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Comparative Study of PAM-4 and NRZ Signaling Based on Measurements From a Dual-Mode Device.

Rob Brink, Agere Systems

Geoffrey Zhang, Agere Systems

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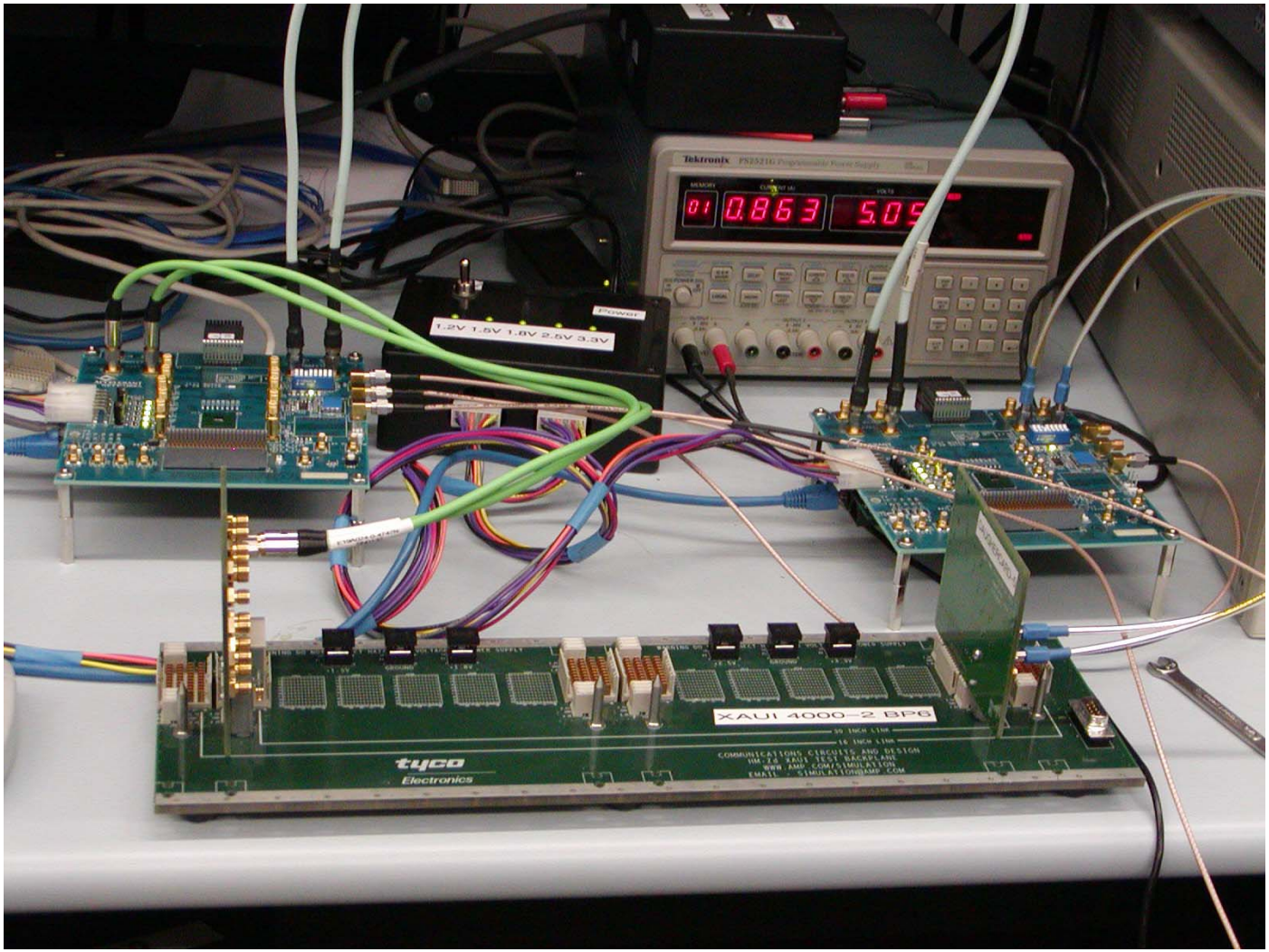
Agenda

- Compare NRZ and PAM-4 signaling over a 34” backplane channel at 3.0 to 5.5Gb/s using 3-tap transmit equalization.
  - Compare effective channel loss to proposed limit.
  - Show eye openings, equalizer requirements, applied jitter effects, and crosstalk effects.
- Compare NRZ and PAM4 signaling over a 68” backplane channel at 4.0Gb/s using 7-tap transmit equalization.
  - Compare to effective channel loss to the 34” case and the proposed limit.
  - Show eye openings, equalizer requirements, applied jitter effects, and crosstalk effects, power consumption, and die temperature.

