Lucent Technologies
Bell Labs Innovations

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

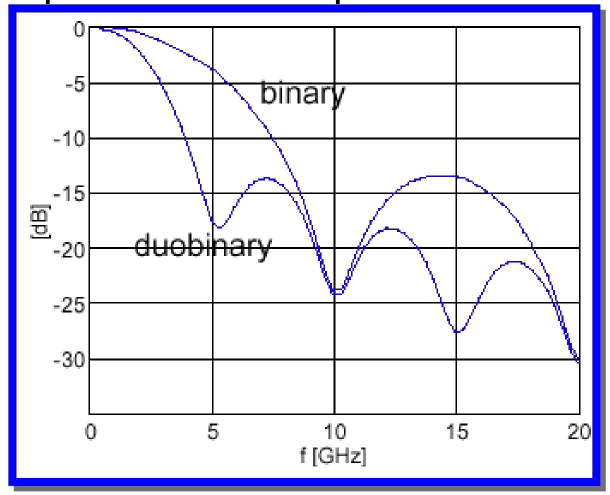
*This contributor supports multi-level signaling standardization for certain applications. His support does not necessarily reflect the support of duobinary over competing technology solutions.

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

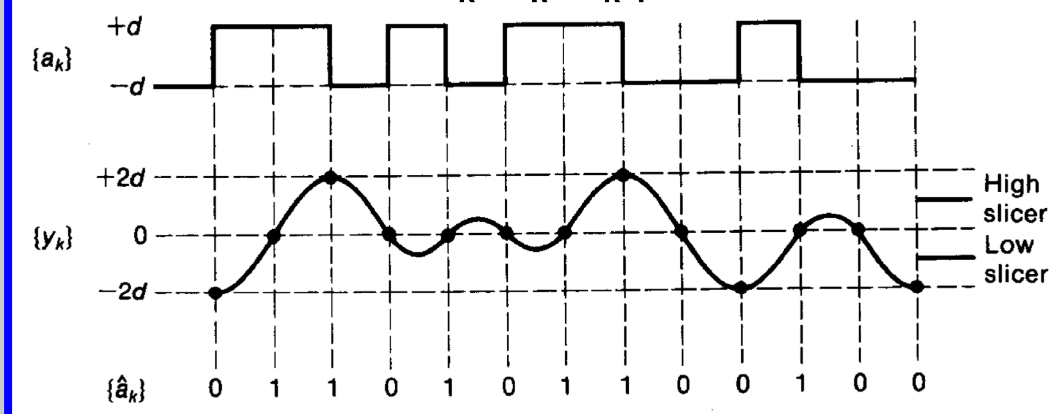


- Simpler implementation than PAM-4
  - Duobinary requires 2 decision thresholds.
  - PAM-4 requires 3.
- Less bandwidth than NRZ
- Easy scalability to higher frequencies
  - Migration to 40 Gb/s over electrical channels should be possible!
- Simple backward compatibility with NRZ systems

What is Duobinary Signaling?

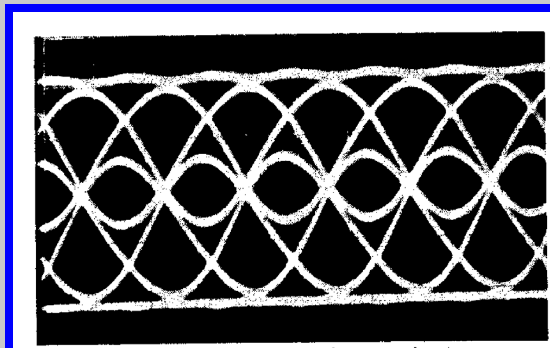
- *A three level signaling scheme that uses intersymbol interference (ISI) in a controlled way instead of trying to eliminate it.*
- *First described by Adam Lender, 1963.*
- *Has been used for low speed (KHz) data communications.*
- *A different formulation of duobinary signaling has recently been used in the optical transmission.*

$y_k = a_k + a_{k-1}$



Smith, D.R., **Digital Transmission Systems**, Boston: Kluwer Academic Publishers, 1985.

