Scenarios of ESD Discharges to USB Connectors

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Abstract–Different real world scenarios which may cause stress voltages on USB connected devices are investigated. This study identifies ESD discharge scenarios and their respective current and voltage levels, stress duration and the rise times for different USB cable shield types.

I. Introduction

Electronic systems have to tolerate electrostatic discharges (ESD) in a typical user environment. The existence of badly shielded cables and poor contact between the shield and the connector requires studying real world waveforms for USB cable discharge events (CDE) [1]. A related study analyzed cable discharge events for Ethernet cables [2]. The coupling of ESD via shields was modeled using circuit and numerical methods in [1] and [3]; the work in [3] focuses on determining the disturbance on the loads connected to the shielded cable.

If a charged cable is inserted into a connector a discharge occurs. Throughout this paper we name this a "plug-in event". Publication [1] determines the robustness of electronic systems for a USB plug-in event using non-shielded and shielded cables. The ESD stress waveform due to the plug-in event was analyzed using measurement and simulation methods.

The USB cable connected devices are potential sources of CDE events. The CDE events occur because of the USB cable being charged and then discharging to the USB connector of the connected device. Typical examples include discharge scenarios such as an ESD to USB drive with no shield, a USB cable connected to cellphone inserted into a grounded device such as a personal computer (PC), a USB HUB connecting multiple electronic devices together via USB cables, etc. The goal of this study is to understand the range of stress levels seen by the USB 2.0 A/B (type A and type B connectors) cable connected devices due to various USB cable discharges as a function of the charging scenario, cable shield quality, and cable connections. Two scenarios based on different USB 2.0 cable connections are investigated experimentally. The first scenario described in Section III, is based on discharge into USB connected devices such as a USB 2.0 cable connected to the PC and cellphone. The second scenario described in Section IV, is based on discharge into a USB connector during a plug-in event such as a charged USB 2.0 cable connected to a cellphone on one end and inserted into a USB connector of a PC.

USB CDE events may cause potential damage to the USB connected devices. Hence, it is useful to study the range of stress levels observed for different USB cable discharge scenarios. The experimental current/voltage stress levels can be used as a reference or design guideline for the EMC/ESD engineers to design protection circuits to protect the electronic devices from the experimentally obtained stress levels on the I/O signals.

II. Overview of Discharge Scenarios

Various USB discharge scenarios are possible. For example, the direct ESD discharge to a USB drive, or a charged human holding a cable and plugging it into a USB connector. The focuses of the study are the discharge into a USB connected device and a discharge into a USB connector during a plug-in event. They are illustrated in Figures 1 and 2, respectively.

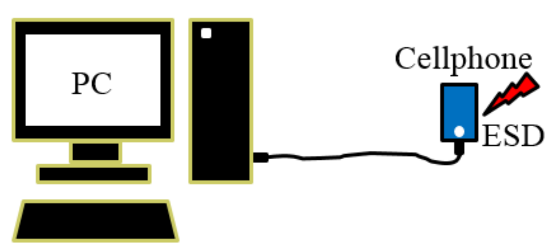

Figure 1: Discharge into a USB connected device scenario.

A cellphone is connected to a grounded device such as a PC by a USB 2.0 cable. A charged human discharges into the cellphone and the ESD discharge source point is at the cellphone. The current flows via the USB cable to the grounded PC. In Figure 2 a charged cable is inserted into the PC. The other end of the cable is connected to a USB device (a cell phone is depicted) which leads to a plug-in event.

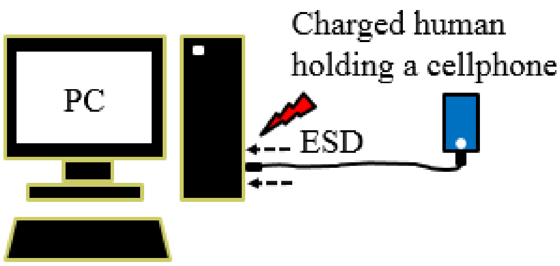

Figure 2: Discharge into a USB connector during a plug-in event.