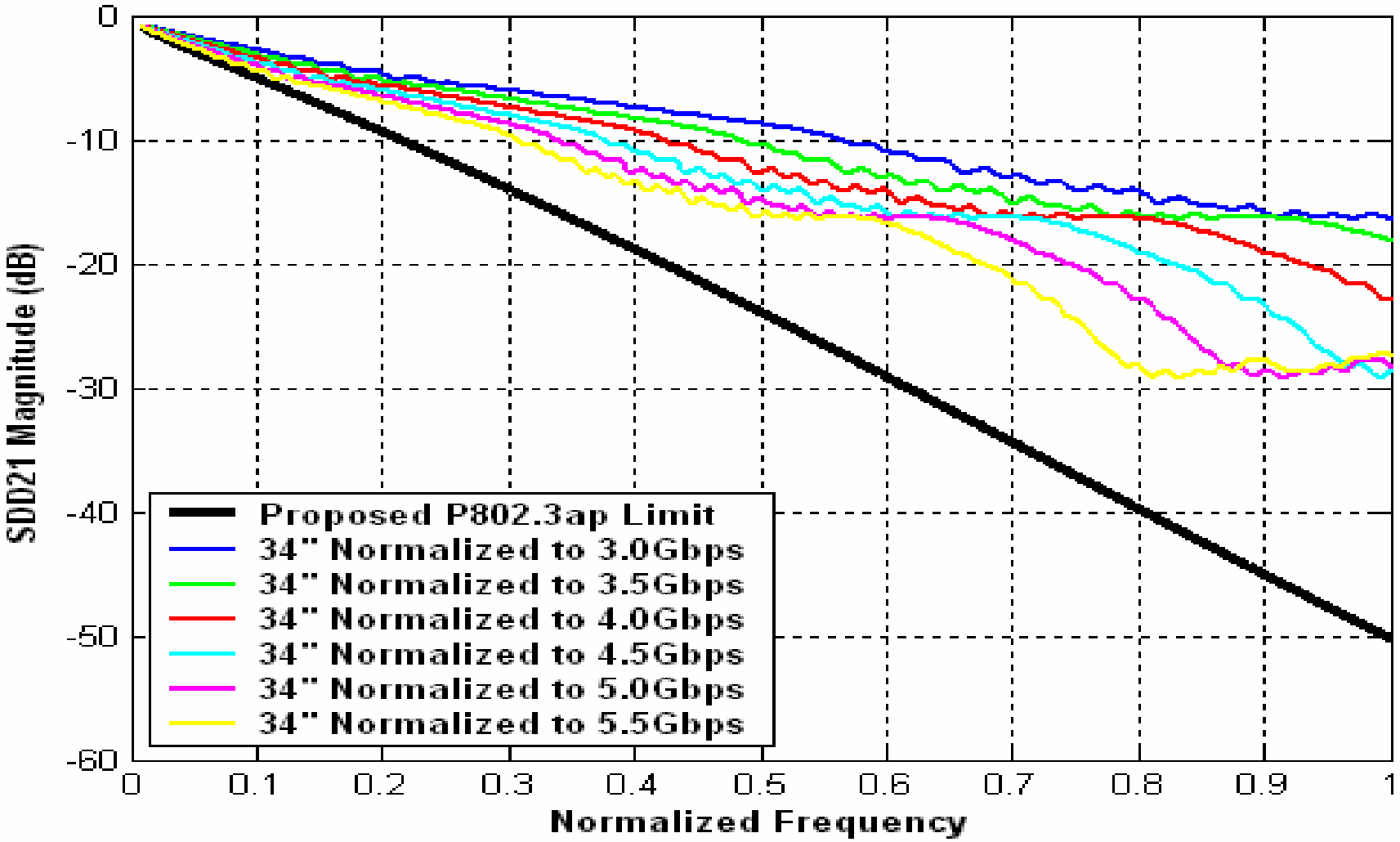
Background Information

- All the data was collected from the same device.
  - Same process, package, and evaluation board…
  - Same transmit jitter performance…
  - Same receiver (CDR) performance…
  - Same measurement methodology.
- PN-31 was the test pattern used for comparison.
- Eye openings (both horizontal and vertical) were measured at 1E-12.
- Test backplane was Tyco XAUI HM-Zd (Nelco 4000-2).
- The launch amplitude was the same for both NRZ and PAM4 ($1.0V_{p-p}$)
- No data scrambling was used for NRZ or PAM-4.
- 0% overhead coding (linear) was used, thus allowing all transitions.
- All NEXT aggressors (3) and FEXT aggressors (4) active for all testing.