Typical Eye Diagram

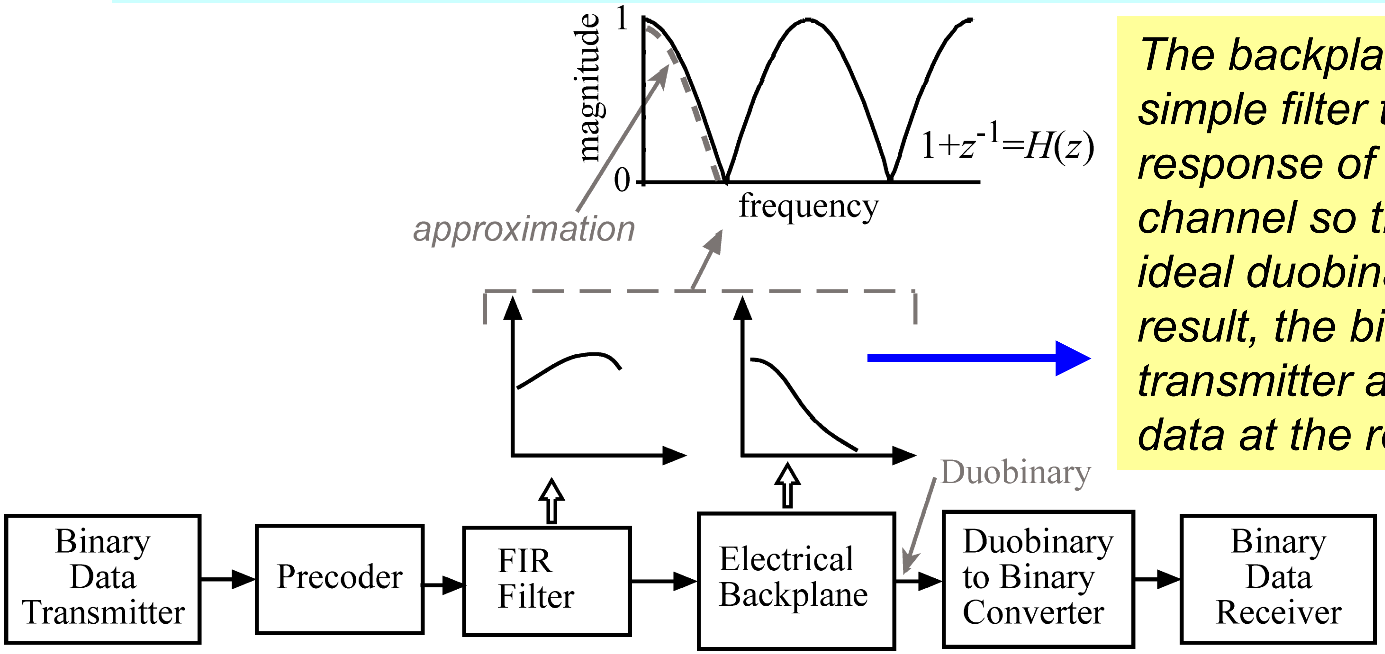


Understanding Duobinary Signal Generation

- 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

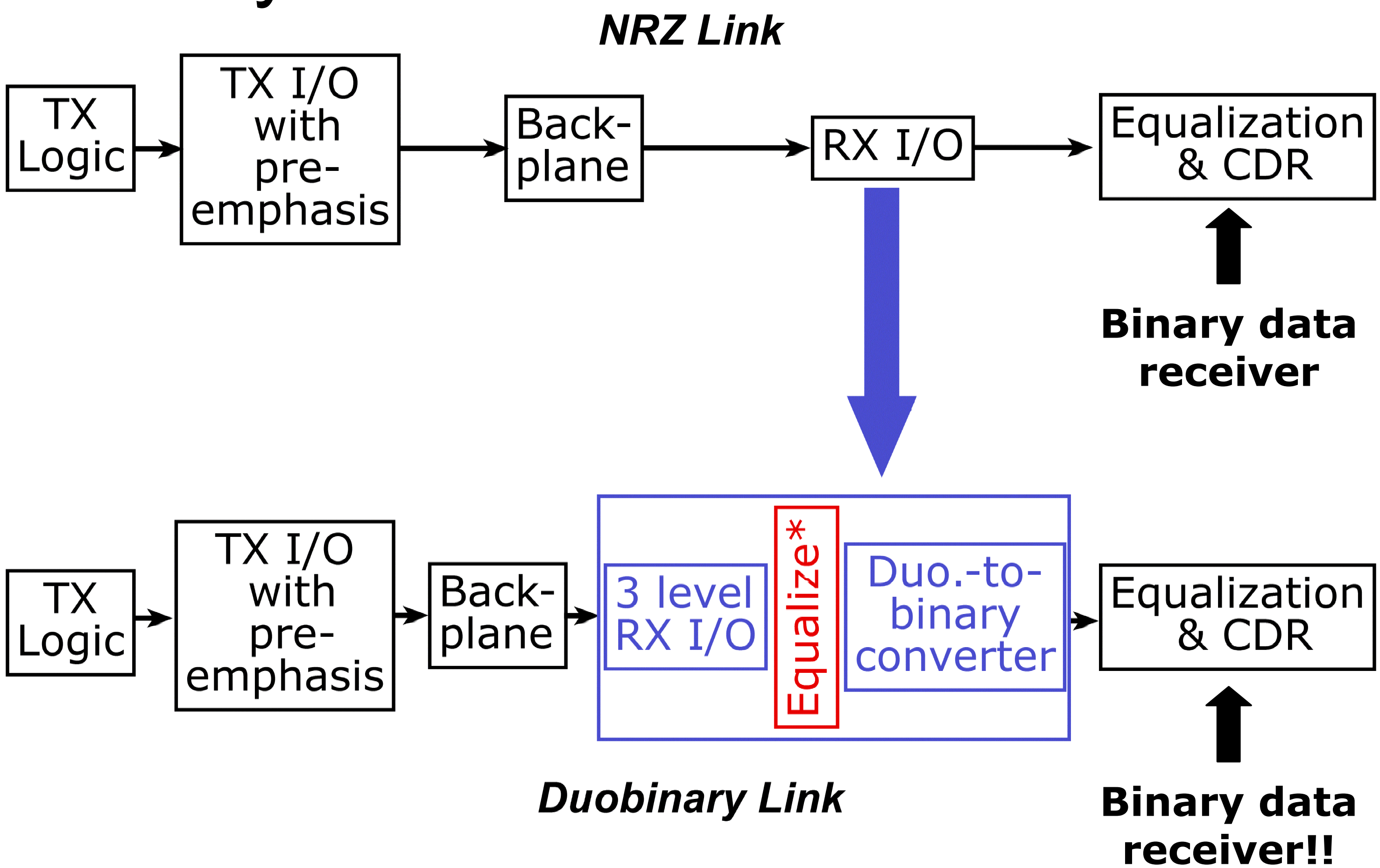
We reshape the binary data spectrum from the transmitter such that the resulting waveform available at the receiver *after* traveling through the backplane is a *duobinary* signal.



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.

