Statistical Characterization of PM-QPSK Signals after Propagation in Uncompensated Fiber Links

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Abstract

- We show by simulation that PM-QPSK signal components, after propagating in uncompensated fiber links, assume a Gaussian distribution, both in linear and non-linear regime, even in the absence of ASE noise.

- After DSP equalization, the statistics of the decision variables is also Gaussian.

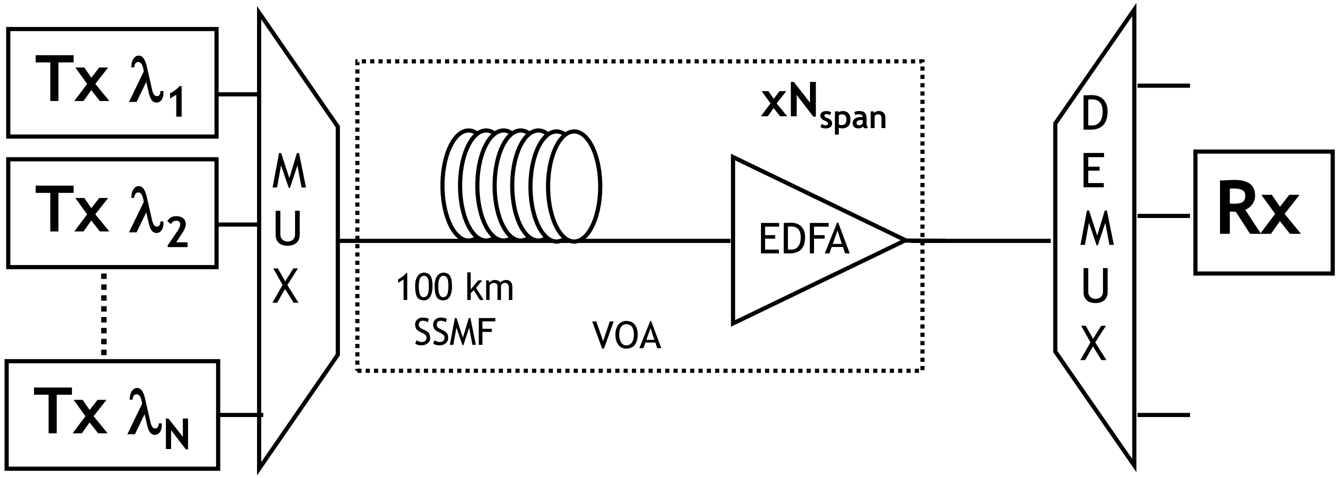
General data

- PM-QPSK
- Symbol rate
  - 25 Gbaud + 11% overhead: 27.75 Gbaud
- WDM propagation
  - Channel spacing Δf= 50 GHz
  - Different and uncorrelated PRBSs (2^{16} bits) were used for all WDM channels

