OPTICAL FIBER COMMUNICATION CONFERENCE 2018

PAPER #W1G.4

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OBSERVING THE INTERACTION OF PMD WITH GENERATION OF NLI IN UNCOMPENSATED AMPLIFIED OPTICAL LINKS

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OPTCOM

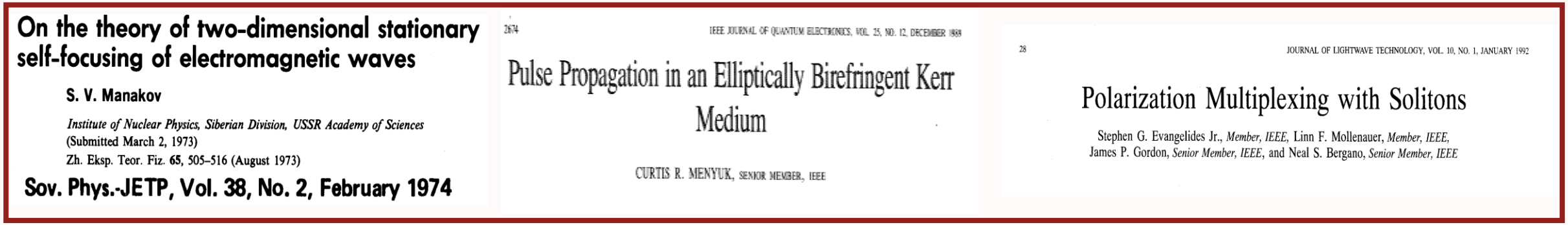
MOTIVATIONS

- Is **NLI generation** the fiber propagation limiting impairment also for **very-large band transmission beyond the C-band?**

- What is the **proper wave equation** to be considered as governing propagation of dual-polarization carrier-less modulation formats relying on coherent&equalized receivers?

THE MANAKOV EQUATION

- Propagation of PM-xQAM in the fiber is typically analyzed solving the **Manakov Equation (ME)**
- **ME** is the **polarization-averaged** fiber wave equation
- The ME was originally **developed to study solitons**



On the theory of two-dimensional stationary self-focusing of electromagnetic waves

S. V. Manakov

Institute of Nuclear Physics, Siberian Division, USSR Academy of Sciences
(Submitted March 2, 1973)
Zh. Eksp. Teor. Fiz. **65**, 505–516 (August 1973)

Sov. Phys.-JETP, Vol. 38, No. 2, February 1974

2074 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 25, NO. 12, DECEMBER 1989

Pulse Propagation in an Elliptically Birefringent Kerr Medium

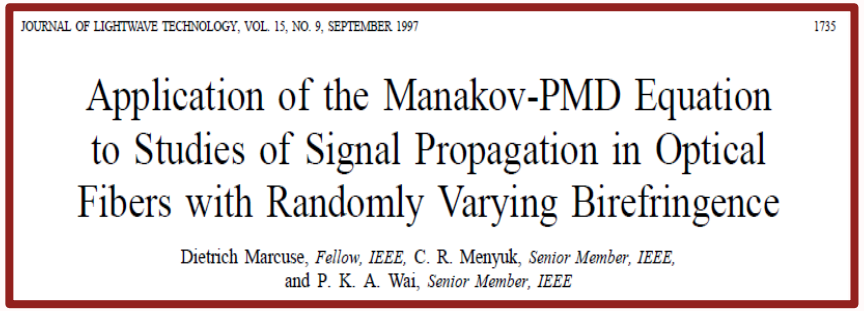
CURTIS R. MENYUK, SENIOR MEMBER, IEEE

28 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 10, NO. 1, JANUARY 1992

Polarization Multiplexing with Solitons

Stephen G. Evangelides Jr., *Member, IEEE*, Linn F. Mollenauer, *Member, IEEE*, James P. Gordon, *Senior Member, IEEE*, and Neal S. Bergano, *Senior Member, IEEE*

- **ME+PMD** : the Manakov-PMD equation (MPE)
- **ME and MPE hold only over narrow bandwidths**



JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 15, NO. 9, SEPTEMBER 1997 1735

Application of the Manakov-PMD Equation to Studies of Signal Propagation in Optical Fibers with Randomly Varying Birefringence

Dietrich Marcuse, *Fellow, IEEE*, C. R. Menyuk, *Senior Member, IEEE*, and P. K. A. Wai, *Senior Member, IEEE*

ME AND MPE: BANDWIDTH ISSUES

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- The fiber is affected by **random birefringence inducing PMD**
- ME and MPE are limited by the **fiber coherence bandwidth:**

$$B_c \cong \sqrt{3/(4\pi^2 \cdot PMD^2 \cdot L_{eff})}\ ^*$$

- $B_c \cong$ **500** GHz in modern fibers
- If the exploited B exceeds B_C
  - **Coupled NLSE** including **random birefringece** as fiber wave equation
  - **Monte Carlo** analyses to verify the **PMD effect**

*G. P. Agrawal, ***Polarization Mode Dispersion***, Elsevier, 2013

NONLINEAR INTERFERENCE (NLI)

