Comparison of PAM-4 and NRZ Signaling
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NRZ is the incumbent signaling method for 3 Gbps and 6 Gbps generations of electrical standards.

Optimal solution for 10-12 Gbps generations of standards currently being investigated. Factors include:

- Complexity of silicon (equalization, signalling method)

- Complexity of channel design (backplane, connectors)

  – Market is fragmented into vendors assuming Greenfield channels and vendors that want to use legacy designs.

- Power dissipation (of silicon -- but higher loss channels will require more power dissipation in silicon)
History and Perception

- Popular perception is that PAM-4 signalling enables use of legacy backplanes and interconnect.

- More detailed analysis of NRZ and PAM-4 signalling methods shows that reality is more complex:
  - PAM-4 does not universally guarantee that legacy backplane designs will be usable.
  - NRZ is not universally excluded from serving legacy designs.
Points of Comparison

NRZ and PAM-4 are compared on the following points:

- Vertical Eye Opening (Differential Amplitude)
- Horizontal Eye Closure (Unit Interval minus Jitter)
- Crosstalk Budget (Difference between amplitude of Noise Aggressor and Signal of Noise Victim)
- Power Analysis
PAM-4 vs. NRZ factors effecting vertical eye opening:

- Channel loss rises with frequency
  - Lower baud rate of PAM-4 implies less loss in channel

- PAM-4 launch amplitude per signal level is 33% of NRZ for equivalent driver technology and supply voltage

- At lower frequencies: Higher launch for NRZ provides greater vertical eye opening.

- At higher frequencies: Lower loss for PAM-4 (because baud rate is 1/2 that of NRZ) compensates for lower launch voltage and results in greater vertical eye opening.
Transmission line analysis shows expected crossover above 35 Gbps.

- NRZ results in bigger eye below crossover (range of current interest)
- PAM-4 results in bigger eye above crossover
Previous comparison assumes similar silicon technologies and power supply voltages for the NRZ and PAM-4 implementations.

Many existing PAM-4 implementations use higher power supply voltages to increase the total available dynamic range.

Advantages:
- Increased transmit eye amplitude

Disadvantages:
- Increased power dissipation
- May require use of dual-oxide devices in silicon implementation

Note: NRZ can also increase transmit amplitude to enable operation on lossy channels.
PAM-4 vs. NRZ factors effecting horizontal eye opening:

- Lower baud rate means more eye width due to base cycle.

- DJ/RJ at the transmitter are related to spectrum of the transmitted signal and tend to scale with baud rate.
  - Implies that absolute value of DJ/RJ for half baud rate design would be 2x that of full baud rate design.
  - With careful design should be able to achieve DJ/RJ for half baud rate design of 1.8x that of full baud rate design.

- Base cycle minus DJ/RJ still results in larger horizontal eye opening for PAM-4 .... if these were the only factors ....
Horizontal Eye Opening Comparison

- PAM-4 vs. NRZ factors effecting horizontal eye opening:
  - PAM-4 results in additional loss in 33% of eye width due to switching between adjacent and non-adjacent levels.
PAM-4 vs. NRZ factors effecting horizontal eye opening:

- Combination of effects will result in larger horizontal eye opening for a PAM-4 solution at transmitter output.
  - *But eye opening for PAM-4 is *not* twice as large as NRZ as would be implied from baud rate difference.*

<table>
<thead>
<tr>
<th></th>
<th>NRZ</th>
<th>PAM-4</th>
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</thead>
<tbody>
<tr>
<td>Total Cycle (11.1 Gbps)</td>
<td>90 ps</td>
<td>180 ps</td>
</tr>
<tr>
<td>Total Jitter</td>
<td>(0.30 UI) 27 ps</td>
<td>(0.27 UI) 48 ps</td>
</tr>
<tr>
<td>Loss in Eye Width for PAM-4</td>
<td>0 ps</td>
<td>(0.33 UI) 60 ps</td>
</tr>
<tr>
<td>Eye Opening at Tx</td>
<td>(0.70 UI) 63 ps</td>
<td>(0.40 UI) 72 ps</td>
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PAM-4 vs. NRZ factors effecting horizontal eye opening:

- Eye width reduction at Transmitter due to PAM-4 switching between adjacent and non-adjacent levels is effectively a form of deterministic jitter.

- Spectrum of this jitter component is near the frequency of the baud rate, substantially above the bandwidth of the channel.

- **Transmit jitter with this spectrum is particularly susceptible to phase noise amplification by the channel.**
PAM-4 Implementation Notes

- Previous comparison assumes no special encoding of data to overcome limitations of signalling technique.

- Many existing PAM-4 implementations use coding to limit or eliminate transitions between non-adjacent levels.

- Advantages:
  - Increased eye width due to reduction/elimination of non-adjacent transition effect.

- Disadvantages:
  - Coding requires overhead (~25% typical) and thereby requires higher baud rate to achieve same bit rate.
  - For 25% overhead, net improvement in eye width is ~ 0.13 UI.

- Note: NRZ can also increase use coding to set minimum run length to control spectral content of signal and thereby reduce frequency dependent losses in channel.
Crosstalk Concerns

- Crosstalk is a substantial contributor to jitter at the receiver.

