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Nonlinear Limits in Single- and Dual-Polarization Transmission

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Outline

- Motivation, objectives, methodology
- Some models of nonlinear effects:
  - 1. nonlinear phase and amplitude noise (NLAN,NLPN)
  - 2. cross-nonlinear phase noise (X-NLPN)
  - 2. cross-polarization modulation (XPolM)
- Simulations of Nonlinear threshold (NLT) vs Baud-rate
  - Conclusions

Motivation

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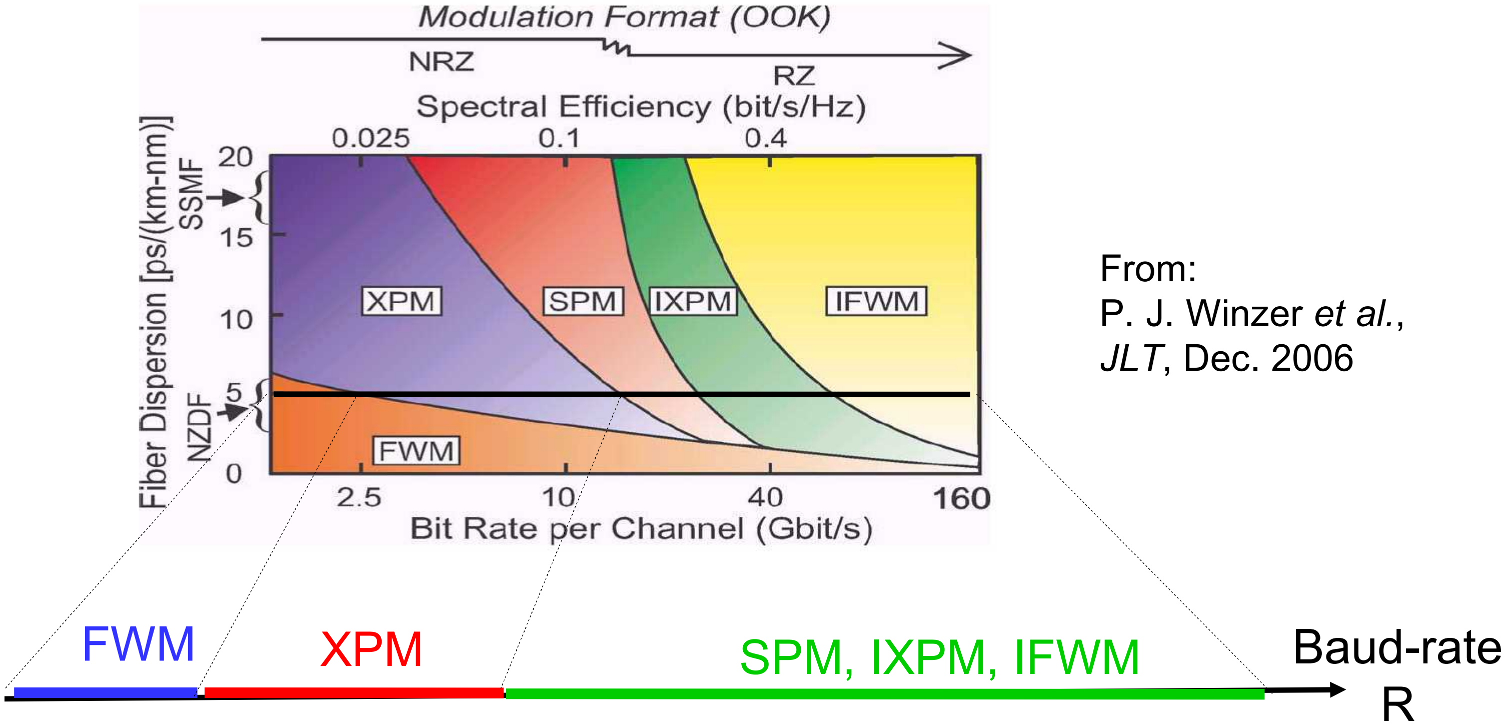
Dominant nonlinearity in OOK WDM DM systems



From:
P. J. Winzer *et al.*,
JLT, Dec. 2006

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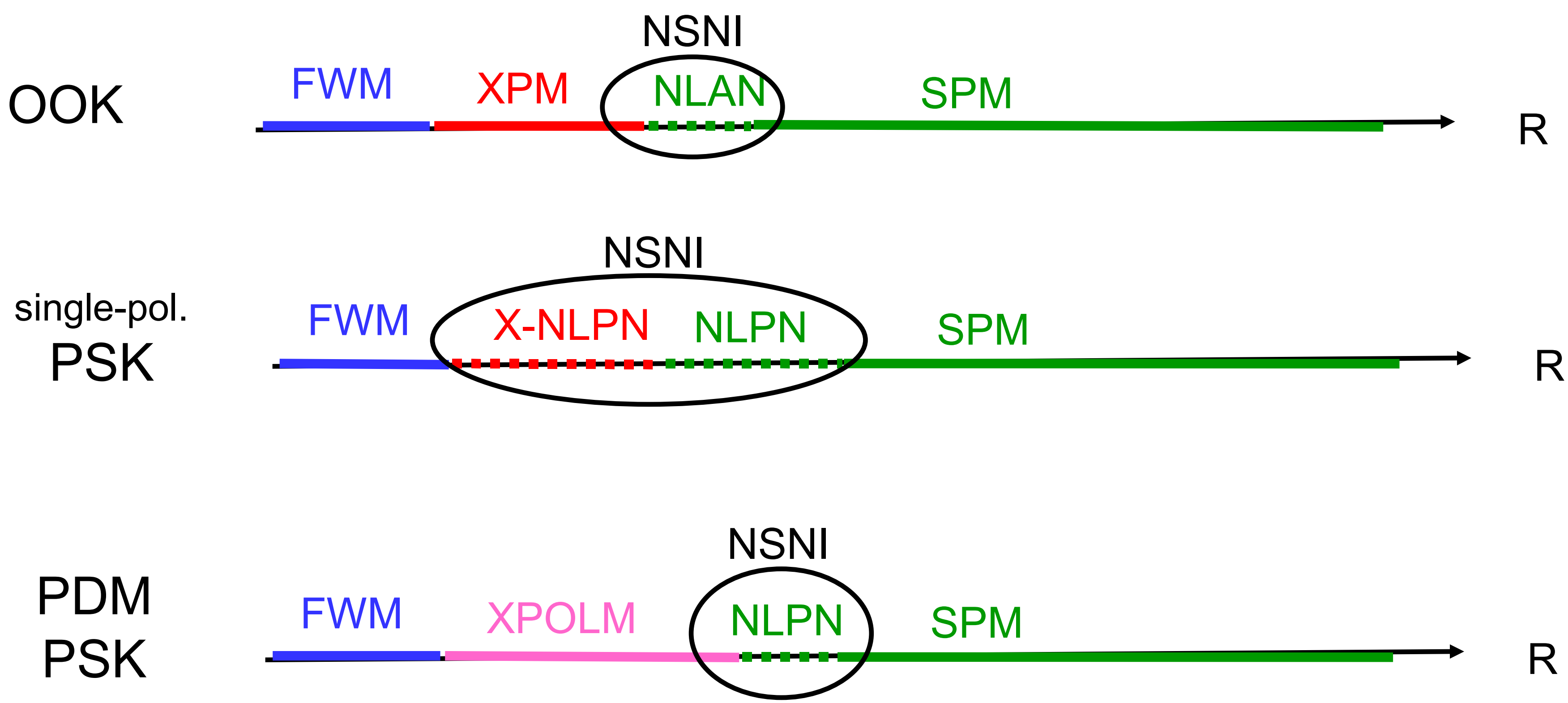
Motivation

Dominant nonlinearity in homogeneous WDM DM systems including nonlinear signal noise interactions (NSNI)

From:
A. Bononi *et al.*,
Opt.FiberTech. 2010



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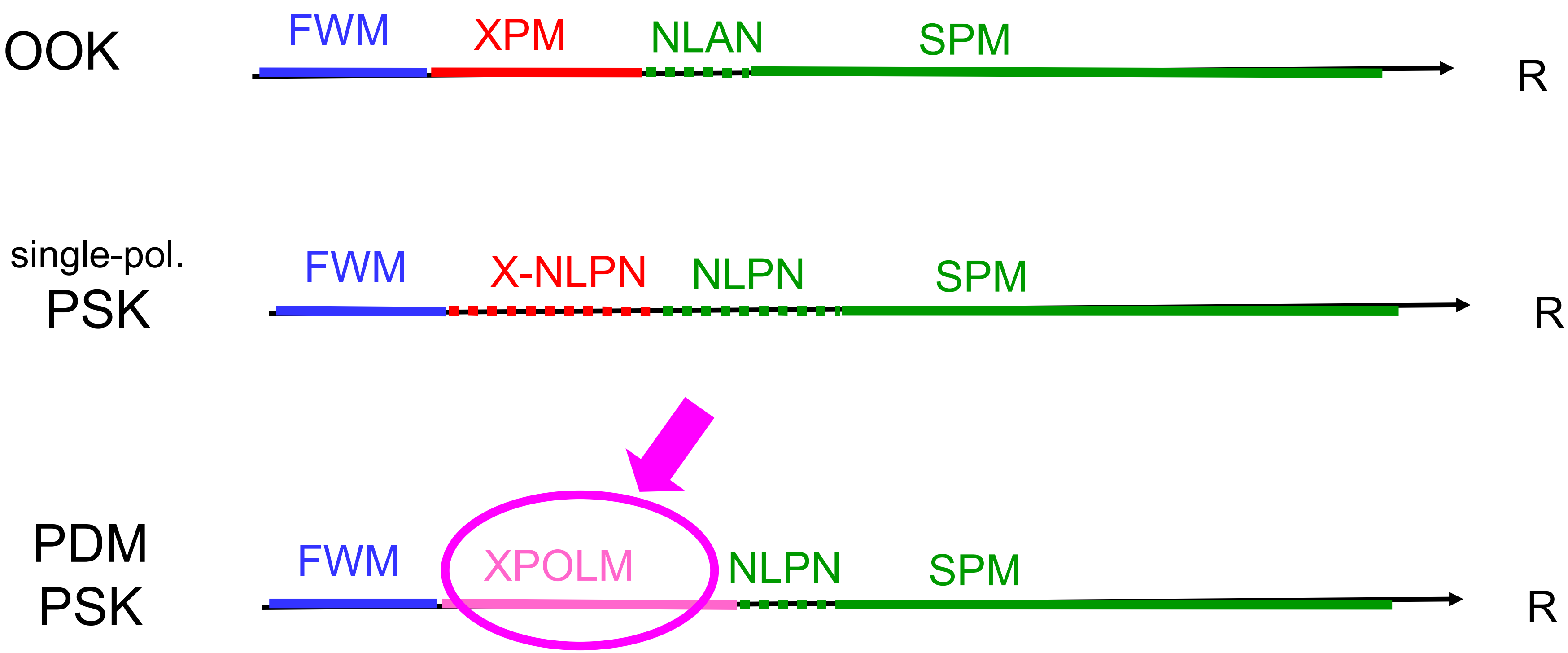
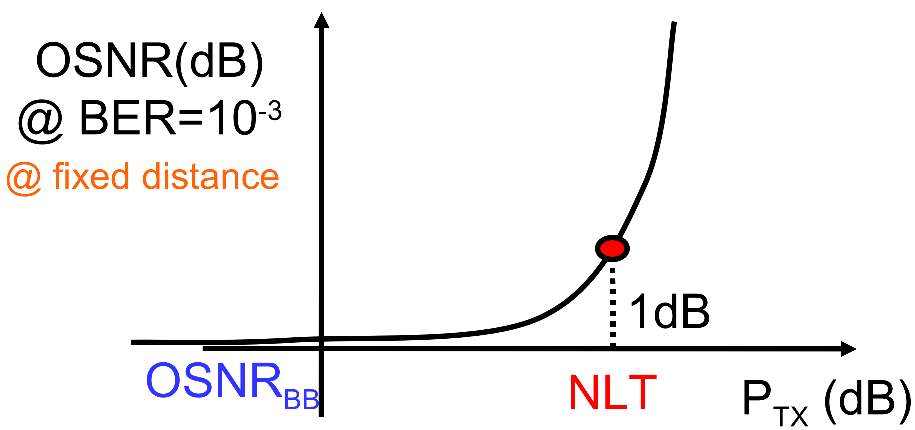
Objectives

