How to Ensure Interoperability and Compliance of USB Type-C Cables and Connectors
Overview

USB Type-C (or USB-C) is a ubiquitous and widely adopted interface in modern electronic devices. The connector supports a smaller form factor, higher data rate, more power capabilities, and flexible connectivity with other protocols. Key USB Type-C focus areas include connecting devices, managing power, and ensuring valid data transmissions.

The USB Type-C connector provides reversibility for ease of use, dynamic power up to 240 W with USB4 protocol, backward compatibility (USB 2.0, USB 3.2, USB 3.1, and USB4), and alternate mode to support DisplayPort, HDMI, and PCIe® protocols for many new and future devices.

Design and test engineers face several challenges when they integrate USB Type-C into their products while simultaneously ensuring interoperability and test compliance. As the USB Type-C compliance test standard grows more complex, successful testing requires highly accurate and standard-compliant test instruments, software, and fixtures.

This application note covers various aspects of the challenges and solutions for the USB Type-C cables and connectors test, including new USB4 and USB4 Version 2.0 compliance test requirements that support higher data transmission and additional functionality.
Overview of USB Type-C cables and connectors

The USB Type-C connector is now much easier to plug in due to a symmetrical design that you can plug in in either direction. The 24-pin USB Type-C connector and cable provide both USB backward compatibility and additional functionality for power management and data transmission.

The USB Type-C power delivery (USB-PD) uses USB4 extended power range (EPR) protocol and can provide up to 240 watts (48V, 5A) for dynamic power and charging of different devices. You can use the transmitter / receiver (Tx / Rx) pairs for USB or guest protocols such as DisplayPort, HDMI, or Thunderbolt data transfer, making it possible to transfer high-speed data, high-quality video, and audio signals.

USB Type-C data transfer rates now support up to 80 Gbps in USB4 Version 2.0 (or USB4 Gen 4) for bidirectional bandwidth, with the ability to achieve 120 Gbps in USB4 asymmetric link mode to send or receive data. The new capabilities create a bigger challenge for design and test engineers who are striving to ensure the interoperability of their USB products by performing USB-IF standard conformance tests.

With previous connectors such as USB Type-A and Type-B, the USB connection consisted of only one power line and two data lines. The USB Type-C channel can dynamically change power levels and data signals. When you make the initial end-to-end USB Type-C connection, the cable orientation uses configuration channel pins (CC1 / CC2) to acknowledge the connection and establish host / device roles. Consequently, the power delivery circuit begins to manage power to each connected device through VBUS and ground (GND) connections. Individual devices determine which of the Tx / Rx pins (and SBU1 / SBU2 pins for alternate protocols) you can use. For example, you can use the Tx / Rx pins for USB or alternate protocols and combine pins in parallel for faster data transfers. The power delivery circuit manages channel power and signal levels, and it can change while a device connects for charging or new transmissions.

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**Figure 1.** USB Type-C pinout features a symmetrical and reversible structure
USB Type-C pin functionality overview

Four transmit / receive pairs (TX1+/-, RX1+/-, TX2+/-, RX2+/-)

Use USB Type-C pins for high-speed data bus or alternate (ALT) mode. The four sets of transmit and receive (Tx / Rx) differential pairs enable you to use one, two, or all four channels for data transmissions at any time. Further, the USB Type-C connection makes it possible for two different protocols to actively transmit and receive simultaneously. In USB4 Gen 4, the asymmetric link mode empowers data transmissions up to 120 Gb/s (40 Gb/s over three lanes) in one transmit / receive direction while maintaining a rate of 40 Gb/s in the opposite receive / transmit direction. The configuration enables USB4 Gen 4 to support DisplayPort Version 2.1 (DP 2.1) high-image resolution transmission and, at the same time, achieve high-speed data transmission without reducing display quality.

![USB4 Symmetric and Asymmetric Link](image)

**Figure 2.** Symmetric and asymmetric link in USB4 Gen 4

Two configuration channels (CC1, CC2), one pin repurposed for V\text{conn}

The pins in CC1 and CC2 determine cable configuration and cable orientation detection. The USB Type-C connector maintains a host-to-device logical relationship, even though it is reversible using a single-wire orientation detection. There is only one CC signal wire present in the USB Type-C cable. When the cable plugs into the receptacle, the wire connects from the CC of the receptacle to either CC1 or CC2 on the other end, which determines the cable orientation. The other CC pin gets repurposed as V\text{conn}, a 3.0 to 5.5 V power rail independent of V\text{bus} for power circuit in active cables or any V\text{conn}-powered USB devices.
Two USB 2.0 differential pairs (D+ / D-)

USB 2.0 data buses serve as dedicated pins to ensure that USB 2.0 backward compatibility is always available.

