Line Signaling Performance Comparison on 1m Improved FR4 Channel

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- 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

<table>
<thead>
<tr>
<th></th>
<th>Option</th>
<th>Backplane</th>
<th>Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>10”</td>
<td>20”</td>
<td>10”</td>
</tr>
<tr>
<td>Board Thickness (mils)</td>
<td>96</td>
<td>220</td>
<td>120</td>
</tr>
<tr>
<td>Trace Widths (mils)</td>
<td>7.5mil</td>
<td>7.5mil</td>
<td>7.5mil</td>
</tr>
<tr>
<td># of Layers</td>
<td>12</td>
<td>26</td>
<td>14</td>
</tr>
</tbody>
</table>

**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
- ~ 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

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**

<table>
<thead>
<tr>
<th>BAUD/2 LOSS (CHAN/E2E)</th>
<th>38/46dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEYEPP(1E-15)</td>
<td>7.7%</td>
</tr>
<tr>
<td>VEYE(1E-15)</td>
<td>7.5mV</td>
</tr>
<tr>
<td>BAUD/2 LOSS RS(352,342)</td>
<td>38/46dB</td>
</tr>
<tr>
<td>HEYEPP(1E-15) RS(352,342)</td>
<td>28.3%</td>
</tr>
<tr>
<td>VEYE(1E-15) RS(352,342)</td>
<td>26.7mV</td>
</tr>
</tbody>
</table>

1DFE1 h1=0.65 Error Propagation  225.8Gbaud/s

**PAM-4**

<table>
<thead>
<tr>
<th>BAUD/2 LOSS (CHAN/E2E)</th>
<th>21/25dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEYEPP(1E-15)</td>
<td>0%</td>
</tr>
<tr>
<td>VEYE(1E-15)</td>
<td>0mV</td>
</tr>
<tr>
<td>BAUD/2 LOSS RS(352,342)</td>
<td>21/25dB</td>
</tr>
<tr>
<td>HEYEPP(1E-15) RS(352,342)</td>
<td>7.2%</td>
</tr>
<tr>
<td>VEYE(1E-15) RS(352,342)</td>
<td>8.3mV</td>
</tr>
</tbody>
</table>

1DFE1 h1=0.65 Error Propagation  225.8Gbaud/s

3No DFE Error Propagation  412.9Gbaud/s
### 1m FR4 Channel Loss Eye Diagrams, RS T=10 m=9

#### NRZ

- **BAUD/2 LOSS (CHAN/E2E)**: 41/50dB
- **HEYEPP(1E-15)**: 0%
- **VEYE(1E-15)**: 0mV

#### PAM-4

- **BAUD/2 LOSS (CHAN/E2E)**: 23/26dB
- **HEYEPP(1E-15)**: 0%
- **VEYE(1E-15)**: 0mV

#### Table of Measurements

<table>
<thead>
<tr>
<th>Description</th>
<th>NRZ</th>
<th>PAM-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAUD/2 LOSS (CHAN/E2E)</td>
<td>41/50dB</td>
<td>23/26dB</td>
</tr>
<tr>
<td>HEYEPP(1E-15)</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>VEYE(1E-15)</td>
<td>0mV</td>
<td>0mV</td>
</tr>
<tr>
<td>BAUD/2 LOSS RS(248,228)</td>
<td>41/50dB</td>
<td>23/26dB</td>
</tr>
<tr>
<td>HEYEPP(1E-15) RS(248,228)</td>
<td>32.2%</td>
<td>11.3%</td>
</tr>
<tr>
<td>VEYE(1E-15) RS(248,228)</td>
<td>23.1mV</td>
<td>12.8mV</td>
</tr>
</tbody>
</table>

1. DFE1 h1=0.65 Error Propagation  
2. 27.2Gbaud/s  
3. No DFE Error Propagation  
4. 13.6Gbaud/s
NRZ HEYE/VEYE vs. Channel Loss, 512b/513b Transcode

