USB3.x Linear Redriver Signal Conditioning Theory and Practical Tuning Method

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Design challenge appears with the communication system traffic speed ramping up. As a high speed digital system, for example USB3.x, in which the data rates extend to 5Gbps (Gen 1), 10Gbps (Gen2) level, even the most experienced engineer cannot overcome the signal integrity issues, only through strict and careful design norm. Not to mention that the numerous category and specification of end equipment result in the tremendous uncertainty in high speed hardware design. While, signal conditioner is the right solution to introduce more design flexibility, reliability, error tolerance and cost advantage.

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1 Introduction

Linear redriver is the most widely-used, effective and economic solution in current USB3.x sig-con solution aggregation. This paper intends to explain the linear redriver signal conditioning function theory, eliminate misunderstanding and provide practical tuning method based on the test results. Most of the test result was gathered from TUSB1002A, but it also could be referred for other TI USB3.2 linear redrivers or active MUXs.

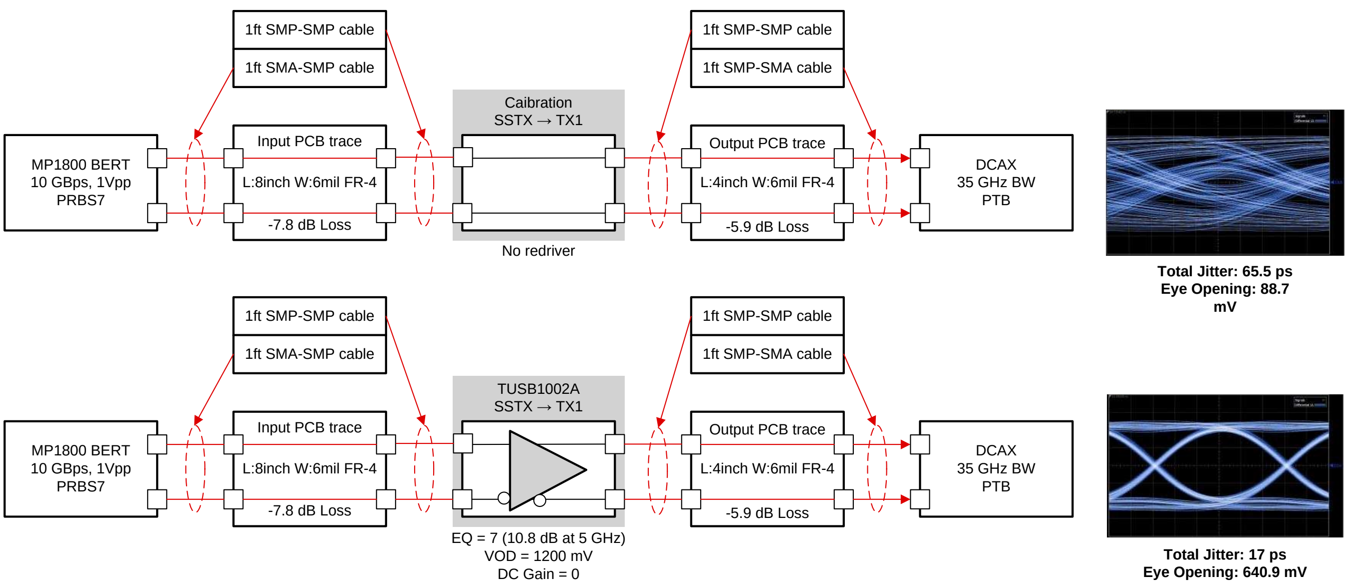


Figure 1. Comparison Between With and Without Redriver

2 High-speed Makes it Come True, High-speed Makes it Worse

Lightly experienced engineer realized by intuition that, when transmission data rate increases, signal quality degenerates. First, make no mistake: digital transmission is accomplished by analog. Figure 2 depicts the USB3.2 system channel model. The transmission media, the PCB trace, cable shows the completely different characters when high speed signal runs. The host and device end transceiver can only push and receive the signal according to a certain electrical specification. Signal integrity issue matters when the media impact on signal quality exceeds the transmitter ability and receiver tolerance limitation.

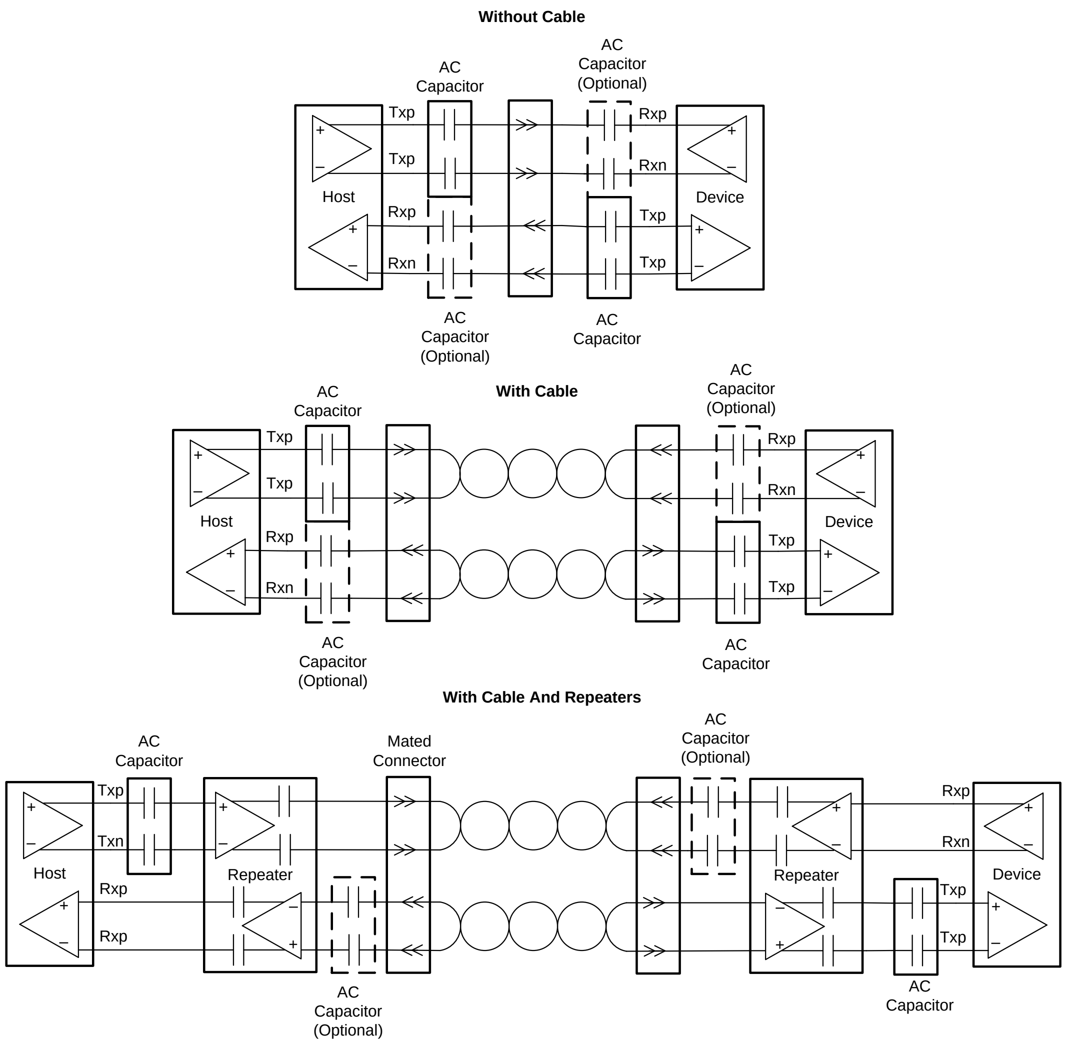


Figure 2. USB3.1 System Channel Model

For the design of modern communication system, such as the USB3.2 system, its physical links electrical specification compliance creates the foundation to ensure the communication success and reliability. For example, engineer should make sure the TX lane eye open satisfies the specific requirement of eye height, eye weight, total jitter, random and deterministic jitter, and RX lane should provide enough jitter tolerance [1].