- **State-of-the art** is polarization-division-multiplexed multilevel modulation formats with **DSP coherent receivers** propagating on **uncompensated links**
- Propagation **impairments** are dominated by the **NLI accumulation**
- After the Rx equalizer and CPE, **NLI is well approximated by four uncorrelated Gaussian random processes**: in-phase and quadrature on two orthogonal polarization states
- **Several models for the NLI** estimation have been developed starting from the ME, so **they in principle hold only over B_C**

OBSERVED WIDEBAND NLI GENERATION

- **NLI** generation has been **observed*** **up to 7 THz** of bandwidth occupation for **ASE noise channels**
  - **Good agreement with models** predicting **log-scaling** of NLI **with** the transmission **bandwidth**
  - Indeed, it was predictable, since **ME holds for** any bandwidth in case of propagation of **depolarized Gaussian noise**
- What happens to **NLI when loading spectrum with modulated channels**?
- So, on **which wave equation** we have to rely on?

* G. Saavedra *et al.*, "**Experimental Investigation of...**", OFC 2017, paper W1G.1
* G. Saavedra *et al.*, "**Experimental Analysis of Nonlinear Impairments**...," JLT, Oct. 2017

WHAT HAPPENS AT LARGE BANDWIDTHS?

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- **Required investigations**
  - **Modulated channels**
  - **Monte Carlo** analyses varying **PMD** realizations
  - **No recirculating loop**
- Experiments are really **challenging**
- **Split-step simulations** can be feasible **using parallel computing on multicore CPUs and exploiting GPUs**

FF.SS.: FAST FIBER SIMULATION SOFTWARE*

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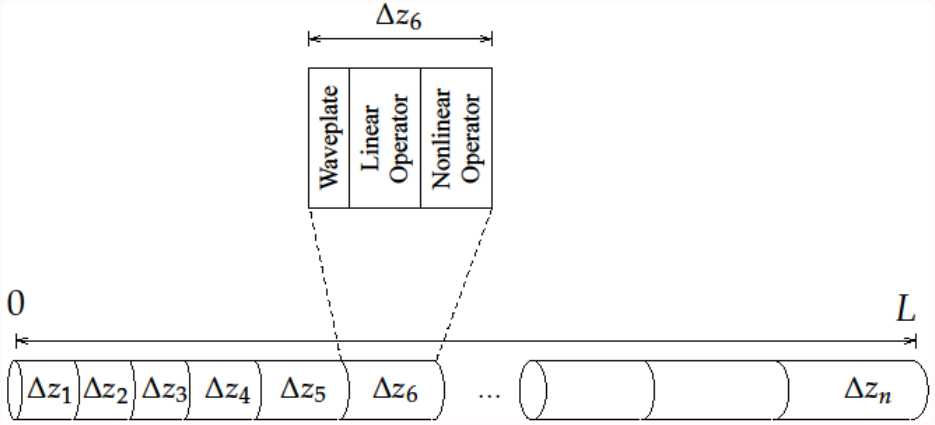
- **Split-step Fourier method** for
  - **Coupled nonlinear Shroedinger** equation jointly solved with
  - **Waveplate** model to emulating random birefringence and induced PMD
  - Machine-tailored Matlab implementation

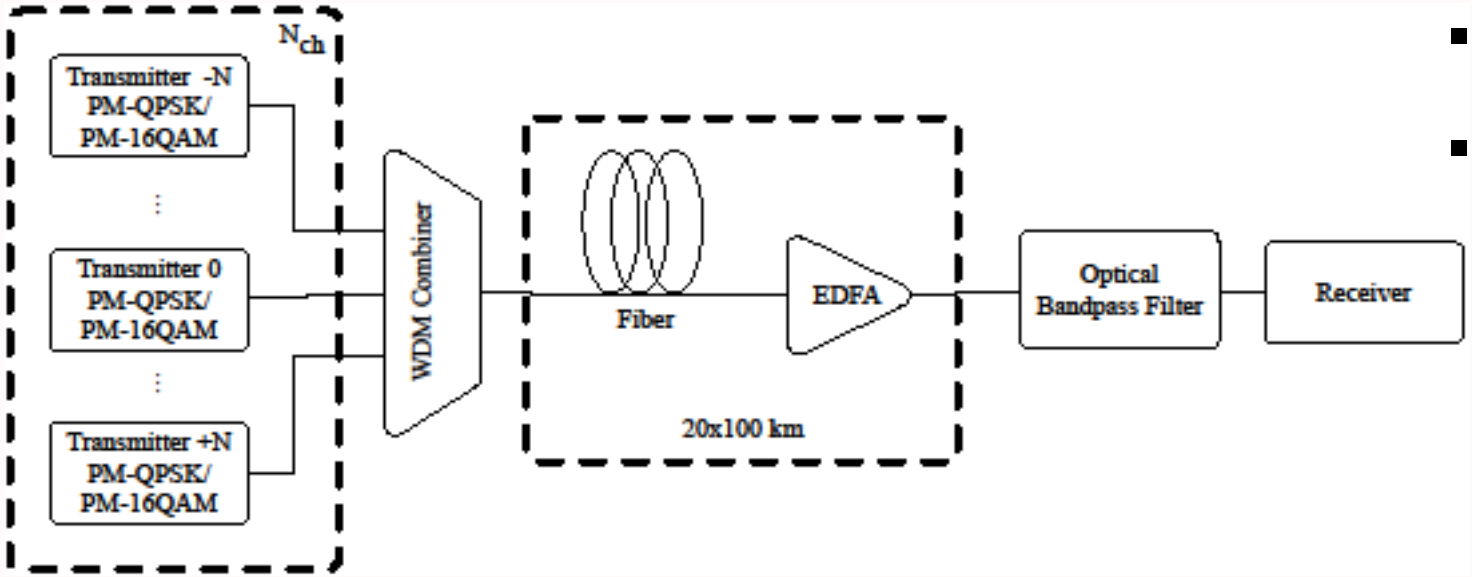
- **Step size** is the **shortest** between **max NL phase-shift and waveplate step**
- Parallel computing and GPU



