Line Signaling Performance Comparison on 1m Improved FR4 Channel

Troy Beukema
Pravin Patel
Mounir Meghelli

100 Gb/s Backplane and Cable Task Force, IEEE 802.3, Atlanta, Nov. 2011

Contributors/Supporters

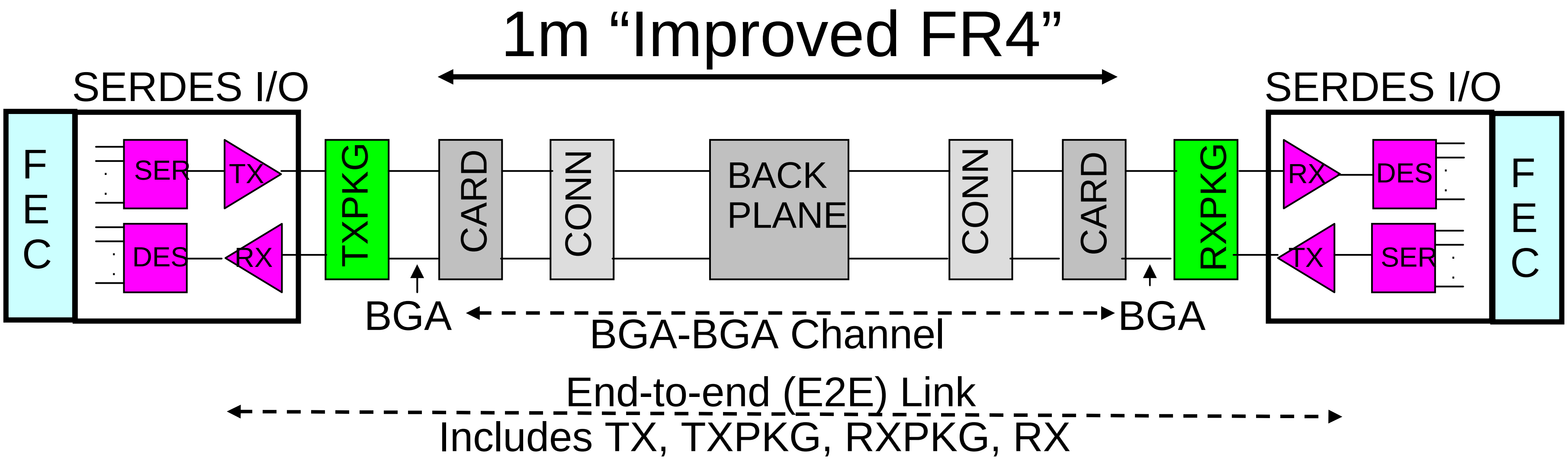
- Chris Cole, Finisar
- Mike Dudek, Qlogic
- Scott Kipp, Brocade
- Mike Li, Altera
- Myles Kimmitt, Emulex
- Peerouz Amleshi, Molex
- Tom Palkert, Xilinx, Luxtra, Molex
- Karl Muth (TI)
- Jitendra Mohan (TI)
- Barry Barnett, IBM
- David Stauffer, IBM
- John Ewen, IBM

Objectives

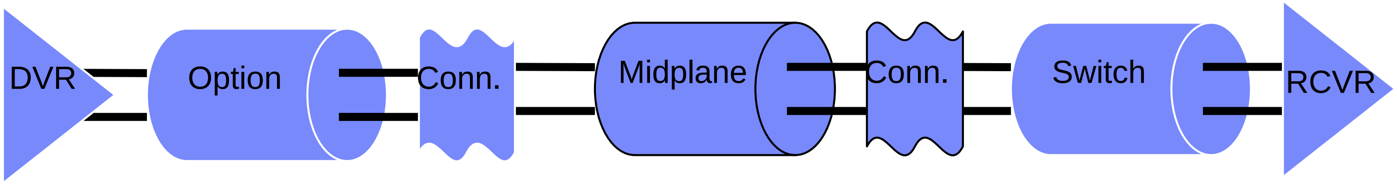
1) **Compare performance of NRZ and PAM4 with FEC over a representative 1m improved FR4 channel**

2) **Conclude the optimum line signaling/minimum FEC needed to achieve the 4x25=100GbE over such a channel**

3) **Present a simplified comparison of NRZ and PAM4 signaling**



Simulated Channel Construction



	Option	Backplane	Switch
Length	10”	20”	10”
Board Thickness (mils)	96	220	120
Trace Widths (mils)	7.5mil	7.5mil	7.5mil
# of Layers	12	26	14

All Printed Circuit Boards:

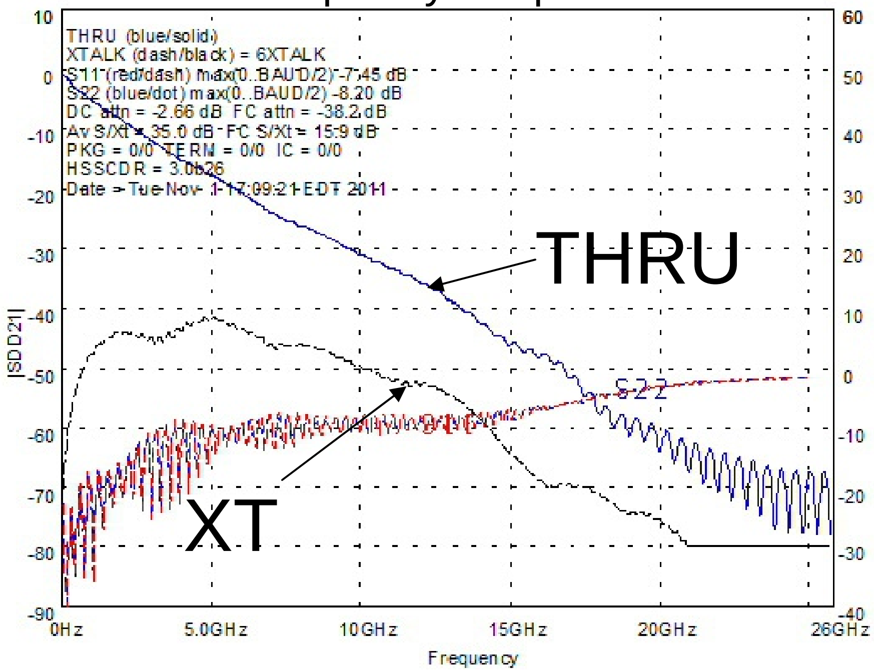
- Signal Layer: 1/2 oz copper
- Stripline: Yes
- Material: 802.3ap Improved FR4
- Dk: 3.6@ 1Ghz and Df: 0.0092 @ 1Ghz
- Via stub: ~ 15mil
- Differential Impedance: 100 Ohm
- Connector: Impact Plus