Then introduce the most basic high speed signal quality degeneration mechanism from insertion loss view and jitter view, which are from the different perspectives but essentially with same root cause.

2.1 Channel Loss Between Transmitter and Receiver

Signal transmission route mainly includes PCB trace, interface, cable and some other components. All as the same, their intrinsic impedance property would make the signal transmitted attenuate, which is called loss, usually expressed in dB. The overall loss of signal transmission is equal to the simple-superposition of each component loss. Also its value is proportional to the length of the transmission path. Insertion loss is usually referred to characterize the loss caused by the transmission medium.

Just talking about the signal attenuating can not indicate the reason, why insertion loss makes the issue hard. The critical aspect is that the attenuating effect has a specific relationship with the signal spectrum frequency composition. That is, the insertion loss of all the cable, PCB trace, and passive route device could be visualized as a low pass filter.

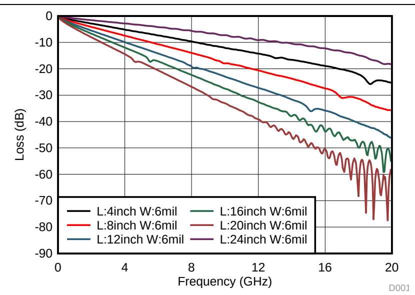


Figure 3. FR4 PCB Trace Insertion Loss vs. Frequency

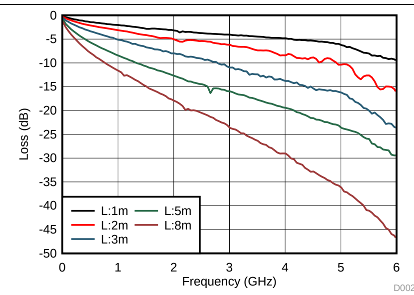


Figure 4. USB3 Cable Insertion Loss vs. Frequency

Take the PCB trace as an example, there are two main types of loss, one is the skin effect loss, another is insulation loss [2]. Leakage and radiation will also have some influence, but it is usually negligible. The skin effect loss of PCB line unit length is mainly related to the surface roughness, copper plating thickness and conductor etching precision. The insulation loss is mainly related to the dissipation factor of PCB sheet. It is important to note that skin effect loss increases proportionally to the square root of the frequency, while dielectric loss increases proportionally to frequency. As a result, the dielectric loss becomes much more dominant than skin-effect loss in multi-gigabit designs. In cable, dielectric loss becomes the dominant factor even at lower frequency point [3]. So when talking about high speed issues, insertion loss could be regarded as proportional to frequency.

Consider the differential transmission circuit model shown in Figure 5. Code 0 and 1 are applied to the data transmission bus by the transmitter in accordance with a specific electrical standard. At this point, the bus between the transmitter and the receiver can no longer be considered as an ideal interconnection, it should be as a transmission line. Traffic through transmission line, at the receiving end, the receiver quickly compare and recognize the bus voltage level according to the specific threshold of one-level and zero-level, realizing the code reception function.

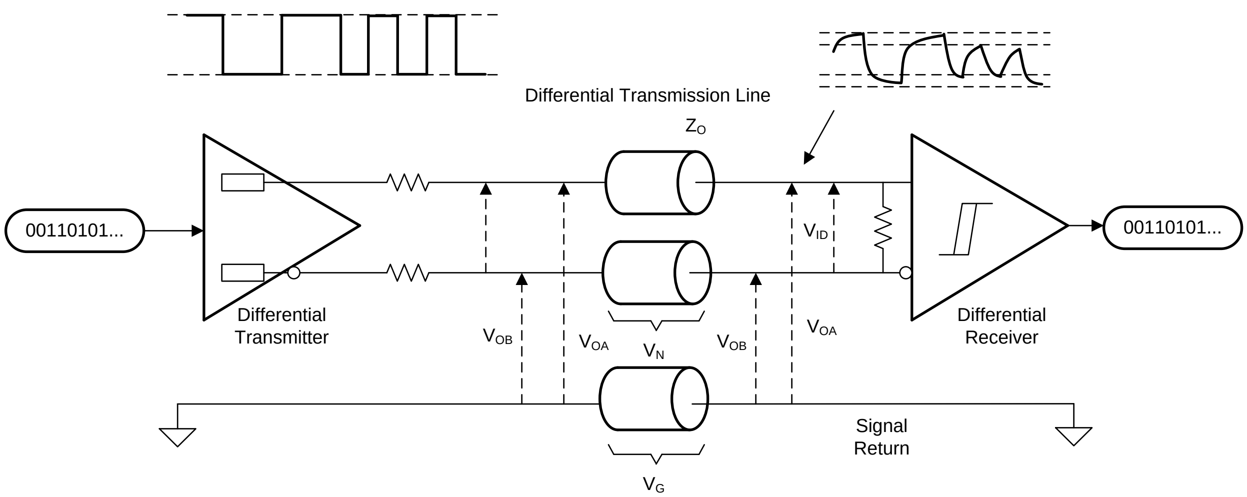


Figure 5. Differential Transmission Circuit Model

PRBS7 is one kind of the code pattern that simulates digital signal behavior, which is often used in high-speed communication tests such as eye diagram analysis. The PRBS7 time-based waveform and spectrum analysis is shown in Section 2.1.1, for the same test setup without redriver as shown in Figure 1. Through the spectrum analysis, we can see that the transmitted signals contain a rich spectrum of components. Based on the foregoing, the low pass characteristic of loss will cause the high frequency components attenuating more. When these attenuations are large enough, it becomes difficult for the receiver to correctly identify the code, and the tolerance for noise and interference is significantly reduced. This also explains why all kinds of high speed communication standards have specific requirements for eye height in eye diagram tests.

