Quantum Limit of Direct-Detection Receivers: Duobinary vs. IMDD

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Introduction

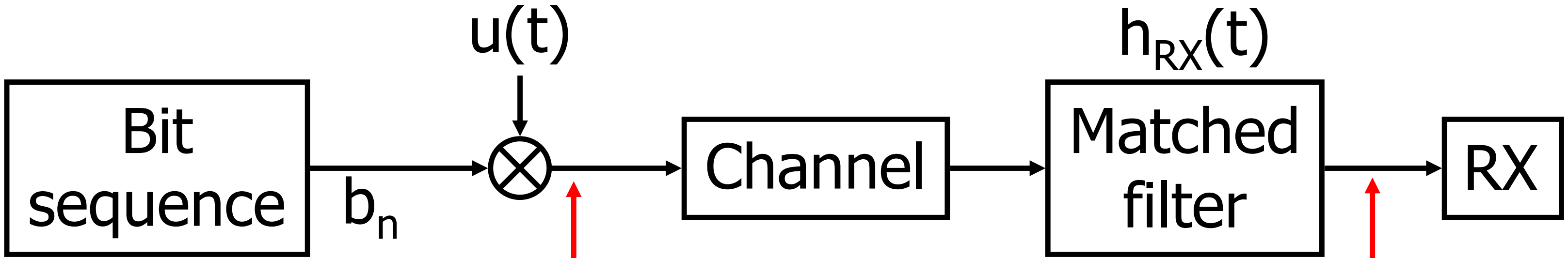
- The duobinary coding is a promising technology for the implementation of ultra-dense WDM optical systems with spectral efficiency close to the Nyquist limit.

- The purpose of this work is to derive, for the first time to our knowledge, the sensitivity of duobinary in ASE noise limited and direct-detected optical systems.

Outline

- Performance limits for Intensity Modulation
- The Duobinary modulation
- Performance limits for Duobinary with a direct-detection receiver
- A practical implementation of optical Duobinary
- Conclusions

Intensity Modulation



$$s_{TX}(t) = \sum_n b_n u(t - nT)$$

$$s_{RX}(t) = \left[\sum_n b_n x(t - nT) + n(t)\right]\hat{v}_p + [m(t)]\hat{v}_o$$

- **Coherent detection**

$$BER = \frac{1}{2} erfc\left(\sqrt{OSNR}\right)$$

$$OSNR = \frac{\bar{P}_S}{2 N_0 R_B}$$

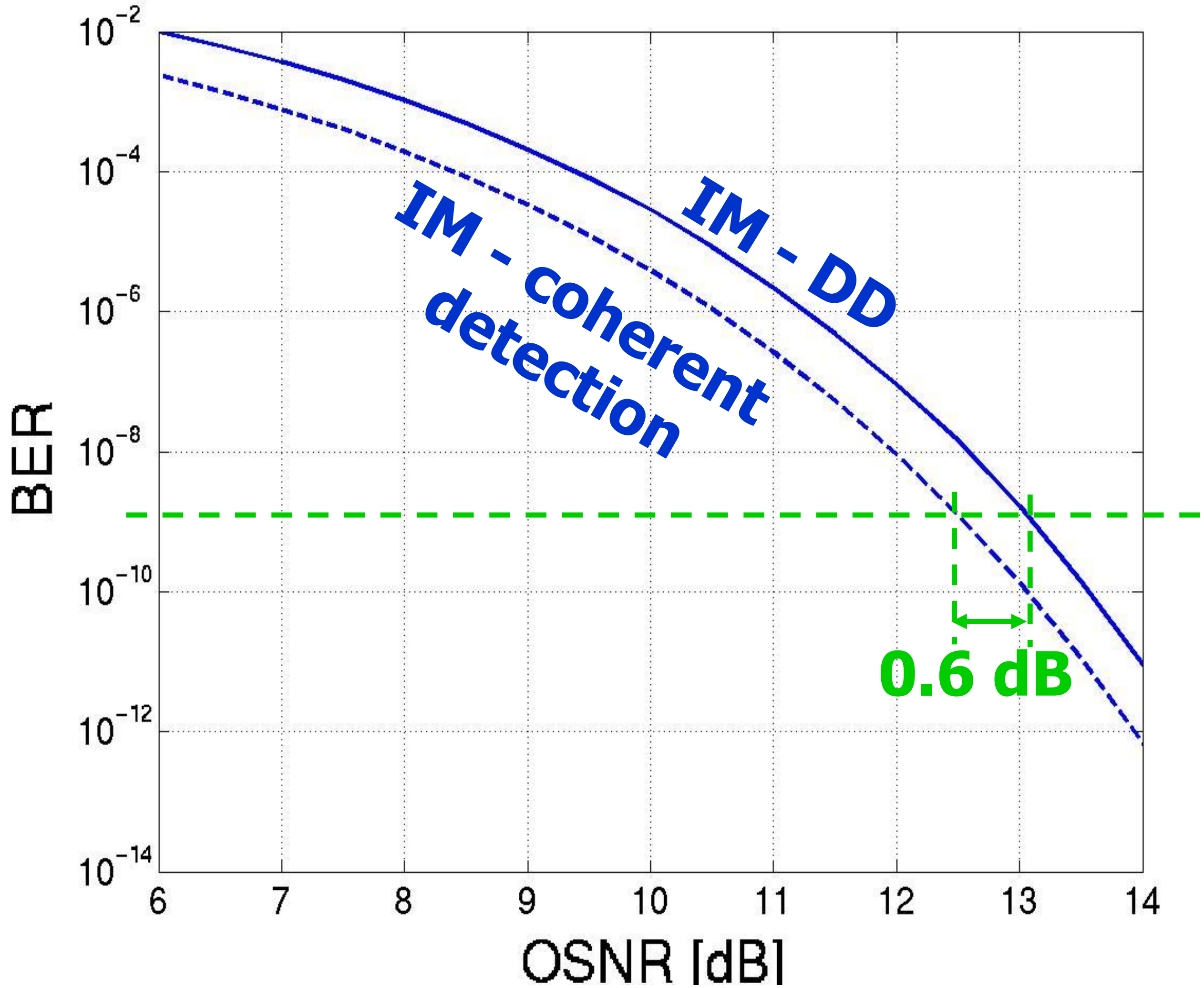
$\bar{P}_S$: Signal power
R_B: Bit-rate
N_0: ASE noise PSD