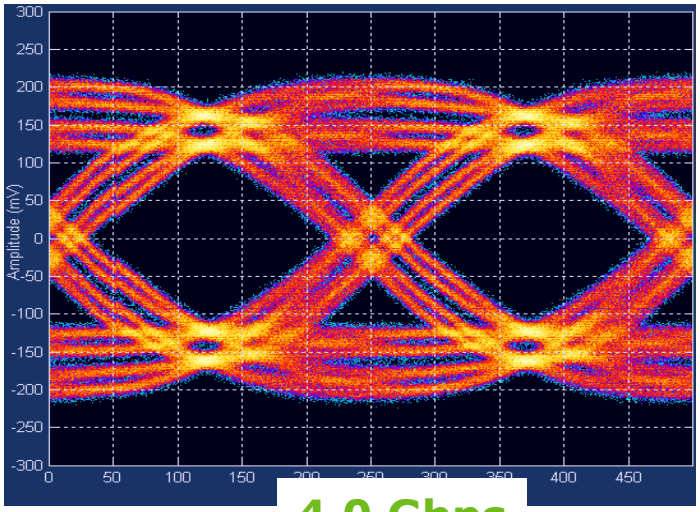
Test Setup


Tektronix
1.2V 1.5V 1.8V 2.5V 3.3V
XAUI 4000-2 BP6
tyco
Electronics

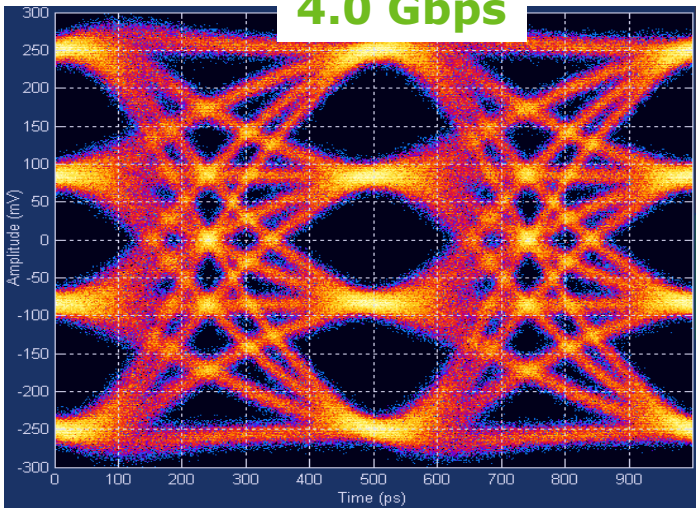
Normalized SDD21 for Tyco 34” Backplane

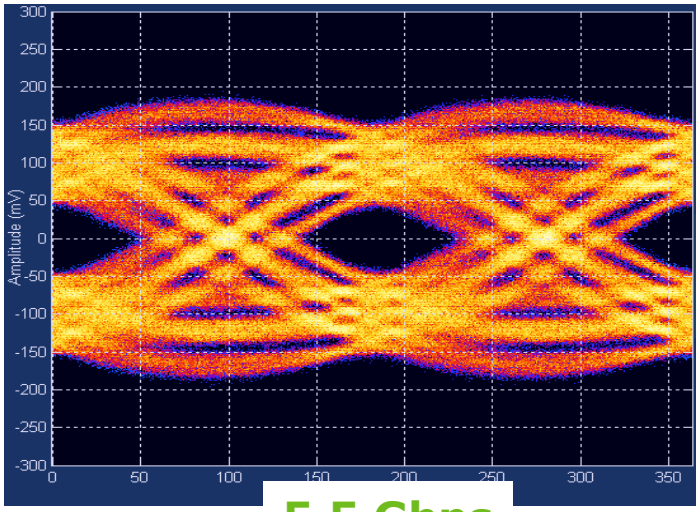


Far End Eye Diagrams with 3-Tap Tx Equalization

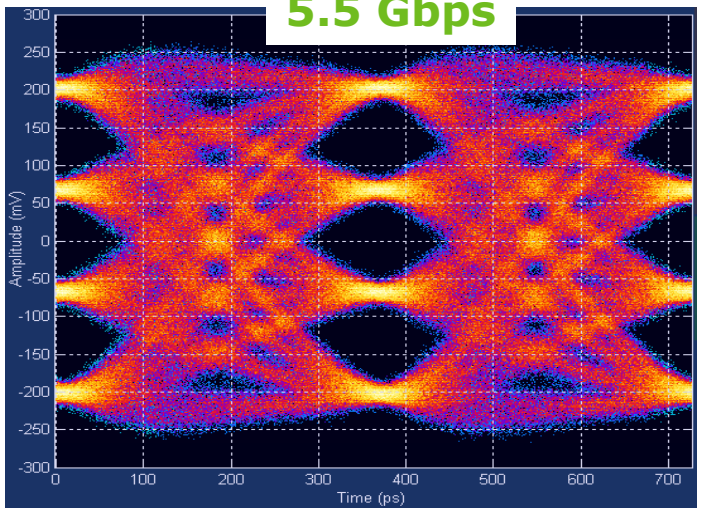


4.0 Gbps

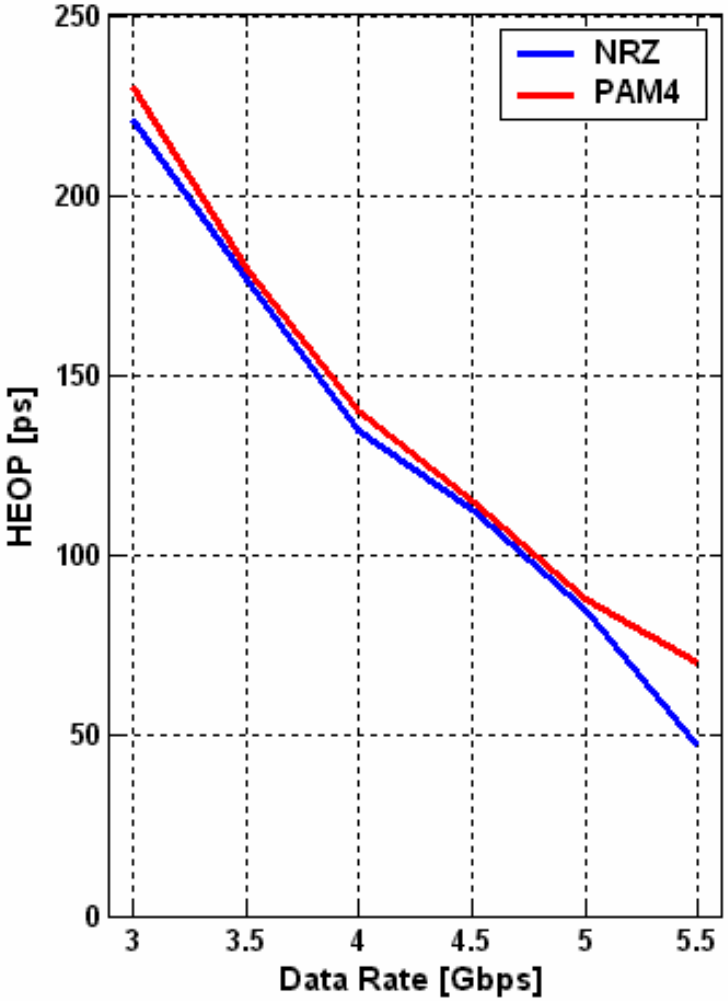


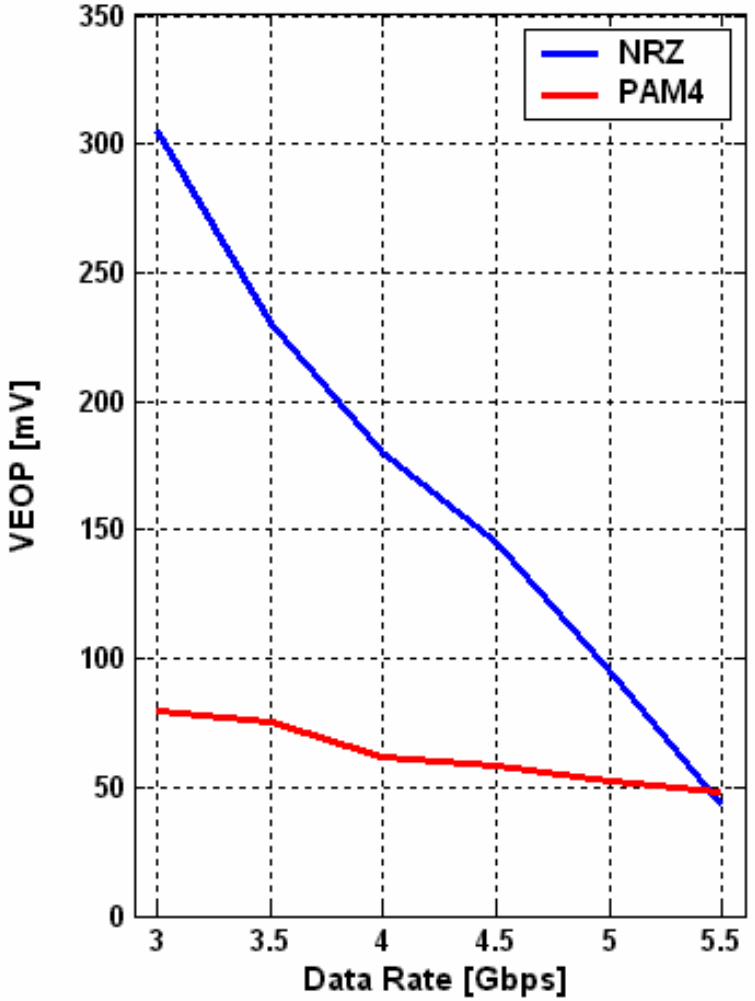


5.5 Gbps



Eye Opening vs. Data Rate