2.1.1 1 Vpp 2.4 bps PRBS7 Waveform and Spectrum Transmitted Through PCB Trace

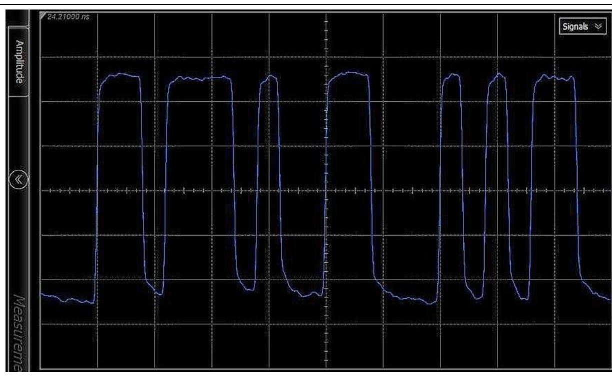


Figure 6. PRBS7 Time-Based Waveform Before Loss

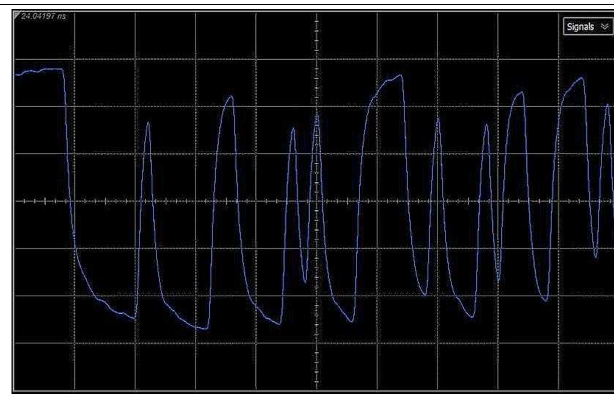


Figure 7. PRBS7 Time-Based Waveform After Loss

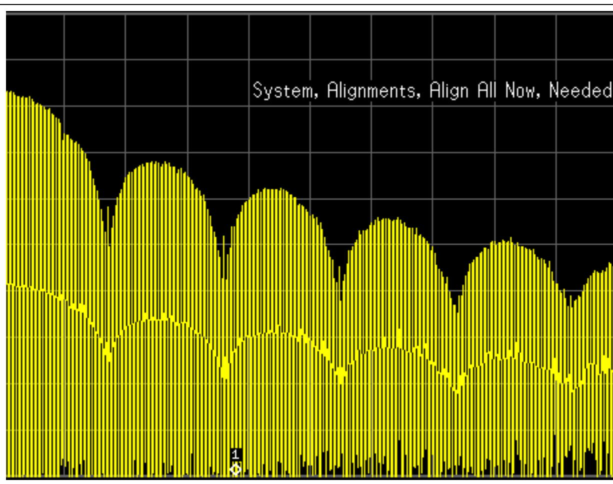


Figure 8. PRBS7 Spectrum Before Loss

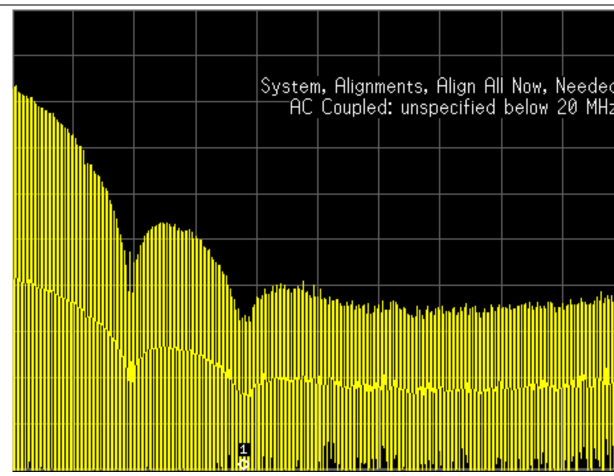


Figure 9. PRBS7 Spectrum After Loss

2.2 *ISI Jitter*

When the electrical entity of the transmitted data degrades to the point that the receiver cannot recognize the symbol correctly, bit error occurs. Reliability of the transmission system is usually evaluated by BER(bit error rate), which means the ratio of the number of error codes to the total number of digital transferred in a given time. Usually, the communication standards have specific requirements on BER, for example USB3.1 Gen 1, which requires the physical layer's BER to be less than 1 in 10 to the 12 power bits [4].

Bit error generation is related to attenuation of signal amplitude, and also it is related to the uncertainty of the digital raising/failing edge, which is called jitter. The jitter can manifest as the actual periodicity distribution deviation of the data or hypothetical reference clock, as well as the slope distortion affected by the transmission path bandwidth limitation and code symbol change, even the interference or noise caused from power supply noise, device thermal noise or other sources. Excessive jitter will reduce the size of the eye in eye diagram test, leading to the difficulty of the receiver correctly recognizing data code increase.

The scale of the jitter in a communication system could be evaluated by statistical histogram. According to the formation principle of all kinds of jitter, it can be divided into two kinds: deterministic jitter and random jitter. And the common used total jitter is sum of all of this jitter. There are multiple causes of deterministic jitter, such as PJ (Periodic Jitter), DCD (Duty Cycle Distortion) jitter, ISI (Inter-Symbol Interference) jitter, but it must be caused by the characteristic of the transmission model, so its distribution is bounded, usually measured by the peak value. While, the random jitter is made up of some kind of thermodynamic effects or flicker noise and regarded as Gaussian distribution. Its distribution is unbounded. As statistics grow in size, their boundaries will always expand. Random jitter usually measured with RMS values.

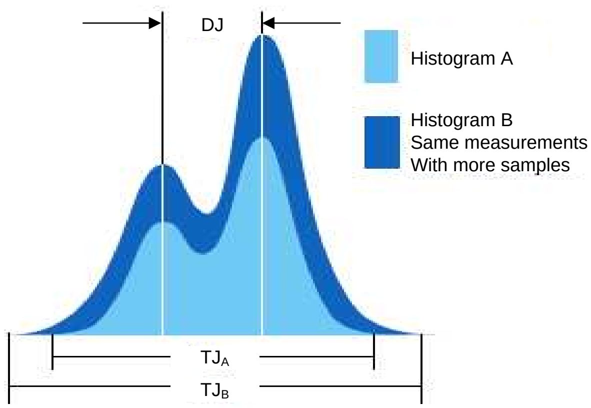


Figure 10. Statistical Histogram

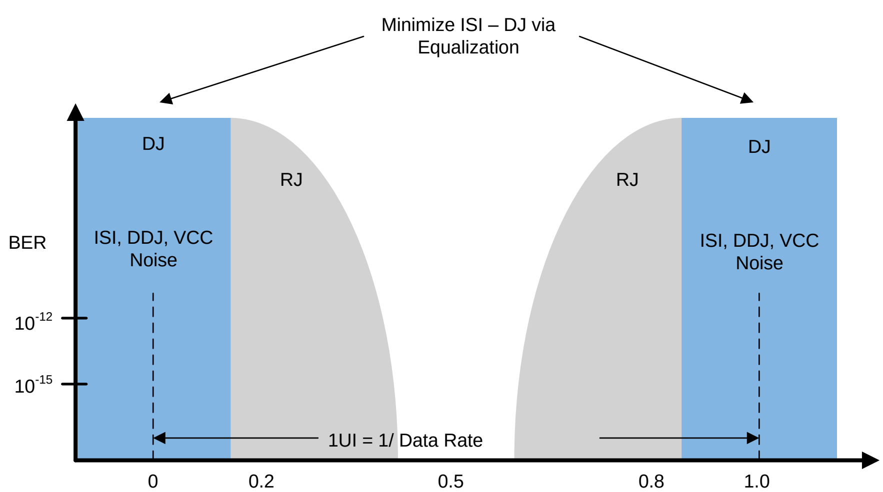


Figure 11. Bathtub Curves

Different jitters impact on system performance is not at the same level. And there are many specialized articles focus on the definition and composition of various jitters. So the main to discuss here is that in the deterministic jitter, there is a kind of jitter called ISI jitter(inter-symbol interference jitter), which is the primary source of jitter in a significant portion within all the designs, and ISI jitter is the only jitter type that can be reduced by the redriver signal conditioning method.

The formation of ISI jitter is related to the code symbol polarity conversion transmitted sequentially. Section 2.2.1 show the continuous NRZ code transmission diagram. Before the point of A, continuous 0101 code with uniform width of the switching allows the electrical level of the signal to remain at a constant median level. At this moment, if the continuous one level code was transmitted, the average voltage level of the transmission medium will be raised by stable charging. When code switching from one level to zero level at point B, because the electrical polarity change rate is limited by the transmission intermediary speed, the average voltage level cannot be restored to the previous median level within a short time. As shown at point B and C, even if the transmission is a continuous and uniform 0101 code type, its uniformity on the horizontal time-base cannot be maintained. Then the jitter is formed. The essential limiting factor is that the bandwidth of the transmission medium limits the rates of the signal rising and falling edge, or to say that, restrict the transmission capacity of the signal high frequency components. So essentially, ISI jitter is same with the attenuation effect caused by frequency-dependent loss.

Another type of ISI jitter is formed by reflections caused by impedance mismatch in the transmission path. When impedance mismatch exists in transmission path, code symbol polar switching would form a reflection after a while, thus forming a DDJ (data dependent jitter), which would impact the eye opening in the vertical and horizontal directions. Good impedance matching can ignore this effect.