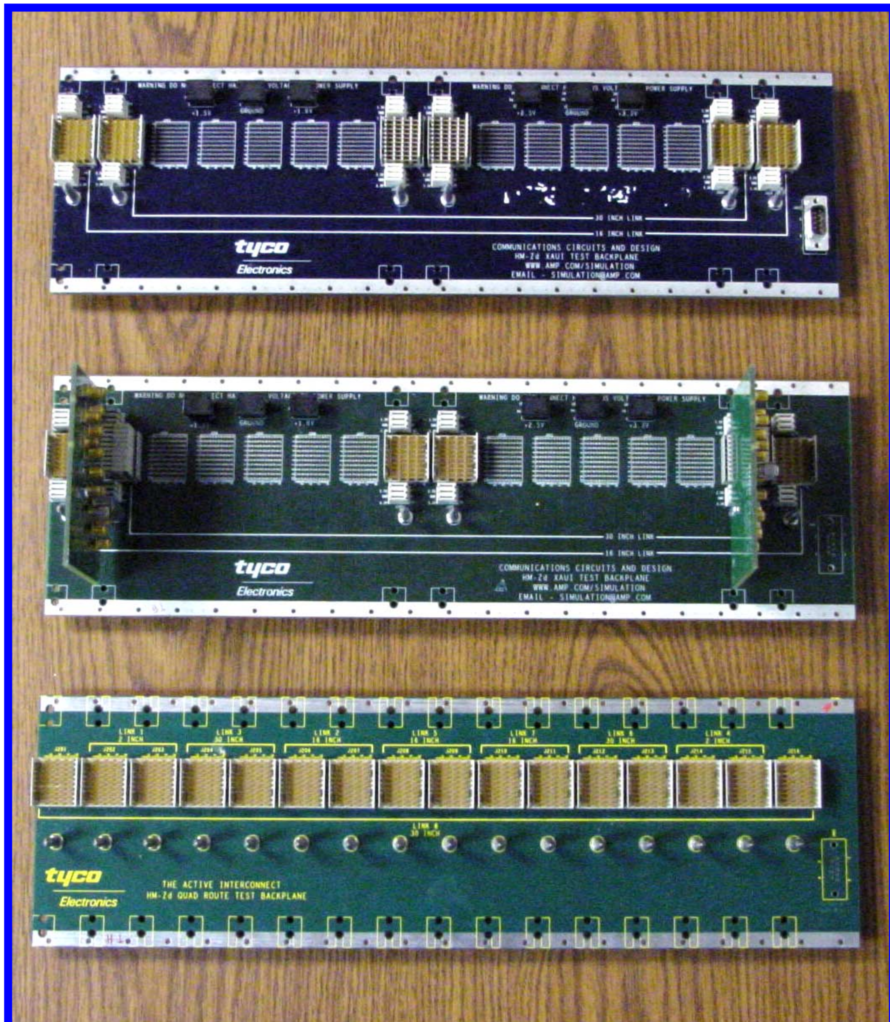
The duobinary data is converted to NRZ using a high-speed duobinary-to-binary data converter and then presented to the receiver .

Architecture Migration from NRZ to Duobinary



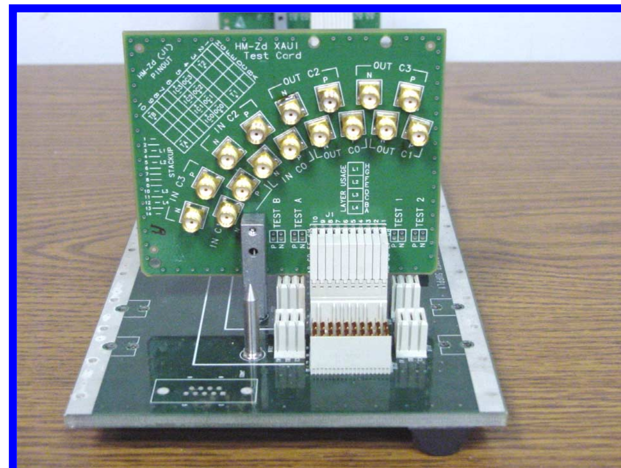
*May not be necessary, TBD

The Tyco Backplanes



Backplane Characteristics

Board Name	Nelco Dielectric	Trace Geometry (width, space, width)	Connector Type
Quadroute@	4000-6	4,6,4 (mils)	HM-ZD
XAUI&	4000-2	10,14,10 (mils)	HM-ZD
XAUI%	4000-6	10,14,10 (mils)	HM-ZD