- **Direct detection**

$$BER = \frac{1}{2}\left\{e^{-\phi}(1+\phi) + 1 - Q_2\left(\sqrt{8\,OSNR}, \sqrt{2\phi}\right)\right\}$$

BER does <u>not</u> depend on the pulse shape

IM: coherent vs. direct detection



IM vs. Duobinary

Intensity Modulation

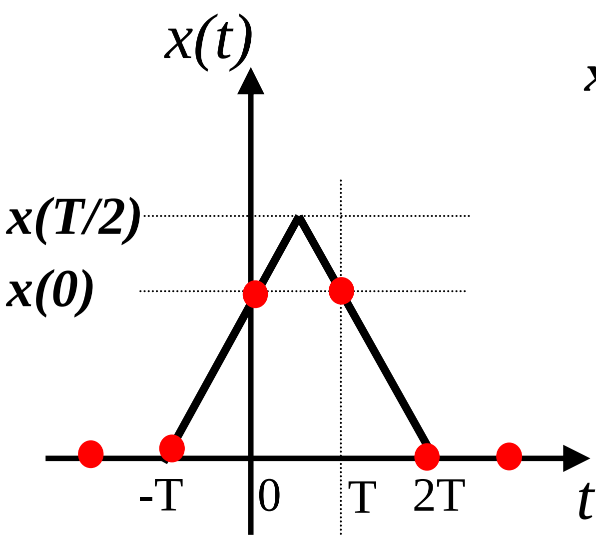
Absence of ISI:

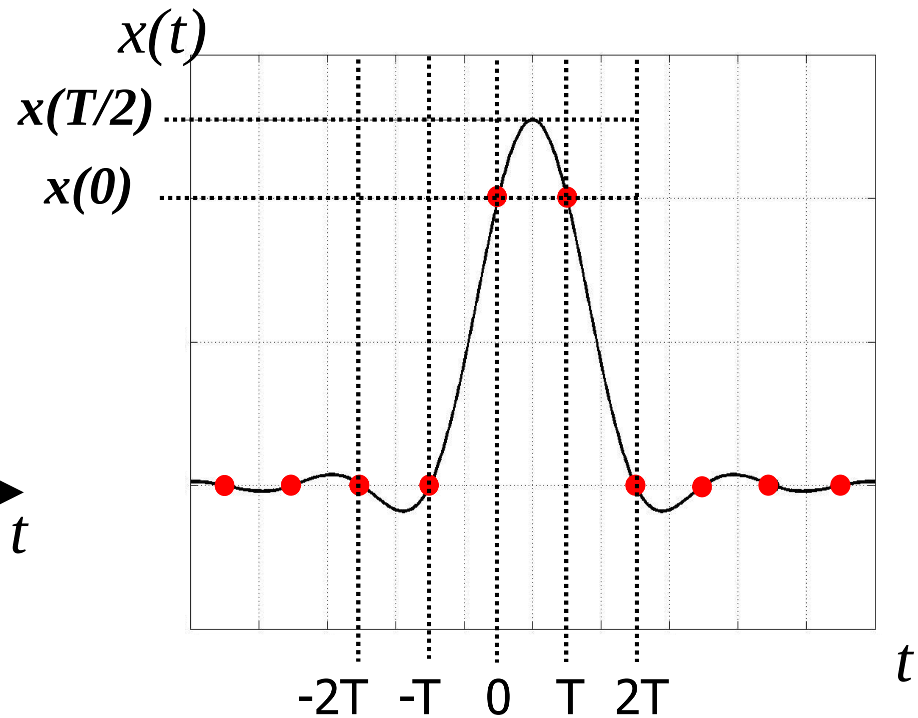
$$x(0) \neq 0, x(nT) = 0, \forall n \neq 0$$