* D. Pilori *et al.*, "***FFSS*: The Fast Fiber Simulator Software**", ICTON 2017

THE SIMULATIVE ANALYSIS

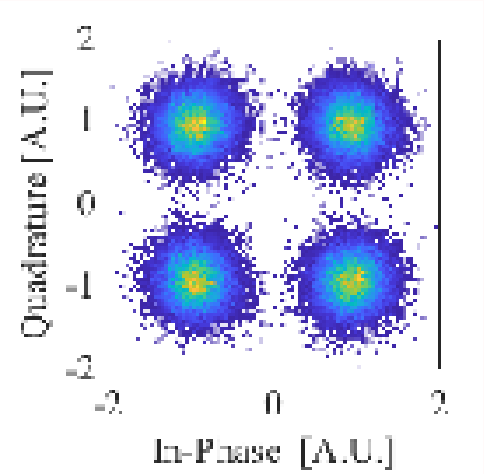
- PM-QPSK or PM-16QAM channels at **32 Gbaud**
- Δf = **50 GHz** and N_{ch} **up to 41 ch**
- **Link**: 20x100 km of SSMF with EDFA

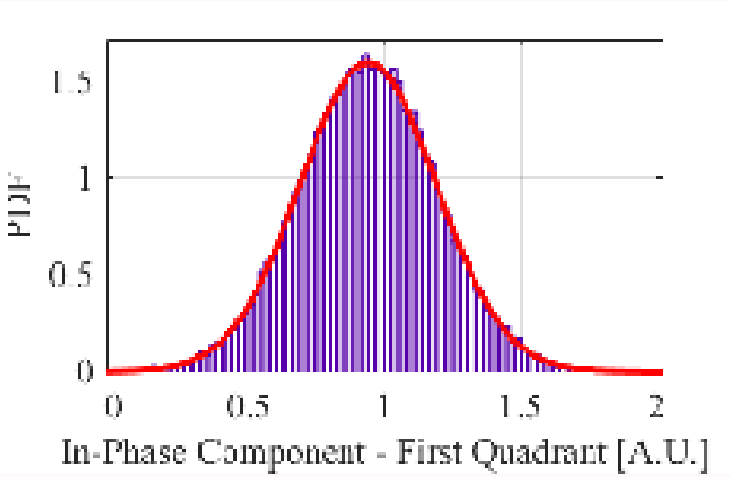


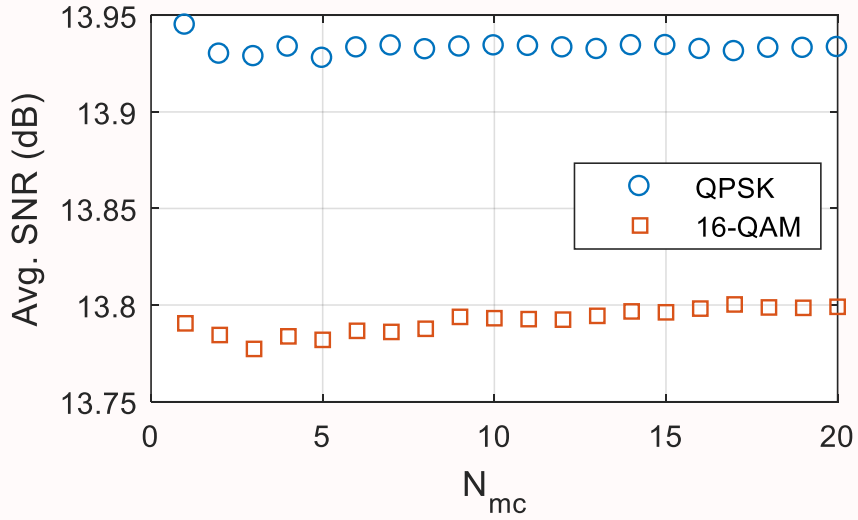
- **Simulations**
  - FF.SS. solving the **ME**
  - FF.SS. solving the **CNLSE** with random birefringence
    - **PMD = 0.05 ps/$\sqrt{km}$ and 1 ps/$\sqrt{km}$**
    - Monte Carlo analyses on **20 different realizations**

