AN2157

Transient Protection in Power Over Ethernet Applications

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INTRODUCTION

Power over Ethernet (POE) applications enable standard Ethernet cables to carry both data and power to remote devices, greatly simplifying the networked system. POE reduces the number of cables needed to connect networked devices and enables systems to access locations where power is not readily available. Applications such as industrial control, video monitoring, and remote sensing are just a few of the many examples that can take advantage of the POE specification. Because POE shares the cable with the standard Ethernet protocol, it requires a higher DC voltage (57V) to traverse the >100m cable length and still provide power to the device.

POE systems must be designed to protect sensitive communication circuitry from transient events, such as Cable Discharge Events (CDE), or Electro Static Discharge (ESD) events. Cable Discharge Events are caused when the high voltage signals make contact through the Ethernet cable. It is important to understand how to choose the right components to provide transient voltage protection to your POE application. This application note will provide a detailed analysis of the sources of transient voltages in POE designs, and recommendations to choose the right components to provide protection against these transient voltages.

The Figure 1 schematic example summarizes recommended specifications to focus on for POE transient protection.

FIGURE 1:   PROTECTION CIRCUIT
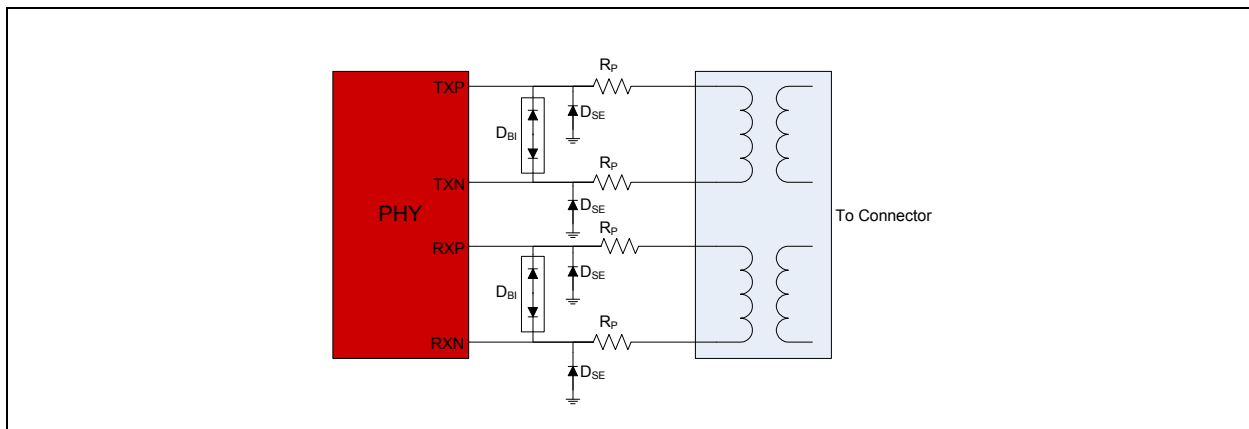
- **Required Minimum TVS Protection Diode:** D_{BI}
- **Additional Rapid Disconnect/Connect Protection:** D_{BI}, D_{SE}, R_P

Table 1 summarizes important parameters to take into account while selecting the right TVS diode for PoE design.

TABLE 1:   TVS DIODE SELECTION SPECIFICATIONS

Parameter	Single Ended (D_{BI} implement with two diodes)	Combined (D_{BI}, or D_{BI} and D_{SE} in one part)
Working Voltage	3.3V	3.3V
1A Clamp Voltage	<5V (Note 1)	<6.6V(Note 2)

TABLE 1:   TVS DIODE SELECTION SPECIFICATIONS (CONTINUED)

Parameter	Single Ended (D$_{BI}$ implement with two diodes)	Combined (D$_{BI}$, or D$_{BI}$ and D$_{SE}$ in one part)
Forward Voltage (Negative V Protection)	<1.8V (Note 1)	NA
Capacitance	<5 pF loading	
Leakage Current	<1.0 µA	

Note 1: TVS steering diodes with Zener clamping should be used.

2: When using two single ended TVS diodes, the sum of the Forward Voltage and 1A Clamp Voltage must be less than 6.6V.

References

The following documents should be referenced when using this application note:

• IEEE 802.3af Specification
• IEEE 802.3AT Specification
• Littelfuse SP4020 TVS Diode Datasheet
• Semtech uClamp3301D Datasheet
• ProTek SR2.8 Datasheet

POWER OVER ETHERNET

Power Negotiation

Power over Ethernet (POE) and POE+ specify two types of devices that exist in a system as defined in the IEEE802.3af and IEEE802.3at, respectively. The Power Sourcing Equipment (PSE) sources power. This can be located inside the Ethernet switch or hub or in series between the Ethernet switch and the powered device. The PSE injects from 44VDC (802.3af) to 57VDC (802.3at) on the center tap of the Ethernet magnetics of one differential pair, and enables a return path on a different pair. Because the two lines are differential, the power is shared equally along both lines and the transformers in the magnetics will only pass the differential signals to the physical communication chip (PHY). Microchip PHYs are designed to tolerate the 5V voltage swings that can occur during Ethernet communication, but they are not designed to handle voltages larger than a 7V differential.

The Powered Device (PD) is designed to handle power on any of the differential pairs or all four pairs for "High Power" POE. The PD device detects the power on the differential pairs, and starts to draw current from the center taps of the Ethernet magnetics. As the system powers up, the PHYs begin communication.

