Methodology Used to Determine SuperSpeed USB 10 Gbps (USB 3.1) – Gen2 Channel and Cable Assembly High Speed Compliance

Yun Ling and Kuan-Yu Chen
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Agenda

- Objective
- Channel Electrical Metrics Review
- Correlation with End-to-End Margin
- Cable Assembly Spec and Compliance
- Discussion
- Summary
Objective

- Develop a SuperSpeed USB 10 Gbps (USB 3.1) Gen2 cable assembly compliance specification that directly correlates to the end-to-end link performance/margin.

In an ideal world ...

Cable assembly S-param

Spec EQ and other Tx/Rx parameters, host and device channels are embedded in simulator

Perfect Simulator to tell if the system works

Does it work?

Pass, if yes

Fail, if no
Review of channel metrics

- The following parameters are used to specify passive channel electrical performance:
  - Insertion fit at Nyquist frequency ($IL_{fit\ at\ Nq}$)
  - Integrated multi-reflection ($IMR$)
  - Integrated crosstalk ($IXT$)

- The justification of using those three parameters is based on physical interpretation and end-to-end correlation.

See backup
Establishing end-to-end correlation

Channel Responses
S-parameters or tr0 files

Use Statistic Tool
Compute end-to-end margin

BER Eye
eH and eW

Calculate Channel metrics
\( x_i = [I_{fitatNq} \; IMR \; IXT] \)

Silicon jitter and EQ
\( u \)

Establish relationship
\[ y = f(x; u) \]

Based on input \( \{x_i; u\} \) and “observation” \( \{y_i\}, i=1:n \)

y = End-to-end margin
f = Prediction function
X = Channel metrics
u = Silicon parameters
Neural network fitting and space filling

- Powerful tool capable of fitting any smooth function.
- Important to have sufficient and well-distributed samples.
Settings for end-to-end simulations

- EQ
  - Spec reference CTLE’s
  - 1-tap DFE with a 50 mV max tap value
  - De-emphasis with and without pre-cursor tap (separate runs)
    - [-0.1 -0.125] or [0 -0.125].

- Buffer
  - 800 mV voltage swing (minimum voltage swing)
  - Risetime: 0.2UI (0-100%)
  - Cpad: 1.1pF (Tx) and 1.0pF (Rx)

- Jitter and noise
  - Per USB 3.1 spec

- Channels
  - ~2500 channels with well-distributed and a wide range of ILfitatNq, IMR and IXT
Fitting results

- Fitting is reasonably good.
  - Typical 95% confidence level: $\sim \pm 10$ mV for eye height and $\sim \pm 5$ ps for eye width
  - Further improvement is difficult, but we are still trying
Channel spec

- The fitting function or prediction formula may be served as the (passive) channel spec:
  \[ y = f(x) > \text{threshold} \]
  \[ \text{ILfitatNq, IMR, IXT} \]

- The threshold usually is zero. But we may need some guard-band (for fitting error and other factors), for example, a 5 ps threshold for eye width.

- We choose either eye height or eye width as the pass/fail criterion
  - eH and eW are correlated
  - The choice may depend on fitting quality
A few pass/fail examples
Reference hosts and devices

- Cable assembly S-param shall be combined with ref host and device to form a full channel.
  - Reference host and device may be viewed as the test fixture for cable assembly.

- Ref hosts/devices shall somewhat represent the “worst-case” hosts/devices.

- A cable assembly shall pass with both “long” host/device and “short” host/device

![Diagram showing reference hosts and devices with cable assemblies and test channels to expose loss and multi-reflection (and crosstalk).]
Long reference channel results

- BCss stands for USB 3.1 Gen1 (5 Gbps) Std-A to Std-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- *Gen1 connectors need improvement and the cable assembly compliance test must weed them out.*

<table>
<thead>
<tr>
<th>Cable Assembly</th>
<th>ILfitatNq</th>
<th>IMR, mV</th>
<th>IXT, mV</th>
<th>eH, mV</th>
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</table>
Long reference channel results, cont.

- BCsm stands for USB 3.1 Gen1 (5 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- Gen1 connectors need improvement.

<table>
<thead>
<tr>
<th>Cable Assembly</th>
<th>ILfitatNq</th>
<th>IMR, mV</th>
<th>IXT, mV</th>
<th>eH, mV</th>
<th>eW, ps</th>
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</table>
BCsm stands for USB 3.1 Gen1 (5 Gbps) Std-A to Micro-B mated cable assembly.

- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- Lower cable impedance has less reflection, so more opened eye.
- The pass/fail criterion set by prediction is $eW < 2 \text{ ps}$.