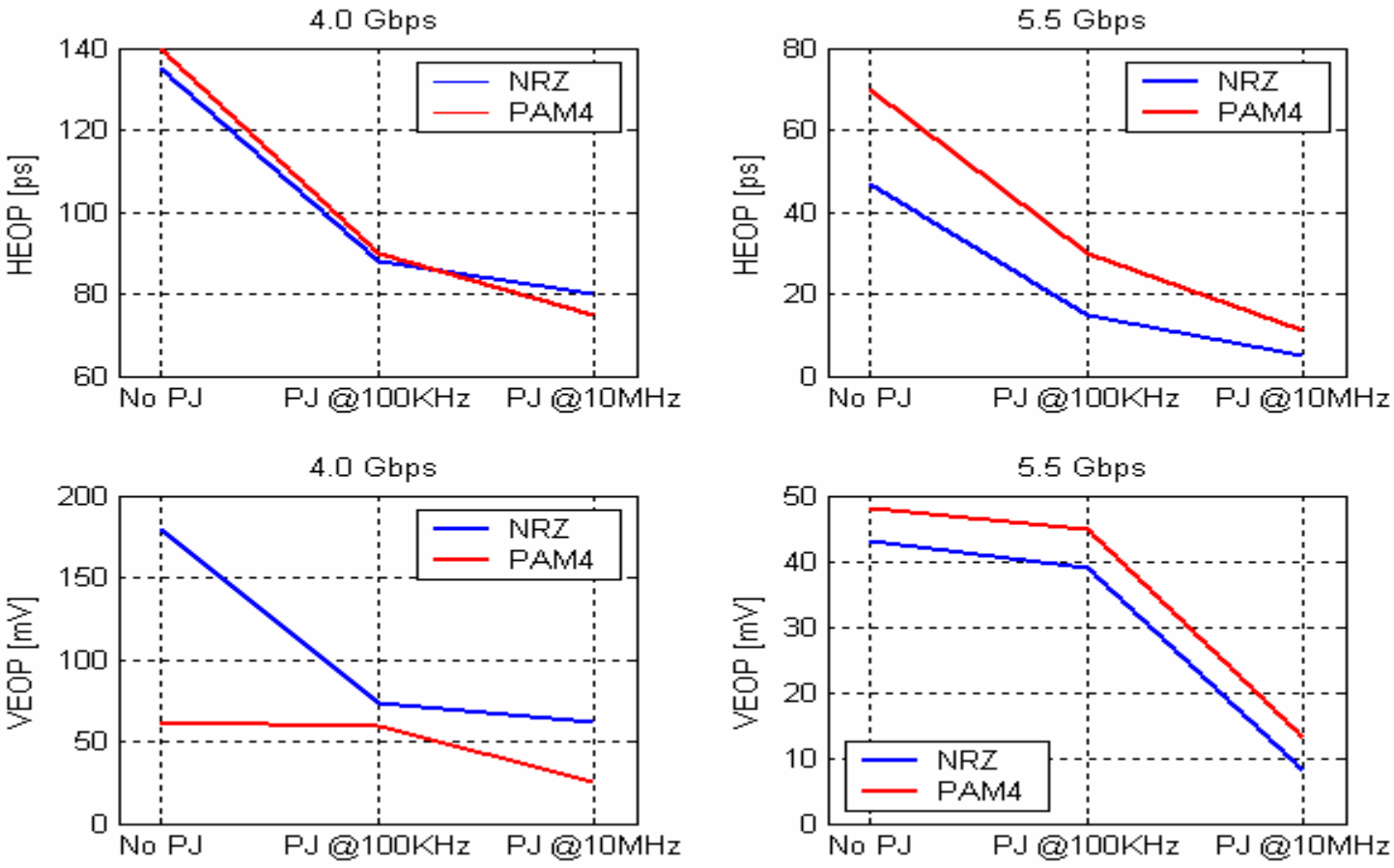
NOTE: VEOP, HEOP measured to 1E-12

Tap Weight Magnitude (3-Tap)

Data Rate		3.0	3.5	4.0	4.5	5.0	5.5
NRZ	Leader	7.88%	10.44%	11.61%	12.50%	12.50%	12.50%
	Symbol	1	1	1	1	1	1
	Trailer	40.30%	46.70%	56.94%	61.41%	65.90%	73.58%
PAM4	Leader	0.79%	1.09%	2.16%	3.25%	4.73%	6.69%
	Symbol	1	1	1	1	1	1
	Trailer	24.42%	24.95%	26.87%	30.08%	33.06%	36.46%

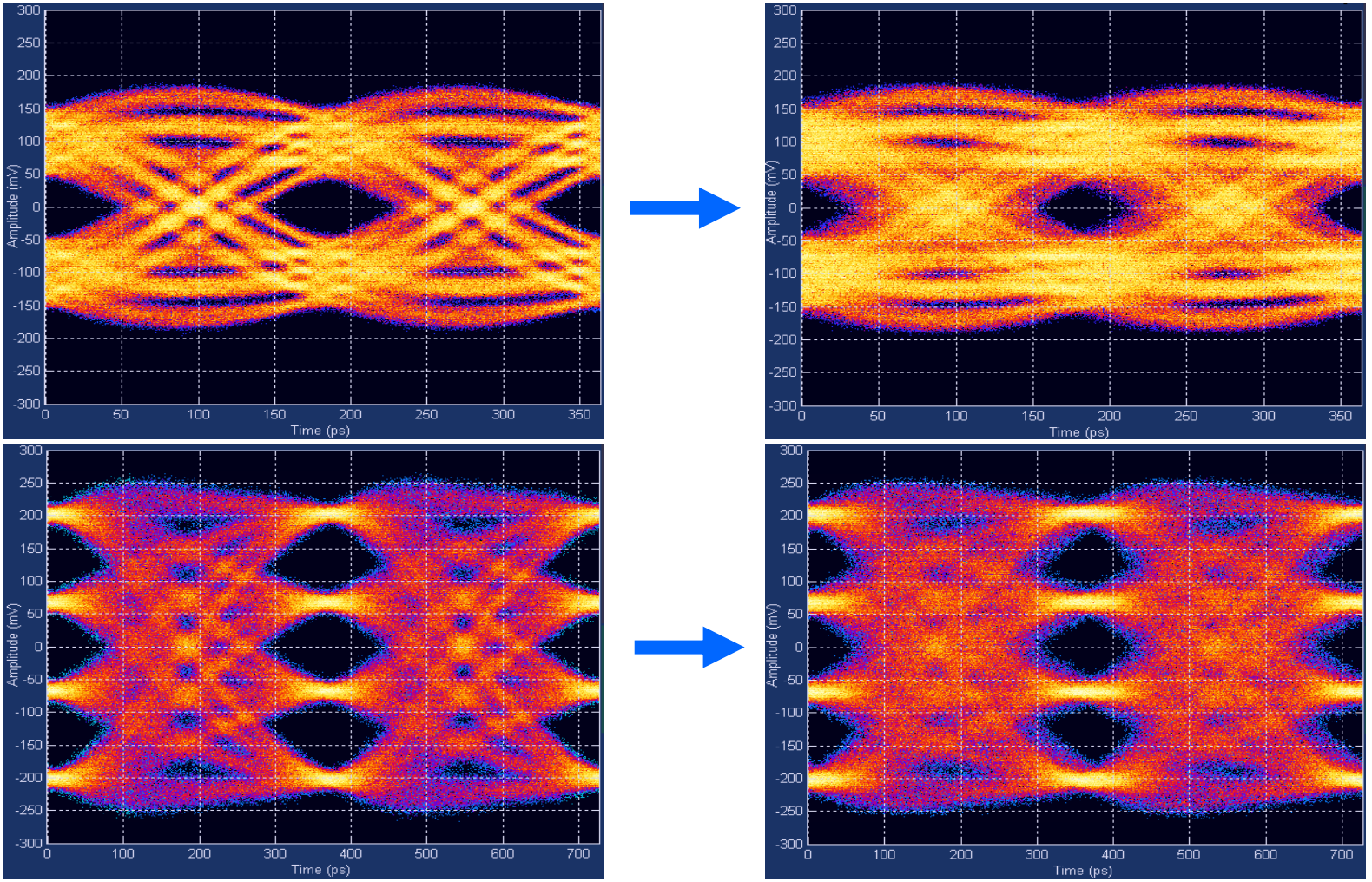
As expected, NRZ requires more aggressive equalization.