Tools:

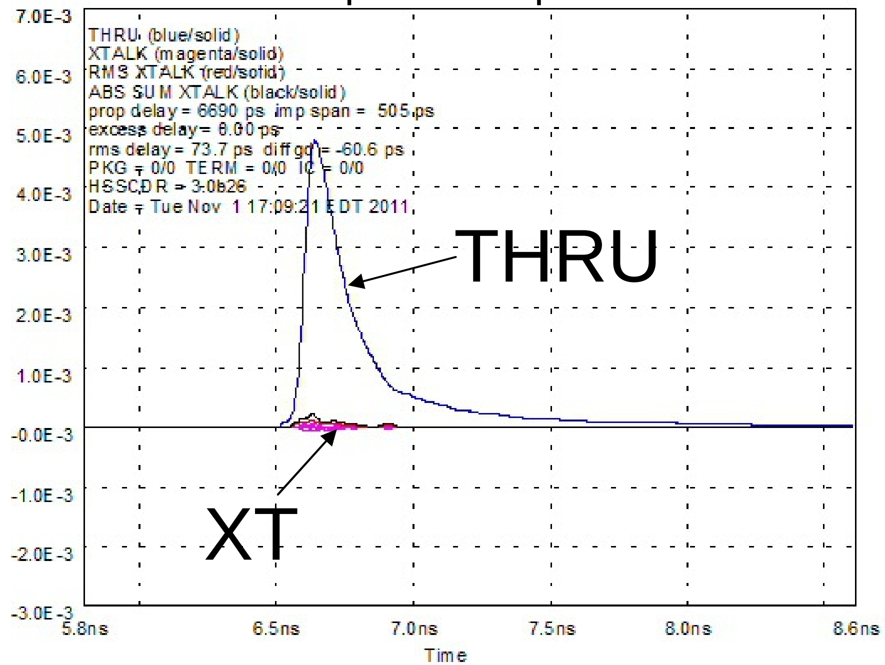
- Ansoft Q3D for Tline models
- Ansoft HFSS for Via model
- Ansoft Designer to combine models
- Djordjevic-Sarkar Model for Frequency dependent loss

1m Improved FR4 Channel Response

Frequency Response



Impulse Response



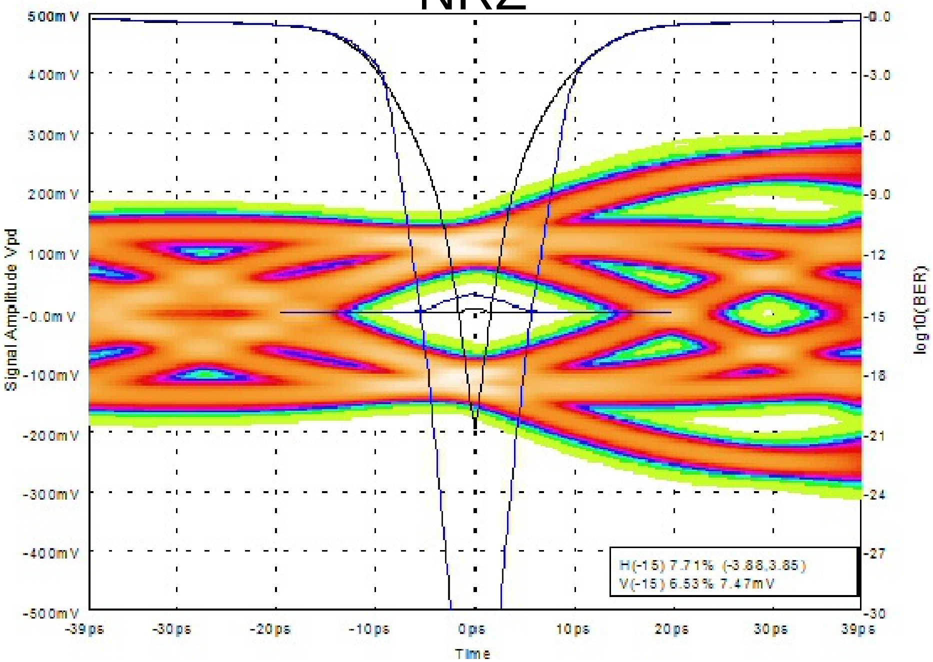
BitRate/2 BGA-BGA loss 38.2dB

6 FEXT Aggressors

BitRate/2 S/Xt 15.9dB

1m FR4 Channel Loss Eye Diagrams, RS T=5 m=9

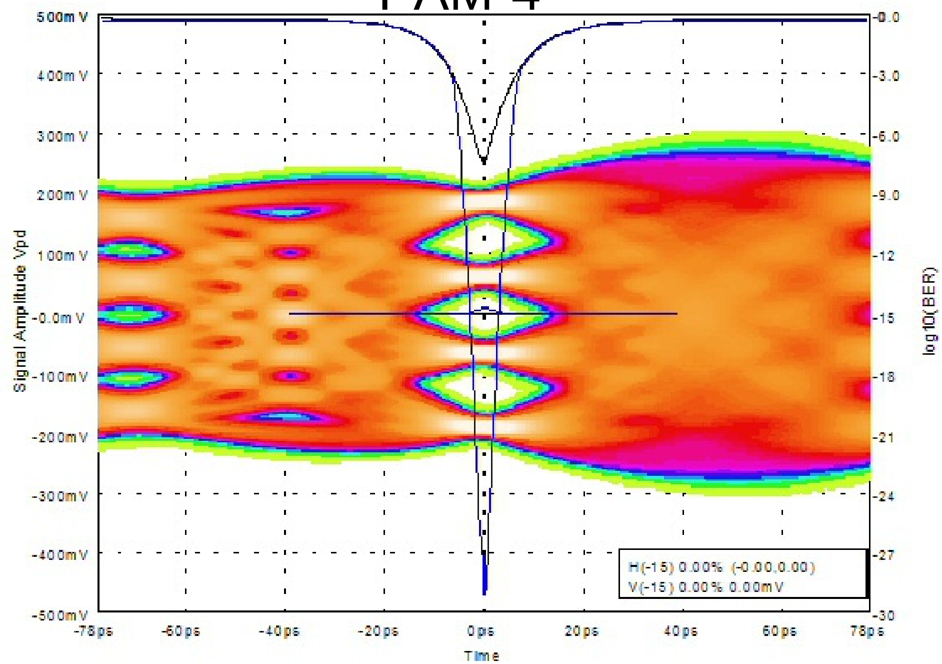
NRZ



BAUD/2 LOSS (CHAN/E2E)[2]	38/46dB
HEYEPP(1E-15)	7.7%
VEYE(1E-15)	7.5mV
BAUD/2 LOSS RS(352,342)[1]	38/46dB
HEYEPP(1E-15) RS(352,342)[1]	28.3%
VEYE(1E-15) RS(352,342)[1]	26.7mV