80 ohm cable is better than 100 ohm cable.
Long reference channel results, cont.

- Chs stands for USB 3.1 Gen2 (10 Gbps) Std-A to Std-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- Gen2 connectors have some improvement but the margin is still at the borderline.

<table>
<thead>
<tr>
<th>Cable Assembly</th>
<th>ILfitatNq</th>
<th>IMR, mV</th>
<th>IXT, mV</th>
<th>eH, mV</th>
<th>$eW$, ps</th>
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<td>10.8</td>
<td>-1</td>
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<td>21.5</td>
<td>10.1</td>
<td>3</td>
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</tr>
</tbody>
</table>
Long reference channel results, cont.

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 100 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- Gen2 connectors have some improvement and the timing margin is decent.
Long reference channel results, cont.

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- Gen2 connectors have some improvement and the timing margin is decent.
**Short reference channel results**

- Csm stands for USB 3.1 Gen2 (10 Gbps) Std-A to Micro-B mated cable assembly.
- Cable length swept from 10 cm to 100 cm.
- Cable impedance is 80 ohms.
- The pass/fail criterion set by prediction is $eW < 2$ ps.
- Gen2 connectors have some improvement and the timing margin is decent.

<table>
<thead>
<tr>
<th>Cable Assembly</th>
<th>ILfitatNq</th>
<th>IMR, mV</th>
<th>IXT, mV</th>
<th>eH, mV</th>
<th>eW, ps</th>
<th>Prediction</th>
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<tr>
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<td>48.7</td>
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</tbody>
</table>
Connector Frequency Response

SuperSpeed USB DDIL Comparison

USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)
Connector Frequency Response, cont.

SuperSpeed USB DDRL Comparison

USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)
Connector Frequency Response, cont.

DDNEXT between SuperSpeed USB Tx and Rx

USB 3.1 Gen1 (5 Gbps); Gen2 (10 Gbps)
Observation and discussion

- Not much margin overall.
  - Options to improve margin:
    - Reference host/device with better performance
    - Better EQ capabilities
    - Tighter Si parameters

- The margin prediction function does its job.
  - Majority of failure cases are caught and some borderline passing cases are predicted “failing” – looking for further fitting accuracy improvement.

- The Gen 1 connectors need improvement, as expected.
  - Gen 2 Std-A to Gen 2 Micro-B cable has the best margin.

- The 80-ohm cable gives better margin than 100-ohm cable
  - Assume they have the same loss.
Cable assembly spec

- Informative – design targets or guidelines; traditional approach.
  - Mated impedance / return loss
  - Insertion loss
  - Crosstalk

- Normative – pass/fail, compliance criteria
  - Using the prediction function derived from neural network fitting, say, \( eW = f(ILfitatNq, IMR, IXT) > eWmin \).
  - Spec should include definitions of
    - \( ILfitatNq, IMR \) and \( IXT \)
    - Reference hosts and devices
    - Standard test fixtures (requirements)
  - Other parameters
    - Mode conversion (SCD21)
    - Other EMC requirements
Traditionally, (passive) channel electrical spec defines separate hard limits for insertion loss, return loss and crosstalk over certain frequency range.

The shortcomings of such a methodology are:

- Specifying limits over a frequency range is challenging and violating the limits at any frequency will fail the spec. But in reality, such channels may work just fine.

- It does not allow tradeoffs among insertion loss, return loss and crosstalk.
  - Channels with less crosstalk or reflection may allow more insertion loss.
  - Channel with less loss can tolerate more crosstalk or reflection.
Summary

- A new approach is proposed for cable assembly compliance, using three simple parameters ILfitatNq, IMR and IXT.

- The compliance criterion is directly related to the end-to-end link performance (BER eye margin).
  - Reasonably good fit was achieved.

- The new spec allows tradeoffs among loss, reflection and crosstalk.

- Continued improvement needed
  - Fitting accuracy
  - Reference hosts/devices
  - Connector designs
  - Si parameters
Backups
Introducing Channel Electrical Metrics

Start with Defining Channel Electrical Metrics
Signal Integrity Impairments

- There are three impairments that impact channel signal integrity:
  - Attenuation
  - Reflection
  - Crosstalk

- Passive channel electrical spec is all about managing those three signal integrity impairments.

- What are the appropriate metrics to describe those three impairments?
**Channel Insertion Loss**

- The effect of attenuation and (multi) reflection is included in channel insertion loss.

- The smooth curve represents “attenuation” without multi-reflection.
- The ripples represent multi-reflection.
Channel Crosstalk

- Channel crosstalk can be described in frequency (S-parameter) or time domain (pulse response) also.
  