Duobinary

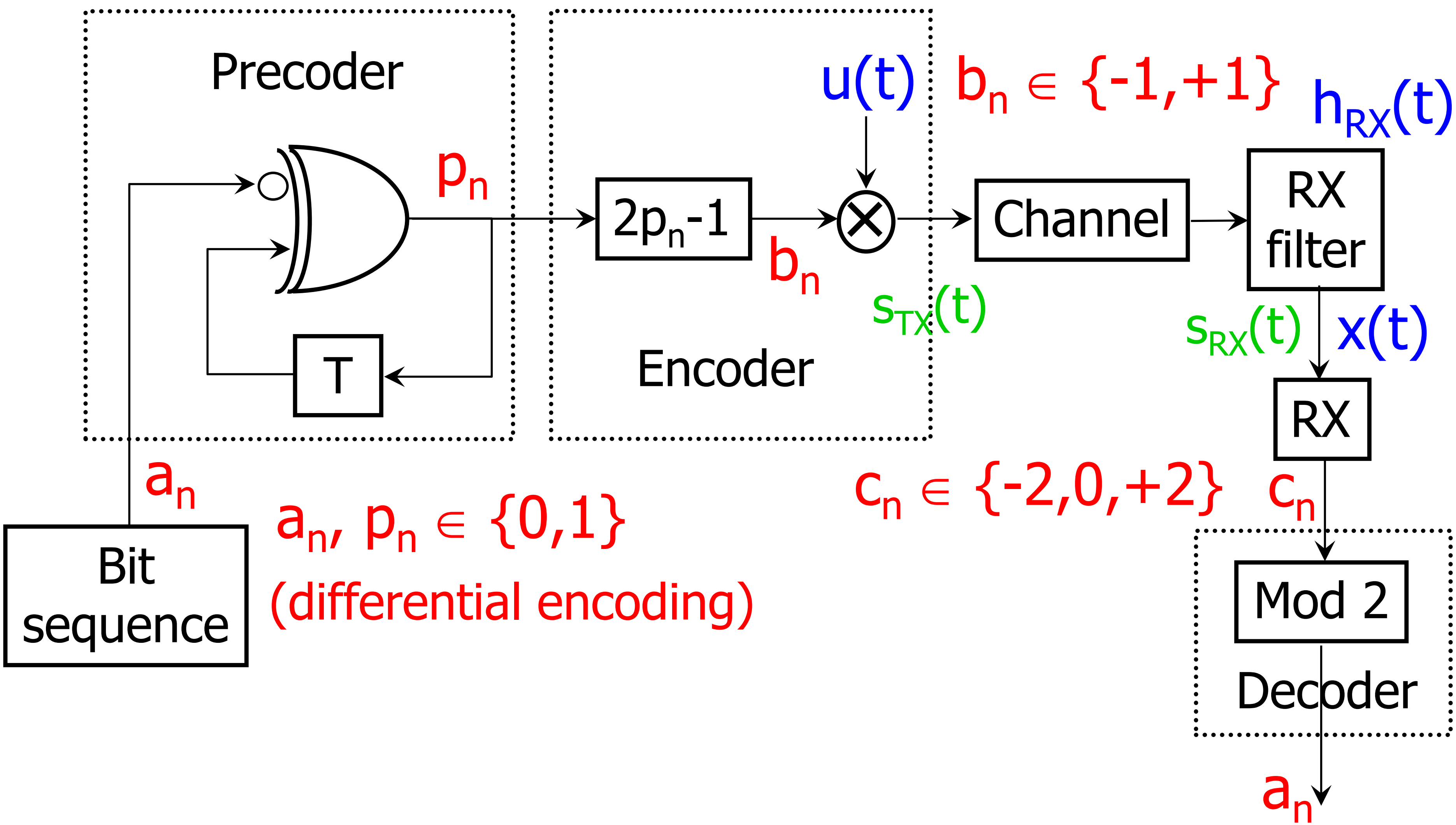
Controlled amount of ISI:

$$x(0) = x(T) \neq 0, x(nT) = 0, \forall n \neq 0{,}1$$





Duobinary system layout



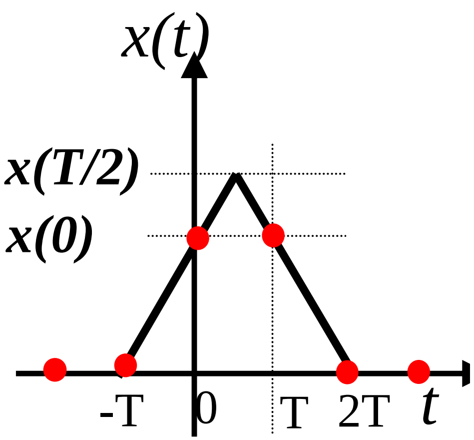
Duobinary received signal

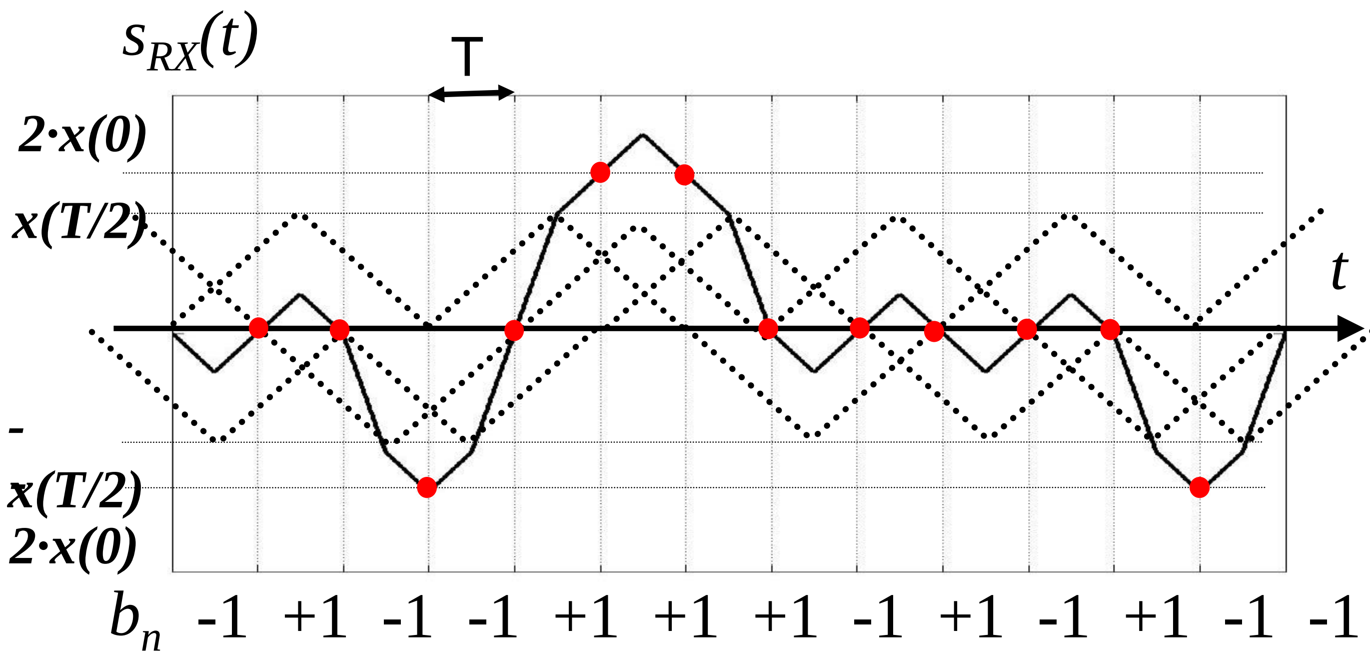
$$s_{RX}\left(t_{opt}\right)=\left[c_n x(0)+n_r+j\,n_i\right]\hat{\mathrm{v}}_{\mathrm{p}}+\left(m_r+j\,m_i\right)\hat{\mathrm{v}}_{\mathrm{o}}$$

n_r, n_i, m_r and m_i are ASE noise contributions: gaussian random variables

$$c_n=\begin{cases}+2 & b_n=b_{n-1}=+1\\ 0 & b_n\neq b_{n-1}\\ -2 & b_n=b_{n-1}=-1\end{cases}$$