2.2.1 ISI Jitter Formation Conceptual Diagram

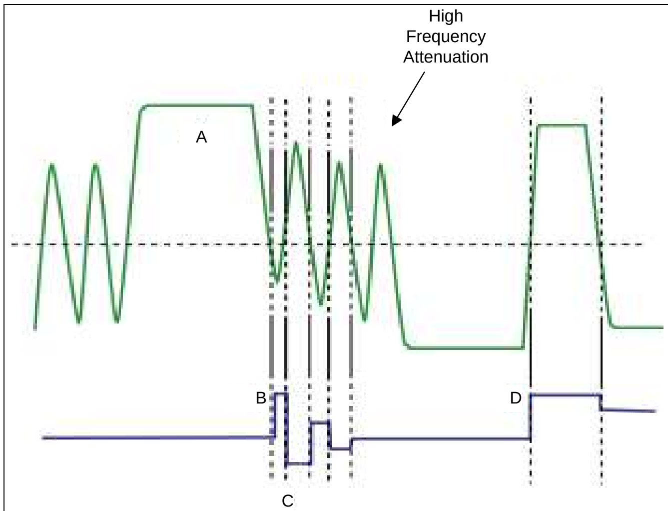


Figure 12. ISI Jitter Caused by Code Symbol

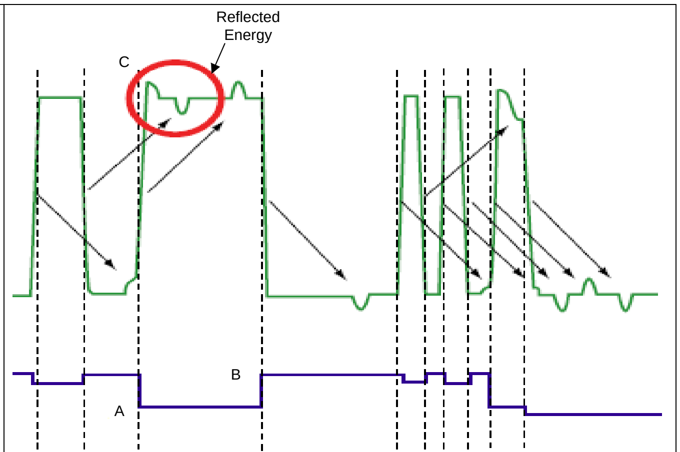


Figure 13. ISI Jitter Caused by Reflection

3 Linear Re-driver and CTLE

In order to restore the signal quality from signal integrity issues, adopting signal conditioner solution into system design could be really effective. In USB3.2 applications, linear redriver should be the exactly basic selection. It is used to compensate the channel insertion loss. And in result, the ISI jitter and total jitter would be reduced significantly. Properly implementing linear redriver could produce a compliant signal at port partner’s receiver, which help the USB3.2 application system design pass compliance test. But it should be noticed that, though linear redriver solution could provide a sufficient signal integrity performance improvement, its ability is limited, because it has nothing to do with the random jitter and non-ISI deterministic jitter.

Just like but opposite in effect with insertion loss, linear redriver provide a frequency-dependent gain on signal passed. It internally employs a continuous time linear equalization (CTEL) component, which can be regarded as a high pass filter. The total channel loss and an equalizer frequency response curve are shown in Section 3.1. By selectively boosting the high frequency components in signal [5], CTLE minimizes the attenuation effect cause by channel loss and strengthen or electrical-equivalently reduce the channel length, to provide more flexibility in PCB layout design.

3.1 Channel Loss Frequency Response Curves

The linear redriver is virtually a passive element in the signal path. It faithfully pass through all electrical characteristics of a signal (such as pre-shoot, de/pre-emphasis, distortion due to discontinuities etc.) as a passive channel would, provided the signal is in its linearity range. So well-performed linear redriver depends on the well-performed response cure of CTLE to overcome channel loss and ISI jitter; however it could add some another kind of jitter with only very small impact.

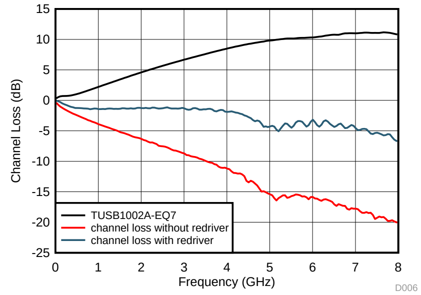
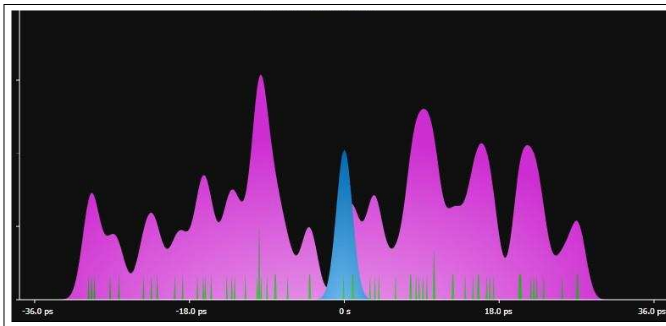
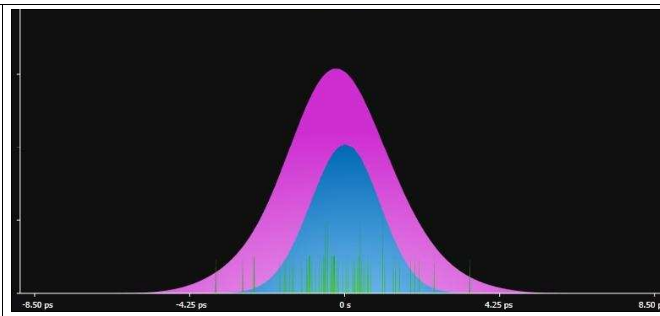


Figure 14. Channel Loss Frequency Response Curve



TJ: 67.9 ps; DJ: 56.1 ps; RJ: 860 fs

Figure 15. Composite TJ Histogram Without Redriver



TJ: 17.6 ps; DJ: 5.9 ps; RJ: 860 fs

Figure 16. Composite TJ Histogram With Redriver

4 Tuning Method Based on TUSB1002A

Correct implementation of linear redriver relies on the proper tuning settings. For TUSB1002A, it provide knobs for adjusting EQ, VOD and DC gains. A linear redriver tuning test based on TUSB1002A is shown as below. The eye diagram measurement was used as the evaluation method to show the effect of different EQ settings [6]. In this test, the pre-channel is 8 inches length and 6 mils width with -7.8 dB loss at 5 GHz. The post-channel is 4 inches length and 6 mils width with -5.9 dB loss at 5 GHz. The test signal source is 10 Gbps differential 1 Vpp PRBS7 pattern without any pre-shoot.

4.1 EQ Settings

The EQ settings tuning test result is shown in Section 4.1.1. It is obvious that, without redriver, the eye is almost close. While with the EQ value increasing, the eye comes to be opened gradually, until excessive equalization makes the eye distorted. So general speaking, for a specific pre-channel and post-channel trace length layout case, there should be a certain EQ value that can result the best eye diagram performance, which means the equalization at the receive end could exactly compensate to the pre-channel loss. It is most usually to compare the parameter TJ (Total jitter) and eye open. Sometimes they could be not coincident, but often the minimum T_J makes more sense than maximum eye open [7]. The total jitter and eye open of different pre-channel and post-channel length statistical charts are shown in Figure 10 and Figure 11. It can be seen that, for the 8 inches pre-channel and 4 inches post-channel case, the best EQ selection is EQ7 with 17.6 ps total jitter and 567.8 mV eye open.

Test conditions

- Pre-channel: -7.8 dB Loss at 5 GHz
  - Length: 8 inches; Width: 6 mils;
- Post-channel: -5.9 dB Loss at 5 GHz
  - Length: 4 inches; Width: 6 mils
- DC Gain: 0 dB, VOD = 1000 mV;
- Signal source: MP1800A BERT 10 Gbps, 1 Vpp, PRBS7
- Scope: 86100D Infiniium DCAX 35 GHz
- Power supply: 3.3 V
- Temperature: 25°C

