10 Gb/s Duobinary Signaling over Electrical Backplanes

*Experimental Results and Discussion*

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*802.3AP Backplane Ethernet*
Supporters

- John D’Ambrosia*  Tyco
- John Khoury  Vitesse
- Majid Barazande-Pour  Vitesse
- Glen Koziuk  Vitesse

*This contributor supports multi-level signaling standardization for certain applications. His support does not necessarily reflect the support of duobinary over competing technology solutions.
Talk Outline

- Motivation – Why Duobinary?
- Description of duobinary signaling
- Proposed Architecture
- Measured results - 10 Gb/s duobinary transmission over Tyco backplanes
- Comparison of eye diagrams for optimally pre-emphasized formats: PAM-4, duobinary, and NRZ using the Quadroute Backplane system – *jitter discussion and cross-talk comments*
- The Future – towards 4x25 Gb/s *electrical* backplanes
- Conclusion
So Why Duobinary?

- **The Bottom Line**: for the channel models of interest, the other solutions are not adequate
  - NRZ requires too much bandwidth
  - PAM-4 requires too much complexity and power

- Duobinary provides a simple, low-power approach to sending 10-Gb/s data through legacy and non-legacy backplane systems.
  - *It is a logical solution*: it takes advantage of the low pass roll off response of the typical backplane channel

- Simpler implementation than PAM-4
  - Duobinary requires 2 decision thresholds.
  - PAM-4 requires 3.

- Less bandwidth than NRZ

- Easy scalability to higher frequencies
  - Migration to 40 Gb/s over electrical channels should be possible!

- Simple backward compatibility with NRZ systems
What is Duobinary Signaling?

- A three level signaling scheme that uses intersymbol interference (ISI) in a controlled way instead of trying to eliminate it.

- First described by Adam Lender, 1963.

- Has been used for low speed (KHz) data communications.

- A different formulation of duobinary signaling has recently been used in the optical transmission.

Typical Eye Diagram

Understanding Duobinary Signal Generation

- When NRZ data is passed through the proper linear circuit, an ideal duobinary signal will result.

- Creating a duobinary signal from NRZ requires a delay and add of two sequential NRZ bits.

- This can be accomplished in multiple ways
  - Delay and add logic
  - Appropriate analog or digital filters that create the correct intersymbol interference (ISI)
    - Pre-emphasis, equalization or both
  - A backplane channel that creates the proper ISI
    - Some additional spectral reshaping is required for real backplanes
  - A combination of filtering and a backplane
**Proposed Duobinary Signaling Concept for Backplane Transmission**

We reshape the binary data spectrum from the transmitter such that the resulting waveform available at the receiver after traveling through the backplane is a duobinary signal.

The backplane is preceded by a simple filter that modifies the response of the communication channel so that it looks like an ideal duobinary data filter. As a result, the binary data from the transmitter appears as duobinary data at the receiver.

The duobinary data is converted to NRZ using a high-speed duobinary-to-binary data converter and then presented to the receiver.
Architecture Migration from NRZ to Duobinary

NRZ Link

TX Logic → TX I/O with pre-emphasis → Back-plane → RX I/O → Equalization & CDR

Duobinary Link

TX Logic → TX I/O with pre-emphasis → Back-plane → 3 level RX I/O → Duo-to-binary converter → Equalization & CDR

*May not be necessary, TBD

Binary data receiver

Binary data receiver!!
The Tyco Backplanes

### Backplane Characteristics

<table>
<thead>
<tr>
<th>Board Name</th>
<th>Nelco Dielectric</th>
<th>Trace Geometry (width, space, width)</th>
<th>Connector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadroute@</td>
<td>4000-6</td>
<td>4,6,4 (mils)</td>
<td>HM-ZD</td>
</tr>
<tr>
<td>XAUI&amp;</td>
<td>4000-2</td>
<td>10,14,10 (mils)</td>
<td>HM-ZD</td>
</tr>
<tr>
<td>XAUI%</td>
<td>4000-6</td>
<td>10,14,10 (mils)</td>
<td>HM-ZD</td>
</tr>
</tbody>
</table>