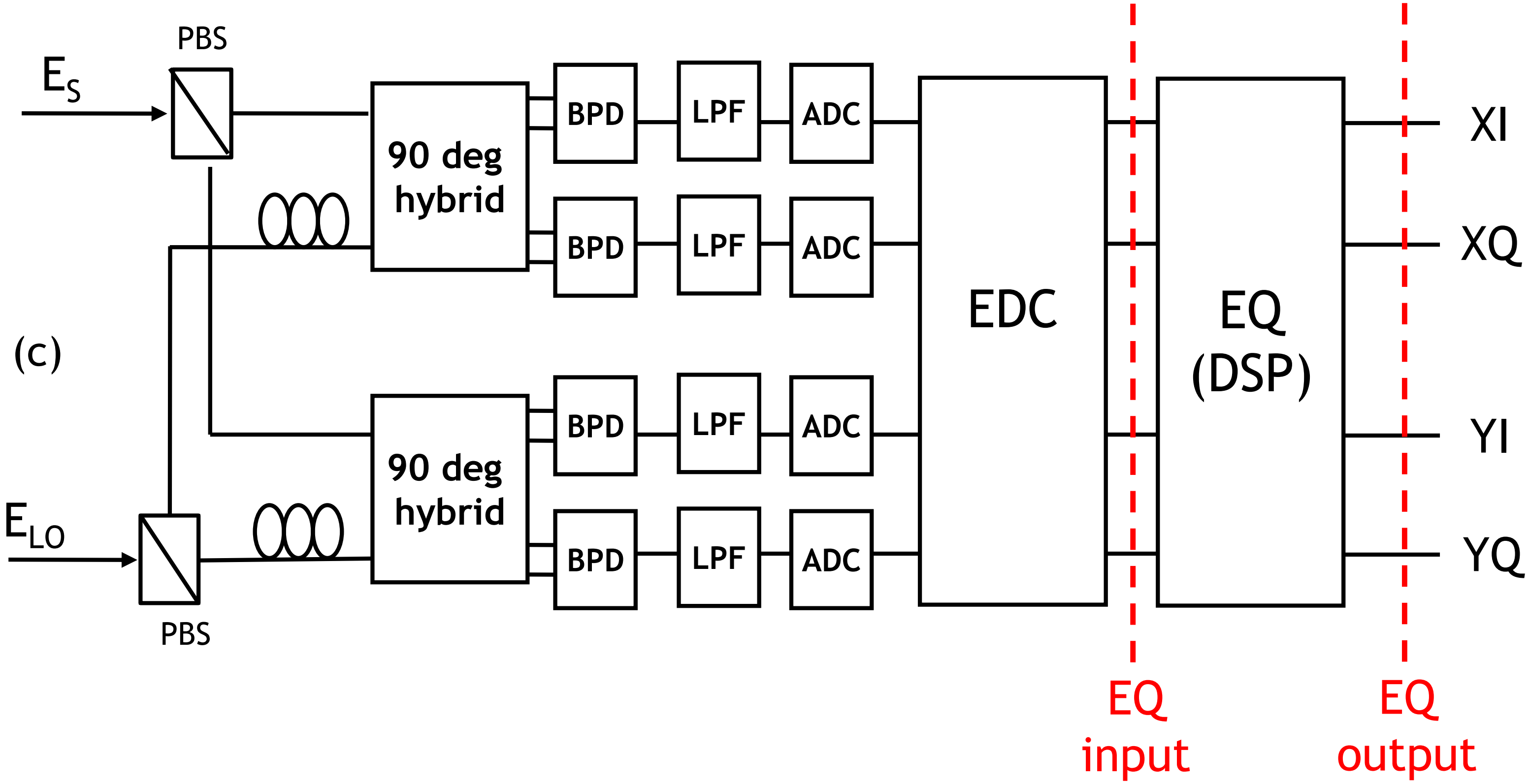
PECULIARITIES of OUR STUDY

Uncompensated link
Absence of any noise source

Link setup



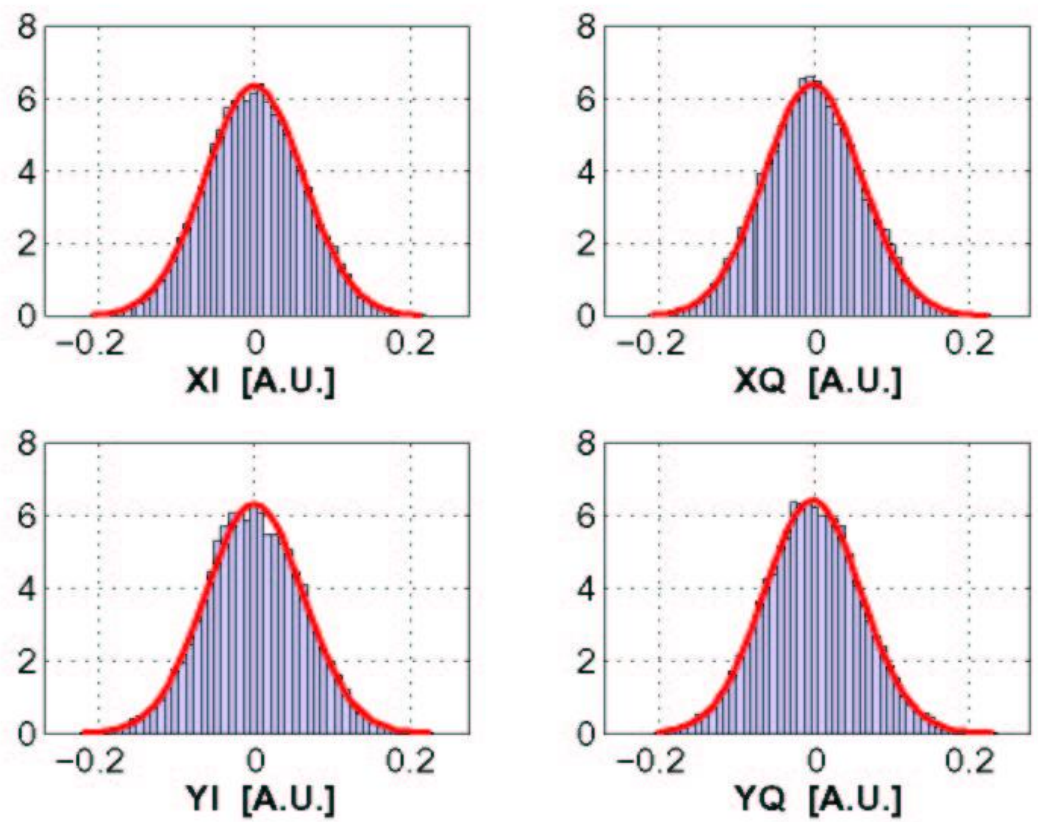
- MUX – DEMUX
  - 4^{th} order Supergaussian with bandwidth B_{opt}=40 GHz
- Fiber parameters
  - D=16.7 ps/nm/km, α=0.22 dB/km, γ= 1.3 1/W/km
- EDFA (completely recovering span loss)
  - ASE noise added by EDFA was not considered in the simulation in order to analyze the distribution of signal components alone.