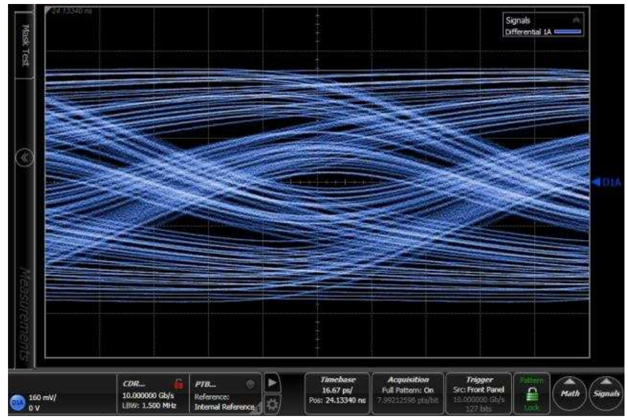


Figure 17. No Redriver

4.1.1 TUSB1002A EQ Sweep Test Eye Diagram

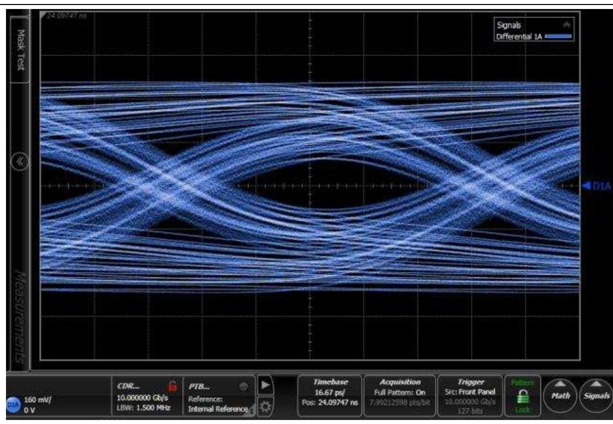


Figure 18. EQ = 1

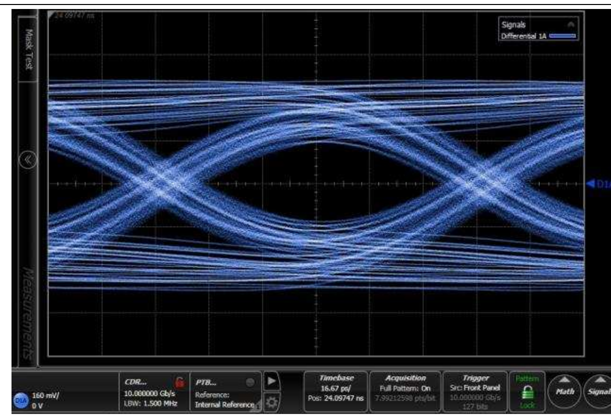


Figure 19. EQ = 2

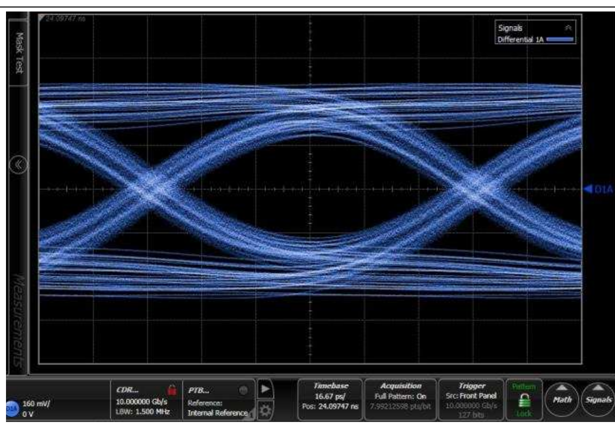


Figure 20. EQ = 3

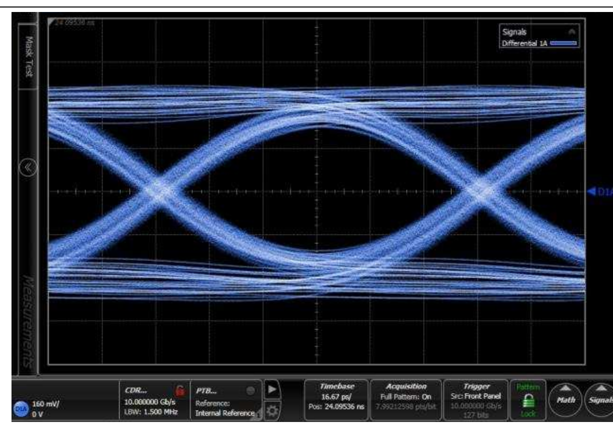


Figure 21. EQ = 4

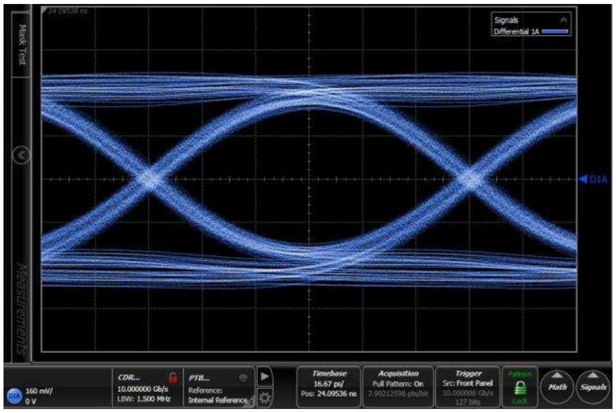


Figure 22. EQ = 5

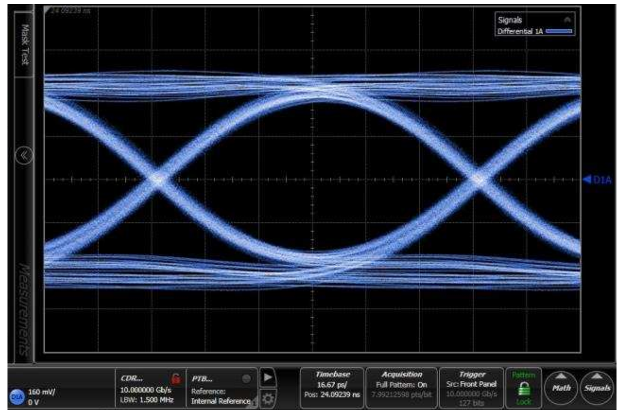


Figure 23. EQ = 6

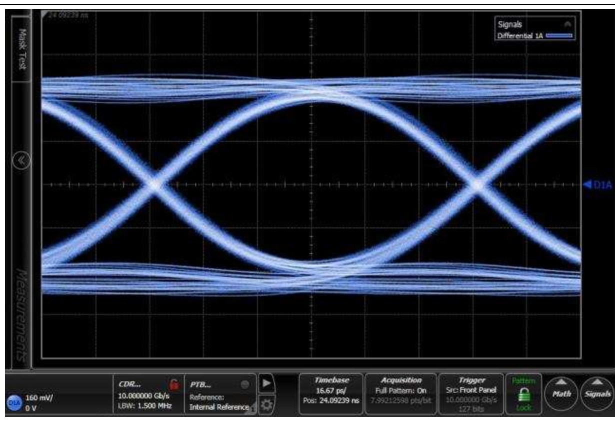


Figure 24. EQ = 7

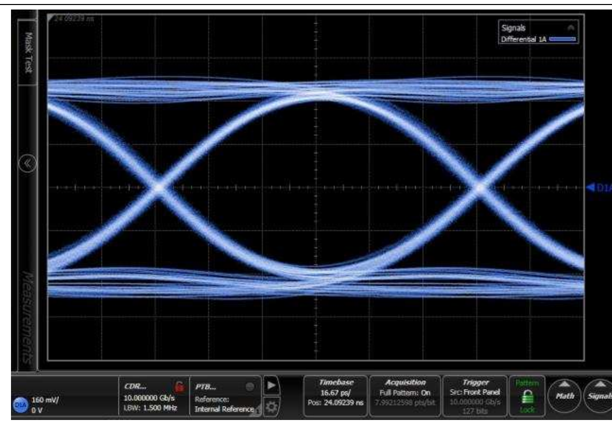


Figure 25. EQ = 8

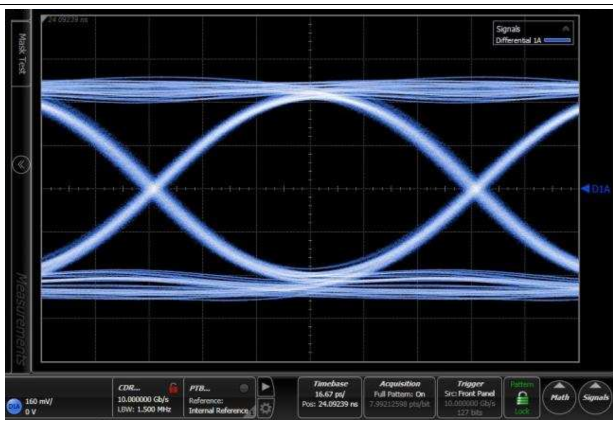


Figure 26. EQ = 9

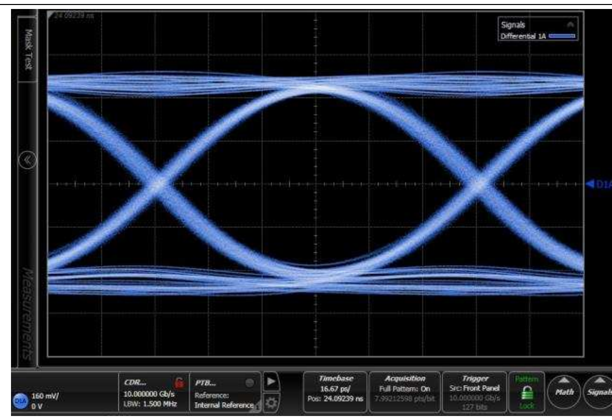


Figure 27. EQ = 10

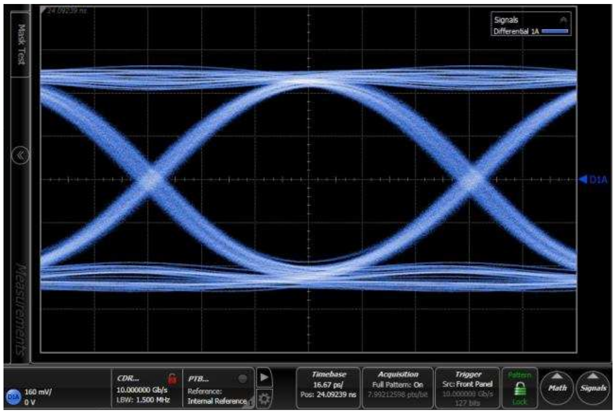


Figure 28. EQ = 11

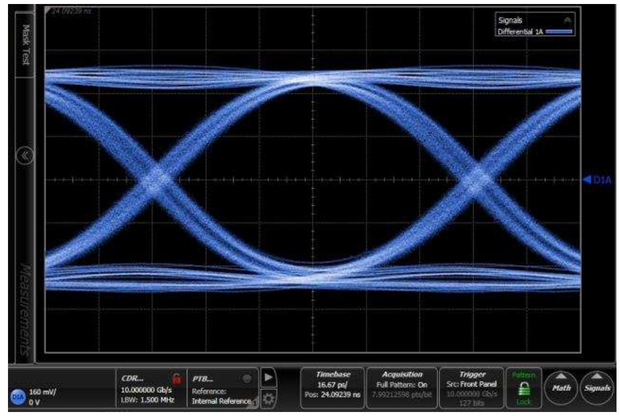


Figure 29. EQ = 12