Review and extend study of dominant NL for single-polarization (SP) and dual polarization (PDM) formats



Methodology

Dominant NL established from Monte-Carlo estimation of NLT vs baud-rate R for each NL effect acting individually



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

Methodology

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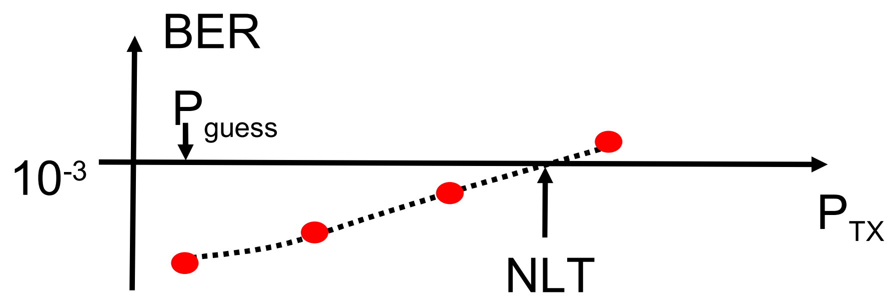
NLT measurement procedure @ given R

- Set $OSNR=OSNR_{BB}+1$ (dB)
- Start with a guess on P_{TX}
- get ampli noise figure NF from ASE power $N_A=OSNR/P_{TX}$
- measure BER by Monte-Carlo error counting, i.e: in a line with that NF, propagate long-enough blocks of random symbols per channel (256 here). Stop simulation when 100 errors on average are counted [*]
- if $BER<10^{-3}$ increase P_{TX} and goto 2.
- Interpolate and get NLT



[*] J.-C. Antona *et al.*, *ECOC '08*, paper We.1.E.3.

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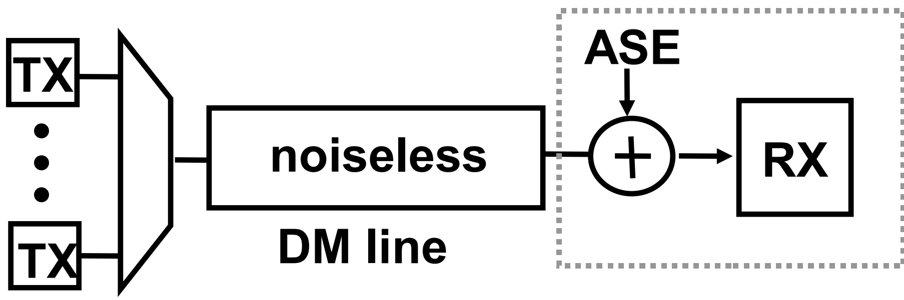
Methodology

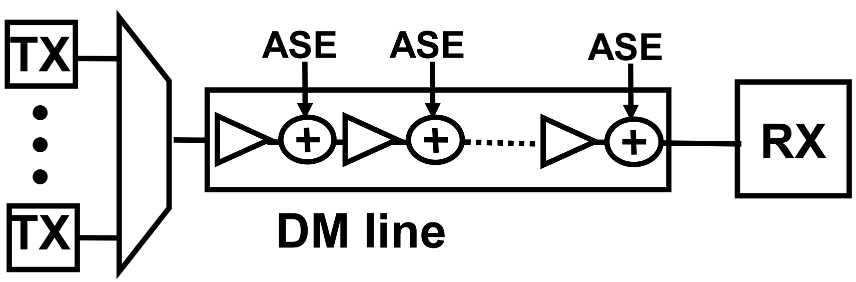
How to toggle ON/OFF signal-noise interactions

NSNI OFF:



noise loading

NSNI ON:



distributed noise

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Methodology

How to single-out NL effects

In single-polarization scalar propagation:

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
WDM	All (SPM,XPM,FWM) (includes also linear XTalk due to spectral overlap)	solve SSFM with WDM comb treated as a single channel.

Methodology

In Dual-polarization: vector Manakov propagation

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*]:

SPM XPM XPolM

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

σ_0 = 2x2 identity matrix

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

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

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Methodology

In Dual-polarization: vector Manakov propagation

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	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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- Motivation, objectives, methodology
- Some **models** of nonlinear effects:
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Models

Classification of **NSNI**

Single-channel
(intra-channel)
⇓
signal interaction with
in-band ASE
through PG

NLAN, NLPN

Multi-channel (WDM)
(inter-channel)
⇓
signal interaction with
ASE on neighboring channels
through X-NL

X-NLPN

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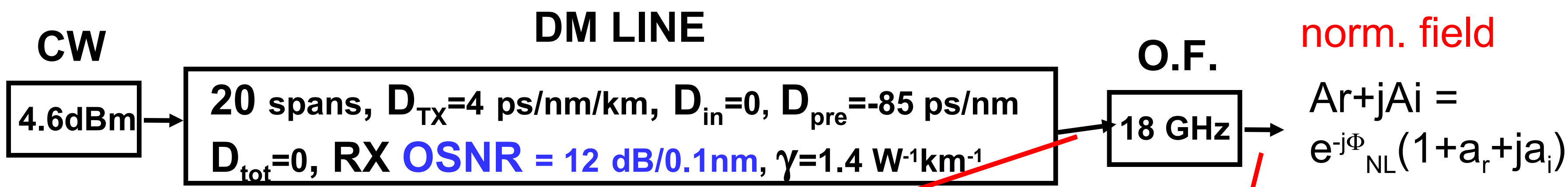
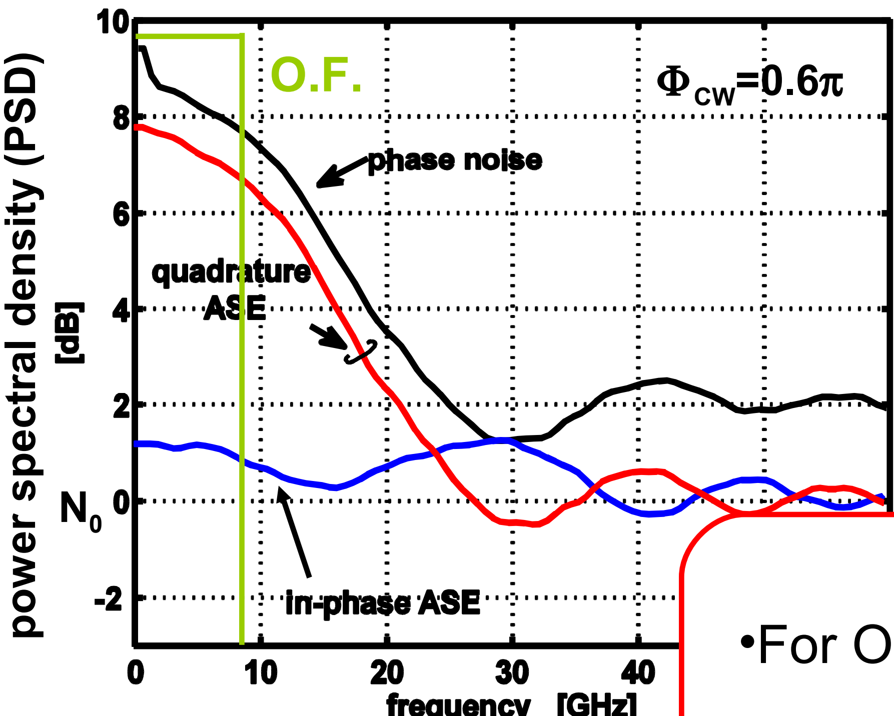
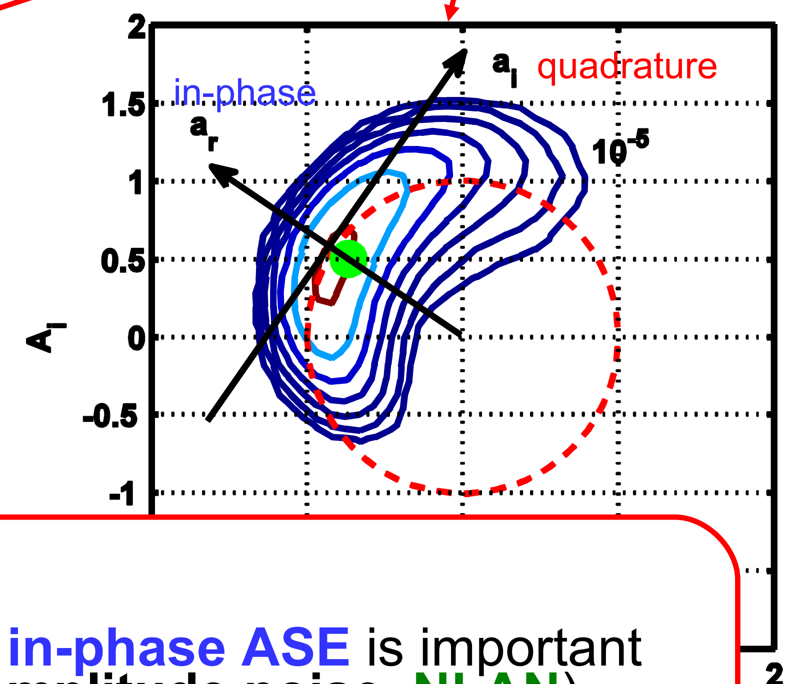
Model 1: NLAN, NLPN



