Performance evaluation in ASE noise limited optical systems: receiver impairments of constant envelope modulation formats

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TOSCA project (MIUR - PRIN 2004)

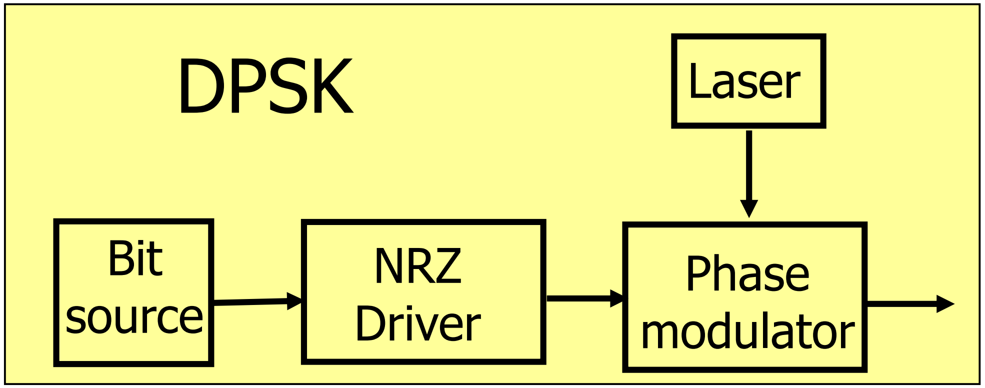
Outline

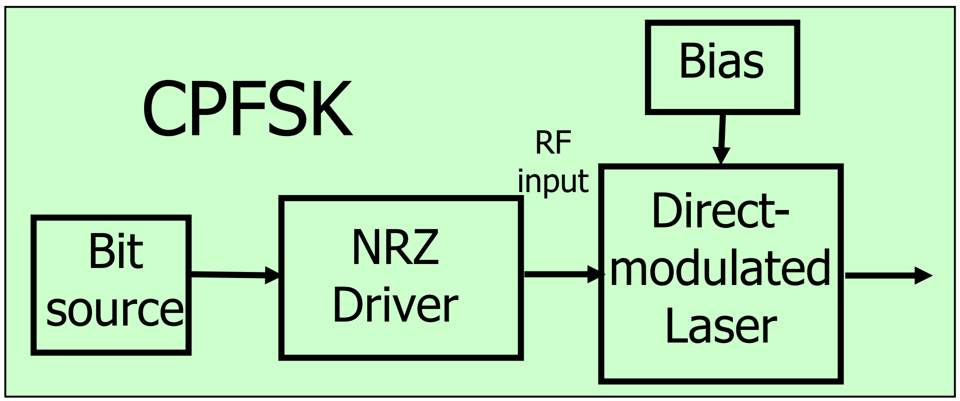
- Motivation: the TOSCA project
- A new simulation method: semi-analytical technique based on KL expansion in frequency domain
- Simulation results: study of receiver impairments
- Conclusions: an unexpected result

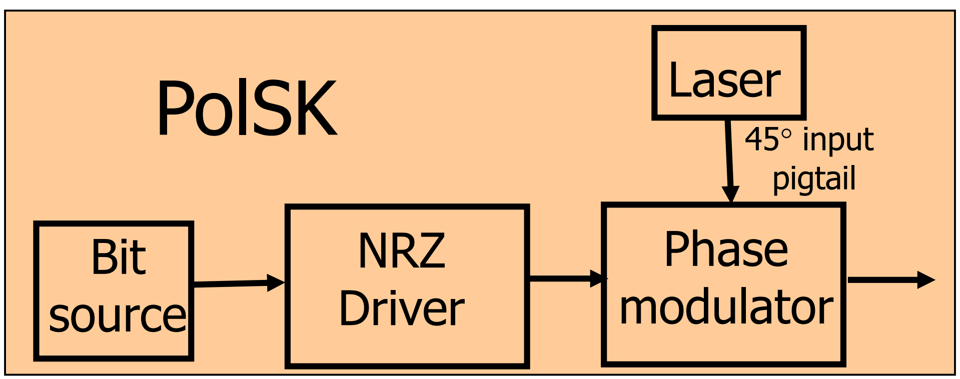
TOSCA project

- TOSCA:
  - Transmission of Optical Signals exploiting Competitive Amplification techniques
- Why SOA?
  - Cheaper! Smaller! Less power-consuming! But nonlinear…
  - IMDD does not allow to implement WDM using SOA
- A promising solution are Constant Envelope formats
  - We consider DPSK, CPFSK and PolSK

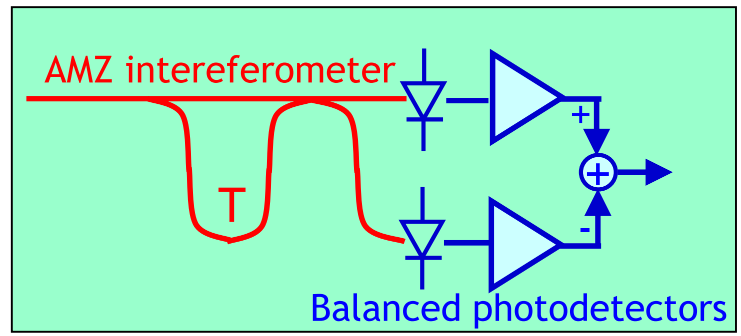
Transceivers for CE modulation formats







Receiver



Performance estimation

- We used a semi-analytical technique based on the BER estimation method presented in [1], which allows to accurately estimate the performance of optical receivers based on the asymmetric Mach-Zehnder interferometer and differential detection.
- This BER estimation method is based on the expansion, in the frequency domain, of optical signal and noise at the input of the receiver filter in Karhunen-Loève series [2].
- Thanks to the series expansion, the decision variable assumes a very simple form:

$$v(t) = \sum_i \left[\beta_i(t) + v_i\right]^2$$

v_i: i.i.d. Gaussian r.v. with zero mean and variance λ_i

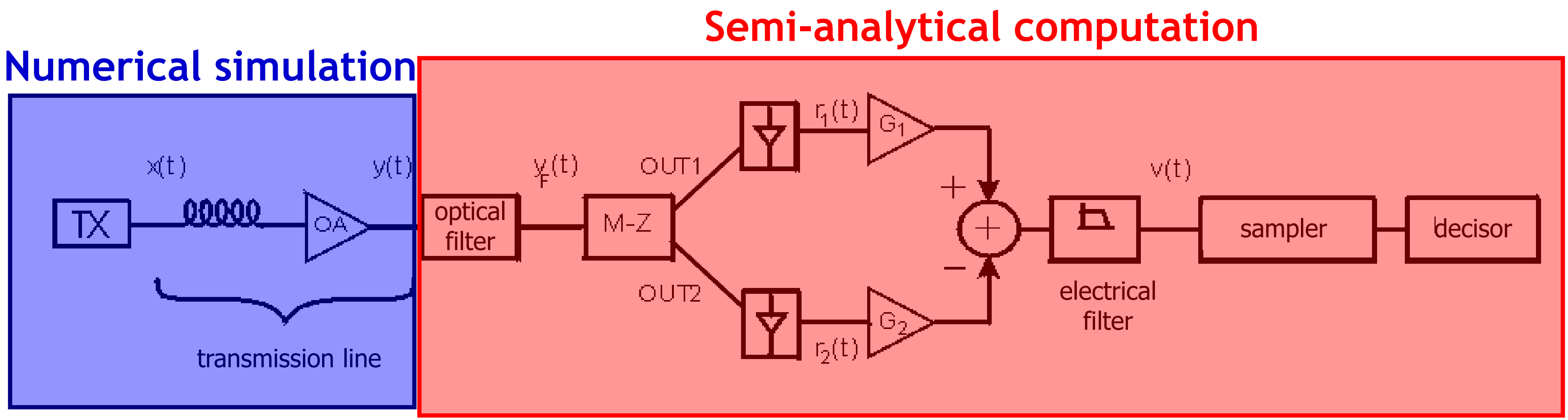
  - where $\beta_i(t)$ and λ_i are the coefficients of the expansion of signal and noise respectively.

[1] A.H. Gnauck, P.J. Winzer, "Optical Phase-Shift-Keyed Transmission," IEEE Journal of Lightwave Technology, vol. 23, n. 1, pp. 115-130, Jan. 2005

[2] J.S. Lee and C.S. Shim, "Bit error rate analysis of optically preamplified receivers using an eigenfunction expansion method in optical frequency domain", *J. Lightw. Technol.*, vol. 12, pp. 1224-1229, 1994.

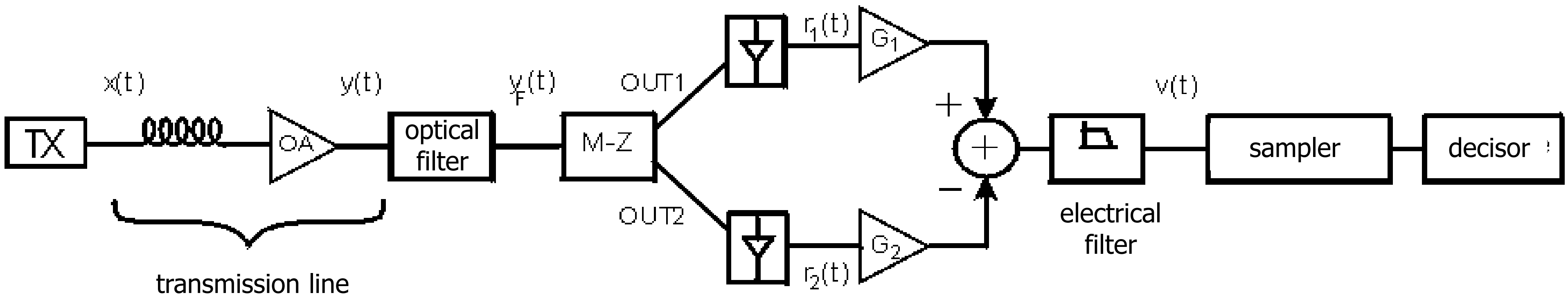
Semi-analytical technique

- Semi-analytical technique:
  - the signal propagation is simulated without noise
  - explicit and analytic formulas are used for BER evaluation (*)



(*) The statistical properties of a random variable like *v(t)* are known in literature and the BER can be easily found by numerically solving an integral involving the characteristic function, which can be written in closed form.

