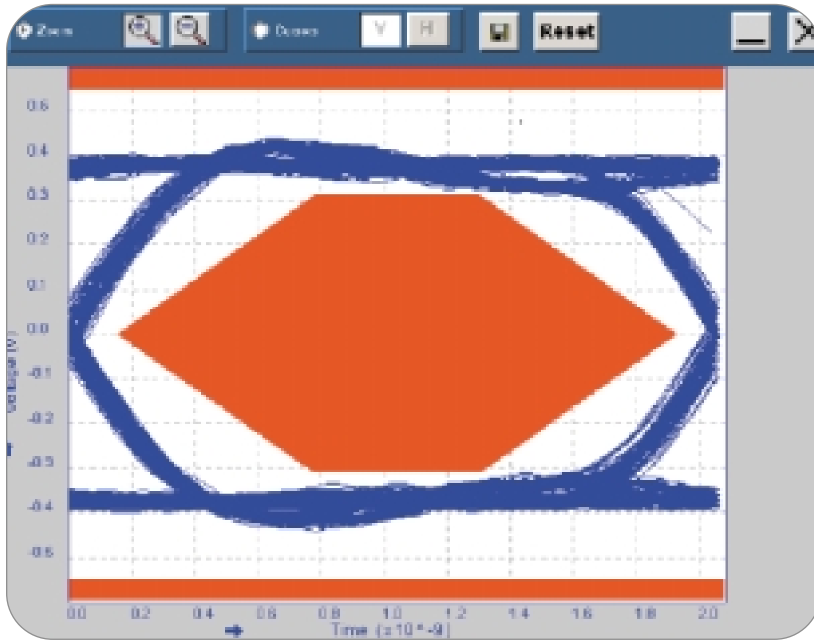
Understanding and Performing USB 2.0 Physical Layer Testing



Introduction

Engineers involved in the design, characterization and validation of USB 2.0 devices face daily pressures to speed new products to the marketplace. Tektronix' comprehensive tool set enables designers to quickly and accurately perform all compliance tests recommended by the USB-Implementers Forum, Inc. (USB-IF).

Universal Serial Bus (USB 2.0) is a connectivity specification aimed at peripherals that connect outside the computer in order to eliminate the hassle of opening the computer case to install cards needed for certain devices. USB-compliant devices translate into ease-of-use, expandability and speed for the user.

USB 2.0 technology has been widely adopted in today's marketplace and introduces a 40 times increase in data rate. This increase in throughput has now opened the door to a whole host of new peripherals ranging from full motion video to auxiliary, wallet-sized, hard disk drives. However, with this tremendous increase in data rate, new levels of test and measurement challenges arise.

The USB 2.0 specification introduces new compliance requirements. USB 2.0 device designers must properly characterize their designs and verify compliance to industry standards before device manufacturers can affix the "certified" USB-IF logo to their packaging. The appropriate tool set is critical for the performance of USB-IF compliance tests, such as eye diagram and parametric testing for low-speed, full-speed and high-speed devices and hubs.

This application note will focus on understanding and performing USB 2.0 physical layer measurements and electrical compliance testing (electrical and high-speed tests) and will include a discussion of the instruments required for each test.

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USB 2.0 Basics

USB 2.0 is a serial bus that utilizes a 4-wire system – V_{BUS}, D-, D+ and Ground. D- and D+ are the prime carriers of the information. V_{BUS} supplies power to devices that derive their primary power from the host or hub.

USB 2.0 describes the following speed selections and rise times:

	Data Rates	Rise Times
Low Speed (LS)	1.5 Mb/s	75 ns – 300 ns
Full Speed (FS)	12 Mb/s	4 ns – 20 ns
High-Speed (HS)	480 Mb/s	500 ps

USB 2.0 devices can be either self-powered (having their own power supply) or bus-powered (drawing power through the host). It is imperative for the self-powered devices to draw as little power as possible. Tests are outlined in the USB 2.0 specifications for this aspect.

USB 2.0 Electrical Tests

USB 2.0 electrical tests include signal quality, in-rush current check, and drop and droop tests.