[1]DFE1 h1=0.65 Error Propagation [2]25.8Gbaud/s

PAM-4

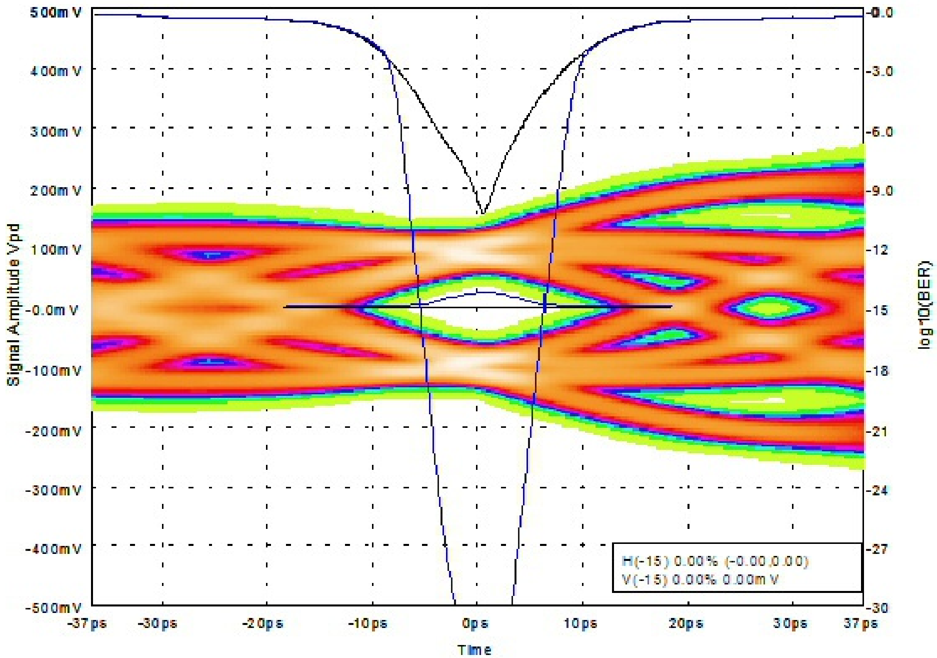


BAUD/2 LOSS (CHAN/E2E)[4]	21/25dB
HEYEPP(1E-15)	0%
VEYE(1E-15)	0mV
BAUD/2 LOSS RS(352,342)[3]	21/25dB
HEYEPP(1E-15) RS(352,342)[3]	7.2%
VEYE(1E-15) RS(352,342)[3]	8.3mV

[3]No DFE Error Propagation [4]12.9Gbaud/s

1m FR4 Channel Loss Eye Diagrams, RS T=10 m=9

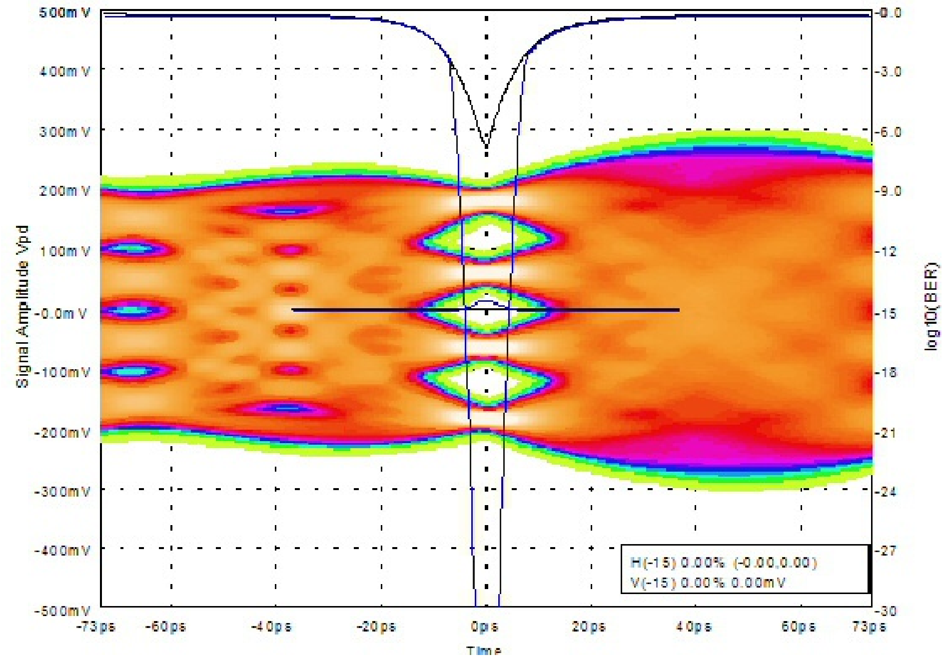
NRZ



BAUD/2 LOSS (CHAN/E2E)[2]	41/50dB
HEYEPP(1E-15)	0%
VEYE(1E-15)	0mV
BAUD/2 LOSS RS(248,228)[1]	41/50dB
HEYEPP(1E-15) RS(248,228)[1]	32.2%
VEYE(1E-15) RS(248,228)[1]	23.1mV