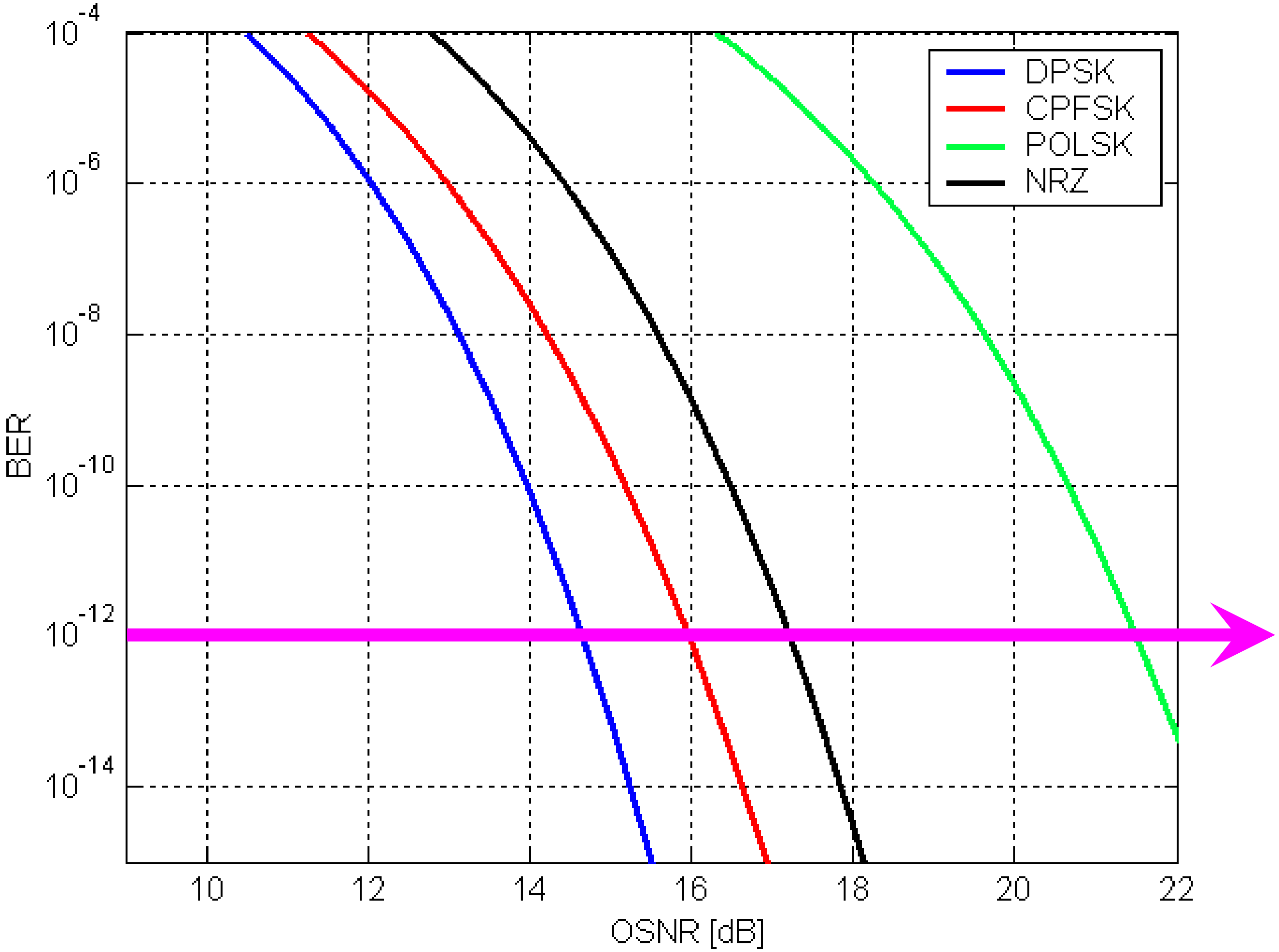
System description



OSNR evaluated over a bandwidth equal to R_B

- Ideal rectangular pulses at the TX
- 2nd order Supergaussian optical filter with bandwidth 10 R_s
- 5-pole Bessel post-detection filter with bandwidth 0.75 R_s.

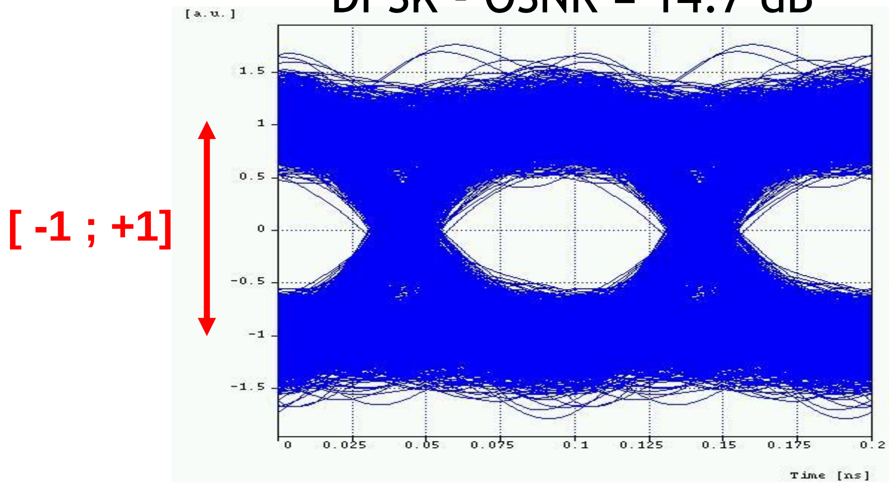
BER vs. OSNR: sensitivity



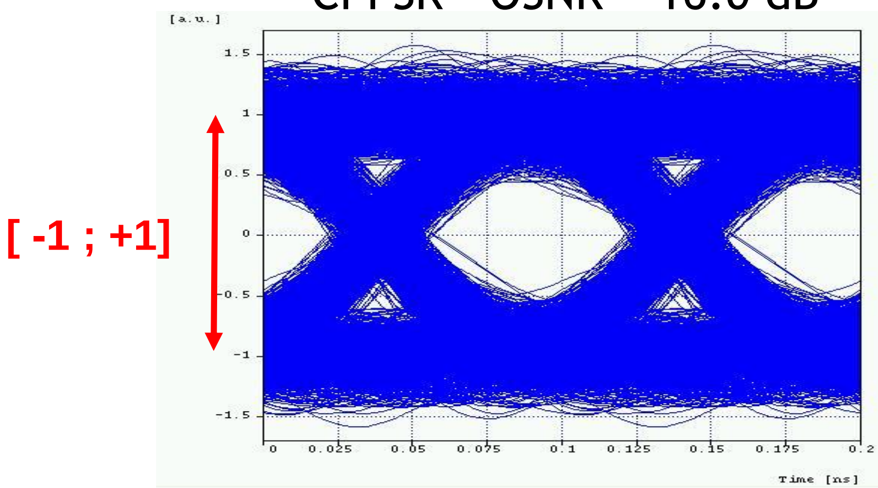
$BER=10^{-12}$	OSNR [dB]
NRZ	17.2
DPSK	14.7
CPFSK	16.0
PolSK	21.5