In this study, randomly purchased USB 2.0 A/B cables (USB 2.0 type B to type A) are classified into three different types based on their cable shield quality. An RLC meter was used to measure the USB connector shell to shell DC resistance of the cable. This gives a first impression on the shield's properties. If the resistance is within several hundred milli-ohm and does not change much when the cable is twisted, the cable is classified as a well-shielded cable. If the resistance is in the range of 1-80 ohms and it changes during twisting, the cable is classified as a badly shielded cable. A few of the USB 2.0 cables purchased had no shields. In addition, we cut the shields of a few additional USB cables. Cables with cut or no shield are classified as an unshielded cable. Every USB cable is labelled with a cable identifier number, which helps to identify a cable used for a specific measurement.

III. Discharge into a USB Connected Device

The measurement results are post-processed to correct for the attenuation introduced by the coax cables and the high voltage pulsed attenuators [4]. The measurement set-up is shown in Figure 3.

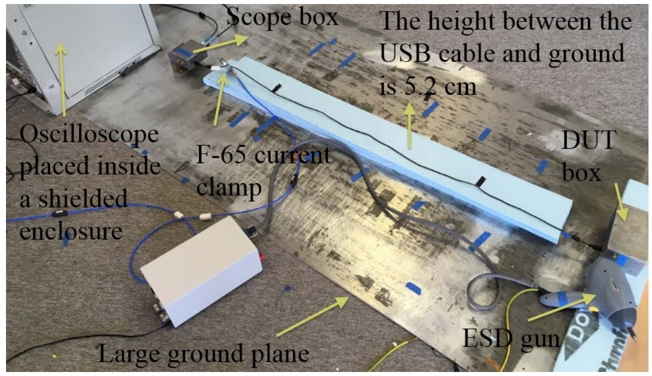

Figure 3: Measurement setup for the discharges into a USB connected device scenario.

A block diagram for this series of tests is shown in Figure 4. The USB cable was connected to the DUT box on one end and to the scope box on the other end. A 2 kV contact mode ESD was injected into the DUT box, resembling a situation in which an ESD occurs to a USB connected device (such as a USB drive) connected to a PC. For such a situation data traffic can be active, while there cannot be data traffic during a plug-in event. The following figures show the common-mode current on the USB cable as captured by the F-65 current clamp close to the scope box and the voltage induced between D+ and ground on the scope box side. The measured waveforms for the well-

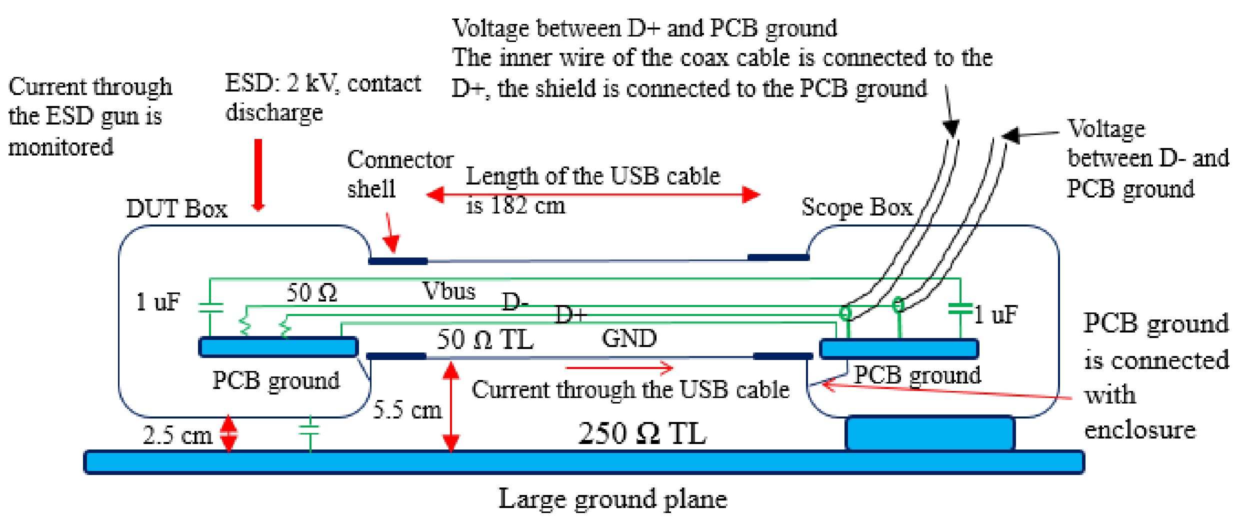

Figure 4: Discharge into a USB connected device.