**FIGURE 2:   SWITCHING CONNECTIONS**
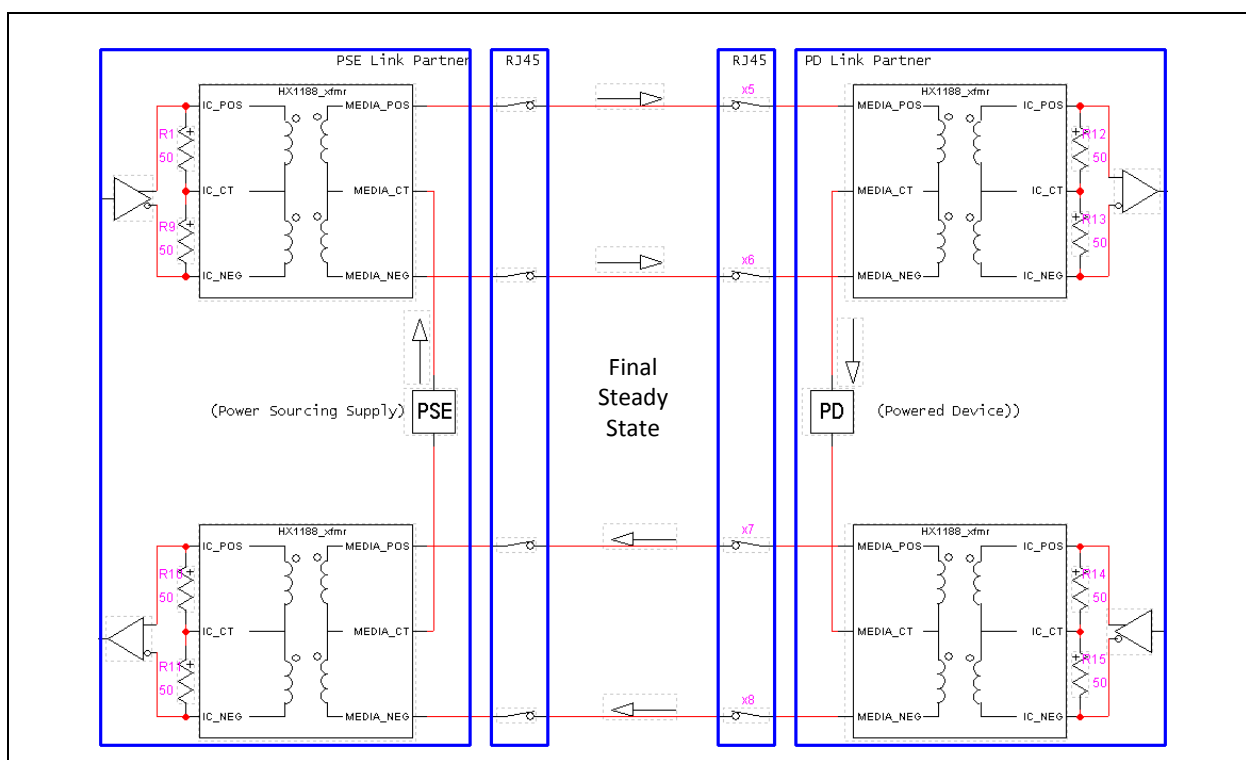
Power Stages

The PSE supports three stages of power. The PD Detection state starts with the PSE generating a 30V open circuit voltage with a current limit of 5 mA. Once a PD has been detected, the PSE moves on to the PD Classification state, where it puts out a maximum 20.5V with a 100 mA limit. PD devices can conform to 5 different power classes. The PD classes are identified by the current draw during this state. Once the class has been identified, the PSE determines if it will support that class, and then increases the current limit and supply voltage. Table 2 details the different PD classes and their power requirements. The maximum voltage in the power on state is 57V with a maximum current limit of 0.600 mA. The final state is the Power On state.

TABLE 2:   POE DEVICE CLASSES

Class	Minimum Power
0	15.4W
1	4.0W
2	7.0W
3	15.4W
4	P_{Type}
4 (Type 1)	57V X 0.35A = 19.95W
4 (Type 2)	57V X 0.60A = 34.2W

FIGURE 3:   PSE SIGNALING POWER STATES
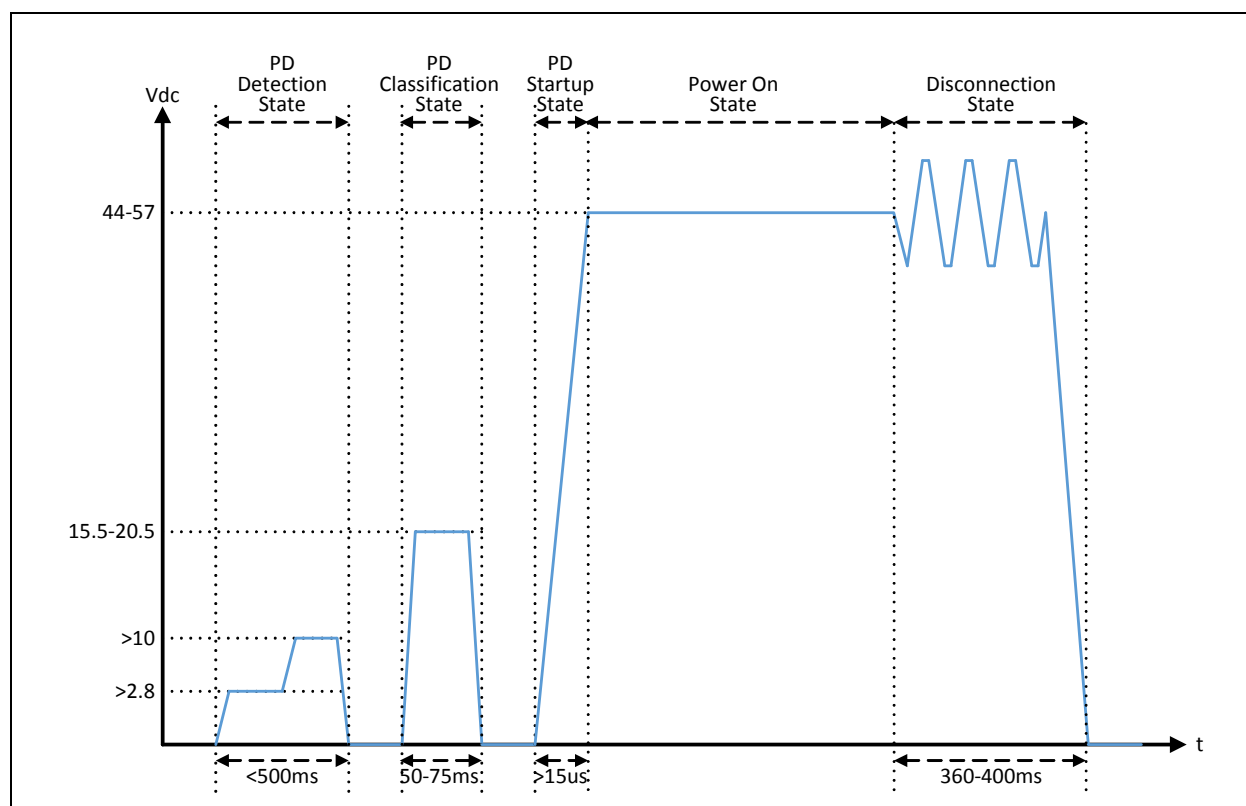
Power States

