White Paper
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USB System Design Considerations: Switches and Redrivers

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There are many components in the USB switching and signal conditioning space. As a system designer it may be difficult to find the right components for your design. This paper aims to give a better understanding of when and where to use switches and redrivers and how they affect the compliance of a USB system.

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1 Introduction

The paper describes the key characteristics of switches and how they affect a USB system. For example, in a USB Type-C application a designer may want to use some of USB features such as supporting the connector flip or Alternate Modes (Alt Modes). In order to use these features, a switch is needed to flip the signal according to the cable orientation and to select what data signals that are present at the external port.

A redriver has a different function and is implemented to condition and amplify a signal that has incurred too much loss. They can be implemented independently of a switch or integrated into a switch for a one-chip solution. A good example of a system that could need a redriver is a laptop/notebook computer where the output ports have a large amount of trace between the host and USB port. In this case, a redriver may be needed to boost the signal near the port allowing the system to pass compliance.

These are a few general examples of how these devices can be used. The remainder of this paper expands upon how these signals incur losses, how these losses affect USB compliance, and how these types of devices can fit into your design.

2 Switch Design Considerations

There are many use cases for a passive switch in a USB system. One example is a device incorporating USB-C; this required at least one switch to handle the reversible connector.

The sections below will describe the main parameters that will factor into choosing the correct switch for a USB application.

3 Signal Speed

The first consideration when choosing a switch is the signal type and signal speed of the intended application. The USB ecosystem now has many different signal types and signal speeds that can be transmitted or received. Figure 1 shows these signals and the data rates with which they are associated.

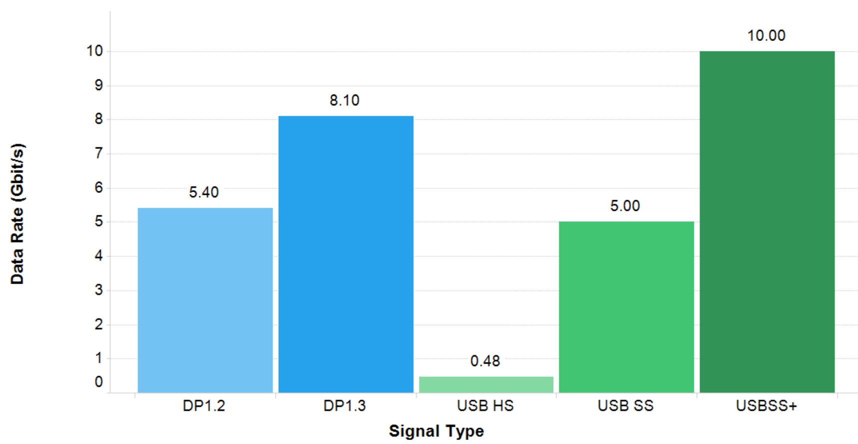

Figure 1. USB-C Signals and Their Associated Data Rates

4 Bandwidth

The next parameter is that the switch must pass is the -3 dB bandwidth. This parameter represents the frequency at which the signal passing through the switch loses half of its amplitude. It is recommended that a switch have a -3 dB bandwidth at least 1.5 times the frequency of the signal. For example, the frequency of a 5 Gbit/s USB SS signal is 2.5 GHz. This signal would need a switch to have a -3 dB bandwidth of at least 3.75 GHz. If the selected device has a bandwidth that is too low, there is a large amount of insertion loss. This factors into the loss budgets discussed in the USB compliance section.

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5 R_{on}

R_{on} is a major contributor to the overall insertions loss of a passive switch. As the R_{on} of the switch increases, the power that the switch dissipates increases as well. This leads to a decrease in the amplitude of a signal.

The switch designer wants to minimize the R_{on} of a device. One of the simplest and most effective ways to do this is to increase the W (width) and L (length) of the transistors inside of the switch. This approach increases the Con of the switch, which is discussed in more detail below.

6 C_{on}

C_{on} is a measure of the parasitic capacitance that the signal experiences as it passes through the switch. C_{on} affects the bandwidth of high speed signals. As Con increases the high-frequency bandwidth decreases.

For most passive switches insertion loss is stable at lower frequencies. This loss is caused by the R_{on} of the device. When the signal frequency reaches the pole of the system, located at:

$$S = \frac{1}{(R_{on})(C_{on})} \quad (1)$$

the insertion loss increases at a higher rate.

7 R_{FLAT}

R_{FLAT}, also referred to as ΔR_{on}, is a measure of the change in the R_{on} in a switch as the input voltage of the signal changes. This parameter affects the linearity of the signal as it passes through the device. Figure 2 shows how R_{on} changes with respect to the input voltage of the signal. Illustrating how R_{FLAT} could affect the linearity of a signal.

