Application Note

Benefits of Adaptive Equalization for the TUSB1146

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ABSTRACT

The TUSB1146 USB Redriver features Adaptive Equalization (AEQ), an equalization (EQ) method allowing two communicating devices to have bit error free operation under different system conditions. AEQ improves upon static EQ by automatically configuring the redriver to use an appropriate EQ setting for the various system conditions. The TUSB1146 redriver implements AEQ functionality at the downstream facing port USB Type-C® 3.2 receivers (RX1 and RX2). This application note provides a comparison between AEQ and static EQ, device tests that produce data supporting the use of AEQ, and further recommendation to use AEQ over static EQ in future applications.

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1 Introduction

Designers that build applications using USB redrivers expect to see consistent bit error free operation for different channel lengths, temperatures, data rates, or other conditions. When using a USB redriver with static equalization (EQ) settings, a significant amount of time is needed to determine an ideal fixed EQ level for the particular system design across these conditions. Even then, the ideal EQ level can not work error free in all practical cases. Many system designs cannot be limited to specific conditions, so the system design is stuck with an error prone solution. This case is where AEQ improves upon static EQ methodology.

AEQ adapts to the various system characteristics by automatically tuning the EQ settings of the redriver, resulting in bit error free operation under different system conditions. Historically, AEQ algorithms are reserved to retimer devices, but retimers are more expensive than redrivers in many applications. TI offers redriver products, like the TUSB1146, that feature AEQ functionality with better cost efficiency. The TUSB1146 redriver implements AEQ functionality at the downstream facing port USB Type-C® 3.2 receivers (RX1 and RX2). This application note discusses the value in using AEQ functionality over static EQ for the TUSB1146 with supporting tests.

2 Test Description

The following tests demonstrate that AEQ performs equivalently, or better, than static EQ across various channel lengths and jitter levels. The result of changing from EQ to AEQ is apparent when selecting EQ values without performing jitter tolerance (JTOL) testing and tuning. This test measures Bit Error Ratio (BER) and eye diagram parameters against a set of channel board lengths for each EQ configuration. The test is first conducted with clean signal, followed by a JTOL test.

There are four test configurations:

1. **No Redriver** - No redriver included in the signal path. This test provides a baseline.
2. **Static EQ** - This test provides a preset constant EQ value, regardless of the connected channel characteristics. The preset can be changed by overriding the default EQ value and setting it manually.
3. **Fast AEQ** - Fast AEQ must be enabled in the registers. Upon cable connection, this configuration determines if the connected channel is considered long or short and chooses the preset EQ setting for either case, as determined by the TUSB1146 algorithm. This preset can be changed in the registers.
4. **Full AEQ** - Full AEQ must be enabled in the registers. Upon cable connection, this configuration checks every EQ value and chooses the optimal setting for the channel characteristics, as determined by the TUSB1146 algorithm. The Full AEQ algorithm takes longer to run than Fast AEQ.

To configure the EQ through registers, the TUSB1146 must be in the I²C mode. Please see the register map on the *TUSB1146 data sheet* for details about register functions and locations, as well as details about Fast versus Full AEQ. Use the *TUSB1146 EVM user's guide* for physical setup assistance.

Note

The tests and test results in this application note can not be used in place of official compliance results and part capabilities. These tests are conducted solely to compare both methods of equalization, not measure their capabilities in application. Attempting to reproduce these results in test or application can yield different outcomes depending on quality or length of cables used, quality of the receiver measuring the signal, and other similar variables.

Figure 2-1 and Figure 2-2 show that the tests in this application note use a TUSB1146 breakout board allowing for direct connection to TUSB1146 pins. If this apparatus is unavailable, this document provides an alternative test that utilizes the TUSB1146EVM, producing JTOL results for comparing EQ configurations. This test description can be found in Alternative Test Procedure.

2.1 Equalization Configuration

The EQ method used by the TUSB1146 depends on the values written to the registers. These values can be controlled through I^2C. The following is a summary about how to configure the TUSB1146 to use each EQ method with the provided register settings:

Static EQ:

1. Ensure AEQ is disabled with AEQ_EN (0x1C bit 0 to 0)
2. Enable the EQ_OVERRIDE (0xA bit 4 to 1) to enable I^2C control of the registers and EQ level
3. Set static EQ value to desired level with EQ1_SEL (0x20 bits 3:0)

The results provided in Section 3 used setting 8 for static EQ, which is approximately 11 dB at 5 GHz.