Signal Quality Test

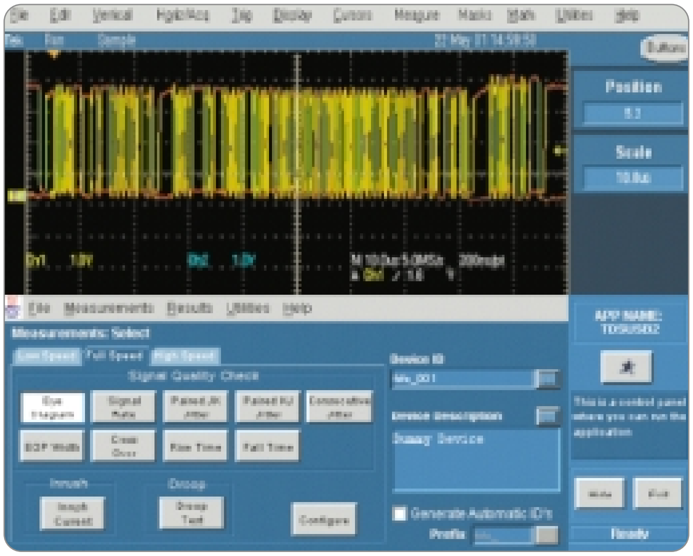
With the advantages of the 40 times increase in data rate comes a variety of design challenges to vendors of USB 2.0 compliant devices. Issues of signal quality, such as board layout, jitter, rise and fall times, EMI, noise, and ground bounce, now rise to the forefront of design concerns. Maintenance of signal quality is one of the keys to ensure that a USB 2.0 device is compliant and will be awarded the USB 2.0 certified logo.

The signal quality test includes:

- Eye Diagram testing
- Signal rate
- End of Packet (EOP) width
- Cross-over voltage range
- Paired JK Jitter
- Paired KJ Jitter
- Consecutive jitter
- Rise time
- Fall time

The eye diagram test is unique and the first of its kind for serial data applications.

The test set-ups for signal quality testing vary for upstream and down-stream testing. In the case of upstream testing, signals transmitted from the device to the host are captured, whereas in the case of downstream testing, signals transmitted from the host are captured for testing. Downstream testing is usually performed on ports of a hub.

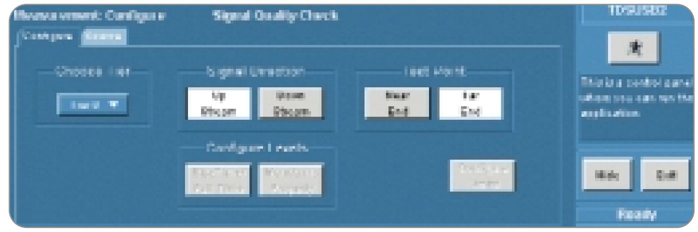


▶ ***Figure 1.*** *TDSUSB2 compliance test package running on a TDS7404 DPO.*

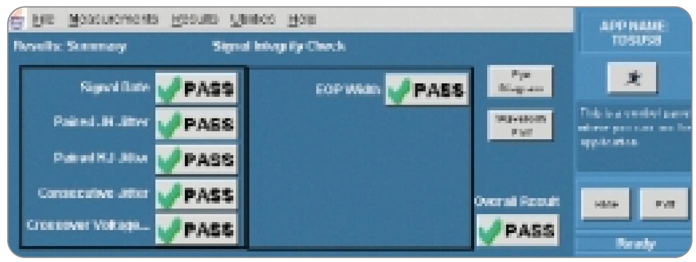
While performing compliance testing, you need to set up the worst-case USB 2.0 topology scenario to ensure a sufficient test margin. Devices are tested in the 6th tier to ensure the worst-case scenario. Further, each hub level is referred to as a tier. The hub-under-test (HUT) is plugged into the 5th tier so that it operates on the 6th tier.

Test Equipment

Signal quality testing requires a real-time oscilloscope, such as the TDS7404 digital phosphor oscilloscope (DPO) or TDS694C digital storage oscilloscope (DSO), and single-ended (low and full speed) and differential (high speed) probes, like the P6243, P6245 and P6248, respectively. In addition, this testing requires test software and a test fixture, such as the TDSUSB2 compliance test package.



▶ ***Figure 2.*** *TDSUSB2 compliance test package running on a TDS7404 DPO.*



▶ ***Figure 3.*** *Measurement results are automatically displayed using the TDSUSB2 compliance test package.*

Figure 1 shows the operation of the TDSUSB2 compliance test package on a TDS7404 DPO. This test package fully automates the signal quality test process, allowing designers to perform quick and easy tests on their designs.