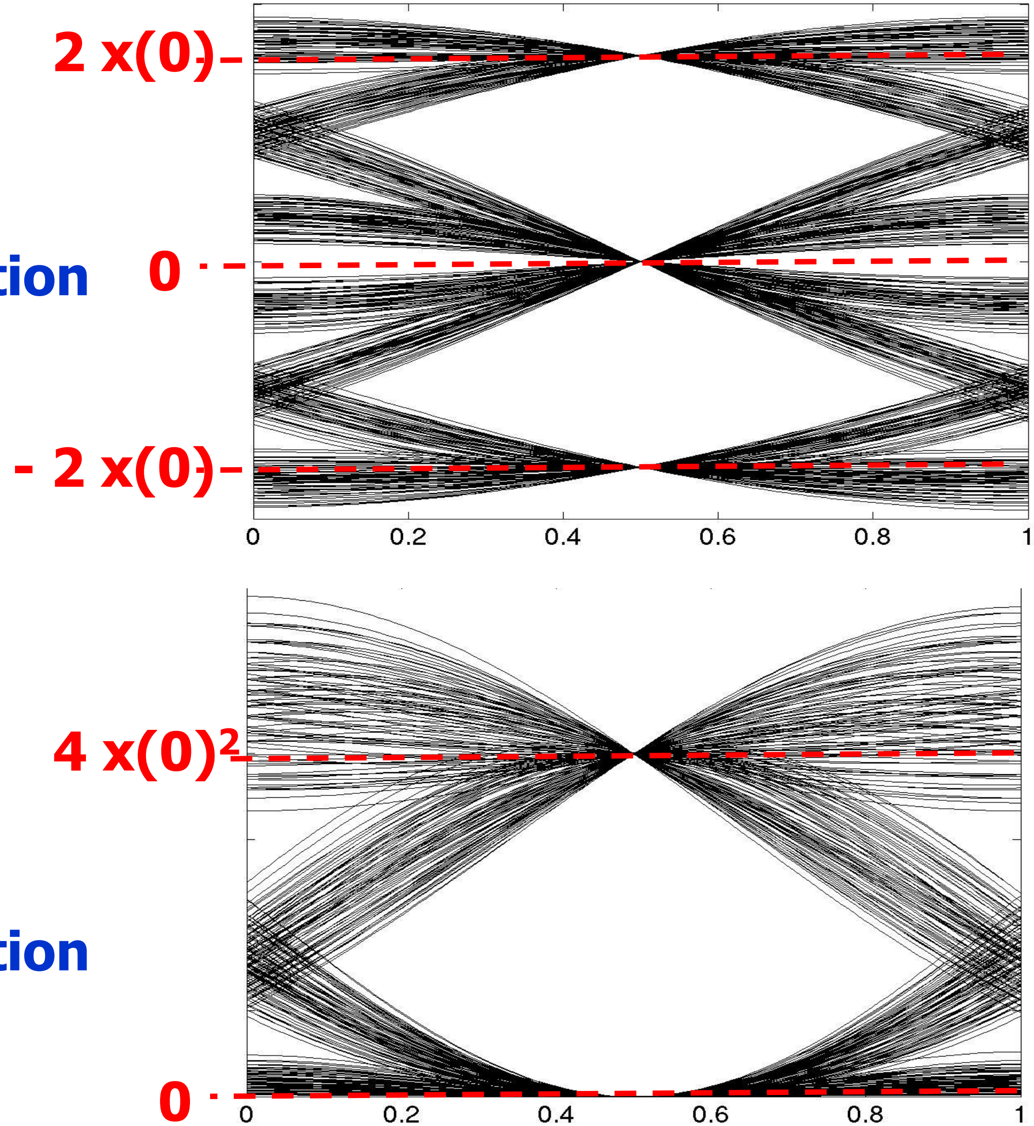
Three-level variable





Noiseless eye diagrams

Minimum bandwidth pulse



Duobinary with direct-detection

- After photodetection, the decision variable is:

$$v = \left| s_{RX}\left(t_{opt}\right) \right|^2 = \left[c_n x(0) + n_r \right]^2 + n_i^2 + m_r^2 + m_i^2$$

- ν is a Chi-square distributed r.v. with centrality parameter $s^2 = (c_n x(0))^2$ and variance σ^2 defined as:

$$\sigma^2 = \frac{N_0}{2} \int_{-\infty}^{+\infty} \left| H_{RX}(f) \right| df = \frac{N_0}{2} \int_{-\infty}^{+\infty} \left| h_{RX}(t) \right| dt$$