Fast AEQ:

1. Enable AEQ with AEQ_EN (0x1C bit 0 to 1) and set AEQ_MODE (0x1C bits 2:1) to Fast (to 00)
2. Enable the EQ_OVERRIDE to enable I^2C control of the registers and EQ level
3. Choose the long channel EQ value with LONG_EQ1 (0x1E bits 3:0)
4. Choose the short channel EQ value with EQ1_SEL (0x20 bits 3:0)
5. Enable the input signal, turn on the TUSB1146, and then reconnect the TX side cable to have the AEQ algorithm run
6. Read the EQ value selected by AEQ with AEQ_STAT (0x3B bits 3:0)

The results provided in Section 3 used setting 1 for short channel and 15 for long channel, which is approximately 1.8 dB and 14 dB at 5 GHz, respectively.

Full AEQ:

1. Enable AEQ with AEQ_EN (0x1C bit 0 to 1) and set AEQ_MODE (0x1C bits 2:1) to Full (to 01)
2. Enable the input signal, turn on the TUSB1146, and then reconnect the TX side cable to have the AEQ algorithm run
3. Read the EQ value selected by AEQ with AEQ_STAT (0x3B bits 3:0)

For more information about the registers and EQ methods, please see the *TUSB1146 data sheet*.

2.2 Eye Test

The Eye Test obtains the received signal data for the given channel. This test requires that the Bit Error Ratio Tester (BERT) emits a test pattern through the Inter-Symbol Interference (ISI) channel board to then be equalized by the TUSB1146 and finally captured by the oscilloscope. This test allows for eye diagrams to be made from the signal and the eye parameters to be measured.

The oscilloscope must be configured for differential signaling. Different oscilloscopes can have different setup processes to render an eye diagram. Refer to the user manual of the oscilloscope for more information.

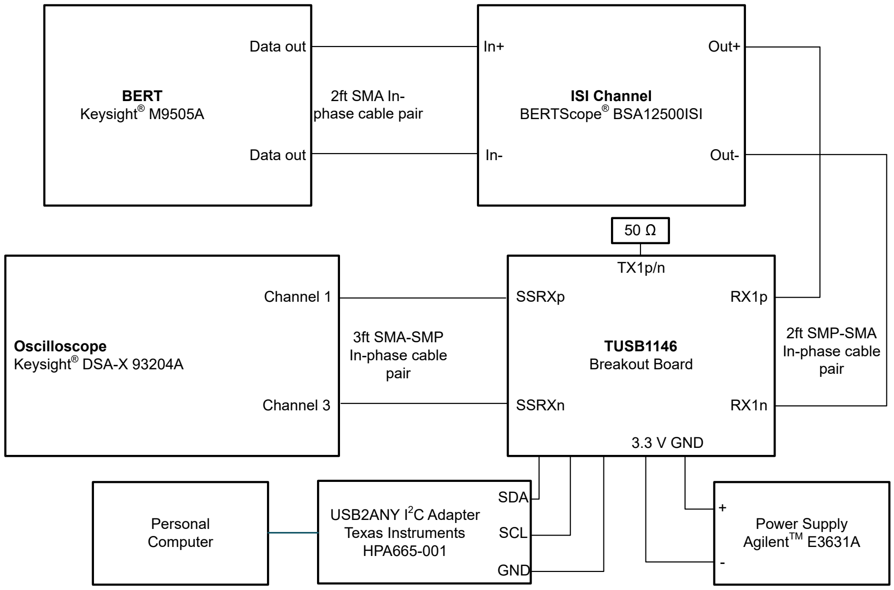


Figure 2-1. Eye Test Setup Diagram

The BERT needs to be configured. For these tests, the set output is a 10 Gb/s, 1:PRBS7, 400 mV amplitude pattern with no pre-emphasis or de-emphasis, and RX CDR disabled. The data trigger is automatically realigned before each trial by the BERT. When performing the JTOL test, 750 mUI Bounded Uncorrelated Jitter (BUJ) is added at the output to sufficiently stress the eye. The BERT needs to have blocking capacitors at the output for proper operation.

