Switching Solutions for Multi-Channel High Speed Serial Port Testing

Application Note

The instruments used in High Speed Serial Port testing are typically high bandwidth Oscilloscopes and/or Bit Error Rate Testers (BERTS). These devices are typically at the cutting edge of electronic performance, and can be quite costly. Many of the current group of High Speed Serial port devices being tested involves multiple high speed channels or lanes. The test equipment must be able to test these multiple lane configurations. Although the instruments are available in Multi-channel configurations, the inclusion of additional channels can drive the cost of these instruments to uncomfortably high levels. One alternative to adding additional I/O channels is the use of a switching device, to connect the test instrument from one port to the next as required. The switch can be far more cost effective, particularly in the production testing or validation test areas, where multiples test sets are needed. In these applications, all of the switching and interconnecting hardware must be carefully selected to maintain the integrity of the test signals. This Application note is intended to illustrate both the benefits and the design considerations involved in implementing such a switching strategy.

Benefits

- Lower cost than adding BERT/Oscilloscope channels
- Reduce Test time, Increase Throughput over manual testing
- Eliminate Test Repeats due to operator Connection Errors
- Increase Repeatability of Test Results
- Automate Testing, facilitates multi-tasking and overnight testing

Some Examples of Applicable Serial Ports

PCIe – PCI Express, 1, 2, 4, 8, 16 and 32 lanes
- Ver 1.0 – Gen1, 2.5 GBps /lane (3 GHz Switches Recommended)
- Ver 2.0 – Gen2, 5 GBps /lane (3 GHz Switches Recommended)
- Ver 3.0 – Gen 3, 8 GBps /lane (6 GHz Switches Recommended)
- Ver 4.0 – Gen4, 16 GBps /lane (18 GHz Switches Recommended)

HDMI
- Ver 1.0 – 4.95 GBps = 1.65 GBps x3 lanes +clk (3GHz Switches Recommended)
- Ver 1.3 – 10.2 GBps = 3.4 GBps x3 lanes +clk (3GHz Switches Recommended)
Bandwidth

Since the BERT’s test signals are digital signals, the highest frequency components are in the rising and falling edges rather than in the data rates. The effect of insufficient switching system bandwidth is to slow down the edge transition times similar to the effect of a low pass filter. The effect on the BERT’s “eye” diagram is to cause narrowing where the transitions have slowed. The diagram to the right (Figure 1) illustrates the difference between the normal signal transitions (in green) versus the effected signal transitions (in red) which has had its edge speeds reduced by a bandwidth limiting switching system.

BERTs up to 32 GB/s generally have 20 ps edges, and BERTs up to 40 GB/s generally have 6 ps to 8 ps edges. To determine the minimum switching system bandwidth without signal degradation, we typically use the formula:

\[
\text{Bandwidth} = \frac{0.35}{R_t}, \text{ where } R_t \text{ is the Rise Time}
\]

<table>
<thead>
<tr>
<th>Specified Bandwidth</th>
<th>Rise-time (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 GHz</td>
<td>58.333 ps</td>
</tr>
<tr>
<td>18 GHz</td>
<td>19.444 ps</td>
</tr>
<tr>
<td>26.5 GHz</td>
<td>13.208 ps</td>
</tr>
<tr>
<td>40 GHz</td>
<td>8.7500 ps</td>
</tr>
<tr>
<td>60 GHz (limited relay configurations)</td>
<td>5.8333 ps</td>
</tr>
</tbody>
</table>

Figure 1

Design Considerations for BERT Testing

QSFP – Quad Small Form-factor Pluggable (40 GB)
- 10 GBps x4 lanes (6 GHz Switches Recommended)
- 16x Fiber Channel, 14 GBps x4 lanes (18 GHz Switches Recommended)

Display Port – 1, 2 or 4 lanes
- Ver 1.0 – 8.64 GBps = 2.7 GBps x4 lanes +aux(3 GHz Switches Recommended)
- Ver 1.2 – 17.28 GBps = 5.4 GBps x4 lanes +aux(3 GHz Switches Recommended)

Thunderbolt – combination of PCIe and Display port
- Ver 1.0 – 10 GBps = 5.4 GBps x2 lanes (3 GHz Switches Recommended)

MIPI – Display Serial Interface or Mobile Industry Processor Interface
- D-PHY, 1.5 GBps (3 GHz Switches Recommended)
- M-PHY, 5.8 GBps (3 GHz Switches Recommended)
There are a few additional considerations in selecting Switches and Cables than just the bandwidth limitation effects on the rising and falling edges. Users will have different preferences for which harmonics they want included in the measurement, and this will have an effect on the switch and cable selection. The error contribution of the switches and cables is somewhat counterintuitive, and experience has shown that the highest bandwidth products do not automatically provide the best measurements. In the illustration to the right, the fundamental signal is depicted. At the speed of these digital signals they appear as a sinusoid. (The diagrams are slightly exaggerated for illustration purposes).

