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

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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
  \[ BER = \frac{1}{2} \text{erfc} \left( \sqrt{\text{OSNR}} \right) \]
  \[ \text{OSNR} = \frac{\bar{P}_S}{2N_0 R_B} \]
  \[ \bar{P}_S : \text{Signal power} \]
  \[ R_B : \text{Bit-rate} \]
  \[ N_0 : \text{ASE noise PSD} \]

- Direct detection
  \[ BER = \frac{1}{2} \left\{ e^{-\phi} (1 + \phi) + 1 - Q_2 \left( \sqrt{8 \text{OSNR}}, \sqrt{2\phi} \right) \right\} \]
  BER does **not** depend on the pulse shape
IM: coherent vs. direct detection

![Graph showing BER vs. OSNR with a difference of 0.6 dB between IM-coherent detection and IM-DD.](image-url)
IM vs. Duobinary

Intensity Modulation
Absence of ISI:

Duobinary
Controlled amount of ISI:

\[
x(0) \neq 0, x(nT) = 0, \forall n \neq 0
\]

\[
x(0) = x(T) \neq 0, x(nT) = 0, \forall n \neq 0, 1
\]
Duobinary system layout

![Diagram of Duobinary system layout]

Bit sequence: $a_n, p_n \in \{0,1\}$ (differential encoding)

- Precoder
- Encoder
- Channel
- RX filter
- RX
- Mod 2
- Decoder

Signals:
- $u(t)$
- $b_n \in \{-1,+1\}$
- $h_{RX}(t)$
- $s_{TX}(t)$
- $s_{RX}(t)$
- $c_n \in \{-2,0,+2\}$
- $x(t)$
- $c_n$
- $a_n$
Duobinary received signal

\[ s_{RX}(t_{opt}) = \left[ c_n x(0) + n_r + j n_i \right] \hat{v}_p + (m_r + j m_i) \hat{v}_o \]

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

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

Three-level variable

\( x(t) \) \hspace{1cm} \( s_{RX}(t) \)

\( x(T/2) \) \hspace{1cm} \( 2 \cdot x(0) \)

\( x(0) \) \hspace{1cm} \( x(T/2) \)

- \( T \) \hspace{1cm} 0 \hspace{1cm} T \hspace{1cm} 2T \hspace{1cm} t \)

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Noiseless eye diagrams

Before photodetection

Minimum bandwidth pulse

After photodetection
Duobinary with direct-detection

After photodetection, the decision variable is:

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

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

\[ \sigma^2 = \frac{N_0}{2} \int_{-\infty}^{+\infty} |H_{RX}(f)| df = \frac{N_0}{2} \int_{-\infty}^{+\infty} |h_{RX}(t)| dt \]
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
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:

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

The BER depends on the pulse shape !!!
Direct detection: IM vs. Duobinary

Obtained with the minimum-bandwidth pulse:

\[ X(f) = 2T \cos(\pi fT) \]

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

\[ X(f) = 0 \] otherwise

\[ f_T \]

\[ f \]

\[ \cos^2(2\pi) \]

\[ X(f) = 0.91 \text{ dB} \]
Practical implementation of optical duobinary

\[ a_n \xrightarrow{\text{Precoder}} P_n \]

\[ 2V_π \text{ NRZ Driver} \]

\[ \text{Single-arm Mach-Zehnder Modulator} \]

\[ \text{Laser source} \]

\[ \text{Low pass filter} \]

\[ \text{Threshold decision} \]

\[ \text{Photo Detector} \]

\[ \text{Super Gaussian filter} \]

\[ B_w = 0.82 \ R_B \]

\[ B_w = 1.6 \ R_B \]

\[ B_w = 0.38 \ R_B \]
Noiseless eye diagrams

Matched filter with minimum bandwidth pulse

(before photodetection)

Practical optical duobinary
Performance comparison

Error counting points

Optimum IM-DD

Best Duobinary-DD

Practical Optical Duobinary-DD

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