The TUSB1146 registers are written to through an I^2C adapter, which is configured by a connected computer. When performing the "No Redriver" test, connect the output of the ISI channel straight to the channel inputs of the oscilloscope, and remove the TUSB1146 from the channel path.

Longer channel lengths can be achieved by feeding one channel into another. Note that this is not a true extension, as additional interference is added in the connection.

Once the hardware is connected and the software is configured, the setup is ready for testing. Make sure that the BERT output signal is enabled before the TUSB1146 is turned on and goes into full power state. By default, the redriver turns on in linear redriver, static EQ USB mode, making the signal output visible on the BERT or oscilloscope. Make sure the TUSB1146 is properly powered and in the CTLSEL (0xA) register, that USB3.1 mode is enabled. When these settings are true, the testing can begin.

Eye Test:

1. Configure the hardware setup in Figure 2-1. For the No EQ configuration, remove the TUSB1146 from the channel path and connect the remaining devices.
2. Select a channel length for the trial and modify the ISI channel board.
3. For static EQ, Fast AEQ, and Full AEQ configuration tests, turn on redriver and configure selected EQ type as described in EQ Configuration.
4. On the oscilloscope, measure and record the differential peak-to-peak voltage, average RMS Jitter, average eye height, average eye width, and pictures or waveform file data for the selected trial length.
5. Repeat steps 2-4 for each trial length.

This test needs to be repeated to complete the clean signal test and JTOL test for each EQ configuration (no redriver, static EQ, Fast AEQ, and Full AEQ). After final completion, there are two sets of data, each for all four EQ configurations, detailing the eye diagram data across channel lengths.

2.3 BER Test

The BER Test measures the bit error ratio for the given channel. This test requires that the BERT emits a test pattern signal through the ISI channel board, to then be equalized by the TUSB1146, and finally read again by the BERT. The BERT compares the sent and received signal to detect errors.

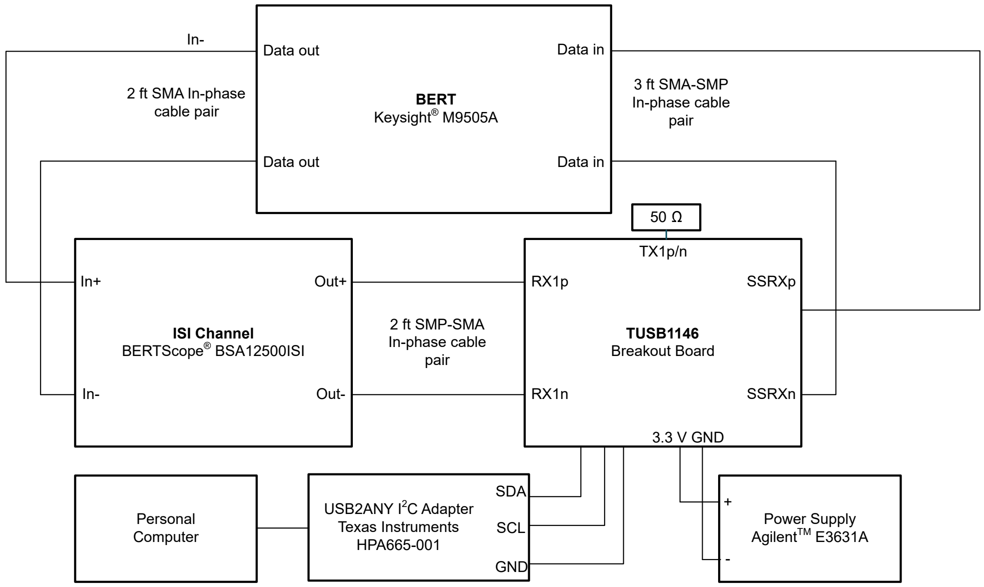


Figure 2-2. BER Test Setup Diagram

This test follows the same setup details as the Eye Test. The BERT needs to be configured with the same pattern and settings. The TUSB1146 registers, the No EQ test, and longer channel lengths can be configured in the same way. The startup procedure in this test is also the same as the previous test.

BER Test:

1. Configure the hardware setup in Figure 2-2. For the "No EQ" configuration, remove the TUSB1146 from the channel path and connect remaining devices.
2. Select a channel length for the trial and modify the ISI channel board.
3. For static EQ, Fast AEQ, and Full AEQ configuration tests, turn on the redriver and configure the selected EQ type as described in EQ Configuration.
4. On the BERT, run the BER test for 1E13 bits and record the value.
5. Repeat steps 2-4 for each trial length.