HEYE and VEYE vs. BGA-BGA Loss

- 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
HEYEpp %UI

1m FR4 VEYE mVp
1m FR4 HEYEpp %UI

~30dB loss
Limit, Un Coded

~40dB loss
Limit, Coded

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

DFE1 h1=0.65 error
Propagation on all
RS code results

1low PUL loss backplane and card laminates (see References 1)
PAM4 HEYE/VEYE vs. Channel Loss, 512b/513b Transcode

HEYE and VEYE vs. BGA-BGA Loss

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

BGA-BGA Loss @ f=Bitrate/2 (dB)

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

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

1low 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. amplitude 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?

→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?

<table>
<thead>
<tr>
<th>Chan Identifier</th>
<th>Trace Length</th>
<th>Loss 6.5GHz</th>
<th>Loss 12.9GHz dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 dB STUB</td>
<td>30&quot;</td>
<td>20.6dB</td>
<td>49dB</td>
</tr>
</tbody>
</table>

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

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

PAM-4

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:
Appendix

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

Line Rate = \( \frac{N}{K} \times \text{Transcode} \times 25.0 \)

<table>
<thead>
<tr>
<th>ECC</th>
<th>N</th>
<th>K</th>
<th>m</th>
<th>T</th>
<th>Trans-code</th>
<th>Line Rate</th>
<th>Rate/156.25</th>
<th>OC</th>
<th>AWGN GAIN 1e-15 BER H1=0</th>
<th>AWGN GAIN 1e-15 BER H1=0.65</th>
<th>Max BGA-BGA Loss¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>NONE</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25.78125</td>
<td>165</td>
<td>0%</td>
<td>0dB</td>
<td>0dB</td>
<td>30dB</td>
</tr>
<tr>
<td>RS</td>
<td>272</td>
<td>260</td>
<td>10</td>
<td>6</td>
<td>64/65</td>
<td>26.5625</td>
<td>170</td>
<td>3%</td>
<td>5.5dB</td>
<td>4.6dB</td>
<td>43dB</td>
</tr>
<tr>
<td>RS</td>
<td>224</td>
<td>208</td>
<td>10</td>
<td>8</td>
<td>64/65</td>
<td>27.34375</td>
<td>175</td>
<td>6.1%</td>
<td>6.2dB</td>
<td>5.5dB</td>
<td>44dB</td>
</tr>
<tr>
<td>RS</td>
<td>280</td>
<td>260</td>
<td>10</td>
<td>10</td>
<td>64/65</td>
<td>27.34375</td>
<td>175</td>
<td>6.1%</td>
<td>6.5dB</td>
<td>6.0dB</td>
<td>45dB</td>
</tr>
<tr>
<td>RS</td>
<td>352</td>
<td>342</td>
<td>12</td>
<td>5</td>
<td>512/513</td>
<td>25.78125</td>
<td>165</td>
<td>0%</td>
<td>5.0dB</td>
<td>4.0dB</td>
<td>41dB</td>
</tr>
<tr>
<td>RS</td>
<td>240</td>
<td>228</td>
<td>9</td>
<td>6</td>
<td>512/513</td>
<td>26.36719</td>
<td>168 + 3/4</td>
<td>2.3%</td>
<td>5.6dB</td>
<td>4.6dB</td>
<td>42dB</td>
</tr>
<tr>
<td>RS</td>
<td>244</td>
<td>228</td>
<td>9</td>
<td>8</td>
<td>512/513</td>
<td>26.80664</td>
<td>171 + 9/16</td>
<td>4%</td>
<td>6.2dB</td>
<td>5.5dB</td>
<td>45dB</td>
</tr>
<tr>
<td>RS</td>
<td>248</td>
<td>228</td>
<td>9</td>
<td>10</td>
<td>512/513</td>
<td>27.24609</td>
<td>174 + 3/8</td>
<td>5.6%</td>
<td>6.6dB</td>
<td>6.0dB</td>
<td>46dB</td>
</tr>
</tbody>
</table>

¹IBM 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)