

Focus on Universal Serial Bus hardware design

An overview of USB and the USB circuit design guidelines.

By Guo Yang Bin, Senior Engineer, USB transceivers, NXP Semiconductors

Introduction

As an "Instant, No Hassle Connection", USB connects more than computers and peripherals. It has the power to connect you with a whole new world of PC experiences. Today, it has been widely applied to not only the PC and PC peripheral, but also embedded systems such as in consumer electronics, and the communications segment. The USB standards including USB 1.1, USB 2.0, USB On-The-Go, and the newest entrant, Wireless USB (WUSB) were released for applications in these various segments. In the specification of these standards, mechanical, electrical and protocol features are specified and detailed for the USB chip designer, but are not adequately addressed for the USB product or application designer. This paper provides an overview of all the USB standards. It is intended to help designers quickly see which USB standard is available for their design. It also provides circuit design guidelines to help designers implement their physical layer design with the current USB chips on the market.

USB background

The serial RS-232 port and parallel port dominated the "wired" communications world for a number of years before USB was widely applied to the PC and PC peripheral. Today, USB has proliferated to the point that it is not easy to find a product with a serial port or parallel port on the market. More importantly, USB is continuing its success. In fact, it has been growing at a very fast rate – one that no one could have imagined ten years ago.

USB enjoys broad market acceptance today. One of the reasons is that there are a number of disadvantages for new technology when it comes to the RS-232 port and parallel port. Some of these disadvantages include a speed limitation (the RS-232 port is 115,000 bps and the parallel port is about 150 kbytes per second; neither of which is adequate for today's technology), the problematic size of the DB9/DB25 connector, and the inability of the power supply to support new technologies.

Another key reason for USB's success is that it is very flexible and has been continuously improved and perfected. Developed to simplify PC peripheral connections, USB allows expandability of the PC's capabilities via an external port. It supports up to 127 physical devices and has an error handling/fault recovery mechanism that is built into the protocol. It supports not only a flexible data transfer rate from 1.5 Mb/s, 12 Mb/s to 480 Mb/s for different applications, but also flexible roles from host, device to dual-role device, and a flexible connection from wired mini-port, standard port connection to wireless connection. Since USB 1.0 was released in January 1996, different revisions of the USB standard have been released, the later versions are all backward compatible. These include:

- Universal Serial Bus Specification Revision 1.0, the first edition, was released in January 1996. It supported 1.5 Mb/s (low speed) and 12 Mb/s (full speed) transfer rates.
- Universal Serial Bus Specification Revision 1.1 was released in September 1998. This edition fixed many of the problems in release 1.0.
- Universal Serial Bus Specification Revision 2.0 was released on April 27, 2000 and increased the maximum transfer speed by a factor of 40 up to 480 Mb/s. USB 2.0 is backward compatible with USB 1.x. The USB 2.0 specification supersedes the USB 1.1 specification. These USB 1.x peripherals continue to operate with no change in Hi-Speed USB systems. The higher bandwidth of Hi-Speed USB permits PC peripherals with more functionality, including higher resolution video conferencing cameras, next-generation scanners and printers, fast storage units, and faster broadband Internet connections. It makes today's user applications more productive, such as taking the time to download a "roll" of digital photos from a few minutes on Original USB down to a few seconds on Hi-Speed USB.
- On-The-Go Supplement to the USB 2.0 Specification, Revision 1.0, released on Dec 18, 2001. Revision 1.2 of the USB On-The-Go Supplement was released on April 4, 2006. The On-The-Go Supplement addresses the need for mobile interconnectivity by allowing a USB peripheral to have the following enhancements: 1. Limited host capability to communicate with selected other USB peripherals, 2. A small USB connector to fit the mobile form factor. 3. Low power features to preserve battery life
- Wireless USB Specification Revision 1.0 was released on May 12, 2005. Certified Wireless USB from the USB-IF is the new wireless extension to USB that combines the speed and security of wired technology with the ease-of-use of wireless

technology. It offers a solution for high bandwidth, low cost, low power consumption and physical size requirements of next-generation consumer electronic devices. Certified Wireless USB performance is targeted at 480 Mbps at 3 meters and 110 Mbps at 10 meters.