A user must select the measurements to be performed for a particular signal speed (low, full or high speed). The application must then be configured based on tier (tier to which the DUT is connected), test point (test point of the DUT – near or far end), and direction of traffic (upstream or downstream testing), as shown in Figure 2. After completing these two steps, the user then runs the application.

The test package eliminates the tedium of manual, time-consuming oscilloscope set-ups, cursor placements and comparison of test results with USB 2.0 specifications. The results are automatically displayed as a results summary and details, as illustrated in Figure 3.

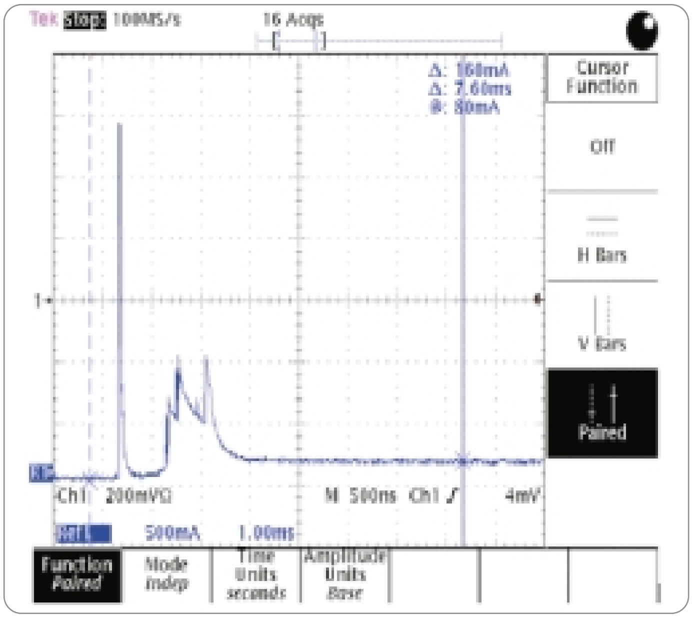


Figure 4. *Illustration of a sharp intake of current followed by a comparatively less steep decay using a TDS694C DSO.*

In-Rush Current Check

Because USB 2.0 is a hot-pluggable technology, extreme care is required to ensure that the current drawn by a device does not exceed a specified limit. If the current drawn exceeds a specified value, the operation of other USB 2.0 devices connected to the bus may be hampered. The in-rush current check is performed for both self-powered and bus-powered devices to verify that the device-under-test (DUT) does not draw too much current when plugged into the port of a hub.

Typically, one expects a sharp intake of current when a device is plugged in. This sharp intake of current is followed by a comparatively less steep decay, as shown in Figure 4. One may observe small humps or perturbations in the current trace depending on when the device is reset.

Theoretically, an in-rush current check involves the calculation of the integral of current over a certain period of time (bounded by the location of two vertical cursors on the oscilloscope).

The USB 2.0 specification dictates that the total charge drawn by the device should be less than or equal to 51.5 uC for a V_{BUS} value of 5.15 V. (The waiver limit for this test is less than 150 uC).

Test Equipment

The in-rush current check requires a real-time oscilloscope, such as a TDS7404 DPO or TDS694C DSO, and current probes, like the TCP202. This test also requires test software and a test fixture, such as the TDSUSB2 compliance test package. The TDSUSB2 test package can be used to automatically set up the oscilloscope for the in-rush current check. This test package provides direct readout of Charge (uC), Capacitance (uF) and an automatic indication of pass or fail.

Drop Test

The USB 2.0 specification requires powered USB ports to provide a V_{BUS} between 4.75 and 5.25 V while bus-powered hubs maintain a V_{BUS} at 4.4 V or greater. Drop testing evaluates V_{BUS} under both no-load and full-load (100 mA or 500 mA, as appropriate) conditions.

$$V_{drop} = V_{upstream} - V_{downstream}$$

$$V_{upstream} = V_{\text{BUS at hubs upstream connection}}$$

$$V_{downstream} = V_{\text{BUS at one of hubs downstream port}}$$

Bus-powered hubs must have a $V_{drop} \leq 100$ mV between their downstream and upstream ports when 100 mA loads are present on their downstream ports. This requirement ensures that the hubs will supply 4.4 V to a downstream device. Bus-powered devices with Captive cables must have $V_{drop} \leq 350$ mV between the upstream connector and downstream port, including the drop through the cable.

Test Equipment

Drop tests require a multi-meter. The TDSUSB2 compliance test package aids in reporting the test results. The multi-meter output for a drop test can be entered into the TDSUSB2 test package, thus providing a consolidated report for the user.