shielded, badly shielded, and unshielded USB cable types are shown in Figure 5.

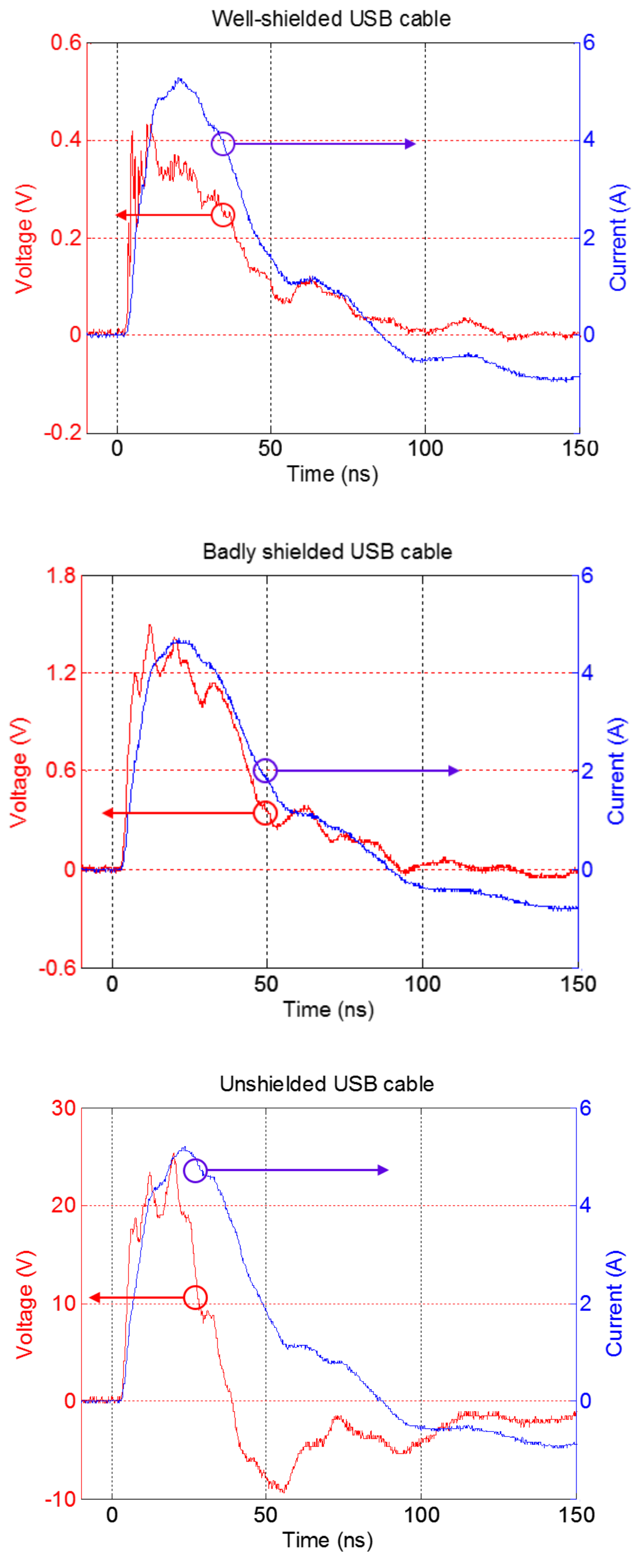

Figure 5: Common-mode current and voltage induced between D+ and ground for a discharge into a USB connected device scenario. Data is shown for well-shielded, badly shielded, and unshielded type USB cables. The ESD gun is discharged at 2 kV in contact mode.