Similar to the Eye Test, this test needs to be repeated to complete the clean signal test and JTOL test for each EQ configuration

2.4 Alternative BER Test

As mentioned in Test Description, the following test is recommended for designers that want to reproduce test results for comparing AEQ with static EQ.

The alternative test gathers JTOL measurements for a given channel. This test requires that the BERT outputs the test pattern through the ISI channel board to be received by the TUSB1146 through a connected breakout board at the receiver. The TUSB1146 can equalize the signal through static EQ or AEQ, and retransmit the signal to a connected SuperSpeed USB device (labeled DUT). The DUT then loops the pattern back through the breakout board transmitter to be gathered by the BERT.

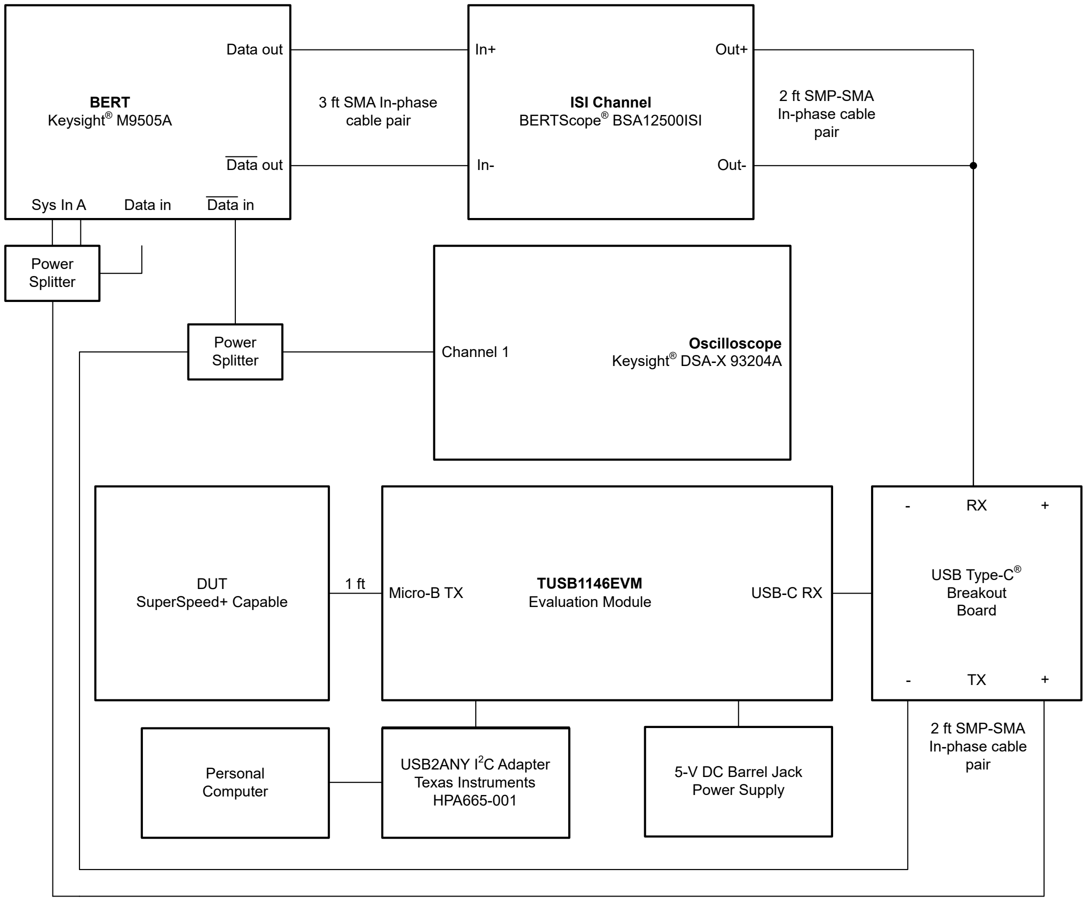


Figure 2-3. Alternative BER Test Setup

Because this test utilizes the TUSB1146EVM, there are several minor modifications to the previous procedures. The first modification is that this test has loss at the TUSB1146EVM transmitter due to the cable connecting it to the DUT. The TUSB1146 does need to be configured to run in limited redriver mode to compensate for potential losses between the DUT and EVM. Please see the *TUSB1146 data sheet* for configuration instructions. The second modification is that this test utilizes USB-IF compliance software provided by Keysight®, LeCroy®, and other oscilloscope brands. The USB-IF compliance software automatically runs compliance tests detailed by the USB-IF specifications board. This test utilizes a USB Type-C SuperSpeed (5Gb/s) Rx Short Channel Jitter Tolerance test to gather data, which runs automatically through BERT software. Because of the altered test setup, results obtained from the tests in this document cannot be used as official USB compliance results.