@modified version of commercial board
&commercially available
%modified version of commercial board
Transfer function through the Quadroute backplane (4000-6)*

<table>
<thead>
<tr>
<th>Link</th>
<th>3 dB Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 inch</td>
<td>1.81 GHz</td>
</tr>
<tr>
<td>20 inch</td>
<td>664 MHz</td>
</tr>
<tr>
<td>34 inch</td>
<td>410 MHz</td>
</tr>
</tbody>
</table>

Note: IEEE model is per May 25, 2004 IEEE802.3AP meeting – Goergen02_0504.pdf, pg. 10.

*modified version of the commercial board
Signal Evolution Through the System – Measured Performance

- **Binary Data Transmitter**
  - **Precoder**
  - **FIR Filter**
  - **Electrical Backplane**
  - **Duobinary to Binary Converter**
  - **Binary Data Receiver**

- **2 taps**
  - **Tyco Quadroute 4000-6 (34” trace)**

- **Pre-emphasized eye**
  - **50 ps/div**

- **Recovered binary signal**
  - **50 ps/div**

- **Duobinary signal out of the backplane**
  - **Decision thresholds**
  - **50 ps/div**

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Test Setup and Experimental Results

**Test Setup and Experimental Results**

- **Trace length**
  - 20 in. (~51 cm)
  - 34 in. (~86 cm)
- **Data rate**
  - 10 Gb/s
  - 10 Gb/s
- **Sequence length**
  - $2^{31}-1$
  - $2^{23}-1$
- **Bit error rate**
  - <10^{-13}\text{**}
  - <10^{-13}\text{**}
- **Backplanes tested**
  - Quadroute, XAUI (both)
  - Quadroute, XAUI (both)
- **FIR architecture**
  - 2-tap
  - 2-tap

**Note:** This was a time limited measurement. We observed 0 errors in a 20 minute measurement period on each of the six traces discussed above.
Comparison of pre-emphasized formats: NRZ, PAM-4, and Duobinary

_Eye Diagrams Through a Tyco Quadroute* Backplane_

Simulation Model

Either NRZ, PAM-4, or Duobinary

Optimized for each data format

Based on measured S-Parameters

Data Transmitter → 2-tap FIR Filter → Electrical Backplane → Oscilloscope Display

600 mVpp single ended

Simulation Notes

• 10 Gb/s data transmission
• All inputs are constrained to a 600 mVpp single-ended amplitude at the OUTPUT of the 2-tap FIR filter
• No noise sources
• Backplane S-Parameters were measured on a vector network analyzer
• PRBS Length = 2^{10}-1
• 2-tap FIR optimization was accomplished by minimizing the BER obtained through semianalytic simulation. The relative tap amplitude and delay parameters were swept to obtain the minimum BER.

*Dielectric is Nelco 4000-6. Modified version of commercial board.
Comparison of pre-emphasized formats: NRZ, PAM-4 and Duobinary

Single-ended backplane output resulting from 10.0 Gb/s transmitter with 600 mVpp single-ended amplitude including 2-tap FIR filter, PRBS $2^{10}-1$

Tyco Quadroute 34” Link

NRZ

PAM-4

Duobinary

Denotes NRZ eye opening measure

15 mV/DIV : 30 ps/DIV

15 mV/DIV : 60 ps/DIV

15 mV/DIV : 30 ps/DIV

Tyco Quadroute 6” Link

NRZ

PAM-4

Duobinary

15 mV/DIV : 30 ps/DIV

15 mV/DIV : 60 ps/DIV

15 mV/DIV : 30 ps/DIV

80 mV/DIV : 30 ps/DIV

80 mV/DIV : 60 ps/DIV

80 mV/DIV : 30 ps/DIV
Comparison of pre-emphasized formats: NRZ, PAM-4, and Duobinary