At 2 kV contact mode a noise voltage of 0.4 V is measured for the well-shielded cable, 1.2 V is measured for the badly shielded cable, and approximately 20 V are measured for the unshielded cable. The contact mode ESD gun discharge results have a linear relationship to the ESD gun voltage setting. If the same measurement is performed at a higher ESD gun voltage, the amplitude of the measured waveform is expected to increase linearly. At 2 kV for an unshielded cable the 20 ns current amplitude is approximately 5 A as shown in Figure 5. The initial peak current would be 8x3.75 A, but it returns via the DUT box to ground capacitance and is therefore not visible in the F-65 current clamp data. If the ESD gun would be set at 8 kV, a current amplitude of 20 A is to be expected. It should be noted that the current measured using the F-65 current clamp is the common-mode current and it is not a function of the type of USB cable used.

The designer is often interested in a realistic worst case specification. Although possible in some rare situations, we disregarded direct discharges into pins and considered the discharge into a USB connected device for the case of an unshielded USB cable as the realistic worst case.

In this case it is reasonable that the common-mode current splits equally over the four wires of the USB 2.0 cable. Approximately a 5 A current will flow on each of the four wires, GND, Vbus, D+, and D-. The assumption is based on the fact that all wires are connected via low impedances to ground. The 5 V (Vbus) is usually connected via a large value capacitor, and D+ and D- have ESD protection diodes either on the board or in the IC. In any case, these diodes will provide a low impedance path to ground. As all wires have similar termination resistances during the ESD event it is reasonable to conclude that the current will be equally split between the four wires. A current of 5 A with pulse widths of 10's of nanoseconds on the I/O lines (D+ and D-) can cause hard failures. Here the pulse width is not determined by the cable length, but by the source. The cable length is important for discharges that are excited by a differential voltage, e.g., a voltage between a shield and D+. However, the cable is connected to a DUT, thus no static voltage can be maintained between a shield and a wire, or between D+ and D-.

IV. Discharge into a USB Connector during a Plug-in Event

When a charged person holds a cellphone connected to a USB cable, the charge will be distributed on the USB

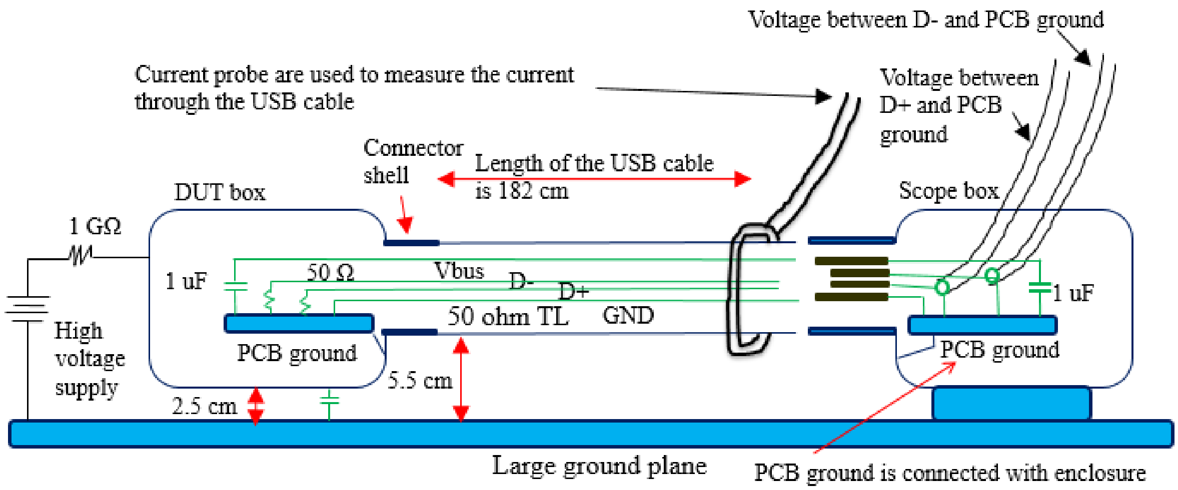

Figure 6: Discharge into a USB connector during a plug-in event.