The USB physical interface

USB 1.0 and USB 1.1 support low-speed (1.5Mb/s) and full-speed (12Mb/s) USB transfer rates. USB 2.0 supports a high-speed (480 Mb/s) USB transfer rate and is backward compatible with USB 1.1. USB On-The-Go adds a connectible feather for USB peripherals on USB 2.0. Wireless USB unwires the high-speed USB and provides the functionality of wired USB without the burden of cables. In Table 1, the key features of the USB physical interface are listed. Note that unwired or high speed is not always 'GOOD'. Losing the cable also means losing a source of power for peripherals. Wireless USB is not available for bus-powered devices. High-speed means higher current consumption and higher cost. It is not necessary to select high-speed if the bandwidth of full speed or low speed is enough for your application.


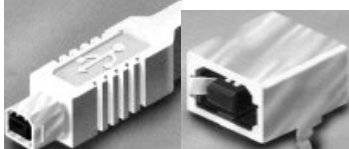
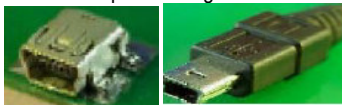
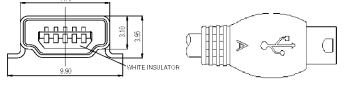
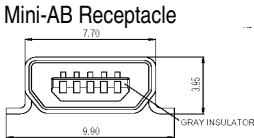
Standard	Available Connector	Cable Assembly	Transfer Speed and Power Ability
USB 1.0 USB 1.1	"A" Plugs/ Receptacles  "B" Plugs/ Receptacles 	A plug to B plug Low-speed Cable Polyvinyl Chloride (PVC) Jacket Red (Vbus) Black (Ground) Green (D +) White (D -) A plug to B plug High/full-speed Cable Polyvinyl Chloride (PVC) Jacket ≥ 65% Tinned Copper Braided Shield 28 AWG STC Drain Wire Red (Vbus) Black (Ground) Green (D +) White (D -)	Transfer speed: Low-speed 1.5 Mb/s Full-speed 12 Mb/s VBUS Current: High-power Function: < 500mA Low-power Function: < 100mA Suspend (High-power with remote Wakeup feature): < 2.5mA Suspend: < 0.5mA
USB 2.0	Backward compatible with USB 1.x Mini-B Receptacle /Plug 	Backward compatible with USB 1.x A plug to Mini-B plug High/full-speed Cable	Transfer speed: Backward compatible with USB 1.x, support low-speed, full speed and high-speed 480 Mb/s. VBUS Current: Same as USB 1.1
USB OTG 1.2	Backward compatible with USB 2.0, Mini-A Receptacle/Plug  Mini-AB Receptacle 	Backward compatible with USB 2.0 Mini-A plug to Mini-B plug cable Mini-A plug to standard-B plug cable Mini-A plug to captive cable Mini-A receptacle to standard-A plug adapter Standard-A receptacle to Mini-A plug adapter. Pin4 'ID' is connected to Pin5 'GND' inside the Mini-A plug. Pin4 'ID' is not connected or is connected to Pin5 'GND' by a resistance of greater than RB_PLUG_ID inside the Mini-B plug.	Transfer rate: Backwards compatible with USB 2.0 VBUS Current: A-Device VBUS Output Current 8-100 mA Unconfigured dual-role B-device < 150 μA Unconfigured peripheral-only B-device < 8mA
Wireless USB	Not needed	Not needed	Transfer speed: 480 Mbps at 3 m 110 Mbps at 10 m Power ability: None

Table 1. This table provides an overview of the USB connector, cable, transfer speed and power ability. Using it, you can determine which type of standard is available for your design.

Selecting the USB cable and receptacle

Before you start your hardware design, first you will need to make a choice of the USB cable and receptacle based on the size requirement of your application. Figure 1 and Table 2 can help you select the proper USB cable and receptacle. Note that if you want to minimize the size of your product, choose the mini size receptacle for your design.

Application	Available Receptacle	Available cable	Receptacle for Small size
Host	A receptacle As Figure 1.	A plug to B plug cable A plug to Mini-B plug cable	
	Mini-A receptacle As Figure 1.	Mini-A plug to B plug cable Mini-A plug to Mini-B plug cable	Mini-A receptacle
Device	B receptacle As Figure 1.	A plug to B plug cable Mini-A plug to B plug cable	
	Mini-B receptacle. As Figure 1.	A plug to Mini-B plug cable Mini-A plug to Mini-B plug cable	Mini-B receptacle
Dual-role device	Mini-AB receptacle. As Figure 1.	A plug to Mini-B plug cable Mini-A plug to B plug cable Mini-A plug to Mini-B plug cable	Mini-AB receptacle.