There are three different voltage potentials that can be on the Ethernet cables in a POE system, these numbers depend on the state of the PSE and impact the level of protection needed.

TABLE 3: POWER STATES

Power State	Max Voltage	Max Current
PD Detection	30V (worst case open circuit)	0.005A (worst case short circuit)
PD Classification	20.5V	0.100A
Power On	57V	0.600A

TRANSIENT VOLTAGE EVENTS

When a cable is first inserted, there is an initial rush of voltage on the pins as the PSE is first connected. The design specifications of the Ethernet connector and the human variability of pressure and angle creates a condition where some signals make contact before others. This variability in the pins can happen in two ways: First, the connections can 'bounce', connecting and disconnecting rapidly. This can happen on both the positive and negative pins, with different timing. Figure 4 illustrates this bounce. 5V was placed on a wire connected to a typical RJ45 connector, and the connector was inserted into a receptacle, the differential pins were probed to record the timing differences.

### FIGURE 4: CONNECTION BOUNCE AND SKEW EXAMPLE
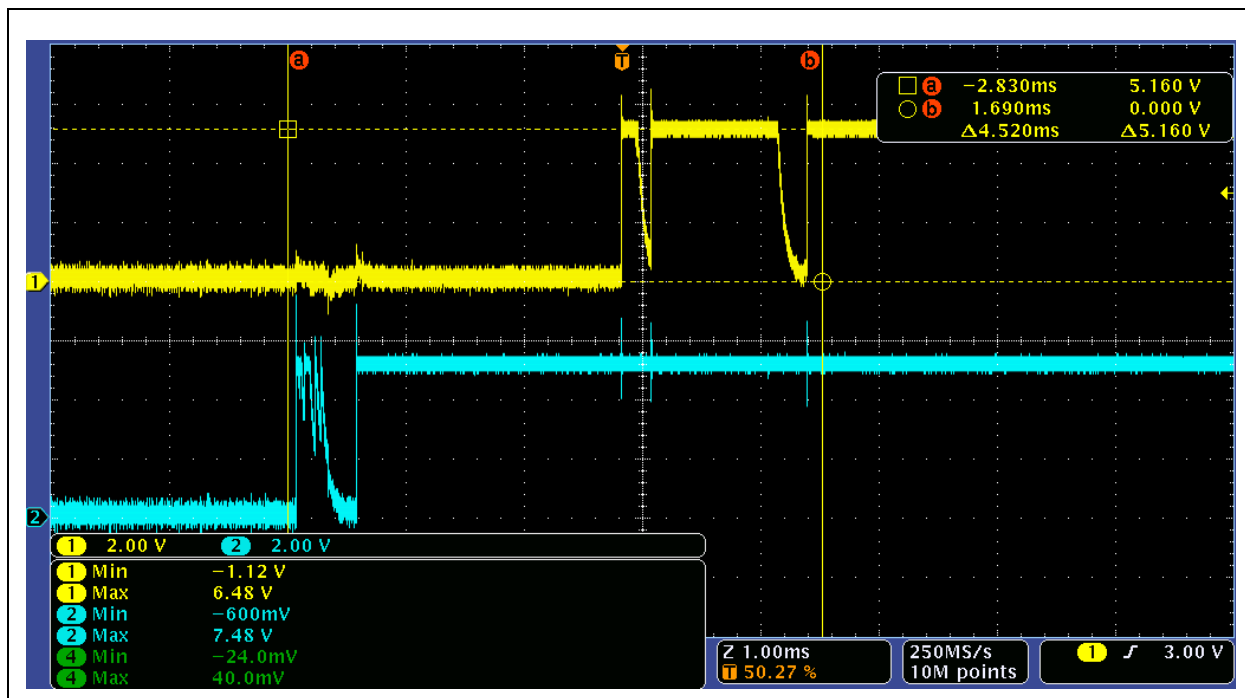
The second variation is when one half of a differential pair is connected while the other half is disconnected. This timing 'skew' means that the differential pair is no longer balanced. The transformer initially sees the voltage difference between TX+ and TX- as an AC signal that is passed through to the PHY. During this short period, the high POE voltages are applied to the PHY and can damage the sensitive communication components.