cable via polarization and/or charge migration. When the person inserts the USB cable into a grounded PC, ESD occurs. Figure 6 illustrates the test set-up used to investigate plug-in events. Because of the design of the USB connectors, the shell will contact first, then the GND/Vbus pin follows, and finally D+/D- will contact. Even if the cable is unshielded, GND/Vbus will contact first. This contact sequence, as shown in Figure 7, ensures that the currents on D+ or D- are rather small, much smaller than in the case discussed in Section III.

A. Plug-in Event Sequence

During the plug-in measurements the cable was charged via 1 GΩ. The unconnected end of the USB cable was held by hand using insulated gloves, then the operator inserted the cable into the scope box. Multiple pulses can occur during the insertion process. To be able to capture pulses that occur with microsecond delay times, a fast re-trigger mode was selected. The measurement was performed using ultra-segmentation (Rhode & Schwarz) or sequence mode acquisition (Teledyne LeCroy) activated on the oscilloscope. The oscilloscope can be triggered on the channel connected to the F-65 current clamp or the D+ signal.

Connecting the DUT box via a high value resistor to a high voltage supply requires consideration of the re-charge times. It must be ensured that the recharging time of the DUT box to ground capacitance should be slower than the total time for all sub-discharges during the plug-in ESD. Otherwise, the cable could be recharged during the sequence.

The USB cable connector may not always enter the scope box in parallel to the connector. It may hit the scope box at an angle to be aligned for entering the scope box connector. This action leads to multiple triggers for a single plug-in event measurement. A possible sequence is illustrated in Figure 7.

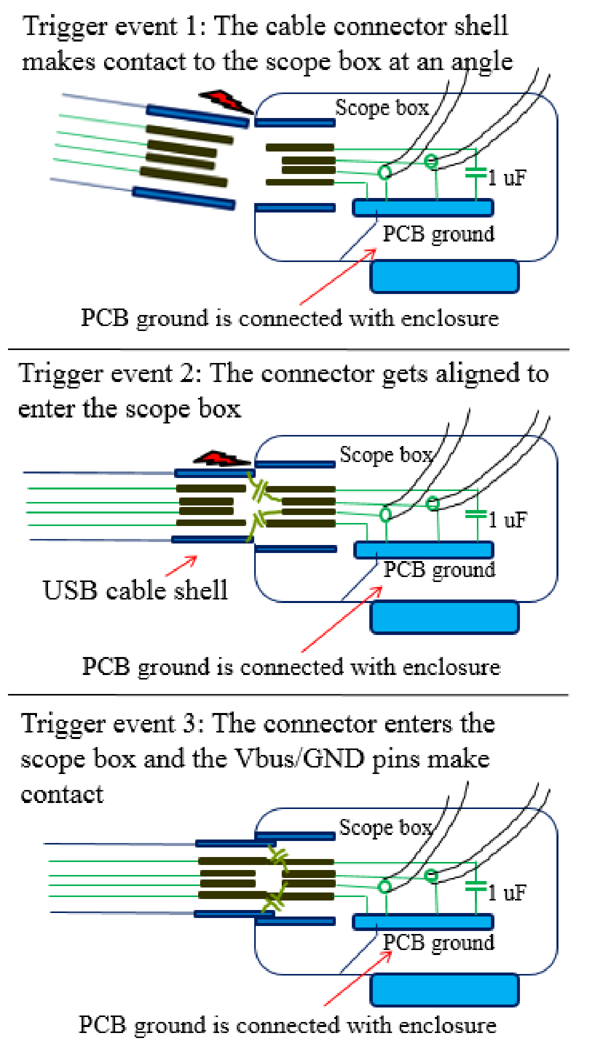

Figure 7: Plug-in event sequence is explained using three triggered events. It should be noted that multiple triggered events can occur in a plug-in measurement.