Table 2. This table provides the USB cable and receptacle choices.

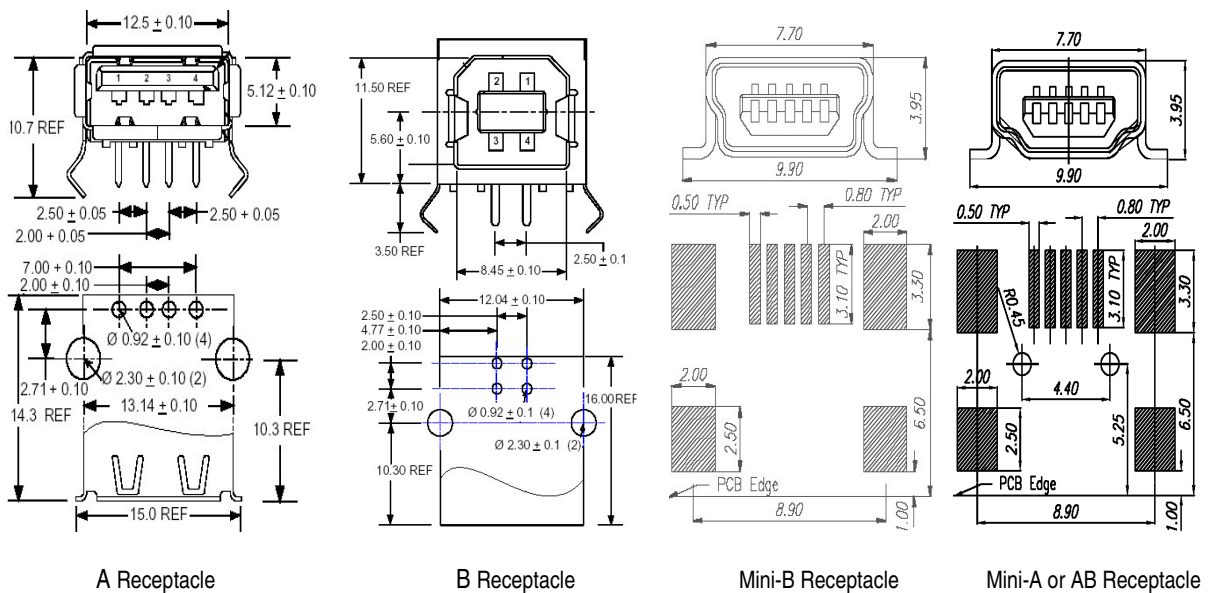


Figure 1. The PCB layout of USB receptacles.

Design guidelines for USB physical interface schematics

Once you select the cable and the receptacle for your design, you then need to determine the USB controller based on the bandwidth, data bus, USB class type, current consumption and cost requirement of your application. Once this is done, you can start to design the schematics of your application based on the following guidelines.

- Follow the data sheet and the reference design of the USB controller.

This is very important since some USB chips can only conditionally achieve the design requirements. Normally though, the reference design provided in the USB controller datasheet is golden and can pass all USB compliance tests.

- Check the capacitance and resistance limitations between VBUS and GND

For the USB upstream port, you need to ensure that the capacitive load of VBUS is more than 1.0 μF and less than 10 μF (1.0 to 6.5 μF for a dual-role device). For the USB downstream port, the VBUS power line must be bypassed with no less than 120 μF of low-ESR capacitance. Please note that the capacitance value is the total equivalent value in the circuit. The capacitor placed in the design should be less than this maximum value and more than the minimum value. The resistance between VBUS and GND should not be less than 40 kohms (40 to 100 kohms for a dual-role device) in USB suspend or idle state (see Figure 2). Also, make sure that the pull-down resistor of VBUS is not less than 40 kohms (the total equivalent value in the circuit).

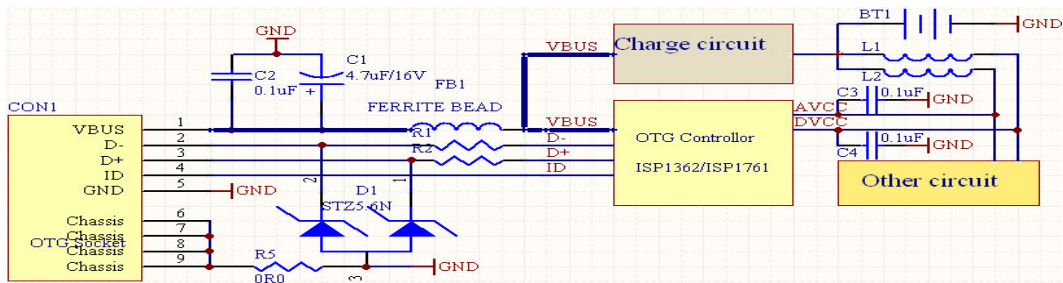


Figure 2. Shown here is the physical interface and power supply reference design for a dual role device.