For more information about the description of this test, guidelines for manual performance, or details about patterns or specifications, see also the Electrical Compliance Test Specification SuperSpeed Universal Serial Bus Revision 1.0a and other related USB-IF documentation.

Alternative BER Test Procedure:

1. Configure the hardware setup in Figure 2-3, and turn on all devices.
2. Select a channel length for the trial and modify the ISI channel board.
3. Configure selected EQ type as described in EQ Configuration.
4. Run the 5G Rx Short Channel Jitter Tolerance Test.

This procedure produces a graph showing the maximum tolerable jitter level for a given frequency before producing major bit errors (1E-10).

3 Test Results

The following data in this section is produced following all the procedures outlined in this document. See EQ Configuration for the EQ settings used in these tests. For graphic purposes, a BER of 1E-12 constitutes no bit errors over the 1E13 bit recording period.

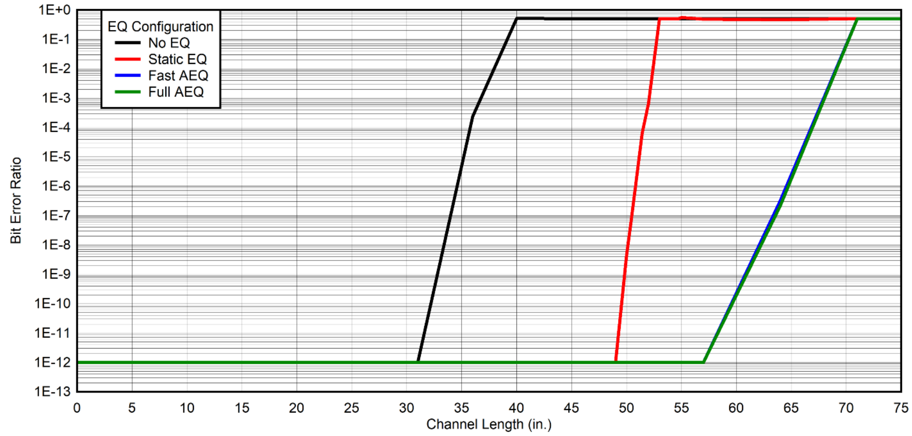


Figure 3-1. BER Test With Clean Signal

As shown in Figure 3-1, a redriver is required for channel lengths longer than 30 inches. For channel lengths less than 30 inches, the test setup produces low BER without equalization because the BERT outputs a low jitter, 10 Gbps clean pattern signal. As the channel length increases further, the redriver is required to compensate the additional ISI. Both Fast and Full AEQ can adapt to higher EQ settings, resulting in lower BER for more channel lengths than static EQ. In this case, it is possible to choose a much higher EQ setting for static EQ to ensure more channels operate without error. However, static EQ then over-equalizes short channels, with the consequences seen in Figure 3-2 and Table 3-1.