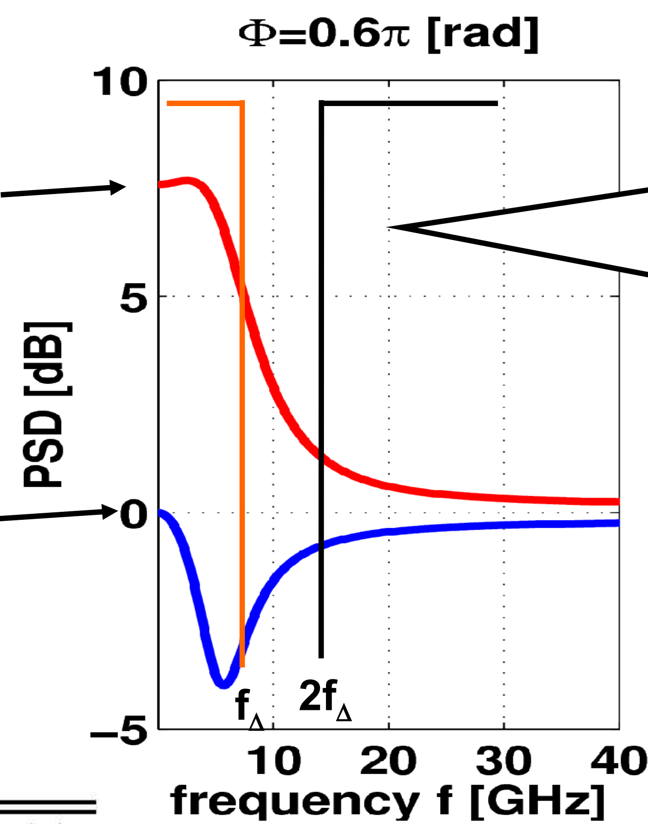


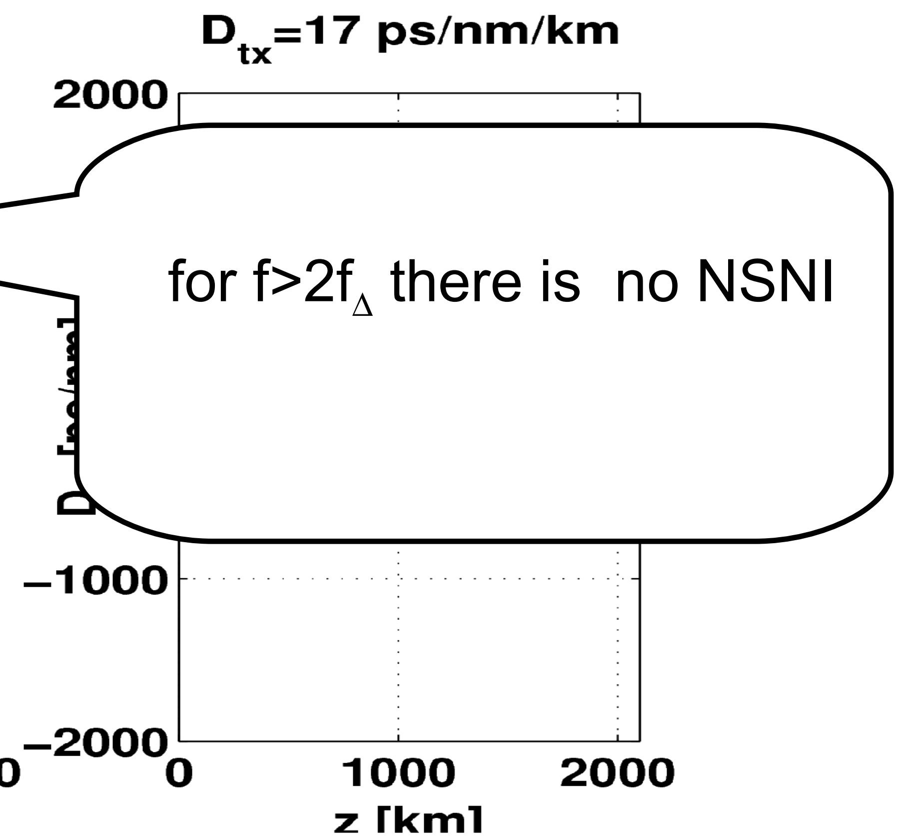


- For OOK, **in-phase ASE** is important (**amplitude noise, NLAN**)
- For PSK, **phase noise** is important (**NLPN**)

Model 1: NLAN, NLPN

DM links





For DM with small in-line:

$$f_\Delta \triangleq \frac{1}{2\pi\sqrt{|\beta_2|/\alpha}}$$

For SMF, **f_Δ=7GHz**

P. Serena et al., JOSA B, Apr. 2007.

Model 1: NLPN

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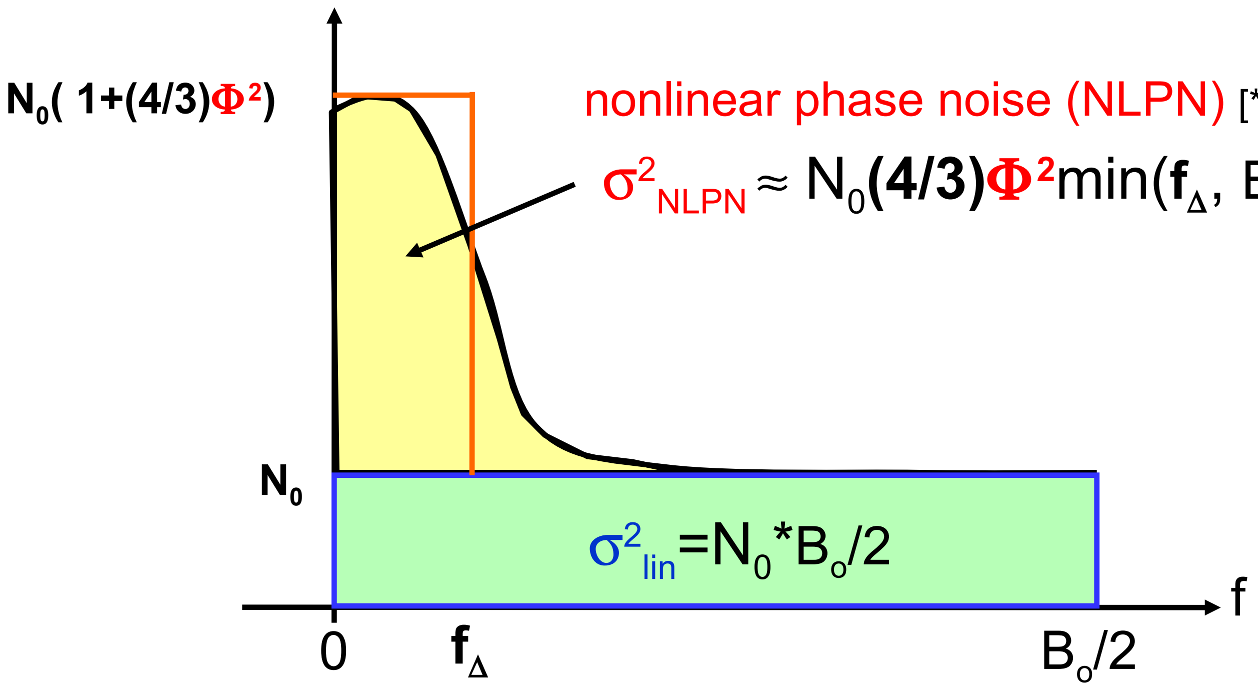
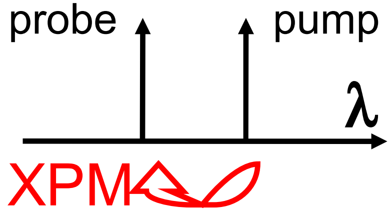
Interpreting quadrature ASE as phase noise, we understand that ....

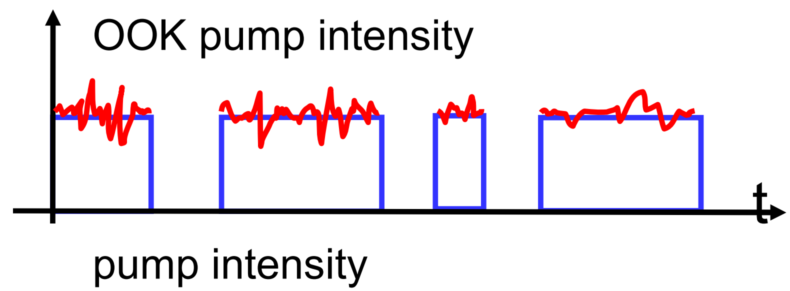


...for increasing symbol rate linear phase noise dominates over nonlinear phase noise

[*] J. Gordon *et al.*, *Opt. Lett.*, vol. 15, pp. 1351-1353, Dec. 1990.

Model 2: X-NLPN

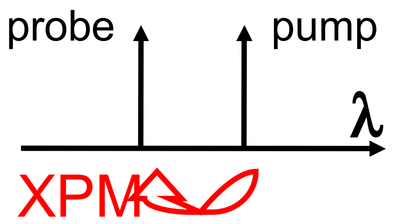


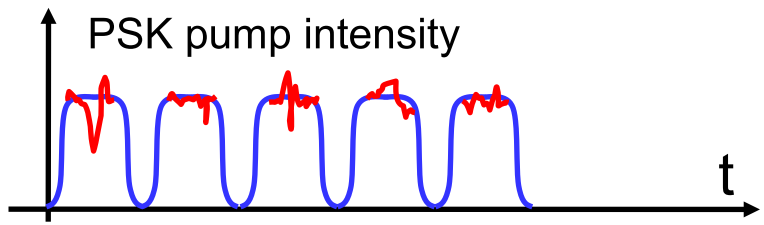


In OOK, XPM due to modulation-induced intensity variations.

ASE-induced intensity variations are a second-order effect

Model 2: X-NLPN





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

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

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

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

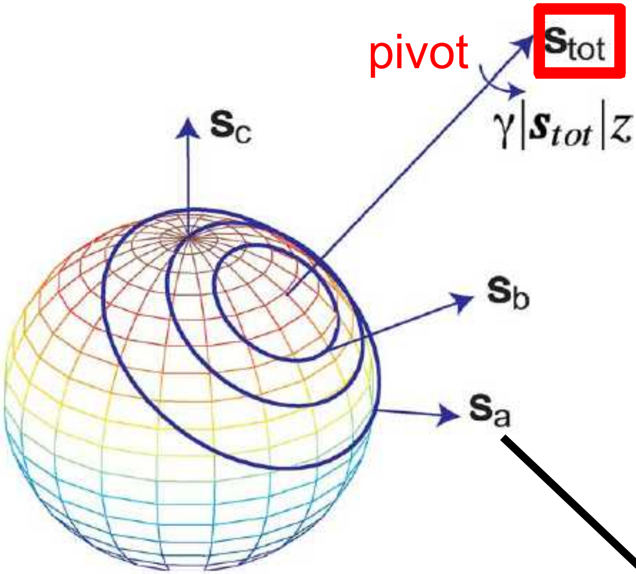
"differential" filtering

K=tap parameter

$\Rightarrow$ ASE-induced intensity variations become a first-order effect: X-NLPN

Model 3: XPolM "carousel"

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



Exact solution of nonlinear step of length z:
$$\vec{A}_n(z) = e^{\frac{-j\gamma z(||\vec{A}_n||^2 + 3\sum_{k\neq n}||\vec{A}_k||^2)}{2}} e^{\frac{-j\gamma z}{2}(\boldsymbol{s}_{tot}\cdot\boldsymbol{\sigma})} \vec{A}_n(0)$$

$$\boxed{\underset{\text{pivot}}{\boldsymbol{s}_{tot}} = \sum_{\substack{All\ channels \\ k}} \boldsymbol{s}_k(0)}$$

$$||\boldsymbol{s}_k||^2 = ||\vec{A}_k||^2$$ stokes length is intensity

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

Since pivot is set by modulation data, then ASE is second-order effect for SOP rotation

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In the next few slides I will provide the details of the simulations, and next I will show the NLT results

DM case study

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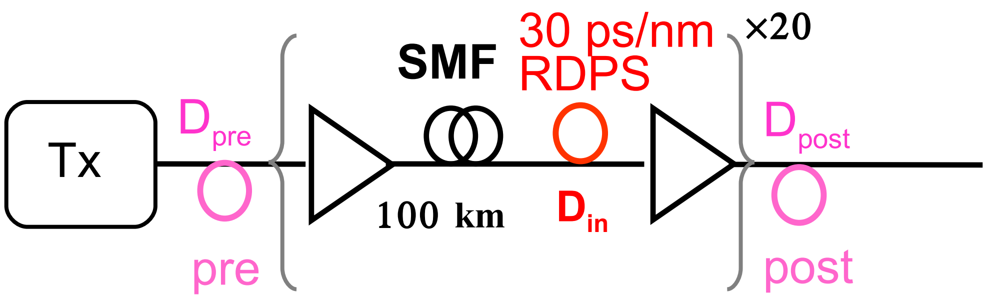
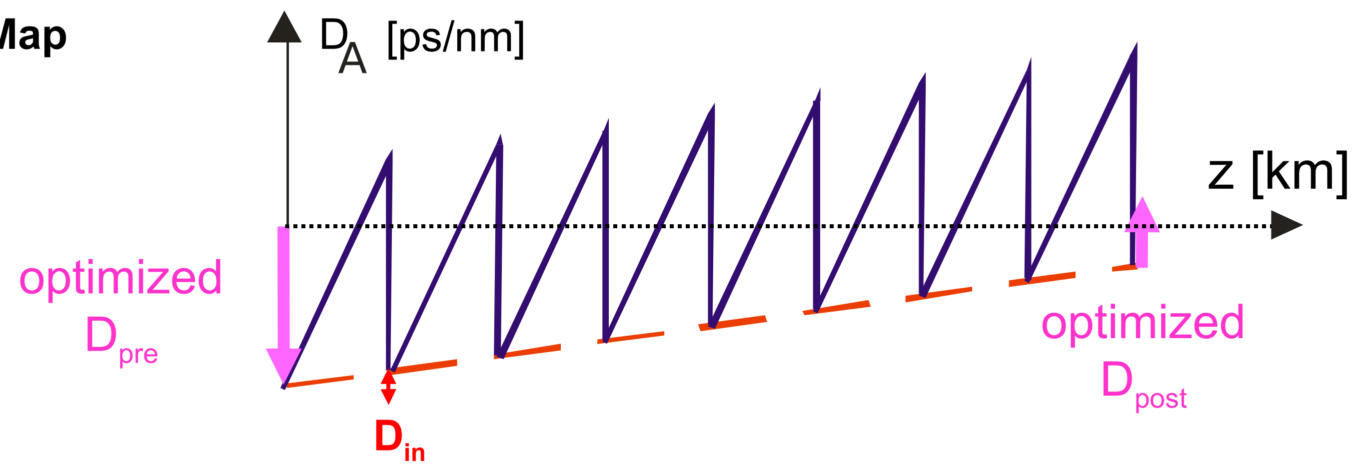