- Power sum is commonly used to combine multiple crosstalks into one.
Appropriate Channel Metrics

- The appropriate (passive) channel metrics should have the following characteristics:

  - Correlate to the channel end-to-end electrical performance.

  - Represent the three channel signal integrity impairments.

  - Are simple scalar parameters, not the whole frequency or time responses or profiles.

  - Can be easily and consistently derived from the channel frequency or time domain responses.
Learn from Backplane Community

- The backplane community has been using the following parameters to specify passive channel electrical performance:
  - Insertion fit at Nyquist frequency
  - Integrated multi-reflection
  - Integrated crosstalk

- The justification of using those three parameters will be based on physical interpretation and end-to-end correlation.
Details of Channel Electrical Metrics
Obtaining Channel IL from tr0

• Channel IL, or more appropriately, transfer function may come from time or frequency domain.

• Deriving channel IL from time domain response is common at Intel, using a Hspice. The result is a tr0 file or a channel step response.
  • *The Tx buffer strength and risetime, and Tx and Rx terminations are included in the step response.*

• Let $sr(t)$ be the channel step response. The channel impulse response is then simply: $ir(t) = \text{diff}(sr(t))$.

• The channel IL is then: $IL(f) = \frac{\text{fft}(ir(t))}{Vsw}$, where $Vsw$ is the magnitude of the stimulus, inputting to the channel.
  • Dividing with $Vsw$ is necessary to be consistent with the IL or transfer function definition – the magnitude of the stimulus impulse to the transfer function should be unit or 1.
Obtaining Channel IL from S-parameter

• Channel S-parameters usually does not include Tx and Rx terminations.

• So the first step is to add Tx and Rx termination to the channel S-parameters.
  • This can be done by cascading abcd-matrices (there are other ways to do so also)
  • The resulting abcd parameters can be converted to z-parameter $Z(f)$. The transfer function $IL(f)$ is then

$$V_{rx}(f) = IL(f)V_{in}(f)$$

where

$$IL(f) = \frac{Z(f)}{R_{tx}}$$

$Z(f)$ is the Z-parameter
Decomposing IL

Insertion loss fit is a smooth function fit of the insertion loss $\text{IL}(f)$, representing the loss without multi-reflection.

Insertion loss deviation represents the loss caused by multi-reflection.

$$\text{IL}(f) = \text{IL} \_ \text{fit}(f) + \text{ILD}(f)$$

$$\text{ILD}(f) = \text{IL}(f) - \text{IL} \_ \text{fit}(f)$$
Insertion Loss Fit

- Use $\text{IL}_{\text{fit}}(f) = \exp(a + b\sqrt{f} + c f + d f^{1.5})$ to fit the insertion loss
  - $a$ – DC loss
  - $b\sqrt{f}$ – skin effect
  - rest – dielectric loss

IL fit at the Nyquist frequency, $\text{IL}_{\text{fit}}(f_0)$, is a good measure of the amplitude and shape of the IL fit pulse response
Multi-reflection

• Multi-reflection noise in frequency domain
  • \( MR(f) = V_{\text{in}}(f) * \text{ILD}(f) \), where \( V_{\text{in}}(f) \) is the input pulse spectrum

• Multi-reflection noise in time domain
  • \( mr(t) = v_{\text{in}}(t) \otimes (\text{ir}_{\text{IL}}(t) - \text{ir}_{\text{fit}}(t)) = \text{pr}_{\text{IL}}(t) - \text{pr}_{\text{fit}}(t) \), where \( \text{ir} = \) impulse response, \( \text{pr} = \) pulse response
Integrated Multi-reflection

- Power due to multi-reflection is:

\[ E_{mr} = \int_{-\infty}^{+\infty} |mr(t)|^2 dt = \int_{-\infty}^{+\infty} |MR(f)|^2 df \]  

(Parceval’s theorem)

- Define the integrated multi-reflection as

\[ IMR = V_{sw} \sqrt{\frac{E_{mr}}{E}} \]  
in V or mV, normalized with a factor of E
Trick about IL Decomposition

- Quality of insertion loss fit is VERY important – poor IL fit will result in a large (unreal) IMR

- Fitting is usually done from $f=0$ to the 2nd or 3rd harmonic

- Appropriate weighting function *must* be used in IL fit – more emphasis should be given from DC to Nyquist frequency

- Use $\text{IL}_\text{fit}(f) = \exp(a + b \sqrt{f} + c f + d f^{1.5})$ as the standard fitting equation - the last term is to improve fitting accuracy

- Use $w = \exp(-k f / \Delta f)$ as the standard weighting function for the least square fit, *where k is an adaptive factor*
Trick about IL Decomposition, cont.