B. Plug-in Event Measurements

The first waveform discussed is based on charging the DUT box to 8 kV and using a well-shielded cable. In this set-up the USB cable behaves as a transmission line (wire above the ground plane) having an impedance approximately equal to 245 Ω. For this case, a set of measured typical waveforms during a plug-in event are shown in Figure 8 and 9.

In this measurement set-up, the USB cable GND wire was directly connected to the scope box PCB ground. The USB cable Vbus wire was terminated with a 1 uF capacitor on the PCB inside the scope box. Both of these wires were not monitored during the plug-in event measurements. However, emphasis was placed on the I/O lines (D+ and D-) of the USB 2.0 cable. The waveforms induced on the D+ and the D- I/O signal lines due to the plug-in event were comparable.

Figure 8 shows the first triggered sequence of the plug-in event measurement. The F-65 current clamp, D+, and D- channels can be used to trigger the oscilloscope. However, the oscilloscope was triggered on the D+ channel and the ultra-segmentation/sequence mode was activated. It should be noted that the oscilloscope is triggered on the D+ channel to observe the waveforms induced on the I/O signal lines due to the plug-in event. This leads to a few of the initial current waveforms through the USB cable not being acquired by the oscilloscope.

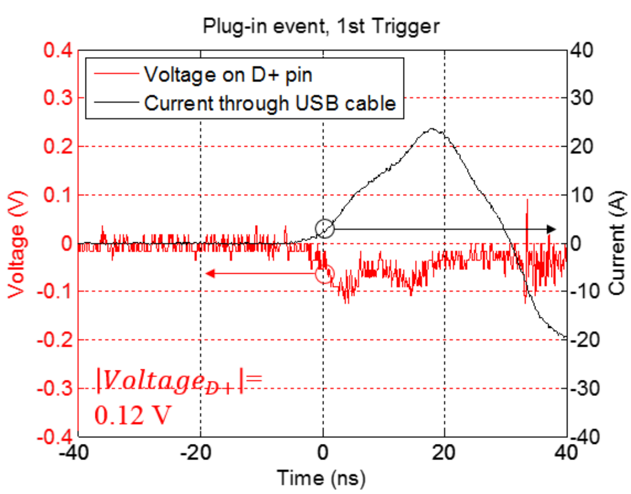

Figure 8: Discharge into a USB connector during a plug-in event. One of the measured waveforms for the first triggered event is shown.

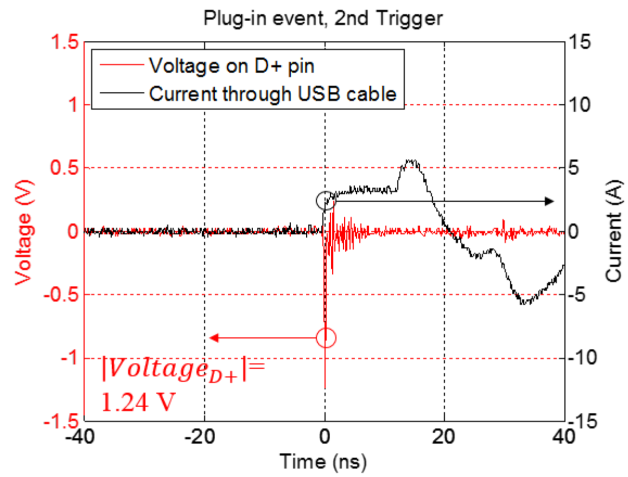

Figure 9: Discharge into a USB connector during a plug-in event. One of the measured waveforms for the second triggered event following the first triggered waveform in Figure 8 is shown.

During the plug-in sequencing (the oscilloscope was triggered on the D+ channel), the first event caused lower ESD-induced voltage (0.12 V shown in Figure 8) on the D+ pin because most of the current flowed between the USB shell and the scope box. The following plug-in triggered events will have higher ESD-induced voltage on the D+ pin (1.24 V shown in Figure 9). This behavior is due to the plug-in event sequencing illustrated in Figure 7.