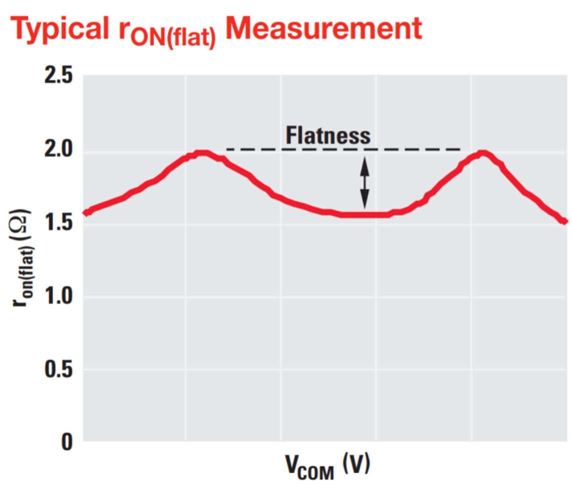

Figure 2. Device R_{on} vs. Signal Voltage

For more information on how these parameters may affect Analog systems, read Analog Swithc Guide (SLYB125).

8 Insertion Loss

Insertion loss is the combination of the signal degradations caused by the R_{on}, Con and other non-idealities of the device. This value range is normally -1dB to -2dB for signals with data rates > 1 Gbit/s. This parameter is what factors into the USB loss budgets that are discussed in more detail.

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9 USB Compliance

Each generation USB is released with general compliance standards. These standards are essential to ensuring interoperability in between all USB certified devices. The following sections give a system level overview of losses in a USB device and how they affect these compliance standards.

10 Loss Types

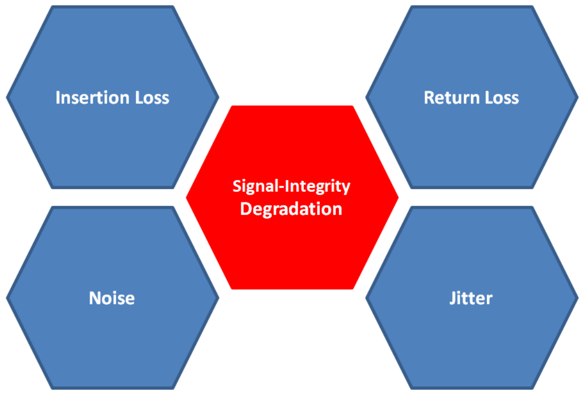

Figure 3. Four Main Causes of Signal Degradation

10.1 Insertion Loss

At a system level is the loss of signal amplitude resulting from components, traces or cables in between the USB transmitter and receiver. The loss increases with the number of added components and the length of the trace or cable.

10.2 Return Loss

Occurs when a signal encounters a change in impedance as it propagates from source to receiver. A portion of the signal power is reflected back to the transmitter while the rest continues in the original direction. Many elements may cause an impedance change including: connectors, components, PCB vias, or a change in trace width.

10.3 Noise

Imparted onto the signal by many outside sources such as electromagnetic interference (EMI) and crosstalk. One benefit of the differential nature of a USB signal is that both of the signal paths incur this noise. When it reaches the receiver it is negated by the difference of the two signals. A signal must maintain a minimum signal-to-noise ratio (SNR) in order to be decoded properly by the receiver.

10.4 Jitter

Any change from the true periodicity of a digital signal. This change can be in terms of phase timing or the width of the signal pulse. Two primary causes of jitter are EMI and crosstalk with other signals. If there is a large amount of jitter present in a signal, it causes a decrease in the width of the Eye Diagram. This could cause the system to fail USB compliance.

11 System Loss

Each component in the system contributes to the loss, or gain in a redrivers case, of the signal. As seen in Figure 4, USB Compliance is divided into three systems: the host, cable, and device. Each of these systems is designated a loss budget to meet USB compliance. These budgets vary depending on the USB revision, signal speed, and connector type.

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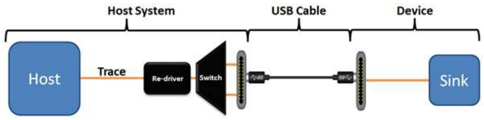

Figure 4. Outline of the 3 Sections of a USB System

Figure 5 and Figure 6 illustrate the system loss budgets for the USB 3.1 specification. The Gen 1 loss budgets allow for a maximum of 20dB loss, but have different budgets for each type of USB connector. In Gen 2 the loss budget was expanded to a maximum of 23dB loss. It also made the budget for the host and device symmetrical. This simplifies the design and use of Dual Role Ports (DRP) systems like tablets and smartphones.