Connection Sequence

During the connection process, the differential pairs may not all connect at the same time, these transition states cause the transformers to pass all of the energy to the other side until they saturate due to the high voltage. This occurs because the transformers only pass changing signals, or AC signals to the other pins. Because the positive signal is at ~48V and the negative signal is still disconnected, it is seen as an AC event. An ideal connector has all the pins uniform and is inserted at a perfect angle.

FIGURE 5:   IDEAL CONNECTION
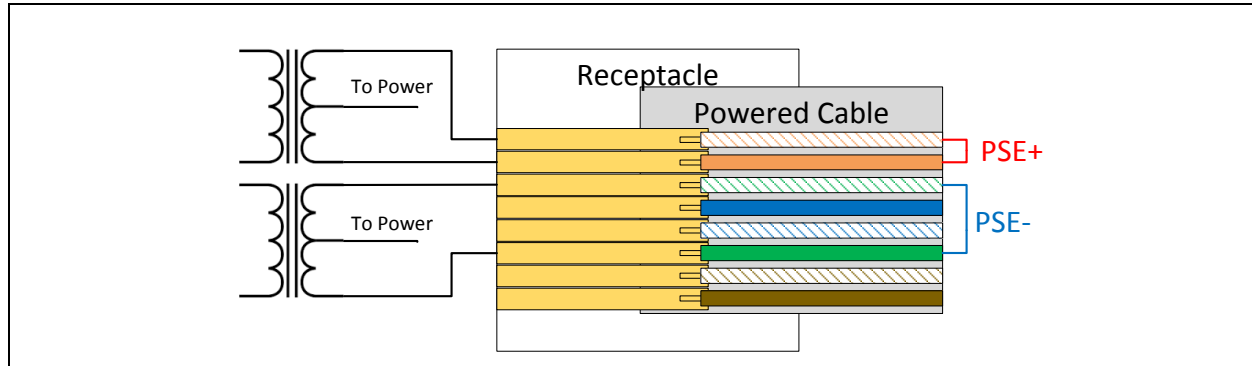
The following is an example of the connection process where all pins do not attach at the same time. As long as one of the pins on the power pair and the return pair are connected, current will flow and voltages will be observed on the lines. In the initial state, nothing is connected and the PSE supply draws no current.

FIGURE 6:   INITIAL STATE
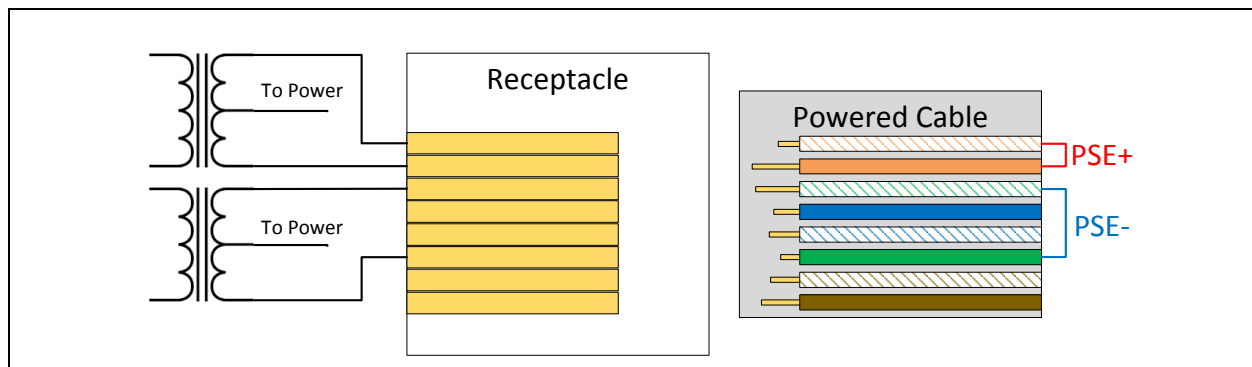
During a partial connection, at least one of the PSE supply lines and return lines are connected to the PD, completing the power circuit. Current now flows into the PD system, but the transformer lines are not balanced. The partial connections can be any combination of the pins, and sometimes the transformers will be balanced, sometimes they will not. This also determines where the transient voltages will occur, and how much power will be transferred across the transformer to the PHY. The worst case transients occur when the return line is fully balanced and the supply line has one pin connected. The full power is transferred to only one communication pair.

FIGURE 7: **PARTIAL CONNECTION**
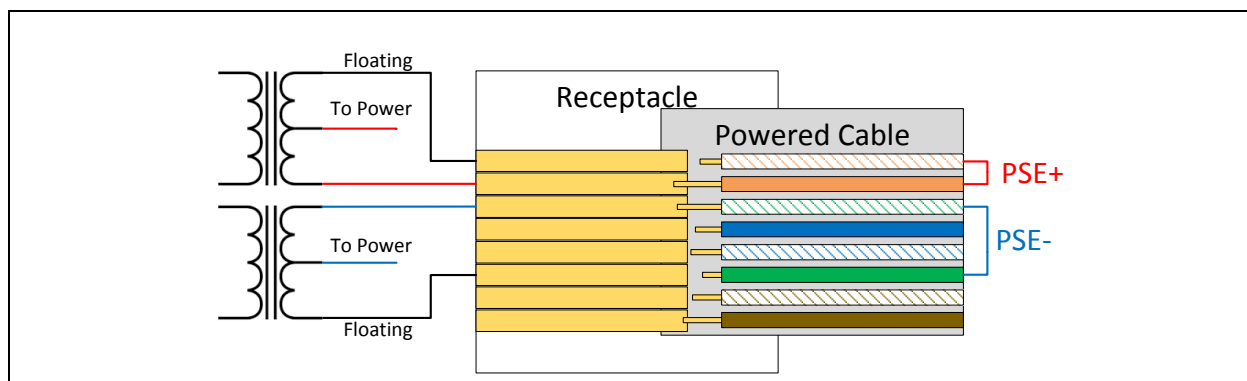
This differential voltage then gets passed through the transformer until it saturates, blocking the energy. The time from when the voltage is passed through the transformer to when the transformer saturates varies based on the power (voltage and current limit) exposed at the connector side of the magnetics.