Neglect NL
inline DCFs

Dispersion Map



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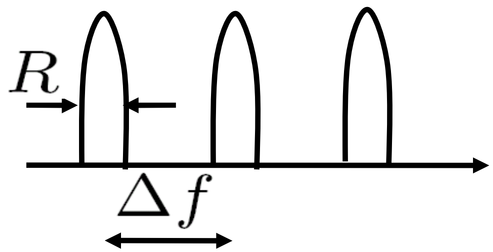
More Simulation Data

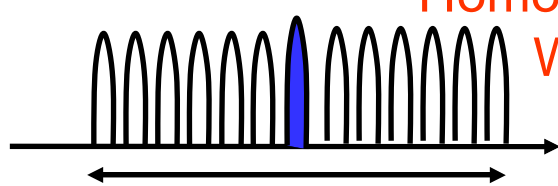
- Supporting pulse: NRZ
- $\eta \triangleq \dfrac{R}{\Delta f} = 0.4$



R=10 Gbaud⇒ Δf=25 GHz
R=20 Gbaud⇒ Δf=50 GHz
R=28 Gbaud⇒ Δf=70 GHz

- No filtering at TX ⇒ linear Xtalk

Homogeneous WDM



- Number of WDM channels [*] :

$$N_{ch} \simeq \left\lceil \frac{\eta}{S} \right\rceil$$

$$S = \frac{|\beta_2|}{\alpha} R^2$$

Map Strength

Eg: SM Fiber at
10 Gbaud ⇒ Nch=5+1+5

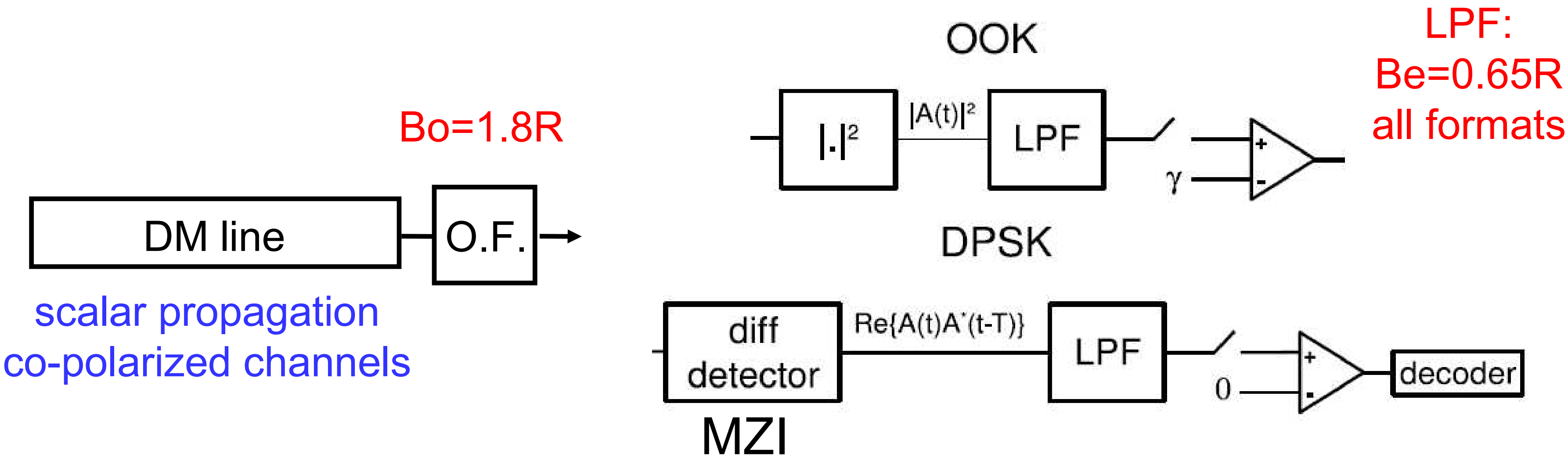
[*] P. Serena *et al.*, *ECOC ‘06*, paper We3.P.129.

Modulation formats

Will consider:

3. Direct-detection OOK
4. Direct-detection DPSK
5. Coherent single-polarization (SP) QPSK
6. Coherent PDM-QPSK

Receivers: OOK, DPSK



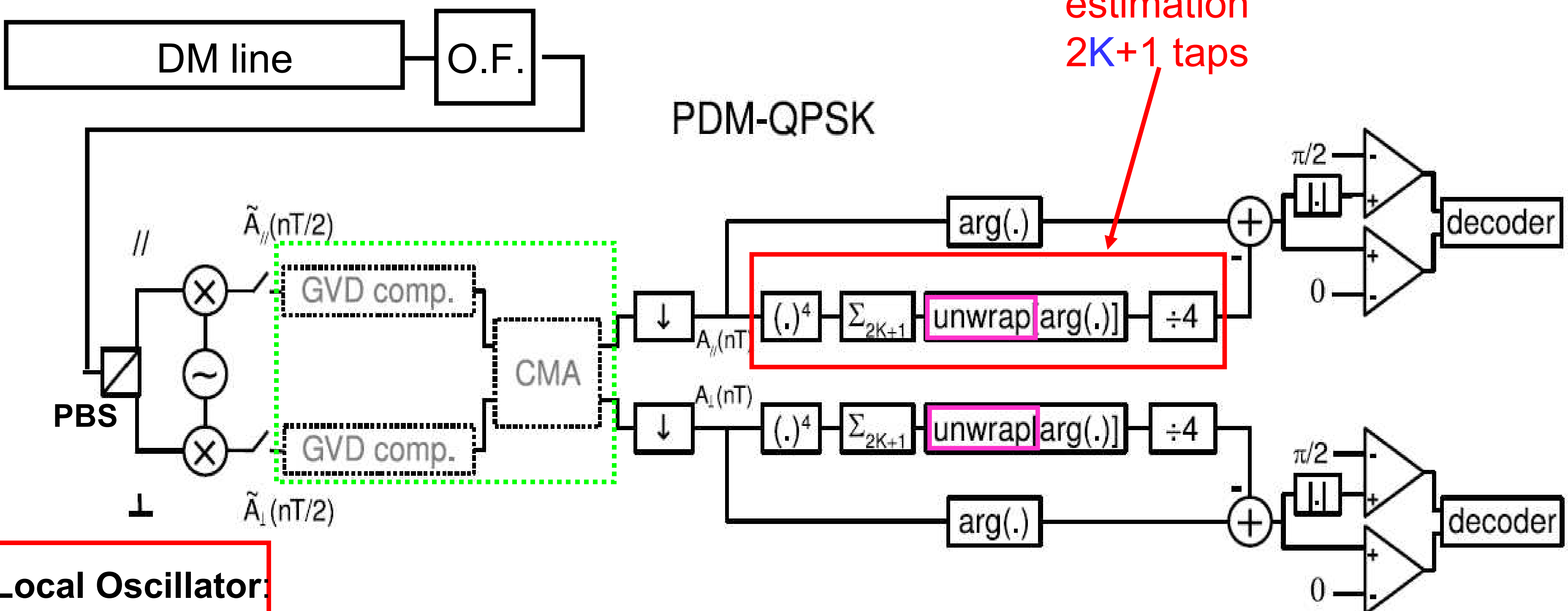
Receivers: PDM-QPSK

Vector propagation
Manakov equation
Random ISOPs
no PMD

Bo=1.8R

No nonlinear phase noise compensation

M-power phase estimation
2K+1 taps



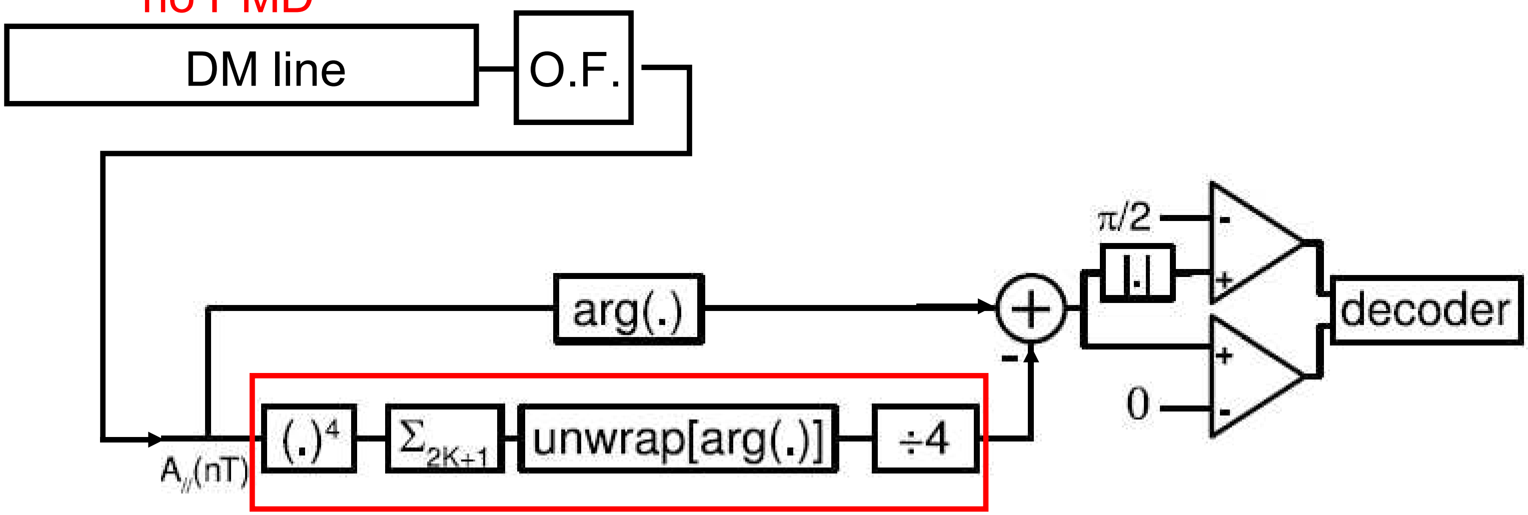
Local Oscillator:
zero freq. offset
no phase noise

Receivers: SP-QPSK

Single-polarization (SP) QPSK:

Vector propagation
Manakov equation
Random ISOPs
no PMD

Bo=1.8R



M-power phase
estimation
2K+1 taps

NLT vs. Symbol Rate

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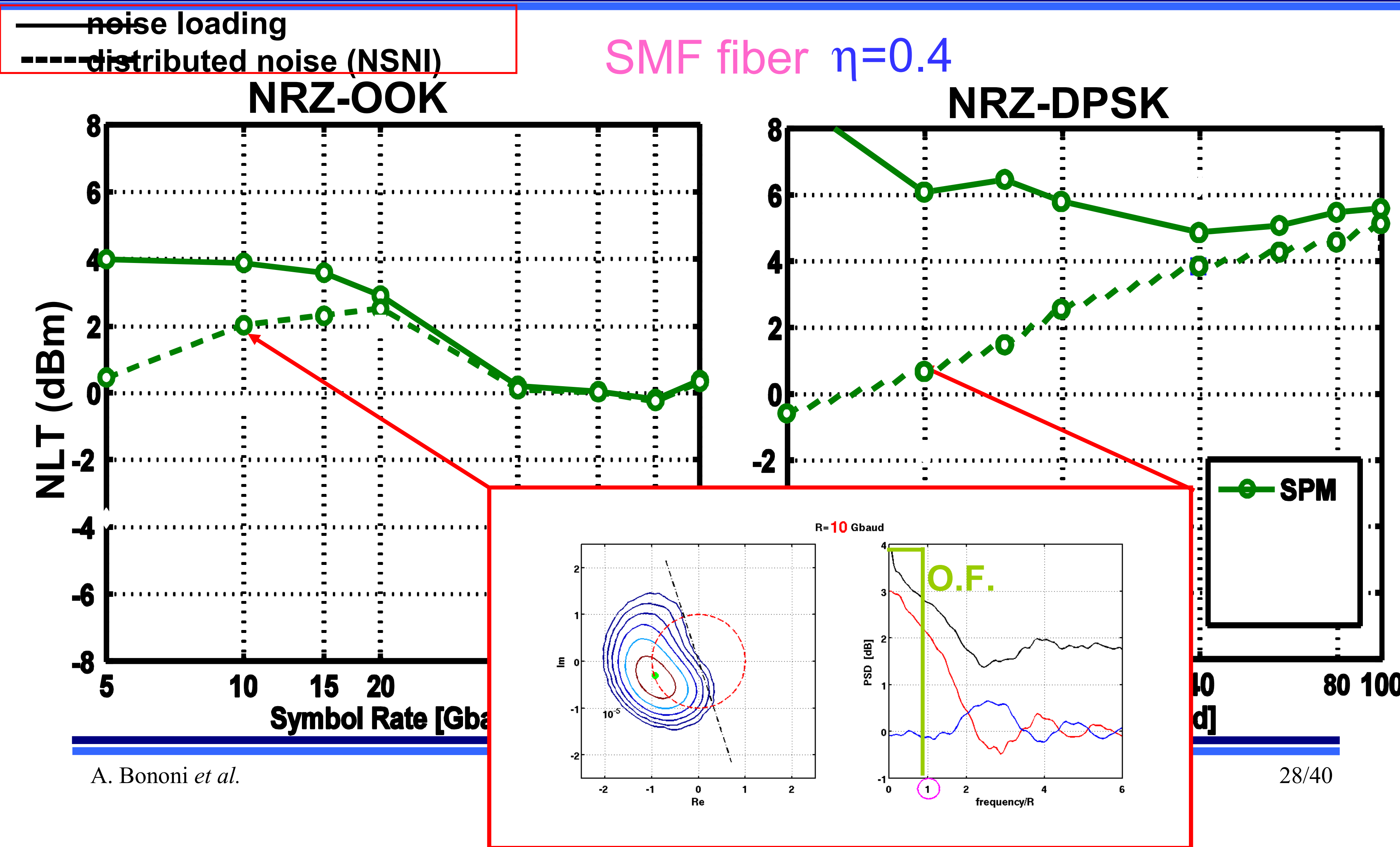

NLT vs. Symbol Rate

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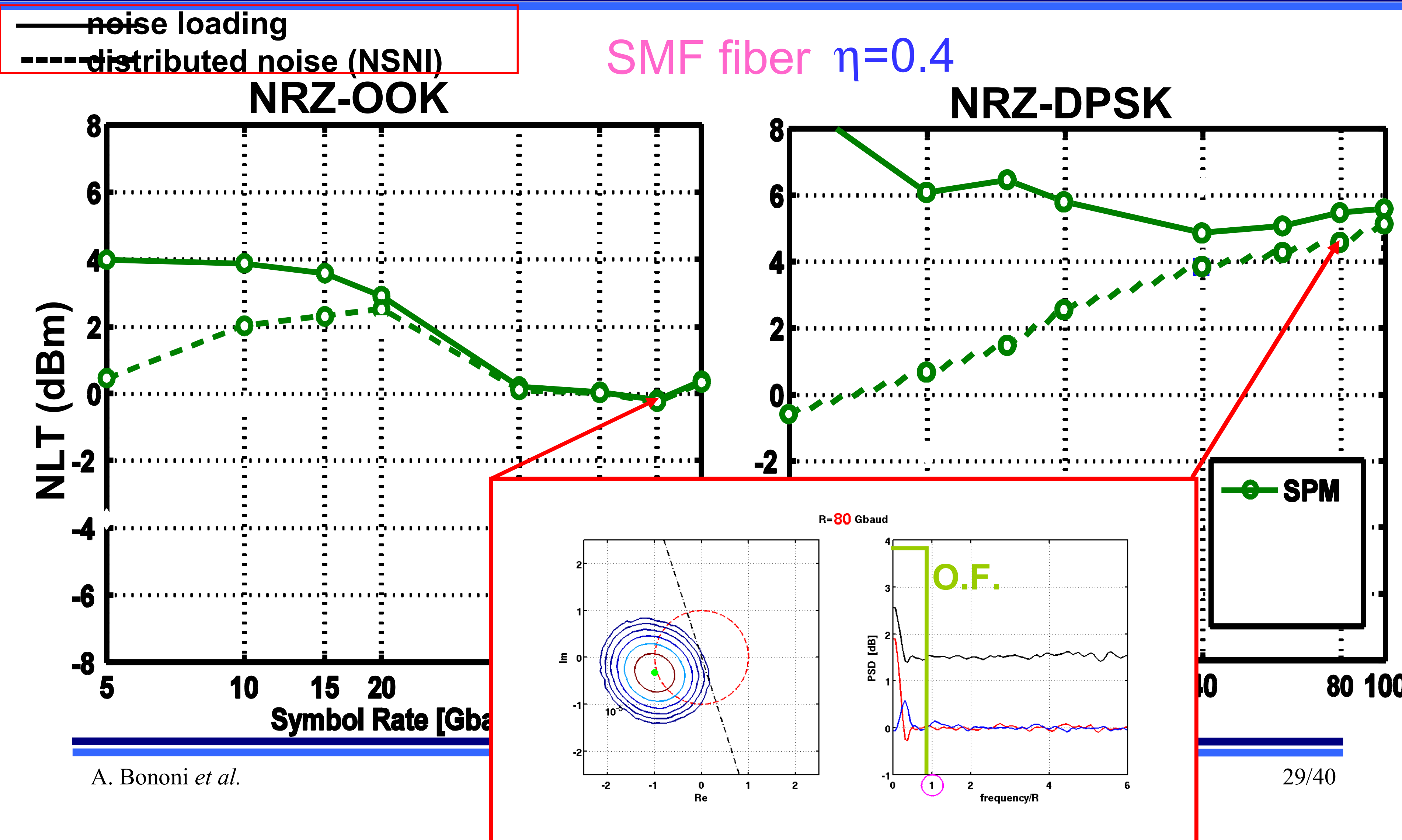
scalar propagation



NLT vs. Symbol Rate

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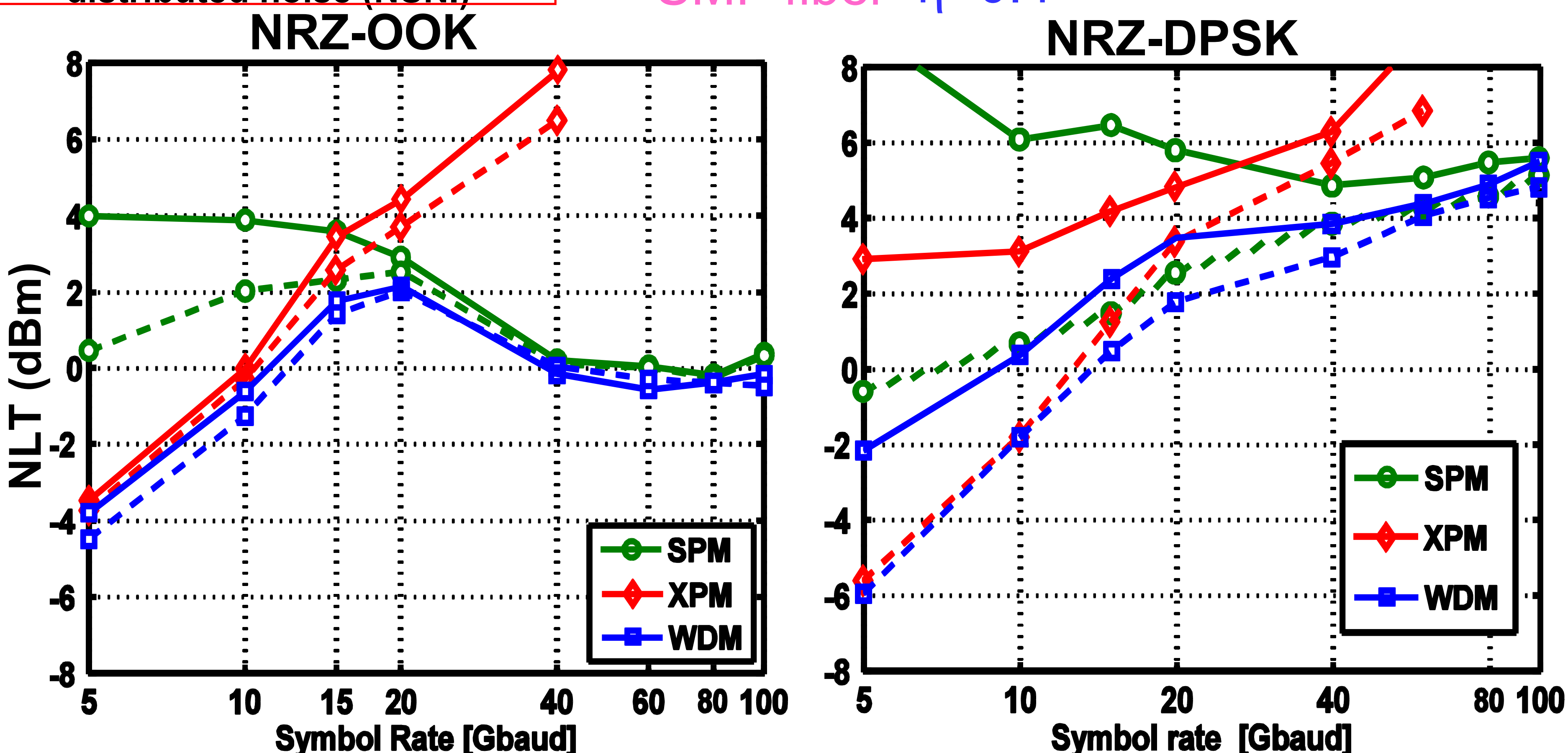
noise loading
distributed noise (NSNI)