If the switching and cabling is selected such that the third harmonic is within the bandpass, the signal will begin to look like the diagram to the right.

The third harmonic has both positive and negative effects. On the positive side, the higher frequency components increase the speed of the rising and falling edges which serves to square up and expand the eye. On the other hand, it also contributes a large dip in the center of the eye, serving to shrink the eye.

Adding in the 5th harmonic has the benefit of further increasing the speed of the rising edge along with counteracting the dip in the center created by the 3rd harmonic. It is generally a good suggestion that systems which are designed to include harmonic frequencies should be designed to include the 5th if the 3rd harmonic is to be included.

Let’s examine a quick example how this can come into play. The highest speed signals at the time of this writing are in the 28 GB range. The highest frequency component of this data stream would come from a data pattern consisting of 10101010, which equates to 14 GHz. The 3rd harmonic is then 42 GHz, and the 5th harmonic is 70 GHz. Based on the currently available Microwave switches, and knowing a high data rate is in use, the inclination might be to select the best available 40 GHz switches and cables. In this case the 3rd harmonic would be passed, and the 5th harmonic would be significantly attenuated, or not passed at all. In this instance the user might get far more satisfactory results using 18 GHz switches and cables which will easily pass the fundamental frequency, but will attenuate both the 3rd and 5th
harmonics. The general rule of thumb for many is if you allow the 3rd harmonic through, the 5th harmonic is essential in order to maximize the eye.

**Insertion Loss**

Since the digital output stream of the BERT is voltage programmable and is typically some value below 2 Volts, the concern is that excessive insertion loss in the switching system would cause the signals to fall below the BERT’s detector input threshold. Since the insertion loss of a microwave switch is frequency dependent, we need to determine what frequency to use for the insertion loss calculation. The highest possible frequency is created with a data pattern of 10101010 which has the appearance of a pulsed DC signal with a 50% duty cycle. In the example, a data pattern of 11001100 would have a frequency of half the previous example (see Figure 2).

The highest possible frequency for the data stream is half of the data rate. We can use the formula typically used for electronic filters and calculate the “worst case” insertion losses. Typical insertion losses will be slightly lower and should generally not have a significant impact on the signal level.

\[
\text{Insertion loss (dB)} = 20 \log_{10} \left( \frac{|V_{\text{in}}|}{|V_{\text{out}}|} \right)
\]

This becomes \( V_{\text{out}} = V_{\text{in}} / \{10^{0.2 \times \text{IL}}\} \)

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Required Bandwidth</th>
<th>Typical Switch Insertion Loss</th>
<th>Output Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Gb/s</td>
<td>7 GHz</td>
<td>0.30 dB</td>
<td>1.74V</td>
</tr>
<tr>
<td>28 Gb/s</td>
<td>14 GHz</td>
<td>0.50 dB</td>
<td>1.59V</td>
</tr>
<tr>
<td>32 Gb/s</td>
<td>16 GHz</td>
<td>0.50 dB</td>
<td>1.59V</td>
</tr>
<tr>
<td>40 Gb/s</td>
<td>20 GHz</td>
<td>0.60 dB</td>
<td>1.52V</td>
</tr>
</tbody>
</table>

Figure 2
Customers often select the highest bandwidth cables thinking that more bandwidth will result in better measurements. This is not necessarily the case as illustrated in the bandwidth section. We can see from the example above, that due to the changes in digital data patterns, the frequency will change constantly. This means that the digital data stream is a series of different frequencies sent in serial form. Examining the attenuation of Coaxial cables with respect to frequency reveals that the lower bandwidth cables have a flatter attenuation curve. Here is an example:

![Attenuation Curve](image)

The flatter curve means that the entire data stream will experience a more consistent insertion loss, where the higher bandwidth cable will attenuate differently at different frequencies. This will have the effect of making the data stream’s amplitude inconsistent. This coupled with the fact that we want to limit the harmonic contributions mentioned earlier; the lower frequency cable is often a better choice.

**Phase Match**

Phase matching signal paths is only of concern when the BERT is being used in the differential mode where all paths along the data+ and data- channel pairs must be phase matched. Since the purpose of the differential mode is to cancel out common mode noise, any phase shift between the + and – channels will cause portions of the leading and/or trailing edges to be removed effectively narrowing the center of the eye diagram. Since the switching system’s design goal is signal preservation, properly phase matched paths are essential. The diagram to the right (Figure 3) illustrates three eye diagrams; the green illustrating the use of a good phase matched switching system, the yellow indicating distortion of the eye caused by incorrect phase matching, and the red indicating extreme distortion. The resulting eye is greatly reduced after the common mode noise is removed from the signal.

