Keysight Technologies
Debugging USB 2.0 for Compliance: It's Not Just a Digital World

Application Note

Who Should Read This Application Note?

Digital designers developing computer systems and peripherals with USB applications/technology.

KEYSIGHT
TECHNOLOGIES

Introduction

It has long been recognized that personal computers (PCs) need to be simpler and easier to use without sacrificing connectivity or expandability. The Universal Serial Bus (USB) was originally developed in 1995 as a low-cost external-expansion bus that makes adding peripherals to a PC as easy as hooking up a telephone to a wall jack. The goal was to create a "Plug and Play" environment. As long as all of the devices adhered to the class definitions then they could be supported by the operating system. The highlights of USB's external-expansion architecture are:

– PC host controller hardware and software
– robust connectors and cable assemblies
– peripheral-friendly master-slave protocols
– multi-port hubs for expandability

Traditionally, peripherals, hubs, and hosts may operate at full speed (12 Mb/s) or low speed (1.5 Mb/s). These speeds are adequate for human-interface devices such as mice or keyboards, but very limiting for next-generation devices such as high-resolution printers and scanners, video-conferencing cameras, and high-density storage devices such as read/write (R/W) DVD drives. High-speed USB is being developed to increase data throughput by a factor of 40 over full speed USB, to a target of 480 Mb/s. The USB 2.0 is a new version incorporating low, full, and high speeds. The USB 2.0 standard is a backward compatible extension of USB 1.1 using the same cables, connectors, and software interfaces, so consumers will see no changes to the usage model.
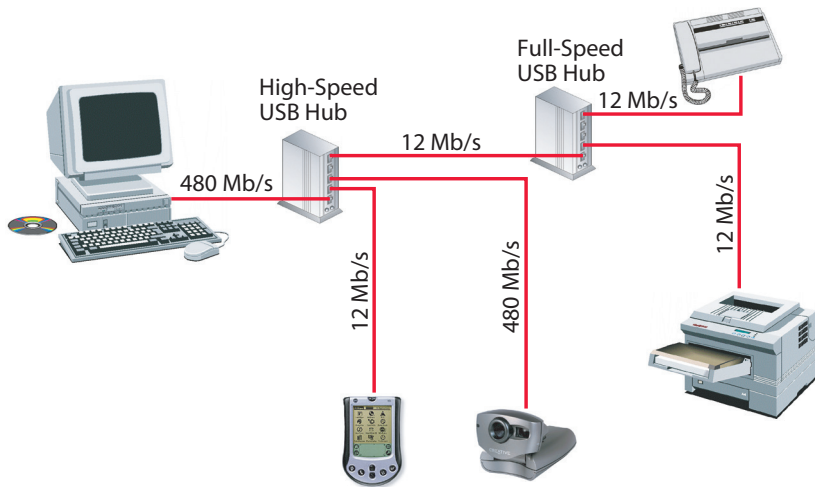
USB Evolution

Figure 1. USB systems can manage all three data rates concurrently.

A description of the major elements of a USB system (host, hubs, and peripherals) is required to understand the evolution to version 2.0. The USB software in the host PC provides a uniform view of the input/output (I/O) system for the applications software, and manages the dynamic attach and detach of peripherals (called enumeration). During run time the host PC initiates transactions to specific peripherals; each peripheral accepts its transactions and responds accordingly. The host PC software also incorporates the peripheral into the system power management scheme.

A hub provides additional connectivity for USB peripherals, provides managed power to attached peripherals, and recognizes dynamic attachment of a peripheral. Hubs can be cascaded up to five levels deep. During run time, a hub operates as a bidirectional repeater and repeats USB signals as required on upstream (towards the host) or downstream (towards the peripherals) cables.

All USB peripherals are slaves that obey a defined protocol; they must react to request transactions sent by the host PC. The peripheral sends and receives data to/from the host using a standard USB data format. This standardized data movement to/from the host PC and interpretation by the peripheral gives USB its enormous flexibility with little host PC software changes.

USB 2.0 is an evolution of the former USB 1.1 specification, with a higher-performance interface. All three speeds can operate together in a hi-speed USB system, as shown in Figure 1. Today's low/full speed connectors and cables will support the higher speeds of 480 Mb/s without any changes. In this figure, hi-speed connections are negotiated between the root hub (in the host PC) and the external hi-speed (HS) hub, and between the external HS hub and the video conferencing camera (a HS USB peripheral). All other connections are at full speed USB data rates. The external HS hub is capable of supporting all three data speeds on its downstream ports. Any downstream port of a HS USB hub can support the dynamic attachment of any speed USB device.

