

WE MEET @ DIGITAL DAYS



SINGLE PAIR ETHERNET FILTER DESIGN

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Simon Mark | Simulations Manager

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

Agenda

- Introduction Single Pair Ethernet
- Signal filtering
- SPE filter solutions
 - 10BASE-T1
 - 100BASE-T1
- **Power over Data Line (PoDL)**
 - Function of components
 - Improvements of PoDL design
 - Solutions for high currents
- 1000BASE-T1



INDUSTRIAL
PARTNER
NETWORK



SINGLE IS MORE

Simplifying IIOT & Automation

SINGLE PAIR ETHERNET

Robust Connection
Robust Connection

Reach

Cost-Effective

MORE

Speed

Intelligence
Intelligence

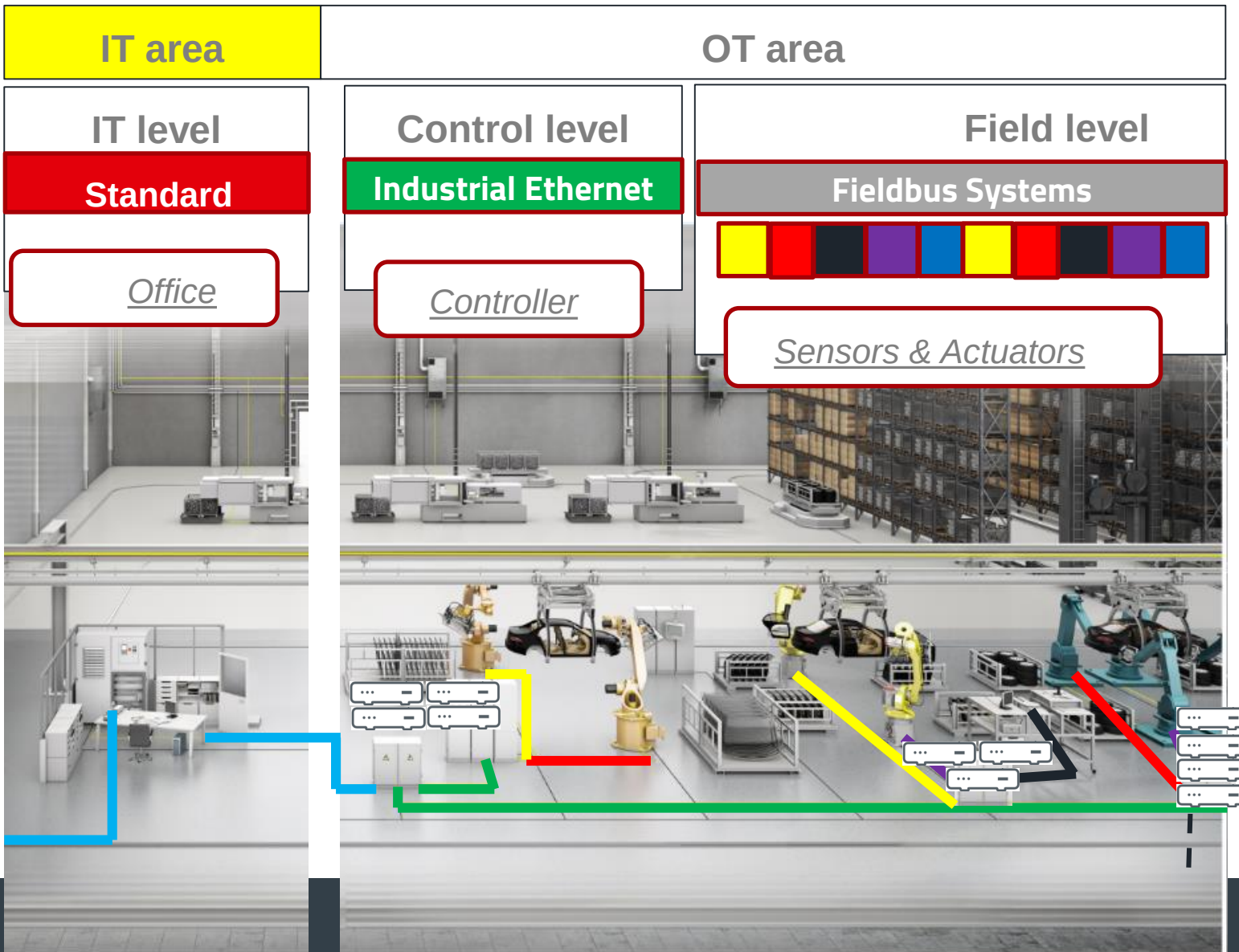
Weight-Saving

Simplicity

Miniaturization
Miniaturization

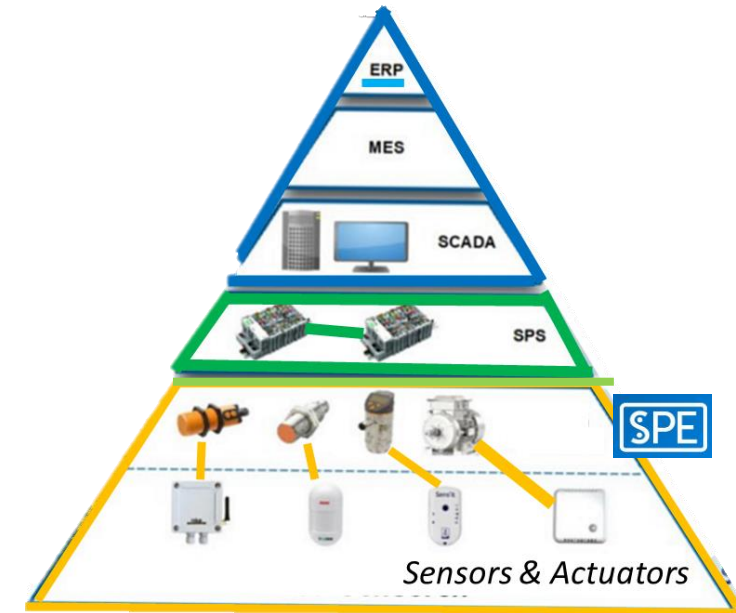
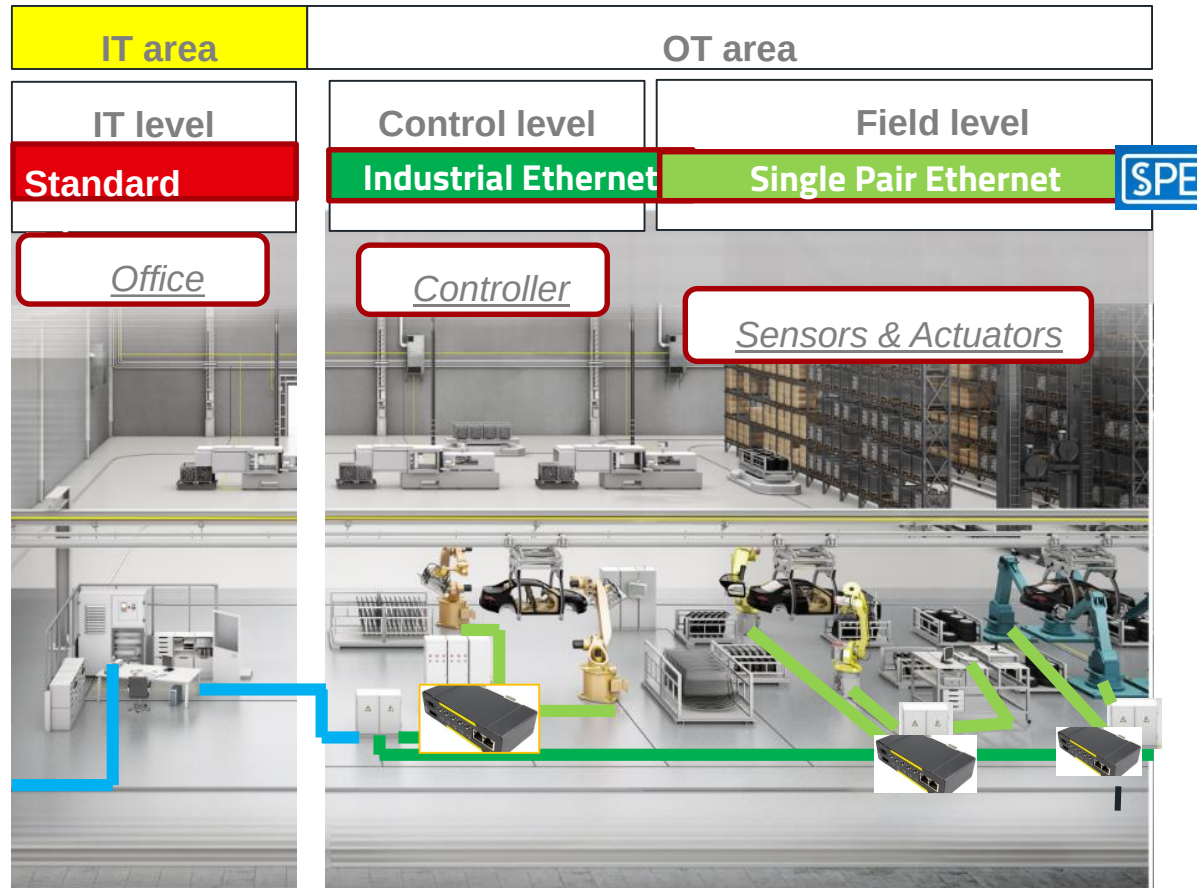


DIVERSE, LAGACY COMMUNICATION IR



Complex communication
by Gateways

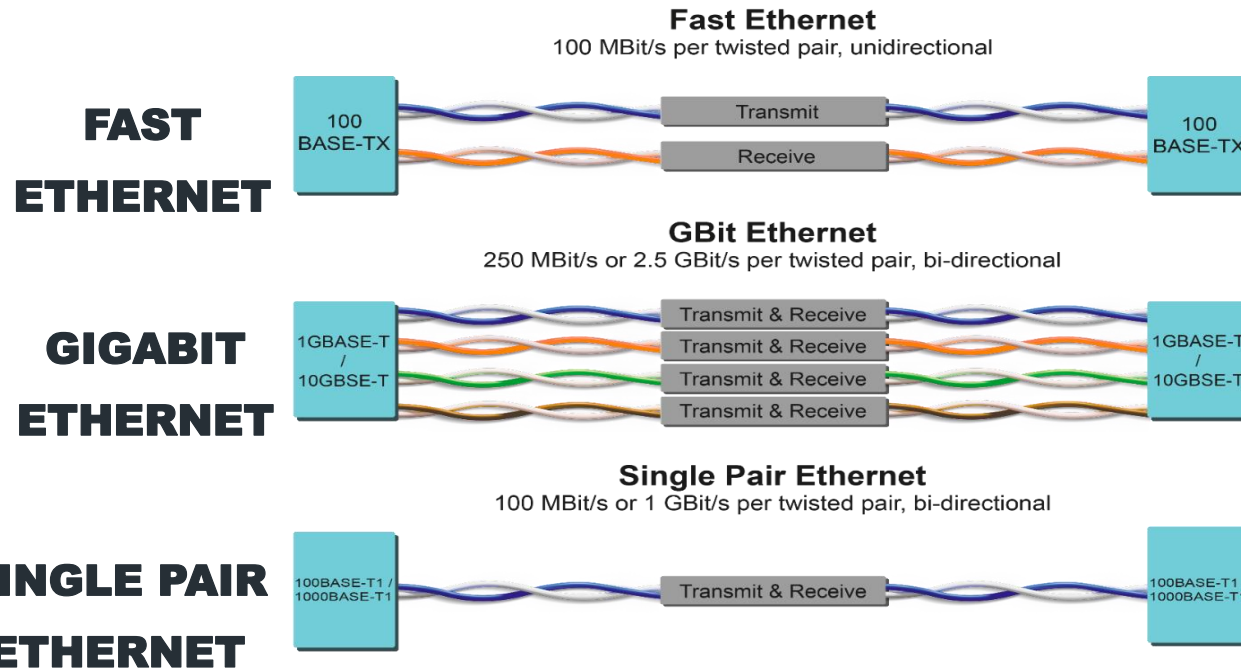
SEAMLESS CONNECTIVITY ACROSS FACTORY AUTOMATION



