ENGINEER'S GUIDE TO USB:
PCB DESIGN AND SIMULATION

EMA Design Automation®

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PCB DESIGN AND SIMULATION

The universal serial bus (USB) is by far the most common interface used to connect peripheral devices, including portable storage units, to computers. Its widespread adoption as a replacement for various manufacturer-specific dedicated connectors has revolutionized wired data and power transfer. Achieving USB compliance during the design phase is critical for PCBs and other electronics that leverage the flexibility, integration, and data rate advantages offered by the USB protocol.

This eBook discusses the importance of USB standards and how to ensure your design is compliant. This includes methods that simplify USB compliance testing and significantly improve the efficiency of your PCBA development process.

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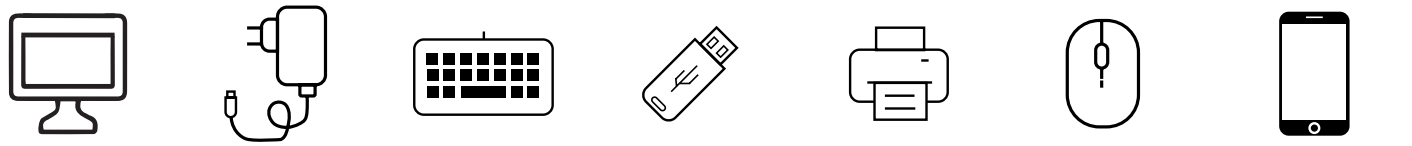
OVERVIEW OF USB

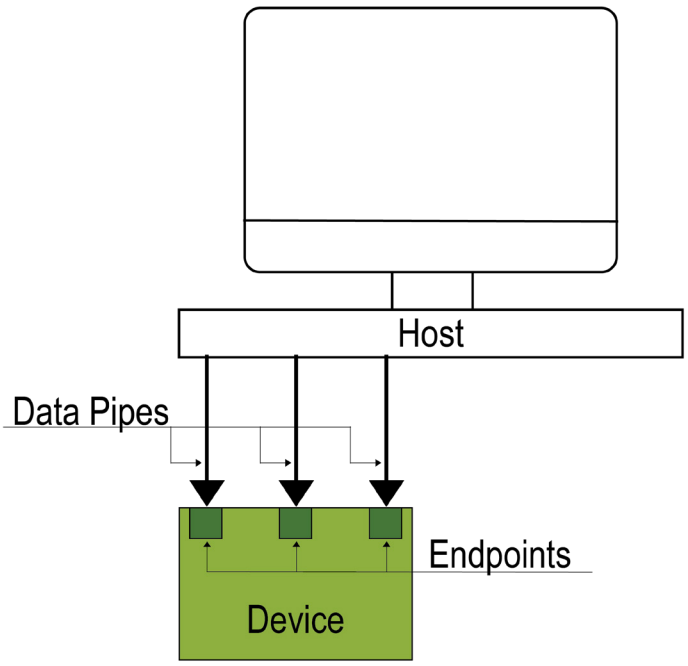
ONE INTERFACE FOR BILLIONS OF DEVICES

In 1995, seven major computing companies collaborated to promote simpler interconnectivity; a "plug and play" hardware configuration between computers and peripherals, where no device setup intervention is required to begin using the device. The results were specifications for USB connectivity and the founding of the Universal Serial Bus Implementers Forum (USB-IF) standards organization. A universal serial bus or USB is a standard interface used for data and power transfer between electronics and is utilized in various products including:



MONITORS CHARGERS KEYBOARDS FLASH DRIVES PRINTERS MICE SMARTPHONES

A USB system consists of a host, logical connections or pipes, and peripheral devices. Transfers along pipes may be either messaging or streaming.



MESSAGING	
BI-DIRECTIONAL CONTROL TRANSFERS	INTERRUPT TRANSFERS
USB Configuration	Status Updates, Mice, and Keyboards

STREAMING	
BULK UNREGULATED TRANSFERS	ISOCHRONOUS TRANSFERS
Sending Data to a Printer	Sending Audio and Video at a Fixed Rate

Regardless of the type of data transfer, reliability for USB devices must be assured through adherence to USB compliance standards. This becomes increasingly difficult as transfer rates for USB devices increase in speed.

