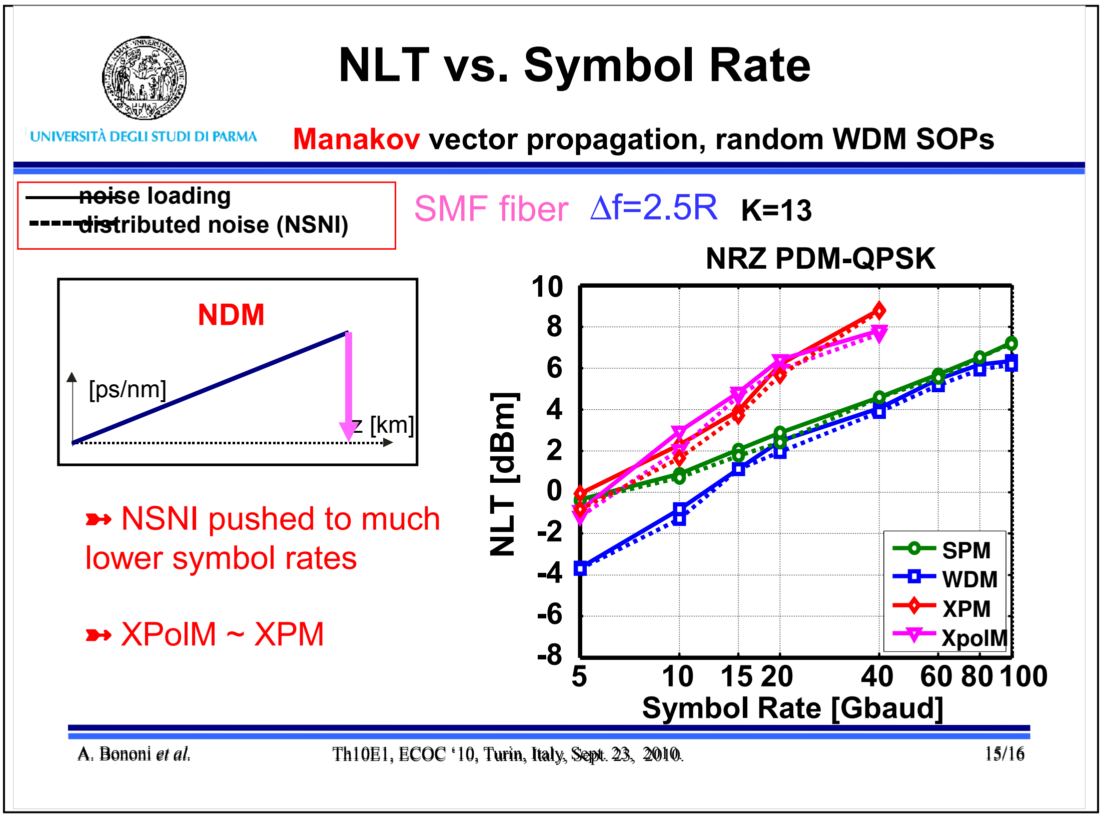
Then we see in purple the XPolM NLT, which is instead almost independent of signal noise interactions

since the XPolM diffusion due to the random motion of the pivot is mostly due to the modulation data which reorient the stokes vectors, and not by

the extra intensity fluctuations due to ASE.

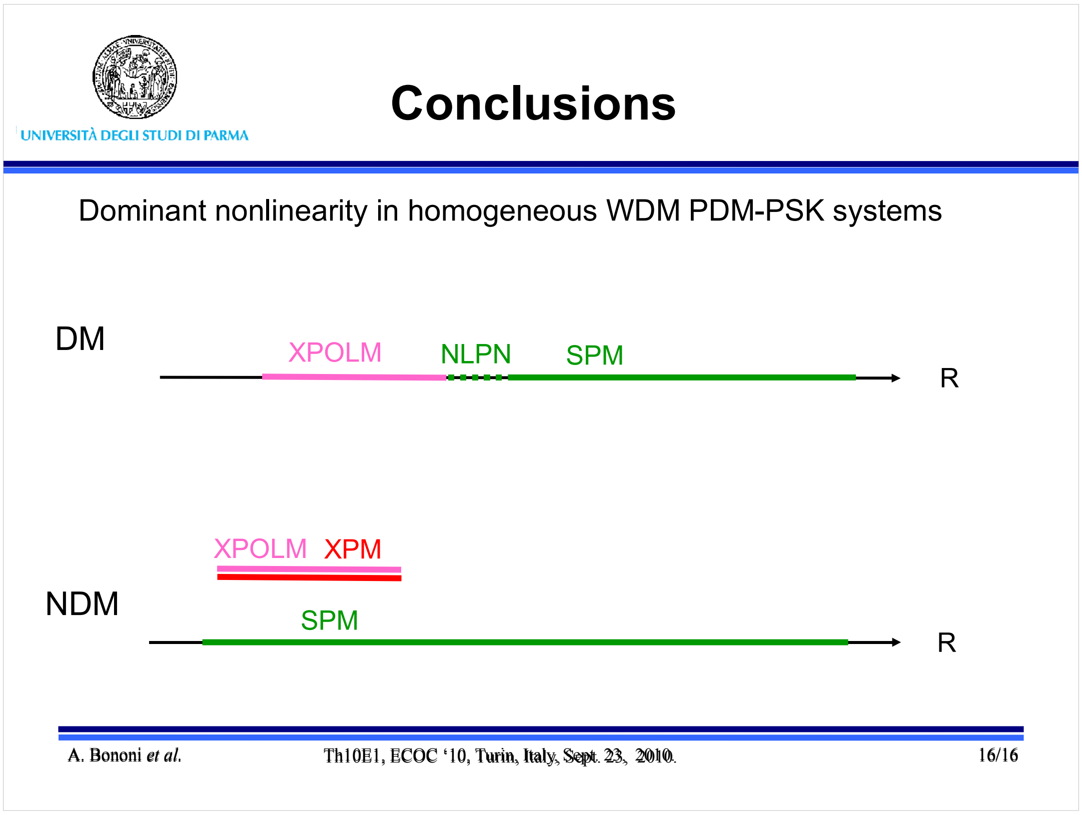
We see that XPolM is the dominant NL effect up to about 30 Gbaud, with NLPN (ie noisy SPM) emerging from 30 to 40 Gbaud, and finally noiseless SPM dominates

at larger baudrates.



If we move instead to the NDM case, we first note the absence of NSNI over the entire baudrate range.

Then we see that the NLTs due to XPM only and XPolM only are of comparable size, but the dominant NL over the entire range is in fact single-channel SPM, with an influence of XPM/XPolM only up to about 20 Gbaud in this study (recall that here channel spacing is 2.5 times the baudrate, so at 28 Gbaud the spacing is 70 GHz).



To conclude and graphcally summarize the findings of this work, here is a taxonomy of the dominant nonlinearities in WDM systems with equal-format PDM-QPSK channels:

For DM systems the dominant NL is XPolM, followed by NSNI emerging as nonlinear phase noise, and finally noiseless SPM

For NDM systems, SPM is the dominant NL, with XPM and XPolM having equal importance and influencing the overall NLT only at lower baudrates, up to 20 Gbaud in the example.