**Simple switch
converts from Industrial
Ethernet to SPE**

SPE TECHNOLOGY

ONE PAIR IS ENOUGH



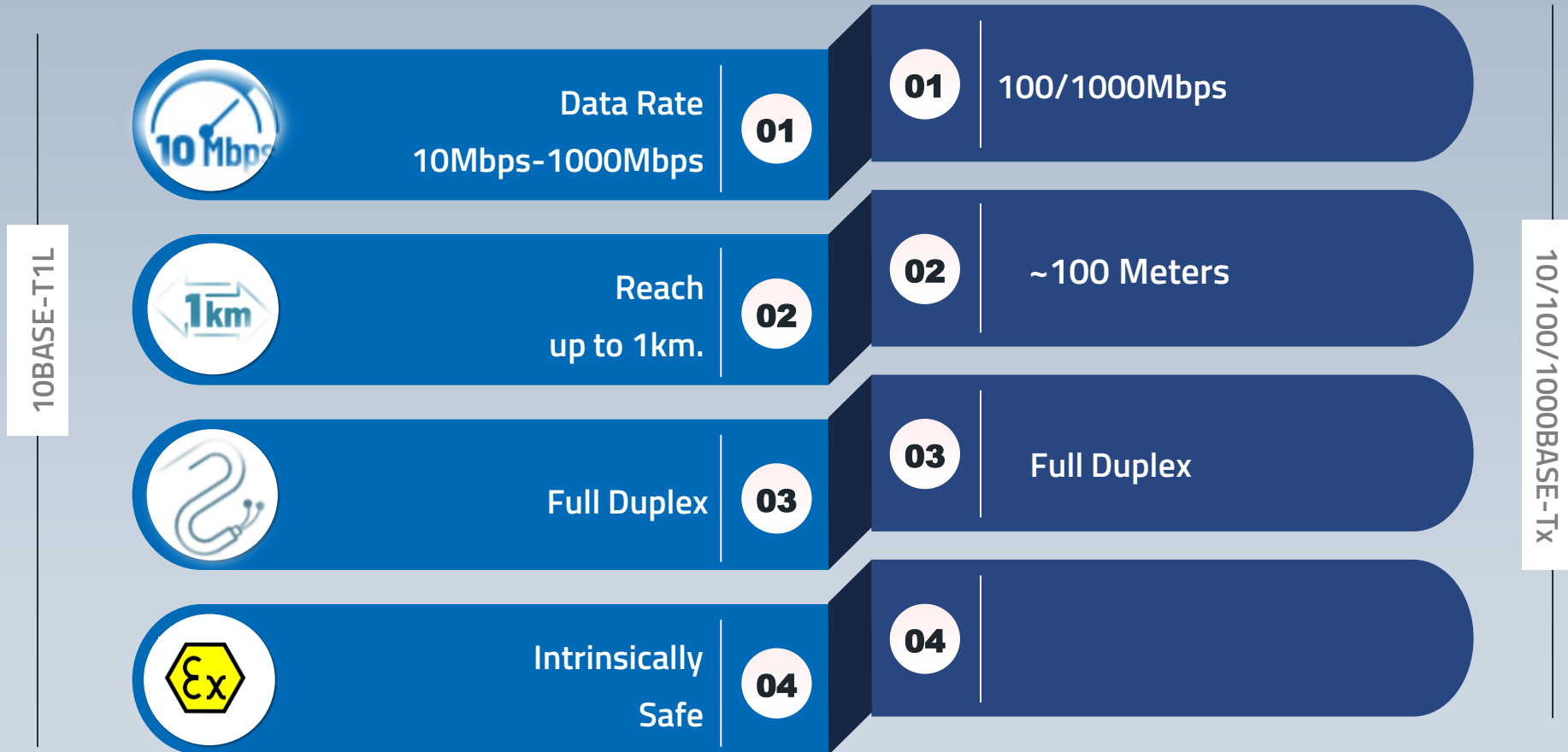
STANDARD GBit
Ethernet 4 Pair Cabling

SPE Single Twisted
Pair Cabling



NEW SPE IEEE STANDARD: IEEE802.3cg™

10BASE-T1L



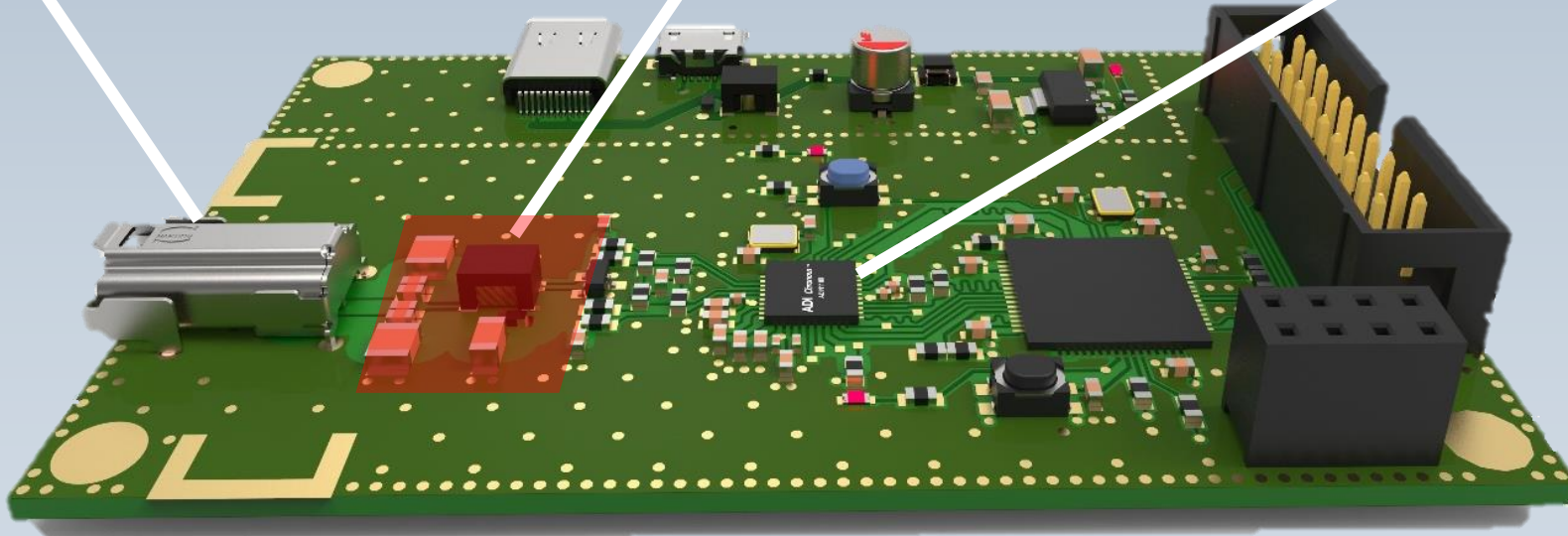
SIMPLIFY DEVELOPMENT, SPEED TIME TO MARKET, REDUCE RISK

PROVEN SOLUTIONS FROM INDUSTRY LEADERS

CONNECTIVITY

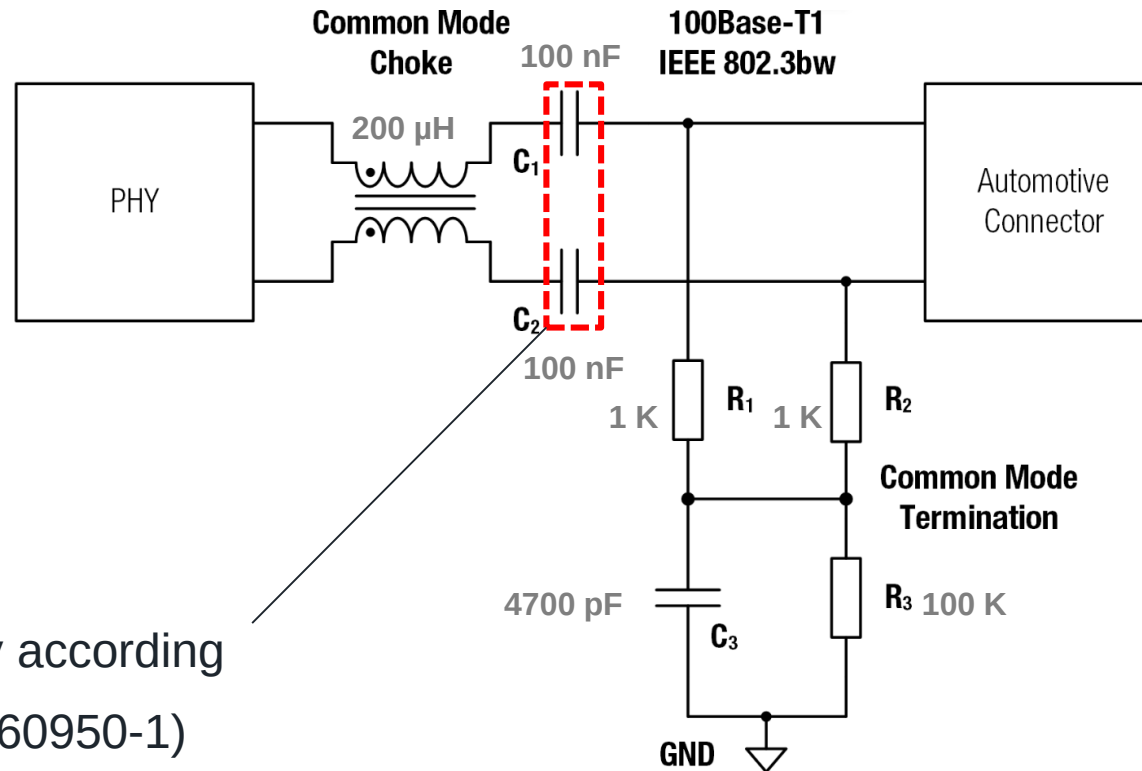
MAGNETICS

**PHYSICAL
LAYER
DEVICES**



WHAT IS THE SPE FILTERING?

100BASE-T1 Automotive Ethernet



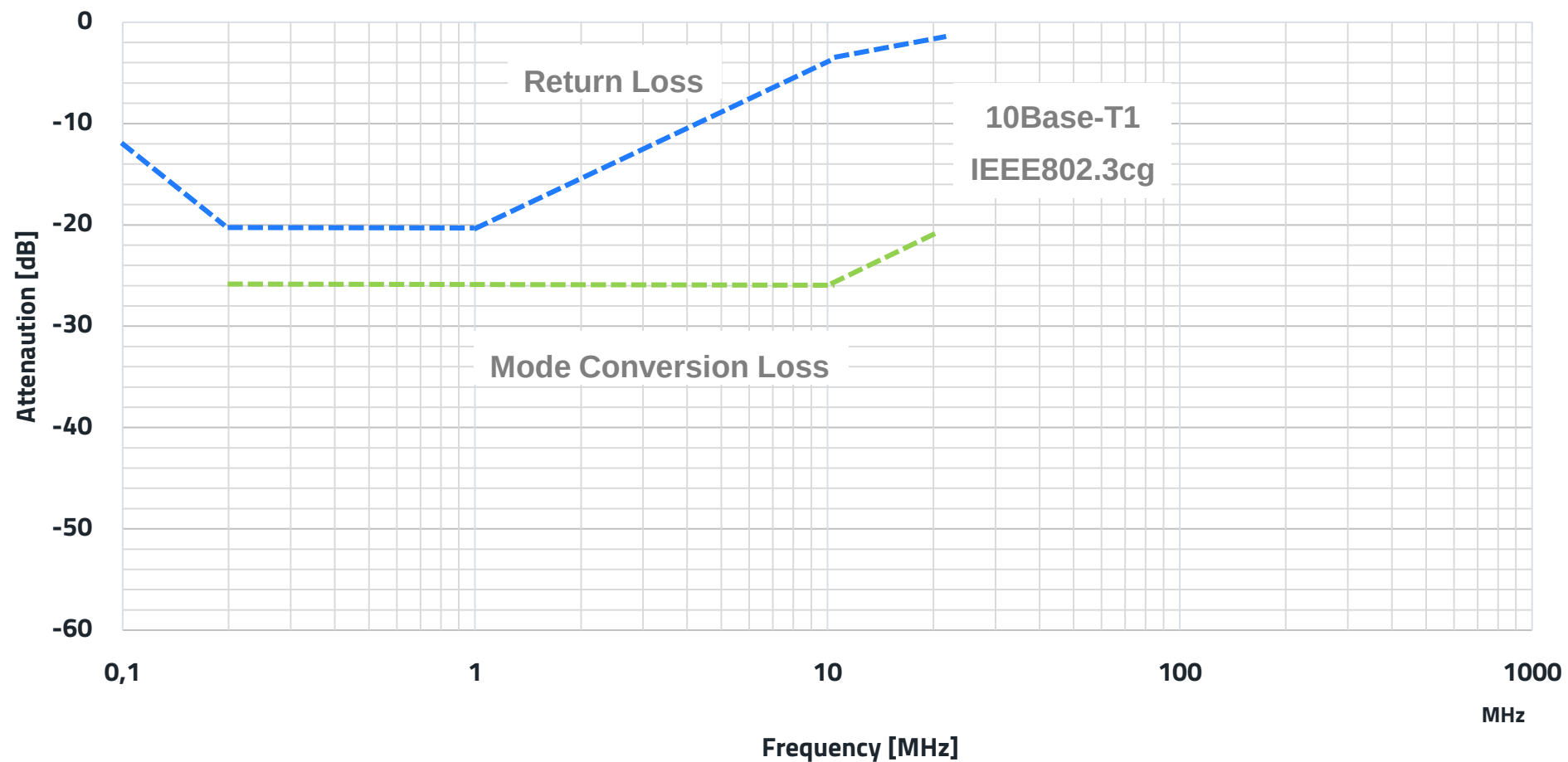
50 VDC isolation

-> Not sufficient for safety according to IEC 62368-1 (old: IEC 60950-1)