THE OBSERVED INTERFERENCE

- **No** relevant **phase noise**
- **Gaussian**-distributed disturbance
- **20** Monte Carlo **runs** on PMD are sufficient to obtain a **good estimation**

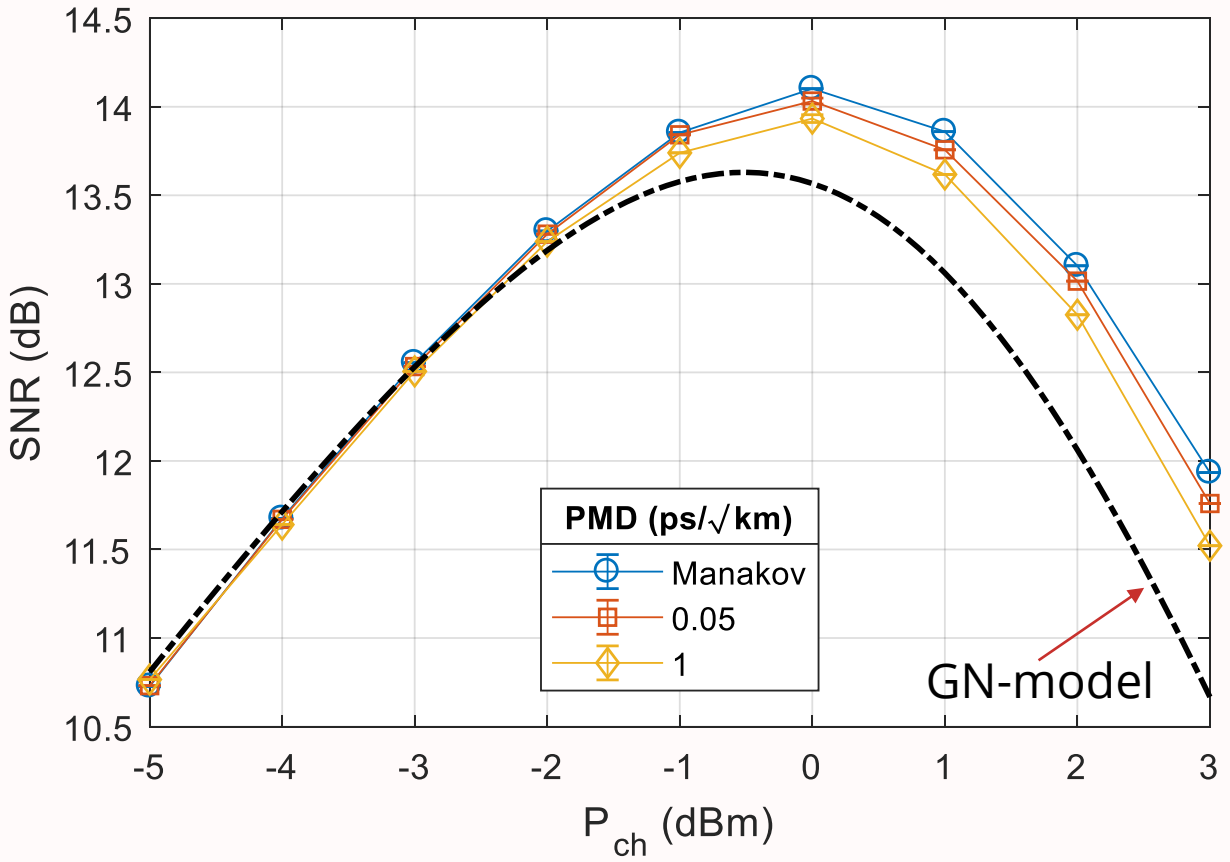




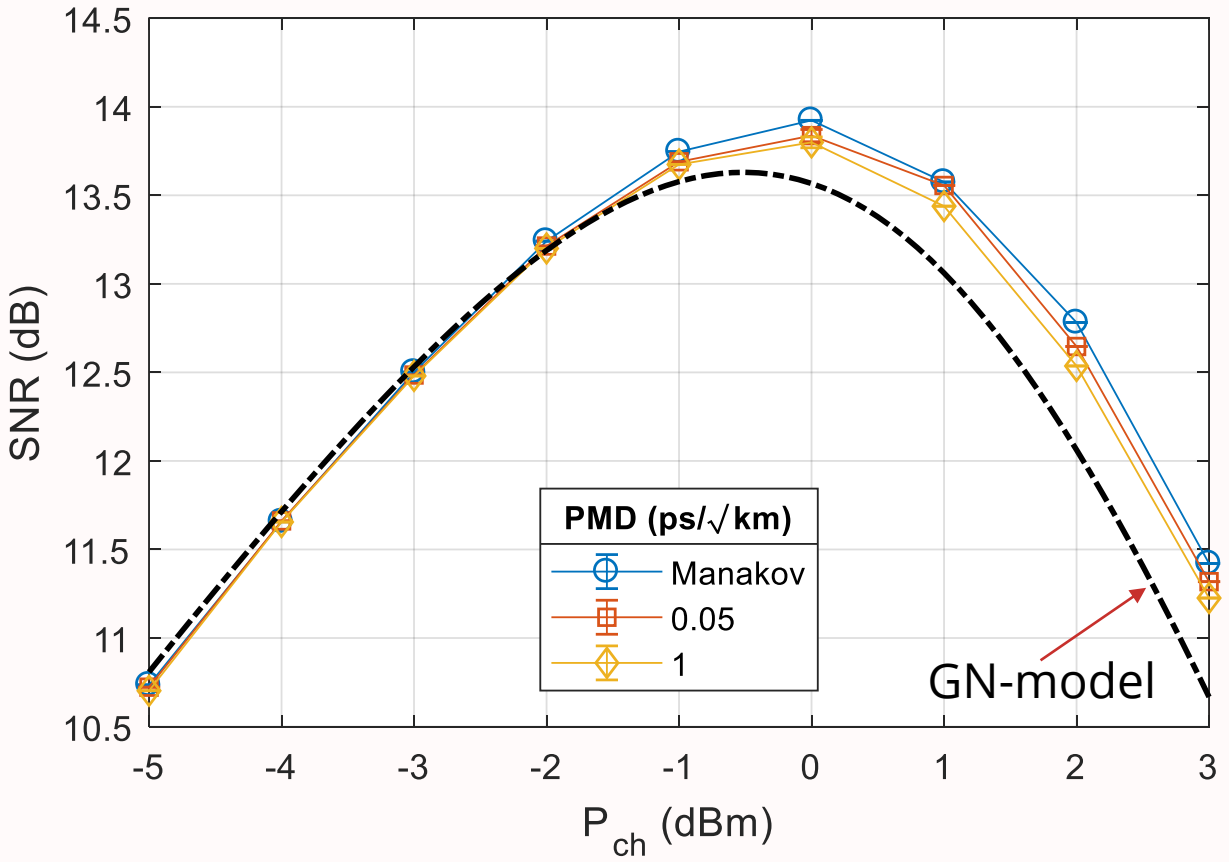