Eye diagrams @ BER=10^{-12}

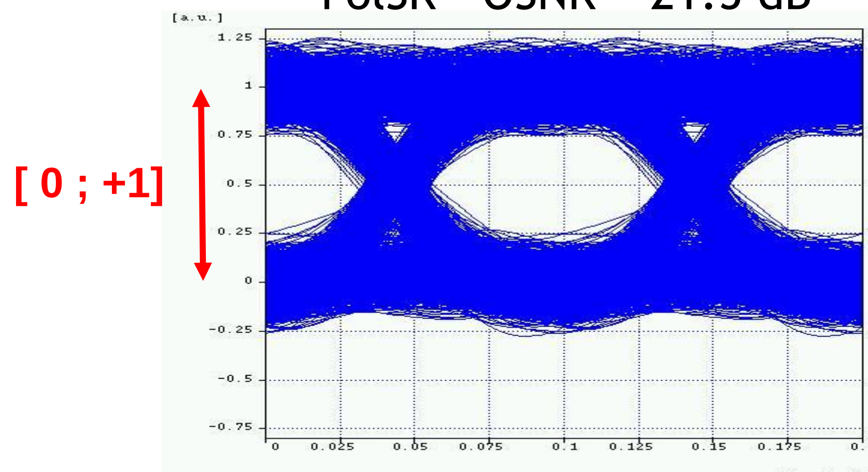
DPSK - OSNR = 14.7 dB



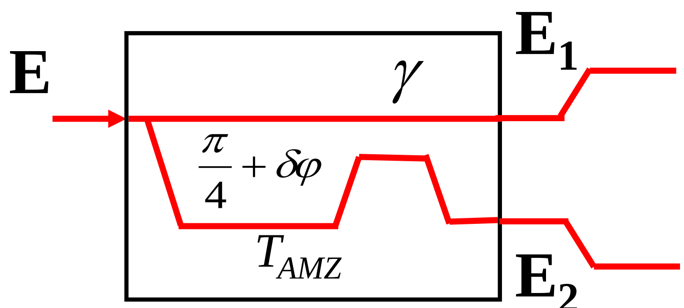
CPFSK - OSNR = 16.0 dB



PolSK - OSNR = 21.5 dB



Asymmetric Mach-Zehnder (AMZ) interferometer



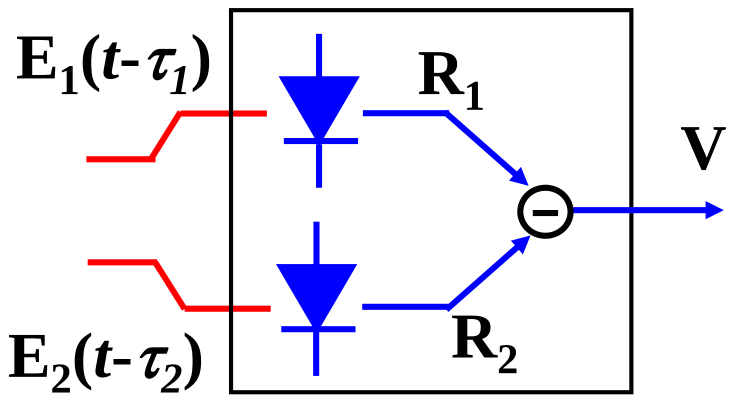
Asymmetric Mach-Zehnder interferometer

$$E_1(t) = \frac{1}{2}\left[E(t) + \gamma\, E(t - T_{AMZ})e^{j\pi/4}e^{j\delta\varphi}\right]$$

$$E_2(t) = \frac{1}{2}\left[E(t) - \gamma\, E(t - T_{AMZ})e^{j\pi/4}e^{j\delta\varphi}\right]$$

- Ideally, $\gamma = 1$, $\delta\varphi = 0$, $T_{AMZ} = T$
  (where *T* is the inverse of the symbol rate)
- **AMZ imperfections**
  - Interferometer phase error ($\delta\varphi \neq 0$) $\Rightarrow$ Frequency detuning
  - Non-infinite extinction ratio ($\gamma \neq 1$)
  - Mismatched inteferometer delay ($T_{AMZ} \neq T$)

Balanced photodetectors (BPD)



$$V(t) = \frac{1}{2}\left[R_1\left|E_1(t-\tau_1)\right|^2 - R_2\left|E_2(t-\tau_2)\right|^2\right]$$

- Ideally, $\tau_1=\tau_2$ and $R_1=R_2$
- **BPD imperfections**
  - Temporal imbalance ($\tau_1 \neq \tau_2$)
  - Amplitude imbalance ($R_1 \neq R_2$)

Receiver impairments

- AMZ frequency detuning Δf [% of bit rate R_b]

$$\frac{\Delta f}{R_b} = \frac{\delta\varphi}{4\pi}\cdot 100 \quad \Rightarrow 0$$

- AMZ extinction ratio ε [dB]

$$\varepsilon = 10\cdot\log_{10}\left[\frac{(1+\gamma)^2}{(1-\gamma)^2}\right] \quad \Rightarrow \infty$$

- AMZ delay error δT [% of symbol time T]

$$\frac{\delta T}{T} = \frac{T_{AMZ} - T}{T}\cdot 100 \quad \Rightarrow 0$$

- BPD temporal imbalance $d\tau$ [% of symbol time T]

$$\frac{\delta\tau}{T} = \frac{\tau_1 - \tau_2}{T}\cdot 100 \quad \Rightarrow 0$$

- BPD amplitude imbalance β

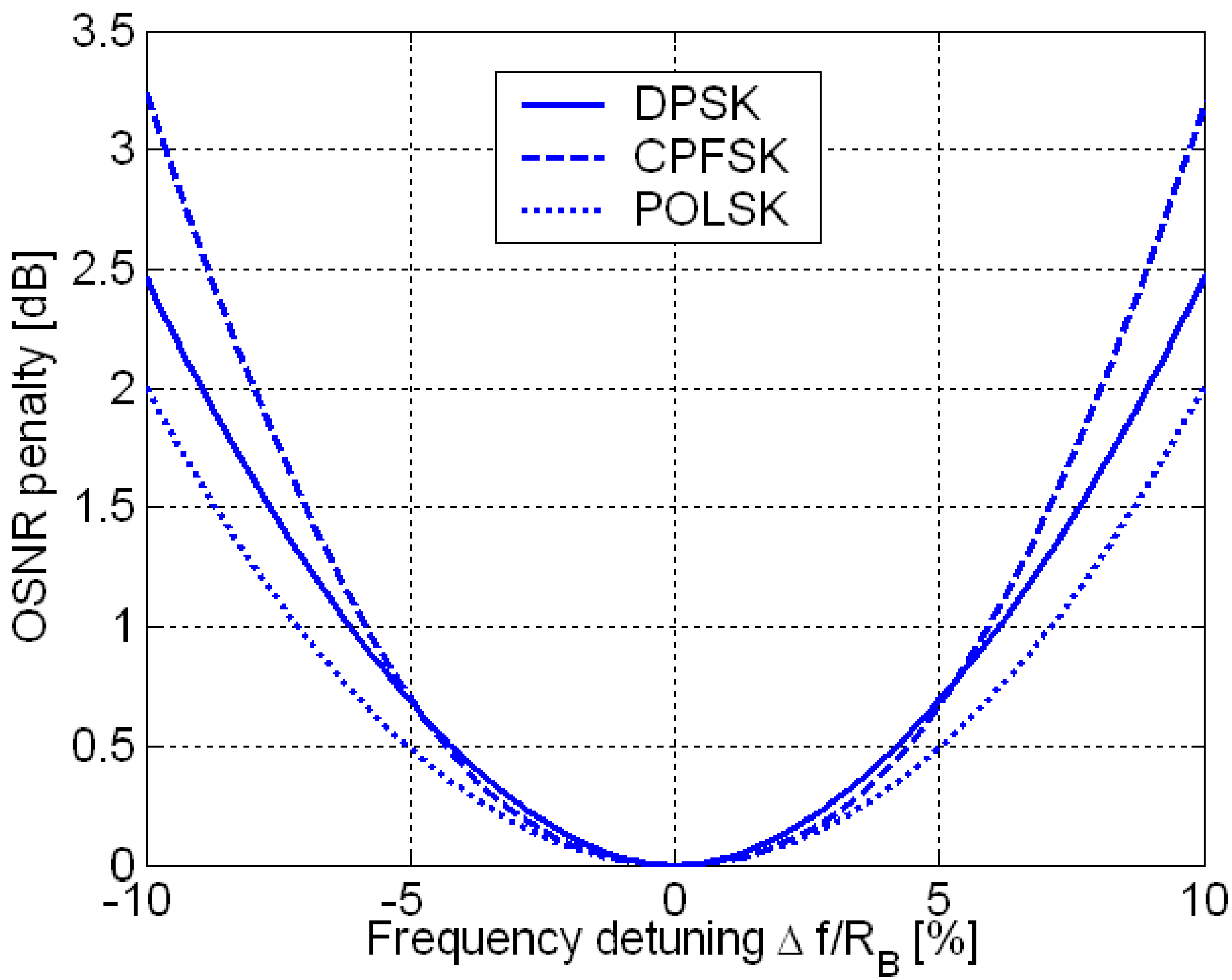
$$\beta = \frac{R_1 - R_2}{R_1 + R_2} \quad \Rightarrow 0, \quad \in [-1,1]$$