Eye Openings with 50ps Added PJ

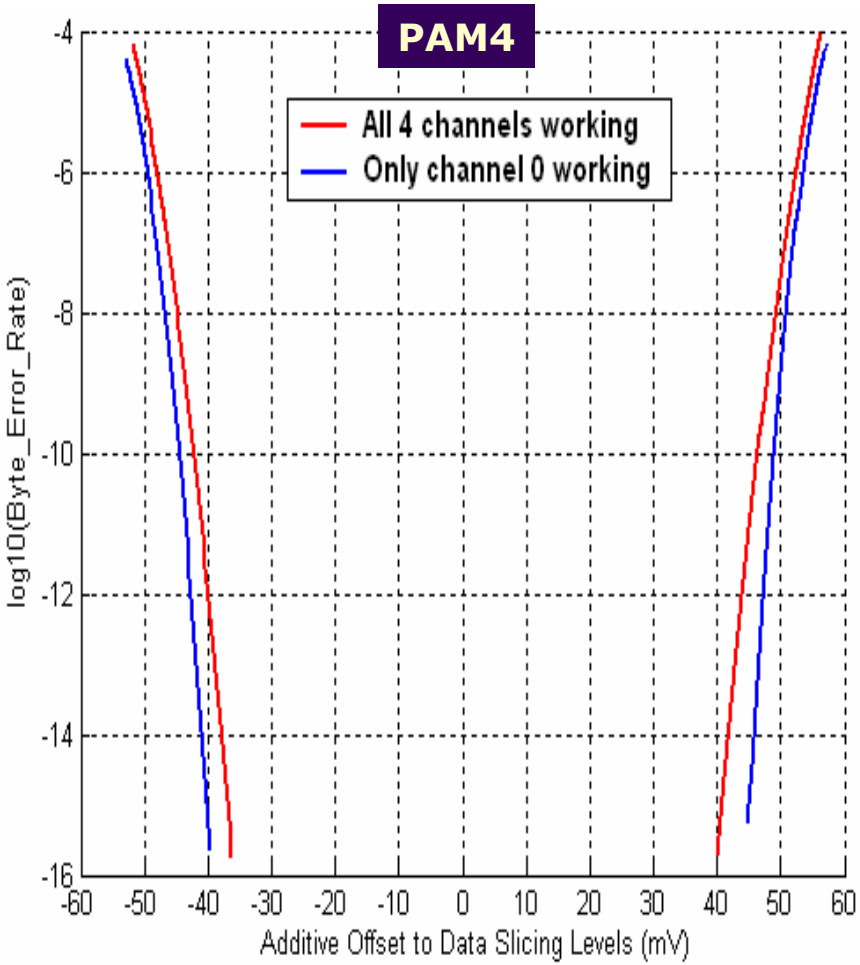


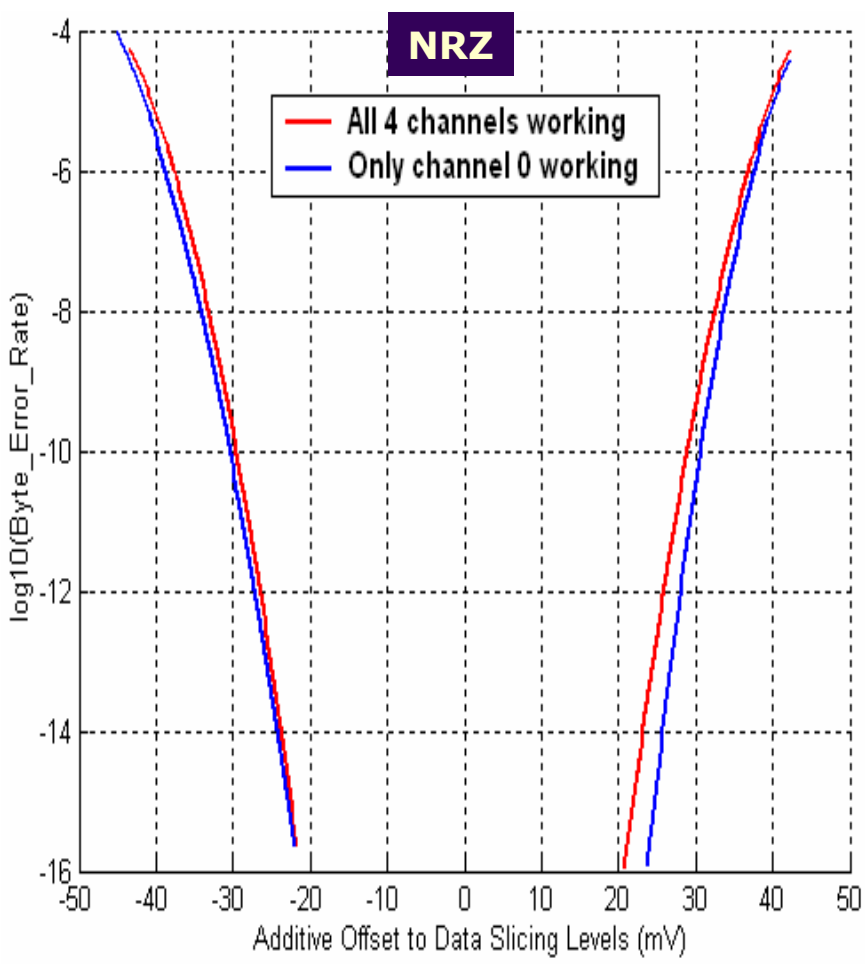
NOTE: VEOP, HEOP measured to 1E-12

5.5 Gbps Eye Diagrams with 50ps 10MHz PJ



Crosstalk Effect (Example at 5.0Gbps)





Crosstalk (4 NEXT and 3 FEXT) does not show more effect on PAM-4 than NRZ.