SNR VS. P_{CH} @ N_{SPAN} = 20 – SSMF – N_{CH} = 41

PM-QPSK



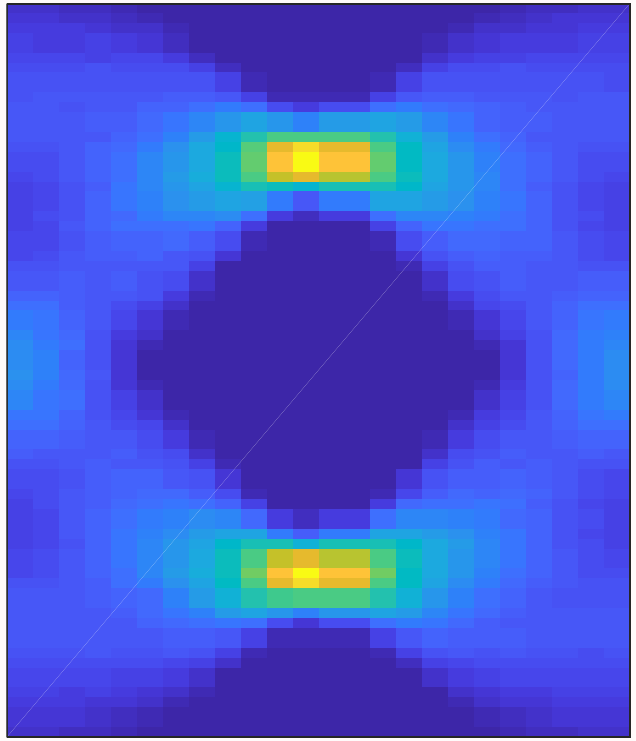
PM-16QAM



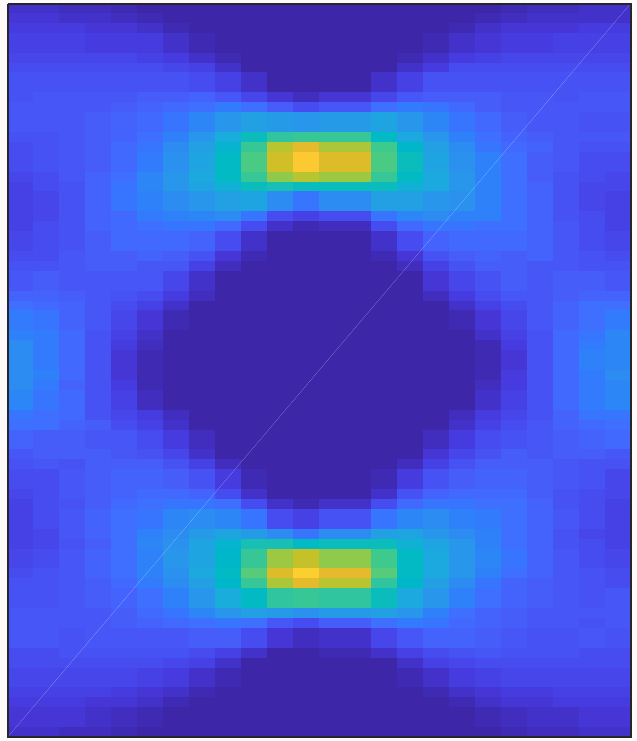
PMD EFFECT ON SIGNAL GAUSSIAN-*IZATION*

Eye diagrams after PM-QPSK propagation over L_{eff}, SSMF, 20000 symbols average window