The final state balances the differential inputs to the transformer, and the steady state is reached. This generally happens within 10 ms.

FIGURE 8: **FINAL STATE**
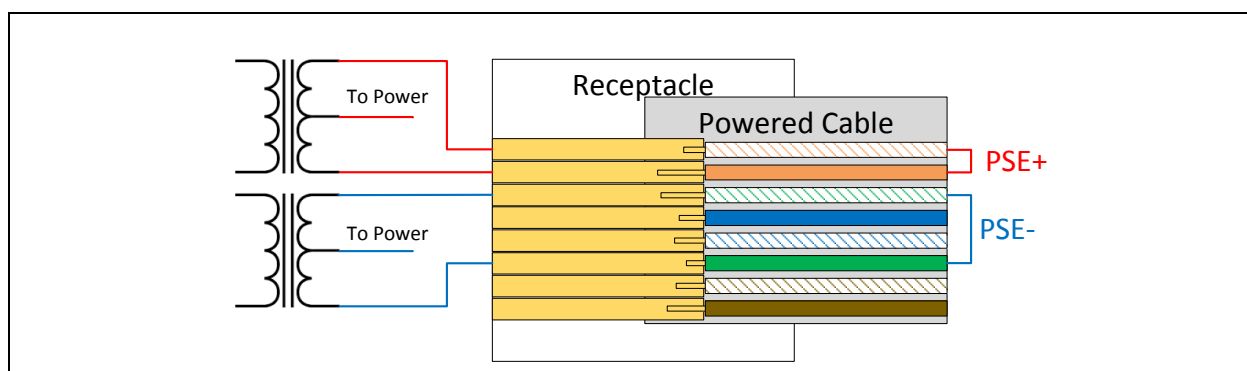
TRANSIENT PROTECTION

Now that the cause of transient responses is understood, the next step is to choose the proper protection or clamping circuitry to prevent high voltages from reaching the communication pins of the Ethernet PHY.

The power transferred is affected by the current limit of the Power Sourcing Equipment. Since the PSE has different power states, there are two types of events that can generate transient voltages:

* Initial Connection Transient
* Rapid Disconnect/Connect Transients

Initial Connection Transient

With the initial connection transient, the PSE is in the PD Connect or PD Classification state. This is the most common transient seen in real world applications. The PSE limits the current to 100 mA for POE+ applications, so the transients will have little power behind the voltages. A bidirectional Transient Voltage Suppression (TVS) diode, or two single ended TVS diodes connected between the TX+ and TX- pins (no GND between) is needed to absorb the transient voltage.

The communication lines (TX+ and TX-) are differentially coupled, so the internal circuitry that generates the signal are tied together. A bidirectional protection circuit is needed because the part is damaged when the difference between differential signals exceeds 7V. When selecting the bidirectional TVS diode, there are a few parameters to look at:

Clamping Voltage - This is the most important parameter while selecting a TVS diode for transient protection. TVS diodes specify the voltage clamped at 1A (Vc), this voltage needs to be less than 6.5V to prevent damage to Microchip Ethernet PHYs. The PD Detection state specifies a 30V maximum, but this is with a 5 mA limit, which reduces the power transferred through the transformer.

Working Voltage - The voltage that the diode is designed to completely pass is the working voltage (Vw), which generally must be at least 3.3V to support Ethernet communication. This specification is not very strict, as it may affect 10BT signals with short cables, but it will not degrade signals enough to prevent communication.

Loading Capacitance - TVS diodes have an inherent voltage dependent loading capacitance, which needs to be taken into account. Microchip recommends using TVS diode with low capacitance (ideally <5 pF). With higher loading capacitance (>10 pF, in most cases), there is a likelihood that the Ethernet PHY fails the three voltage levels 100BASE-TX signal (MLT-3) compliance test. However, the device can be still operational and allows for successful communication.

Figure 9 shows MLT-3 eye diagram, captured on KSZ8081 Ethernet PHY with TVS protection using Bourns CD143A-SR2.8 diode and Fairchild MBR0520LCT-ND Schottky rectifier on cable pairs with total ~10 pF capacitance.

FIGURE 9: **KSZ8081 ETHERNET PHY WITH TVS PROTECTION**
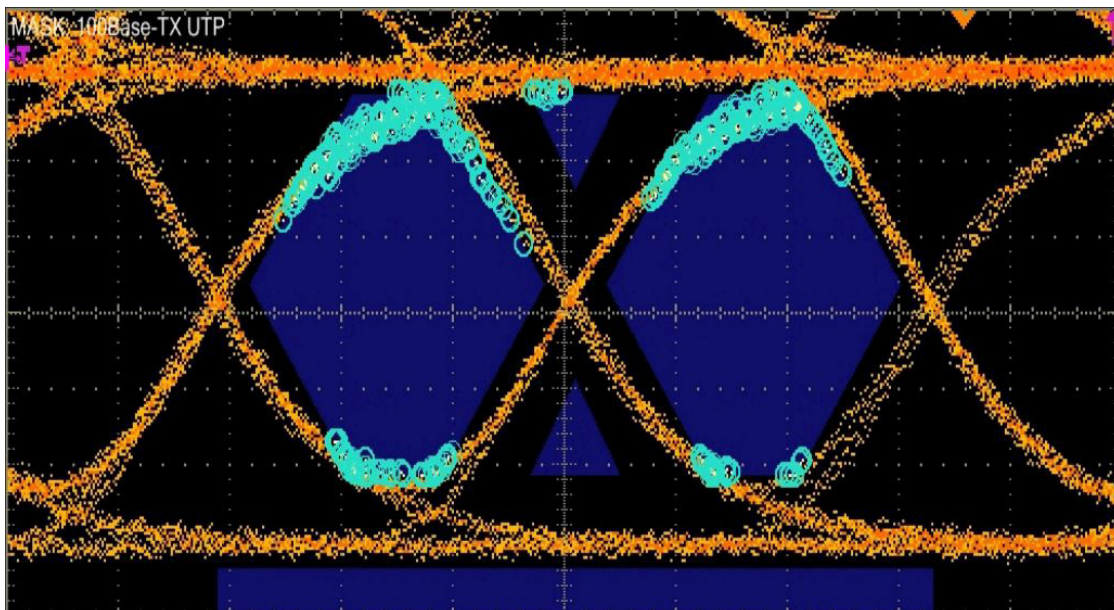
Due to high capacitance of the TVS diode protection, the MLT-3 test for above eye diagram has failed the compliance test. However, the device has been found to be still operational and allows for normal 100BASE-TX communication.