OSNR penalty

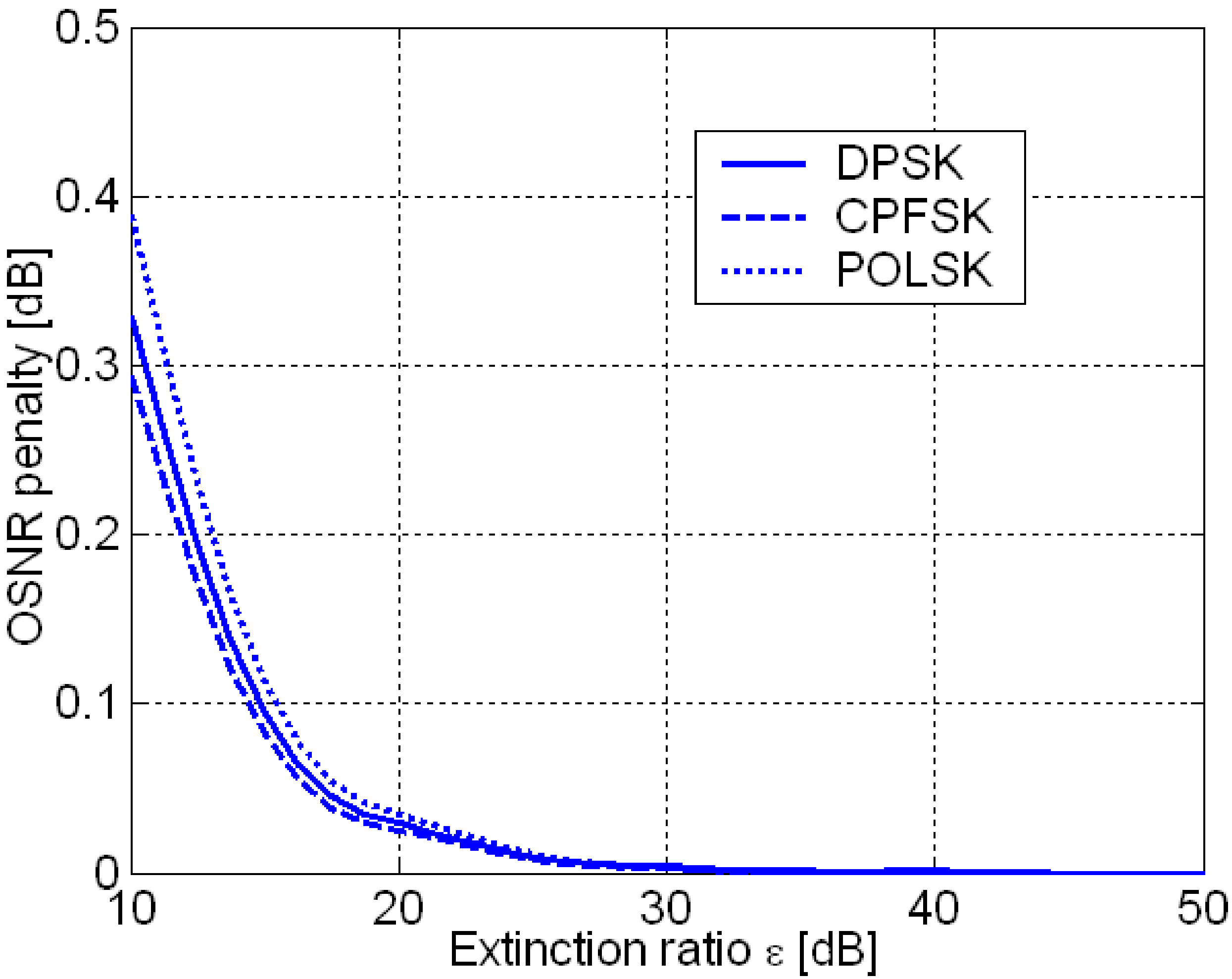
- We ran a set of simulations to evaluate the **OSNR penalty**
- It is defined as the increase in OSNR needed to obtain the same BER as that a system with no RX imperfections
- The reference BER was set to 10^{-12}, which corresponds to the following values of OSNR at the input of the RX, in the absence of impairments:

System	$OSNR_{ref}$
DPSK	14.7 dB
CPFSK	16.0 dB
POLSK	21.5 dB

AMZ frequency offset



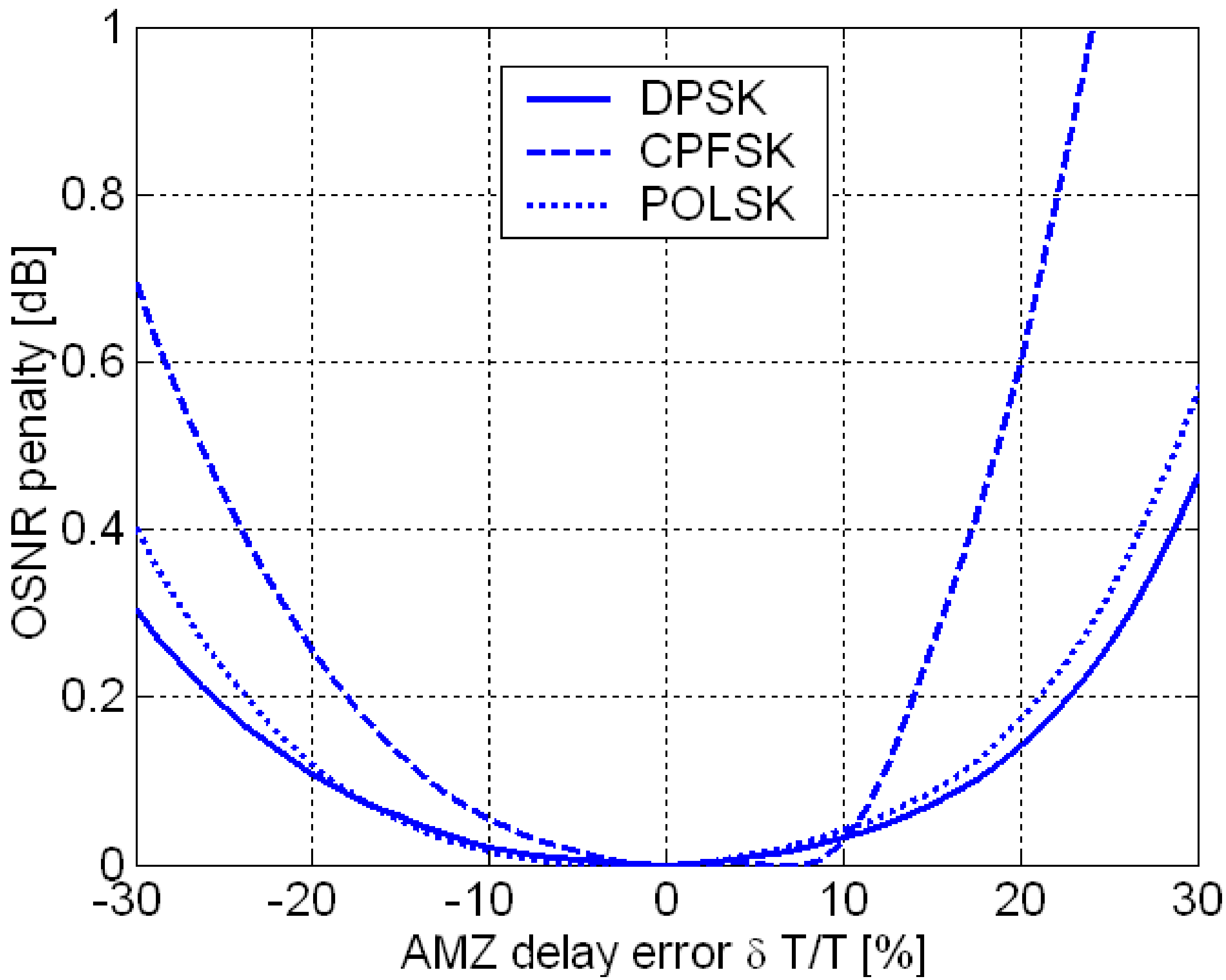
Extinction ratio



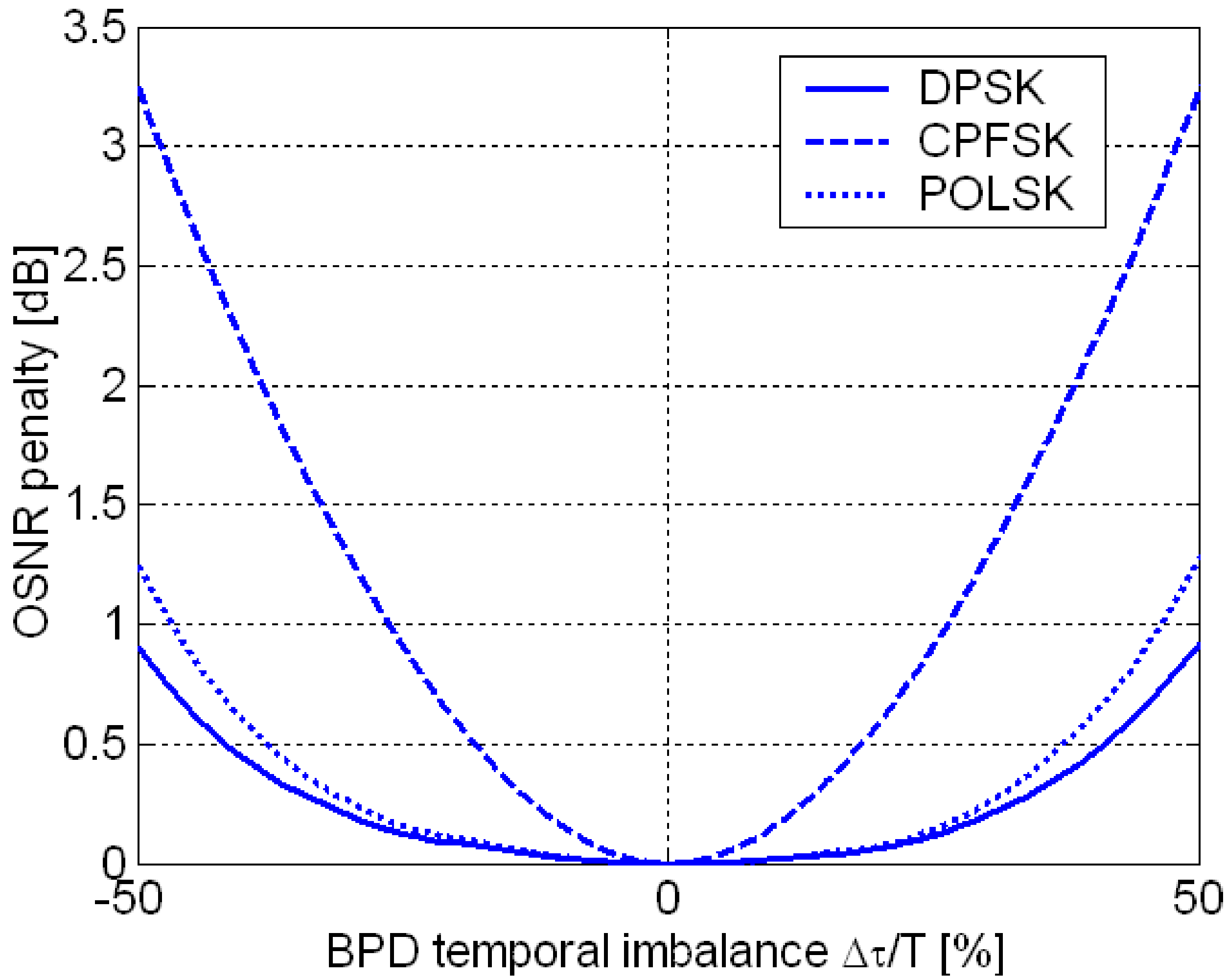
OSNR penalty due to extinction ratio is different from zero only if $\beta \neq 0$