- LPF: 5^{th} order Bessel with bandwidth B_{-3dB}=20 GHz
- ADC: 2 samples per symbol, ideal resolution
- Equalizer: 15 taps updated through LMS

EQ input - L=100 km - P_{TX}= 0 dBm

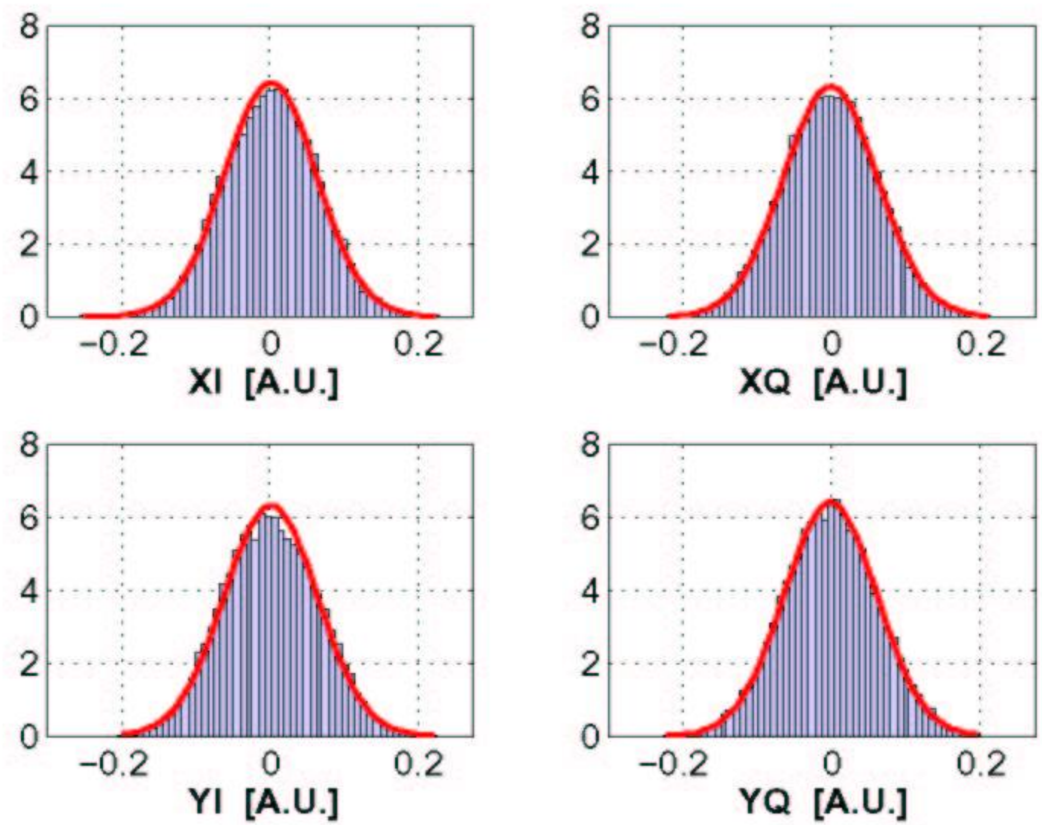
WDM – Non-linear



- The statistical distribution of all four signal components very quickly (100 km are enough) becomes zero-mean and essentially Gaussian, irrespective of the sampling instant.