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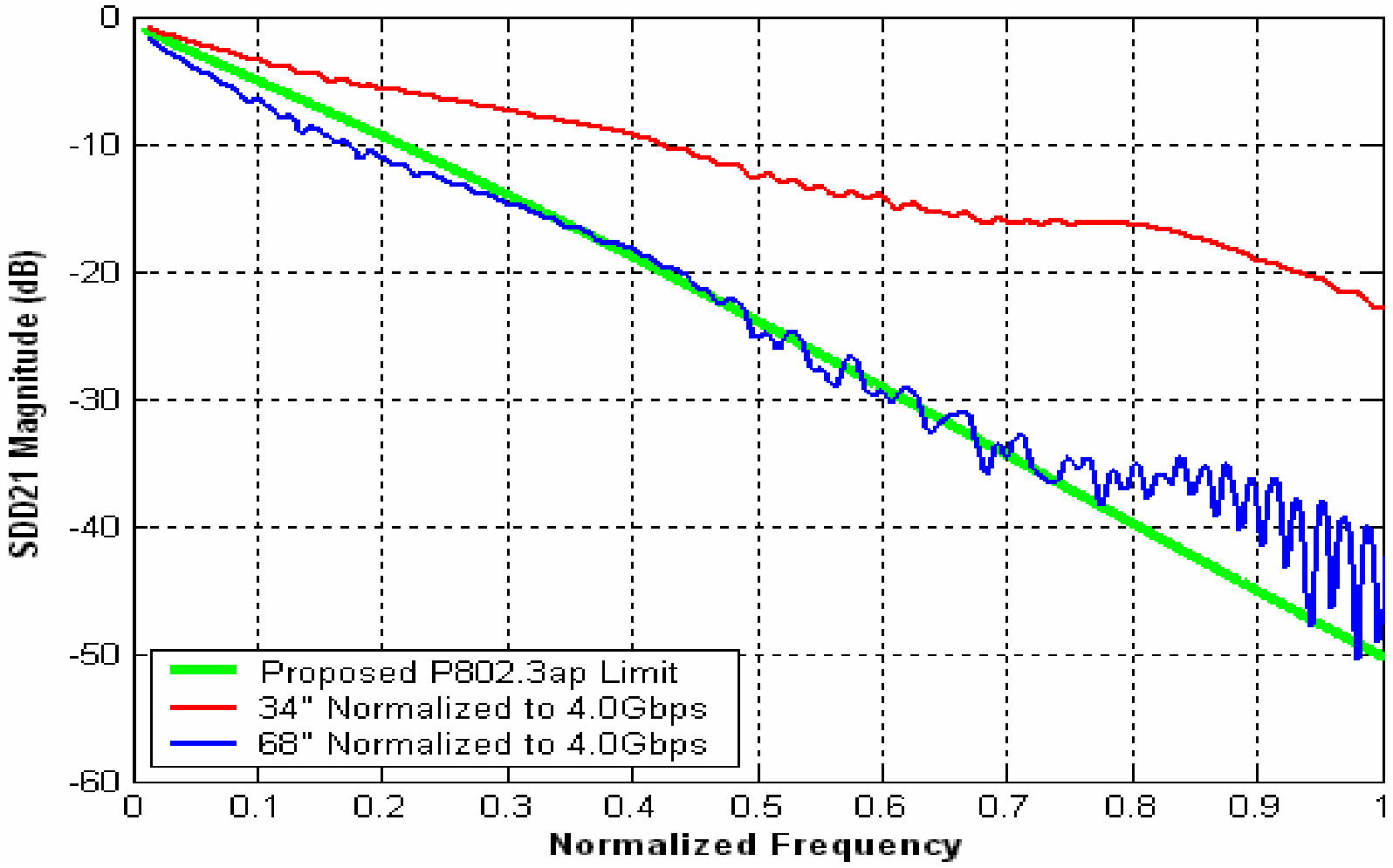
Observations

- For low-loss channels, the NRZ eye opening may be as high as 3X the PAM-4 eye opening.
  - "Low-loss" channels may be channels with inherently low loss, or channels compensated with adequate equalization.
  - Still, PAM-4 operates over these channels, with margin, to the BER of interest.
- An equalizer of given complexity will be able to compensate for more distortion in a PAM-4 system in an NRZ system.
  - The amount of equalization effort applied to an NRZ system, versus the amount of effort applied to a PAM-4 system, sets the eye height cross-over point.

Normalized SDD21 for 68” Backplane Channel



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Data at 4.0 Gbps for 68" Backplane

- All 4 channels are active – 4 NEXT and 3 FEXT aggressors.
- All 7 taps for Tx EQ are active.

		Boost at Nyquist	Power (Relative to PAM4)	Die Temperature
NRZ		21.3 dB	1.77	70.6 °C
PAM4		11.4 dB	1.0	55.2 °C
		0ps PJ	50ps PJ at 100KHz	50ps PJ at 10MHz
NRZ	HEOP	96 ps	62 ps	48 ps
	VEOP	29 mV	28 mV	16 mV
PAM4	HEOP	110 ps	85 ps	55 ps
	VEOP	32 mV	30 mV	19 mV

NOTE: VEOP, HEOP measured to 1E-12

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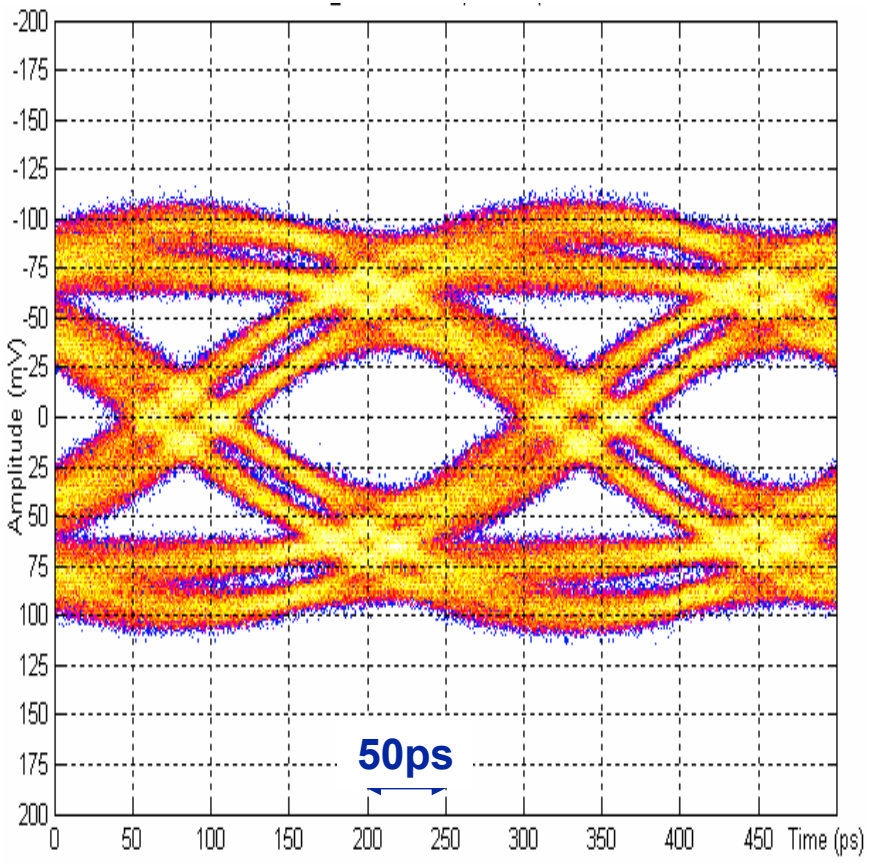
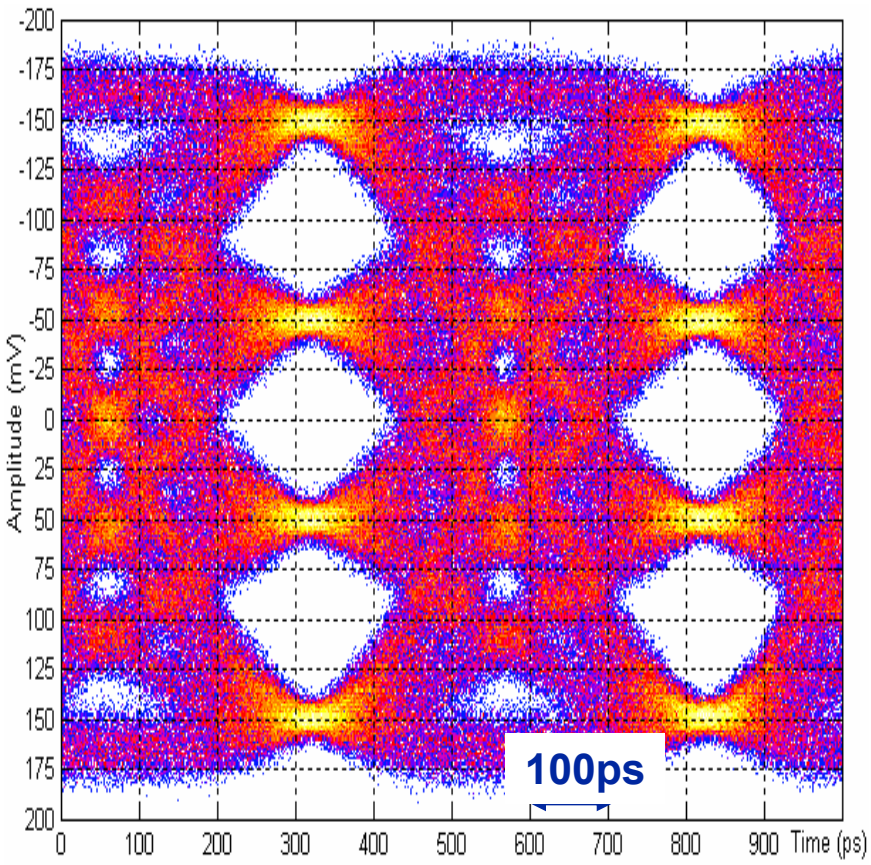
Tap Weight Magnitude (7-Tap) at 4.0 Gbps