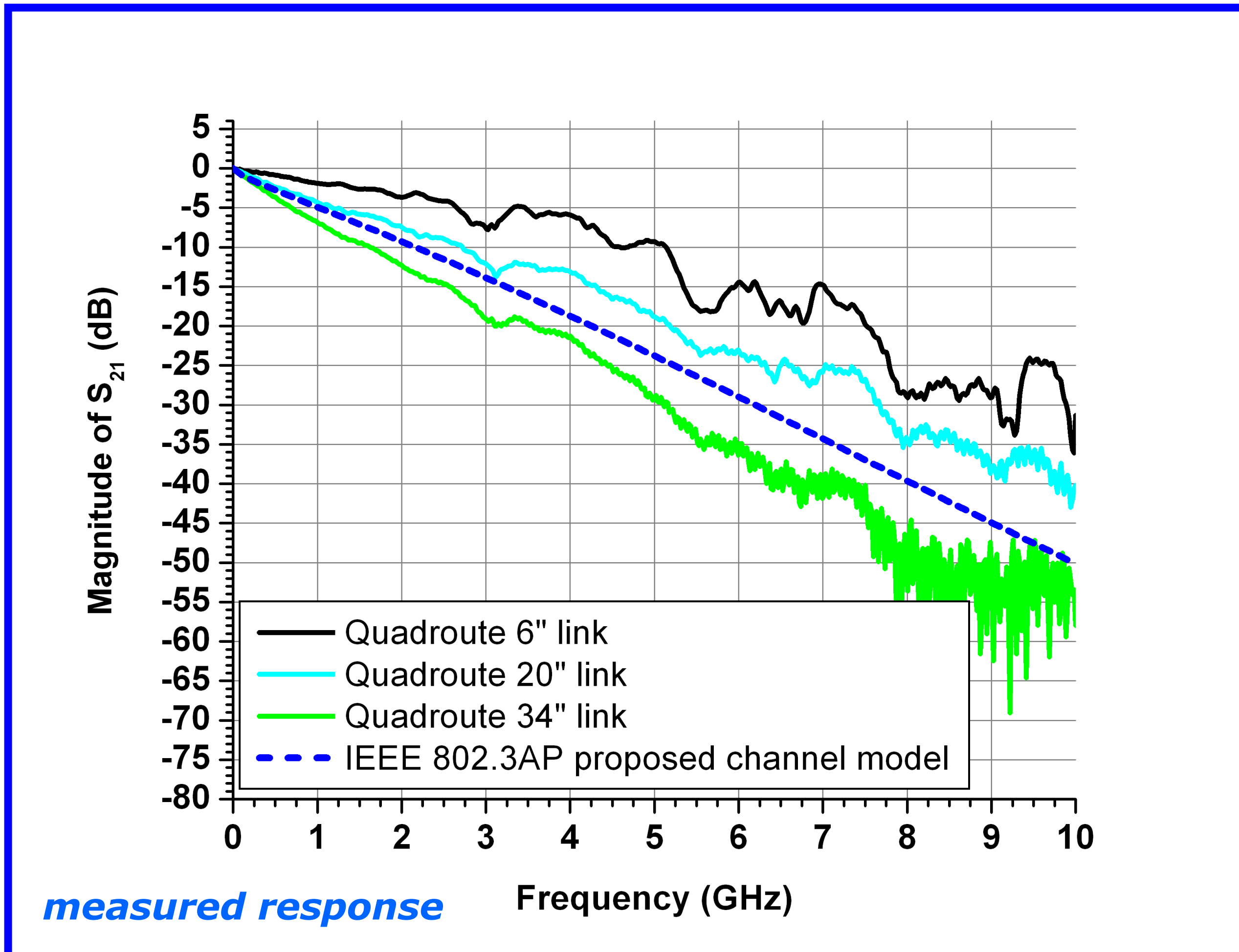
@modified version of commercial board
&commercially available
%modified version of commercial board