Pulse and filter choice

- Which is the optimum receiver?
- It is still an open issue
  - We found counterexamples proving that a matched filter is not always the optimum
- In general, performances depend on both the transmitted pulse u(t) and the receiver filter $h_{RX}(t)$
- Notwithstanding, in order to compare with IM, we selected the matched filter

Using the optical matched filter

- Choosing a matched optical filter, we get:

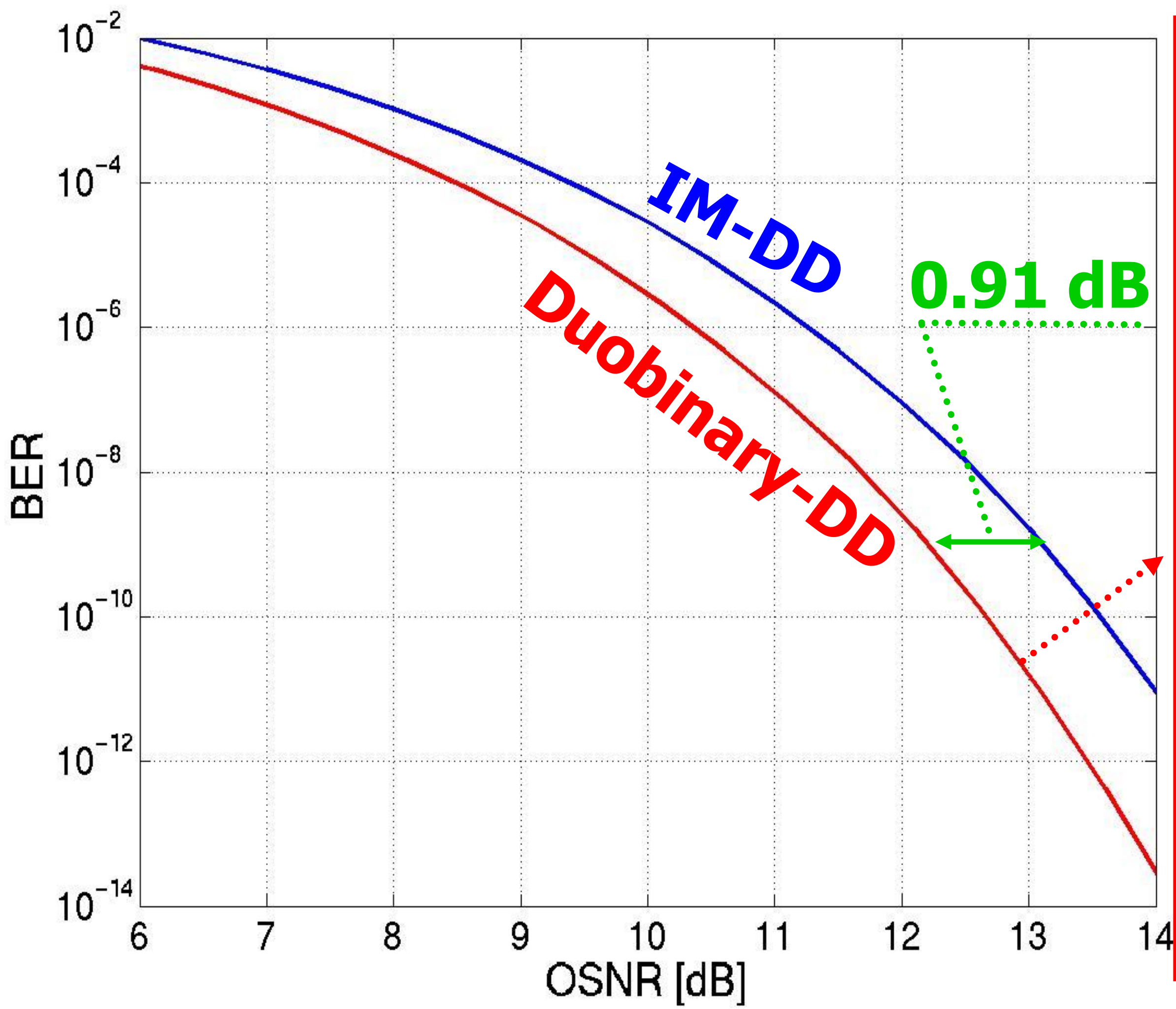
$$\sigma^2 = x\left(\frac{T}{2}\right)\frac{N_0}{2}$$