	Leader	Symbol	TrailerA	TrailerB	TrailerC	TrailerD	TrailerE
NRZ	12.50%	1.00	80.00%	12.50%	-2.10%	1.57%	-0.81%
PAM4	9.45%	1.00	58.81%	1.99%	-0.78%	-0.39%	-0.52%

As expected, NRZ requires more aggressive equalization

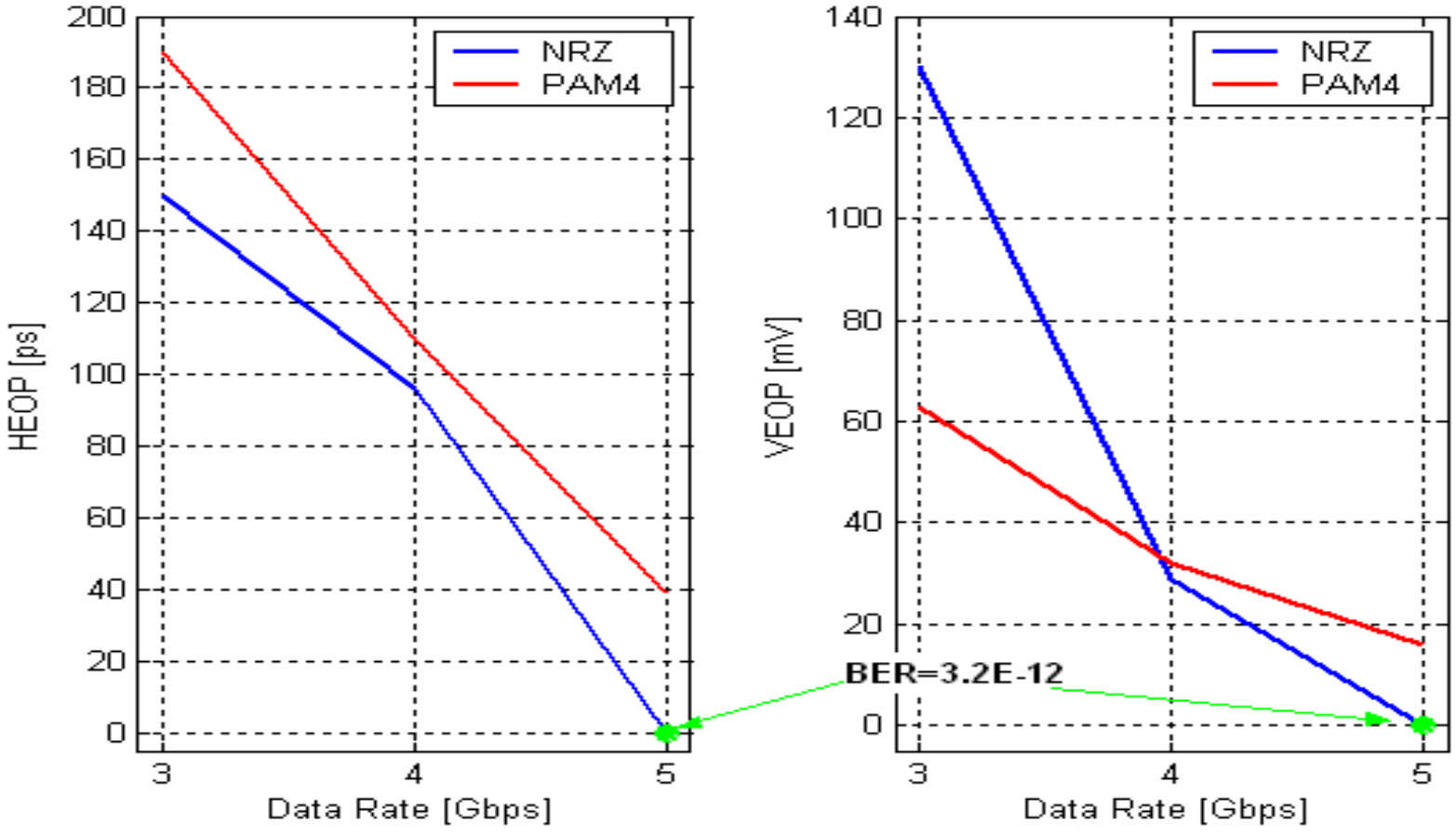
Eye Diagrams at 4.0 Gbps for 68”