Droop Test

V_{droop} equals the difference in V_{BUS} voltage when a no-load condition is applied and when a 100 mA load is applied to the port-under-test (PUT) (all other ports are fully loaded).

The USB 2.0 specification allows a maximum droop of 330 mV. The droop test evaluates worst-case droop by alternately applying a 100 mA load and no-load condition to the port under test while all other ports are supplying the maximum load possible. All V_{BUS} measurements are relative to local ground.

Test Equipment

Droop tests require a real-time oscilloscope, such as a TDS7404 DPO or TDS694C DSO, and single-ended probes, like a P6243 or P6245. In addition, this testing requires test software and a test fixture, such as the TDSUSB2 compliance test package.

The TDSUSB2 test package automatically sets up the oscilloscope for the desired test configuration. Running the application acquires the signal, provides the V_{droop} measurement, and subsequently provides a pass or fail indication and detailed measurement results of the test.

USB 2.0 High-speed Tests

Fundamentally, USB 2.0 device compliance tests closely follow the compliance test protocol for USB 1.1 devices. Primary additions concern USB 2.0 high-speed mode. High-speed mode adds a new level of complexity to USB device design. USB 2.0 high-speed tests include receiver sensitivity, CHIRP, monotonocity and impedance measurement tests.

Receiver Sensitivity Test

To increase robust operation in a noisy environment, a USB 2.0 high-speed device must respond to IN* tokens with NAKs* when the signal level that equals or exceeds the specified level. The test requires placement of the DUT in Test_SE0_NAK mode. The host is then replaced by the DG2040 to continue to transmit IN tokens. The signal amplitude is presented to the DUT at a level at or above 150 mV. At these levels, the DUT must be in the unsquelched mode, responding to IN packets with NAKs. The amplitude is then reduced to <100 mV and at this level, the DUT must be squelched and does not respond to IN tokens with NAKs.

*Please refer to the USB 2.0 specifications for more information about IN tokens and NAKs.

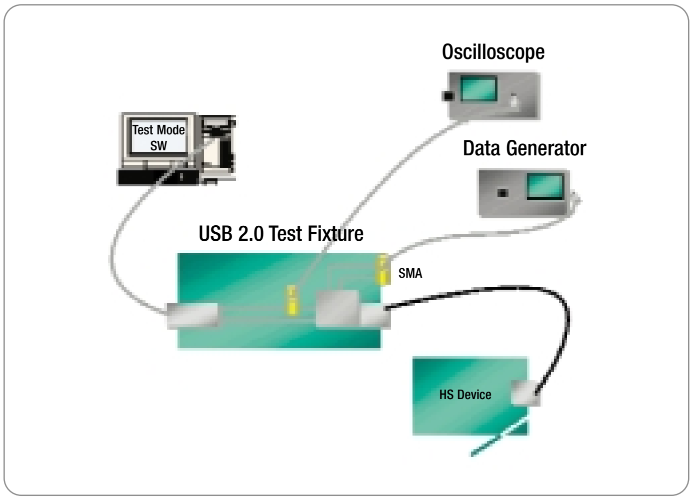


Figure 5. *Set-up for a receiver sensitivity test using a TDS7404 DPO and DG2040 data generator.*

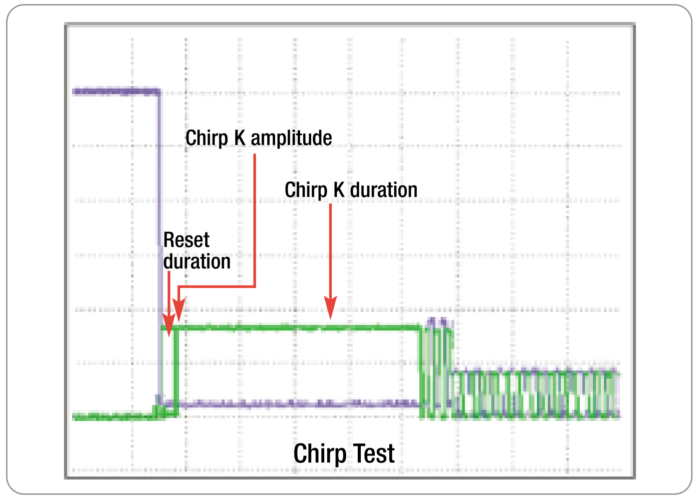


Figure 6. *Test parameters for a CHIRP test.*

Test Equipment

The receiver sensitivity test requires a real-time oscilloscope, such as a TDS7404 DPO or TDS694C DSO, and a high-speed data source that can transmit IN tokens of varying amplitude, such as a DG2040. This test also requires differential probes, like a P6248, and test software and a test fixture, such as the TDSUSB2 compliance test package.