Hi-speed USB data rates permit bandwidth-hungry peripherals to use a USB system, while also creating debugging problems. If only square waves weren't made up of lots of pesky sine waves, then the world would be truly digital, and life would be simple. Back in the good old days of low speed USB, signaling rates were merely 1.5 Mb/s. Now, with the analog effects of the hi-speed data rates (480 Mb/s), radio frequency (RF) and even microwave design techniques must be used. Signal integrity becomes a critical part of every design. However, the digital world, or "data domain," also creates issues that af-

fect the designer: interaction of devices, multi-speed traffic, and large amounts of data. Because the analog and digital behaviors are interrelated, designers of hi-speed USB devices need to take a holistic approach to debugging, validating, and characterizing their designs.

The first step in the testing process is the initial turn-on of the hardware—looking with an oscilloscope at fundamental analog signals being transmitted and received. Key analog measurements need to be reviewed and are ultimately required for compliance testing. The USB 2.0 measurement suite includes signal integrity, in-rush current, drop, droop, and many more.
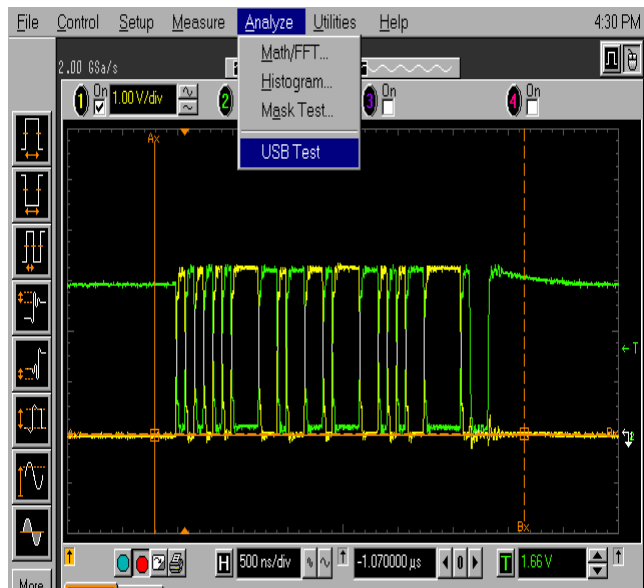
Signal Integrity is Critical

Figure 2. D+ and D- data signals are automatically bracketed by the Keysight Infiniium 54800 Series USB test option.

Figure 3. Including MATLAB within the Keysight Infiniium 54800 Series oscilloscopes simplifies USB measurements.

The first hardware test is to look at the D+ and D- lines with an oscilloscope, as shown in Figure 2, to verify that they meet the USB Implementers' Forum (USB-IF) electrical test specification. These test requirements can be met using an oscilloscope and then running The MathWorks MATLAB® analysis software with the USB-IF test scripts. The goal of this measurement series is to test signal quality (including such parameters as EOP (end-of-packet) width, measured signaling rate, crossover voltage range, and jitter), as well as the data signal eye to verify that the data fits the specified eyediagram parameters.

Keysight Technologies, Inc. Infiniium Series oscilloscopes, along with Keysight probes and test fixtures, or "breakout boards," are crucial for replicating the USB-IF compliance tests. The Infiniium USB test option makes USB signal integrity compliance testing as simple as making an automatic measurement. Infiniium has significantly reduced the work associated with USB testing by eliminating the need to manually transfer oscillo-scope data to another PC for analysis. The Infiniium USB test option features a run-time version of MATLAB embedded in the scope for use with the USB-IF test scripts—a one-box solution that speeds signal quality testing. Figure 3 shows an eye-diagram measure-ment generated by the Keysight Infiniium Series oscilloscope, using the internal run-time MATLAB software.