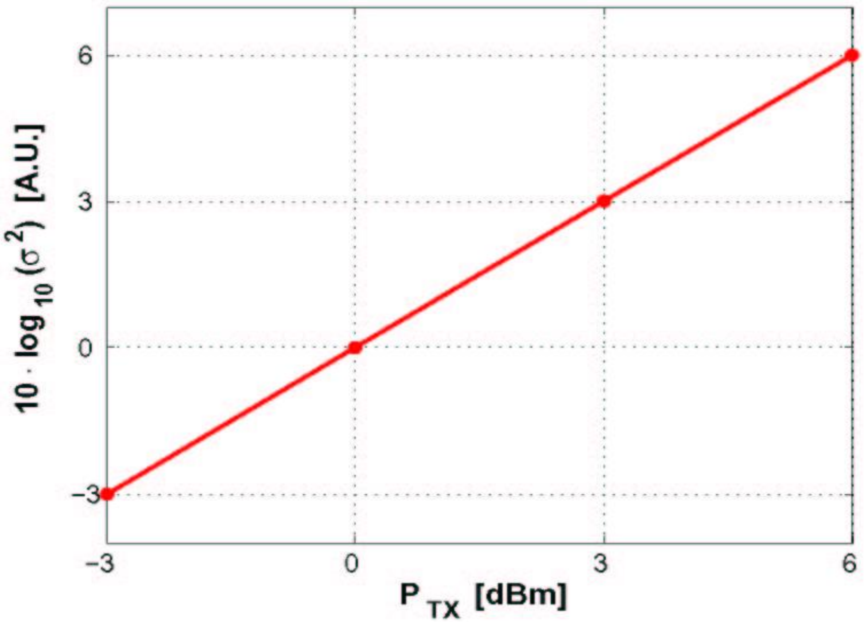
EQ input - L=500 km - P_{TX}= 0 dBm

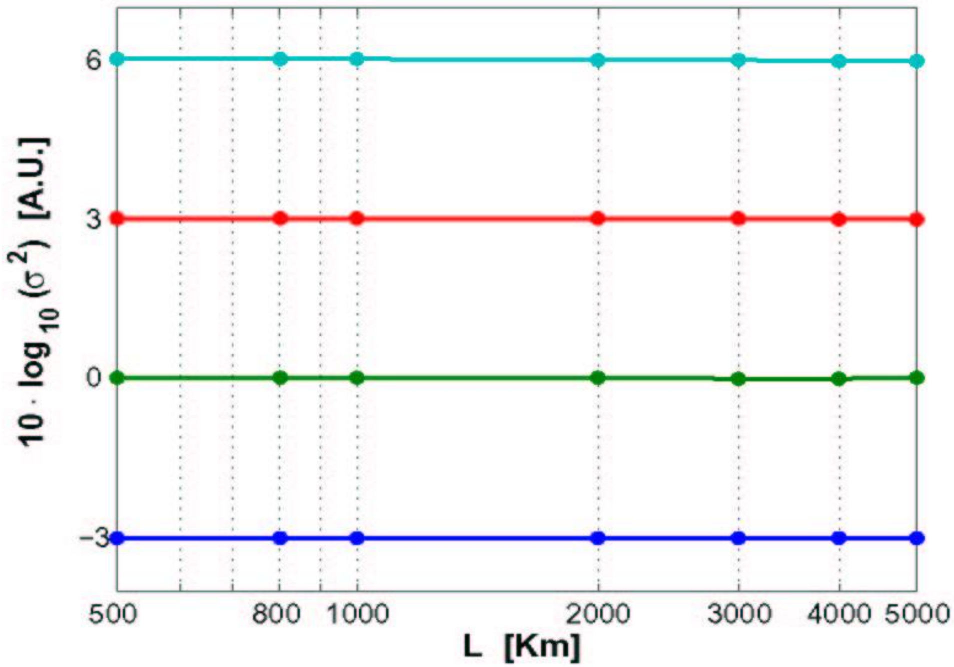
WDM – Non-linear



- The distribution of the four components does not change along the link and in fact seems to increasingly adhere to Gaussian.
- The variance of the Gaussian distribution is directly proportional to the overall signal power and is always identical for all four signal components