The curves have been obtained using $\beta=0.25$

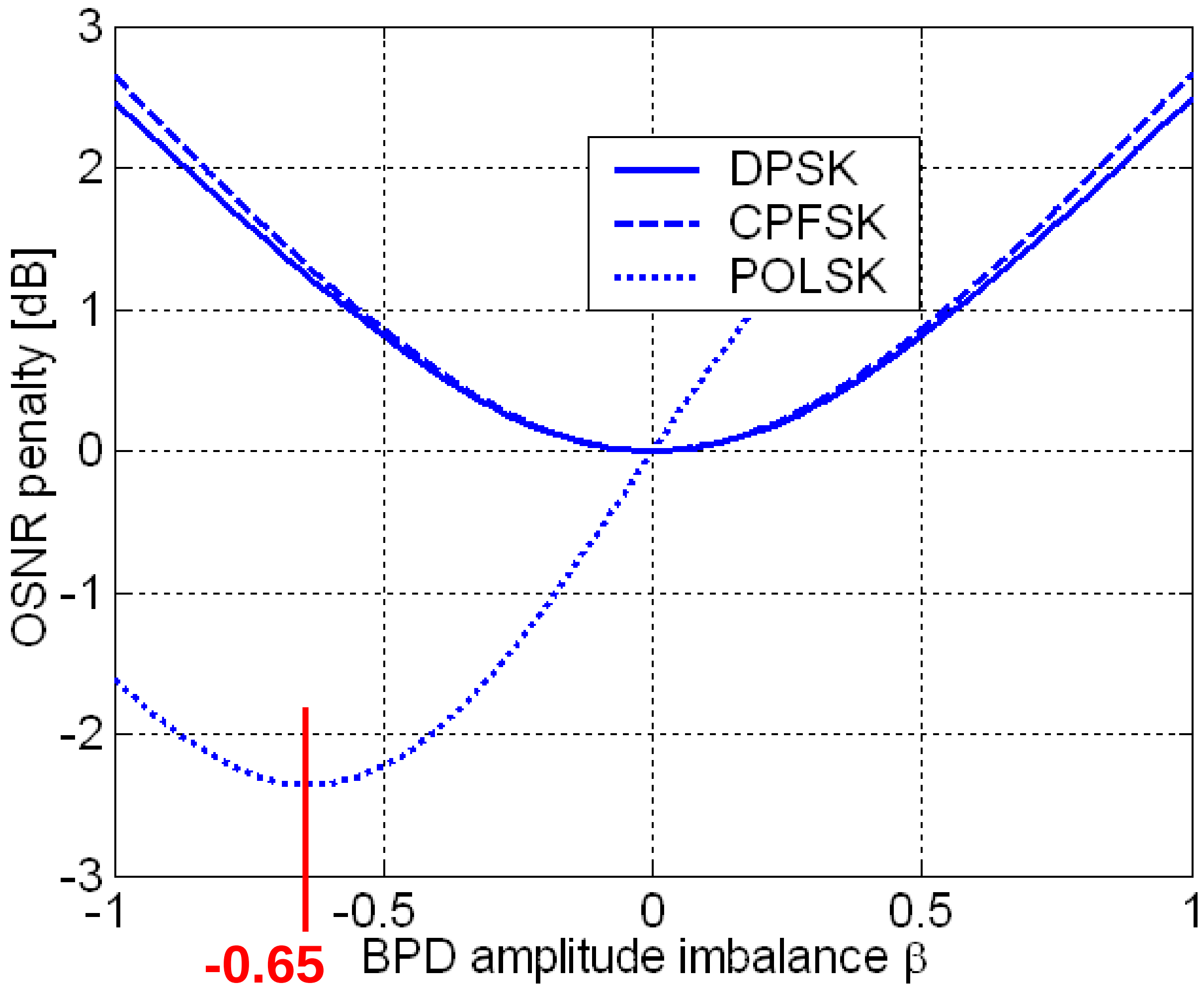
AMZ delay error



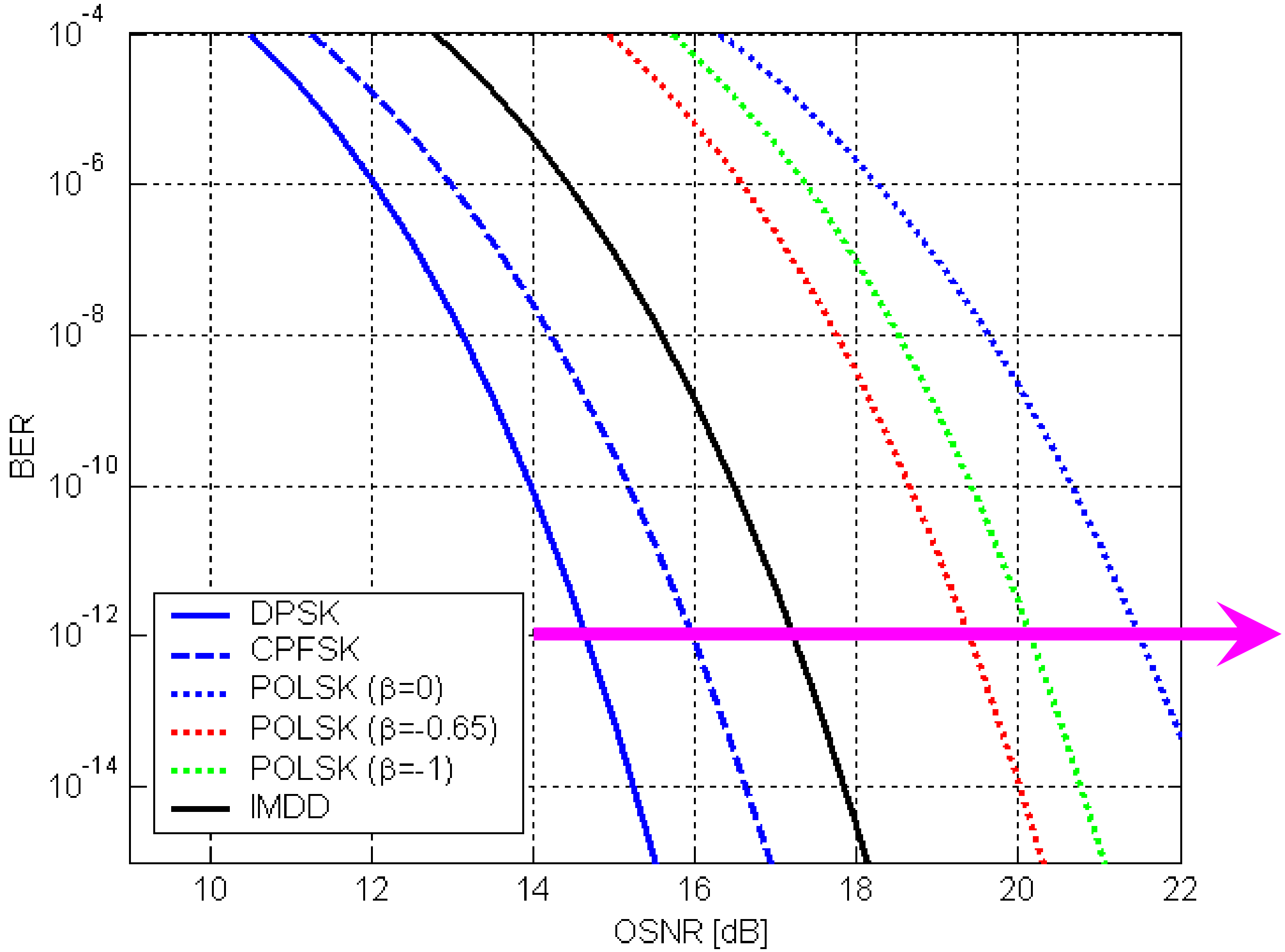
BPD temporal imbalance



BPD amplitude imbalance



BER vs. OSNR



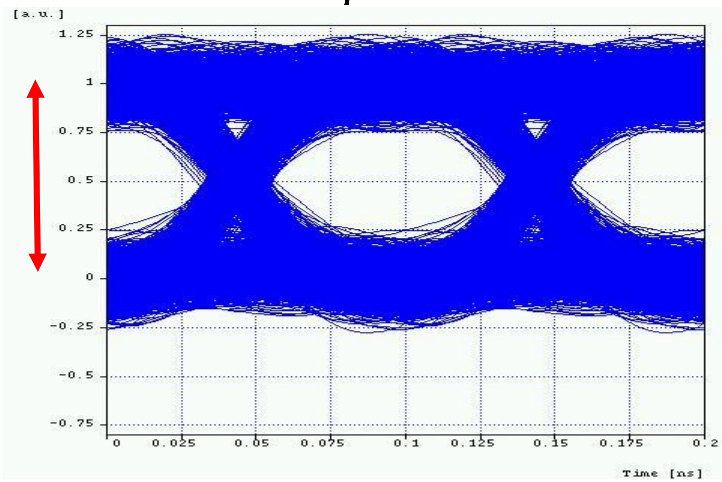
BER=10^{-12}	OSNR [dB]
NRZ	17.2
DPSK	14.7
CPFSK	16.0
PolSK(β=0)	21.5
PolSK(β=-0.65)	19.2
PolSK (β=-1)	20.1

Eye diagrams for PolSK

OPTCOM

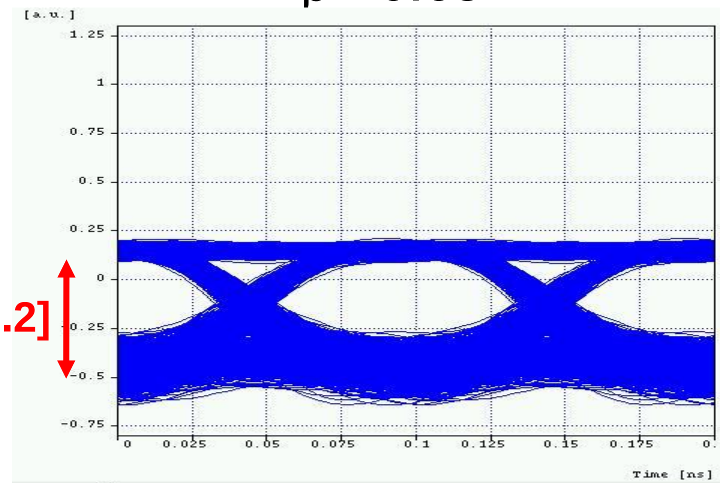
β=0

[0 ; +1]



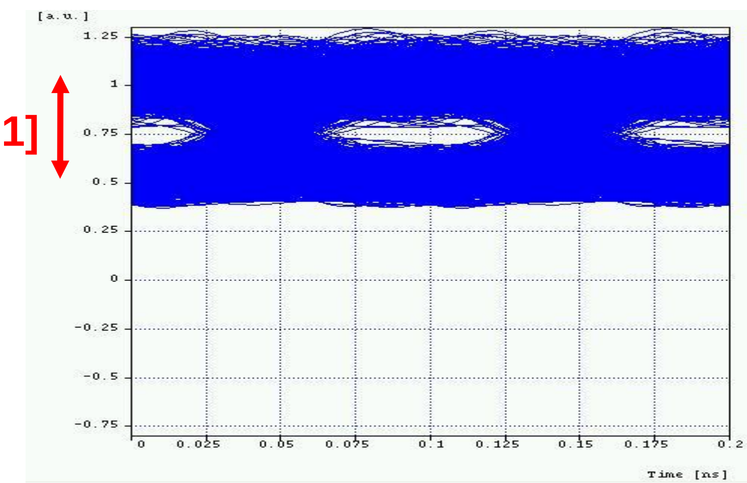