![Eye Diagrams](image)
Manufacturers of Microwave cables can typically match the length of a pair of cables to about 0.001”. At 26.5 GHz, this equates to about 20° of phase shift, but in the digital world this information is only useful in picoseconds. It should be noted that as the frequency increases, the physical length of a wave decreases and since the physical match length remains constant, the ability to phase match cables at higher frequencies is diminished. Using the formula:

\[
\text{Phase Shift (ps/deg)} = \frac{(1/f)}{360°} \quad \text{at 26.5 GHz is 0.104822 ps/deg, and at 20° is 2.09644 ps}
\]

It is possible to match cables closer than 20° or 2 ps, but this becomes difficult and drives higher cost. Either special manufacturing processes are employed or the more brute force method of simply building extra cables and hand matching pairs is employed. It must also be taken into account that it is not uncommon for a path to consist of several switches and cables, thus the matching of two paths may involve measuring and matching several cables. A manufacturer may build a group of cables all matched to within 2 ps, but some will be a perfect match at 0 ps, and some will be +1 ps and some will be -1 ps. Overall system phase match can be improved by measuring and tabulating all of the cable lengths by serial number, such that a +1 ps cable and a -1 ps cable are in the same path. This path will have the same overall electrical length as a path built from two 0 ps cables. The illustration (Figure 4) shows an example where a switching system has been constructed of numerous mis-matched cables to provide a system which is completely phase matched. Note that the important match is between the two data channels as highlighted in yellow, and not between the channels of any particular switch. It should be obvious that the engineering effort involved in this process can be a considerable cost driver.

One other issue which must be considered is phase stability of the cables. The two enemies of phase matching are temperature change and cable flex. Since the equipment will likely be used in a temperature controlled environment, temperature effects should be minimized and consistent. Bending, even a good phase stable cable around a 5 cm mandrel can result in 2° to 5° of phase shift or 0.524 ps. Several bends can easily add over a picosecond. It is for this reason that semi-rigid cables are usually recommended for the front panel interconnecting cables. Cables to the DUT typically need to be flexible cables, and all efforts should be made to minimize any bends.
Application Examples

PCIe Video Board Testing – Oscilloscope Multiplexing

This example assumes 16 Lane PCIe, but the solution can be scaled down for fewer lanes, or multiple devices could be tested in parallel. The same Switch Chassis is used to test both the HDMI Ports, and the PCIe ports as described below:

Specifications:

- 4(1x8) Terminated Switches.
- For 16GB PCIe, 18 or 26.5 GHz switches are recommended.
- Insertion loss = 0.6dB
- Unused ports terminated in 50Ω.
- S-Parameters can be provided for de-embedding the switches.
Application Examples, cont’d

Four Lane Serial Port BERT Testing – QSFP, SAS, MIPI
This example assumes a 4 lane device. The product under test is a QSFP chipset being tested using a BERT. The BERT has a single Stressed channel which needs to be switched to any lane, while maintaining traffic on the remaining three lanes. The use of transfer switches provides this capability.

Specifications:
- Semi-Rigid cables matched to ±2 ps, matched pairs indicated on diagram below. Gray cables are supplied by customer, and require phase matching.
- 18 GHz Switches were selected for this application.
- All lanes not connected to the Rx BERT, are terminated to 50 Ω.
- DUT can be bypassed for calibrating BERT for full automation.
- Calibration paths to Scope are included for full automation.
- S-Parameters can be provided for de-embedding the switches
Sample Configurations for Giga-tronics Model 8901 and 8902 Switching Systems

- Can be custom configured as required

General Specifications:
- 3, 6, 18, 26.5 and 40 GHz Switches available, 1x8 limited to 22 GHz
- Terminated or un-terminated Switches available
- Up to 10M Cycle Reliability (2M cycles for sizes over 1x6)
- Repeatability ±0.03 dB
- Cable Phase Matching available ±2 ps typical, closer available upon request

Dual 1x8 Terminated for Single Ended Applications (2U)

Quad 1x8 Terminated for Differential Applications (2U)

Dual 1x16 Terminated for Single Ended Applications (2U)

Quad 1x16 Terminated for Differential Applications (3U)
Quad 1x32 Terminated for Differential Applications (6U)

Quad 1x36 Un-Terminated for Differential Applications (4U)

Quad 1x36 Terminated for Differential Applications (6U)
Giga-tronics point-to-point software features:

- Just point and click and the software closes the appropriate relays
- Relay closure counter for preventative maintenance
- Path storage and recall to simplify test development
- Manual control with position indicator lights for troubleshooting
http://www.gigatronics.com/ASCOR-Ask-Jeff