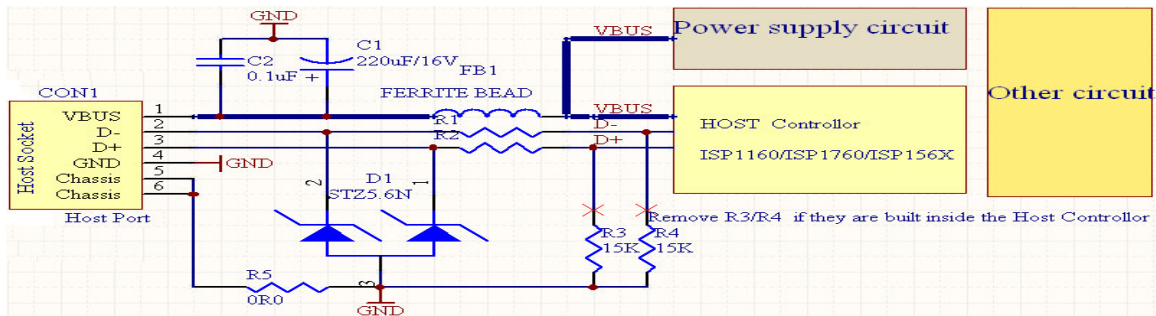


Figure 3. The physical interface reference design for a host application.

- Grounding

USB specifications mention that the shield should be connected to GND at the host side, as in Figure 3, and that no USB device should connect Shield to GND. Actually though, in some designs, connecting the shield of the USB device to GND as in Figure 4 can result in better Eye Pattern. Therefore, use a 0-ohm resistor to short the Shield to GND. If it is not necessary when you do USB test, you can easily remove it from the PCB board.

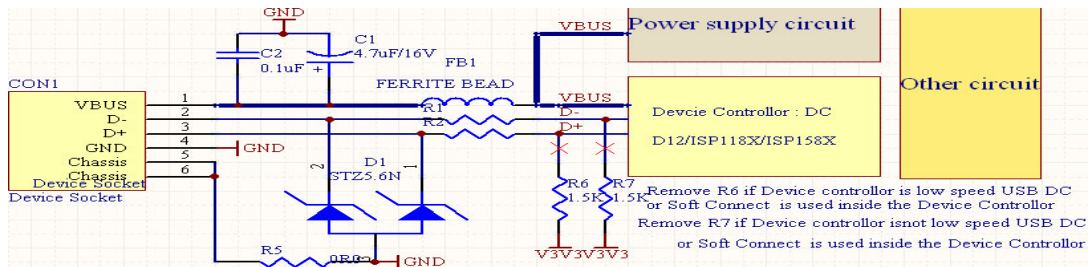


Figure 4. The physical interface reference design for a device application.

- Signal integrity on the D+ and D-

Signal integrity is affected by the impedance on the D+ and D- line. Your design must meet the USB loading specifications. The value of the serial resistor (R1/R2) should exactly follow the data sheet of the USB controller.

- ESD (Electro-Static Discharge) and EMI (Electro-Magnetic Interference)

EMI control and ESD protection circuits are generally not required, although the datasheet mentions that it is absolutely necessary. Therefore, carefully select suitable components for EMI control and ESD protection. Note that the EMI control and ESD protection circuits will affect the impedance on D+ and D-. Redo the USB test as necessary if the EMI control and ESD protection circuits are modified.

In Figure 5, the USB device is self powered from the CON3 connector, and its power supply can be switched by VBUS. Once the VBUS is lost, the power supply will be switched off. This reference design can fully overcome the 'backup voltage' failing problem of the self-powered USB device.