[1]DFE1 h1=0.65 Error Propagation [2]27.2Gbaud/s

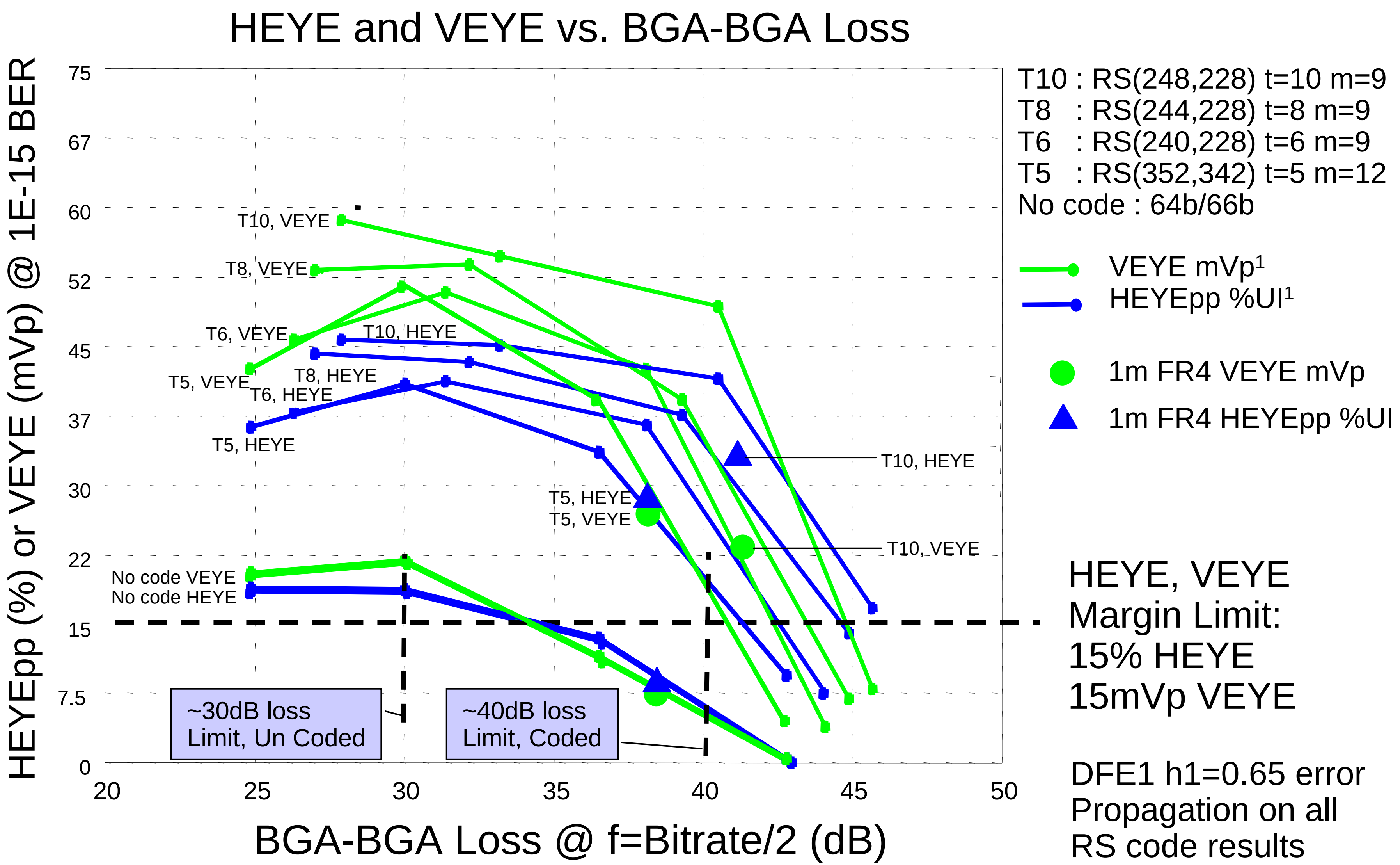
PAM-4



BAUD/2 LOSS (CHAN/E2E)[4]	23/26dB
HEYEPP(1E-15)	0%
VEYE(1E-15)	0mV
BAUD/2 LOSS RS(248,228)[3]	23/26dB
HEYEPP(1E-15) RS(248,228)[3]	11.3%
VEYE(1E-15) RS(248,228)[3]	12.8mV

[3]No DFE Error Propagation [4]13.6Gbaud/s

NRZ HEYE/VEYE vs. Channel Loss, 512b/513b Transcode

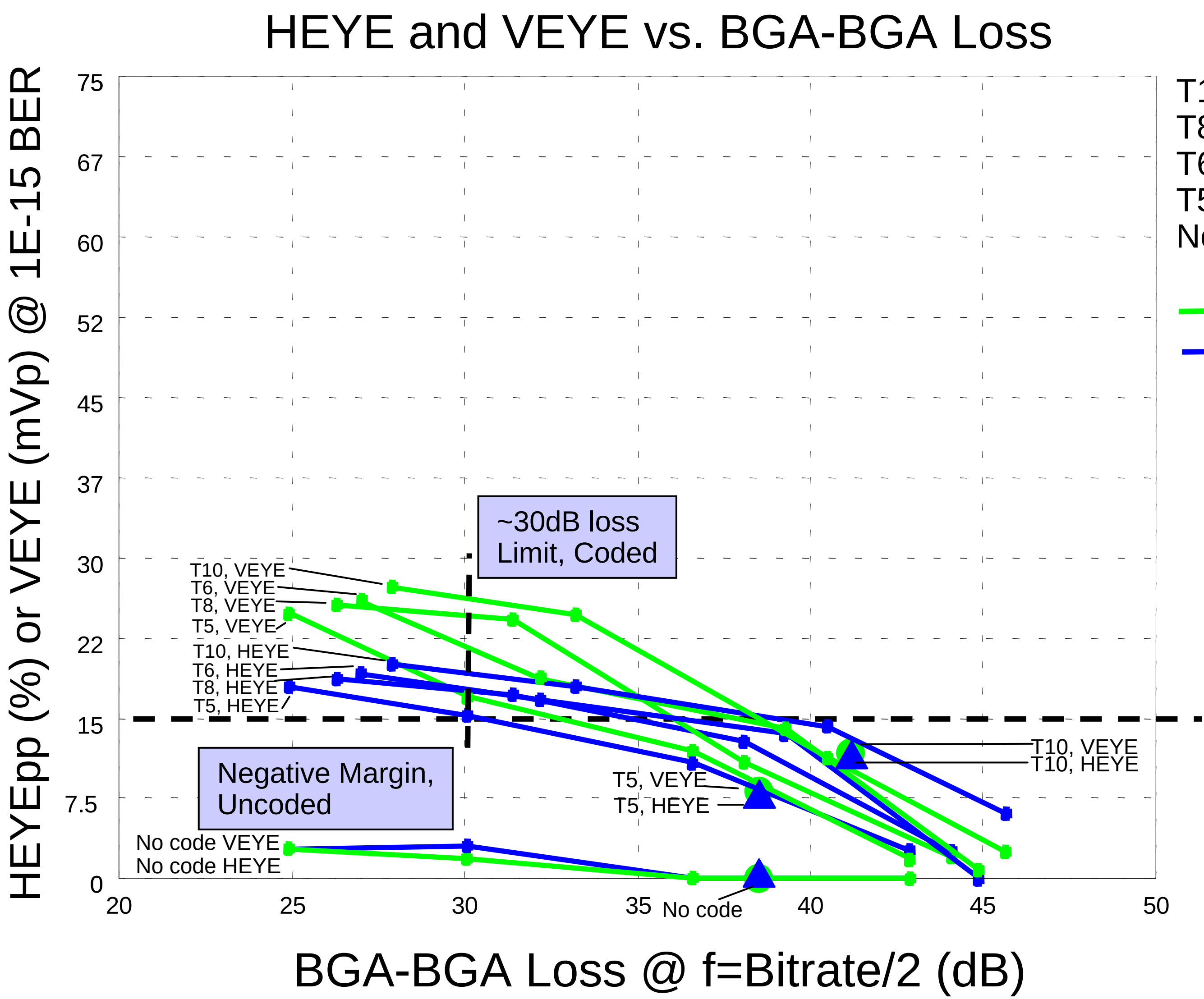


HEYE, VEYE
Margin Limit:
15% HEYE
15mVp VEYE

DFE1 h1=0.65 error Propagation on all RS code results

[1]low PUL loss backplane and card laminates (see References 1)