OVERVIEW OF USB

MEETING THE NEED FOR SPEED

The journey to the over $35 billion market size of the USB device industry has been evolutionary and so has the technological advancements seen with each generation of the USB.

UNIVERSAL SERIAL BUS DATA RATE EVOLUTIONS			
NAME	**VERSION(S)**	**MAX DATA TRANSFER RATES**	**YEAR INTRODUCED**
USB 1	USB 1.0	12 Mbps	1996
	USB 1.1		1998
USB 2	USB 2.0 USB 2.0 Revised	480 Mbps (High-Speed)	2000 2007
USB 3	USB 3.1 Gen 1 USB 3.1 Gen 2	5 Gbps (SuperSpeed) 10 Gbps (SuperSpeed Plus)	2008
	USB 3.2 Gen 1 USB 3.2 Gen 2	5 Gbps (SuperSpeed) 10 Gbps (SuperSpeed Plus)	2013
	USB 3.2 Gen 2x2	20 Gbps	2017
USB 4	USB 4 1.0	40 Gbps	2019
	USB 4 2.0	80 Gpbs	2022

The most significant evolution in the USB has been the continual increase in maximum data transfer rates, which have been instrumental in the USB becoming one of the most implemented electrical connectors. Possibly equally important is the consistent yet flexible system operational model and standard that provide well-defined methods of achieving USB certification.

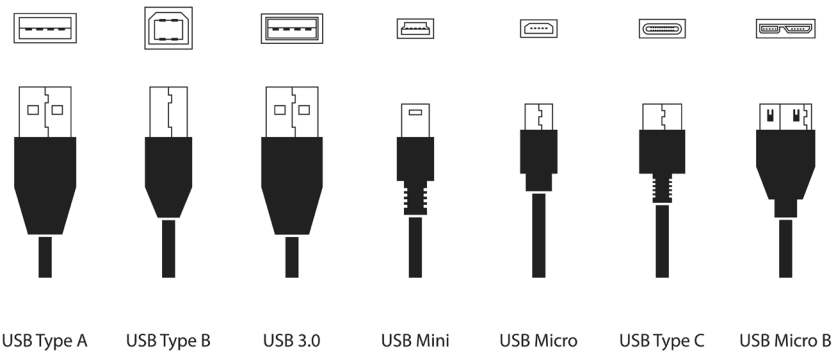
USB CERTIFICATION
REQUIREMENTS

There are several paths to obtain a USB-IF certification for your PCB design, including:

- Transfer of certification ownership from a supplier.
- Obtain "qualification by similarity" certification without testing.
- Have your product tested at a USB-IF-authorized independent testing laboratory (ITL).
- Have your product tested at a USB-IF-sponsored compliance workshop.
- Attend the USB-IF Platform Interoperability Lab (PIL) compliance testing.

Having a product USB certified by one of the methods above allows developers and distributors to label their product as USB-IF certified, which is the prevailing quality standard for USB devices. USB certification assures OEMs, ODMs, and others that your product satisfies functionality and interoperability requirements with other devices.

Devices are distinguished according to the class codes. These codes are important, as they define what drivers are required to interface with the device for proper operation and USB system functionality. Devices must securely transmit and receive data and power across the applicable channel, which may be via a PCB trace or a cable with one of the following connector types.



For most devices and connectors, certification requires experimental verification or USB compliance testing. USB compliance testing can be time-consuming and costly, as it is performed by a designated lab at a cost per item. Unnecessary or duplicate testing can easily push a project over budget and off schedule, making it crucial to simulate and analyze compliance before experimental testing.