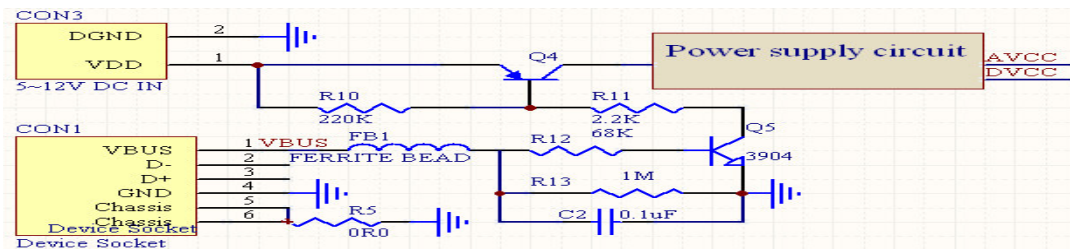


Figure 5. Power supply reference design for a self-powered USB device.

In Figure 6, this application can work in USB, Audio or UART mode and the USB connector can transfer USB, audio or UART signals. The typical applications include an MP3 player or mobile phone with only one external interface (USB mini port). Users can connect it to a charger, USB host port or headphone/microphone/speaker via the same USB mini port.

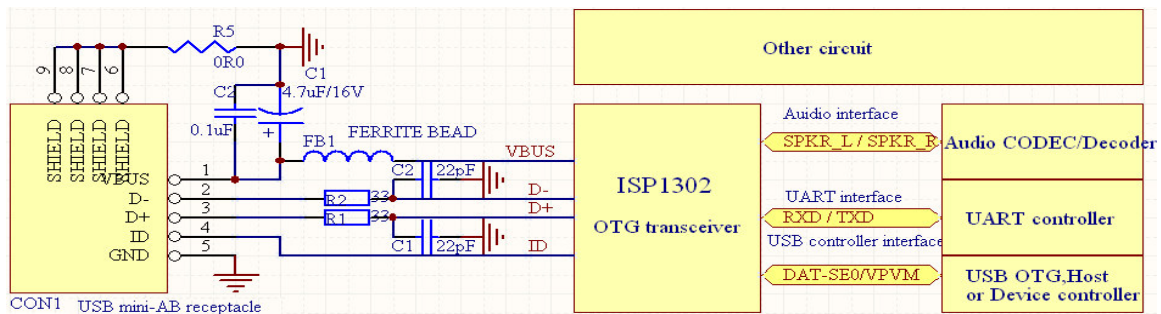


Figure 6. The physical interface reference design for signaling audio, UART or USB on the same USB port.

USB physical interface PCB design guidelines

With respect to printed circuit board design, first place the USB controller chip, USB receptacle and other major components on the unrouted board. Then route high-speed USB traces as close, short and straight as possible on the same layer whenever possible. The followings are the guidelines of the USB physical interface PCB design.

- The trace width and the space between two traces should be constant.

Maintain parallelism between DM and DP. As shown in Figure 7, the maximum trace-length mismatch between DM and DP is 150 mils. The minimum suggested spacing to clock signals is 50 mils and the minimum spacing to other signal traces is 20 mils. 7.5 mil traces with 7.5 mil spacing results in approximately 90 ohms differential trace impedance.

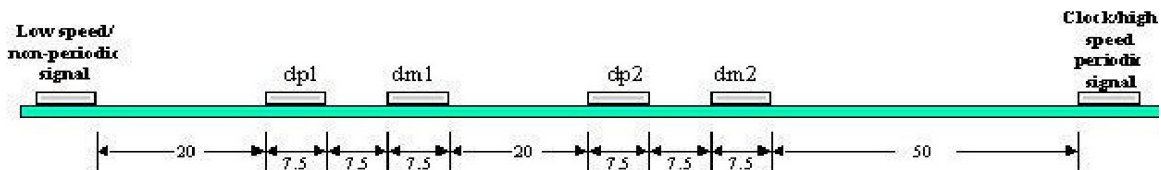


Figure 7. Recommended trade spacing is shown here in mils.

- USB signals (D+, D-) traces should avoid crossing power or ground splits and therefore must be on a continuous power system plane underneath the pair of traces (see Figure 8).

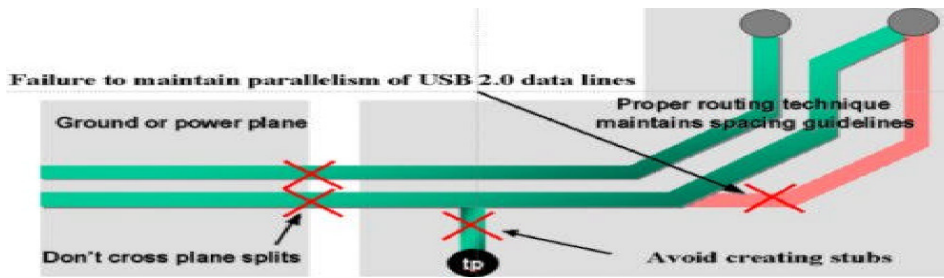


Figure 8. Violation of proper routing techniques.