Transfer function through the Quadroute backplane (4000-6)*

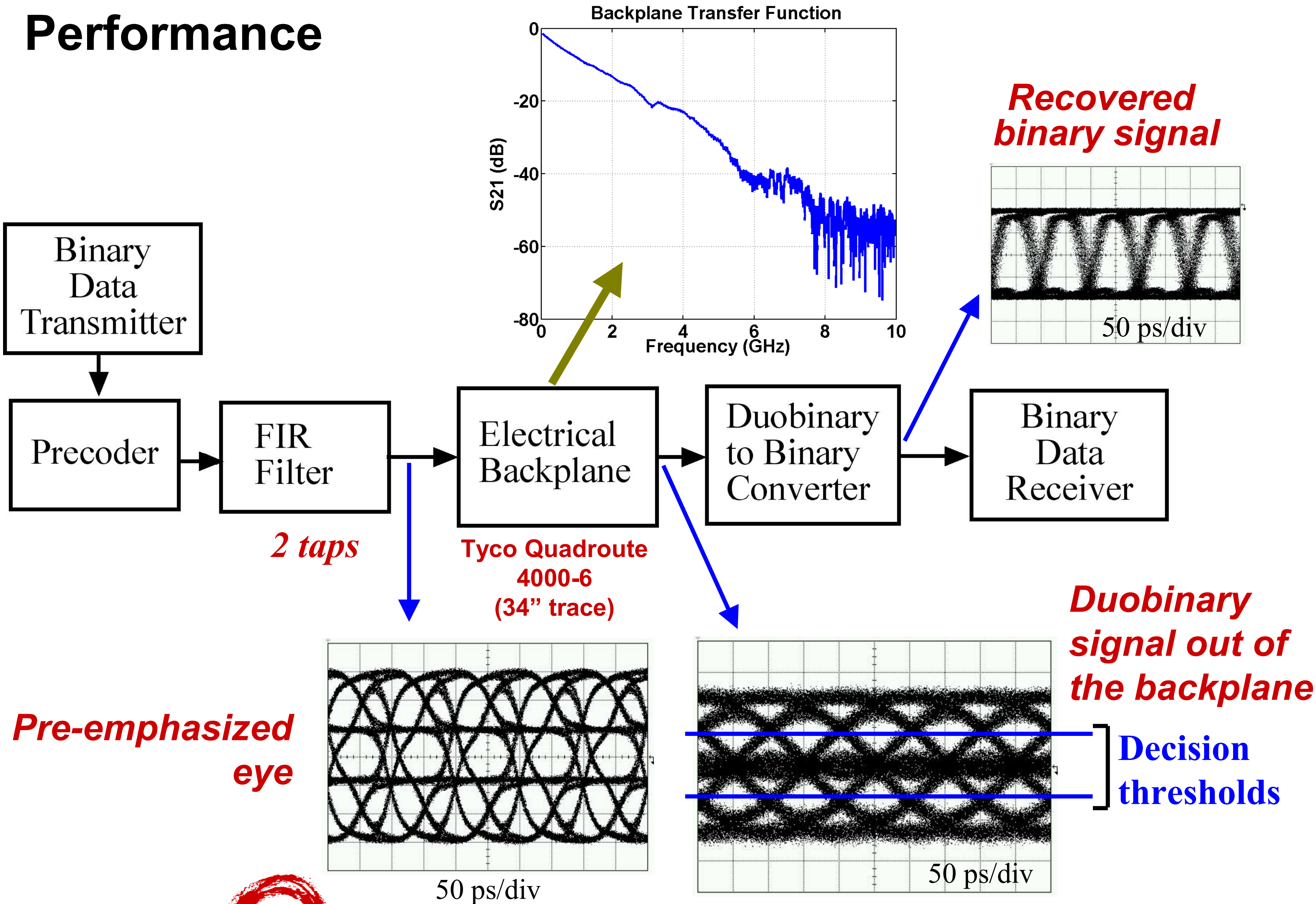
Link	3 dB Bandwidth
6 inch	1.81 GHz
20 inch	664 MHz
34 inch	410 MHz

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

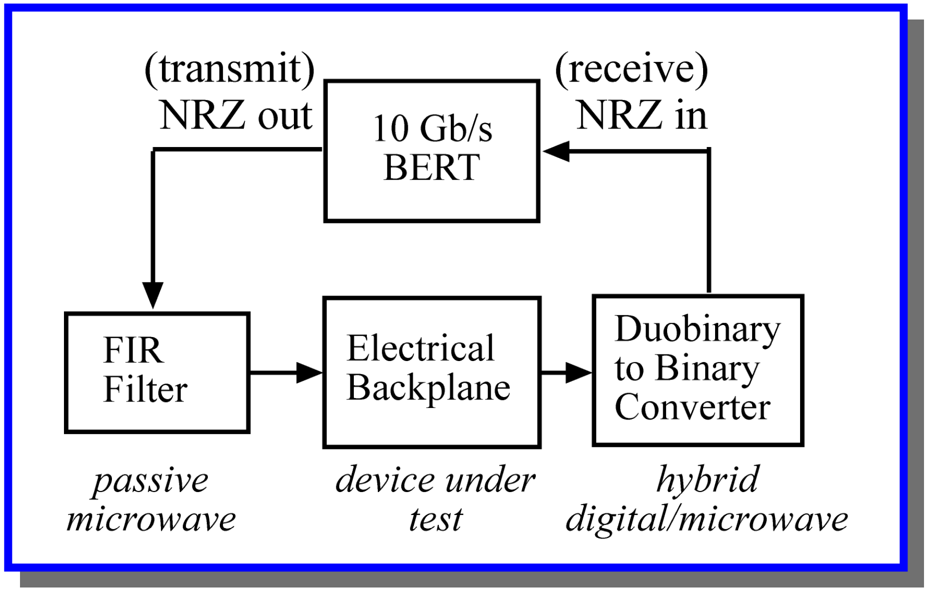
*modified version of the commercial board