- The BER can be analytically written as:

$$BER = \frac{1}{2}\left\{ e^{-\phi}(1+\phi) + 1 - Q_2\left(\frac{x(0)}{x(T/2)}\sqrt{16\,OSNR}, \sqrt{2\phi} \right) \right\}$$

The BER depends on the pulse shape !!!

Direct detection: IM vs. Duobinary

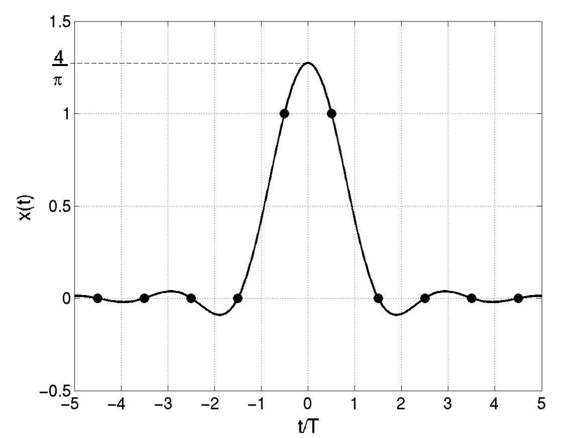


Obtained with the minimum-bandwidth pulse:

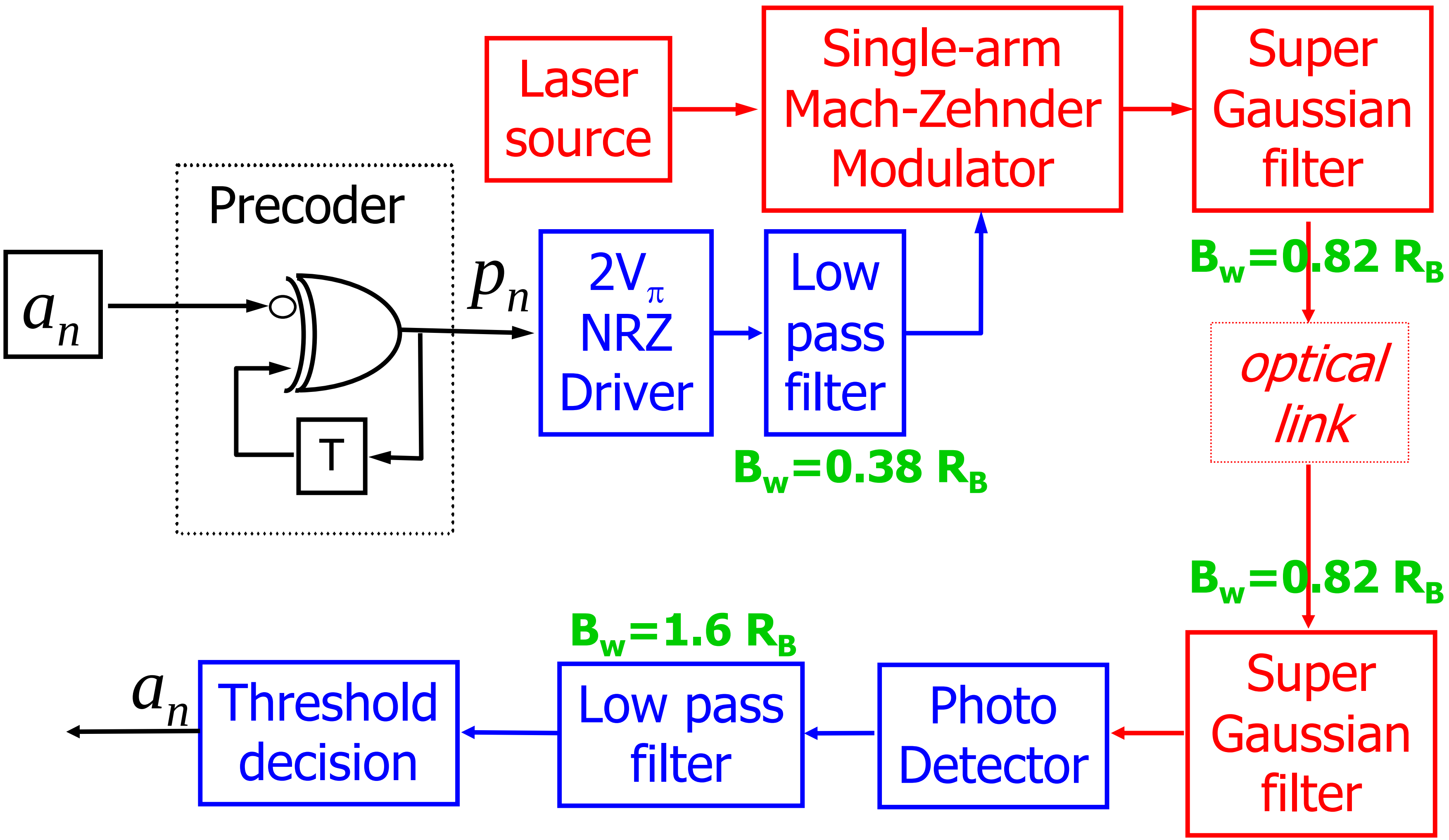
$$X(f) = 2T\cos(\pi fT)$$

$$\text{for } f \in \left[-\frac{1}{2T}, \frac{1}{2T}\right]$$

$$X(f) = 0 \text{ otherwise}$$



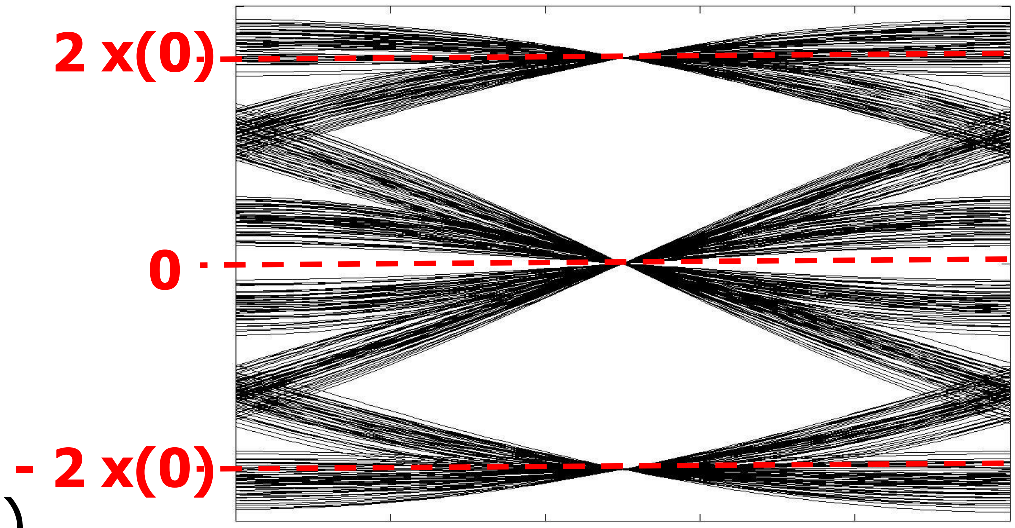
Practical implementation of optical duobinary