EQ input: dependence on P_{TX} and L

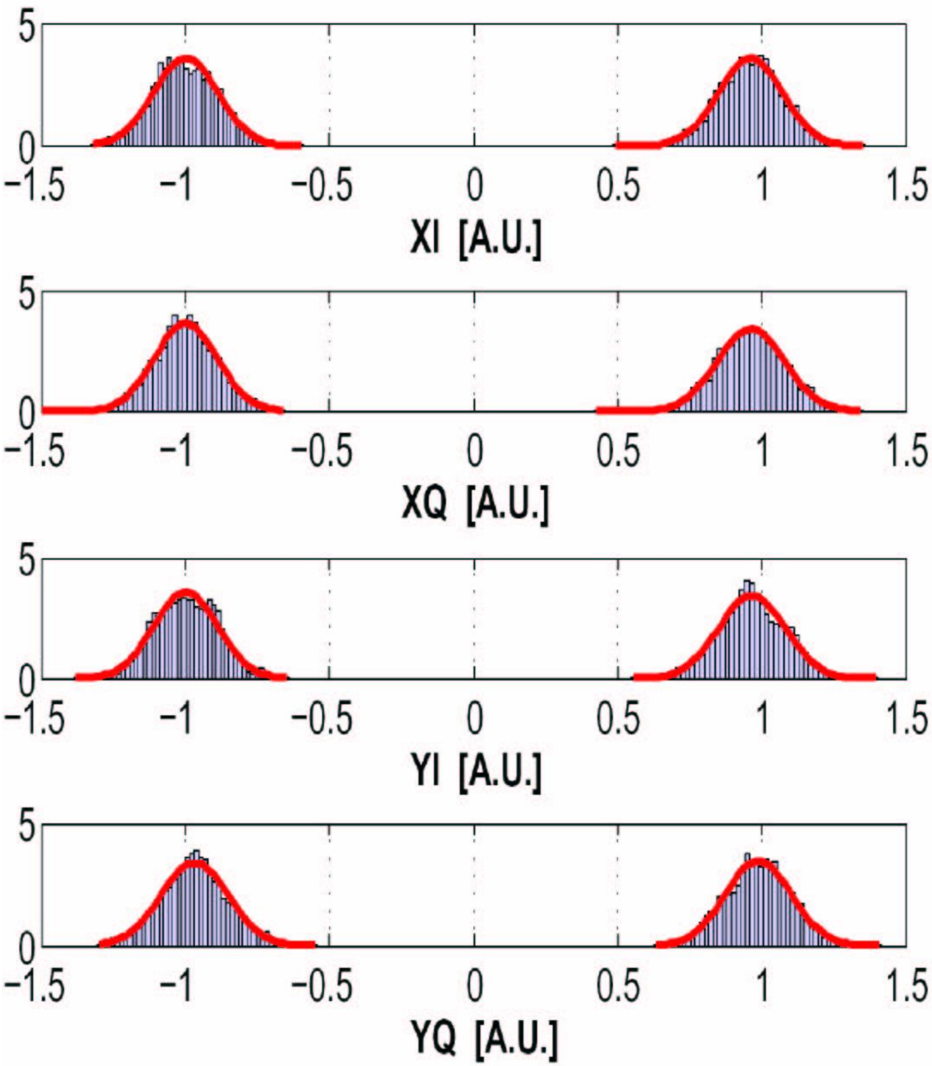




- These results hold true both in linear and non-linear regime, at least within the power boundaries and total distance shown above.
- Both with and without non-linear effects, the four components appear to have negligible cross-correlation. This is an interesting result too, since in the non-linear case some correlation might have been expected.