SMF fiber η=0.4



NLT vs. Symbol Rate

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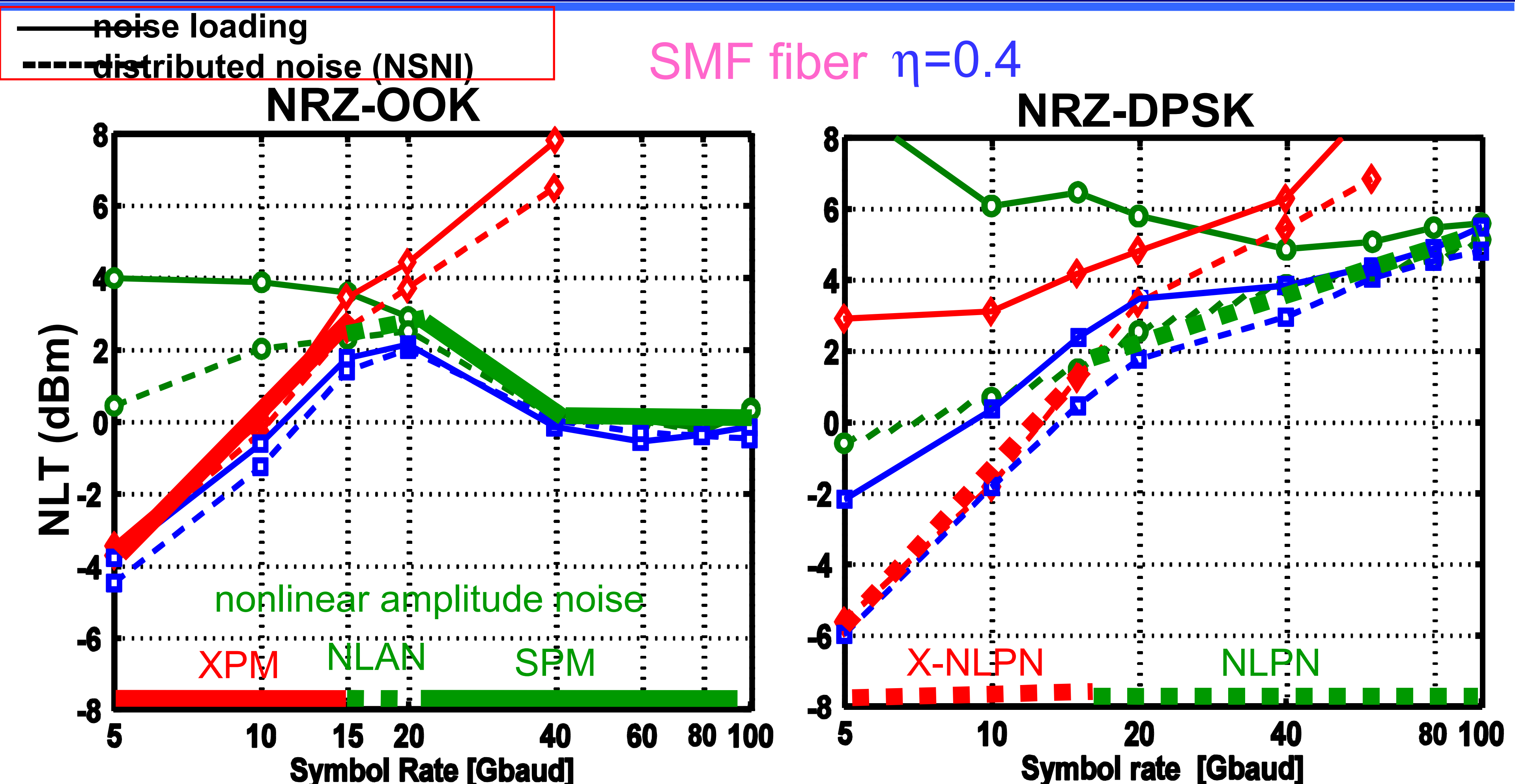

NLT vs. Symbol Rate

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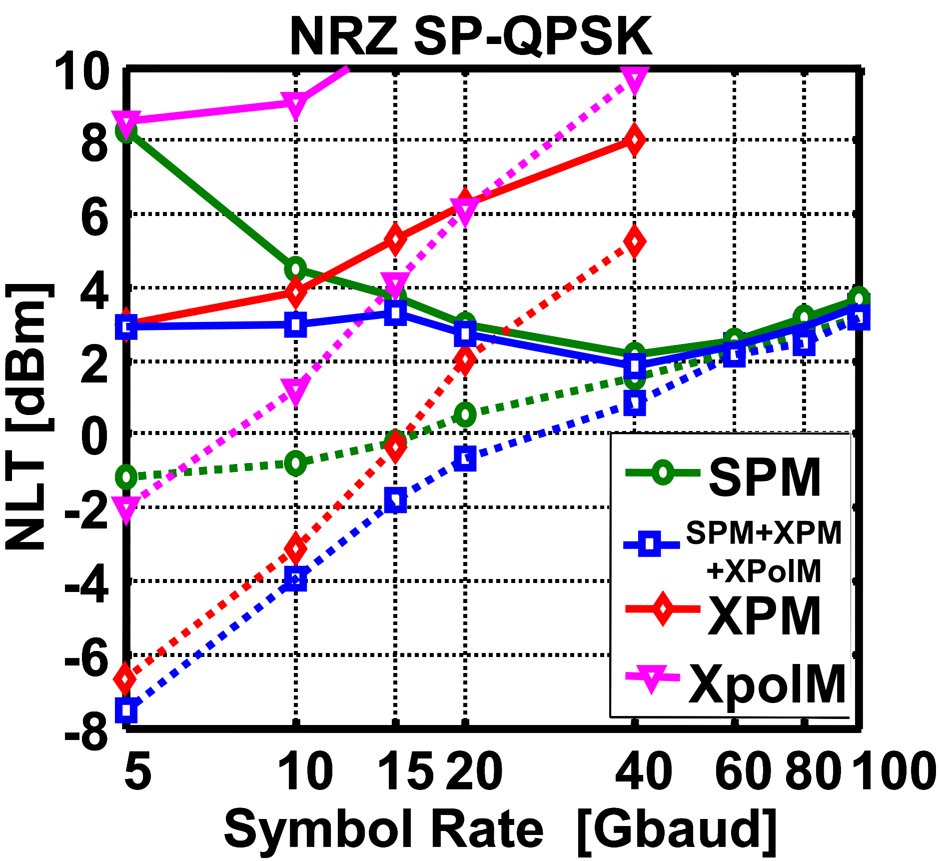
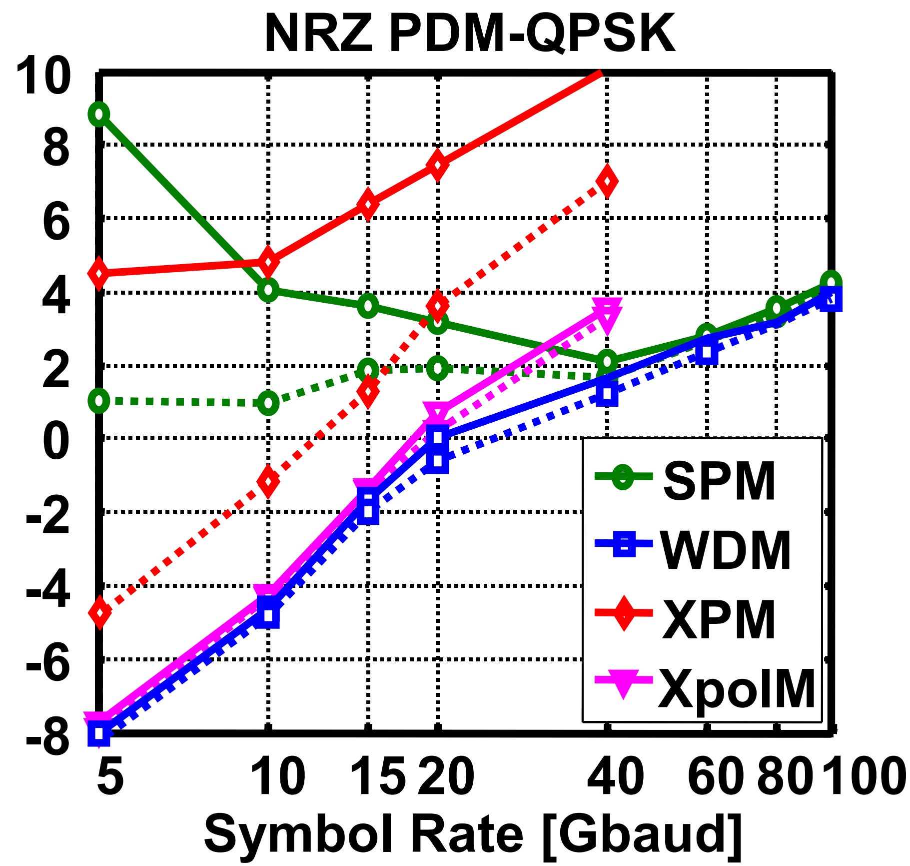
Manakov vector propagation, random WDM SOPs

—— noise loading
----- distributed noise (NSNI)

SMF fiber η=0.4 K=13





NLT vs. Symbol Rate

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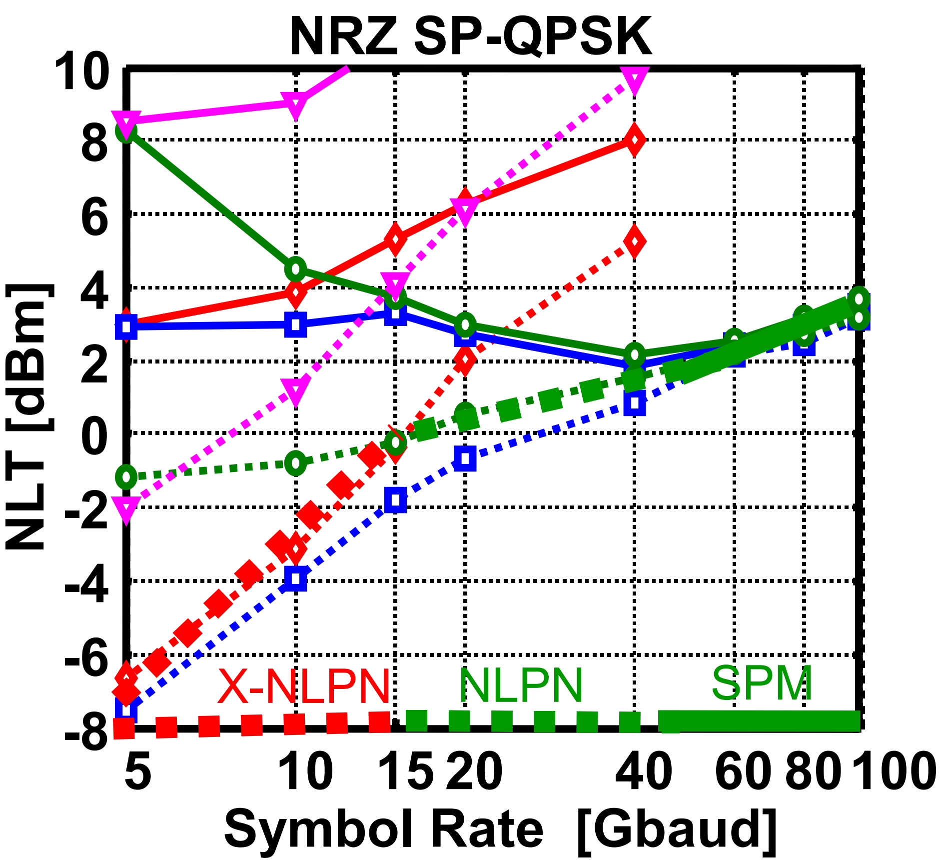
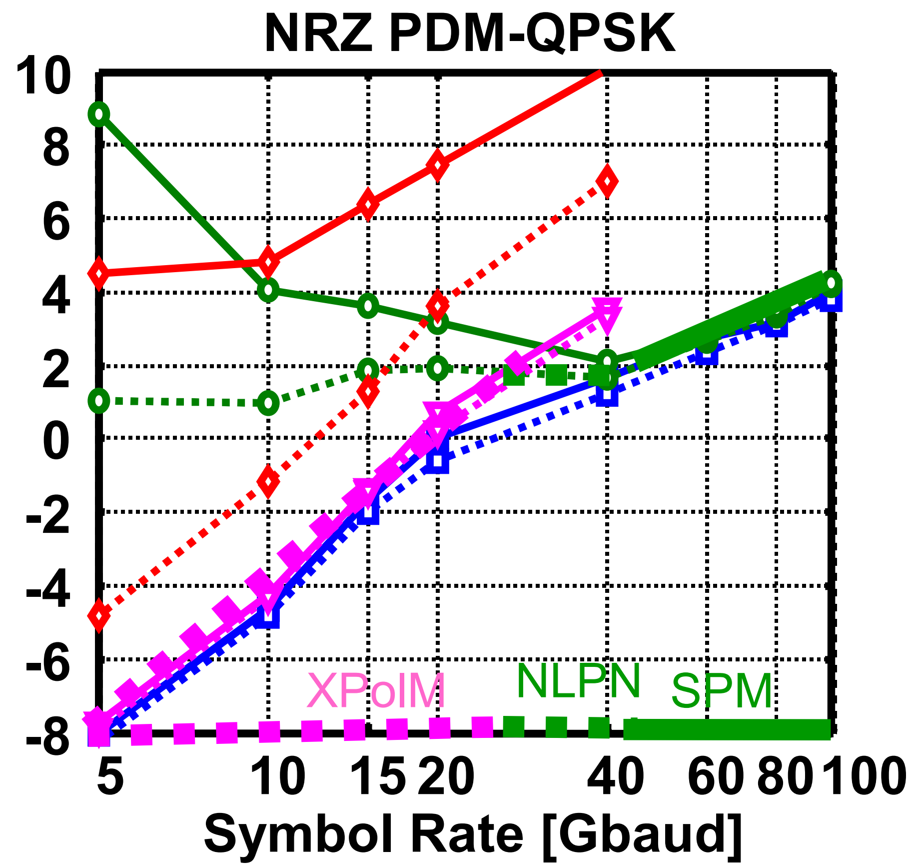
Manakov vector propagation, random WDM SOPs