USB DEFINED CLASS CODES

00h: General
01h: Audio
02h: Communication and CDC Control
03h: Human Interface Device (HDI)
05h: Physical
06h: Interface
07h: Printer
08h: Mass Storage
09h: Hub
0Ah: CDC-Data
0Bh: Smart Card
0Dh: Content Security
0Eh: Video
0Fh: Personal Healthcare
10h: Audio/Video
11h: Billboard Device Class
12h: USB Type-C Bridge Class
3Ch: I3C Device Class
DCh: Diagnostic Device
E0h: Wireless Controller
Efh: Miscellaneous
Feh: Application Specific
FFh: Vendor Specific

Source: USB Defined Class Codes

USB CERTIFICATION
REQUIREMENTS

New product introduction (NPI) is a significant investment that can be become bloated with unnecessary and wasteful expenditures when redesigns and respins are needed during PCBA development. By simulating and verifying USB compliance during the PCBA design process, you minimize development time, eliminate unnecessary costs, and maximize ROI. USB devices both transmit and receive data; therefore, for comprehensive compliance analysis, both the quality of signal transmitting and receiving should be evaluated. Regardless of the function of the USB (Host or Device), the following compliance items should be verified:

- Receiver Jitter Tolerance
- Transmitter Eye Height
- Transmitter Jitter

While the required compliance tests are the same for USB 3 SuperSpeed and SuperSpeed Plus, the acceptable values differ due to the technological differences:

USB 3 SUPERSPEED

SuperSpeed refers to USB 3.1 Gen 1 and USB 3.2 Gen 1 devices. These devices have a **maximum transfer rate** of:

5 Gbps

USB 3 SUPERSPEED PLUS

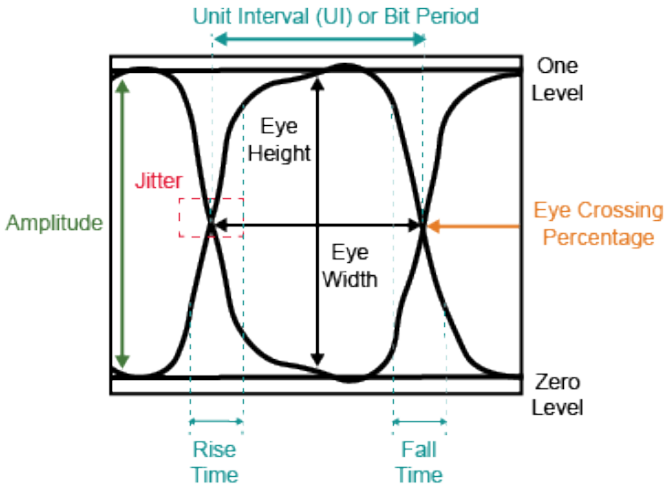
SuperSpeed Plus refers to USB 3.1 Gen 2 and USB 3.2 Gen 2 devices. These devices have a **transfer rate** of:

10 Gbps & 20 Gbps

Due to the high-speed transfer rates resulting in decreased margins for USB 3 SuperSpeed Plus functionality, noise has a greater impact on signal transmission. For realistic analysis and successful compliance testing, crosstalk should be incorporated into compliance simulations.

EYE DIAGRAMS

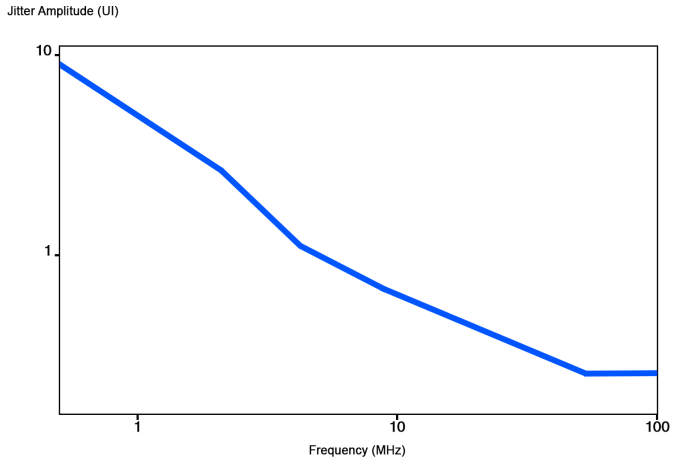
Adherence to USB 3 compliance standards can be analyzed through the simulation and evaluation of eye diagrams. Eye dimensions are critically important measurements for signal quality as they define how identifiable and distinguishable (or not) individual bits in a data sequence are. Characteristics of the eye diagram for the receiver and transmitter must be analyzed to identify problems, such as insufficient eye diagram height and too much jitter, which will cause your board to fail USB certification verification.