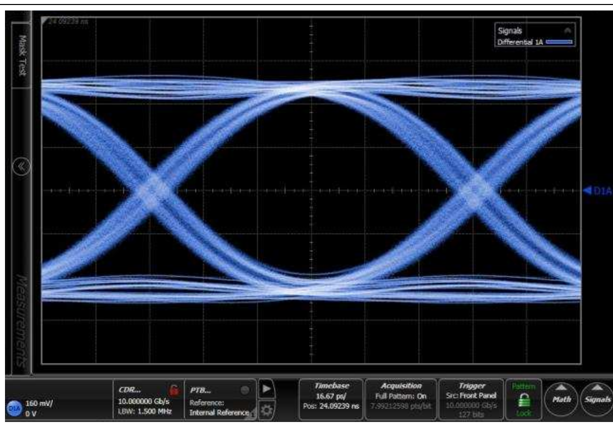


Figure 30. EQ = 13

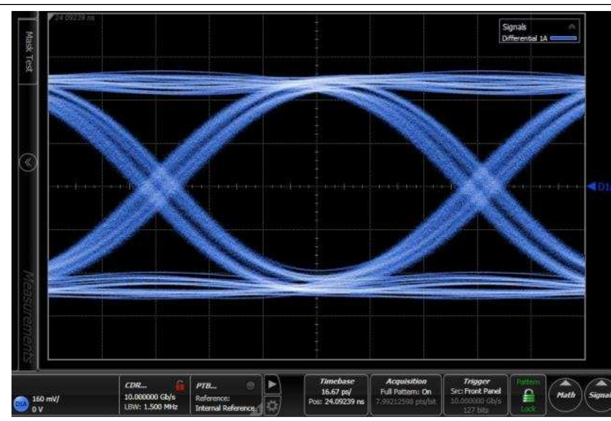


Figure 31. EQ = 14

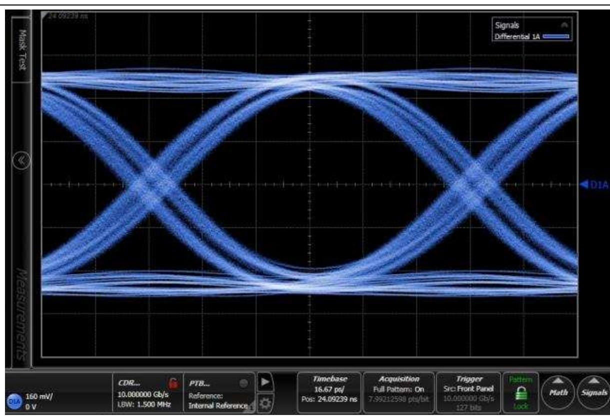


Figure 32. EQ = 15

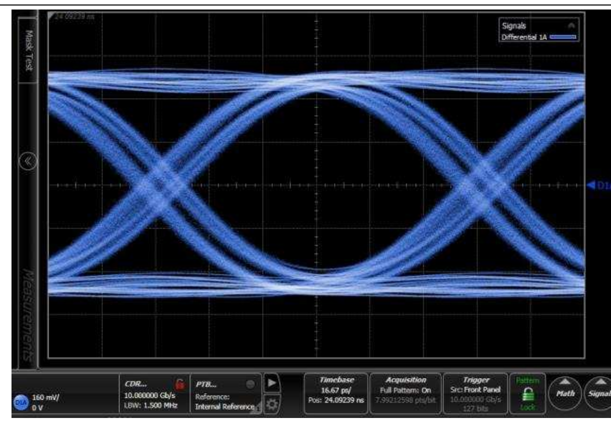


Figure 33. EQ = 16

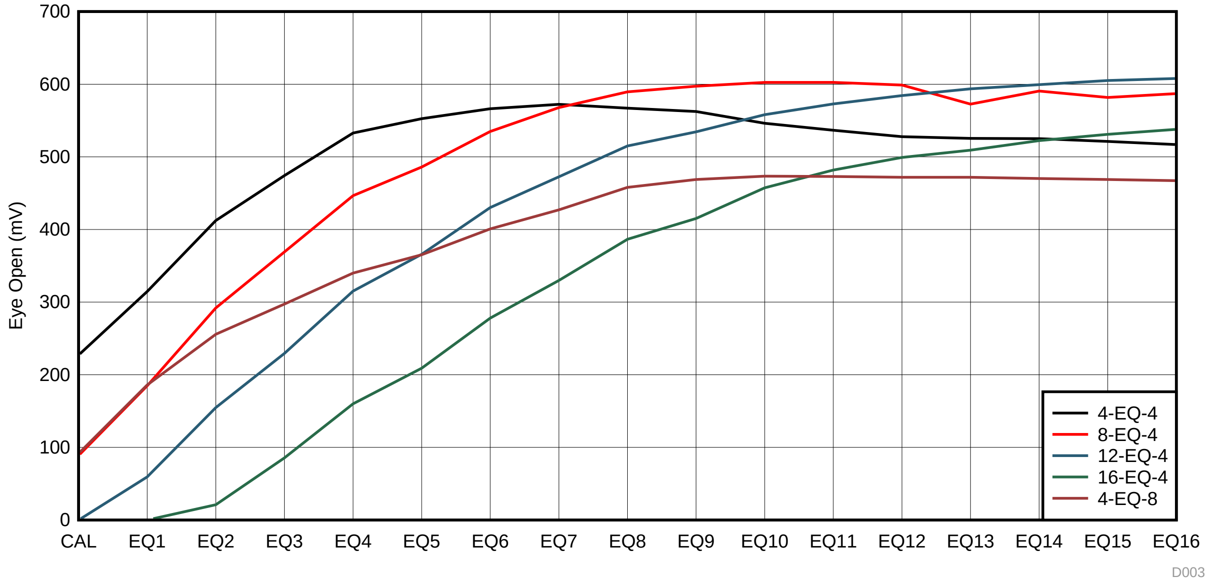


Figure 34. Total Jitter Over EQ Sweep

Table 1. Total Jitter Over EQ Sweep

Units = ps	CAL	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15	EQ16
4-EQ-4	43.9	33.3	28.7	26.4	24.2	22.96	20.5	20.8	20.7	20.9	22.3	24	26.1	27.3	27.7	28	31.9
8-EQ-4	65.5	45.3	34.1	28.1	23.4	21.4	18.6	17.6	18.3	18.9	19.8	20.8	22.4	23.5	25.2	26.7	28
12-EQ-4	80.2	66.2	48.3	38.5	29.9	26.3	21.9	19.4	17.6	17.6	28.3	18.9	20.1	23.5	22.4	23.4	24.9
16-EQ-4			74.5	59.1	45.6	38.8	30.8	26.3	21.8	19.8	17.7	17.7	18.9	19.5	20.9	22.2	23.6
4-EQ-8	65.1	45.7	37.1	33.2	29.8	28	25.3	23.3	22	22.2	22.1	22.9	24.9	26.3	28.2	29.3	30.5