Figure 5. USB 3.1 Gen 1 5GBit/s Insertion Loss Budget

Figure 6. USB 3.1 Gen 2 10GBit/s Insertion Loss Budgets

For more in-depth information on USB 3.1 loss budgets, read the following paper: USB 3.1 Channel Loss Budgets

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12 PCB Trace Loss

PCB traces are the largest contributor to insertion loss in most host and device systems. The loss in a trace is affected by the length and width of a trace. The longer or thinner a trace is the more loss that is incurred as a signal travels along it. In host systems such as a desktop or laptop computer, the USB ports are often a large distance from the host chipset. This is a case where the signal may not meet USB compliance and would need a redriver. Figure 7 illustrates the loss in a PCB trace corresponding the length, and width of the trace as well as the signal frequency.

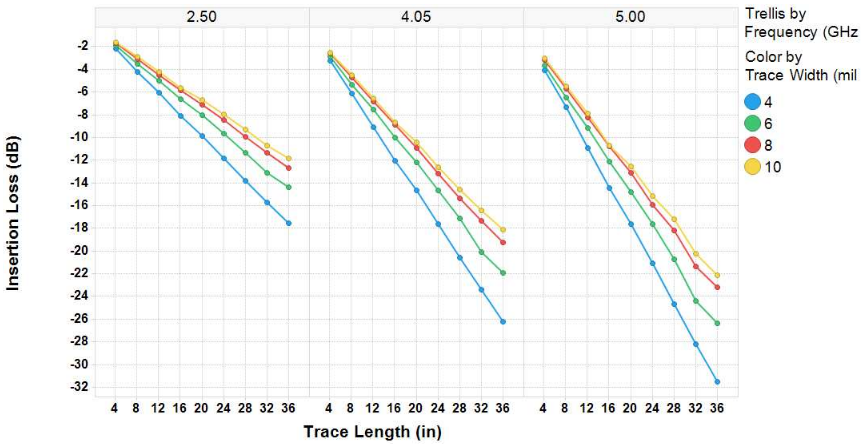

Figure 7. PCB Trace Insertion Loss vs. Signal Frequency

13 Eye Diagrams

There are many factors that go into USB certification, but a good tool to get an overview of compliance is an Eye Diagram. The Eye Diagram is an overlap of the Data+ (D+) and Data- (D-) signals that allow you to visualize the rise time, fall time, signal amplitude, and jitter in the system. As seen below, there is a USB compliance mask that can be overlaid onto the signal. This allows the signal to be checked to see if it meets the requirements for eye height, eye width, and signal amplitude. Figure 8 and Figure 9 illustrate an ideal Eye Diagram and a USB 2.0 Eye Diagram with a compliance mask.

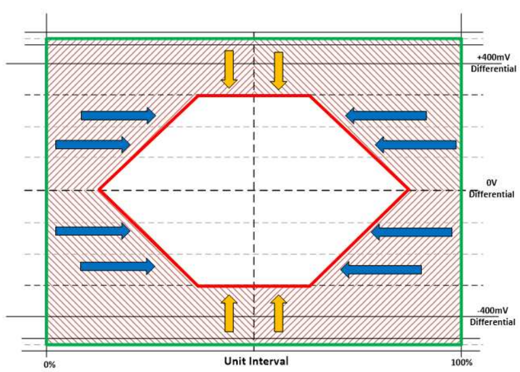

Figure 8. Ideal Eye Diagram with Example Parameters

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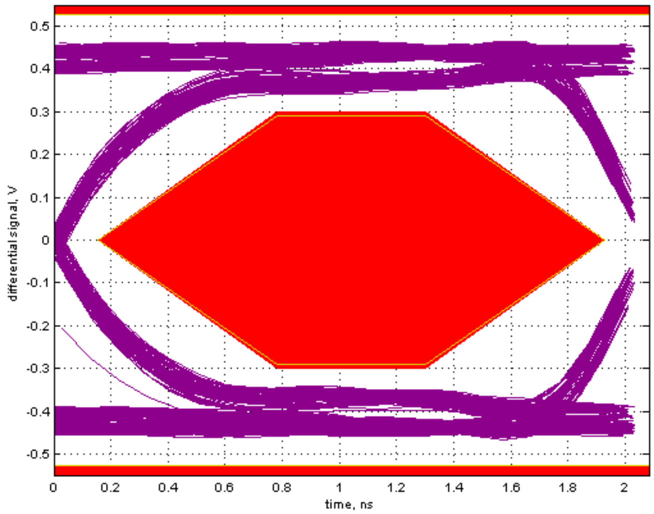

Figure 9. USB 2.0 Eye Diagram through TS3USBCA4 with Compliance Mask in Red

14 When Redrivers are Needed

This section focuses on the cases where the total loss in a USB host exceeds the loss budget assigned. A USB-C SS+ system is used as an example because it incorporates a high-speed signal at 10 Gbit/s, a passive switch.