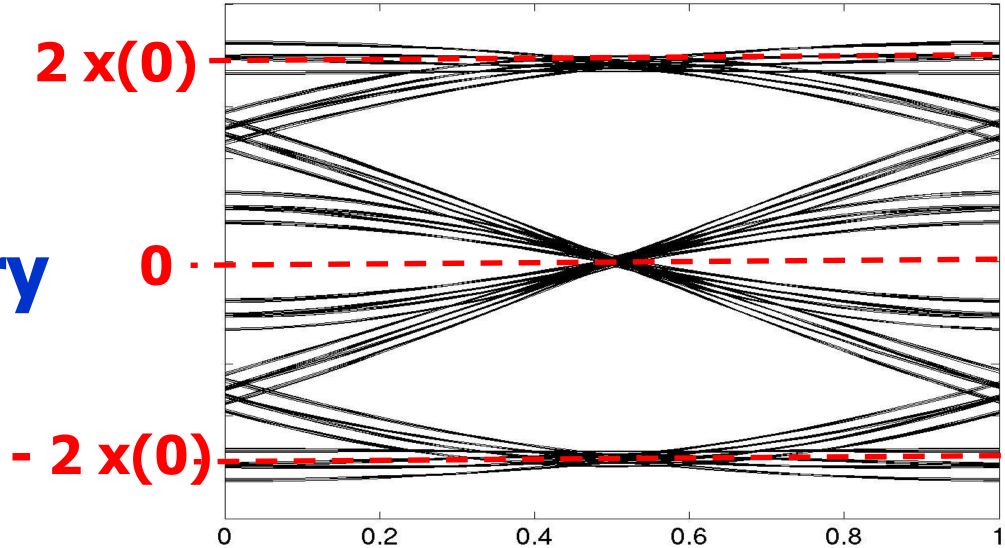
Noiseless eye diagrams

Matched filter with minimum bandwidth pulse

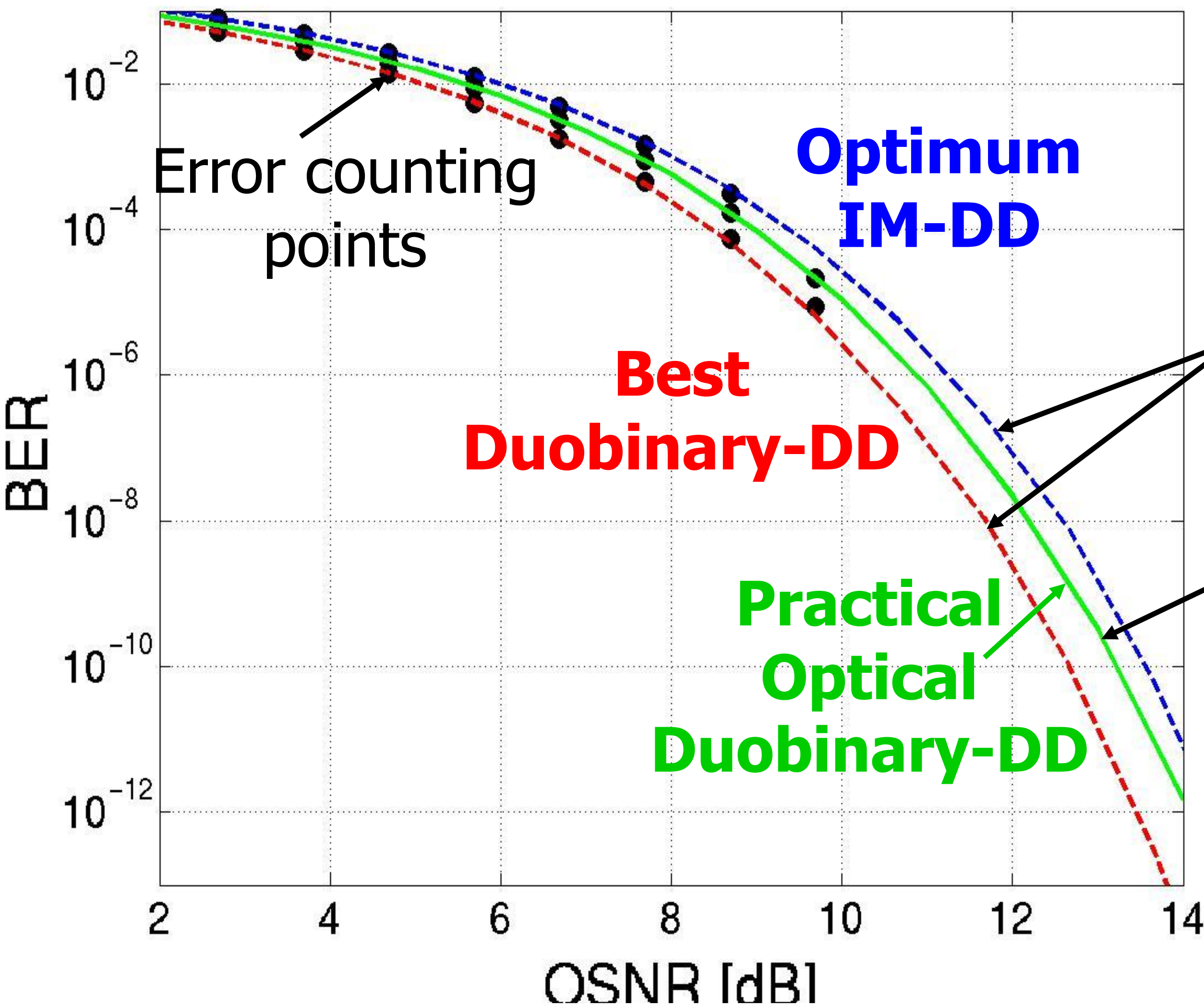
(before photodetection)



Practical optical duobinary



Performance comparison



analytical

Evaluated through simulation using the semi-analytical technique described in:

G. Bosco et al., "A novel analytical approach to the evaluation of the impact of fiber parametric gain on the bit error rate", *IEEE Trans. on Commun.*, vol. 49, no.12, pp. 2154-2163,Nov. 2001

Conclusions

- An expression of the BER for an ASE noise limited optical system employing the duobinary modulation format has been derived.
- The expression of the BER for the duobinary depends on the pulse shape.
- The back-to-back sensitivity of direct-detection duobinary is at least 0.91 dB better than IMDD.
- Practical implementations of optical duobinary have the potential of exceeding the quantum limit of IMDD.