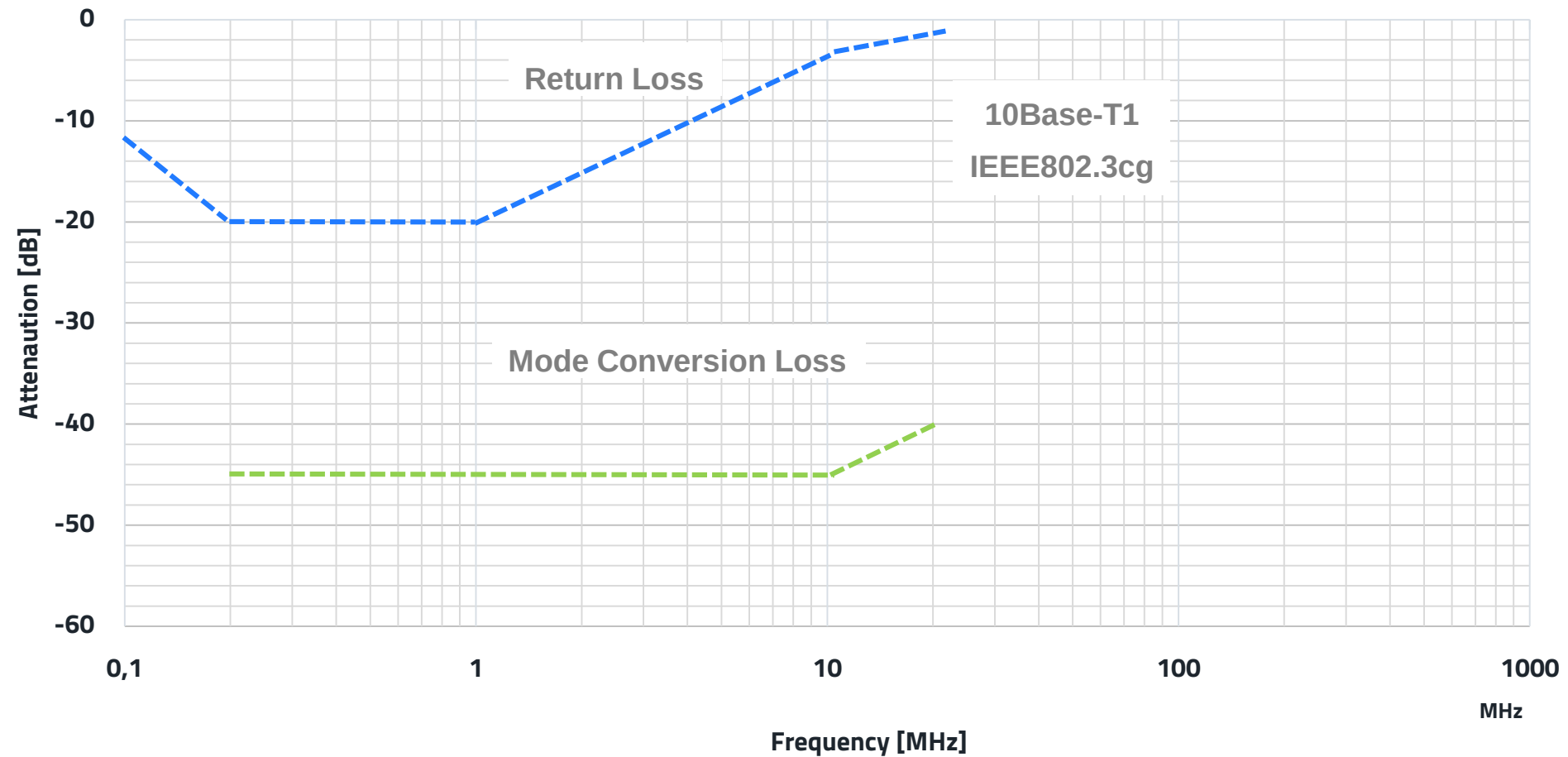
10BASE-T1



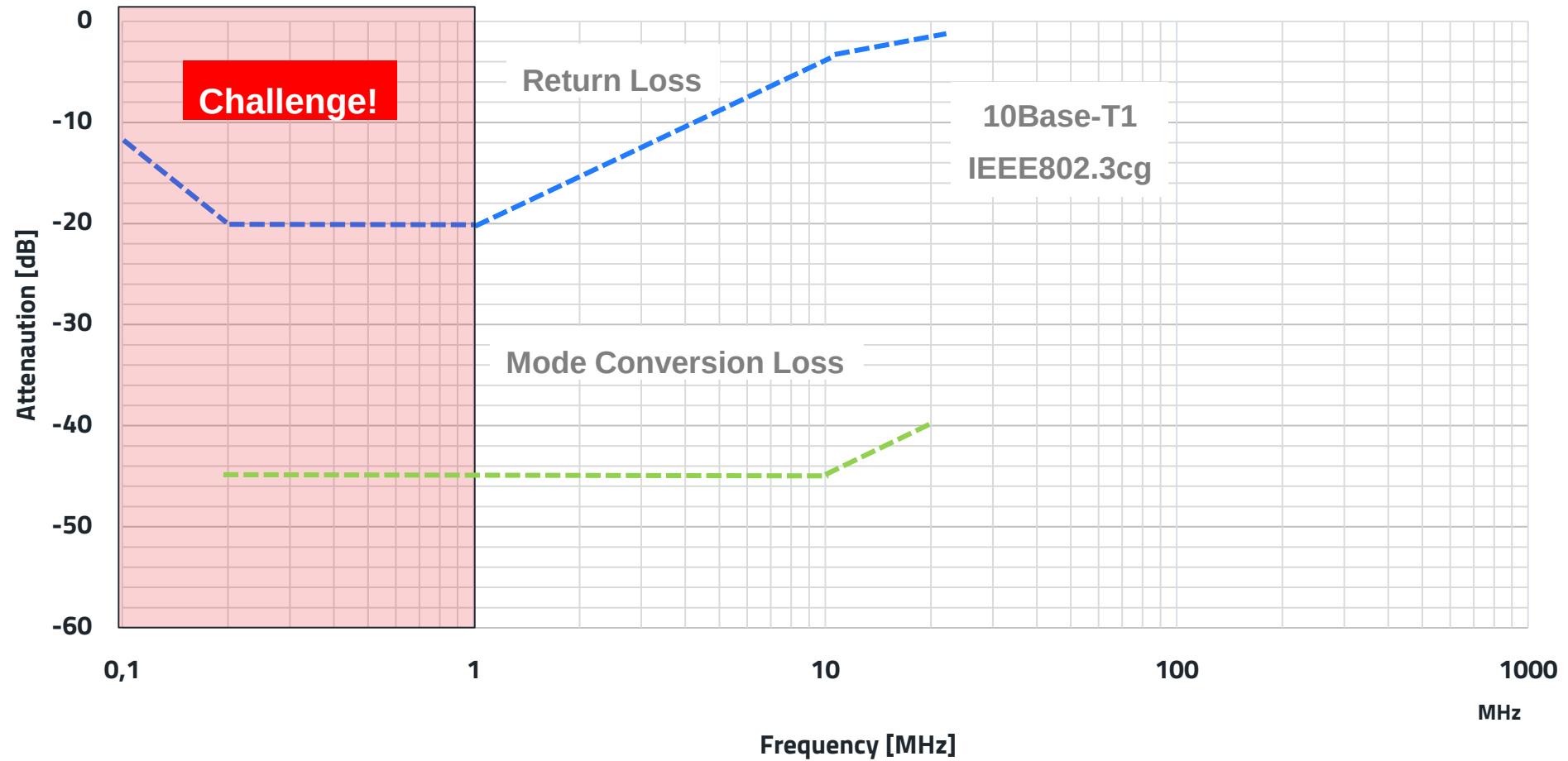
10BASE-T1



10BASE-T1



10BASE-T1

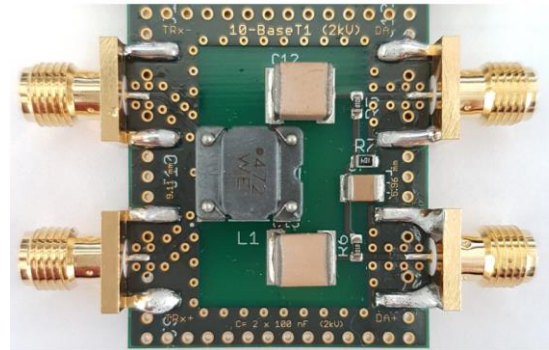


10BASE-T1

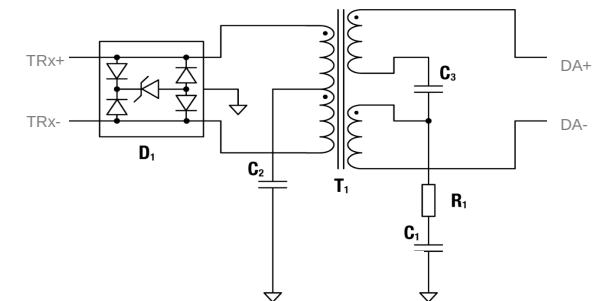
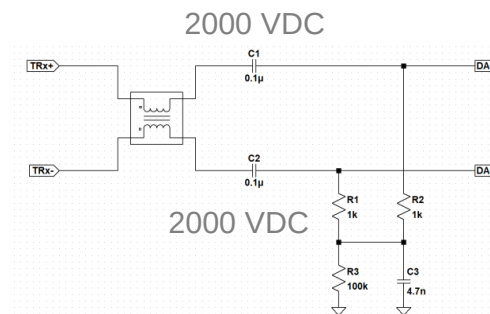
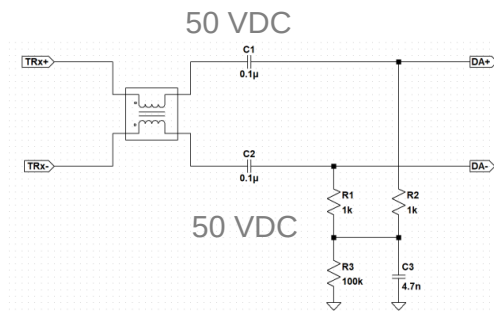
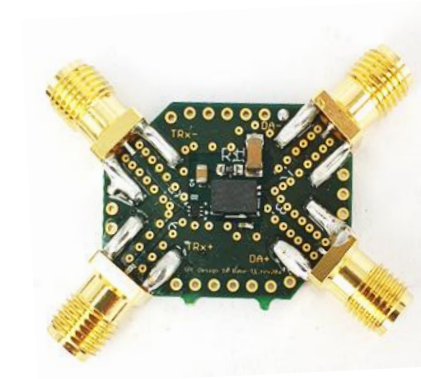
50 V Capacitors