- Termination resistors and pull-up resistors should be placed close to USB signals to avoid stubs (see Figure 9).

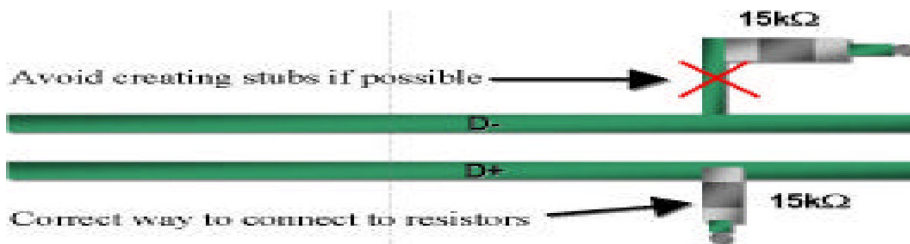


Figure 9. Creating unnecessary stubs.

- Place D+/D- in one layer. An arc turn is better than two 45° turns, and two 45° turns are better than a single 90° turn (see Figure 10).

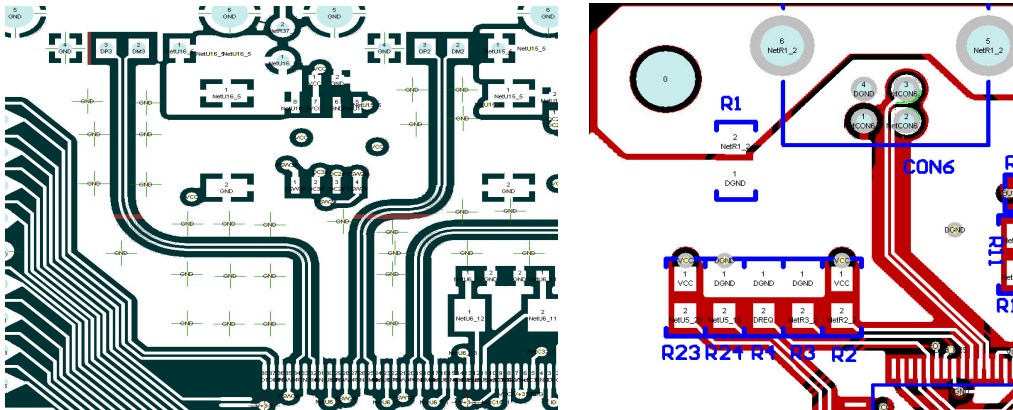


Figure 9. The reference routing of downstream port of ISP1761 and upstream port of ISP1581

USB compliance testing

Most of the USB chips on the market today have already been certified for the USB-IF's USB logos. But, if you design a new PCB board or your PCB board is modified, you will need to redo USB electrical tests. Four tests are required to pass USB electrical tests to get the logo of your product.

- High-speed signal quality

The signal quality is affected not only by the USB chips, but also by the ESD, the resistor and capacitor on D+ and D- lines, and the PCB layout of your product. All high-speed capable devices are required to perform this test.

- Full-speed signal quality

All full-speed and high-speed capable devices are required to perform this test.

- Time Domain Reflectometry (TDR)

TDR is a way to evaluate impedance values and variations along a transmission line such as board, cables, connectors or a microstrip.

- In-rush current

Limiting in-rush current requires controlling the on-board capacitance between VBUS and ground and minimizing contact arcing, thereby prolonging connector contact life. To help minimize the in-rush current, reduce the on-board capacitance between the VBUS and GND of the USB device and increase the VBUS serial resistance.

Conclusion

USB technology, which uses a much higher data transfer rate than many others communication methods, has brought true innovation to world of connectivity – transforming it from complexity and confusion to something that is easy and clear. Designing USB products, of course, is not quite so easy. It requires the engineer to observe a lot of rules that are specified by the USB standards. With a clear understanding of the general hardware design rules for the USB schematics design, PCB design and USB compliance testing, the engineer can be assured a greater chance of implementation success.

ABOUT THE AUTHOR

Guo Yang Bin is a Senior Engineer in product line USB/WUSB of NXP Semiconductors.