PAM4 HEYE/VEYE vs. Channel Loss, 512b/513b Transcode



T10 : RS(248,228) t=10 m=9
T8 : RS(244,228) t=8 m=9
T6 : RS(240,228) t=6 m=9
T5 : RS(352,342) t=5 m=12
No code : 64b/66b

VEYE mVp[1]
HEYEpp %UI[1]

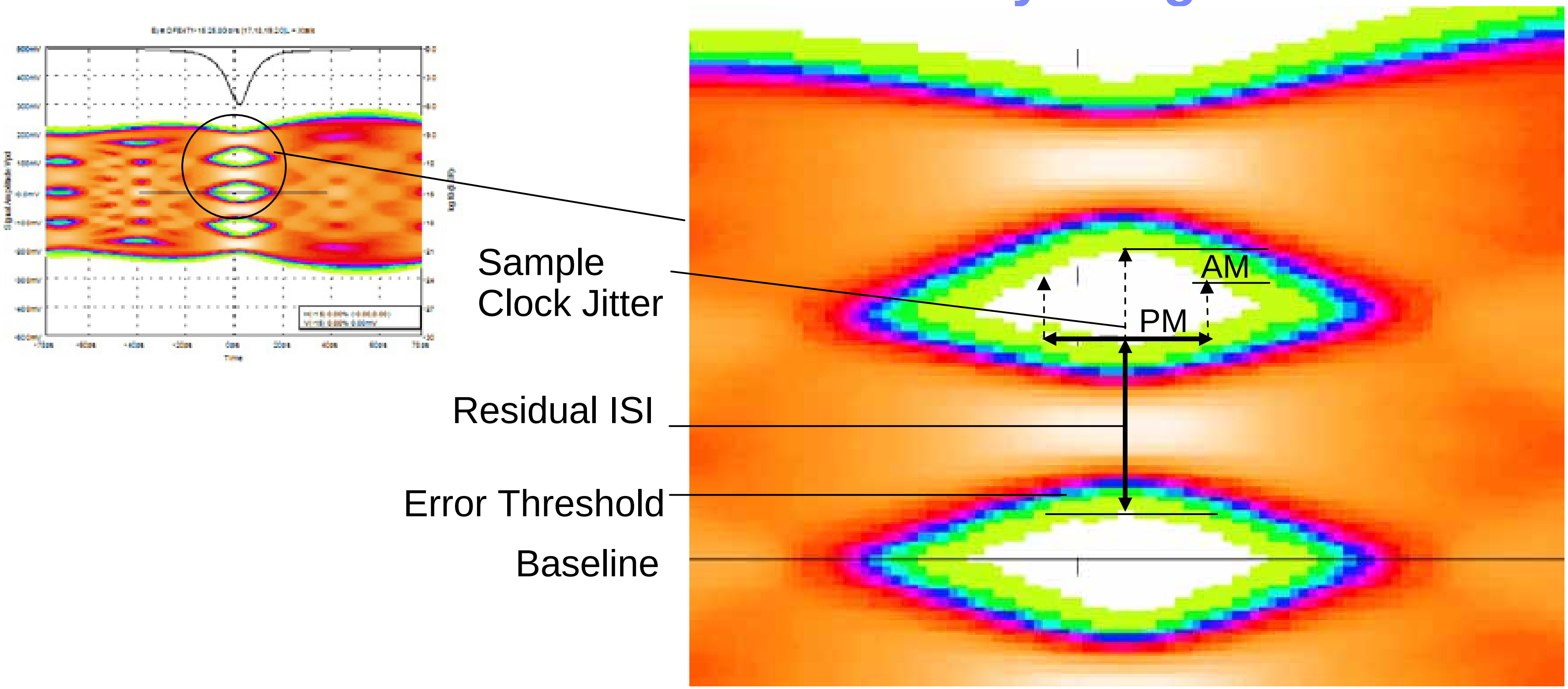
1m FR4 VEYE mVp
1m FR4 HEYEpp %UI

HEYE, VEYE
Margin Limit:
15% HEYE
15mVp VEYE

No DFE error
Propagation on
RS Code Results
(DFE h1 is very small)

[1]low PUL loss backplane and card laminates (see References, 1)