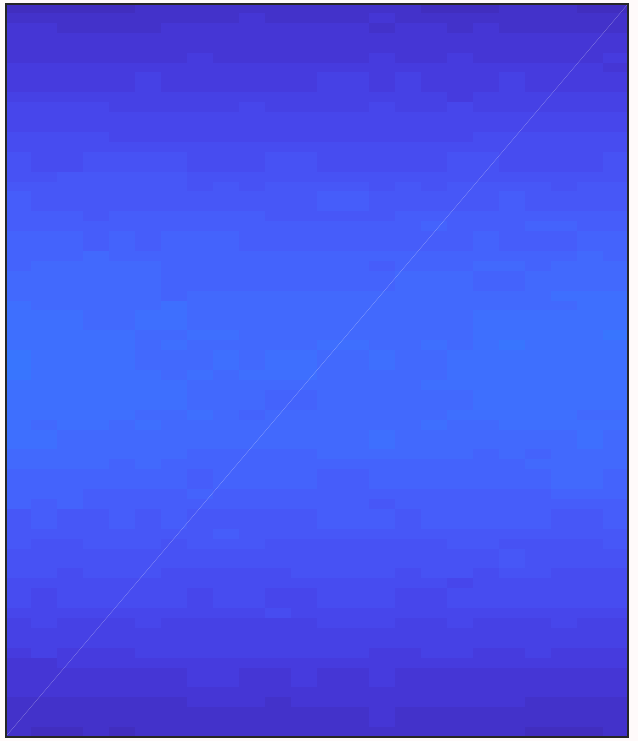
Ideal



PMD only



CD+PMD



SNR VS. BANDWIDTH @ N_{SPAN} = 20 – SSMF – P_{CH} = 0 DBM