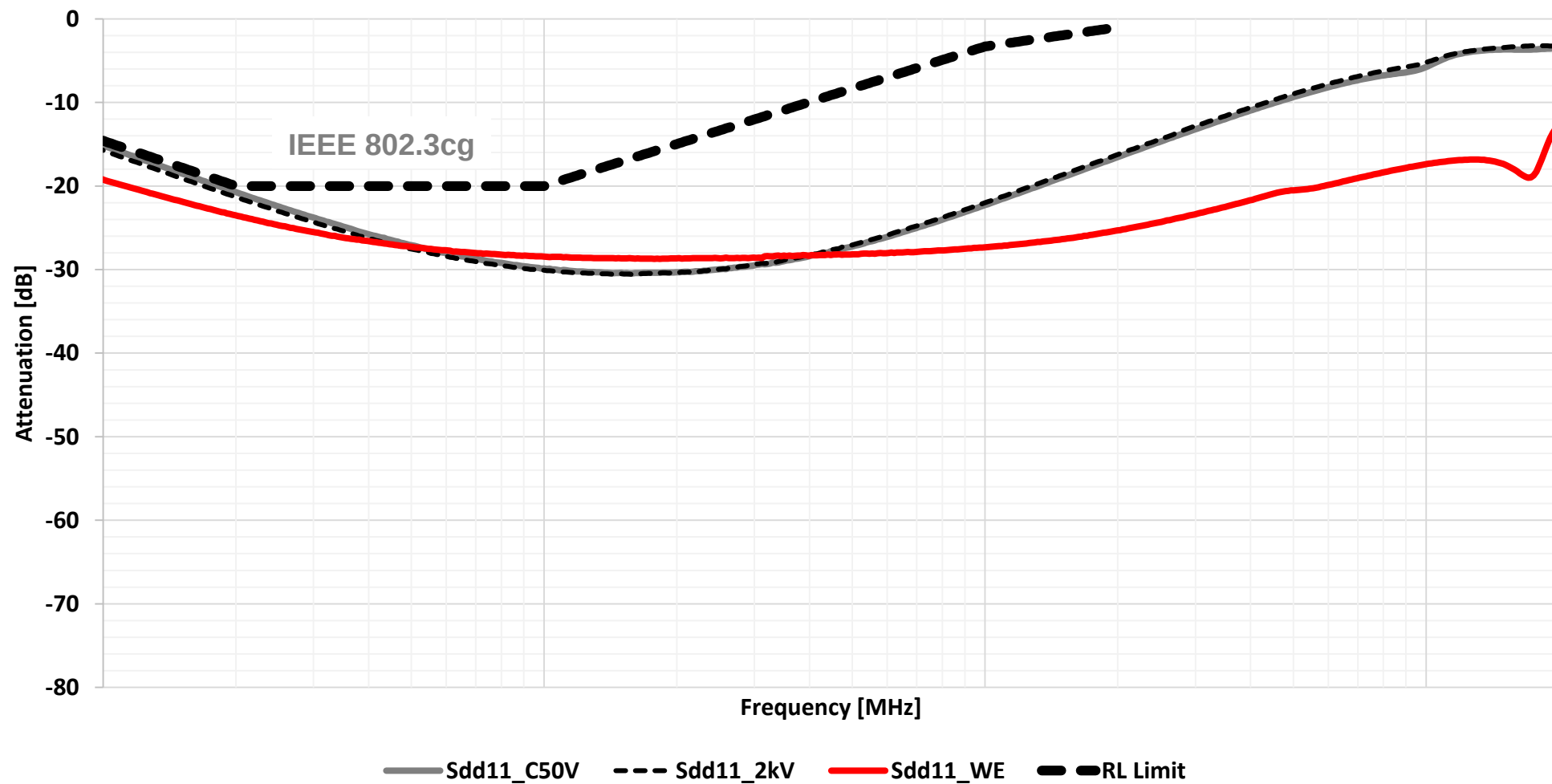
2000 V Capacitors



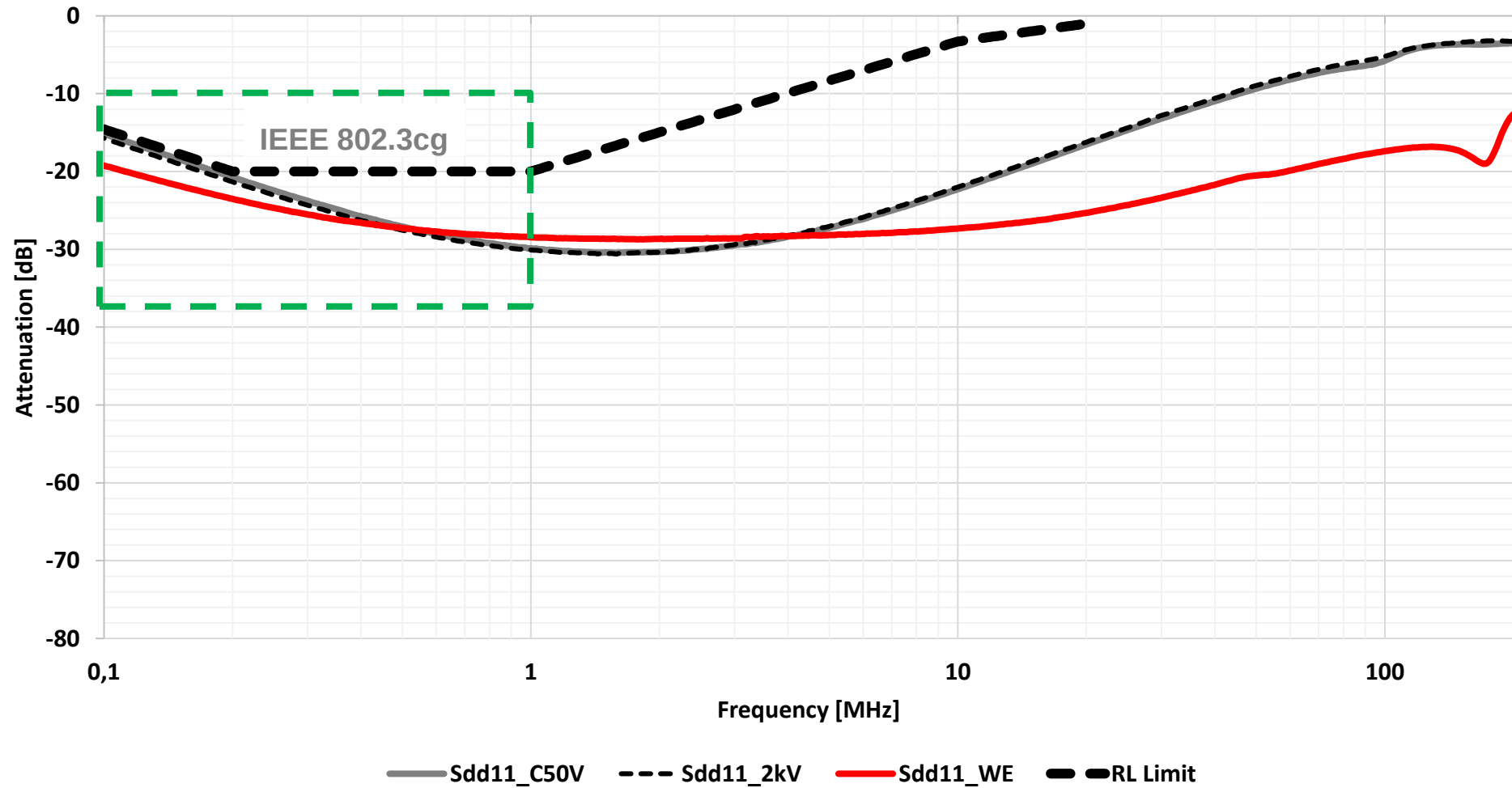
Signal Transformer



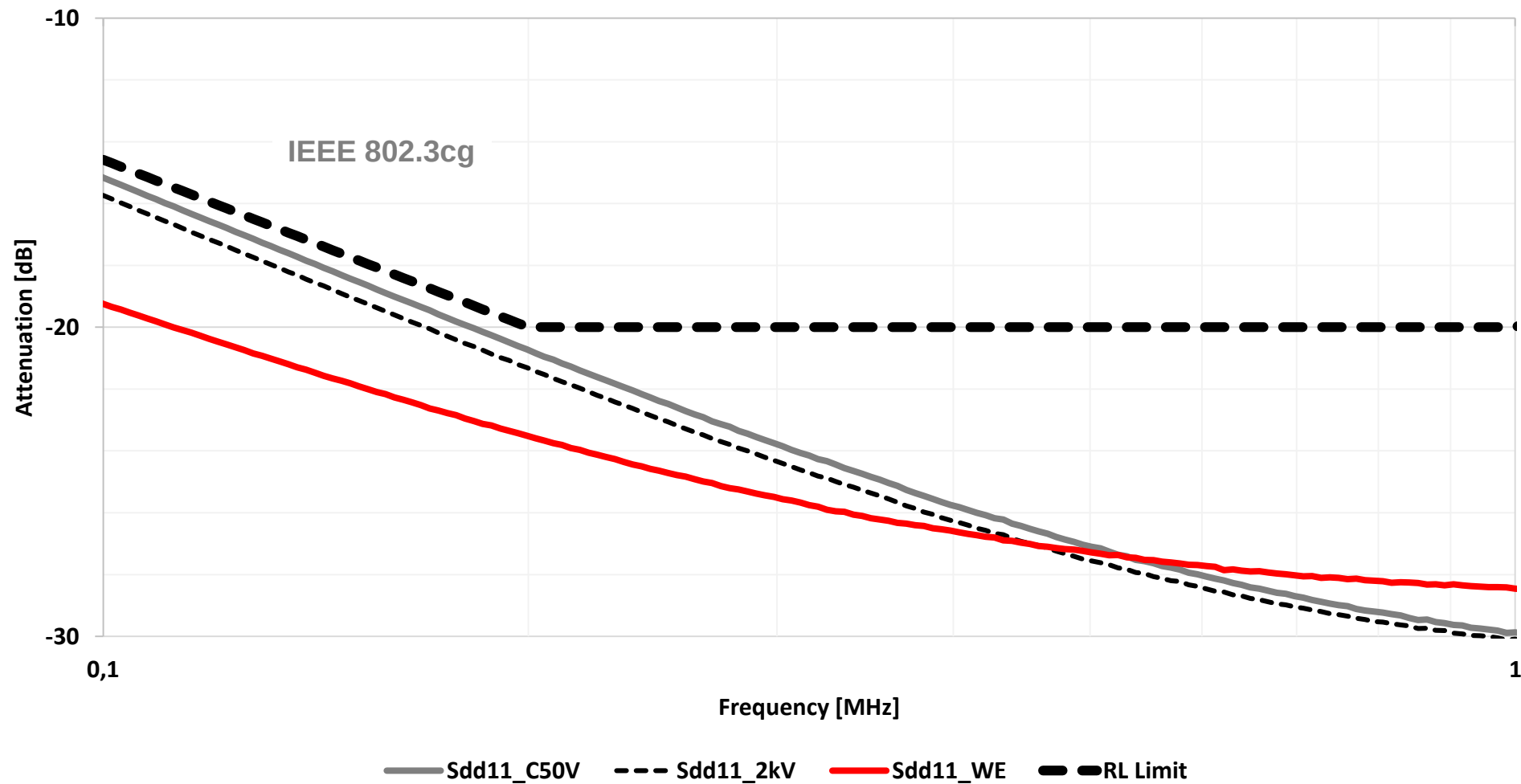
10BASE-T1



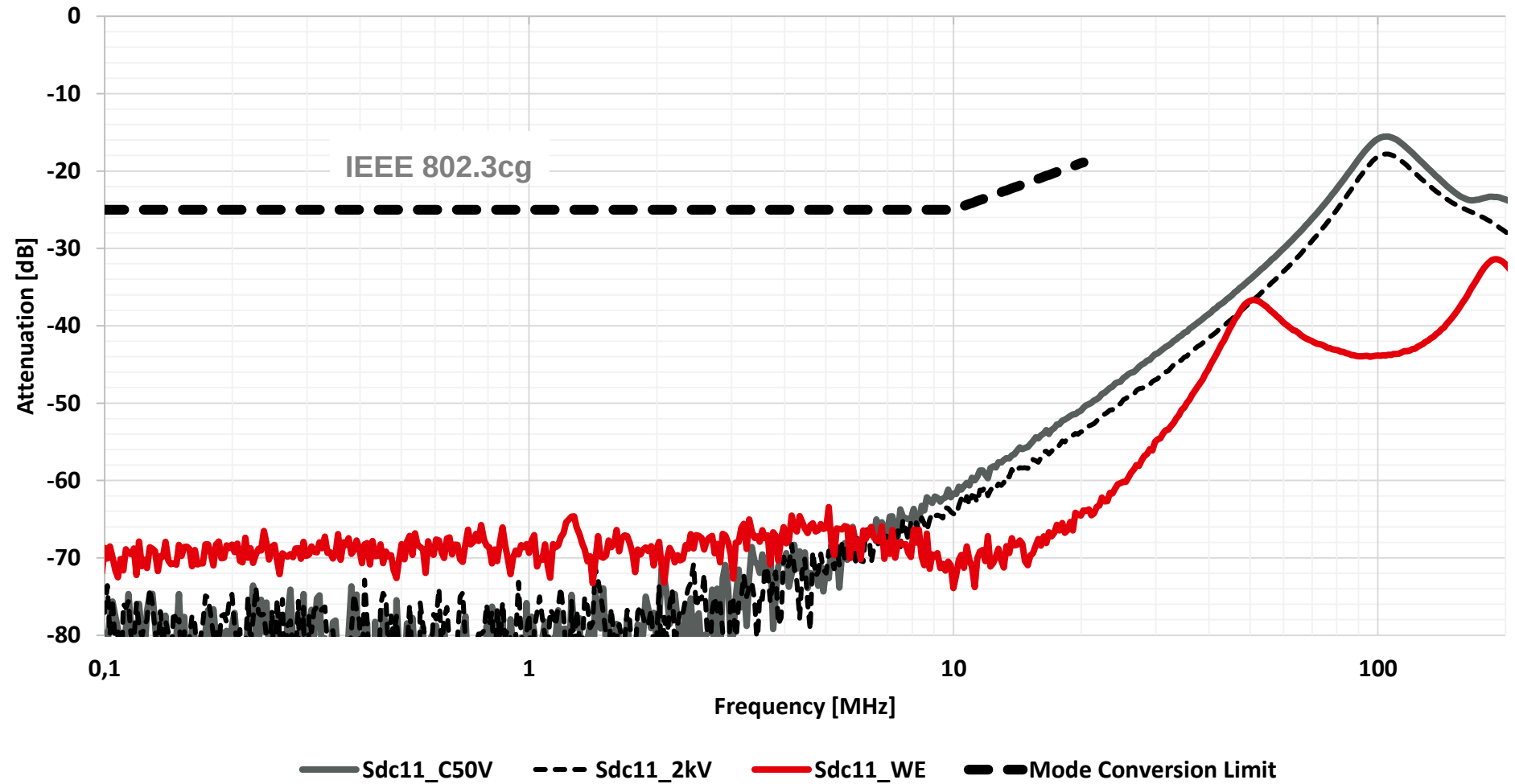
10BASE-T1



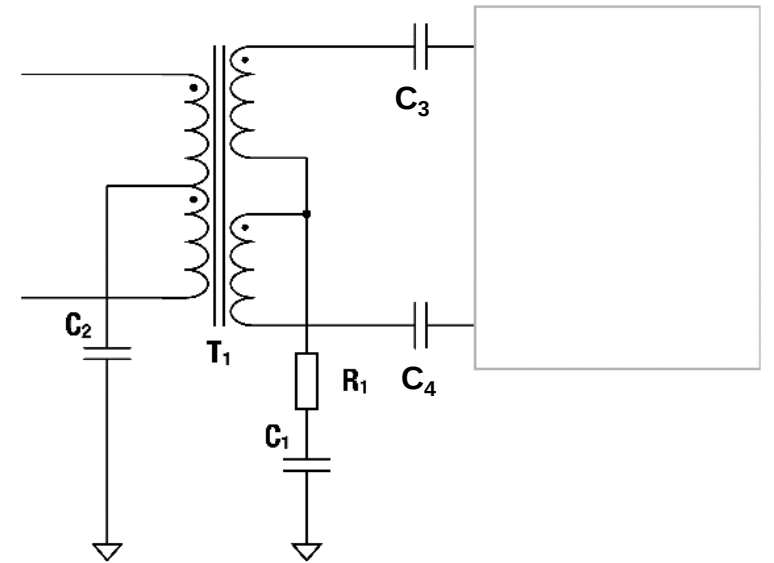
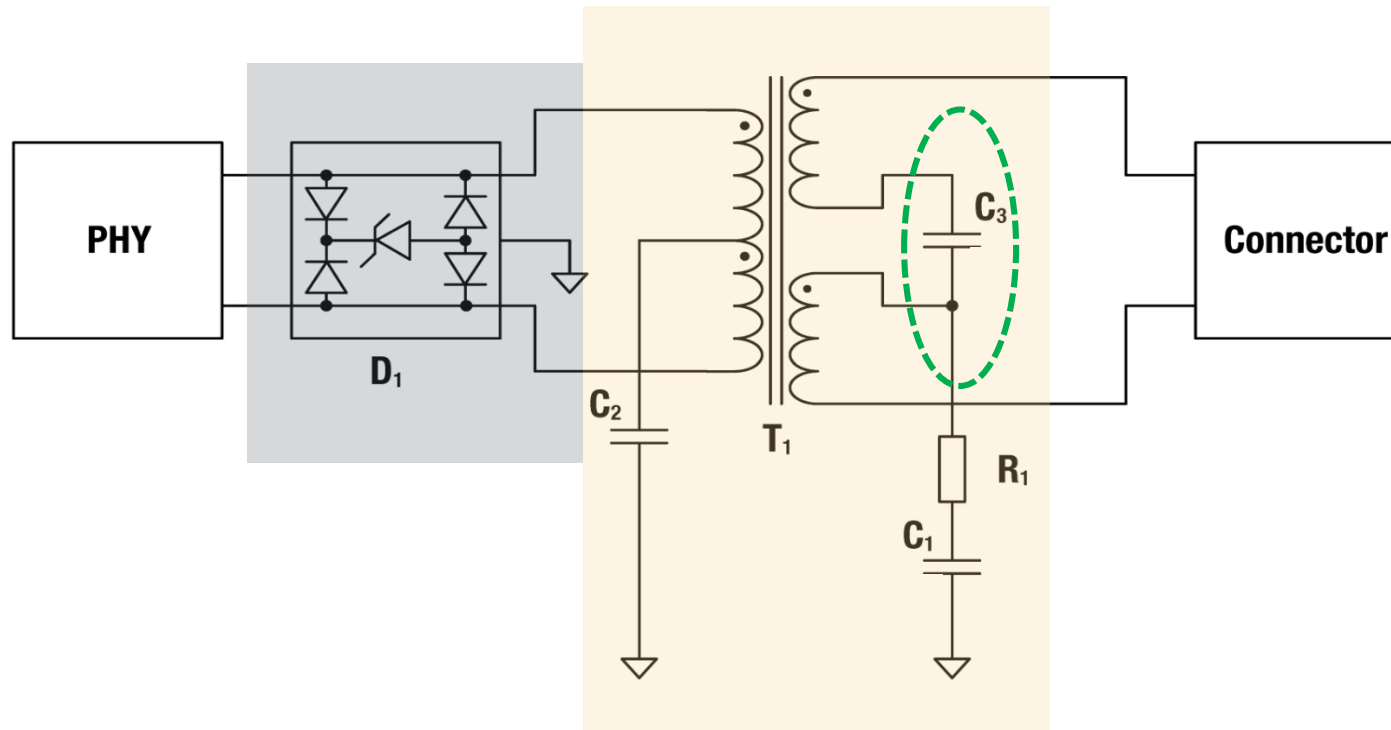
10BASE-T1



10BASE-T1



10BASE-T1



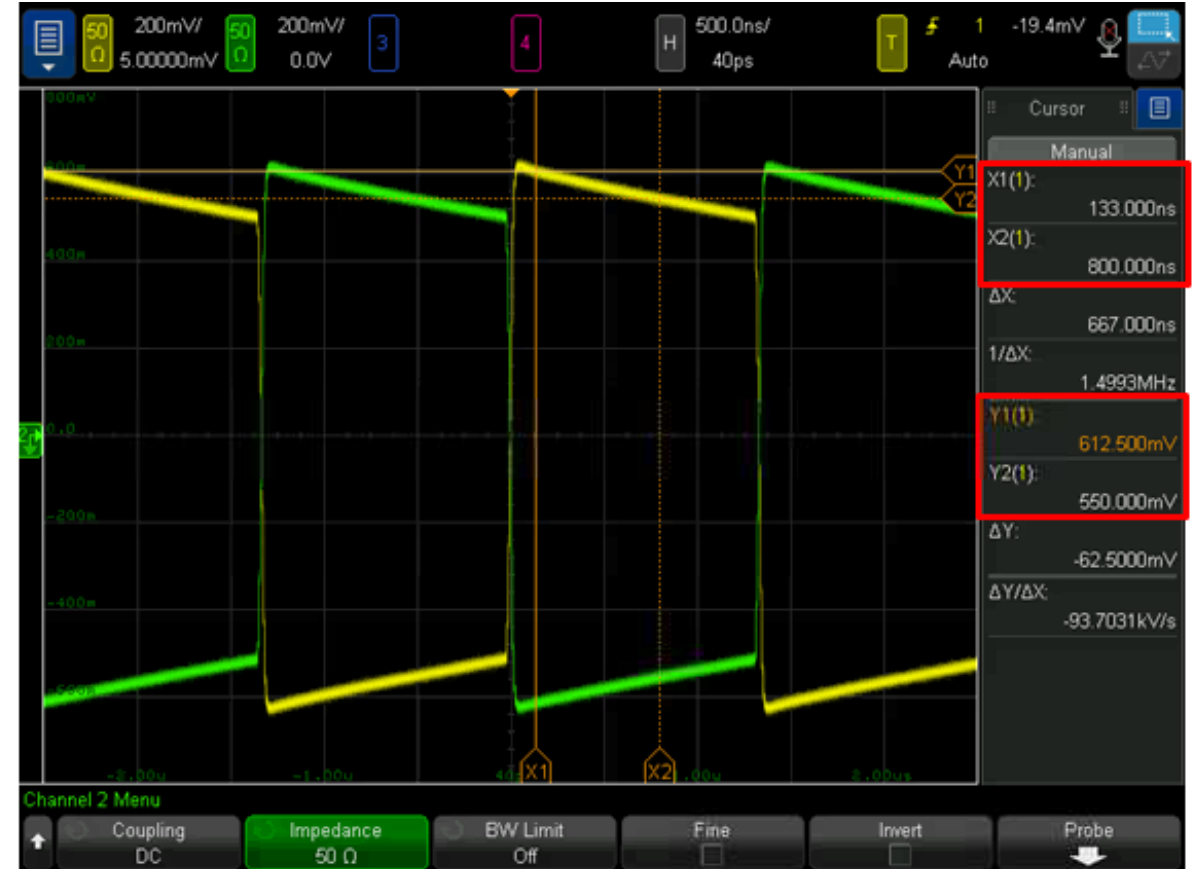
Droop measurement

146.5.4.2 Transmitter output droop

With the transmitter in test mode 2 and using the transmitter test fixture shown in Figure 146–20, the magnitude of both the positive and negative droop shall be less than 10% measured with respect to an initial value at 133.3 ns after the zero crossing and a final value at 800 ns after the zero crossing.