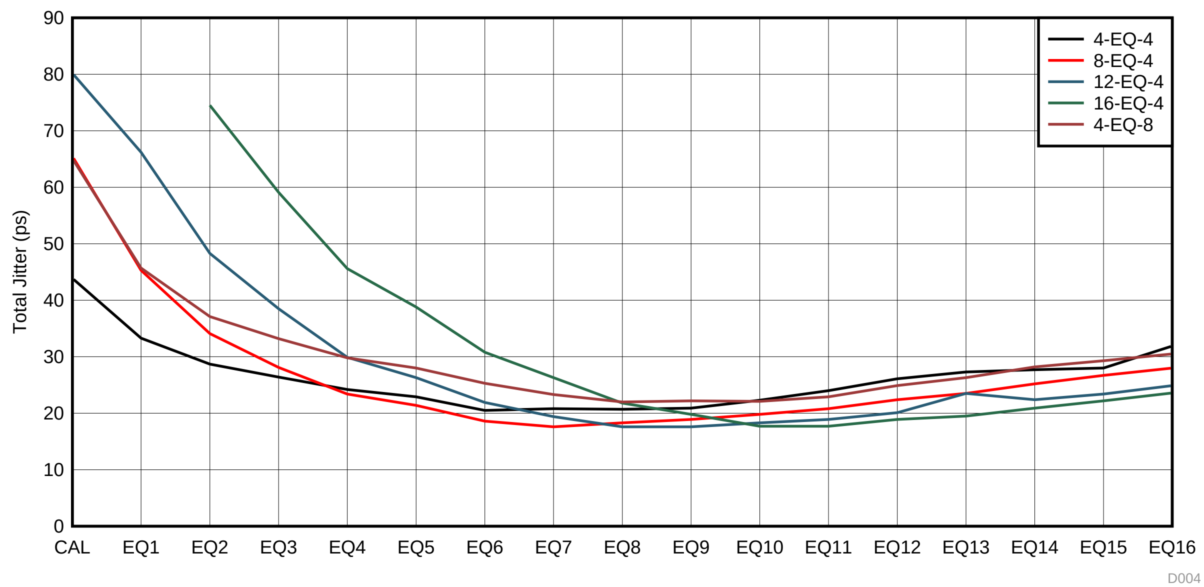


Figure 35. Eye Open Over EQ Sweep

Table 2. Eye Open Over EQ Sweep

Units = mV	CAL	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15	EQ16
4-EQ-4	227.06	314.6	412.3	474.2	532.8	552.5	566.3	572.3	567	562.4	546.2	536.6	527.8	525.4	525.1	521.2	516.9
8-EQ-4	88.7	184.8	292	369.1	446.6	486	535	567.8	589.4	597.2	602.5	6.2.6	598.8	572.6	590.6	581.8	587.2
12-EQ-4	0	59.4	154.9	229.4	315.2	365.9	430.2	472.6	515	534.4	558	572.8	584.4	593.6	599.4	605	608
16-EQ-4	0	0	21.1	85.6	160.1	209	278	329.9	386.6	415.2	457.4	481.8	499.2	509.2	522.4	531	538
4-EQ-8	91.5	185.9	255.7	297.3	340	365.2	400.8	427	458	468.8	473.4	473	471.8	471.8	470.2	468.8	467.2

Due to the equalizer boost function, besides total jitter and eye open, EQ settings also have an impact on signal amplitude. It would always enlarge signal amplitude when EQ settings increase. The signal amplitude statistical chart of the eye diagram in Section 2.1.1 was shown in Section 2.2.1. The signal amplitude result is also related with input signal amplitude and redriver VOD linear range settings. In this test, the input signal amplitude is differential 1 Vpp and the VOD setting is 1000 mV.

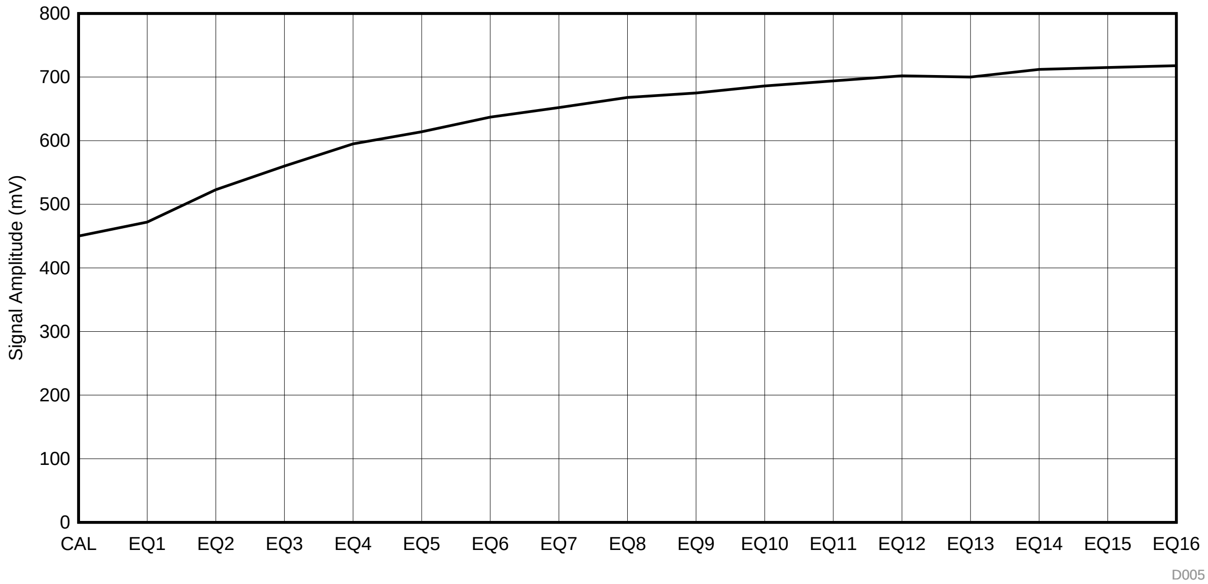


Figure 36. Signal Amplitude Over EQ Sweep

Table 3. Signal Amplitude Over EQ Sweep

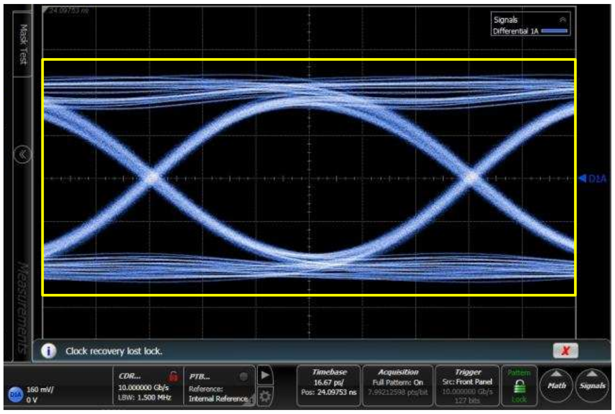
Units = mV	CAL	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15	EQ16
8-EQ-4	450	472	523	560	595	614	637	652	668	675	686	694	702	700	712	715	718

4.2 VOD and DC Gain Settings

Based on the EQ result, go further step to tune the VOD and DC Gain settings could help to produce a more compatible eye and provide more jitter margin.