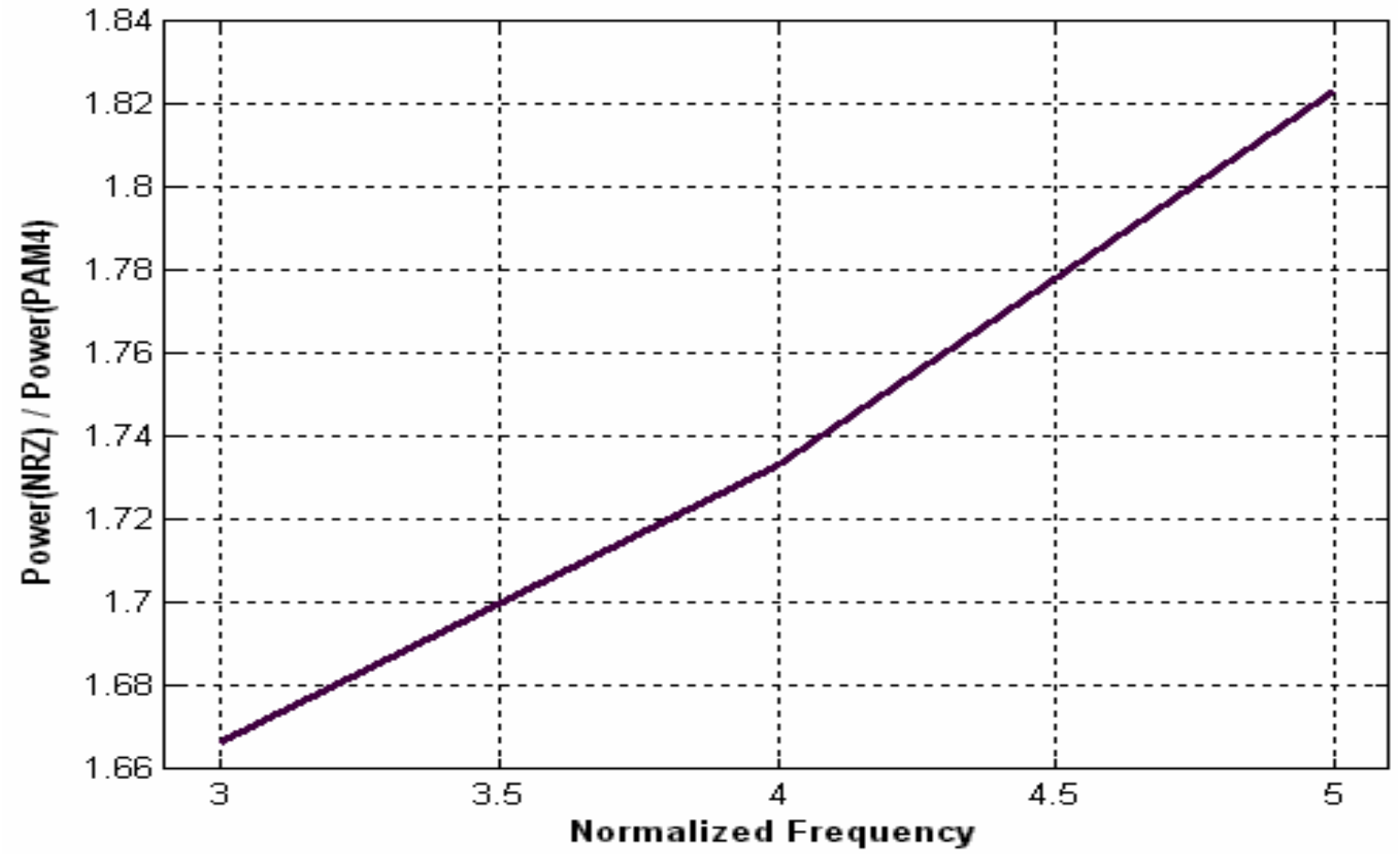
Same launch amplitude NRZ suffers much greater attenuation.

Eye Openings for 68” Backplane



NOTE: VEOP, HEOP measured to 1E-12

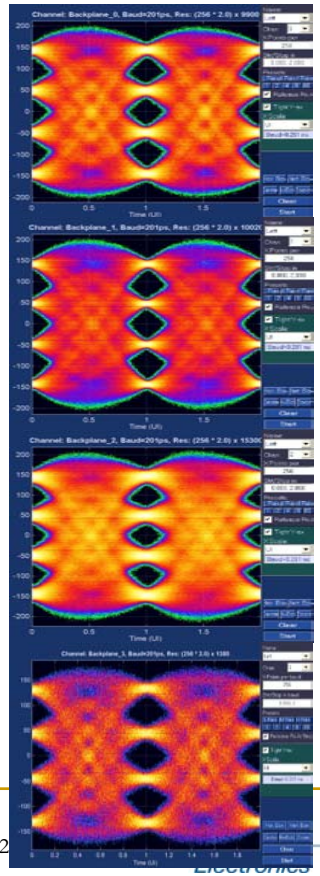
Power Consumption Comparison



NRZ uses significantly more power for same BER.

Proven Operation at 10Gb/s

Accelerant Networks / Synopsys Measured 10G Payload Data



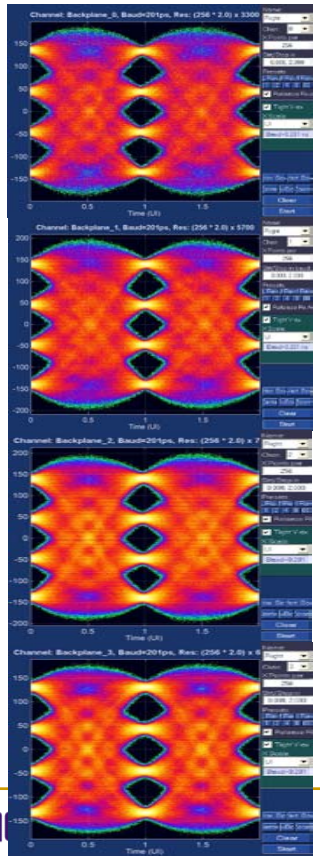
5G PAM4 .13u device running at 10G. Gray Encoding, 0% Overhead

All 8 pairs active on QuadRoute FR4 4000-13SI, full crosstalk conditions (4 FEXT, 4 NEXT)

All devices tested to BER 10^-12 using 2^31 PRBS Pattern over 36 inches

8" and 22" link conditions across all 6 materials passed BER 10^-12 using 2^31 PRBS Pattern

Out of 336 links tested, 34 36" link configurations did not pass and will be the subject of future simulation work on a mutually agreed to channel model with purpose built 10G designs



Data taken from D'Ambrosia, "PAM-4 Link Analysis", IEEE P802.3ap Task Force, Long Beach, May 2004.

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Conclusions

- PAM-4 does not require higher launch amplitude than NRZ to support 1E-12 or better BER over the channels of interest.
- No measurable difference regarding the impact of crosstalk on PAM-4 or NRZ with the backplanes and speeds tested.
- PAM-4 is no more vulnerable to the presence of added jitter (PJ) than NRZ on a per-picosecond basis.
- PAM-4 offers better amplitude and timing margin than NRZ, for the worst-case channel of interest.
- PAM-4 is capable of operating (at BER better than 1E-12) beyond the worst-case channel of interest.
- For this implementation, the PAM-4 operating mode achieved this with significantly lower power.
- PAM-4 operation has been confirmed with measurements at 10Gb/s.