Transmitter Pre-Compensation for 320 MB/sec SCSI

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Objectives

- Look at two forms of transmitter pre-compensation that might be used for 320 MB/sec SCSI
  - Mathematically model timing pre-compensation
    - How does timing pre-compensation help:
      - Isolated pulses
      - High frequency patterns (0, 1, 0, 1, etc.)
  - Use experimental data to examine amplitude pre-compensation using real cables with real loads.
    - How much does amplitude pre-comp improve signal integrity?
    - How much amplitude pre-comp is required for:
      - short cables?
      - long cables?
    - Determine the optimum value for amplitude pre-comp
Transmitter Pre-Compensation
for 320 MB/sec SCSI

Part I
Timing Pre-Compensation Study
Disclaimer

- All data collected in this section of the presentation is based on a simple *optimistic* model for SCSI signals.
- Real factors such as DC attenuation, reflections, offsets, frequency dependent skew, differential skew, etc. will degrade performance even more than suggested.
- This simple model is used to facilitate the analysis and to gain some insight into what can be expected in actual practice.
• Adjust the timing of pulse edges to improve receiver amplitude noise margin and set-up time.
• If the pulse is sent earlier, then response will rise further past the threshold.
• If the pulse is earlier, there is more set-up time, and less hold time for the previous bit.
• Timing pre-comp has largest effect for an isolated pulse.
• Timing pre-comp has no effect for high-frequency patterns (0, 1, 0, 1, etc.).
Effect on Received Amplitude

Simplified Transmitter Waveform:

Bit interval: $T$

Send this pulse edge earlier by $\Delta t$

Receiver Waveform:

For additional amplitude margin at sampling instant

Amplitude at sampling instants
Assuming a first order model for cable the received waveform during bit interval \((k+1)\) can be expressed as:

\[
v_{k+1}(t) + 500mV = \begin{cases} 
X_{k+1} = 0 & V_k \exp(-t/\tau) \\
X_{k+1} = 1 & 1000mV - (1000mV - V_k)\exp(-t/\tau)
\end{cases}
\]

Where:
- \(X_{k+1}\): is the bit sent during interval \((k+1)\)
- \(V_k\): is the amplitude at the end of bit interval \((k)\)
- \(\tau\): is the dominant first-order time constant of the cable
- \(v_{k+1}(t)\): is receiver waveform during bit interval \((k+1)\)

This model assumes a zero-delay, just a first-order amplitude roll-off with frequency and normalized peak-to-peak amplitude of 1000mV
Receiver Waveform Model

\[ v_{k+1}(t) + 500mV = \begin{cases} 
X_{k+1} = 0 & V_k \exp(-t/\tau) \\
X_{k+1} = 1 & 1000mV - (1000mV - V_k) \exp(-t/\tau) 
\end{cases} \]

- This assumes several optimistic scenarios:
  - input is an ideal square wave
  - no frequency dependent time skew in cable
  - Output has a voltage swing of 1V (no attenuation in the cable)
First order cable model:
- attenuation versus frequency
- characterized by a single pole roll-off
Pre-comp Amplitude Margin

- Receiver input is sample of waveform at the sampling instant \((T_{sample})\)
- Sampling instant defined by position of zero crossings for high frequency pattern (de-skew).

\[
v_{k+1}(T_{sample}) + 500mV = \begin{cases} 
X_{k+1} = 0 & V_k \exp(-T_{sample} / 2\tau) \\
X_{k+1} = 1 & 1000mV - (1000mV - V_k) \exp(-T_{sample} / 2\tau)
\end{cases}
\]

- For worst case (isolated bit) we have:
  \[X_{k-N}, .. X_k = 0, X_{k+1} = 1, X_{k+2} = 0 : : V_k = 0.\]
- Without pre-compensation the amplitude is:
  \[v_{k+1}(T_{sample}) = (1000mV - 1000mV \exp(-T_{sample} / 2\tau)) - 500mV\]
- With timing pre-comp shift \((\Delta t)\) the amplitude is:
  \[v_{k+1}(T_{sample}) = (1000mV - 1000mV \exp(-(T_{sample} + \Delta t) / \tau)) - 500mV\]
• Numerical calculations for isolated pulse:
  • $\tau \approx \frac{1}{2 \pi 40 \text{ MHz}}$, $\Delta t = 0 \text{ps} \rightarrow 2\text{ns by 500ps}$
• Amplitude margin vs. timing pre-comp shift ($\Delta t$) for $f_c = 40$MHz:

![Graph showing Amplitude Margin vs. Precomp shift (ps)]
- Improvement in amplitude margin with timing pre-comp shift $\Delta t$ for $f_c = 40$ MHz:
Timing Pre-comp and Set-up/Hold Time

Transmitter Waveform:

Receiver Waveform:

Send this pulse edge earlier by $\Delta t$

Set-up/hold from sampling instant

Positive threshold

Negative threshold

$v_{th}=100mV$

additional set-up time

reduced hold time
Set-up/Hold Time

- Time before sampling instant \((T_{sample})\) that waveform passes positive threshold \((V_{setup})\)
  \[
t_{su}(V_{setup}) = T_{sample} + \Delta t + \tau \ln\left(\frac{500\text{mV} - V_{setup}}{1000\text{mV}}\right)
  \]

- Set-up time for current bit linearly increases with pre-comp shift \((\Delta t)\)

- Hold time for previous bit linearly decreases with pre-comp shift \((\Delta t)\)
  \[
t_{h}(V_{hold}) = T_{sample} - \Delta t - \tau \ln\left(\frac{500\text{mV} - V_{hold}}{1000\text{mV}}\right)
  \]

- Isolated bit set-up/hold times calculated assuming that the starting voltage \(V_k = 0\) (ISI voltage)
Set-up/Hold Time

-500m

\( v(t) \)

500m

\( X_k = 0 \)

\( X_{k+1} = 1 \)

\( X_{k+2} = 1 \)

\( X_{k+3} = 1 \)

\( (k)T \)

\( (k+1)T \)

\( (k+2)T \)

\( (k+3)T \)

Set-up time for bit \( X_{k+1} \)

Hold time for bit \( X_k \)

V\(_{\text{setup}}\) = 100mV

V\(_{\text{hold}}\) = 0mV

V\(_{\text{setup}}\) = 100mV

V\(_{\text{hold}}\) = 0mV

Set-up time for bit \( X_{k+1} \)

Hold time for bit \( X_k \)
- Numerical calculations for isolated pulse:
  \[ \tau \approx \frac{1}{(2 \pi 40 \text{ MHz})}, \ \Delta t = 0\text{ps} \rightarrow 2\text{ns by 500ps} \]

Hold time is time after sampling instant that level crosses 0mV

Set-up time is time before sampling instant that level crosses 100mV

1st Order Isolated Pulse Response

Sample \( k-1 \)  Sample \( k \)  Sample \( k+1 \)
Fast and Slow Case Set-up/Hold Times

- Numerical calculations for isolated pulse:
  - slow case cable: \( \tau \approx \frac{1}{(2 \pi) \times 40 \text{ MHz}} \), \( \Delta t = 0 \text{ps} \rightarrow 2 \text{ns by 100ps} \) (dashed)
  - fast case cable: \( \tau \approx \frac{1}{(2 \pi) \times 120 \text{ MHz}} \), \( \Delta t = 0 \text{ps} \rightarrow 2 \text{ns by 100ps} \) (solid)

**Precomp Shift vs Setup/Hold**

![Graph showing the relationship between Precomp Shift and Setup/Hold for Fast and Slow cases.](image-url)
For the high-frequency pattern, shifting each edge by $\Delta t$ is the same as no pre-comp; all edges move over by the same amount (i.e., timing pre-comp just defeats de-skew).

What is the set-up/hold time for the high frequency pattern.

The first-order waveform equation in bit interval $(k+1)$:

$$v_{k+1}(t) + 500mV = \begin{cases} 
X_{k+1} = 0 & V_k \exp(-t / 2\tau) \\
X_{k+1} = 1 & 1000mV - (1000mV - V_k) \exp(-t / 2\tau) 
\end{cases}$$

Where $V_k$ is the amplitude at the start of bit interval $(k+1)$ (i.e., ISI)

Can calculate $V_k$ for \(\{X_k, X_{k-1}, X_{k-2}, \ldots\} = \{\ldots, 1, 0, 1, 0, \ldots\}\)
• The residual ISI voltage \( (V_k) \) for a high frequency pattern is the peak voltage of the high frequency waveform.

\[
\begin{align*}
X_k &= 0 \\
X_{k+1} &= 1 \\
X_{k+2} &= 0 \\
X_{k+3} &= 1 \\
\end{align*}
\]

\[
v_{k+j}(t)
\]

\[
\begin{array}{c}
500m \\
\text{v}_{k+j}(t) \\
-500m \\
\end{array}
\]

\[
kT_{\text{sample}} \\
(k+1)T_{\text{sample}} \\
(k+2)T \\
(k+3)T
\]

\[T_{\text{su}} = 525\text{ps}\]

Assuming you have skew compensated perfectly!
The residual voltage ($V_k$) for a high frequency pattern depends on the cable cut-off frequency and the total receiver amplitude.