Two secondary bus pins (SBU1, SBU2)

The purpose of a secondary bus or sideband auxiliary signals is to support alternate mode transmissions that require a separate channel for signaling. In USB4, these signals serve as sideband channels (SBTX and SBRX) to carry analog audio signals over USB Type-C in audio adapter accessory mode.

Four power / ground pairs (VBUS / GND)

The power delivery circuit manages multiple peripheral devices and provides power for devices to operate at their set power levels. Devices can request the power they need and get more power when a specific application requires it.

USB Type-C cable and connector test challenges

Cable manufacturers, product designers, and system integrators perform the standard USB Type-C cable and connector compliance tests based on the compliance test specification (CTS) set by the USB Implementers Forum (USB-IF). The CTS ensures that cable manufacturers and product designers produce standard-compliant USB-C cables and devices that meet interoperability requirements. Only products that complete USB-IF certification may use the certified USB marks to identify supported performance and protocols. The USB Type-C cable and connector CTS outlines the test requirements for each type of cable assembly from fully-featured Type-C cables to Type-C to legacy cables, adapters, and mated connectors.

The USB Type-C connector launched in 2014, and CTS Revision 1.0 came out for the USB 3.1 specification in the same year. CTS Revision 2.0 came out in 2019 and focused on Type-C to Type-C (C2C) cable’s high-speed electrical specification to support USB4 for 40 Gbps transfer rate. The latest CTS Revision 2.2, released in October 2022, further defines the electrical characteristics of the USB4 Gen 4 passive cables and USB active cables, such as linear re-driver (LRD) and optically isolated active cable (OIAC). According to the USB-IF, USB Type-C must be backward compatible and support previous versions of USB specification signals (USB 2.0 and USB 3.x).

In addition to the backward compatibility requirement, the USB-IF defines the following USB Type-C cables with Type-C plugs at each end:

- The full-featured Type-C cable with a full-featured Type-C plug at both ends for USB4, USB 3.2, and full-featured applications.
- The USB 2.0 Type-C cable with a USB 2.0 Type-C plug at both ends for USB 2.0 applications (typically for mobile charging).
- The captive cable with either a USB full-featured Type-C plug or USB 2.0 Type-C plus at one end.
- The USB4 and USB 3.2 active cable.

The slight increase of USB4 Gen 4 fundamental frequency from 10 GHz to 12.8 GHz enables the use of existing USB4 and Thunderbolt 4 Type-C cables. You do not need to meet a new test requirement for USB4.
Gen 4 passive standards as the electrical characteristics of the USB4 Gen 3 passive cable are equivalent to USB4 Gen 4. However, there are new and defined test requirements for USB4 Gen 4 active cable.

Loss, reflection, crosstalk, and mode conversion affect USB Type-C channel response. Traditionally, engineers characterize interconnections by measuring parametric characteristics, such as impedance and skew for the time domain, insertion loss, and return loss in the frequency domain over a specific parameter limit. The parametric specification has conservatively set limits, requiring interoperability for cables that marginally pass the parametric test items. This test method is no longer the best solution because it does not allow for trade-offs between the parameter performances. For example, a channel with less loss could tolerate more crosstalk or reflection and vice versa. USB Type-C channel characterization requires a new test methodology and improvements in the pass / fail judgment method.

New test requirement for USB4 Gen 3 and USB4 Gen 4 cable

The CTS for USB4 Type-C is much more complex than the previous USB 3.2 Type-C CTS. The higher bit rates that support USB4 Gen 4 protocols introduce additional signal integrity challenges and require more stringent integrated test parameters that correspond to the incidental / reflective behaviors over a wide frequency range.

A new test group, Test Group B-8, and Test Group A-8 requirements target the high-speed signal’s integrated S-parameters (except for insertion loss and differential-to-common-mode conversion). The reason for this is to avoid the potential rejection of a functioning cable assembly that may fail the traditional S-parameters’ specification at a few frequencies. In the case of integrated return loss (IRL), the test now manages the reflection between the cable assembly and the rest of the system (host and device), with more IRL permitted if the cable loss is smaller.