Dominant Sources of PAM4 Eye Degradation

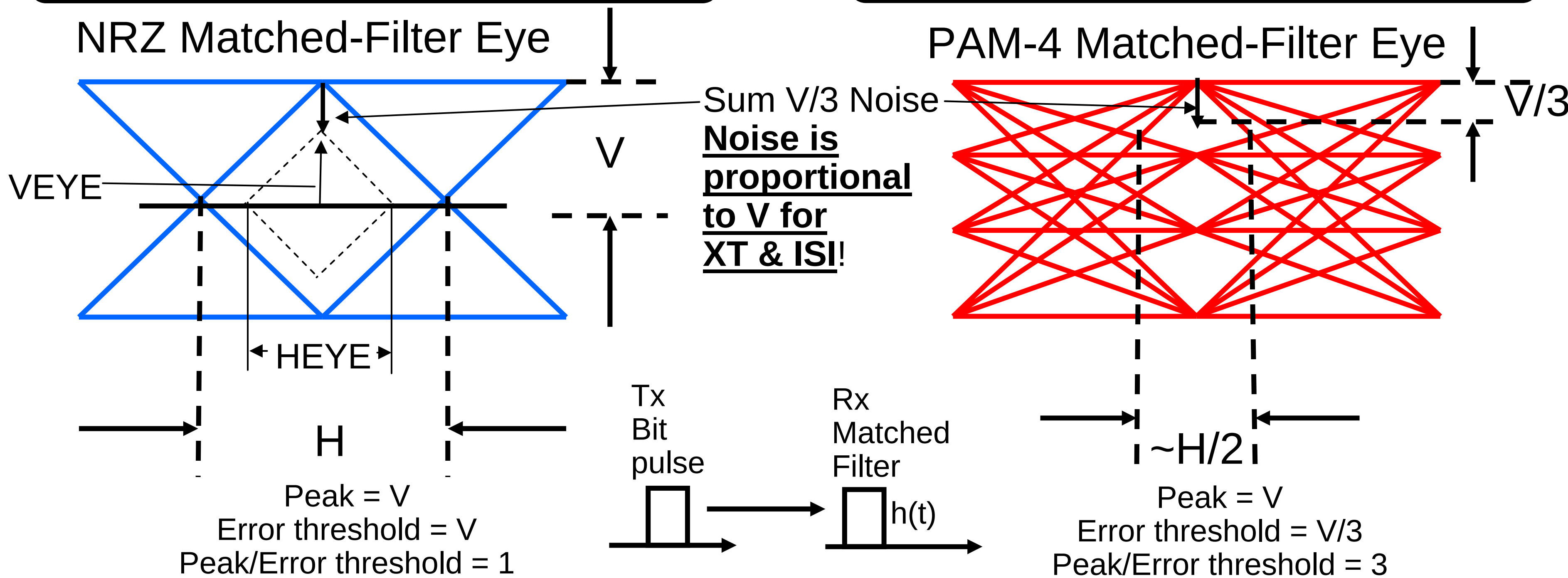


1) **Residual ISI** (after FFE/DFE) pushes signal near or over Error Threshold even without added non-deterministic noise
   → Practical equalizers cannot eliminate residual ISI due to equalizer complexity limits
   → This degradation may not be considered by “simplified” SNR analysis which assumes ISI can be cancelled
2) Sample clock is not constantly at eye center, but is jittered back and forth a significant fraction of the eye by Gaussian noise. **Sample Clock Jitter** closes both the HEYE (bathtub curve) and VEYE (vertical offset margin)
   → This degradation may not be considered by “simplified” SNR based analyses which do not incorporate sample clock jitter
3) Horizontal eye of PAM4 is severely degraded by **multiple edge transitions** with dV/dT ~1/3 of NRZ, increasing AM-PM degradation (i.e. ampltiude ISI/Noise is translated to horizontal eye closure with 3x more voltage/time gain)
4) The **Peak/Error threshold ratio** in PAM4 is 3x that of NRZ, increasing degradation from crosstalk and residual ISI by a peak factor of 3 (9.5dB) compared to NRZ (see next slide).

Why is NRZ so much better performing than PAM4?

66% HEYE 66% VEYE

0% HEYE 0% VEYE

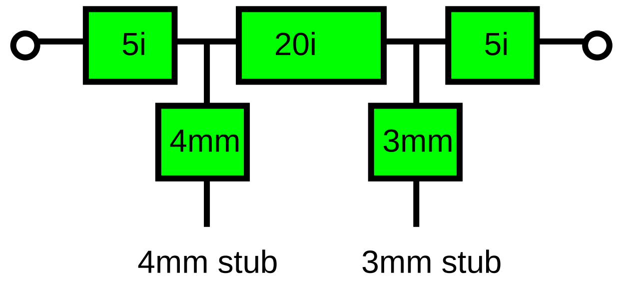


→CROSSTALK AND ISI DEGRADATION PEAK 3X (9.5dB) BIGGER EFFECT WITH PAM4 RESULTS IN LARGE RELATIVE HEYE/VEYE PERFORMANCE LOSS WITH PAM4 vs. NRZ (probability of PAM4 peak symbol=50%)

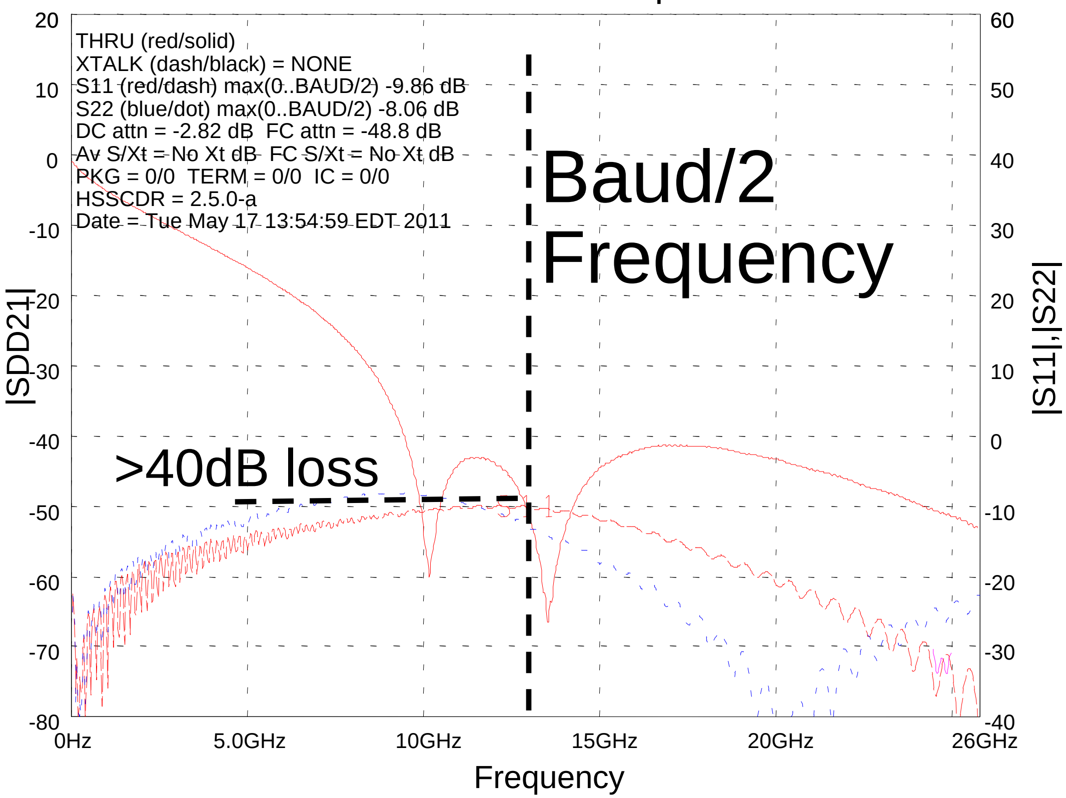
When is higher density signaling beneficial?