Figure 10 shows a capture of the differential signals at the PHY when no protection circuitry is installed. The transient voltage measured showed up to ~16V on systems with no protection, other observations have been as high as 24V. The voltage is measured on both pins to get the 16V.

**FIGURE 10:   INITIAL TRANSIENT**

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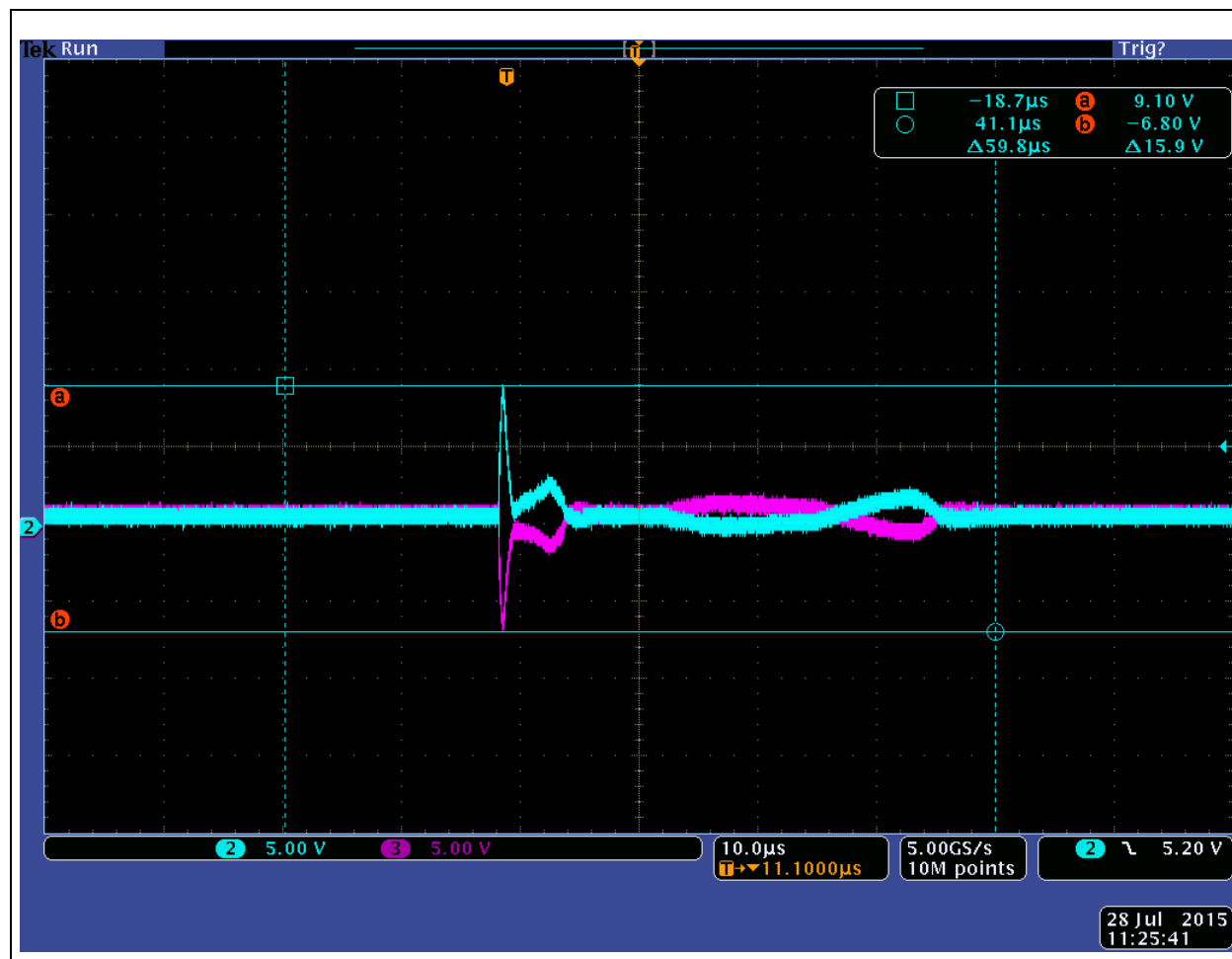
The transient waveforms were microseconds long and, at 16V, can damage the PHY. A TVS diode was selected that did not meet the required clamp voltage, and although the transient was reduced, it was not enough to prevent damage to the PHY.