Figure 5 shows the set-up to perform this test using a TDS7404 DPO and DG2040 data generator. The TDSUSB2 test package provides various test set-ups and the test patterns for the DG2040, needed for receiver sensitivity testing.

CHIRP Test

The CHIRP test examines the basic timing and voltages of both upstream and downstream ports during the speed detection protocol. For a hub, the CHIRP test must be performed on both upstream and downstream ports.

To perform CHIRP testing, the DUT is hot-plugged and signaling is measured with single-ended probes on both data lines. Data is analyzed for CHIRP K amplitude, CHIRP K duration, Reset duration, Number of KJ pairs before High Speed termination and delay after KJKJKJ before device-applied termination.

Figure 6 illustrates various test parameters for the CHIRP test using a TDS694C DSO.

Test Equipment

The CHIRP test requires a real-time oscilloscope, such as a TDS7404 DPO or TDS694C DSO, with single-ended probes, like a P6243 or P6245. In addition, this test requires test software and a test fixture, such as the TDSUSB2 compliance test package.

Manual analysis of the various CHIRP types and conditions is a time-consuming process. The TDSUSB2 test package automates this process and automatically documents the results.

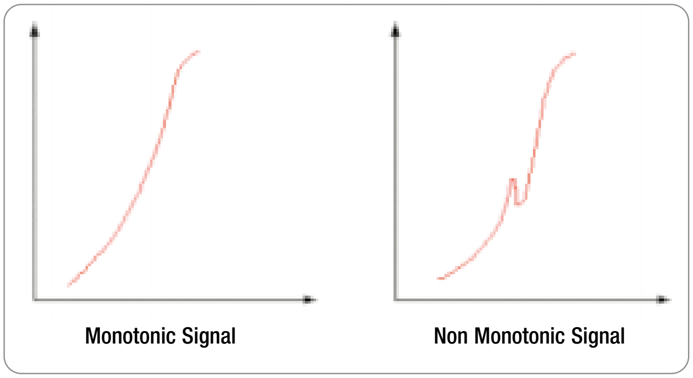


Figure 7. *Illustration of monotonic and non-monotonic USB 2.0 high-speed signals with a rise time of 500 ps.*

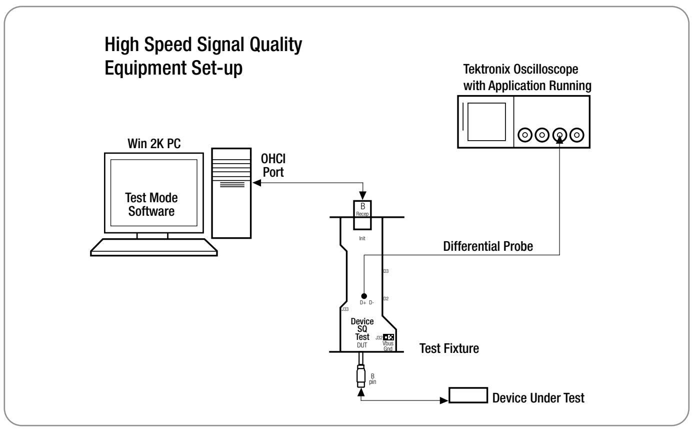


Figure 8. *The TDSUSB2 compliance test package captures the test packet and examines each rising and falling edge for monotonic operation.*

Monotonicity Test

When performing a USB 2.0 high-speed compliance test, a developer needs to verify that the signal under question is monotonic. Monotonicity verifies that a transmitted signal should smoothly increase or decrease in amplitude without deviation in the opposite direction. Non-monotonic signal behavior is caused by metastability, high-frequency noise and jitter problems in a circuit. Figure 7 compares a monotonic signal with a non-monotonic signal using a USB 2.0 high-speed signal with a rise time of 500 ps.