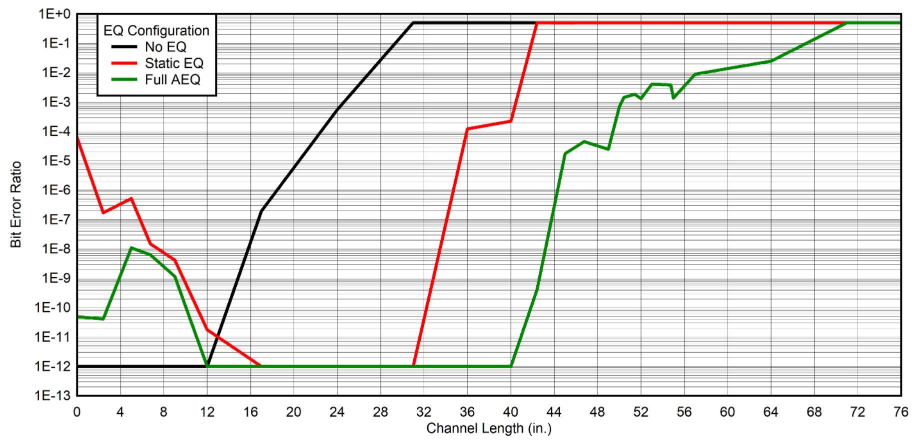


Figure 3-2. BER Test With JTOL Stressed Eye

Static EQ over-equalizes in the JTOL test in Figure 3-2. Over-equalization occurs when too much EQ is applied for the given ISI in a channel, causing jitter effects present in the channel to be amplified. Over-equalization produces the results seen in Figure 3-2, where static EQ has a high BER for the short channel due to over-equalization, as well as having a high BER in the long channel for under-equalization. The Full AEQ out-performs static EQ for the entire JTOL test. Fast AEQ is not included in this test as the chosen settings in EQ Configuration greatly over-equalizes, similar to static EQ.

Table 3-1. Impact of Over-equalization on Eye Test

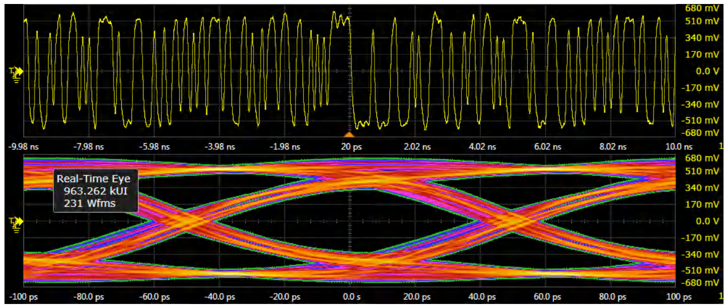
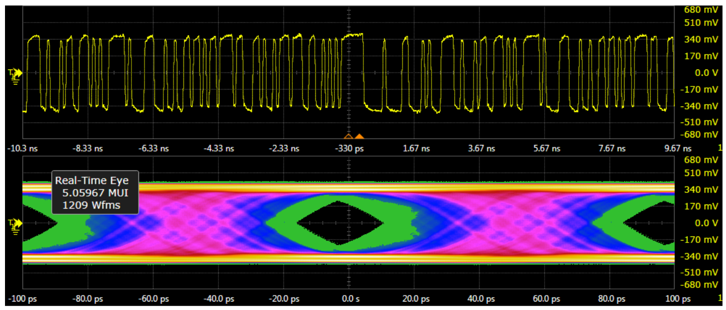
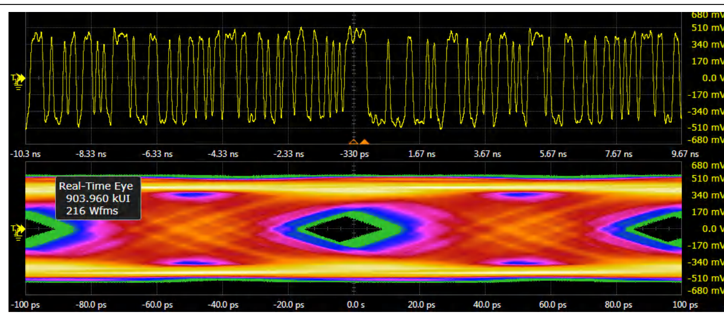
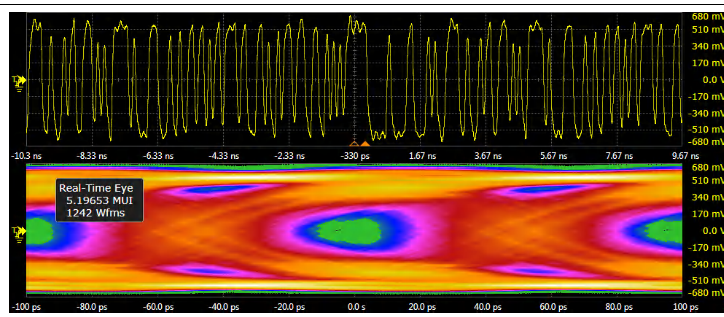
Test Description	Eye Diagram	Comments
24-inch channel, EQ setting 15, clean signal		Eye is slightly over-equalized, but the amplified jitter barely reduces eye width.
2.54-inch channel, No redriver, 550 mUI BUJ stressed eye		Eye has little ISI reducing the height, just the jitter added to the test reduces width.
2.54-inch channel, EQ setting 4, 550 mUI BUJ stressed eye		Eye height and width significantly reduced from the no redriver test due to over-equalization.
2.54-inch channel, EQ setting 15, 550 mUI BUJ stressed eye		Eye height and width entirely reduced due to the excess over-equalization.