USB COMPLIANCE TESTING

RECEIVER JITTER

For compliance testing of the USB receiver, the eye diagram must be analyzed at the Bit Error Rate (BER) of interest. Bit Error Rate (BER) is the number of bits received in error at the receiver compared to the total number of bits received. For USB 3, the BER of interest is 10^{-12}.



RX JITTER TOLERANCE

RX Jitter Tolerance, or stressed eye testing, is the evaluation of the frequency versus the amplitude of periodic jitter. The worst-case (stressed) eye diagram should be analyzed to determine the maximum jitter amplitude allowed in order to produce a discernable eye at the desired BER for every frequency point.

WHY IS IT IMPORTANT?

Jitter Tolerance allows you to analyze how much jitter margin you can have while still maintaining a discernible data stream. This lets you assess the level of resilience of your USB design against flawed transmissions.

HOW DO YOU MEASURE IT?

Jitter tolerance can be measured with a Stressed/Swept Jitter Test in which sinusoidal jitter with increasing frequency should be incorporated into the stressed eye analysis. For every frequency point, increase the amplitude of periodic jitter and identify the value when the eye is no longer discernable at the BER of interest. Compile a plot of the last jitter amplitude values that produced a discernable eye.

WHAT IS AN ACCEPTABLE VALUE?

The jitter amplitude must be higher than the specified sinusoidal jitter values dictated by USB compliance standards:

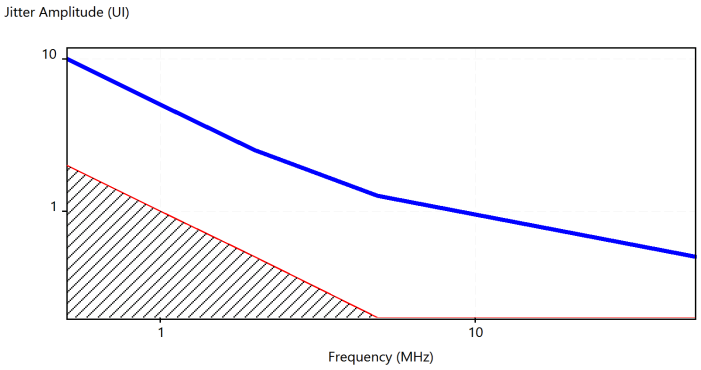
SUPERSPEED

FREQUENCY	JITTER TOLERANCE
500 kHz	2 UI
1 MHz	1 UI
2 MHz	0.5 UI
4.9 MHz	02. UI
50 MHz	0.2 UI

SUPERSPEED PLUS

FREQUENCY	JITTER TOLERANCE
500 kHz	2 UI
1 MHz	1 UI
2 MHz	0.5 UI
4.9 MHz	02. UI
50 MHz	0.2 UI

Plotting the specified sinusoidal jitter values will create a jitter mask in which the measured results can be visually compared to ensure compliance.



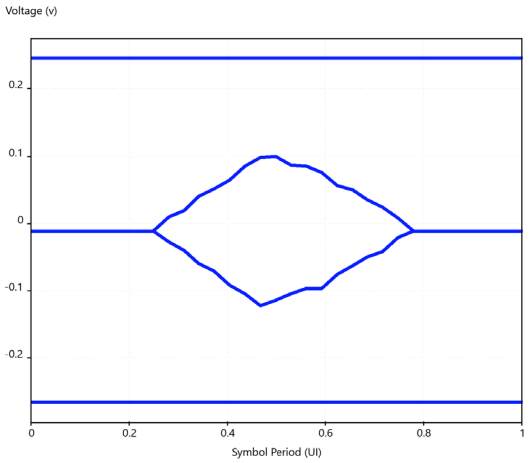
RX Jitter Tolerance failure indicates the USB design is too susceptible to jitter. Algorithmic Modeling Interface (AMI) Models should be incorporated into the simulation to accurately analyze the USB design, determine the ideal configuration, and increase tolerance. AMI models incorporate internal component and connectivity information to perform statistical simulation based on the channel pulse response or time-domain simulation.