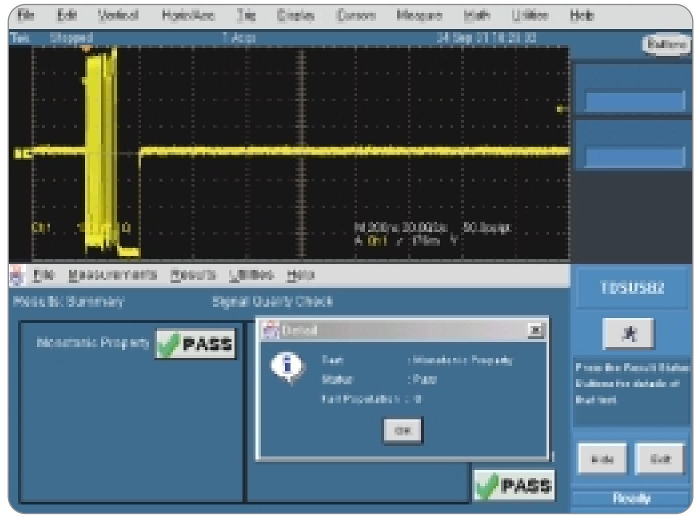
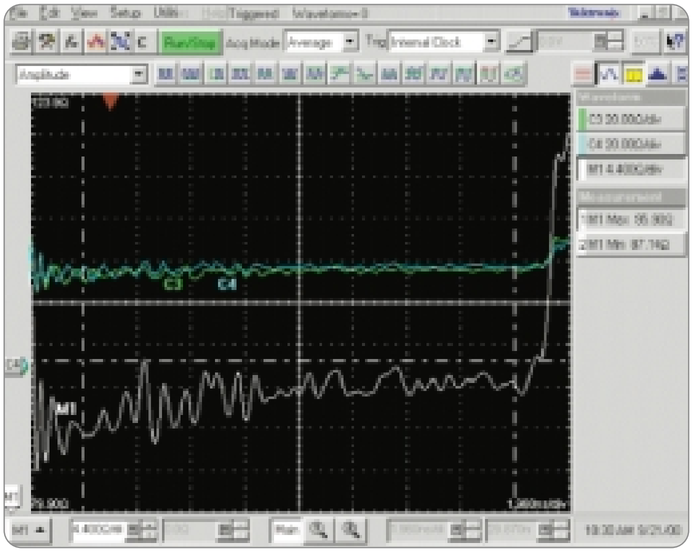


Figure 9. *The monotonicity test set-up uses the high-speed signal quality test configuration.*

Test Equipment

To verify monotonic behavior of a signal, the oscilloscope used should have a sample rate high enough to capture as many sample points as possible on a rising or falling edge. In addition, the oscilloscope should have enough bandwidth to ensure that the high frequency non-monotonic transition is not attenuated. Hence, an oscilloscope with a sample rate of 10 GS/s and a bandwidth of 3 or 4 GHz, such as the TDS694C DSO or TDS7404 DPO, is the ideal tool for monotonicity testing.

Monotonicity testing also requires test software and a test fixture, such as the TDSUSB2 compliance test package. The monotonicity test for a USB 2.0 device is verified during test packet examination. The TDSUSB2 compliance test package captures the test packet and examines each rising and falling edge for monotonic behavior, as shown in Figure 8. Set-up uses the high-speed signal quality test configuration, as illustrated in Figure 9. The TDSUSB2 compliance test package, coupled with a high-performance oscilloscope, automates this process and ensures repeatability of test results.



▶ ***Figure 10.*** *TDR measurement made with a TDS8000 digital sampling oscilloscope coupled with an 80E04 TDR sampling module.*

Impedance Measurement Test

Due to the high signal rates of USB 2.0 High-Speed mode, trace and packaging impedance have become critical parameters. The USB 2.0 High-Speed specification now requires differential impedance measurements of cables, silicon and devices.

The USB 2.0 specification requires that the differential TDR impedance step response be set to 400 ps. The USB specification defines the impedance limits referenced from the DUT connector. In general, the impedance should be between 70 Ohm and 110 Ohm at a given distance from the connector. Cables are also required to meet specific impedance limits. These limits are 90 Ohm ± 15%.

Test Equipment

The impedance measurement test requires a time domain reflectometer, such as the TDS8000 digital sampling oscilloscope with 80E04 TDR sampling module, which offers unmatched TDR performance on up to eight channels simultaneously.

Figure 10 shows a TDR measurement made with a TDS8000 digital sampling oscilloscope. The Min and Max measure within the tolerance specified by the USB differential specification of 90Ω ± 15%.