Signal Evolution Through the System – Measured Performance



Test Setup and Experimental Results



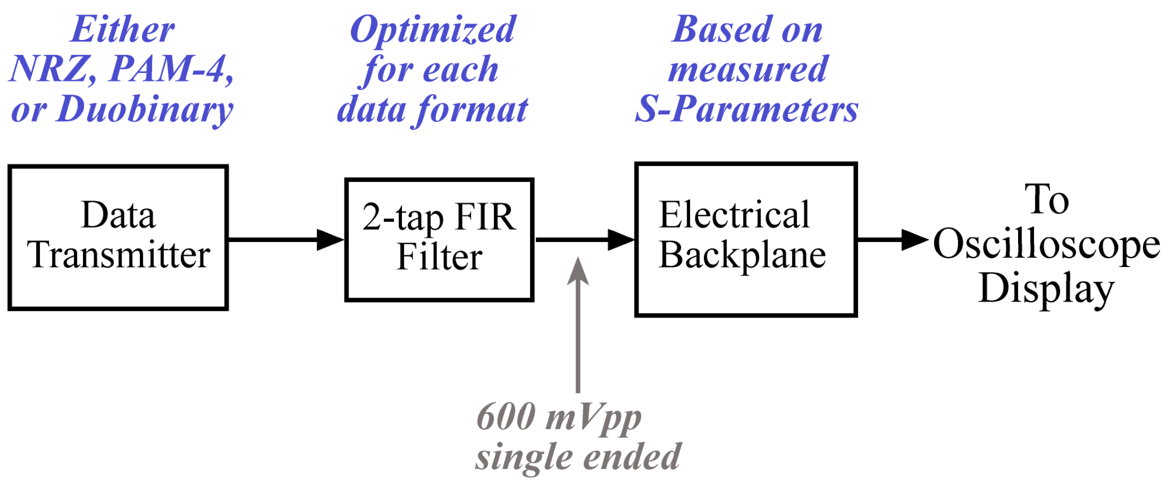
Trace length	20 in. (~51 cm)	34 in. (~86 cm)
Data rate	10 Gb/s	10 Gb/s
Sequence length	2^{31}-1	2^{23}-1
Bit error rate	$<10^{-13}$**	$<10^{-13}$**
Backplanes tested	Quadroute, XAUI (both)	Quadroute, XAUI (both)
FIR architecture	2-tap	2-tap

** 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



*Dielectric is Nelco 4000-6. Modified version of commercial board.

Simulation Notes

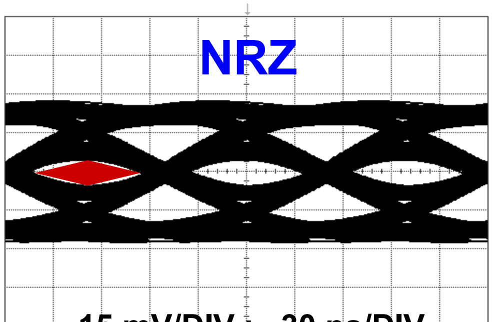
- 10 Gb/s data transmission
- All inputs are constrained to a 600 mV_{pp} single-ended amplitude at the OUTPUT of the 2-tap FIR filter
- No noise sources
- Backplane S-Parameters were measured on a vector network analyzer
- PRBS Length = 2^{10}-1
- 2-tap FIR optimization was accomplished by minimizing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

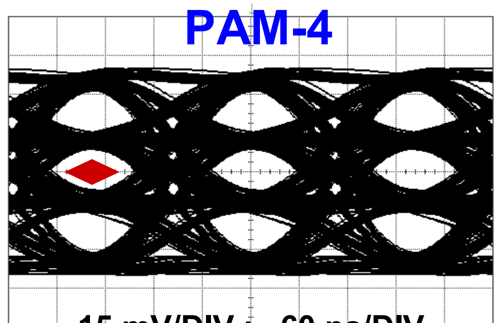
Comparison of pre-emphasized formats: NRZ, PAM-4 and Duobinary