At $f_c = 40\text{MHz}$, $V_k = 330\text{mV}$ for a $1\text{V}_{\text{pk-pk}}$ signal swing.
With signal starting from ISI residual voltage the set-up time is:

\[ t_{su}(V_{setup}) = T_{sample} + \tau \ln \left( \frac{500mV - V_{setup}}{1000mV - V_k} \right) \]

The threshold voltage \( (V_{setup}) \) is specified at 100mV.
High Frequency Pattern Set-up Time

- Set-up time versus cable cut-off frequency.
  - For $f_c = 60\text{Mhz} (=1/2\pi \tau)$, set-up time = 1.75ns
  - For $f_c = 40\text{Mhz} (=1/2\pi \tau)$, set-up time = 525ps
• Hold time versus cable cut-off frequency
Quantum believes that timing pre-compensation alone is insufficient to compensate for ISI at 320 MB/sec SCSI transfer rates
Transmitter Pre-Compensation for 320 MB/sec SCSI

Part II
Amplitude Pre-Compensation Study
Amplitude Pre-Compensation Basics

- Increase the amplitude of transmitted signal on signal transitions
- If there is no transition, return amplitude to nominal level (normalized to 1)
- $\Delta A$ - amplitude increase is design parameter
Experimental Setup #1 - Short Cable

- Hitachi 0.625 meter, 32AWG twisted-flat ribbon cable, 12.5cm load spacing, plus 6-slot back-plane.
- Waveforms captured @ 4Gs/s
  - no pre-comp: $\Delta A = 0.0$
  - amplitude pre-comp: $\Delta A = 0.2, 0.5, 0.8$
Electrical Setup #1 - Short Cable

Termination 110ohms, located at end of backplane

V+ 50ohm source

12.5cm

V- 50ohm source

Receivers are boards 1 through 10, boards 1 to 4 are on connectors along ribbon cable, boards 5 to 10 are on the backplane
Waveform Data: bd1, \( \Delta A = 0.0 \)
Eye Diagram: bd1, $\Delta A = 0.0$

- **setup time**: ~2.8ns
- **hold time**: ~3.2ns
Waveform Data: bd1, $\Delta A = 0.2$

bd1comp1p2.dat
Eye Diagram: bd1, \( \Delta A = 0.2 \)

setup time ~2.8ns

hold time ~3.2ns
Waveform Data: bd1, $\Delta A = 0.5$

### Graph

- **Title**: bd1comp1p5.dat
- **Axes**:
  - X-axis: Time (ns)
  - Y-axis: Amplitude (mV)
- **Data Source**: bd1comp1p5.dat

The graph shows a waveform with a series of peaks and troughs, indicating data over time and amplitude.
Eye Diagram: bd1, $\Delta A = 0.5$

- Setup time: $\sim 2.8$ ns
- Hold time: $\sim 3.2$ ns
Waveform Data: bd1, $\Delta A = 0.8$
Eye Diagram: bd1, $\Delta A = 0.8$

- Setup time: ~2.8ns
- Hold time: ~3.0ns
Waveform Data: bd4, $\Delta A = 0.0$
Eye Diagram: bd4, $\Delta A = 0.0$

- **setup time**: ~2.6ns
- **hold time**: ~3.0ns

Diagram: bd4nocomp.dat

- Amplitude (mV)
- Time (ns)
Waveform Data: bd4, $\Delta A = 0.2$

The diagram shows the waveform data for bd4comp1p2.dat, with the amplitude (mV) on the y-axis and time (ns) on the x-axis. The waveform consists of multiple peaks and troughs, indicating a periodic signal. The amplitude values range from approximately -800 to 800 mV, with the time range from 50 to 400 ns.
Eye Diagram: bd4, $\Delta A = 0.2$

- setup time ~2.8ns
- hold time ~3.0ns
Waveform Data: bd4, $\Delta A = 0.5$
Eye Diagram: bd4, $\Delta A = 0.5$

- Setup time: ~2.8 ns
- Hold time: ~2.8 ns

Graph showing eye diagram with amplitude in mV and time in ns.