Source: IEEE802.3cg

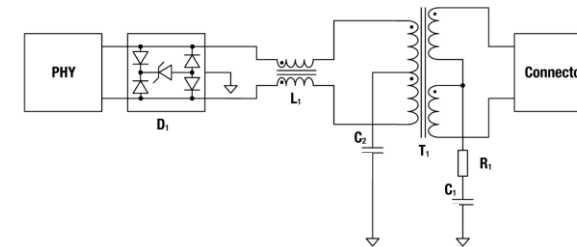
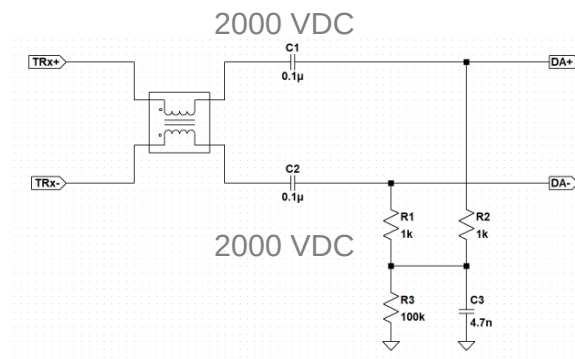
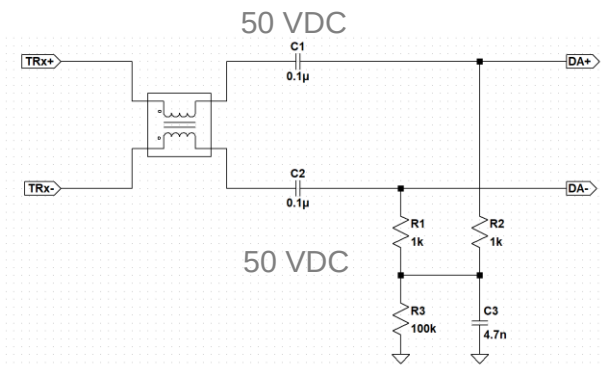
$$\begin{aligned} U_{\Delta\%} &= \frac{100\%}{V_{133ns}} * (U_{133ns} - U_{800ns}) \\ &= \frac{100\%}{612,5\text{ mV}} * (612,5\text{ mV} - 550\text{ mV}) = 10,2\% \end{aligned}$$