- $k$ may vary from 0 to 20 – increasing $k$ shifts more emphasis to lower frequencies. In the extreme case of $k=0$, $w=1$ for all frequencies, which means no weight or equal weight for all frequencies!

- **Adaptively choose $k$ such that IMR is a minimal. This allows us to get consistent/unique IL fit for each IL**

IL fit with $\min_k IMR$
Integrated Crosstalk

- Integrated crosstalk noise is defined as the power sum of all crosstalk sources:

\[ E_{xt} = \sum_{-\infty}^{+\infty} \int |x_{t_i}(t)|^2 dt = \sum_{-\infty}^{+\infty} \int |X_{T_i}(f)|^2 df \]

\[ IXT = V_{sw} \sqrt{E_{xt} / E} \]

in V or mV, normalized with a factor E
Channel Electrical Metrics Summary

- Three simple (scalar) parameters are used as the channel electrical metrics to account for three different impairments:
  - IL fit at Nyquist frequency: ILfitatNq
  - Integrated multi-reflection: IMR
  - Integrated crosstalk: IXT

- Parceval’s theorem establishes the frequency and time domain equivalency!

- An adaptive method is used for IL fit, which uniquely defines the IMR:
  - The IL fit is done such that the IMR is minimized!
Channel Electrical Metrics and PDA
Start with pulse response

- **ISI+**
  - $y(t+0\times T)$
- **ISI-**
  - $y(t+2T)$
  - $y(t+5T)$

- **T=UI**

- **y(t-T)**
- **y(t+T)**

- **precursor**
- **cursor**
- **postcursor**
PDA Eye Equations

\[ s_1(t) = y(t) + \sum_{k=-\infty}^{\infty} y(t - kT) \bigg|_{y(t-kT)<0} + \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} y^i(t - kT - t_i) \bigg|_{y^i(t-kT-t_i)<0} \]

Worst-case 1 eye edge

where \( t_i \) is the relative sampling point of each crosstalk pulse response.

\[ s_0(t) = \sum_{k=-\infty}^{\infty} y(t - kT) \bigg|_{y(t-kT)>0} + \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} y^i(t - kT - t_i) \bigg|_{y^i(t-kT-t_i)>0}. \]

Worst-case 0 eye edge
PDA Eye

\[ e(t) = s_1(t) - s_0(t) = y(t) - \sum_{k=-\infty}^{\infty} |y(t-kT)| - \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} |y^i(t-kT-t_i)| \]
Re-arranging the PDA Equation

Decomposing ISI pulse into attenuation and multi-reflection

\[ y(t) = y_{att}(t) + mr(t) \]

PDA eye becomes:

\[ e(t) = \left[ y_{att}(t) - \sum_{k=\infty}^{\infty} y_{att}(t - kT) \right] - \left[ \sum_{k=\infty}^{\infty} |mr(t - kT)| - mr(t) \right] - \left[ \sum_{i=1}^{n} \sum_{k=\infty}^{\infty} |xt_i(t - kT - t_i)| \right] \]

Attenuation \quad Multi-reflection \quad Crosstalk
IL fit at Nyquist Frequency (ILfitatNq)

- ILfitatNq is measured at the IL fit, which is a smooth, monotonic curve (almost like straight line in dB at relatively high frequency)

- It is a reasonable representation of the “reflection-free” pulse response

- So ILfitatNq roughly catches the first term (attenuation)

\[
e(t) = \left[ y_{att}(t) - \sum_{k=-\infty \atop k \neq 0}^{\infty} |y_{att}(t-kT)| \right] - \left[ \sum_{k=-\infty}^{\infty} |mr(t-kT)| - mr(t) \right] - \left[ \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} |xt_i(t-kT-t_i)| \right]
\]
Integrated Multi-reflection (IMR)

- IMR by definition is the integration of $mr(t)^2$. Alternatively, the integration of $|mr(t)|$ is probably equally valid
  - Integration of power $mr(t)^2$ is probably better because of the Parceval’s theorem of time and frequency domain equivalency

- IMR is a figure of merit for multi-reflection impact
  - Summation and integration are directly correlated

\[
IMR \propto \int_{-\infty}^{+\infty} |mr(t)|^2 dt = \int_{-\infty}^{+\infty} |MR(f)|^2 df
\]

\[
e(t) = \left[ y_{att}(t) - \sum_{k=-\infty}^{\infty} y_{att}(t-kT) \right] - \left[ \sum_{k=-\infty}^{\infty} mr(t-kT) - mr(t) \right] - \left[ \sum_{i=1}^{n} \sum_{k=-\infty}^{\infty} xt_i(t-kT-t_i) \right]
\]
Integrated Crosstalk (IXT)