FIGURE 11: **TRANSIENT WITH LIMITED PROTECTION**
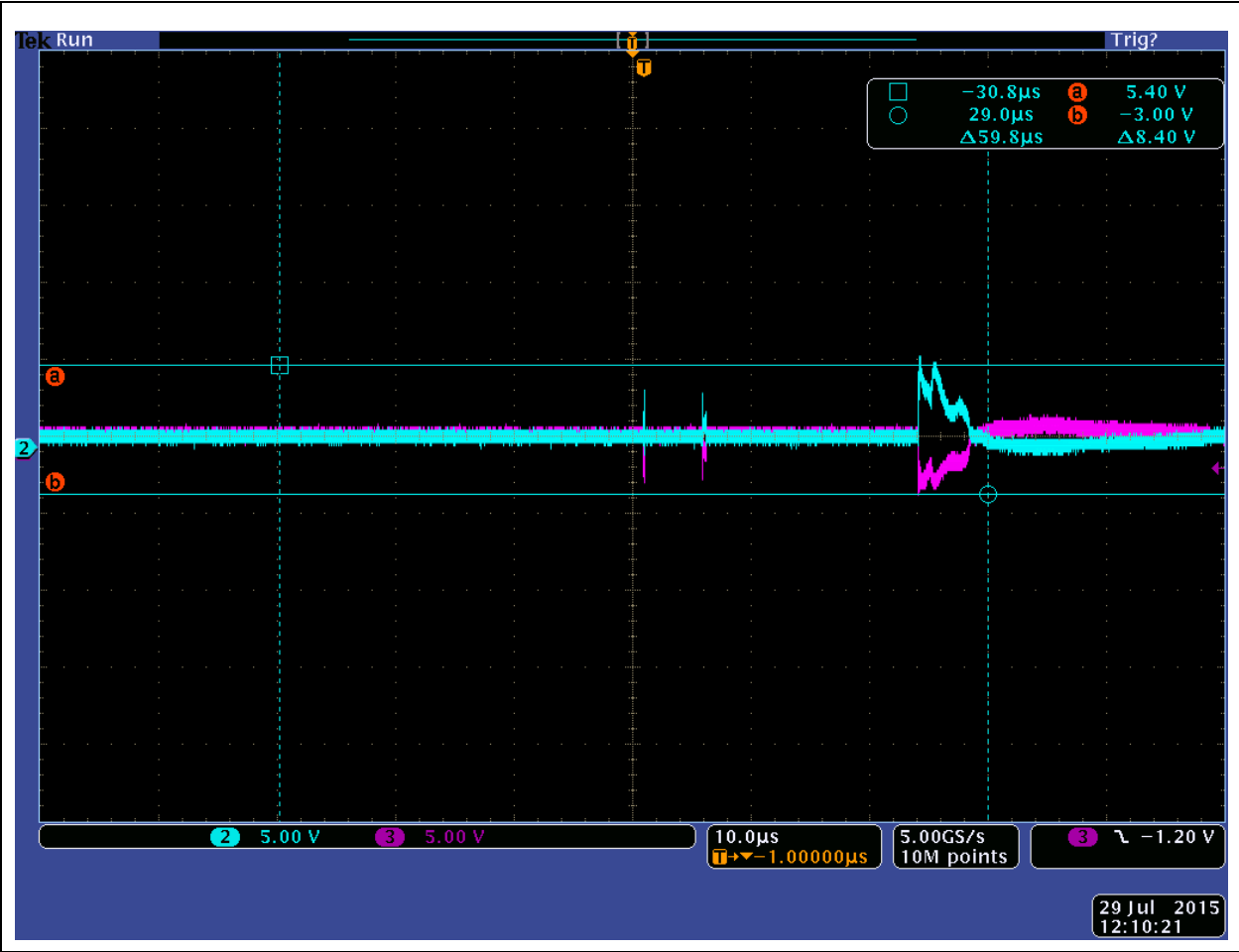
The Semtech uClamp3301D, Littelfuse SP4020, and Protek SR2.8 are good examples of diodes that can protect against the initial connection transients. There may still be small voltage spikes, but these voltages last nanoseconds instead of microseconds, and the internal ESD diodes are designed to protect against voltage events in that time frame.