Chan Identifier	Trace Length	Loss 6.5GHz	Loss 12.9GHz dB
30 dB STUB	30”	20.6dB	49dB

CHANNEL MODEL



Stub Channel Response

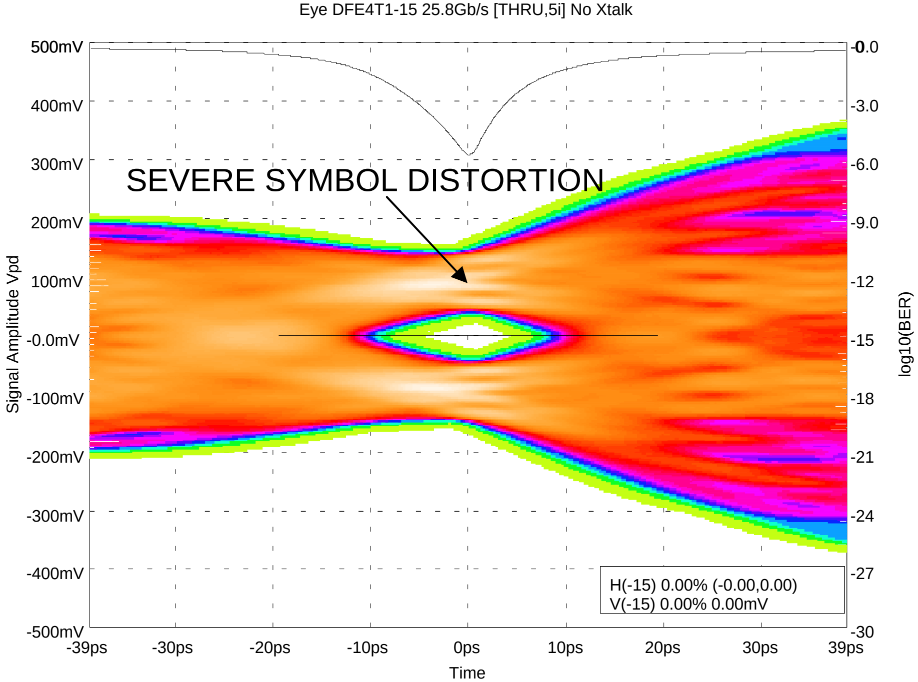


Extreme channel loss in range of BAUD/2 frequency causes too much signal energy to be lost and too much distortion for NRZ

Uncoded NRZ vs. PAM4 over Stub Channel

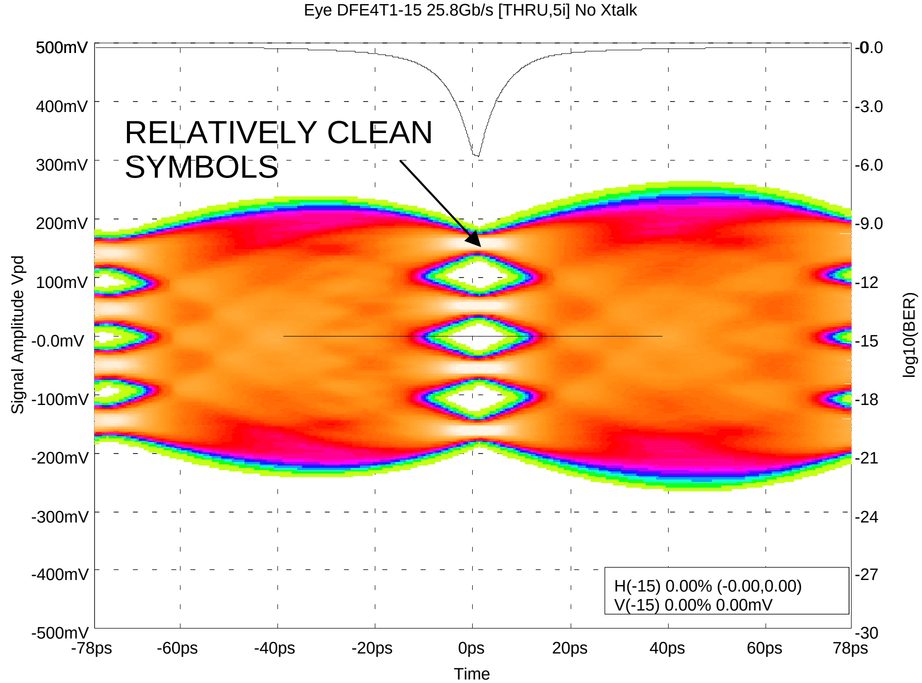
Both NRZ and PAM4 indicate an uncoded BER floor of about 1E-6, but NRZ has clearly far more distorted channel symbols compared to PAM4

NRZ



E2E BAUD/2 LOSS =~57dB
BER FLOOR ~1E-6

PAM-4



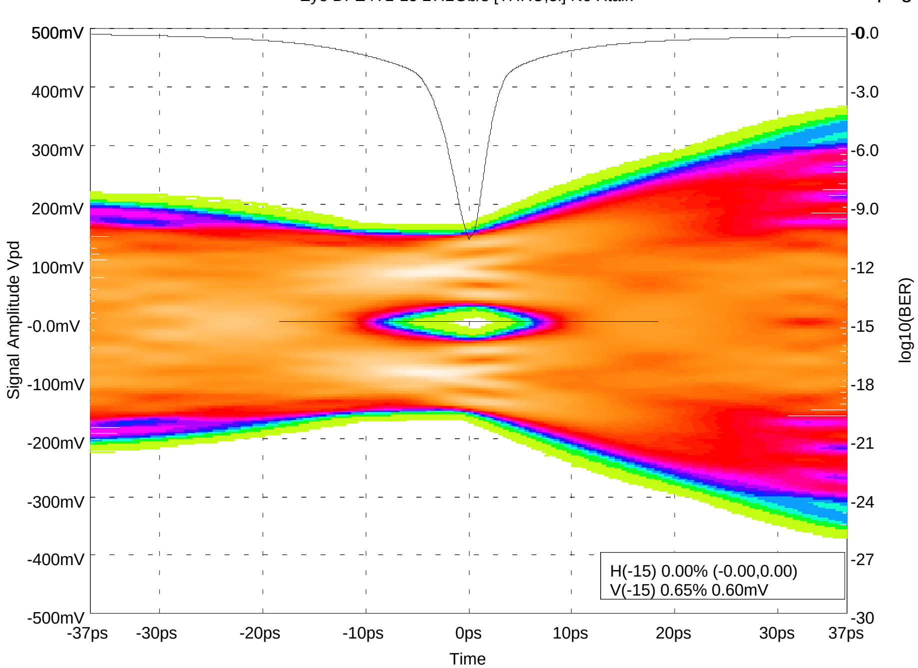
E2E BAUD/2 LOSS = ~23dB
BER FLOOR = ~1e-6