The system illustrated in Figure 10 includes a USB 3.0 host controller, 4 inch of 6 mil trace, and a dual-channel differential MUX connected to a USB-C receptacle.

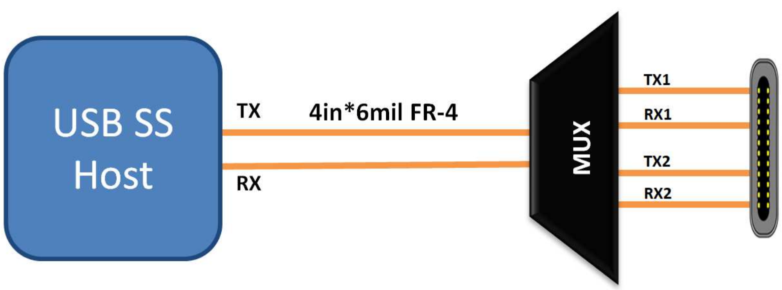

Figure 10. Illustration of a Small System Such as a Smartphone

The system in Figure 10 is representative of a smaller device, such as a smartphone. The total loss of the system can be estimated by finding the loss of each part of the system and summing them. Referencing Figure 6, 4 inch of 6 mil FR-4 trace adds approximately -4 dB of loss. The TI datasheet HD3SS3212 is referenced to find the loss for a 2-Channel USB SS+ MUX; this device adds -1.6 dB in loss, leaving the overall system with -5.6 dB of loss. This type of system passes compliance for the USB 3.1 Gen2 loss budget shown above.

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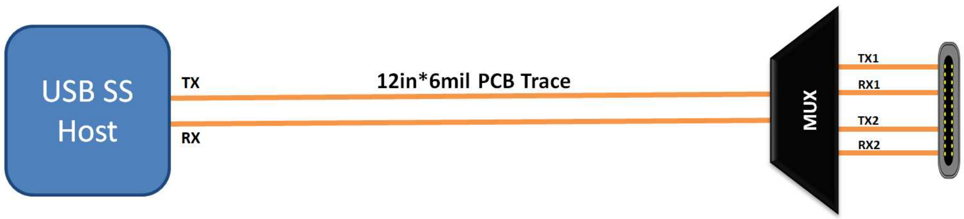

Figure 11. Illustration of a Larger USB System Such as a Laptop or Desktop PC

The system in Figure 11 is representative of a larger device such as a notebook or desktop PC. The 12 inch of 6 mil FR-4 trace adds approximately -8.5 dB of loss. With the loss for the MUX added, the system has total loss of -10.1 dB. Therefore, it fails to meet the loss budget standard of -8.5 dB. This type of system needs some type of signal conditioning to meet specification. More information on signal conditioning and redrivers can be found in the paper Strengthening the USB Type-C™ signal chain through redrivers, as well as the blog post Create an eye-opening experience with a 10G USB3 redriver.

15 Summary

At the high-data rates present in the USB-C ecosystem understanding the characteristics of components and the affects they have on the USB compliance of a system is more important than ever. Switches allow for lower cost, smaller footprints and less design time for smaller systems. As the size of the target system increases signal integrity and issues arise. Redrivers allow designers to overcome these challenges as well. TI recognizes these issues and has developed a versatile portfolio of solutions to solve any issues in the signal routing and conditioning space.

16 References

USB 3.1 Channel Loss Budgets

https://www.usb.org/sites/default/files/USB_3.1_Loss_Budget_Rev_1.0_-_2015-03-02.pdf

HD3SS3212 Product Page

http://www.ti.com/product/HD3SS3212

Alternate Mode for USB Type-C™: Going Beyond USB

Why use a USB Type-C™ redriver in your personal electronics designs?

https://e2e.ti.com/blogs_/b/analogwire/archive/2016/10/25/the-need-for-usb-type-c-redrivers

Don’t Leave Home Without It: Redrivers for USB Type-C Designs

https://www.electronicdesign.com/power/don-t-leave-home-without-it-redrivers-usb-type-c-designs

Strengthening the USB Type-C™ signal chain through redrivers

Analog Switch Guide

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