FIGURE 12:   TRANSIENT EVENT WITH PROTECTION
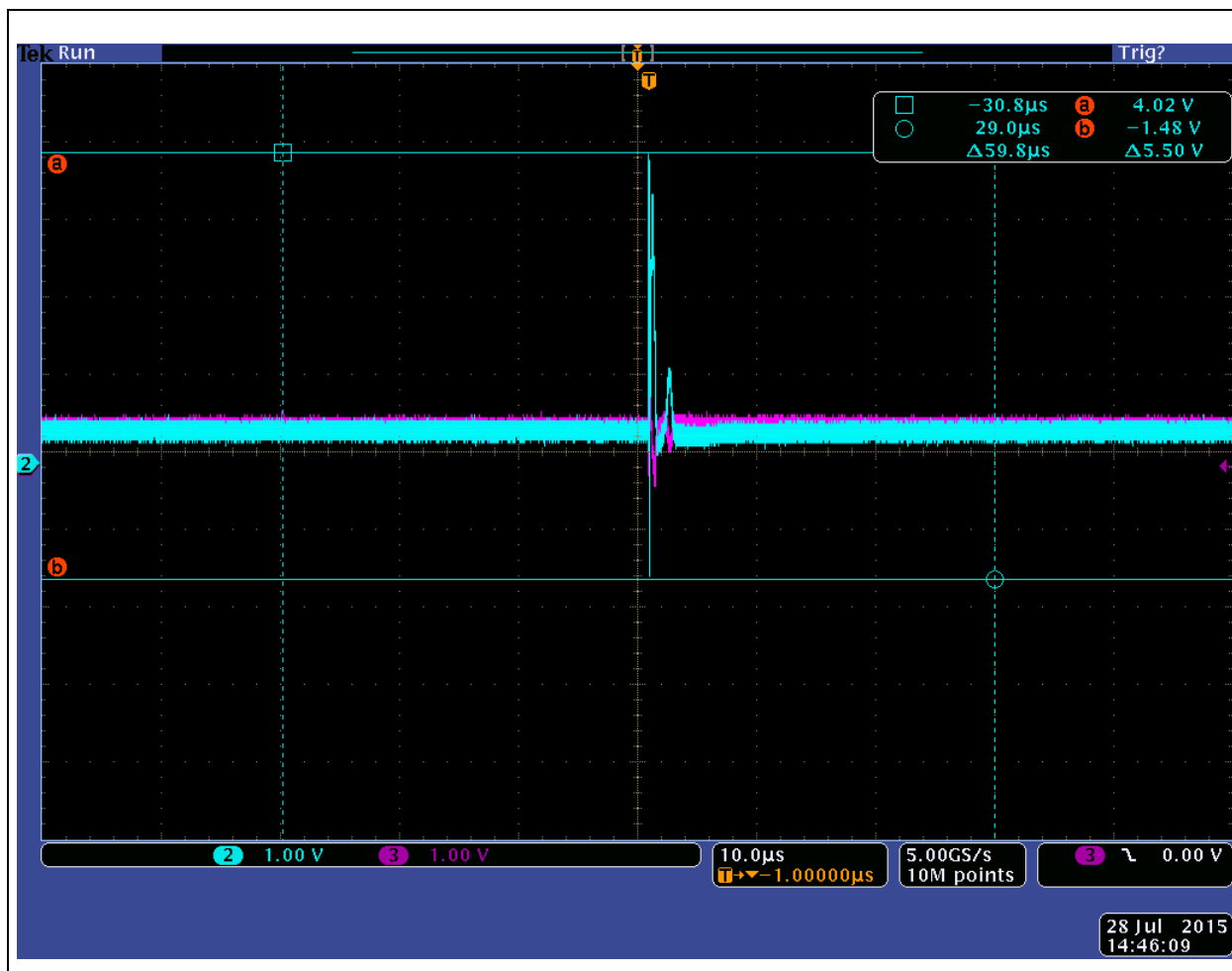
Rapid Disconnect/Connect Transients

Once the PSE has enabled the higher current supply, it will continue to keep the supply enabled long after the PD has been disconnected. The same situation can arise with the initial connection transient, where one side of the differential pair is removed. Because the main supply has a much larger voltage level and current limit than the PD Detection and Class Detection supply, when this supply is enabled, the transients require more protection. The level of protection depends on the voltage supply of the PSE device. Because the voltage is higher, the TVS diode will sink more current when clamping, generally exceeding the specified 1A limit. For higher voltage protection, the series resistance of the diode needs to be calculated. The series resistance can be derived from the **working voltage** and **clamping voltage**. Ic is the current that the **clamping voltage** is specified for, generally 1A.

EQUATION 1:

$$Rs = \frac{Vc - Vw}{Ic}$$

Extra components are needed to help destroy the energy passed through transformer during the disconnect event. This requires a combination of the TVS diodes used in the Initial Connection protection combined with a series resistor (Rp) to break down the voltage.

The series resistance between 0Ω and 5Ω will not affect the Ethernet data, but they will drop the voltage seen by the PHY after the TVS diodes clamp the voltage. To calculate Rp, find the maximum voltage of the transient the system needs to protect against and use the voltage divider equation to drop the voltage down to ~6.6V at the PHY.

EQUATION 2:

$$Rp > \frac{(Vmax - 6.6V)Rs}{6.6V}$$

FIGURE 13:   RECOMMENDED CIRCUIT FOR RAPID DISCONNECT/CONNECT PROTECTION
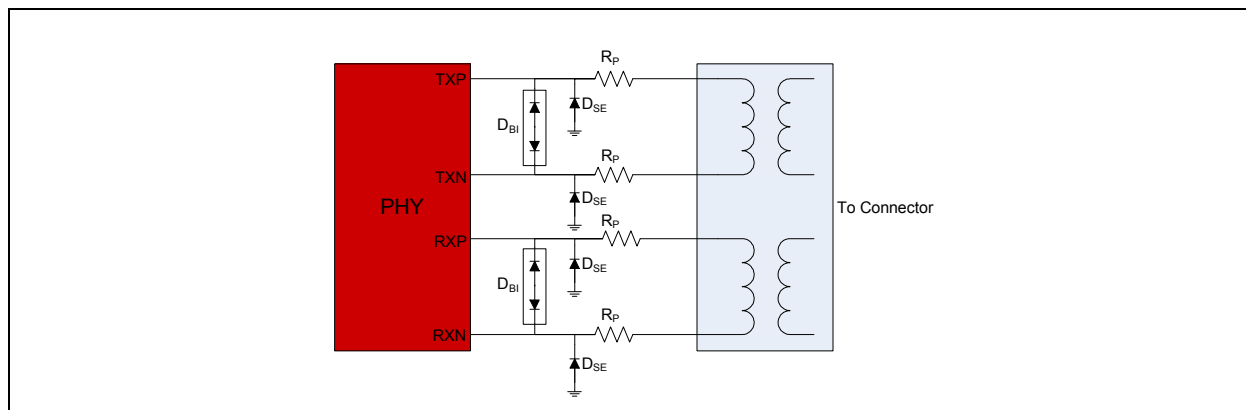
APPENDIX A: APPLICATION NOTE REVISION HISTORY

TABLE A-1:   **REVISION HISTORY**

Revision Level & Date	Section/Figure/Entry	Correction
DS00002157B (01-12-17)	All	Updated images and minor format/text changes. Specified "MLT-3" (previously only "MLT" throughout the document).
	Initial Connection Transient on page 8	Updated definition of Loading Capacitance and information regarding Figure 9.
DS00002157A (05-24-16)	All	Initial release.

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