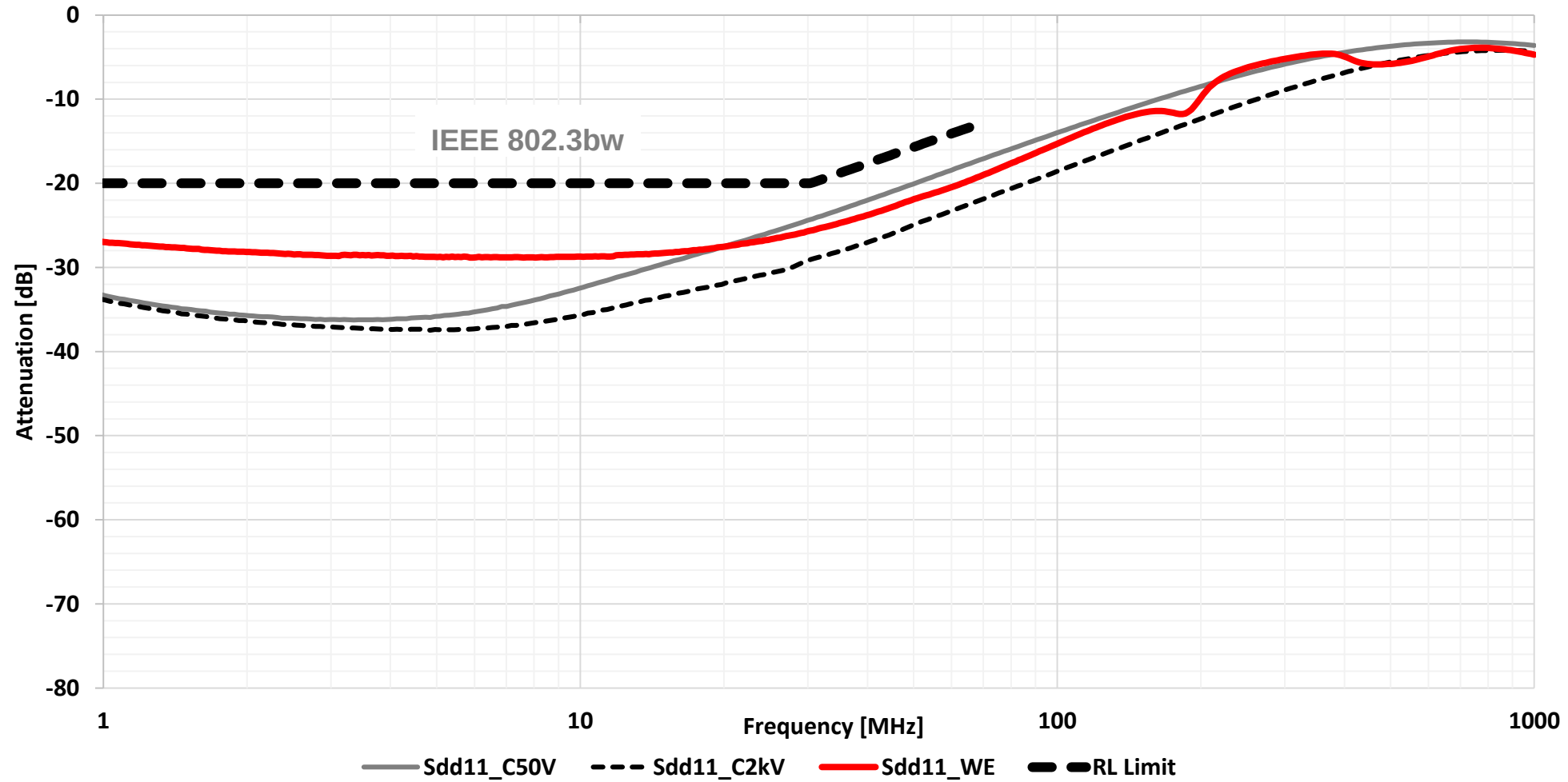
100BASE-T1



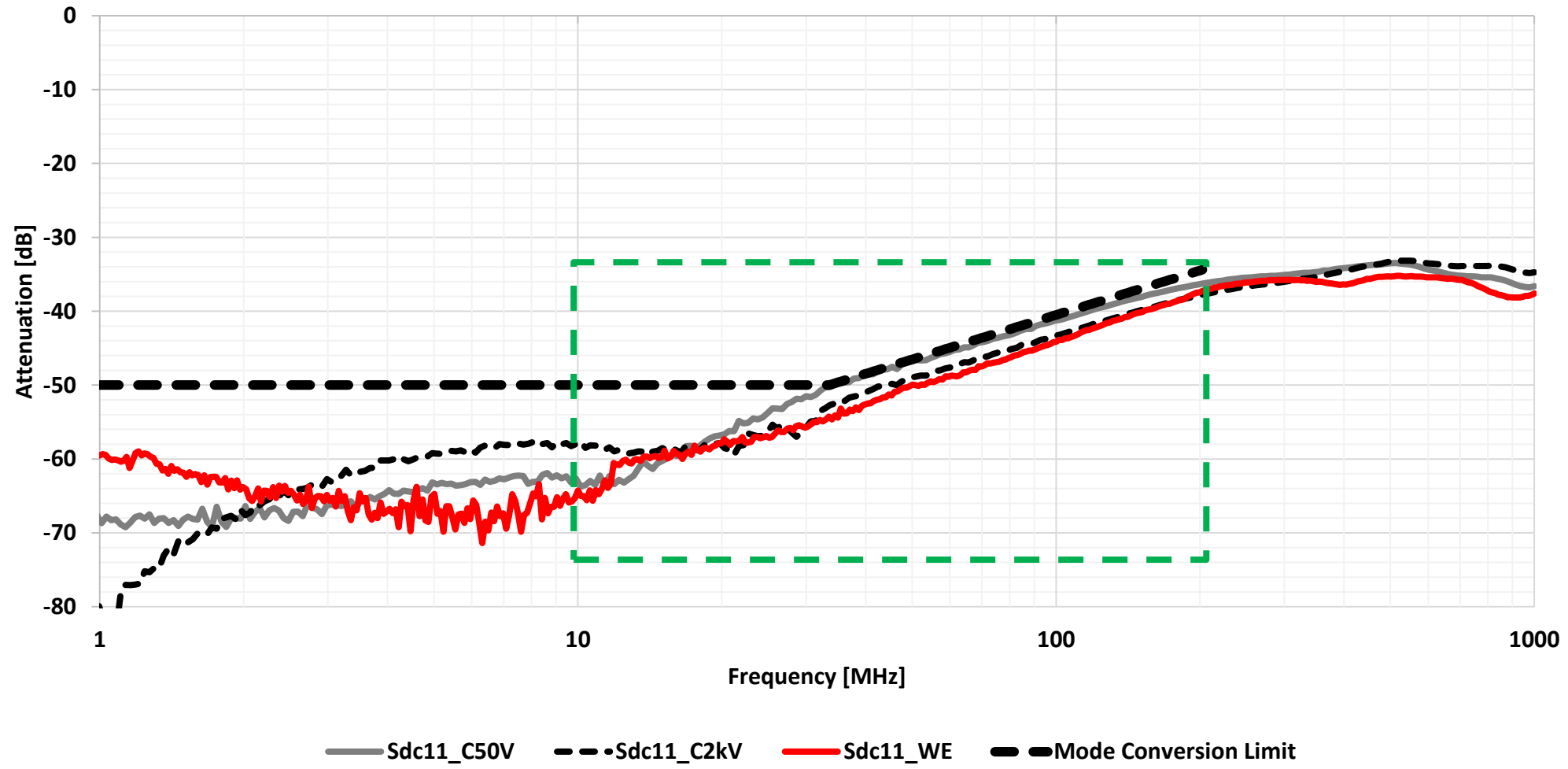
100BASE-T1



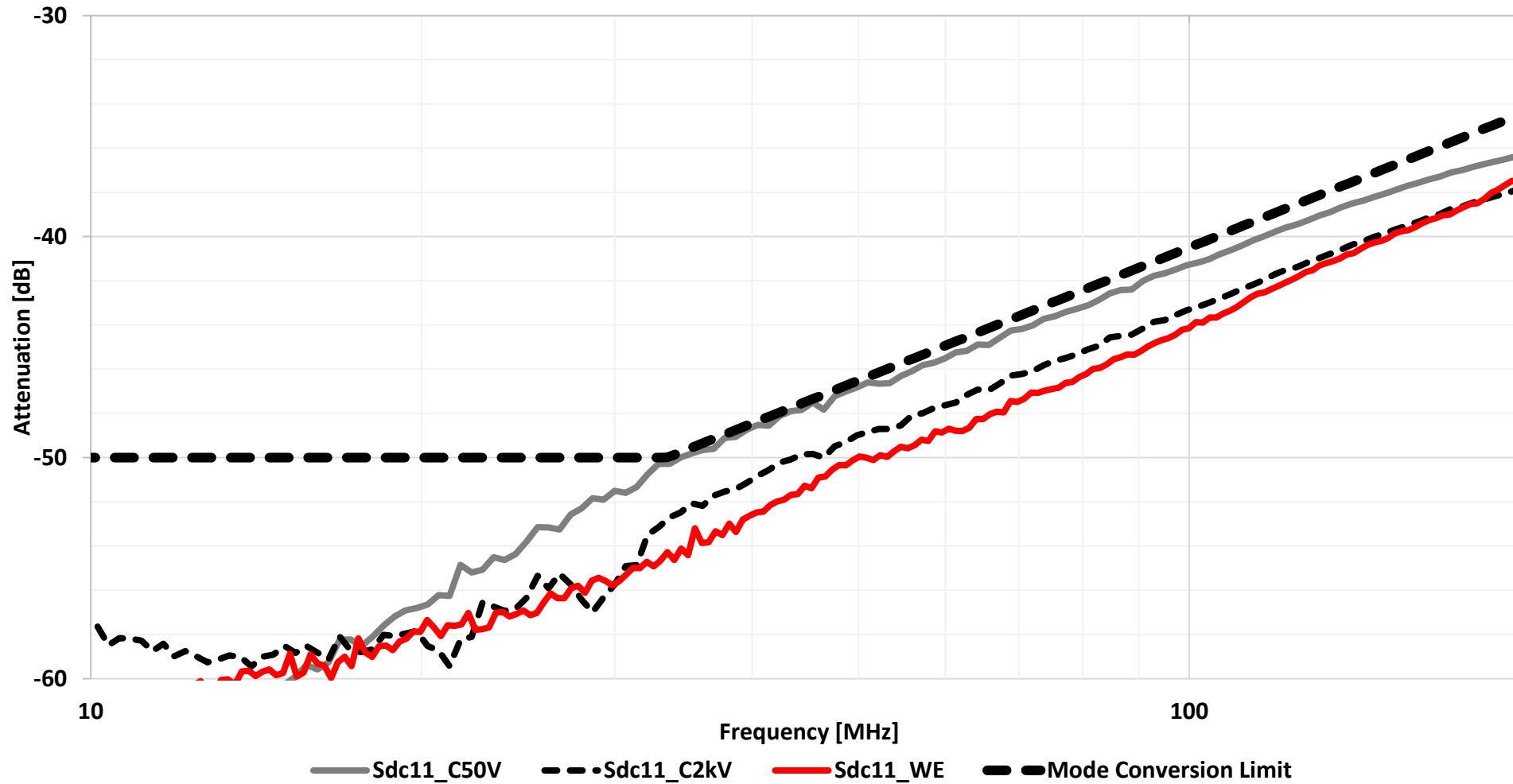
100BASE-T1



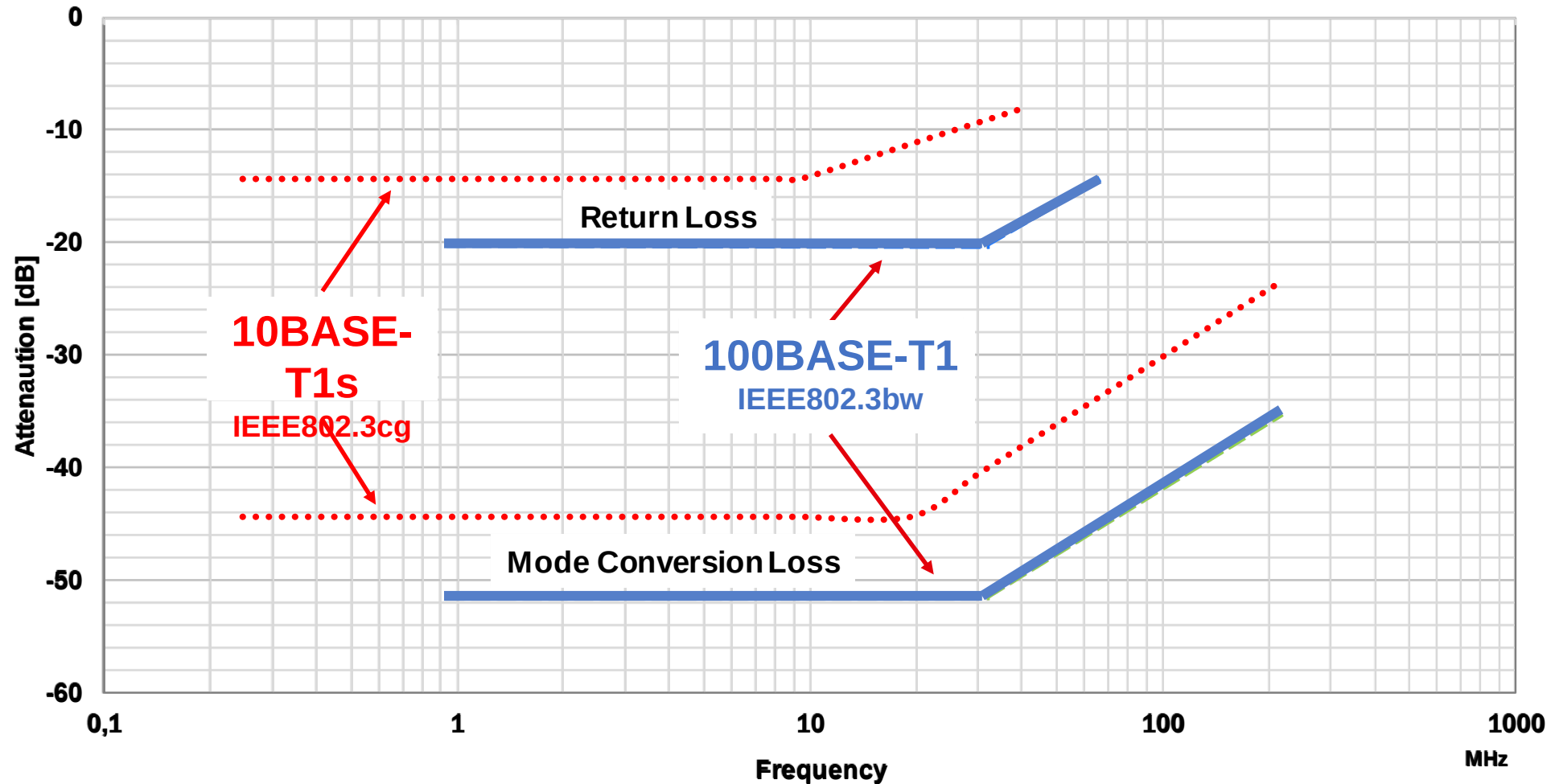
100BASE-T1



100BASE-T1



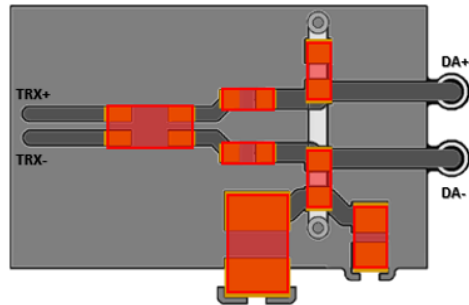
100BASE-T1 vs. 10BASE-T1s



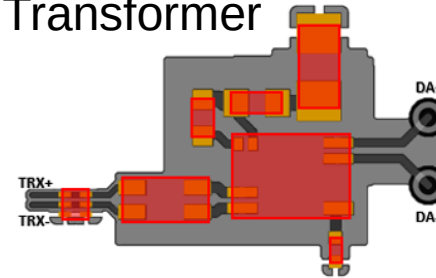
Schematic for 100BASE-T1 can be used for 10BASE-T1S!

100BASE-T1

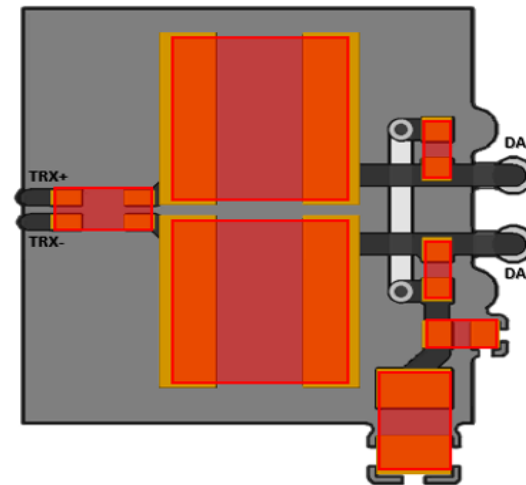
50 V



Transformer



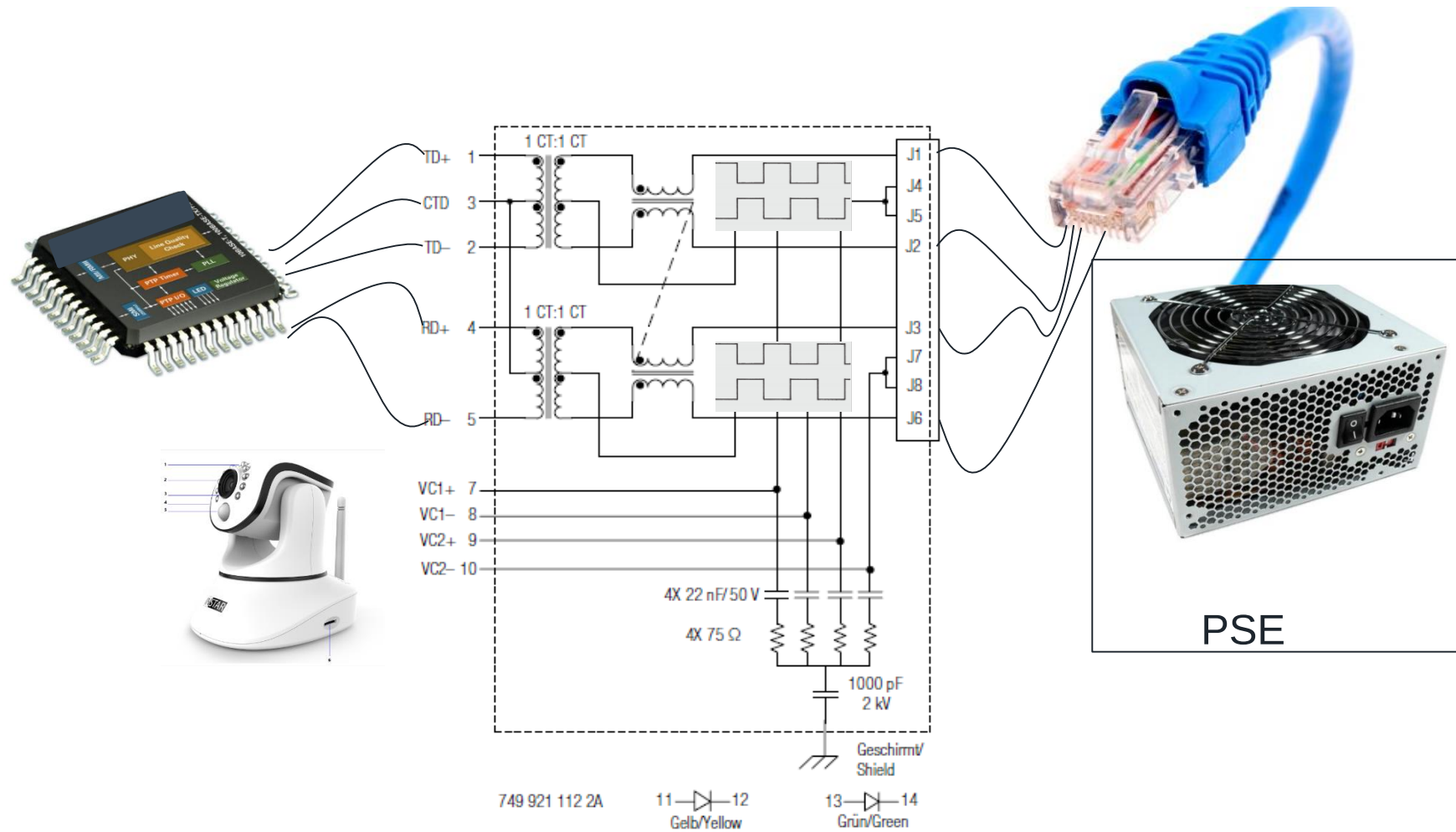
2000 V



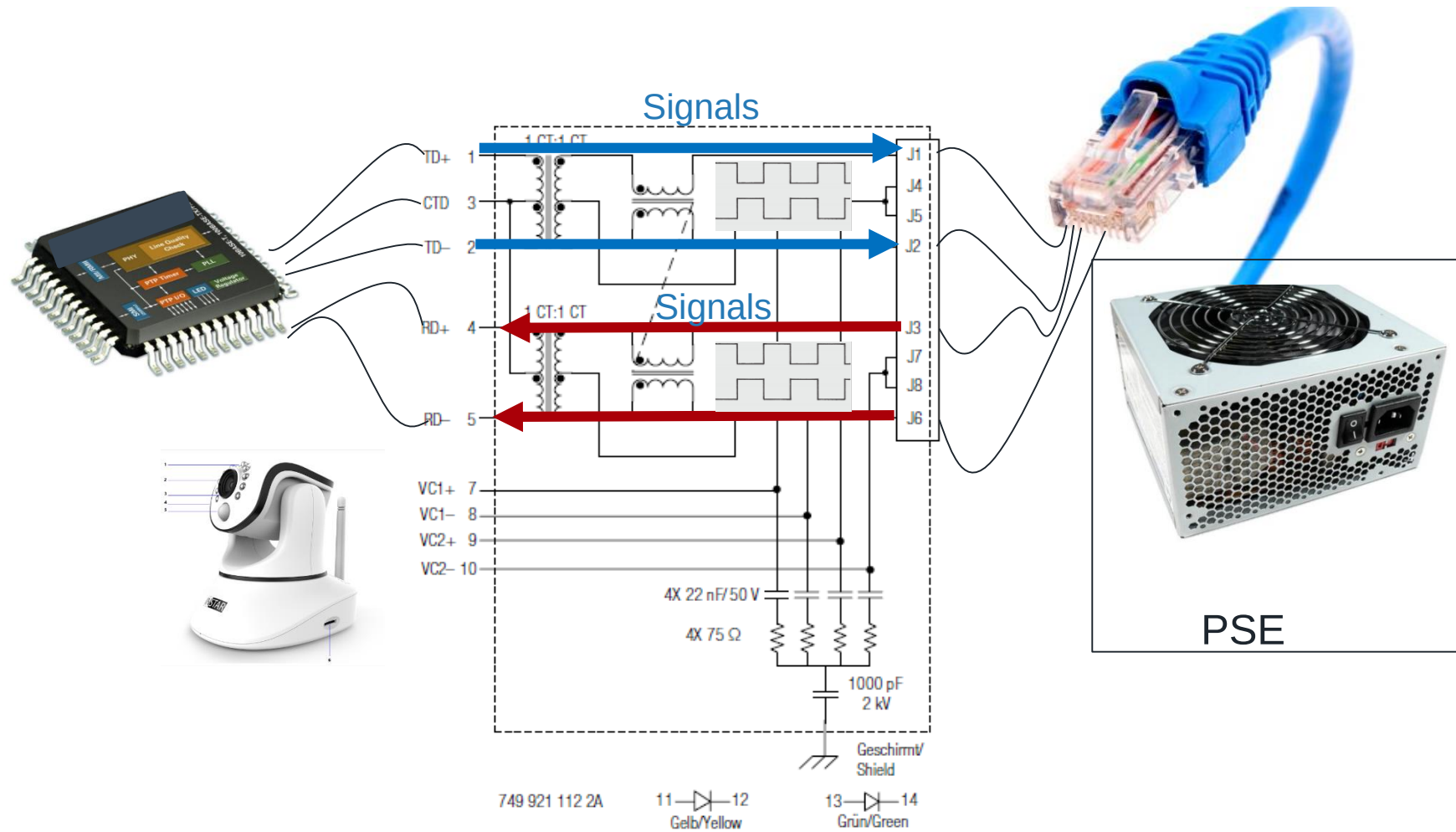
POWER OVER DATA LINE (PODL)