- IXT by definition is integration and power sum of all crosstalk sources
- In PDA, the crosstalk term is the summation of all crosstalk sources at a certain fixed phase \( t_i \)
- In statistic analysis, crosstalks are often uncorrelated with random phase and power sum is probably more appropriate

\[
IXT \propto \sum_{-\infty}^{+\infty} \int |xt_i(t)|^2 dt = \sum_{-\infty}^{+\infty} \int |XT_i(f)|^2 df
\]

\[
e(t) = \left[ y_{att}(t) - \sum_{k=-\infty}^{0} |y_{att}(t-kT)| \right] - \left[ \sum_{k=-\infty}^{0} |mr(t-kT)| - mr(t) \right] - \left[ \sum_{i=1}^{n} \sum_{k=-\infty}^{0} |xt_i(t-kT-t_i)| \right]
\]
Channel Metrics and PDA

• The development of the channel electrical metrics directly parallels the contribution to PDA eye by attenuation, multi-reflection and crosstalk.

• It is known that PDA eye is closely correlated with the channel end-to-end performance.

• So it is reasonable to expect the proposed channel metrics to correlate with channel end-to-end performance also.

• The ultimate justification is to directly demonstrate the correlation between ILfitatNq, IMR and IXT and the end-to-end BER eye margin.
Establishing End-to-End Correlation
Flow to Establish Correlation

Channel Responses
S-parameters or tr0 files

Use Statistic Tool
Compute end-to-end margin

BER Eye
eH and eW

Calculate Channel metrics
\[ xi = [\text{ILfitatNq}; \text{IMR}; \text{IXT}] \]

Silicon jitter and EQ
\[ u \]

Establish relationship
\[ y = f(x; u) \]

Based on input \( \{xi;u\} \) and "observation" \( \{yi\} \), \( i = 1:n \)

Establish relationship
\[ y = \text{End-to-end margin} \]
\[ f = \text{Prediction function} \]
\[ X = \text{Channel metrics} \]
\[ u = \text{Silicon parameters} \]
Neural Network Fit

- Neural network fitting is a powerful tool, capable of fitting almost any smooth function.

- Neural network fitting can be used to establish the relationship between \(\{x; u\}\) and \(\{y\}\). (Note that \(u\) may be mostly fixed, hidden from customers)

- The key to get good fit with neural network is appropriate space filling.
Space Filling

• The independent variables shall fill up the whole intended "design" space as uniformly as possible

• Not doing so will cause inaccurate fitting such as overfit
SATA Direct-Connect Rx Fit

**EH**
- $R = 0.981$
- $\text{RMSE} = 6 \text{ mv}$

**EW**
- $R = 0.979$
- $\text{RMSE} = 2 \text{ ps}$
SATA Rx Fit Profiler
SATA Direct-Connect Tx Fit

Very good fit for EH and reasonable fit for EW
USB 3 Rx Fit Quality

**EH**
- $R = 0.995$
- RMSE = 6 mv

**EW**
- $R = 0.994$
- RMSE = 6 ps
USB 3 Rx Fit Profiler

![Graph showing the relationship between various parameters and their measured values.](image)
USB 3 Tx EH Fit

EH: R = 0.998, RMSE = 2 mV
USB 3 Tx EW Fit

EW: $R=0.996$, RMSE=3 ps
PCIe3 Example – LGA Rx: fitting quality
PCIe3 Example – LGA Rx: Profiler

Fitting with ILfit@Nquist, IMR, IXtlk
PCIe3 Example – LGA Tx: fitting quality
PCIe3 Example – LGA Tx: profiler
DisplayPort HBR1 Fit
Summary

- Three simple (scalar) parameters are used as the channel electrical metrics to account for three different impairments
  - IL fit at Nyquist frequency: $IL_{fit \text{ at } Nq}$
  - Integrated multi-reflection: IMR
  - Integrated crosstalk: IXT

- Parceval’s theorem establishes the frequency and time domain equivalency!
  - It doesn’t matter in time domain or freq domain!

- An adaptive method is used for IL fit, which uniquely defines the IMR
  - The IL fit is done such that the IMR is minimized!
Summary, cont.

• Neural network fitting together with space filling is used to fit the channel electrical metrics against the end-to-end eye margin to establish the (passive) channel electrical spec

• The proposed (passive) channel electrical metrics, ILfitatNq, IMR and IXT, are closely correlated with the channel end2end BER eye margins
  - *We have tested this for virtually all differential interfaces and haven’t found any exception so far*

• The fitting quality is in general good, usually better than the typical fitting in DOE.