Legend:
- $t_{\text{setup}}$
- $t_{\text{hold}}$
- $t_{\text{sample}}$
Waveform Data: bd4, $\Delta A = 0.8$
Eye Diagram: bd4, $\Delta A = 0.8$

- Amplitude (mV)
- Time (ns)

- $t_{\text{setup}}$: ~2.8ns
- $t_{\text{hold}}$: ~2.6ns
Waveform Data: bp5, $\Delta A = 0.0$
Eye Diagram: bp5, $\Delta A = 0.0$

- Setup time: $\approx 2.4\text{ns}$
- Hold time: $\approx 3.0\text{ns}$
Waveform Data: bp5, $\Delta A = 0.2$

Diagram showing waveform data from bp5comp1p2.dat. The graph displays amplitude against time with values ranging from $-800$ to $800$ mV and time from $50$ to $400$ ns.
Eye Diagram: bp5, $\Delta A = 0.2$

- **Hold Time**: $\sim 3.0$ ns
- **Setup Time**: $\sim 2.8$ ns
Waveform Data: bp5, $\Delta A = 0.5$

![Waveform Data Diagram](bp5comp1p5.dat)
Eye Diagram: bp5, $\Delta A = 0.5$

- Amplitude (mV) vs. Time (ns)
- Setup time: $\approx 3.0\text{ns}$
- Hold time: $\approx 2.6\text{ns}$
- Sample time

Data file: `bp5comp1p5.dat`
Waveform Data: bp5, $\Delta A = 0.8$

![Waveform Graph](bp5comp1p8.dat)

- Amplitude (mV)
- Time (ns)
Eye Diagram: bp5, $\Delta A = 0.8$

- **Amplitude (mV)**
- **Time (ns)**

Setup time: ~3.0ns
Hold time: ~2.6ns
Experimental Setup #2 - Long Cable

- Hitachi 10 meter, 32AWG twisted-flat ribbon cable, 25cm load spacing, plus 6-slot back-plane.
- Waveforms captured @ 4Gs/s:
  - no pre-comp: \( \Delta A = 0.0 \)
  - amplitude pre-comp: \( \Delta A = 0.2, 0.5, 0.8 \)
Electrical Setup #2 - Long Cable

- **V+ 50ohm source**
- **V- 50ohm source**
- Termination 110ohms, located at end of backplane
- 7.25m
- receive at boards 1 through 15, boards 1 to 9 are on connectors along ribbon cable, boards 10 to 15 are on the backplane
Waveform data: bd9, $\Delta A = 0.0$
Eye Diagram: bd9, $\Delta A = 0.0$

Nominal setup time $\sim 1.6$ns

Nominal hold time $\sim 2.4$ns
Waveform data: bd9, $\Delta A = 0.2$
Eye Diagram: bd9, $\Delta A = 0.2$

Additional set-up time ~200ps

Additional hold time ~0ps
Waveform data: bd9, $\Delta A = 0.5$
Eye Diagram: bd9, $\Delta A = 0.5$

Additional set-up time ~600ps

Additional hold time ~200ps
Waveform data: bd9, $\Delta A = 0.8$
Eye Diagram: bd9, $\Delta A = 0.8$

Additional set-up time: ~1.0ns

Additional hold time: ~400ps
Waveform data: bp10, $\Delta A = 0.0$
Eye Diagram: bp10, $\Delta A = 0.0$

Nominal set-up time
~400ps

Nominal hold time
~1.6s
Waveform data: bp10, $\Delta A = 0.2$
Eye Diagram: bp10, $\Delta A = 0.2$

Additional set-up time
~800ps

Additional hold time
~400ps
Waveform data: bp10, $\Delta A = 0.5$
**Eye Diagram: bp10, \( \Delta A = 0.5 \)**

- Additional set-up time: \(~1.6\text{ns}~\)
- Additional hold time: \(~600\text{ps}~\)
Waveform data: bp10, $\Delta A = 0.8$
Eye Diagram: bp10, $\Delta A = 0.8$

- Additional set-up time: $\sim 2\text{ns}$
- Additional hold time: $\sim 600\text{ps}$
Amplitude Pre-comp Vs Setup Time