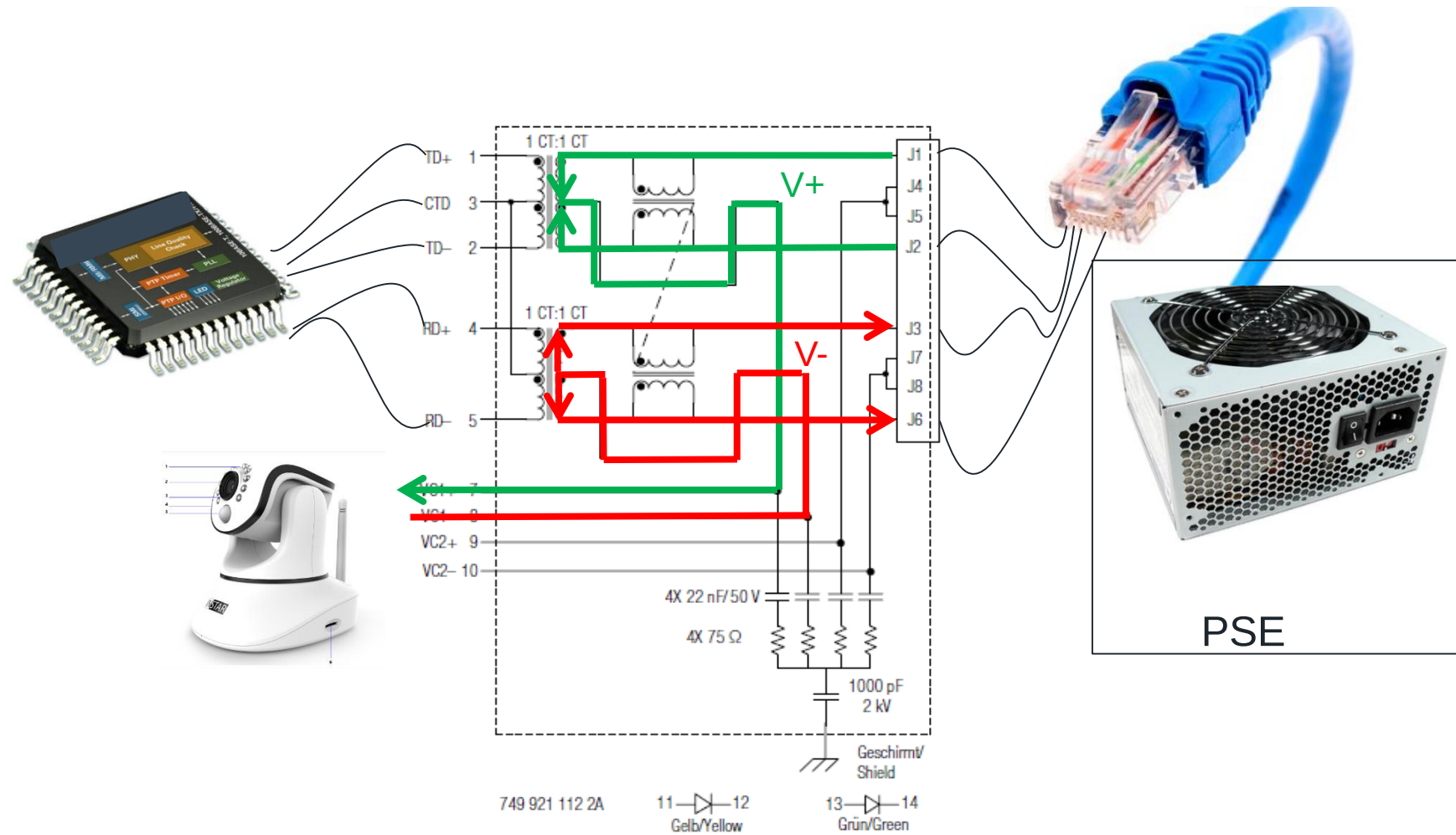
Power over Ethernet



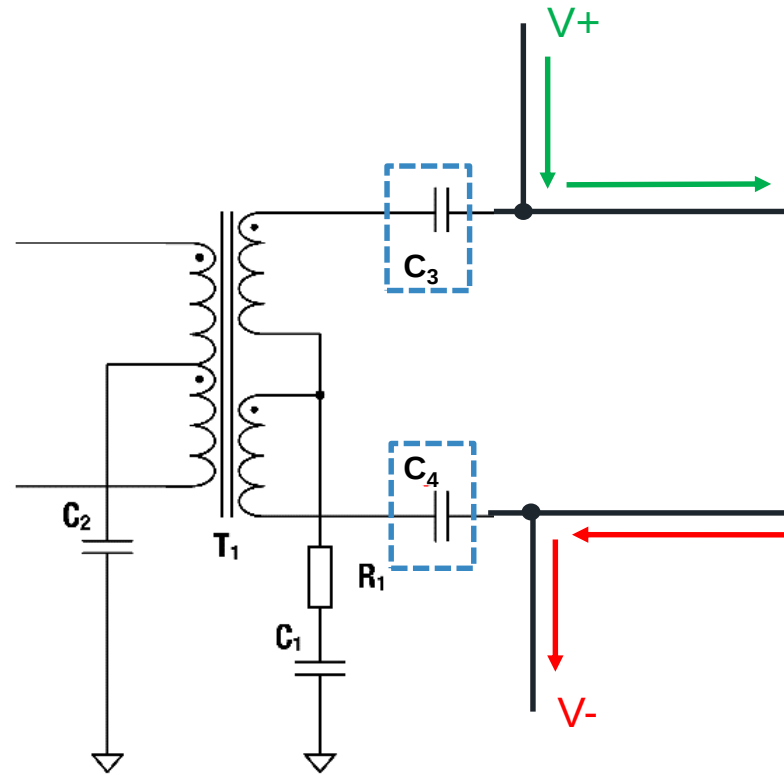
Power over Ethernet



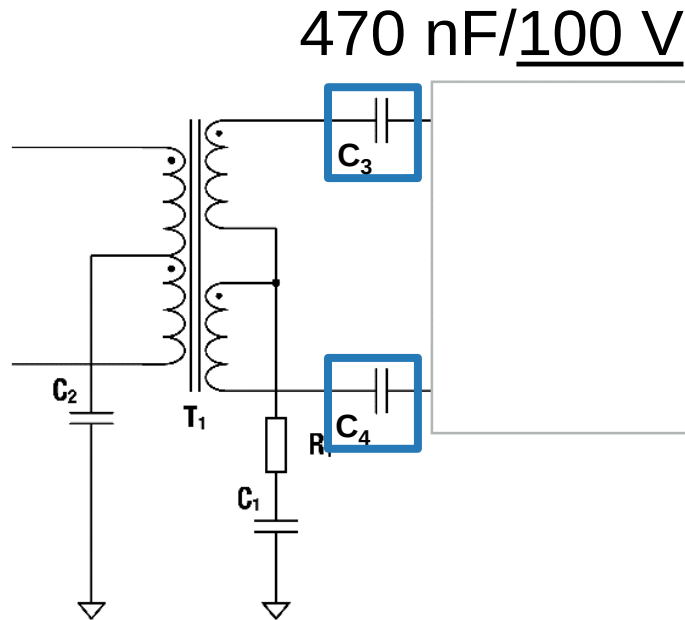
Power over Ethernet



Power over data line

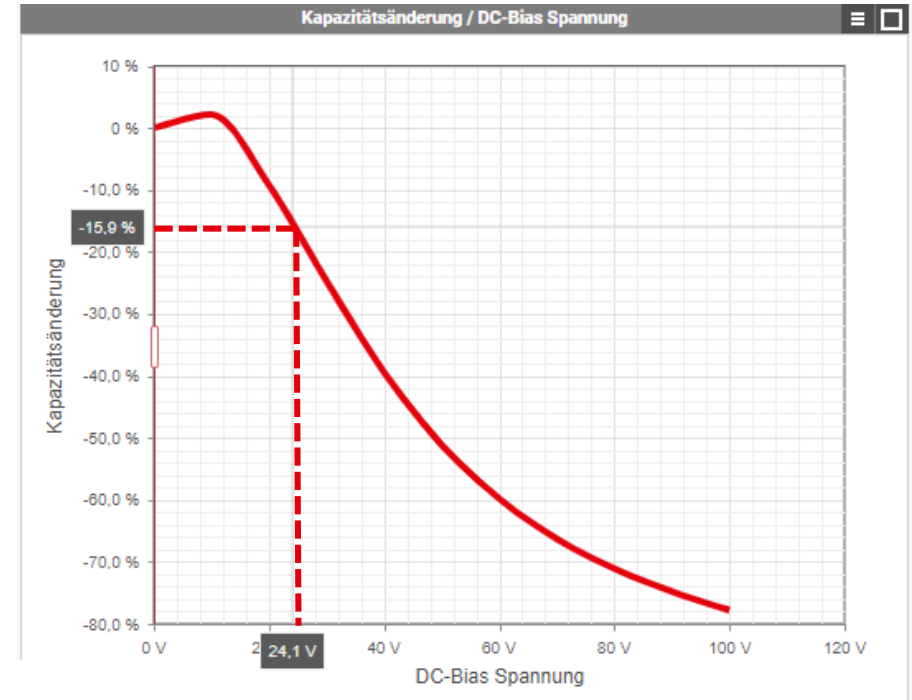


Power over data line

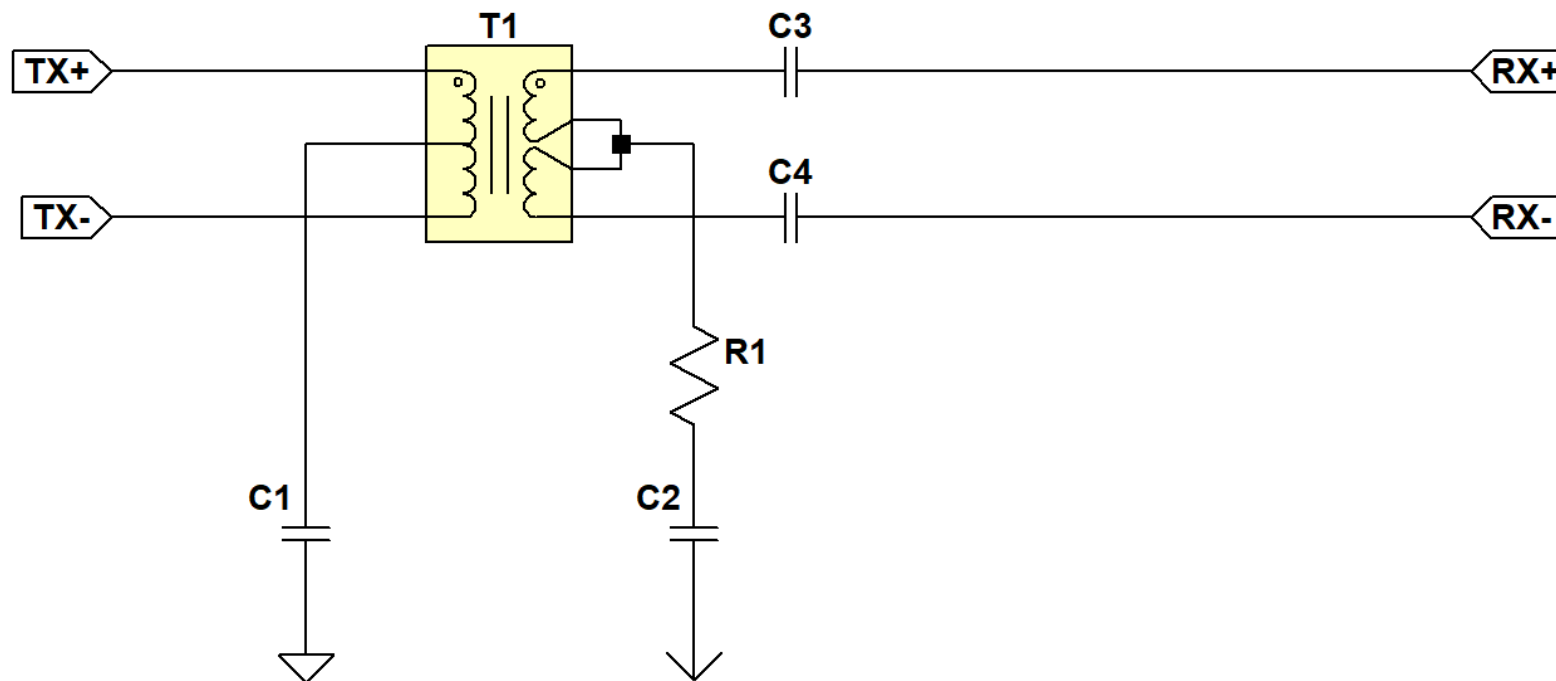


146.8.5 MDI DC power voltage tolerance

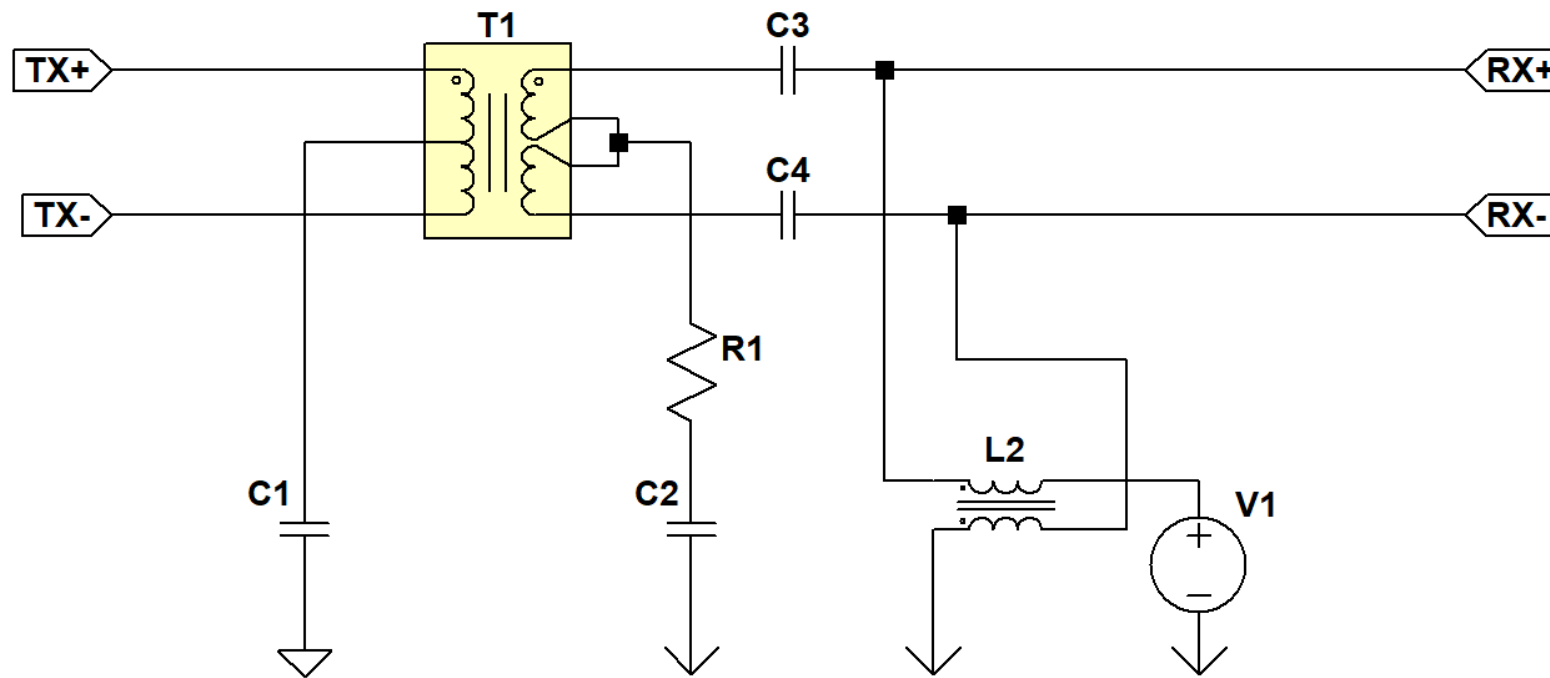
The DTE shall withstand without damage the application of any voltages between 0 V dc and 60 V dc with the source current limited to 2000 mA, applied across BI_DA+ and BI_DA-, in either polarity, under all operating conditions, for an indefinite period of time. This requirement ensures that all devices tolerate DC powering voltages, such as those in Clause 104, even if the device does not require power.



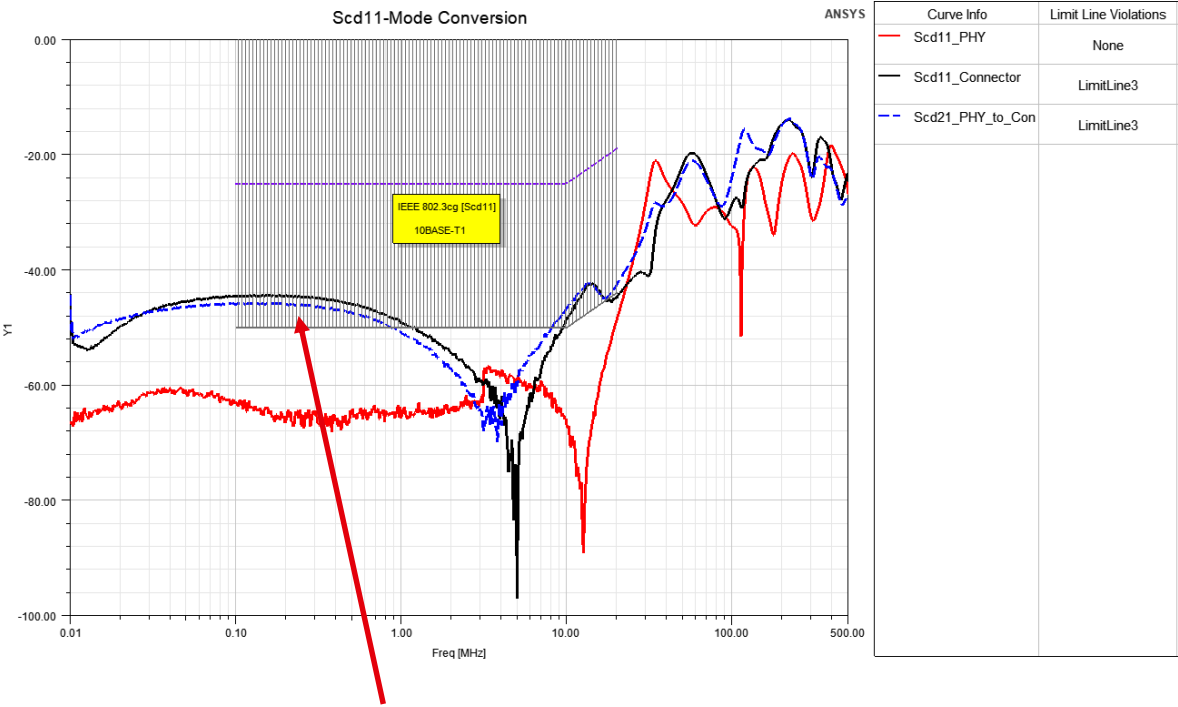
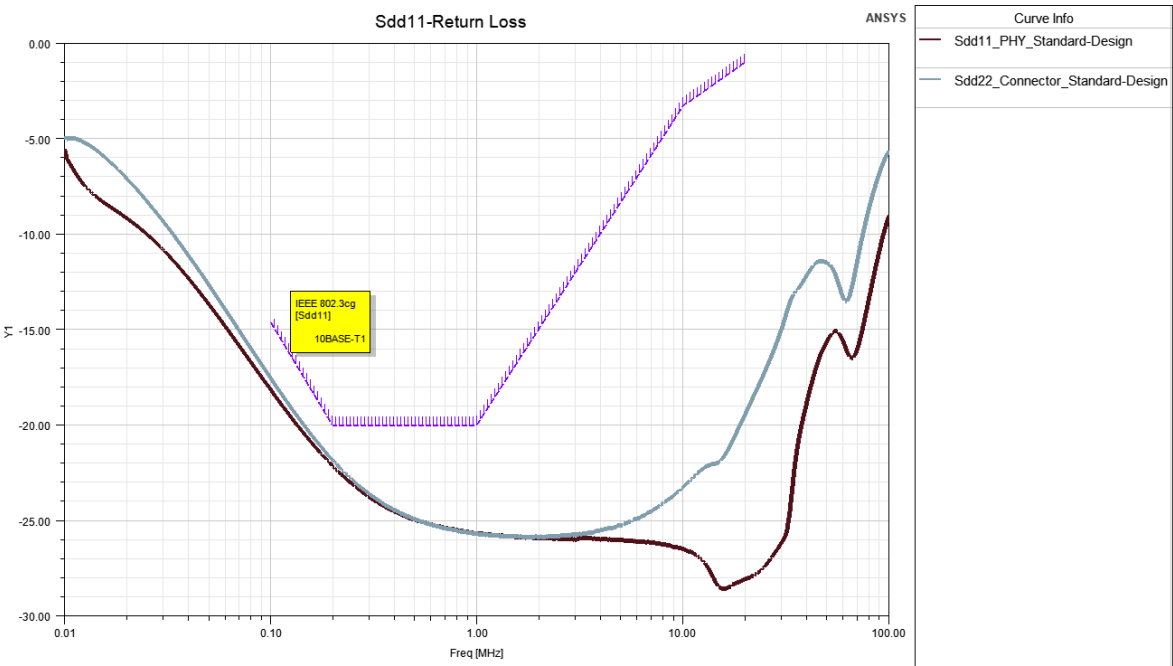
Power over data line