![Figure 3. Electrical compliance test group in USB Type-C CTS](image-url)
There is a new test called channel operating margin (COM). The COM test qualifies USB4 Gen 3 and USB4 Gen 4 cables. COM is a figure of merit to measure the channel’s electrical quality and is essentially the channel’s signal-to-noise ratio (SNR). In the COM equation in Figure 4, $A$ is the signal amplitude and $N$ is the combined noise at bit error ratio (BER). COM test compilation includes the consideration of noise sources from intersymbol interference (ISI), crosstalk, transmitter jitter, receiver equalization, and more. To calculate COM, you need a measured cable’s S-parameters, reference hosts/devices (Tx jitter and equalization settings based on USB4 specifications), reference Tx/Rx termination, and a COM configuration file.

**Figure 4.** The COM test requirement in USB4 Gen 3 and USB4 Gen 4

The IEEE Std 802.3bj™-2014 Clause 93a, commonly used in high-speed gigabit Ethernet transceivers and interconnects, is the foundation upon which the technical details of COM rest.

**Introduction of USB-IF compliance test tools**

To compile COM and integrated S-parameters results, USB-IF introduces a new Matlab-based compliance test tool called Get_iPar.exe. The compliance test tool requires 44 sets of S-parameter measurements in touchstone S4P file format. The USB4 Gen 2 and USB 3.2 Gen 2/Gen 1 high-speed signal tests use another Matlab test tool called IntePar.exe with 30 sets of touchstone S4P files for compiling results. You can apply the same compliance test tools for USB4 and USB 3.2 active linear re-driver (LRD) cables.

**Figure 5.** Follow manual steps to implement the USB-IF compliance test tool (Get_iPar.exe) for USB4 Gen 3 and USB4 Gen 4 high-speed signal test
The conventional way of performing a USB Type-C cable test using a four-port vector network analyzer (VNA) and following the method of implementation (MOI) document required numerous port reconnections to complete the full sets of touchstone S4P measurements. These manual operations may lead to a longer test time (three to five hours for one high-speed signal test) and are prone to user errors which make compliance testing inefficient and more challenging. One way to automate and speed up USB Type-C compliance testing is to use modular multiport network analyzers such as PXIe VNAs or a switch matrix system capable of handling multiport measurements with USB-C compliance test software.

**Removing test fixture effects**

Conduct electrical characterization of the USB Type-C cable using a VNA with a test fixture to connect from the cable DUT to VNA ports. Complete removal of the test fixture is crucial to prevent fixture artifacts from impacting test results, especially at higher frequencies. You can achieve fixture removal through calibration or de-embedding processes. Use the automatic fixture removal (AFR) de-embedding technique for USB Type-C testing. Keysight is well-versed in the AFR technique which can dramatically reduce the complexity of directly measuring the S-parameters of the fixture. Using signal processing in the time domain to extract the unique values of S-parameters is an essential element of the AFR technique. With AFR, you can uniquely extract each S-parameter element of the fixture and transform the complex error correction algorithm into an output AFR file that loads into VNA firmware for de-embedding. Figure 6 demonstrates a significant loss at higher frequencies without proper calibration (in red) and de-embedding processes during the measurement (in blue). AFR is a rigorous approach for removing fixture effects to measure the true performance of the device. Learn more about de-embedding in the ABCs of De-embedding application note.
Choosing the right instrument for your high-speed interconnects measurement is crucial to ensure it meets compliance test requirements and guarantees robust performance. Given advancements in chip complexity and data speeds, a VNA has become a must-have system for performing S-parameter and other RF measurements in most of high-speed digital standard compliance tests.

The Keysight E5080B ENA, Streamline VNA series, and PXI-VNA is an ideal solution for manufacturing and R&D engineers evaluating RF components and interconnect circuits for frequency ranges up to 53 GHz. Some market solutions rely on a time-domain oscilloscope to perform time-domain reflectometry (TDR) and convert the impulse response to the frequency domain using a fast Fourier transform (FFT). Overall, a time-domain oscilloscope might be a more cost-effective solution. However, as a long-term investment, the Keysight VNA is a faster and more accurate solution to meet the demand for lower noise, higher dynamic range testing in high-speed digital interconnects.

The Keysight VNA with enhanced time domain analysis (E-TDR option) application provides a one-box solution that measures all compliance parameters:

- Supports test MOI, a step-by-step procedure for specified parameter measurement upon the release of USB-IF compliance documentation.
- Provides a state file with pre-defined measurement parameters and test mask limits based on the USB-IF compliance test specification for each supported VNA model.