Table 3-1 shows that while over-equalization is inconsequential to the eye in ideal system conditions, over-equalization quickly becomes an issue in high interference conditions. Table 3-1 visualizes what happens to static EQ versus Full AEQ in Figure 3-2 as Full AEQ chooses a lower EQ value. Despite this equalization, all EQ configurations experience difficulty due to limitations of the redriver in compensating for jitter.

Table 3-2. Impact of Under-equalization on Eye Test

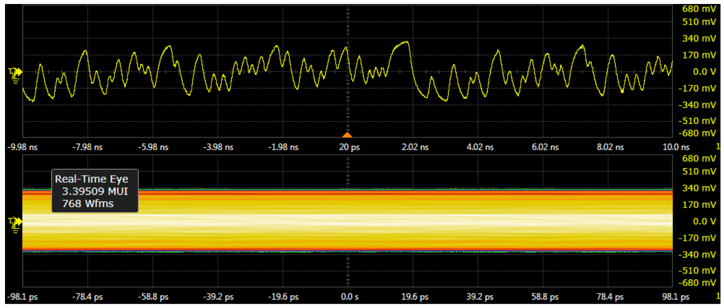
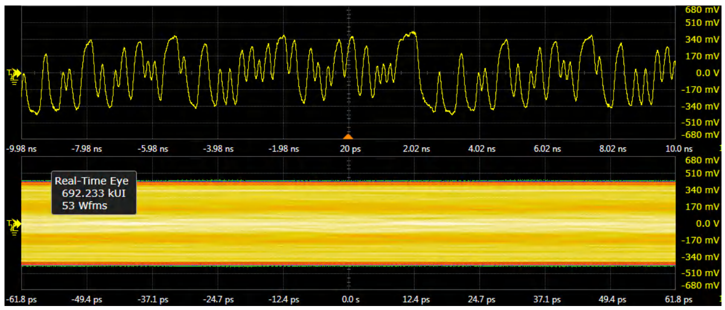
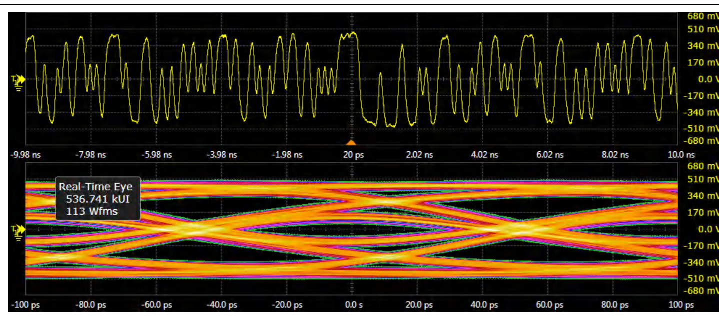
Test Description	Eye Diagram	Comments
52-inch channel, no redriver, clean signal		No eye present due to ISI making transient signal impossible for oscilloscope to lock onto.
52-inch channel, EQ setting 8, clean signal, static EQ value		EQ setting is not high enough, same situation as before.
52-inch channel, EQ setting 15, clean signal, AEQ value		EQ setting is high enough to recover eye and achieve full signal integrity.

Table 3-2 shows what occurs in Figure 3-1 at 52-inch channel length. Static EQ becomes inadequate in the long channels unless configured for the channel length, while AEQ can equalize all channel lengths within the limitations of the TUSB1146.

The following results are outputs from performing the Alternative Test, as detailed in Alternative Test Description.