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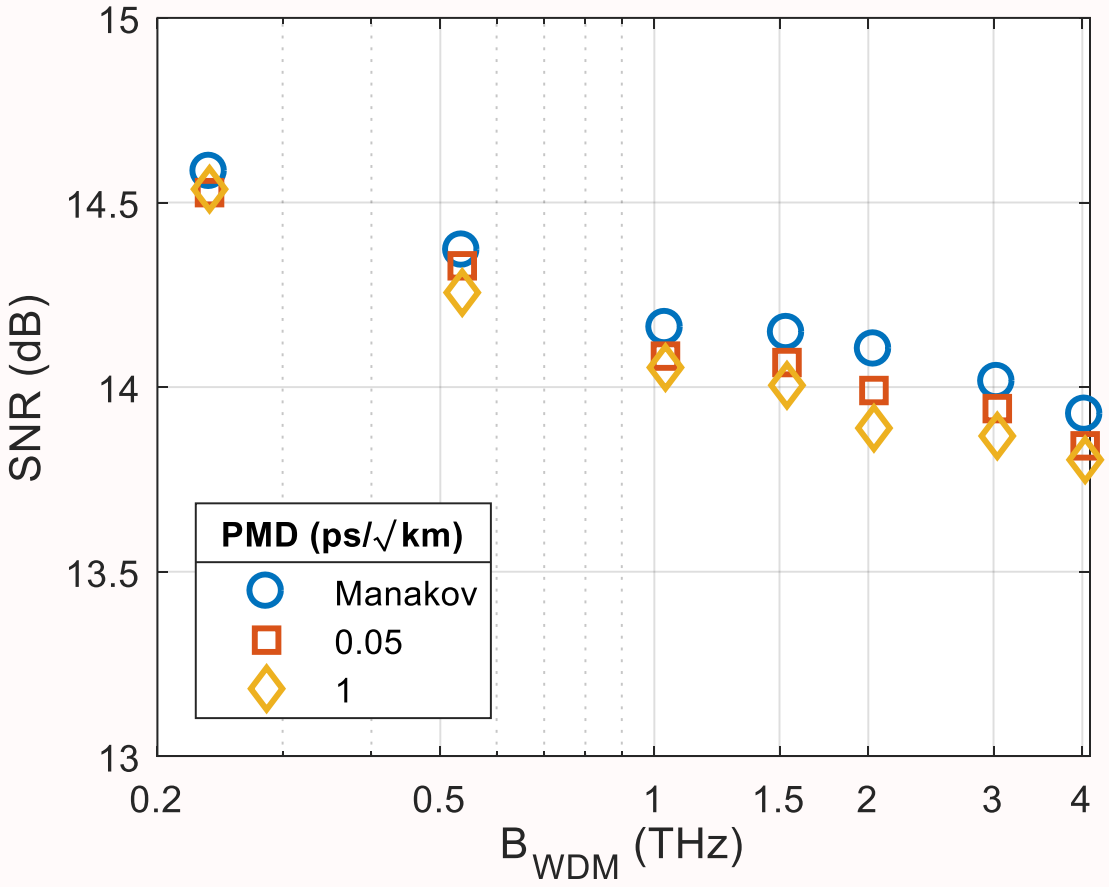
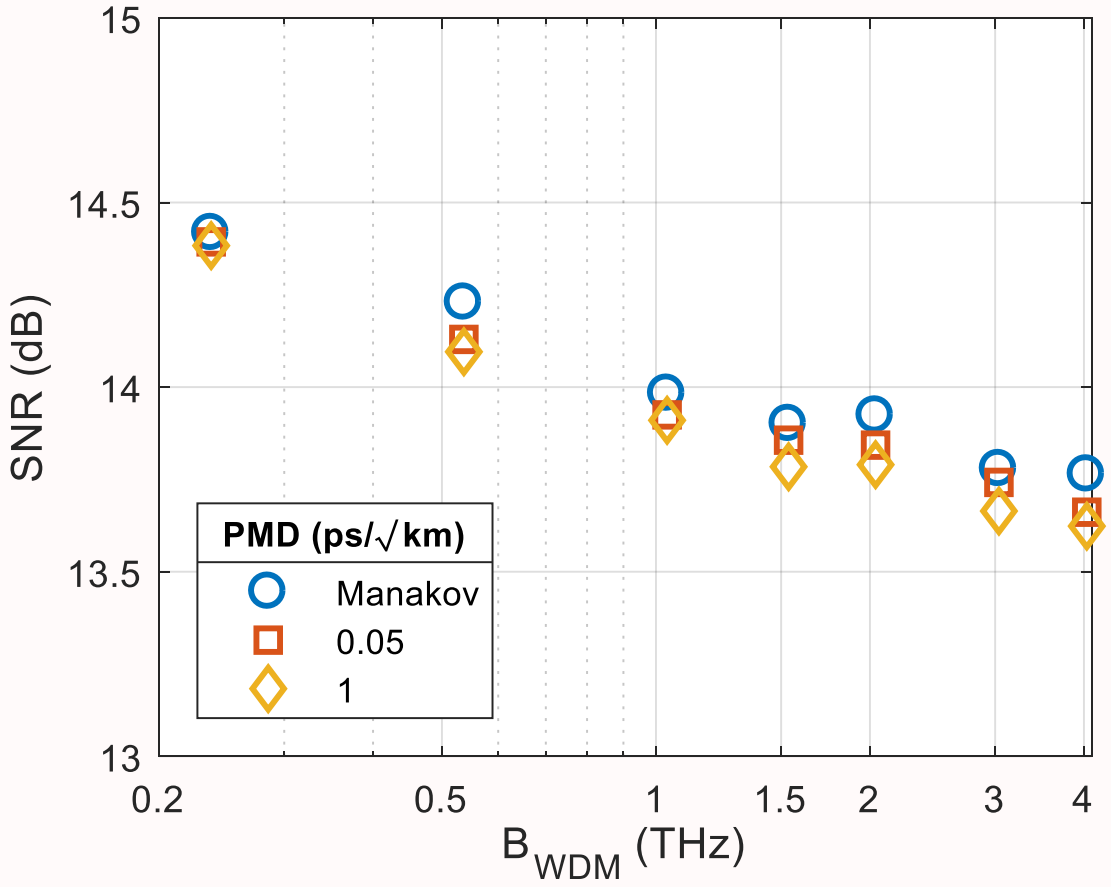
PM-QPSK