Test Equipment	Signal Quality Test	Inrush Current Check	Droop Test	Receiver Sensitivity Test	CHIRP Test	Impedance Measurement Test
Real-time Oscilloscope	Y	Y	Y	Y	Y	
Time Domain Reflectometer						Y
Data Generator				Y		
Test Fixture	Y	Y	Y	Y	Y	Y
Test Software	Y	Y	Y	Y	Y	
Differential Probes	Y			Y		
Single-ended Probes	Y		Y		Y	
Current Probes		Y				

Note: Drop test requires a multi-meter.

Instrumentation Requirements for USB 2.0 Physical Layer Testing

The tremendous increase in bit rate afforded by the high-speed data rate extensions of USB 2.0 opens up a whole new range of USB consumer applications to make the PC a more user friendly and valuable tool in the workplace and home. With any consumer product opportunity, time to market is crucial. USB designers are keenly aware that the correct tool aids in meeting schedule objectives. Especially critical are the bandwidth, rise time and sample rate of the oscilloscope, along with the test fixture and fully automatic test software.

USB 2.0 physical layer validation and electrical compliance testing require a host of test equipment, as the chart above illustrates.

Figure 11. *TDS7404 digital phosphor oscilloscope.*

Selecting Tools for USB 2.0 Physical Layer Testing

Real-Time Oscilloscope

A real-time oscilloscope is the most crucial test instrument for USB 2.0 measurements. When selecting an oscilloscope for these measurements, it is important to consider the oscilloscope's rise time, bandwidth and sample rate. The following section deals with the required performance characteristics of the real-time oscilloscope.

Effect of Oscilloscope Bandwidth/Rise Time on Measurement Accuracy

Rise time needs of the oscilloscope depend closely on the rise times of the signals to be measured. The following empirical formula gives the relation between measured rise time [RT(measured)], oscilloscope rise time [RT(oscilloscope)] and signal rise time [RT(signal)];

$$RT(measured) = \sqrt{[\ RT(signal)2 + RT(oscilloscope)2\ ]}$$

The following table illustrates the variation of percentage error versus the ratio of oscilloscope rise time to signal rise time, based on this relationship.

Rise/Fall Time vs Oscilloscope Bandwidth and Rise Time

Bandwidth (GHz)	Rise Time (ps)	Measured Rise Time*	% Error
4	100	509	1.80%
3	120	514	2.80%
2	180	531	6.20%
1	340	604	21%
1	400	640	28%

* Based on a signal with a 500 ps rise time.

When the oscilloscope rise time specification is five times that of the signal, the error decreases to 1.8%. However, lower oscilloscope rise times would signify higher error in measurements with respect to signals. Therefore, in order to measure a signal with a rise time of 500 ps, the oscilloscope used should ideally have a rise time of 100-120 ps, like a TDS7404 DPO or TDS694C DSO.

Effect of Oscilloscope Sample Rate on Testing

To capture information at edge speeds as fast as 500 ps, you need at least 10 sample points on an edge. This requirement becomes even more important when performing a monotonicity test, mandatory for high-speed testing.

Tektronix Solutions

In order to have 10 sample points on a 500 ps edge, the oscilloscope should have a sample rate of at least 20 GS/s.

The following chart lists various Tektronix real-time oscilloscopes.

Specification	TDS7404	TDS694C	TDS7254
Rise/Fall Time	100 ps	120 ps	160 ps
% Error	1.8%	2.80%	4.80%
Sample Rate	20 GS/s	10 GS/s	20 GS/s

Note: USB 2.0 can encounter edge rates as fast as 500 ps.

The TDS7404 digital phosphor oscilloscope (DPO) is the highest performance member of the TDS7000 Series Windows-based oscilloscopes. With 20 GS/s maximum real-time sample rate and 4 GHz bandwidth, the four-channel TDS7404 is the gold standard for high-performance solutions for verification, debug and characterization of USB 2.0 designs. This instrument features exceptional signal acquisition performance, operational simplicity and open connectivity to the design environment. The TDS7404 delivers more than 400,000 wfms/s waveform capture rate, enabled by proprietary DPX™ acquisition technology, to detect and capture elusive events with confidence and ease.