- PAM-4 maximum signal swing is similar to NRZ and therefore the noise level from the aggressor signal is the same for both PAM-4 and NRZ.

- PAM-4 vertical eye opening is 33% of NRZ and therefore the victim signal's tolerance for crosstalk is less.

- Crosstalk budget for PAM-4 therefore starts out 9 dB less than for NRZ.

- Greater channel attenuation at higher frequencies reduces this advantage for NRZ to the 3-6 dB range (depending on channel design).
Power Concerns

- Power analysis is based on implementation experience in TSMC 0.18 um and 0.13 um CMOS.

- PAM-4 provides power savings for Tx/Rx circuits over NRZ:
  - 3:1 ratio of PAM-4 Tx/Rx circuits to NRZ Tx/Rx circuits
  - Each circuit operates at 1/2 baud rate and uses 1/3 the power (average dependent on circuit design)
  - *Net is PAM-4 Tx/Rx uses same power as NRZ Tx/Rx*

- *Assumes equivalent power supplies*

- *Assumes equivalent power utilization by equalization circuits*
PAM-4 systems generally use larger power supply voltages to overcome vertical eye disadvantages. Increase in launch amplitude results in power dissipation increase (placing PAM-4 at a power disadvantage).

To achieve equivalent power dissipation, less complex equalization scheme must be assumed for PAM-4. Equivalent equalization schemes require significant increase in power dissipation for PAM-4 vs. NRZ due to implementation complexity (placing PAM-4 at a power disadvantage). PAM-4 with DFE is also undesirable due to DFE error propagation considerations.

Techniques used to improve performance of PAM-4 carry significant power penalties, negating any power advantage of PAM-4.
Statistical Eye Analysis technique is described in [2].

- Algorithm uses S-parameter measurements of a channel along with ideal transmitter and receiver models to determine whether the channel can pass a receivable signal.

- Algorithm selects optimal coefficients for transmit pre-emphasis and the receiver filter, and then uses statistical techniques to determine the resulting eye opening after receiver equalization.
Goal of this analysis is to compare an NRZ solution to a PAM-4 solution of approximately equivalent complexity and power dissipation.

Performed analysis using 5 backplanes:
- Four backplanes are existing backplanes from various companies designed for 10 Gbps demonstration.
- One legacy backplane (backplane E).

Equalization assumptions (based on existing best-of-breed for each signalling technique):
- NRZ with preemphasis and 4-tap DFE
- PAM-4 with linear equalization

Similar supply voltage for both NRZ and PAM-4 drivers is assumed (i.e. signal swing for each PAM-4 signal level is 33% of NRZ case).
Statistical Eye Analysis (Pass/Fail Criteria)

- Analysis performed for 1 to 6 crosstalk aggressors.

- Pass / Fail Criteria:
  - Amplitude is open if > 0.0 V
  - Jitter is okay if < 0.90 UI

- NRZ and PAM-4 cases can be compared by determining number of crosstalk aggressors at which one or both of the pass/fail criteria indicate failure.
NRZ Eye:
- Vertical Eye is Open for \( \leq 2 \) aggressors
- Horizontal Eye is okay for \( \leq 1 \) aggressors

PAM4 Eye:
- Closed
Backplane B Results

NRZ Eye:
- Vertical Eye is Open
- Horizontal Eye is okay for ≤ 2 aggressors

PAM4 Eye:
- Closed
Backplane C Results

NRZ Eye:
- Vertical Eye is Open
- Horizontal Eye is okay

PAM4 Eye:
- Closed
Backplane D Results

NRZ Eye:
- Vertical Eye is Open for ≤ 3 aggressors
- Horizontal Eye is okay for ≤ 2 aggressors

PAM4 Eye:
- Closed
**Backplane E (Legacy Case) Results**

**Vertical Eye**
- NRZ Eye: Closed
- PAM4 Eye: Closed

**Horizontal Eye**
- NRZ Eye: Stabilized
- PAM4 Eye: Stabilized
Conclusions

- PAM-4 does not have a demonstrated performance advantage over NRZ for this set of backplanes.
  - *PAM-4 is not a magic bullet to achieve legacy support.*

- PAM-4 will perform better or worse than NRZ based on channel design factors. The results show NRZ performed better for the five backplanes being measured.
  - Backplanes A, B, C, and D passed NRZ with at least 1 aggressor and all of these failed to pass PAM-4 even with 0 aggressors.
  - Backplane C passes NRZ with 6 aggressors, but fails to pass PAM-4 even for 0 aggressors.
  - Only Backplane E failed to pass NRZ; it also failed to pass PAM-4.
Conclusions

- For the channels examined, NRZ provided better results.

- PAM-4 has an advantage for very high loss channels (such as cables), however this advantage is not universal.

- Existing PAM-4 implementations use techniques such as coding or higher transmit amplitude to overcome limitations of the PAM-4 signalling.
  - Similar techniques can be applied to NRZ signalling.
  - When comparing signalling methods, care must be taken to ensure advantages/disadvantages are attributable to the signalling method and not to other factors.

- Given no clear-cut advantage of PAM-4, incumbent NRZ signalling methods should be pursued.
References