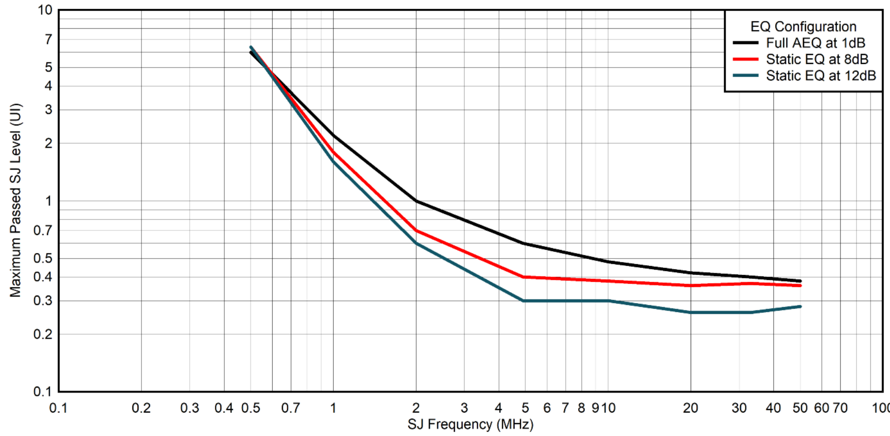


Figure 3-3. Alternative BER Test in Short Channel

Figure 3-3 shows the results of progressively increasing jitter in a 2.54-inch channel. These results are consistent with the previous tests, as static EQ over-equalizes and significantly decreases the jitter tolerance of the channel.

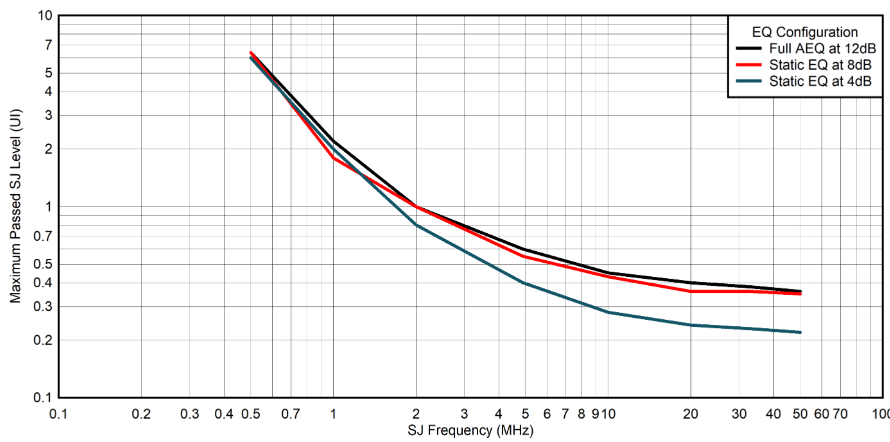


Figure 3-4. Alternative BER Test in Long Channel

Figure 3-4 shows the results of progressively increasing jitter in a 60-inch channel. These results are consistent with previous tests, as static EQ under-equalizes and decreases the jitter tolerance of the channel. Combining the results of Figure 3-3 and Figure 3-4 shows that AEQ out-performs static EQ on the short and long channel end, as the shared 8-dB static EQ setting is out-performed by AEQ in both instances. Fast AEQ is not included in this test as the chosen settings match the effectiveness of Full AEQ.

4 Summary

Using the AEQ over static EQ on the TUSB1146 and other applicable products is recommended. AEQ provides benefits such as improved redriver capabilities, decreased development time, and improved cost efficiency. In the tests provided in this application note, AEQ performs with less bit errors than static EQ across the tested channel lengths and conditions. While static EQ is an effective solution for static channels, AEQ automates the tuning process and can adapt to dynamic system conditions, decreasing development time. Lastly, AEQ makes the TUSB1146 more competitive with retimer designs because of the effectiveness of AEQ combined with the cost benefits of redrivers. This document serves as support for this recommendation, as well a guide for how to use these EQ configuration in applications, and what variables to consider when testing and using an EQ configuration in an application.

5 References

- Texas Instruments, *TUSB1146 USB Type-C™ Enabler EVM*, EVM user's guide
- Texas Instruments, *TUSB1146 USB Type-C™ DisplayPort™ Alt Mode 10-Gbps Linear Redriver Crosspoint Switch*, data sheet
- USB Implementers Forum, Electrical Compliance Test Specification Superspeed Universal Serial Bus Revision 1.0a, test specification