The TDS694C digital storage oscilloscope (DSO) provides the USB 2.0 device designer with a solution for digital design characterization and debug. This four-channel oscilloscope employs 3 GHz bandwidth and 10 GS/s per channel real-time sample rate to verify design margins, characterize setup-and-hold times and measure data jitter on the USB differential data bus. The TDS694C offers 29 automatic measurements, with measurement statistics, to simplify design verification and characterization.

Time Domain Reflectometer

A time domain reflectometer is required for the impedance measurement test. The TDS8000 digital sampling oscilloscope with 80E04 TDR sampling module provides true differential time domain reflectometry (TDR), making it an ideal solution for USB 2.0 device and cable impedance measurements. This oscilloscope and sampling module can display both the individual positive and negative TDR waveforms of differential line characteristics and directly measure the impedance of each conductor or common mode voltage of the differential line. This test system can also display the true differential measurements of both these lines and display the impedance in the unit of ohms, providing the user with the required measurements to validate any USB 2.0 device.

Signal Source

A signal source is required for the receiver sensitivity test. The DG2040 is a 1.1 GHz low jitter data generator that is easily programmed to output compliant USB 2.0 high-speed data. The two-channel output permits non-standard differential signaling used by USB devices.

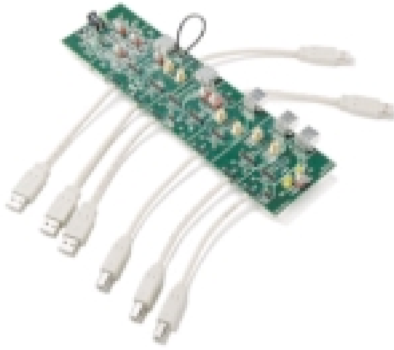


Figure 12. Test fixture.

Test Fixture

The test fixture is the most crucial component that enables probing for every test set-up. The ideal test fixture should provide access to the differential data lines (D+, D- and V_{BUS}) and offer access/connections via on-board USB connectors or wired dongles.

For receiver sensitivity testing, SMA cables are needed to connect the data generator to data lines to stimulate the device. Cable access is also needed to allow impedance measurements by a TDR measurement device.

The TDSUSB2 test package offers a comprehensive compliance test fixture to enable USB 2.0 testing, as shown in Figure 12.

Test Software

A user may choose among fully automatic test software, semi-automated test software and manual testing.

Fully Automatic Test Software

Fully automatic test software, such as the TDSUSB2 compliance test package, substantially improves test efficiency by providing automatic oscilloscope set-ups, automated high-speed tests and quick "one-touch" testing. This test package drastically reduces the test time and chances of any erroneous measurements.

Semi-Automated Test Software

As the name implies, this kind of solution automates certain tests but invariably omits certain requirements of compliance testing, resulting in reduced overall throughput.

Examples of some tests that still need to be manually performed are high-speed compliance tests such as receiver sensitivity, CHIRP and monotonicity tests, as well as rise and fall time calculations.

Manual Testing

Traditionally, developers have been using MATLAB scripts to perform compliance testing. While using the MATLAB scripts, the user must perform the entire test process manually, which includes setting up the oscilloscope, placing cursors accurately, storing the captured signal as a .tsv file, and running MATLAB scripts.

The complexity of the tests and setups demands a phenomenal amount of expertise from the test engineer. Setting up the oscilloscope is the most tedious and time-consuming task, as oscilloscope setups differ for various test configurations. A user is compelled to make continuous references to exhaustive documentation about test procedures, making testing difficult and significantly reducing efficiency.

Probes

Probes are a critical component of the measurement system to perform various USB 2.0 compliance tests. Tektronix offers differential (P6248), single-ended (P6243, P6245) and current (TCP202) probes that allow access to high-density boards with fine-pitch, hard-to-reach components while maintaining maximum signal fidelity.

Conclusion

USB 2.0 technology introduced a 40 times increase in data rates that offers the device designer a migration path for high-performance peripherals that preserve the ease-of-use consumers have come to demand. However, this tremendous increase in data rates also presents new design challenges that the device designer must resolve.

Tektronix offers a comprehensive tool set – sophisticated oscilloscopes, true differential TDR, high-speed data generator, industry-leading probes and a fully automated compliance test package – to enable USB 2.0 device designers to perform quick and accurate electrical compliance testing and physical layer validation of their designs. Collectively, this tool set provides superior performance with unparalleled ease-of-use, making it an ideal solution for USB 2.0 measurements.

Tektronix maintains a complete library of updated resources for the USB device designer at www.tektronix.com/usb.

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