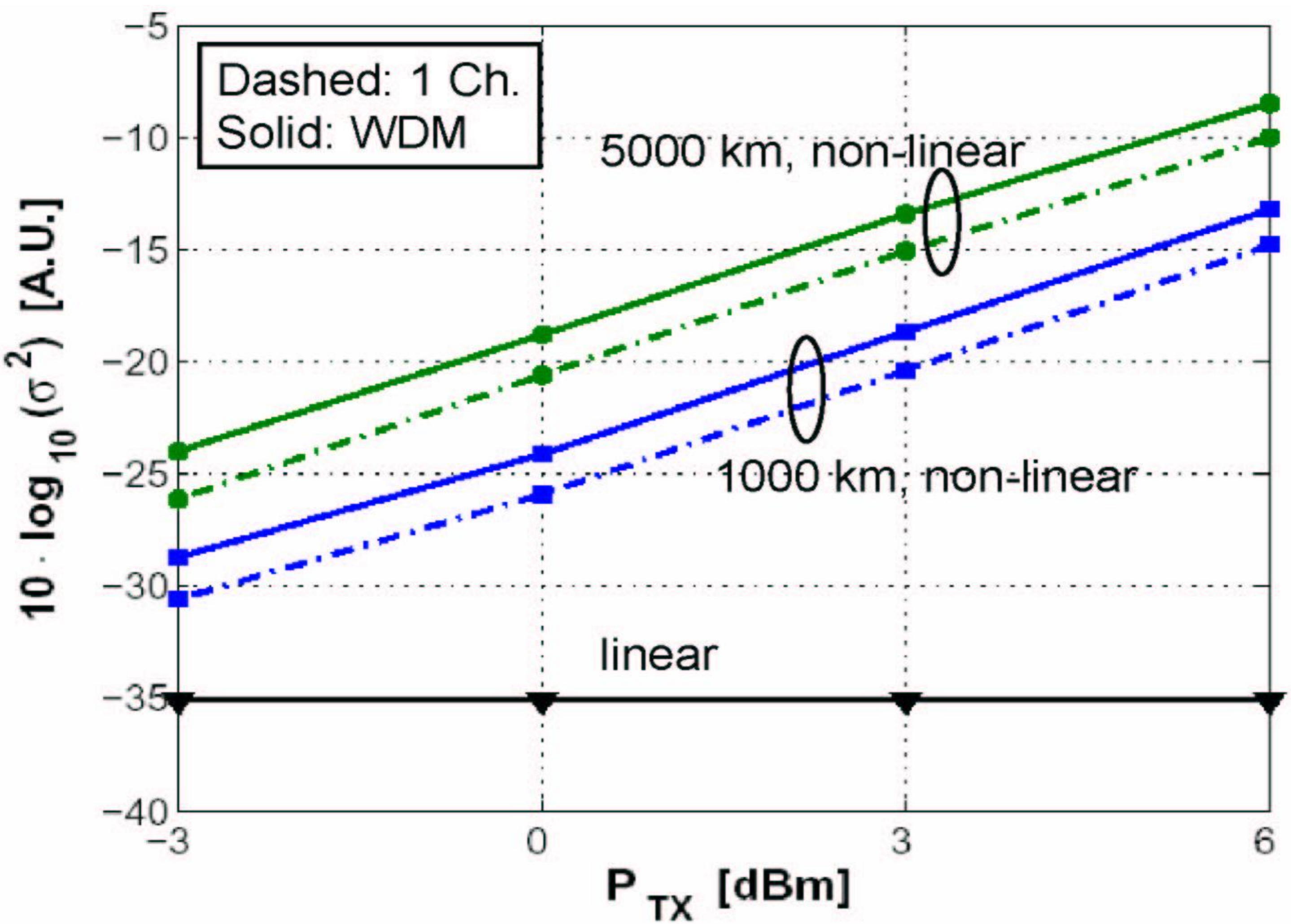
EQ output - L=1000 km - P_{TX}= 3 dBm

WDM – Non-linear



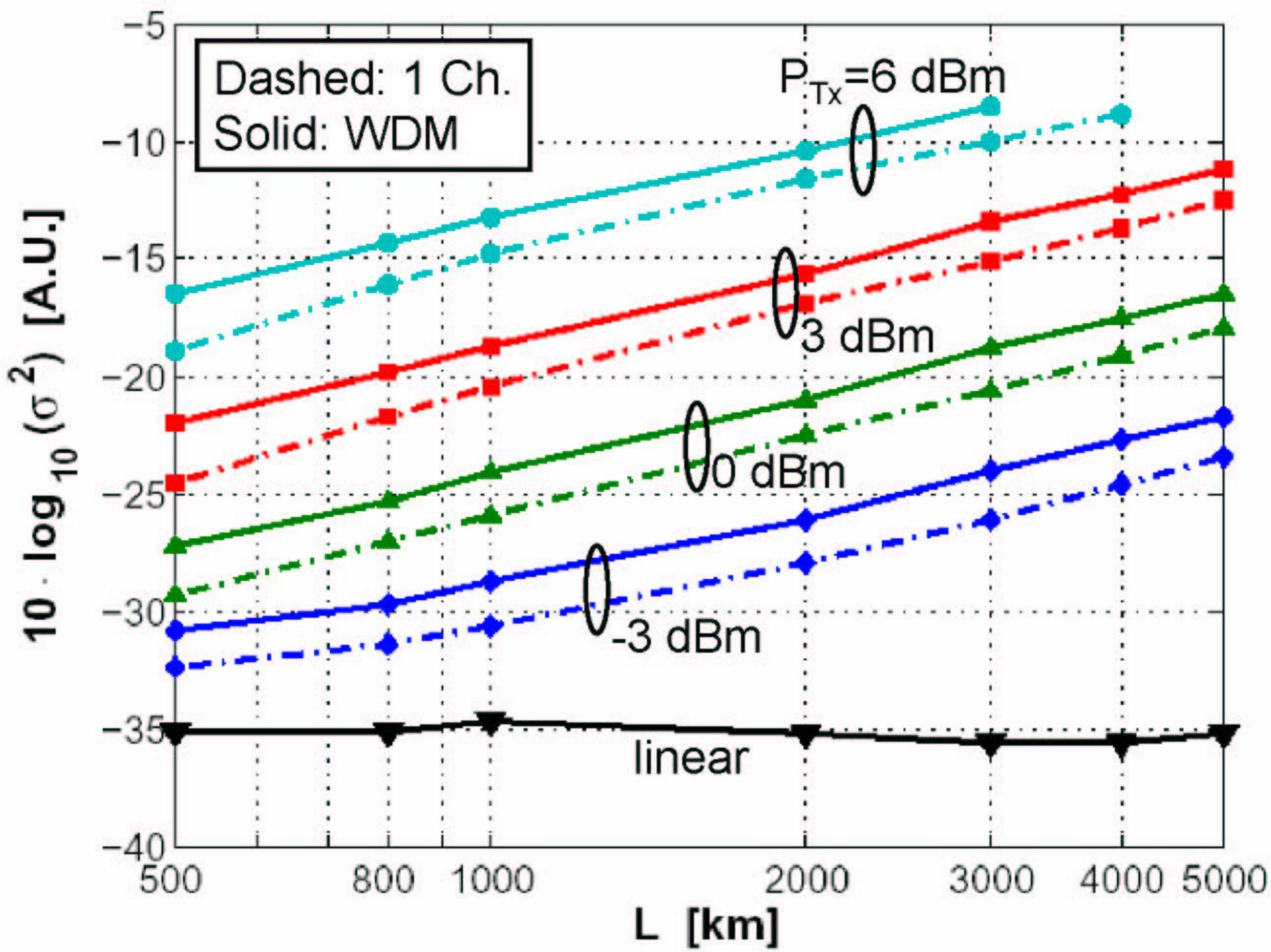
- The distribution about each peak in all considered cases (WDM and single channel, different power levels and distance) is again remarkably Gaussian.
- We found the same variance for all Gaussian distributions and no correlation among signal components, resulting in circular scattering diagrams.
- Note that propagation was completely noiseless: the Gaussian distribution is induced by non-linearity alone

EQ output vs P_{TX}



- In non-linear regime, both for single-channel and WDM, the variance increases proportionally to P_{Tx}^2 (i.e. a 1-dB increase in power causes a 2-dB increase in variance).

EQ output vs L



- Single channel and WDM, though distinct, have the same trend.
- In linearity (bottom solid line) the variance is extremely small and almost constant. It is due to residual ISI.

Notes

- This study was based on a full-band dual-polarization split-step simulation. Hence, all non-linear interactions were taken into account, including those involving polarization, such as cross-polarization modulation (XPolM).

- The shown distributions would not pass tight tests for Gaussianity. However, given the target BERs of current systems, far tail distribution become irrelevant and the shown distributions are equivalent to Gaussian to any practical extent.

Conclusions

- For the first time to our knowledge, we have shown that, in the absence of ASE noise, PM-QSPK signal components are Gaussian-distributed both before and after DSP, and signal components are statistically independent.

DSP INPUT

- The uncorrelated Gaussian distribution properties directly apply to the optical PM-QPSK signal propagating in the fiber.
- Such properties could be a starting point for deriving new simplified models of non-linear fiber propagation for WDM PM-QPSK signals.

DSP OUTPUT

- Gaussian-like noise is induced by non-linear effects and its variance has a simple dependence on transmitted power and distance.
- These findings might help in understanding and evaluating the impact of non-linear effects on PM-QPSK channels.