——— noise loading
- - - - distributed noise (NSNI)

SMF fiber η=0.4 K=13





Hybrid PDM-QPSK / OOK

DM, 20x100km SMF

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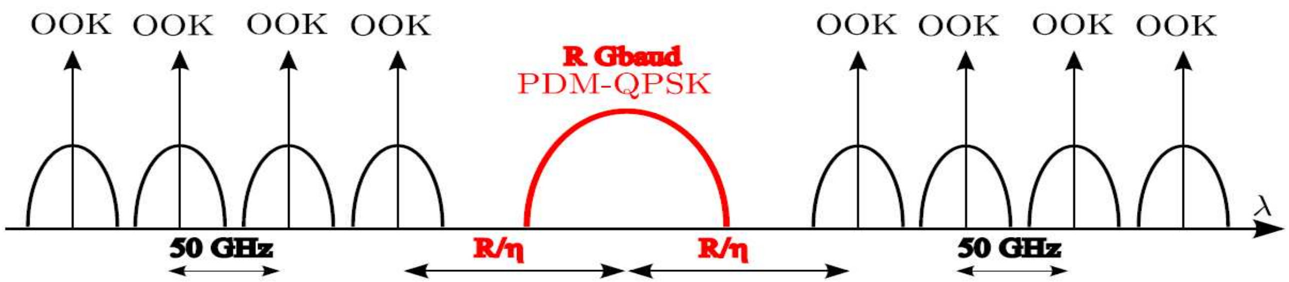
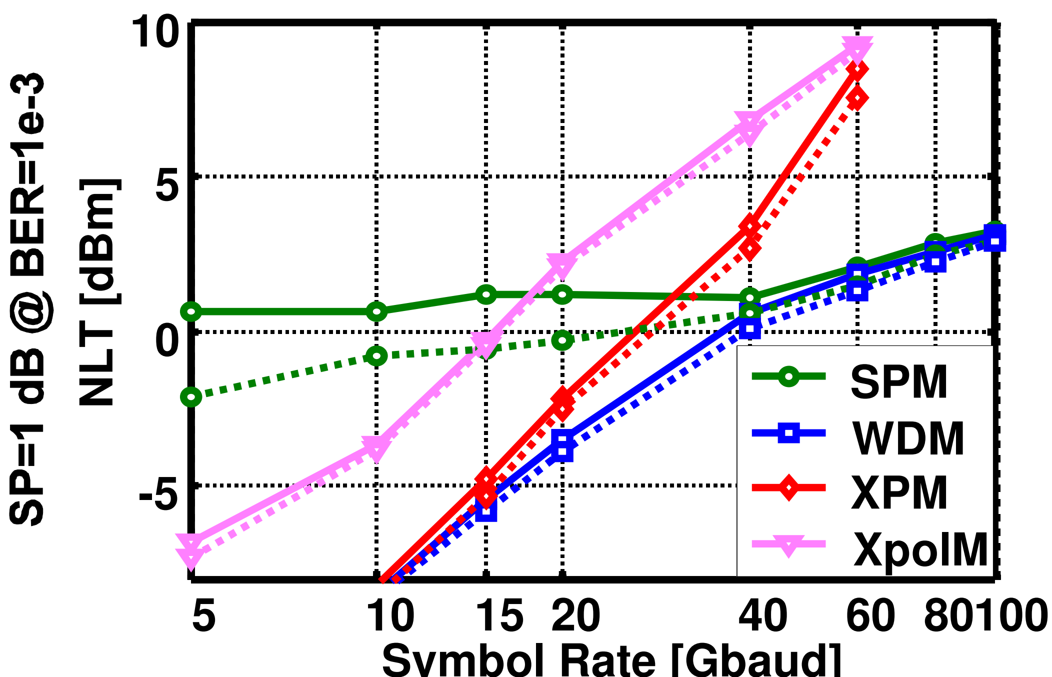


$$\eta \triangleq \frac{R}{\Delta f} = 0.4$$

K=13 in V&V

TX Gauss(4) filter B=0.9R



OOK channels power s.t. in B2B BER=10^-3 and SP<1dB

- XPM dominates XPolM
- steeper slopes of X-NL w.r.t homogeneous case
- NSNI negligible

NDM Homog PDM-QPSK

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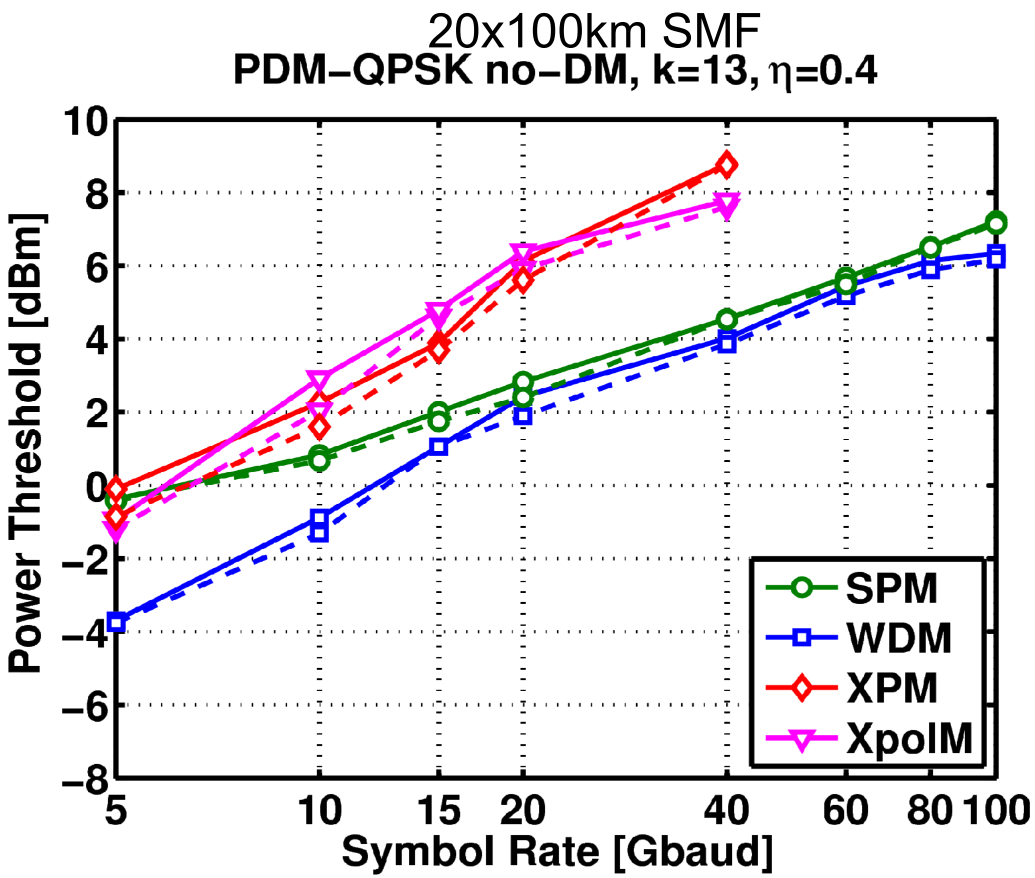
noise loading

distributed noise (NSNI)



- NSNI disappeared: why?

Model 1: NLAN, NLPN

NDM links

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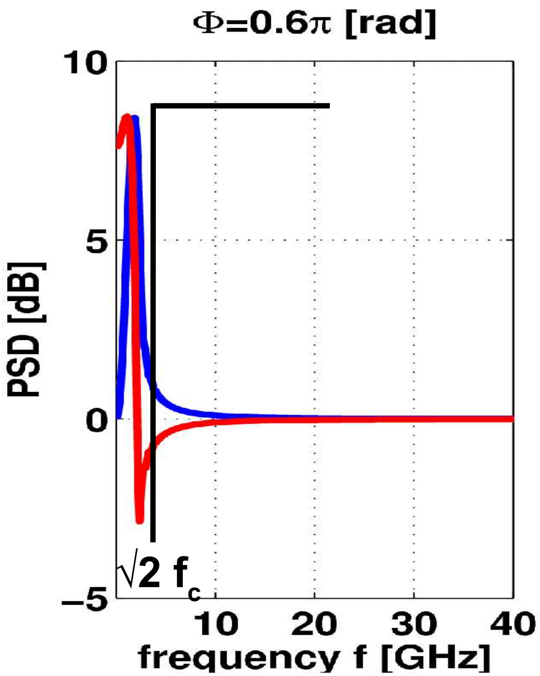
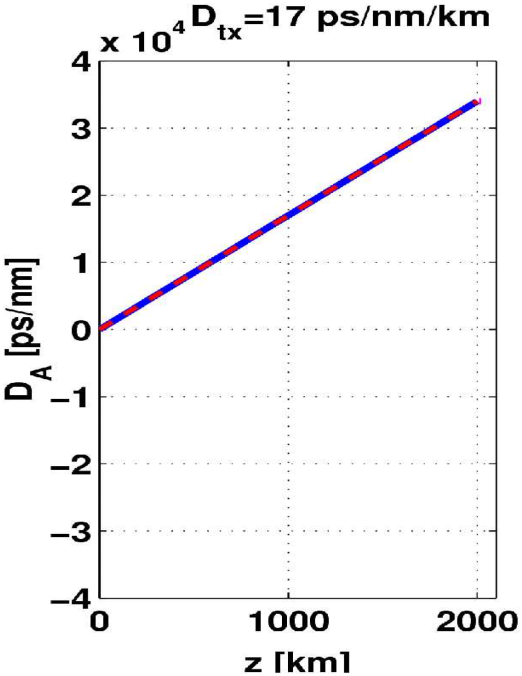
For NDM, NSNI cutoff at

$$\sqrt{2}f_c = \frac{1}{\pi}\sqrt{\frac{1}{|\beta_2|L_{NL}}}$$





$$\frac{f_{NDM}}{f_{DM}} = \sqrt{\frac{1/\alpha}{L_{NL}}} = \sqrt{\frac{\Phi_{NL}}{N}}$$

Ratio of cutoffs depends on nonlinear phase per span

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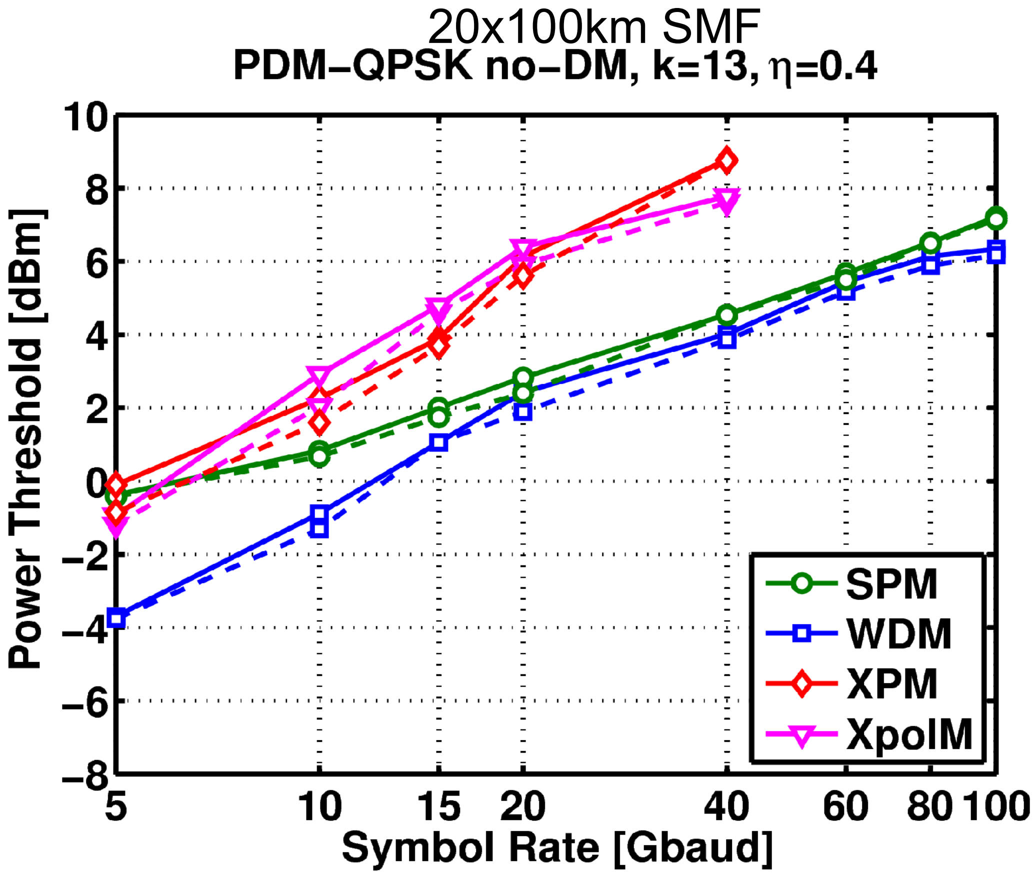
NDM Homog PDM-QPSK