Amplitude Precomp Vs Setup Time

Setup Time (ns)

Precomp

- Long Cable Board 9
- Long Cable Board 10
- Short Cable Board 1
- Short Cable Board 4
- Short Cable Board 5

11/01/99
SCSI T10 Meeting Monterey Bay
Amplitude Pre-comp vs Hold Time

- Long Cable Board 9
- Long Cable Board 10
- Short Cable Board 1
- Short Cable Board 4
- Short Cable Board 5
<table>
<thead>
<tr>
<th>Timing Budget (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Period</td>
</tr>
<tr>
<td>DT-Period</td>
</tr>
<tr>
<td>Period Tolerance</td>
</tr>
</tbody>
</table>

**Deterministic Errors**

- Silicon TX Driver Skew                             | 1.000 |
- Package Skew (Initiator)                           | 0.065 |
- PCB Layout Skew (Initiator)                        | 0.200 |
- Cable Skew (@25ps/ft)                              | 2.500 |
- PCB Layout Skew (Target)                           | 0.200 |
- Package Skew (Target)                              | 0.065 |
- Silicon Rx Routing Skew                            | 1.000 |
- HL vs LH Matching                                  | 0.500 |

**Non-Deterministic Errors**

- Low Vt vs Substrate Noise                          | 0.200 |
- PLL Jitter                                         | 0.250 |
- Cross Talk Induced Jitter                          | 0.500 |
- **Cable Period Distortion ISI**                    | 2.000 |
- Input Slew Rate Dependent Skew                     | 0.200 |
- Receiver Amplitude Dependant Skew                  | 0.200 |
- Self Cal Accuracy (± 100ps)                        | 0.200 |

- **Data Valid Window**                              | 1.850 |
- **Data Setup/Hold**                                | 0.925 |
Conclusions on Amplitude Pre-Comp

- Amplitude pre-comp appears to work for long cables and for closely-spaced loads (i.e., set-up time improves, amplitude margin improves).
  - Without it (or something else) certain configurations will fail: zero set-up time, no amplitude margin.
  - Optimum value for pre-comp amplitude is between 1.5 and 1.8.
  - This value depends on the configuration.

- Amplitude pre-comp does not improve signal integrity for short cables:
  - Extra signal amplitude contributes to ringing and overshoot;
  - Amplitude pre-comp can even slightly decrease available hold time.

- Unsolved issues with EMI, Power, cross-talk, and capacitance.
Comments on Amplitude Pre-Comp

- Data presented is for various pre-comp boost values over a ‘low frequency’ drive level of 400mV peak differential.
- Driver and terminators are ideal
  - Other errors due to driver/terminator mismatch and interconnect resistance, requires an addition of approximately 70mV in the receiver margin above the 100mV in Figs 47,48 of SPI-3.
- Only 1 line is driven, no cross-talk components are included.
- Setup & hold measurements must include a timing error for residual skew.
- Transmit pre-comp appears able to meet the present interconnect configuration range, but:
  - fixed value of pre-comp is non-optimum at many drops.
  - meeting the 12m / 15 drop configuration stresses available driver output signal capabilities.
  - little or no range left to accommodate speed increase to 640.
Comments on Amplitude Pre-Comp

- **Driver Issues for Amplitude Pre-comp**
  - Data shows that a Pre-comp boost of 1.5 to 1.8 is required to handle 12m cable / 15 load case
  - Expect bus DC errors similar to U160
  - Expect cross-talk and reflection problems with pre-comp boost to be worse than with U160
    - **There is no reason to expect that a minimum (un-boosted) transmit signal lower than the 360mV min in SPI-3 is workable.**
  - Taking the SPI-3 360mV minimum, and +/-20% driver tolerance → 400mV nominal un-boosted level
    - 1.8x boost → 720mV nominal boosted level
    - + 20% driver tolerance → 864mV peak differential boosted signal
    - **These signal ranges exceed the present SPI-3 min/max limits and will present driver design difficulties and increased power dissipation.**
Next Steps

- We will collect more data on different configurations:
  - heavily and lightly loaded busses
  - typical and atypical
  - point-to-point
- We will investigate:
  - can lower amplitudes be used to address large chip power requirements?
  - how bad will common-mode degrade for large amplitudes?
  - would receiver compensation work?
  - how much capacitance will be added by larger drivers?
  - how much capacitance is acceptable?
  - could we use a different terminator scheme?