Summary of Simulation Results*

For Tyco Quadroute Links
(Using optimized 2-tap FIR pre-emphasis)

<table>
<thead>
<tr>
<th></th>
<th>6” Link (#1)</th>
<th>20” Link (#5)</th>
<th>34” Link (#8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>78 mVpp</td>
<td>37 mVpp</td>
<td>10 mVpp</td>
</tr>
<tr>
<td>DUO</td>
<td>137 mVpp</td>
<td>85 mVpp</td>
<td>25 mVpp</td>
</tr>
<tr>
<td>PAM4</td>
<td>101 mVpp</td>
<td>51 mVpp</td>
<td>15 mVpp</td>
</tr>
</tbody>
</table>

Minimum Single-ended Vertical Eye Opening at Threshold:

Horizontal Eye Opening at Threshold:

<table>
<thead>
<tr>
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<th>6” Link (#1)</th>
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<th>34” Link (#8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>65 ps</td>
<td>71 ps</td>
<td>69 ps</td>
</tr>
<tr>
<td>DUO</td>
<td>39 ps</td>
<td>52 ps</td>
<td>49 ps</td>
</tr>
<tr>
<td>PAM4</td>
<td>94 ps</td>
<td>84 ps</td>
<td>84 ps</td>
</tr>
</tbody>
</table>

*Based on measured S-Parameter data
Comments on Cross-talk*

- To first order, cross-talk increases with frequency
  - NRZ requires roughly twice the bandwidth of duobinary and PAM-4

- To first order, susceptibility to cross-talk increases with formats that require higher signal-to-noise
  - PAM-4 requires about 7 dB more SNR than NRZ to achieve the same bit error rate.
  - *Duobinary requires about 2.1 dB more SNR than NRZ to achieve the same bit error rate.*

- For channels such as the one proposed by this task force (per Goergen, May 2004), duobinary should be the winner because…
  - Multilevel signaling is needed due to the steep backplane rolloff.
  - Duobinary provides nearly 5 dB SNR advantage over PAM-4 while occupying the same bandwidth.

* For detailed simulations showing the impact of cross-talk on duobinary signaling, see the Vitesse presentation, IEEE 802.3AP, July 2004, entitled, “Crosstalk and Receiver Equalization for 10G Serial Ethernet.”
The Future – Electrical 25+ Gb/s Transmission!

- What is after 10 Gb/s?
  - Duobinary enabled 25+ Gb/s!

- Our duobinary-to-binary decoder should scale to 40 Gb/s
  - Demonstration of concept

- Requires improved electrical channel compared with 10Gb/s
  - However, microwave-quality electrical backplanes are obviously much more attractive than moving to an optical backplane

- Simulation of 30 Gb/s transmission based on differential S-Parameter measurements
  - Three-tap pre-emphasis
  - Duobinary signaling
  - Board Characteristics
    - FR4 backplane – 50cm
    - Rogers interface cards
    - Back-drilled vias
  - The use of a microwave substrate (e.g. Rogers) for the backplane would result in a larger eye and the potential for a working link.
Conclusion

- **Electrical duobinary signaling is the logical choice for providing 10 Gb/s transmission over both legacy and non-legacy backplane systems.**
  - It provides spectral compression and only a 2.1 dB SNR penalty over NRZ, providing the best of both worlds.
  - It takes advantage of the natural roll off of backplane systems instead of trying to work around it.

- Using the proposed technique, we have demonstrated 10 Gb/s data transmission over legacy backplanes, specifically the Tyco Quadroute and XAUI using HM-ZD connectors.

- Implementation is very similar to standard NRZ except for the need for a precoder, a duobinary-to-binary converter, and different taps weights for pre-emphasis circuitry...The Result...a simpler and lower power solution than can be provided by other techniques.