Learn more about the USB Type-C cable and connector assembly MOI:
www.keysight.com/find/ena-tdr_usbtype-c-cabcon
Figure 7. Keysight VNA one-box solution for interconnects testing

Keysight Enhanced TDR (E-TDR) application

In addition to USB, the Keysight VNA and the E-TDR application are certified to support various high-speed digital interconnects standards. Test MOI procedures and state file are available for download at:

www.keysight.com/find/ena-tdr_compliance

**Option 1: One-box solution using four-port VNA**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network analyzer</td>
<td>Min. four ports, 20 GHz recommended as USB4/Type-C cable/connector requires measurements up to 20 GHz (Low-speed signal test required start frequency at 300 kHz) • E5080B-4K0: 4-port test set, 9 kHz to 20 GHz or • P5024A/P5024B-400 Streamline USB/TBT Series VNA or • M9804A-400 PXI Multiport VNA</td>
<td>1</td>
</tr>
<tr>
<td>VNA software</td>
<td>• S9x011B enhanced time-domain analysis with TDR • S9x007B automatic fixture removal (optional) * Selection is based on the VNA platforms. x=6 for ENA, x=7 for Streamline VNA, x=5 for PXI, x=3 for PNA family</td>
<td>1</td>
</tr>
<tr>
<td>ECal</td>
<td>N4433D-010/0DC four-port electronic calibration (ECal) module</td>
<td>1</td>
</tr>
<tr>
<td>Test fixture</td>
<td>USB Type-C official test fixture Fixtures for testing USB Type-C and USB 3.x legacy cable assemblies are available for purchase through LUXSHARE-ICT</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: the list includes key setup configurations. For full details, please refer to USB Type-C Test MOI.
Option 2: Automated solution using S94USBCB compliance software

The conventional test method using a four-port VNA (Option 1) could lead to longer test time and lower productivity when it comes to testing USB4 Type-C cables that require multiple port reconnections.

Keysight enabled the industry’s first USB-C high-speed interconnect test solutions to fully automate the time-consuming and error-prone process of manual port setup and USB-IF standards compliance tools. The solution includes the S94USBCB USB Type-C interconnects compliance test software, a four-port VNA, and a 20-port switch matrix system to lower the cost of multiport testing. Learn how the new automated interconnects test solution helps improve test efficiency and achieve more than a 90 percent time-savings by reading the case study.

The Keysight automated interconnects test solution:

- Supports flexible test configurations across all Keysight VNAs: E5080B VNA, PNA family, P502xA/B Streamline VNA Series, and PXI-VNA Series.
- Uses Keysight PathWave Test Automation platform for test sequencing and test automation.
- Automates all multiport measurements with the L8990M four- to 20-port switch matrices system.
- Enables quick setup and calibration with the setup wizard.
- Delivers accurate measurements with test fixture de-embedding using Keysight 2x THRU AFR algorithms.
- Integrates USB-IF compliance test tools (Get_iPar and IntePar) for full compliance test automation.
- Provides deeper insights of measurements with comprehensive HTML test reports.
- TAP platform compatible to test DisplayPort and DP Alt Mode cables with the additional software license on S94DPPCB.

Figure 8. Keysight USB Type-C compliance test solution
<table>
<thead>
<tr>
<th>Support mode</th>
<th>Item</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
</table>
| Semi-automated    | Network analyzer             | Minimum four ports, 20 GHz is recommended  
* E5080B-4K0: four-port test set, 9 kHz to 20 GHz or  
* P5024A/P5024B-400 Streamline USB/TBT Series VNA or  
* M9804A-400 PXI Multiport VNA  | 1        |
| VNA software      |                               | • S9x011B Enhanced time-domain analysis with TDR  
* S9x007B Automatic fixture removal (optional)  
* Selection is based on the VNA platforms. x=6 for ENA, x=7 for Streamline VNA, x=5 for PXI, x=3 for PNA family  | 1        |
| Fully automated   | Four-port mode setup         | Using same setup configurations as above four-port semi-automated mode.                        | 1        |
| mode              | Switch matrix                | L8990M-0LZ: four- to 20-port switch matrix system, DC-26.5GHz. All required cables (24 test cables and 16 semi-rigid cables) are included. | 1        |

Note: The list includes key setup configurations. For full details, please refer to S94USBCB product datasheet.
Web Resources

- www.keysight.com/find/S94USBCB
- www.keysight.com/find/usb-c-testing
- Product Video - Automated Cable Test Solution
- Demo video - USB Type-C MOI and State File Solution
- www.keysight.com/find/ena-tdr_compliance
- www.keysight.com/find/ena
- www.keysight.com/find/usb-vna
- www.keysight.com/find/na
- www.keysight.com/find/vnasoftware
- www.keysight.com/find/ecal

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