USB COMPLIANCE TESTING

TRANSMITTER EYE HEIGHT AND JITTER

Analyzing the eye diagram for the transmission of the USB device allows you to evaluate the signal transfer quality between USB hosts and devices.

TX EYE HEIGHT



Eye height measures the vertical opening of the eye and evaluates how much amplitude separation there is between 0s and 1s during USB device or host transmission.

WHY IS IT IMPORTANT?

Eye height is critical for good signal quality. If the eye height is too short, data identification is unreliable and may lead to data loss, erroneous system behavior, or even shut down.

HOW DO YOU MEASURE IT?

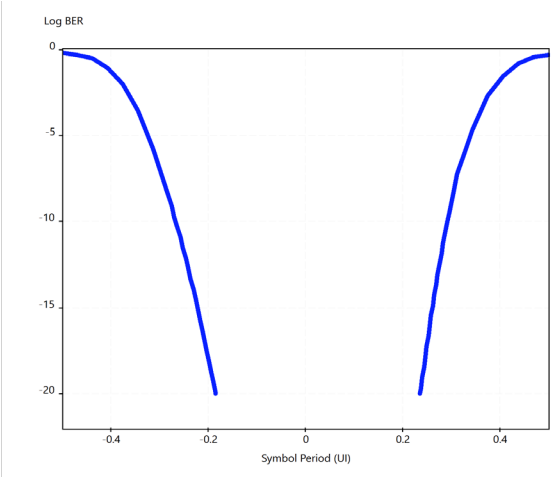
Eye Height can be determined by generating the BER Eye with a voltage scale. Measure the maximum distance between the innermost '1' bit representation and the inner most '0' bit representation. This should be taken in the +/-10% vicinity of the center of the bit interval or unit interval.

WHAT IS AN ACCEPTABLE VALUE?

SuperSpeed: Between 0.1 V and 1.2V
SuperSpeed Plus: Between 0.07V and 1.2V

Insufficient Eye Height or a closed eye is typically a result of noise during the USB signal transmission.

TX TOTAL JITTER



Total Jitter analyzes whether the rise and fall time transitions are in sync with the transmission clock. Variations in transition time for the eye width is referred to as jitter.

WHY IS IT IMPORTANT?

Excessive jitter indicates a lack of system synchronization that can result in misinterpretation of control codes, incorrect function, and/or system malfunction.

HOW DO YOU MEASURE IT?

Simply put, total jitter is the sum of the deterministic jitter and random jitter. Jitter can be efficiently analyzed by graphing the BER over time, resulting in a bathtub curve. The bathtub curve can be used to analyze the deterministic jitter (where BER remains steady over time) and the random jitter (where BER varies over time).

WHAT IS AN ACCEPTABLE VALUE?

SuperSpeed: Less than 0.66UI
SuperSpeed Plus: Less than 0.714UI

High jitter values can be caused by various sources of noise in the design including simultaneous switching noise (SSN) or reflections.

ENSURING USB SUCCESS

Ensuring USB compliance can be a time-consuming and challenging process. Failure to pass verification testing can significantly escalate development costs and time, not only affecting your NPI or delivery schedule but also impacting your ROI and profitability. To pass compliance testing the first-time, it's crucial to incorporate and analyze USB compliance throughout the PCB design process.

Sigrity provides kits specifically developed to help achieve USB 3 Gen 1 and Gen 2 compliance by:

- Performing all essential tests for USB compliance
- Automatically analyzing simulation results against USB-IF specified values
- Providing easy to read pass/fail results
- Automatically generating reports
- Providing seamless integration with other software design and analysis tools

To learn more go to:

ABOUT EMA DESIGN AUTOMATION

EMA Design Automation is a leading provider of the resources that engineers rely on to accelerate innovation. We provide solutions that include PCB design and analysis packages, custom integration software, and engineering expertise, which enable you to create more efficiently.

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