Failures at this stage can be caused by a variety of conditions. Failure to meet the upper and/or lower voltage levels is typically caused by improper termination. Reduction or collapse of the data eye is often caused by jitter. A common source of jitter is noise from the clock or from the power supply, but there are many other sources that also must be considered.
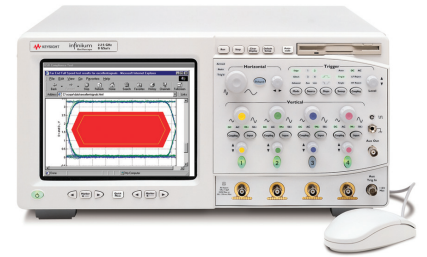
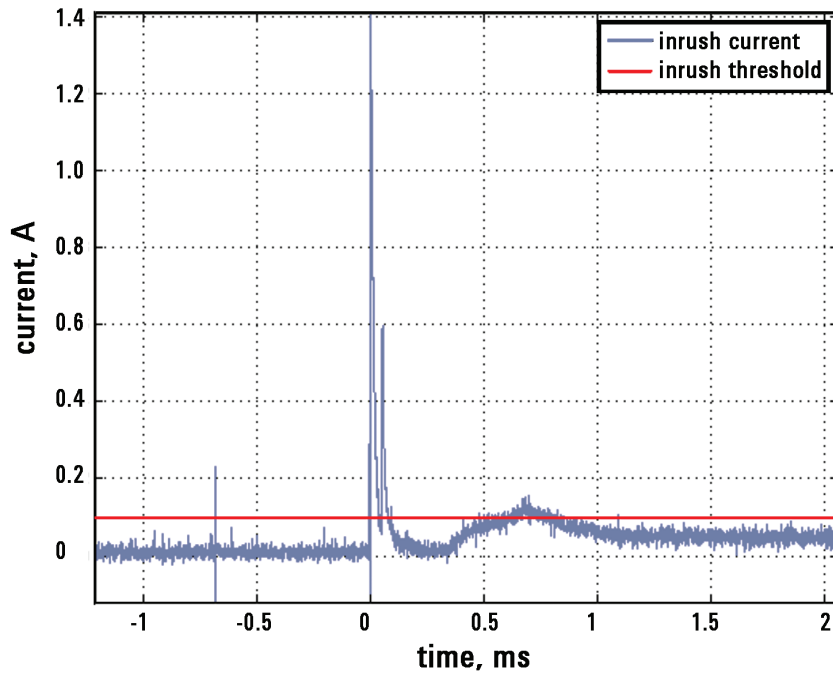# Attention To Detail Prevents Current Violations

Figure 4. Peak and average current values as measured by an oscilloscope.

Another analog concern that requires detailed attention is current measurement. Whether a device is self-powered or buspowered, there are numerous combinations of current conditions. USB 2.0 designers need to measure current draws from hotplug conditions, low-power states, suspend states, and other conditions. The operating current draw and suspend current draw are DC current values that can be measured with a simple DC ammeter. The transient current measurements, such as hot-plug in-rush current and peak operating current, require an oscilloscope and a current probe. The dynamic nature of many of the current specifications makes this the only possible way to acquire these measurements. A Keysight Infiniium Series oscilloscope with an current probe is capable of capturing these transient current events. The triggering capabilities of a scope may also be necessary to measure the bus at a specific instant in time. Figure 4 shows peak and average current measurements on an oscilloscope. The most common types of current specification failures occur when the maximum current draw is exceeded, which typically happens during a hot-plug condition.

Verification of Data Integrity

ADDR	FUTUREPLUS SYSTEMS	PID	DATA	ENDPNT	PID	ADR	MCLK
Hex	USB BUS TRANSACTIONS	Symbols	Hex	Hex	Hex	Hex	Binary
021	IN ADDR=02 END_POINT=1	IN	FD2F	1	02	02	0
021	NO ACKNOWLEDGE	NCK	FD2F	1	1A	02	0
021	IN ADDR=02 END_POINT=1	IN	FD2F	1	02	02	0
021	DATA0= 0000	DATA0	0000	1	05	02	0
021	DATA0= 0052	DATA0	0052	1	05	02	0
021	DATA0= 0000	DATA0	0000	1	05	02	0
021	DATA0= 0000	DATA0	0000	1	05	02	0
021	DATA0 CRC=4D62	DATA0 CRC	4D62	1	07	02	0
021	ACKNOWLEDGE	ACK	4D62	1	19	02	0
021	IN ADDR=02 END_POINT=1	IN	4D62	1	02	02	0
021	NO ACKNOWLEDGE	NCK	4D62	1	1A	02	0
021	IN ADDR=02 END_POINT=1	IN	4D62	1	02	02	0
021	NO ACKNOWLEDGE	NCK	4D62	1	1A	02	0
021	IN ADDR=02 END_POINT=1	IN	4D62	1	02	02	0
021	NO ACKNOWLEDGE	NCK	4D62	1	1A	02	0

Figure 5. Logic analyzer protocol listing shows a trigger on a CRC error.