Coded NRZ and PAM4 over Stub Channel

Using a T=10 RS code, PAM4 has eye opening, but still not enough margin for practical operation
NRZ doesn't achieve any eye opening at overclocked BAUD (27.2Gb/s) to support T=10 RS code

NRZ

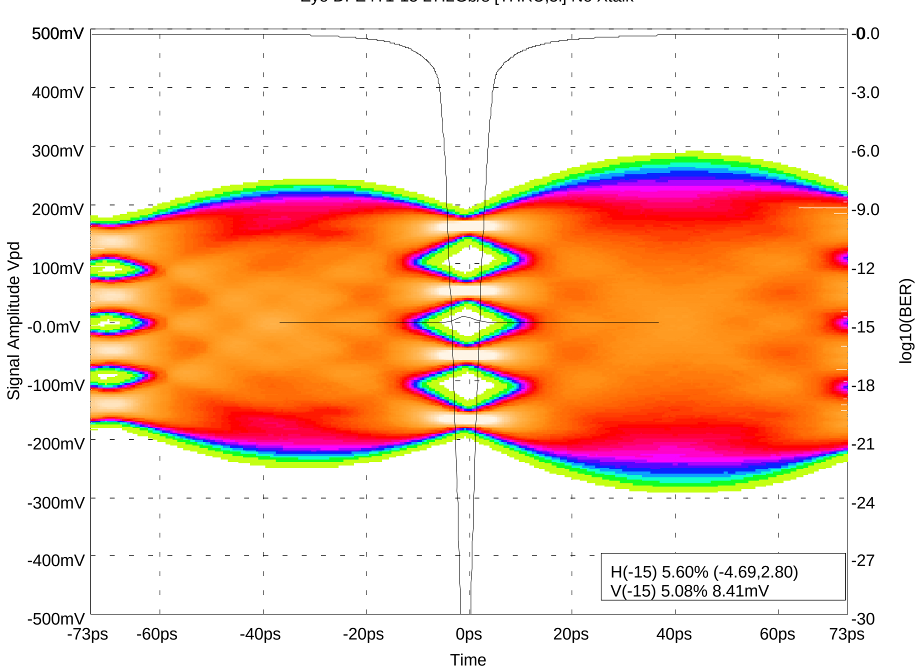
DFE1 h1=0.65 Error Propagation



E2E BAUD/2 LOSS =~62.4dB
BER FLOOR 7e-11

PAM-4

No DFE Error Propagation



E2E BAUD/2 LOSS = ~25dB
HEYE=7.5, VEYE = 8.41mV

Summary/Proposals

Link Simulations show NRZ line signaling is far superior to PAM4 over a high loss (38dB) 1m “improved FR4” channel constructed with low-cost material.

- ❑ **NRZ line signaling is proposed as the only PHY necessary to define in the 100GbE BP/Cable Standard for a “1m improved FR4” objective**

To provide sufficient operating margin to accommodate crosstalk, reflections, and practical I/O core non-idealities:

- ❑ **Standard compliant 1m NRZ channels should have less than 35dB of loss at BAUD/2 Frequency**

Due to expected insufficient link operating margins at >30dB channel loss which can occur with low-cost material channels, **FEC is required** :

- ❑ **A RS code with largest T possible, >=5, at <3% overclock while meeting desired latency is recommended for the FEC layer.**

References

1) IBM Test Fixture Channel NRZ/PAM4 study / IO Core Models :

Troy Beukema, Mounir Meghelli : “Line Signaling and FEC Performance Comparison for 25Gb/s 100GbE”, Sept. 2011 IEEE 100GbE Working Group meeting, Chicago.

Appendix

- Summary of Example RS Block Codes
- Known Errata in PAM4 results

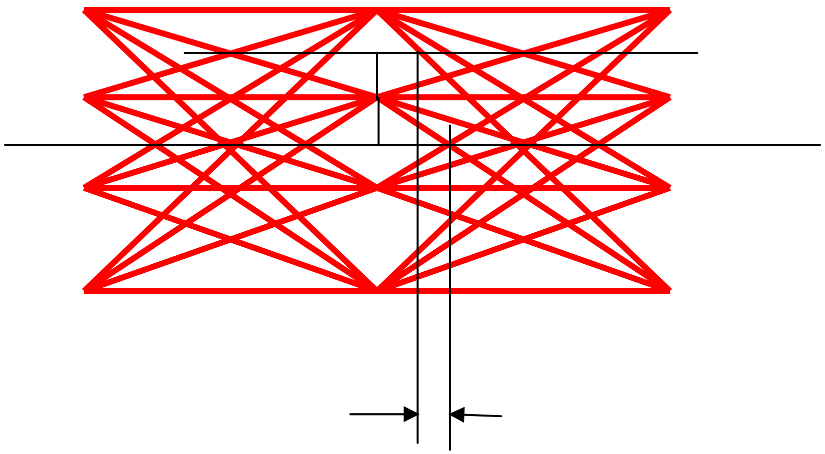
Summary of Example RS Block Codes

Line Rate = N / K / Transcode * 25.0

ECC	N	K	m	T	Trans-code	Line Rate	Rate/ 156.25	OC	AWGN GAIN 1e-15 BER H1=0	AWGN GAIN 1e-15 BER H1=0.65	Max BGA-BGA Loss[1] 15%HEYE 1-15 BER H1=0.65
NONE	-	-	-	-	-	25.78125	165	0%	0dB	0dB	30dB
RS	272	260	10	6	64/65	26.5625	170	3%	5.5dB	4.6dB	43dB
RS	224	208	10	8	64/65	27.34375	175	6.1%	6.2dB	5.5dB	44dB
RS	280	260	10	10	64/65	27.34375	175	6.1%	6.5dB	6.0dB	45dB
RS	352	342	12	5	512/513	25.78125	165	0%	5.0dB	4.0dB	41dB
RS	240	228	9	6	512/513	26.36719	168 + 3/4	2.3%	5.6dB	4.6dB	42dB
RS	244	228	9	8	512/513	26.80664	171 + 9/16	4%	6.2dB	5.5dB	45dB
RS	248	228	9	10	512/513	27.24609	174 + 3/8	5.6%	6.6dB	6.0dB	46dB

[1]IBM Test Fixture Channels, described in References 1)

Known Errata in PAM4 Results



Excess HEYE shutdown in upper and lower eye due to asymmetric edge transitions not factored into results (to determine best achievable PAM4 result if +-3 -> -+3 transitions were coded out)