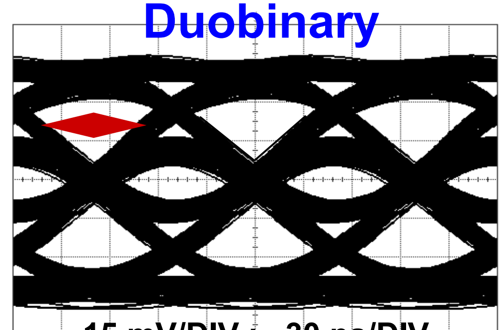
Single-ended backplane output resulting from 10.0 Gb/s transmitter with 600 mVpp single-ended amplitude including 2-tap FIR filter, PRBS 2^{10}-1

Tyco Quadroute 34" Link

mask for 34" NRZ



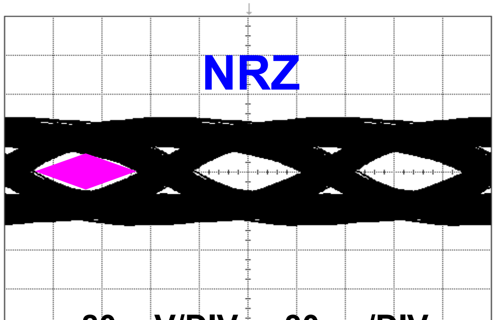


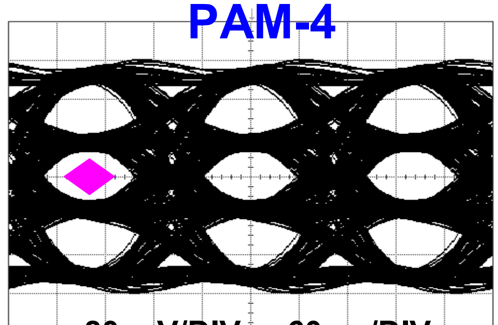


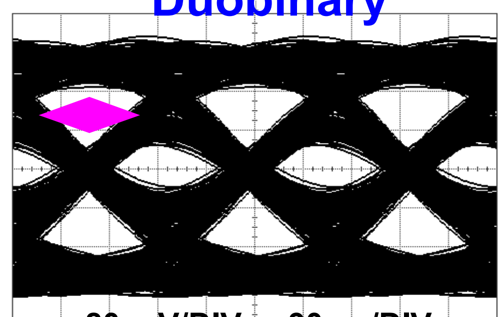
Denotes NRZ eye opening measure

Tyco Quadroute 6" Link

mask for 6" NRZ







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)

Minimum Single-ended Vertical Eye Opening at Threshold:

	6” Link (#1)	20” Link (#5)	34” Link (#8)
NRZ	78 mV_{pp}	37 mV_{pp}	10 mV_{pp}
DUO	137 mV_{pp}	85 mV_{pp}	25 mV_{pp}
PAM4	101 mV_{pp}	51 mV_{pp}	15 mV_{pp}

Horizontal Eye Opening at Threshold:

	6” Link (#1)	20” Link (#5)	34” Link (#8)
NRZ	65 ps	71 ps	69 ps
DUO	39 ps	52 ps	49 ps
PAM4	94 ps	84 ps	84 ps

*Based on measured S-Parameter data

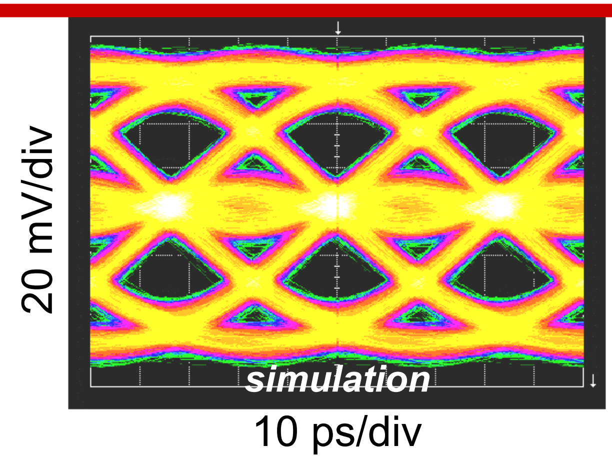
Comments on Cross-talk*

- 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 7dB 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.