β=-0.65

[-0.6 ; 0.2]



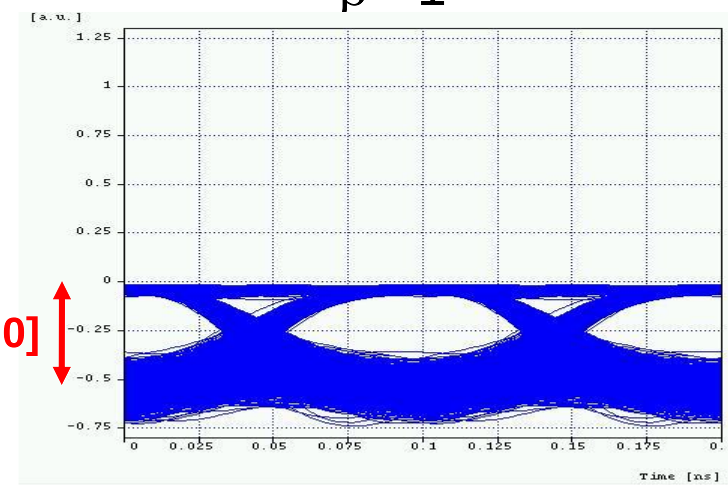
β=1

[+0.5 ; +1]



β=-1

[-0.5 ; 0]



Conclusions

- We have implemented a semi-analytical technique allowing for calculation of BER also in asymmetric Mach-Zehnder based receivers
- Using such technique we are able to define the impact of main receiver impairments
- For PolSK, we found that the optimum receiver is not a balanced one: a sensitivity gain of about 2 dB can be achieved with a single-ended receiver