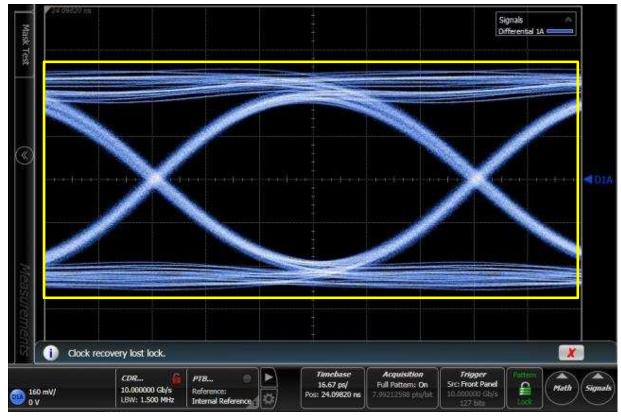
VOD settings adjust the output voltage swing linear range, because it could wholly shift the equalizer frequency domain curves up or down. For eye diagram tune effect, it could be regarded as to stretch the eye vertically while keep the eye shape and distribution same, which could be useful to make the eye compatible with the eye mask height and one-level, zero-level limitation requirement. Section 4.2.1 shows the result to change the VOD as different values. In this test, the EQ value is 7 and DC gain is 0. Then the best total jitter could be 17.2 ps.

4.2.1 VOD Settings Eye Diagram Test



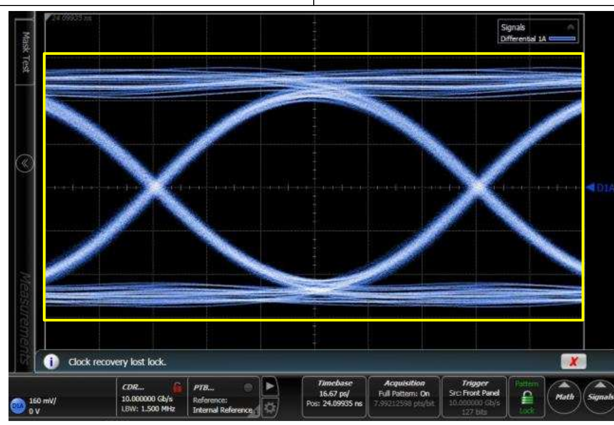
EQ = 7; DC Gain = 0; Total jitter: 17.6 ps
Signal amplitude: 633 mV; Vertical scale: 160 mV/div

Figure 37. VOD = 900 mV



EQ = 7; DC Gain = 0; Total jitter: 17.2 ps
Signal amplitude: 677 mV; Vertical scale: 160 mV/div

Figure 38. VOD = 1000 mV

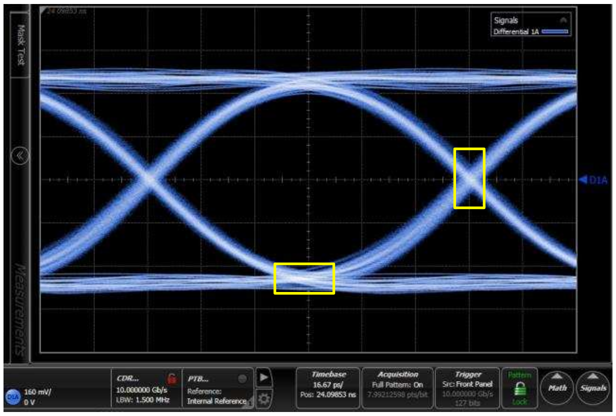


EQ = 7; DC Gain = 0; Total jitter: 17.2 ps
Signal amplitude: 748 mV; Vertical scale: 160 mV/div

Figure 39. VOD = 1200 mV

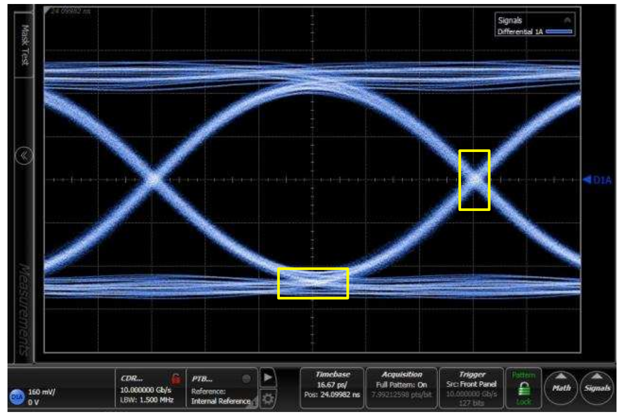
4.2.2 DC Gain Settings Eye Diagram Test

Together with EQ and VOD, DC Gain also help shape the produced eye. DC Gain mainly decides the equalizer gain at DC and low frequency section till to part of the equalizer's linear boost section, which could slightly trim the eye pattern lines distribution and boundaries factors. Figure 10 shows the result of changing the DC Gain setting to different values. In this test case, the EQ is set to 7 and VOD is 1200 mV. DC Gain = 0 provides the best total jitter performance. Combining with some other test results, it is experienced that, because the EQ7 is a moderate equalization value, so a moderate DC gain could get a best result, that is DC Gain 0. While if a relatively low EQ value was need, then higher DC Gain may get the best tune result; if a relatively high EQ value was need, then low DC Gain may get the best tune result.



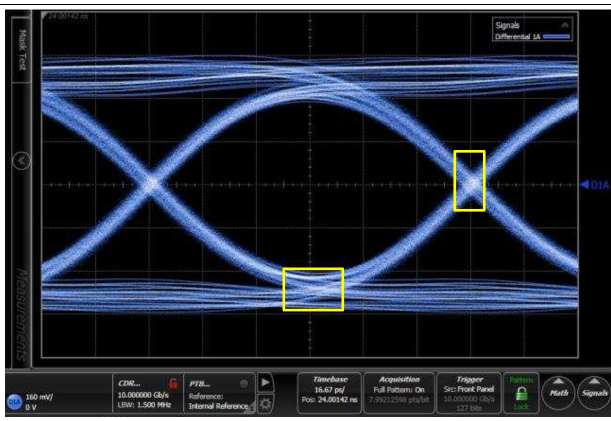
Eye open: 641.3 mV; Total jitter: 18.7 ps

Figure 40. DC Gain = -1



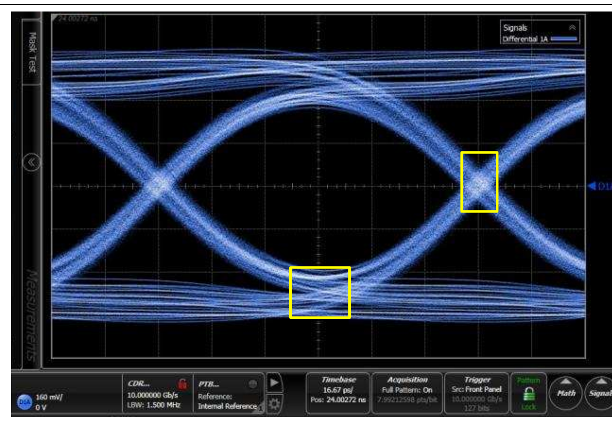
Eye open: 640.9 mV; Total jitter: 17.0 ps

Figure 41. DC Gain = 0



Eye open: 613.4 mV; Total jitter: 18.3 ps

Figure 42. DC Gain = 1



Eye open: 582.7 mV; Total jitter: 21.3 ps

Figure 43. DC Gain = 2

5 Summary

With the data transmission rates requirement of communication standards running faster and faster, linear redriver plays a more important role in the high speed sig-con solution portfolio. It's really effective and economic method to implement redriver solution to overcome the signal integrity issue and provide more layout flexibility in high speed communication application design, such as the USB3.2 Systems. Texas Instrument developed excellent-performed linear redriver products. But to really take advantage of the linear redriver function, need to make sure to take the correct understanding and consideration into the system design process.

6 References

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