PM-16QAM



SNR VS. P_{CH} @ N_{SPAN} = 20 – NZDSF – N_{CH} = 41

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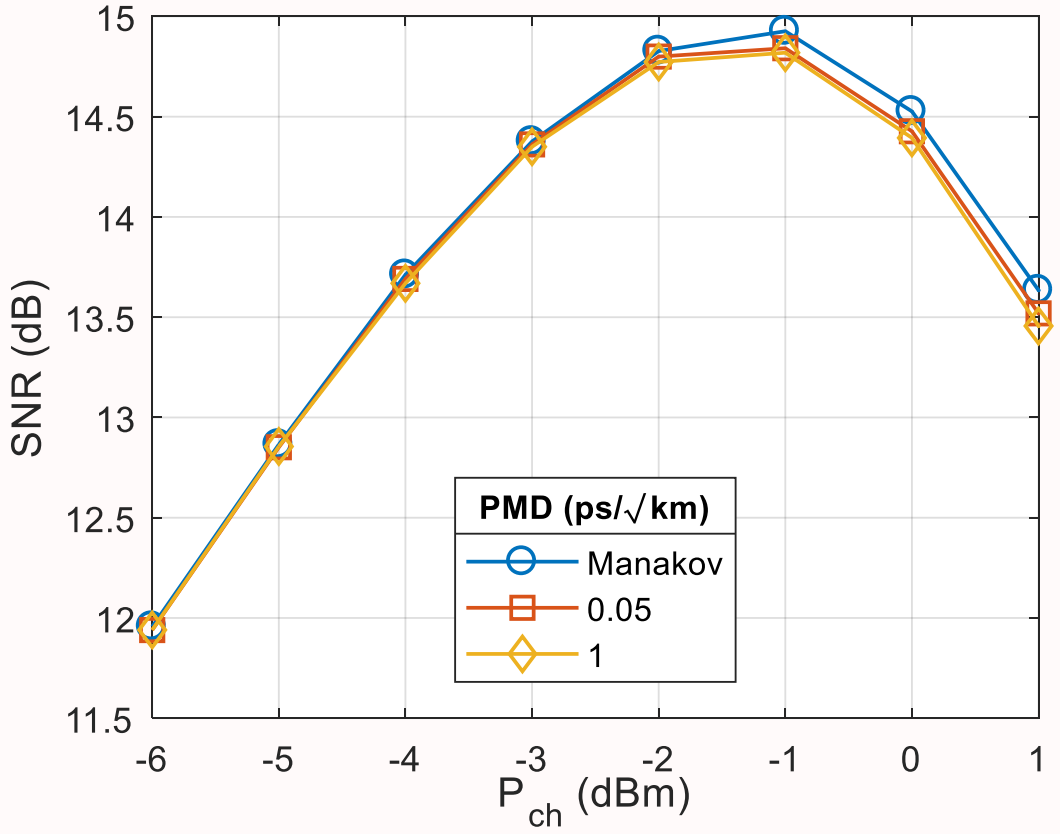
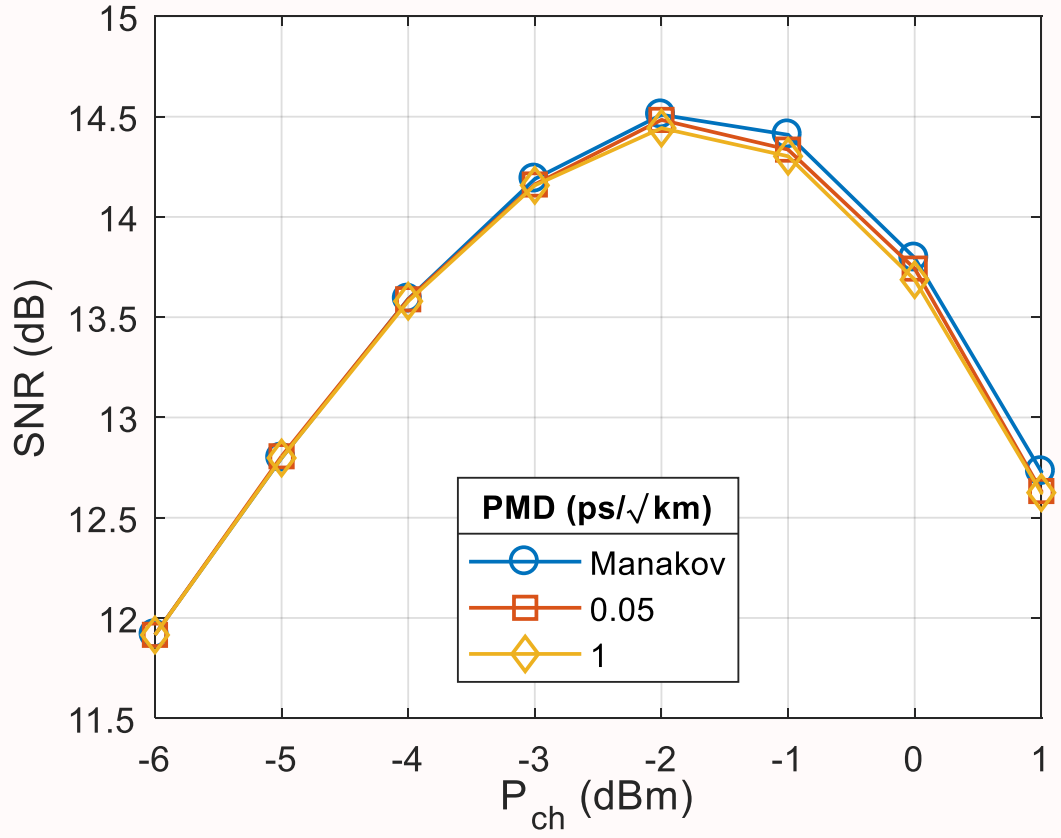
PM-QPSK



PM-16QAM



COMMENTS AND CONCLUSIONS

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- When propagating multilevel modulation formats **dominant impairment is ASE+NLI**, also **when considering random birefringence** and far exceeding the fiber coherence bandwidth
- **Statistical variations** with respect different realizations of random birefringence are **practically negligible**
- Results obtained integrating **ME and CNLSE+WM** are practically **superimposed**
- The only **effect of PMD is a minor speeding-up in Gaussian-*ization*** of signals: no relevant effect
- **ME can be used** to study propagation of multilevel modulation formats also **far beyond the theoretical validity bandwidth for ME** itself
- Consequently, **models derived** from the ME hold also at **large bandwidth**
- Gain/loss variations with space/frequency must be included, starting from the **interaction NLI-SRS: GGN***
- **Presentation will be available at www.optcom.polito.it/talks**

*M. Cantono et al, ***Modeling the impact of SRS on NLI generation in commercial equipment: an experimental investigation***, OFC 2018, M1D2.1