Once it has met USB 2.0 voltage, signal integrity, and current requirements, the DUT is likely to be a good bus citizen at the physical level. However, the challenge is just starting; the device must now be tested for compliance with the Universal Serial Bus Implementers' Forum (USB-IF) interoperability specification. Any peripheral device on the bus must be able to communicate with its hub. The hubs must be able to communicate with the host, each other, and up to seven peripherals, while handling all three data transfer rates plus isochronous and bulk data transfers.

A USB system is a form of network with a wide variety of interdependencies, so determining the cause of a data error or a performance problem can be very difficult. A logic analyzer lets you see data traffic, make critical timing measurements, and verify protocols, making it the best tool for detecting and debugging higher-level problems such as enumeration failure or corrupted data packets. Deep acquisition memory and powerful real-time triggering provide a quick and reliable method of capturing elusive problems.

In Figure 5, the logic analyzer protocol (or transaction) listing shows that the logic analyzer triggered on a cycle redundancy check (CRC) error. Because of the logic analyzer's deep acquisition memory, the designer can see the events that led up to the failure (pre-trigger events) and how the device responded to this error condition (post-trigger events). The ability to turn off input and/or output negative acknowledge characters (NAKs) allows more efficient use of memory and saves the user from having to wade through information that may not be useful.

Being able to measure time relationships between events, like a request and an acknowledge, is an important tool for debugging a wide variety of problems. This measurement methodology is commonly referred to as event timing. Logic analyzers and other types of protocol tools do have the ability to provide event timing through the use of time stamp. A time stamp is simply a counter that keeps track of the time between each state event. This key feature has always been a part of logic analyzers and provides event timing with accuracy to 4 ns.

If accuracy greater than 4 ns is needed or if true asynchronous timing is required, then a scope should be connected to the D+ and D- lines or to the output of the transceiver interface chip.

Integration of Tools Equals Simplification

A wide variety of tools are needed to make accurate analog scope measurements, current measurements, and to capture and analyze data. The complexities of oscilloscopes, MATLAB software, logic analyzers, and breakout boards turn debugging, performance characterization, and specification compliance testing into daunting tasks. Fortunately, there are tools available to USB 2.0 designers that simplify the process by taking advantage of the integration of PCs and test equipment. For example, MATLAB software is integrated into the Keysight Infiniium Series oscilloscopes, eliminating the need to make a measurement and then transfer the data to a PC to do the analysis. Now all of these steps can be performed as a single measurement step. The same is true for current measurements using the oscilloscope. Today's logic analyzers and oscilloscopes are integrated so that cross-triggering and even sharing of data on a single display simplify the debug process.

Another key test and debug technique now available is cross-bus analysis. To determine the root cause of a problem, it may be necessary to simultaneously and separately measure the input and output of a hub or hubs, to study a hub and the PCI bus on a USB/PCI adapter card, or to observe the interaction between the USB, PCI, and PC memory system. Logic analyzers are capable of looking at multiple buses simultaneously, having one bus trigger other buses, and having all of the time-correlated data presented on a single display.

USB 2.0 is a fast, reliable bus architecture that improves the usefulness and capabilities of the PC world. However, it is not a slow, simple digital bus: It is complex and sophisticated, and requires designers to exercise their skill and talent. By following the guidelines and advice set forth by the USB-IF and using tools designed for the hi-speed analog/digital world, you can develop reliable USB 2.0 products and quickly bring them to the marketplace.

Analysis Probe for USB 1.1 and 2.0

The FS 4120 USB analysis probe from FuturePlus Systems Corporation (Keysight part number FSI-60050), when combined with the Keysight 16700 Series logic analysis systems and Infiniium Series oscilloscopes, provides engineers with complete system debugging, verification, and compliance testing of USB 2.0 peripherals, hubs, and USB-based systems.