- NSNI disappeared
- XPolM ~ XPM

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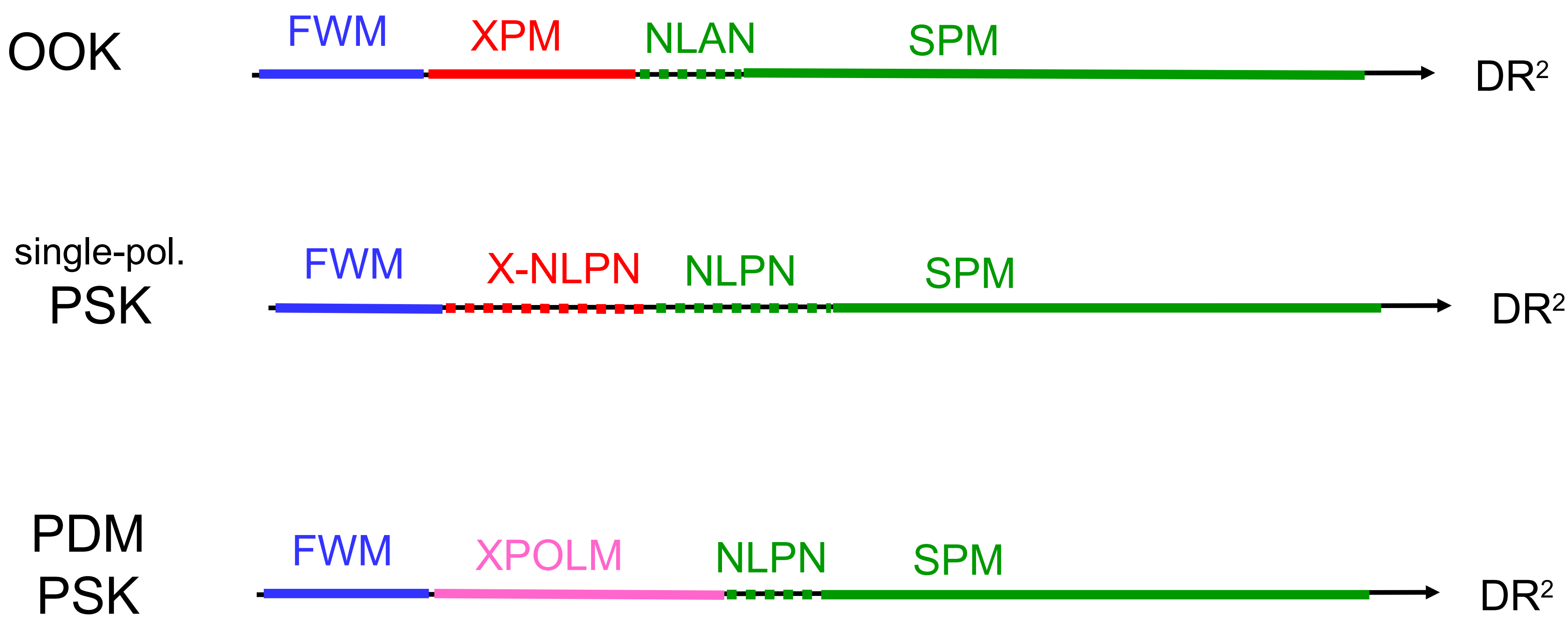
Conclusions 1

Dominant nonlinearity in homogeneous DM WDM systems



Conclusions 2

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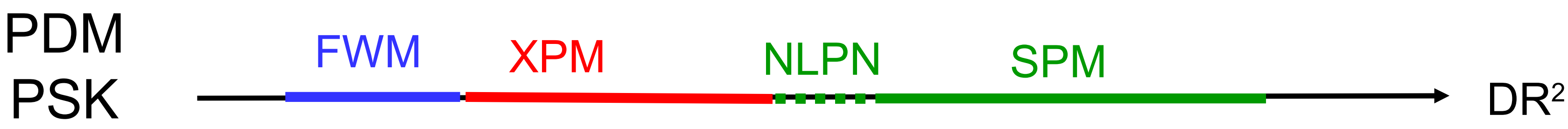
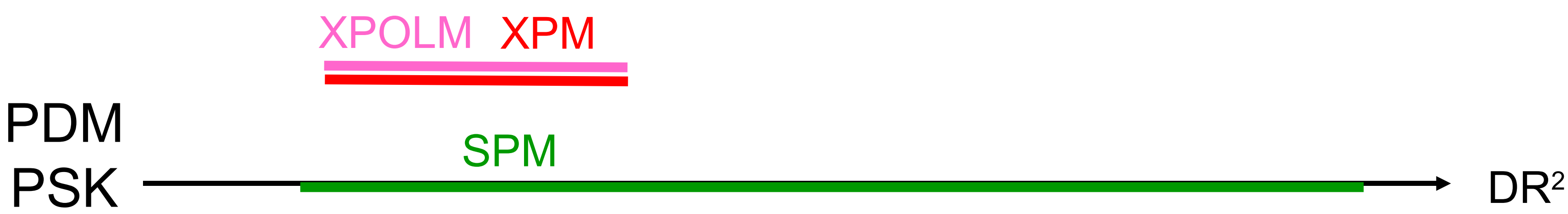
Dominant nonlinearity in OOK-hybrid WDM DM systems



Dominant nonlinearity in homogeneous WDM Non-DM systems



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Thank you.
Questions?

NLT vs. Symbol Rate

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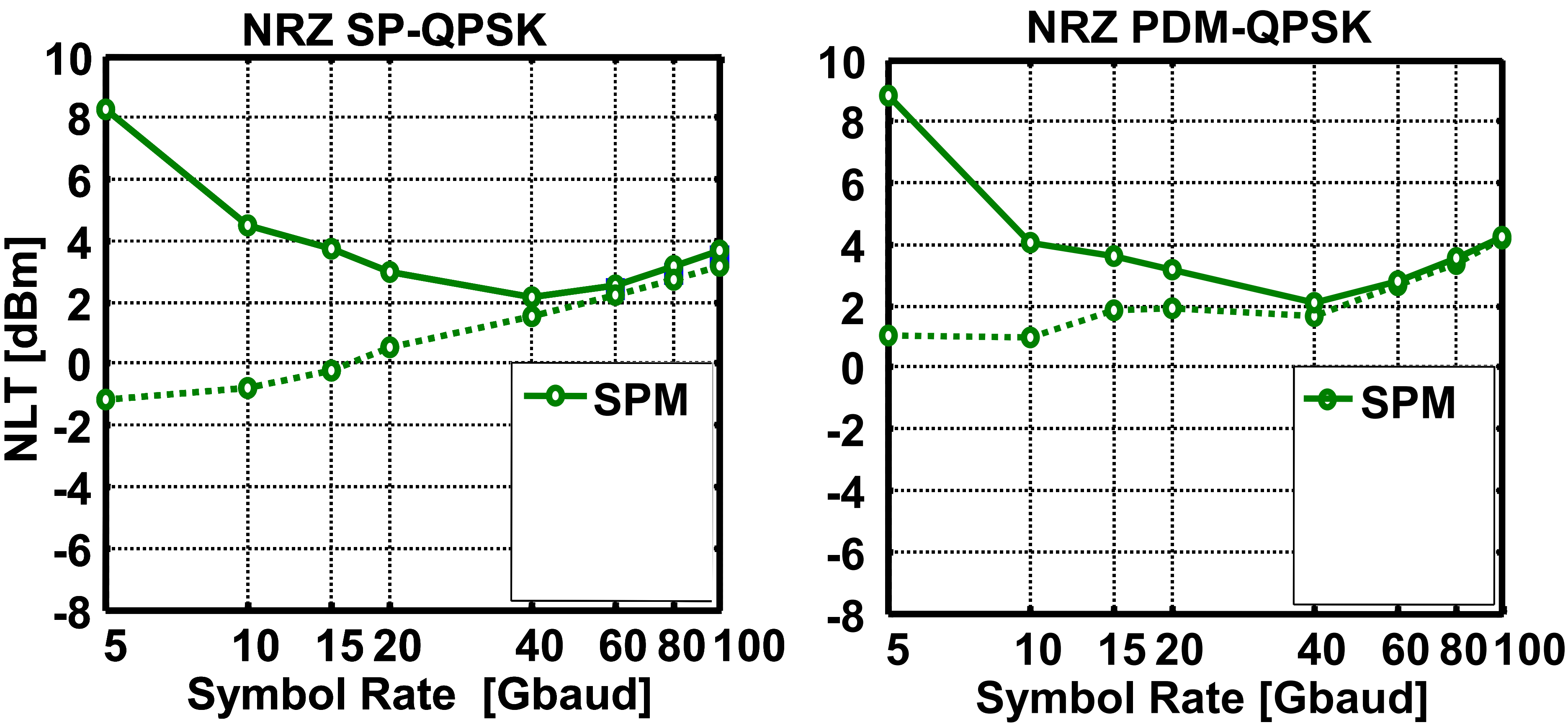
Manakov vector propagation, random WDM SOPs

—— noise loading
---- distributed noise (NSNI)

SMF fiber η=0.4 K=13



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SP vs PDM NLT

1) Dominant noiseless SPM

$$SP_{SP} = 10\log_{10}(1 + c \cdot SNR_{bb}\Phi_{SP}^2)$$

$$\Phi_{SP} = \gamma N_{span} L_{eff} (|A|^2)$$

$$\Phi_{PDM} = \phi_x = \phi_y = \gamma N_{span} L_{eff} (|A_x|^2 + |A_y|^2)$$

$$SP_{PDM} = 10\log_{10}(1 + c \cdot SNR_{bb}\Phi_{PDM}^2)$$

Hence at equal SP need:

$$\Phi_{SP} = \Phi_{PDM}$$

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SP vs PDM NLT

2) Dominant NLPN

$$SP_{SP} = 10\mathrm{Log}_{10}(1 + \boxed{\frac{2}{3}C_{vv}\Phi^2_{SP})}$$
$$\Phi_{SP} = \gamma N_{span}L_{eff}(|A|^2)$$

Prop to NLPN variance

A. Bononi et al., JLT sept 09

$$\Phi_{PDM} = \phi_x = \phi_y = \gamma N_{span}L_{eff}(|A_x|^2 + |A_y|^2)$$
$$SP_{PDM} = 10\mathrm{Log}_{10}(1 + 2 \cdot \frac{2}{3}C_{vv}\Phi^2_x)$$
$$= 10\mathrm{Log}_{10}(1 + 2 \cdot \frac{2}{3}C_{vv}(\frac{\Phi_{PDM}}{2})^2)$$

Doubled NLPN variance

Hence at equal SP need: $\Phi^2_{SP} = 2(\frac{\Phi_{PDM}}{2})^2$

$$\sqrt{2}\Phi_{SP} = \Phi_{PDM}$$