C. Influence of USB Cable Shield Quality

To investigate the influence of the USB cable shield quality, the DUT box is charged to 8 kV for each cable type. The measurement set-up is shown in Figure 6. As air discharge is involved, the experiment is repeated four times and the highest observed voltage on the D+ pin is reported in Figure 10. D+ is terminated into a 50 ohm oscilloscope channel.

The well-shielded USB cables (shield resistance in mΩ) #15, #56, and #11 have lower peak voltage in the range of 2 V. The badly shielded USB cables (shield resistance in 10s of Ωs) #22, #20, #6, and #4 have peak voltage up to 3.4 V. The unshielded USB cables #17 and #27 have peak voltage up to 12.5 V. The difference in well-shielded and badly shielded USB cable-induced voltages on the D+ pin is less than the stress level seen for an unshielded USB cable. The comparison of different USB cable shield quality during a plug-in event is shown in Figure 10.

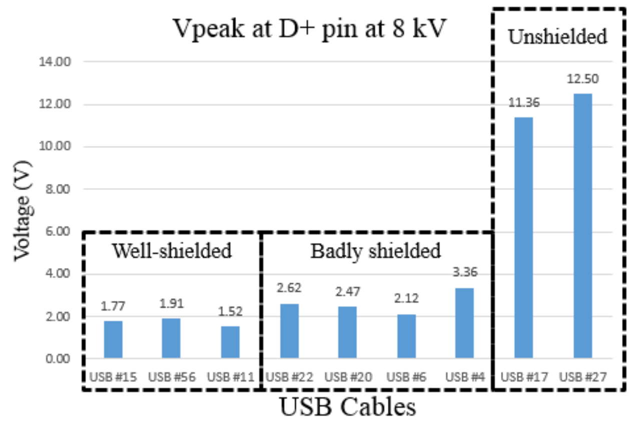

Figure 10: Comparison of different USB cable shield types for the DUT box charged at 8 kV using a high voltage source.

Discussion and Conclusion

Two USB 2.0 CDE scenarios were investigated. The first scenario investigated ESD on a USB cable connected system. The second scenario investigated a plug in event of a device connected USB cable.

In the measured waveforms for the first scenario, the discharge into a USB connected device shows pulse widths on D+ (I/O signal) of 20-40 ns and 2-10 ns rise times at 2 kV contact mode ESD to the USB connected device. At 2 kV discharge level, a voltage of 0.4 V at the 50 Ω oscilloscope channel was developed. This related to a current of 8 mA for the well-shielded cable. For the badly shielded cable a voltage of 1.2 V related to approximately 24 mA, and for the unshielded USB cable a voltage of 20 V related to a current of 400 mA. In relative comparison, the unshielded cable led to a higher induced stress on the I/O lines (D+ or D-). If 8 kV is set as the expected reliability level for the user environment, then the ESD protection needs to be able to handle 5 A for 10s of nanoseconds on D+ and D- at the same time. Here, damage, but also latch-up or soft failures may need to be considered.

The plug-in of an already device-connected cable has a lower chance of causing damage. The voltages induced in D+ by a discharge between a USB cable and a grounded connector during the insertion show less than 5 V at 8 kV for the well-shielded and the badly shielded cables. For the case in which the USB cable has no shield, approximately 12 V would be induced at 8 kV. It should be noted that even though this voltage amplitude may look significant, the duration of the pulse width is less than 10 ns as shown in Figure 9. The short pulse width suggests that the plug-in event is less likely to cause damage. Soft failures may still be possible if a cable is inserted into a USB HUB servicing multiple USB connections. Here, other active connections could be interrupted by the insertion of a charged USB cable even if the voltage is rather small. The designer needs to accept that a large portion of the marketed cables either have no shield. We found about 1/3 of the USB 2.0 cables had no shield or no shield to USB connector shell connection. ESD protection circuits should be designed to protect the electronic devices from CDE stress levels resulting up to 5 A for 10s of nanoseconds on the D+/D- I/O lines for an 8 kV device reliability level. The worst case scenario is due to the use of unshielded USB cables by users to connect various electronic devices.

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