The FS 4120 probe provides an electrical and mechanical interface for passive bus analysis between a USB DUT and Keysight logic analyzers. It has test points for DC current, in-rush current, and suspend current measurements for bus-powered devices. SMA connectors and hardwareassisted oscilloscope triggering are provided for easy oscilloscope triggering and measurements. Key features of the new probe include:

- complete USB serial-to-parallel decoding, providing a protocollevel view of bus traffic
- dual-bus operation with time-correlated displays for hub debug
- support for current measurements on bus powered devices, including in-rush current
- external power supply connection for USB devices
- error detection, including bad PID, invalid PID, serial bit stuffed, CRC, Start of Frame, USB reset, and USB bus communication errors
- operation at all USB speeds: 480 Mb/s, 12 Mb/s, and 1.5 MB/s
- support for all types of data transfers, including isochronous transfers
- LEDs that provide quick visual identification of bus status and activity
- SMA connections for easy triggering and connection to a high-speed oscilloscope
- Input/Output - NAK suppression (FS/HS) capability

Analysis Probe for USB 1.1 and 2.0 Powerful triggering can be set up on any address, end point, data pattern, data CRC, or USB error. All USB cycles and transaction identifiers are decoded by protocol-sensitive clocking logic. Packet identifiers enable users to store all USB traffic, store only certain packet types, or store only packets to/from a user-specified function. The included software provides a complete color-coded transaction and packet level decode of all the USB traffic.

The FS 4120 has two independent USB and analyzer interfaces. This unique feature enables the designer to independently measure a hi-speed device and a full-speed device at the same time, without having to purchase a second analysis probe.
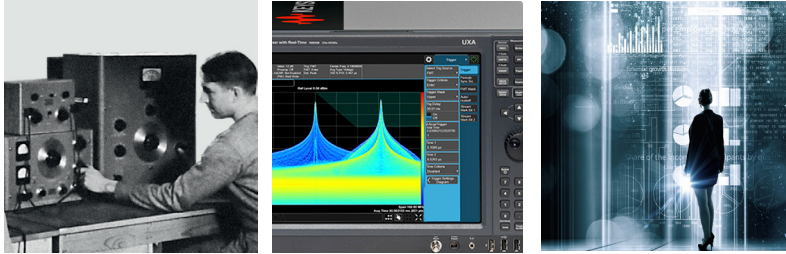
Related Literature

Publication Title	Publication Type	Publication Number
Infiniium USB Test Option N5416A	Data sheet	5989-4044EN

Evolving Since 1939

Our unique combination of hardware, software, services, and people can help you reach your next breakthrough. We are unlocking the future of technology. From Hewlett-Packard to Agilent to Keysight.

myKeysight

myKeysight
www.keysight.com/find/mykeysight
A personalized view into the information most relevant to you.

http://www.keysight.com/find/emt_product_registration
Register your products to get up-to-date product information and find warranty information.

Keysight Services
KEYSIGHT SERVICES
Accelerate Technology Adoption.
Lower costs.

www.keysight.com/find/service
Keysight Services can help from acquisition to renewal across your instrument's lifecycle. Our comprehensive service offerings—one-stop calibration, repair, asset management, technology refresh, consulting, training and more—helps you improve product quality and lower costs.

Keysight Assurance Plans
www.keysight.com/find/AssurancePlans
Up to ten years of protection and no budgetary surprises to ensure your instruments are operating to specification, so you can rely on accurate measurements.

Keysight Channel Partners
www.keysight.com/find/channelpartners
Get the best of both worlds: Keysight's measurement expertise and product breadth, combined with channel partner convenience.

This document was formally known as Application Note 1382-3

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at:
www.keysight.com/find/contactus

Americas
Canada	(877) 894 4414
Brazil	55 11 3351 7010
Mexico	001 800 254 2440
United States	(800) 829 4444

Asia Pacific
Australia	1 800 629 485
China	800 810 0189
Hong Kong	800 938 693
India	1 800 11 2626
Japan	0120 (421) 345
Korea	080 769 0800
Malaysia	1 800 888 848
Singapore	1 800 375 8100
Taiwan	0800 047 866
Other AP Countries	(65) 6375 8100

Europe & Middle East
Austria	0800 001122
Belgium	0800 58580
Finland	0800 523252
France	0805 980333
Germany	0800 6270999
Ireland	1800 832700
Israel	1 809 343051
Italy	800 599100
Luxembourg	+32 800 58580
Netherlands	0800 0233200
Russia	8800 5009286
Spain	800 000154
Sweden	0200 882255
Switzerland	0800 805353
	Opt. 1 (DE)
	Opt. 2 (FR)
	Opt. 3 (IT)
United Kingdom	0800 0260637

For other unlisted countries:
www.keysight.com/find/contactus
(BP-9-7-17)

DEKRA Certified
ISO9001 Quality Management System

www.keysight.com/go/quality
Keysight Technologies, Inc.
DEKRA Certified ISO 9001:2015
Quality Management System

KEYSIGHT TECHNOLOGIES