Power over data line



PoDI Performance (Standard Design)

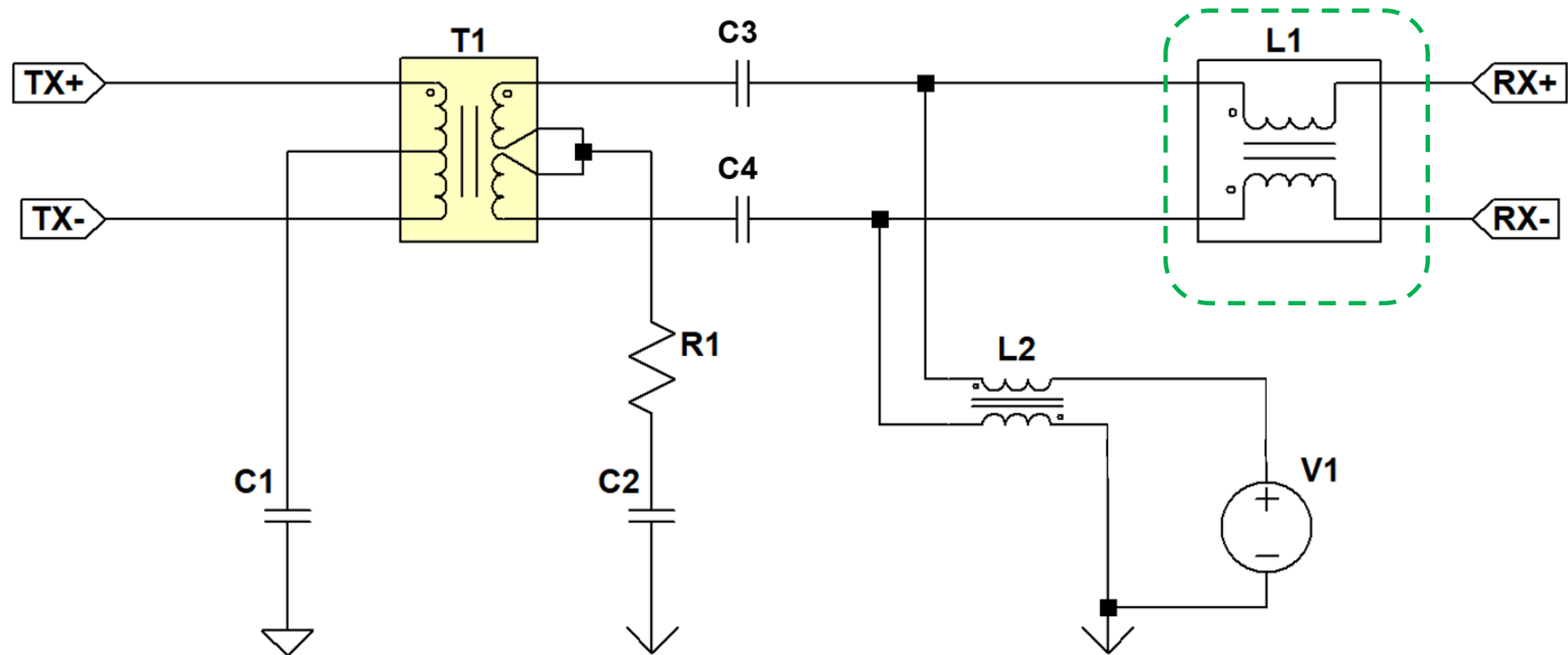


-45 dB violation: high mode conversion

IMPROVEMENTS ON THE PODL DESIGN

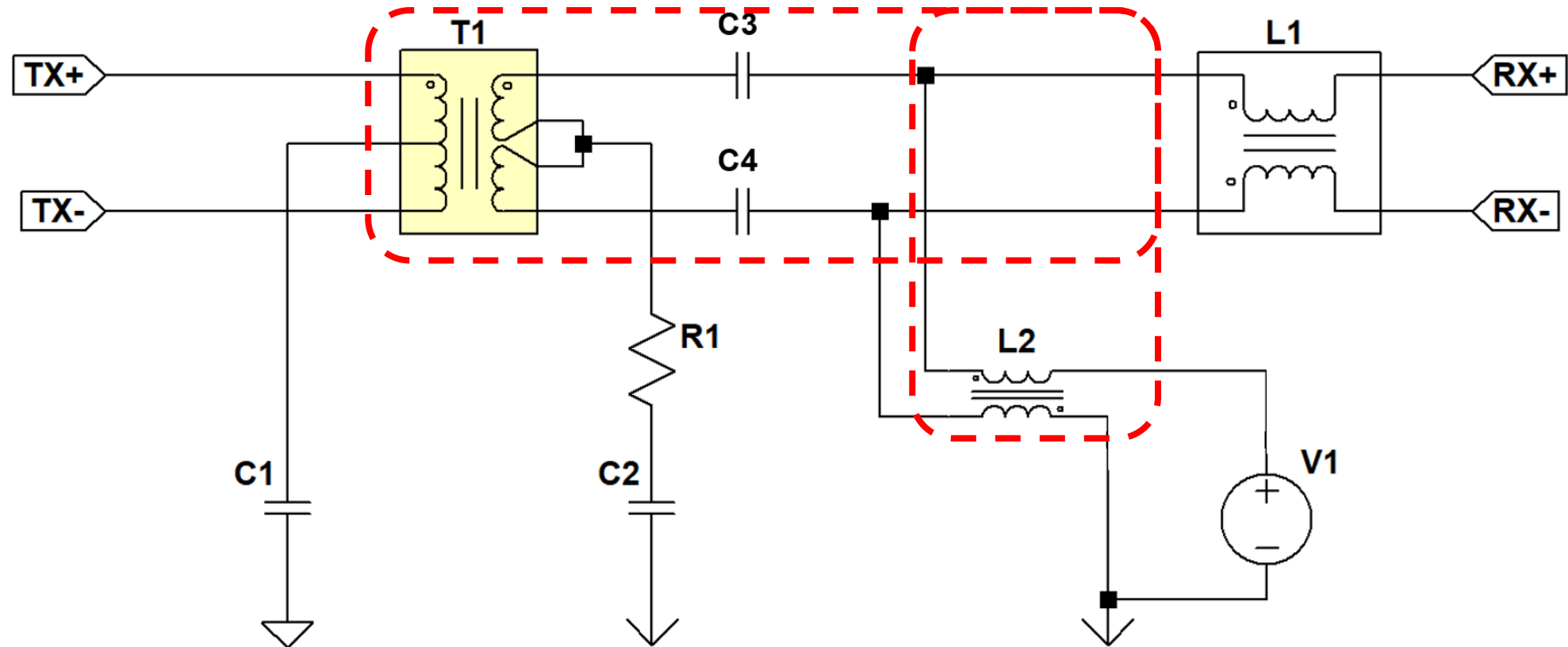


Design improvements



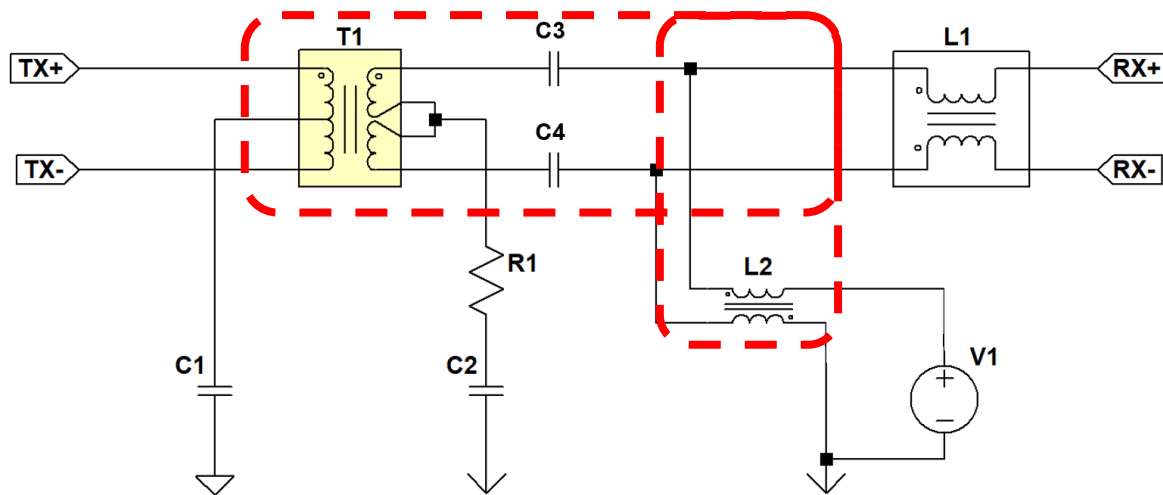
Design improvements

Patent US000008044747B2

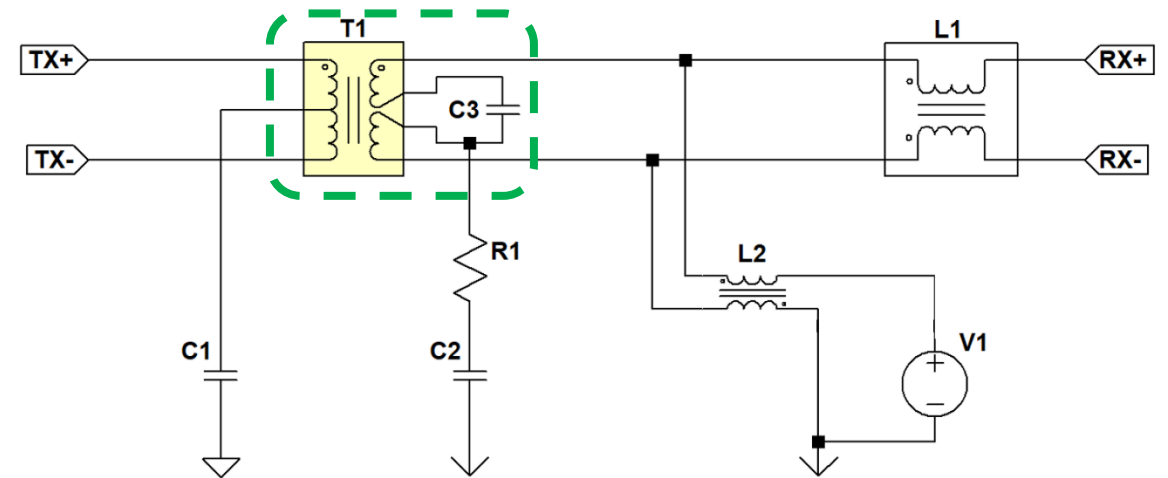


Design improvements

Patent US000008044747B2

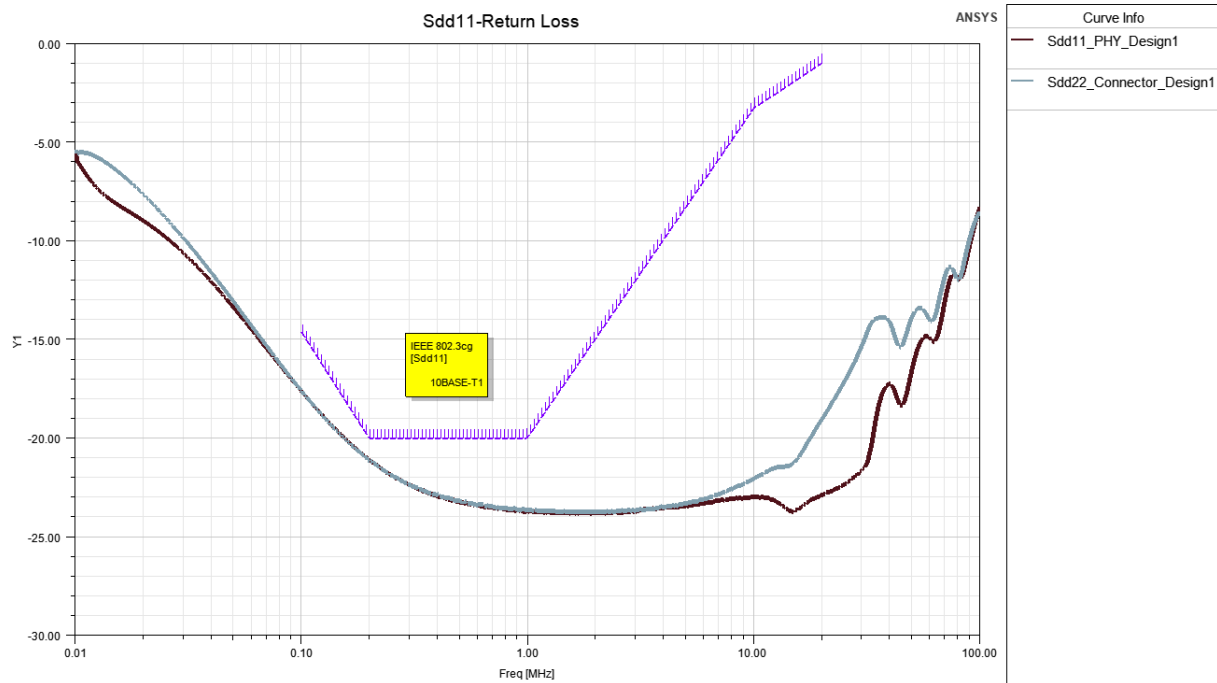


Alternative

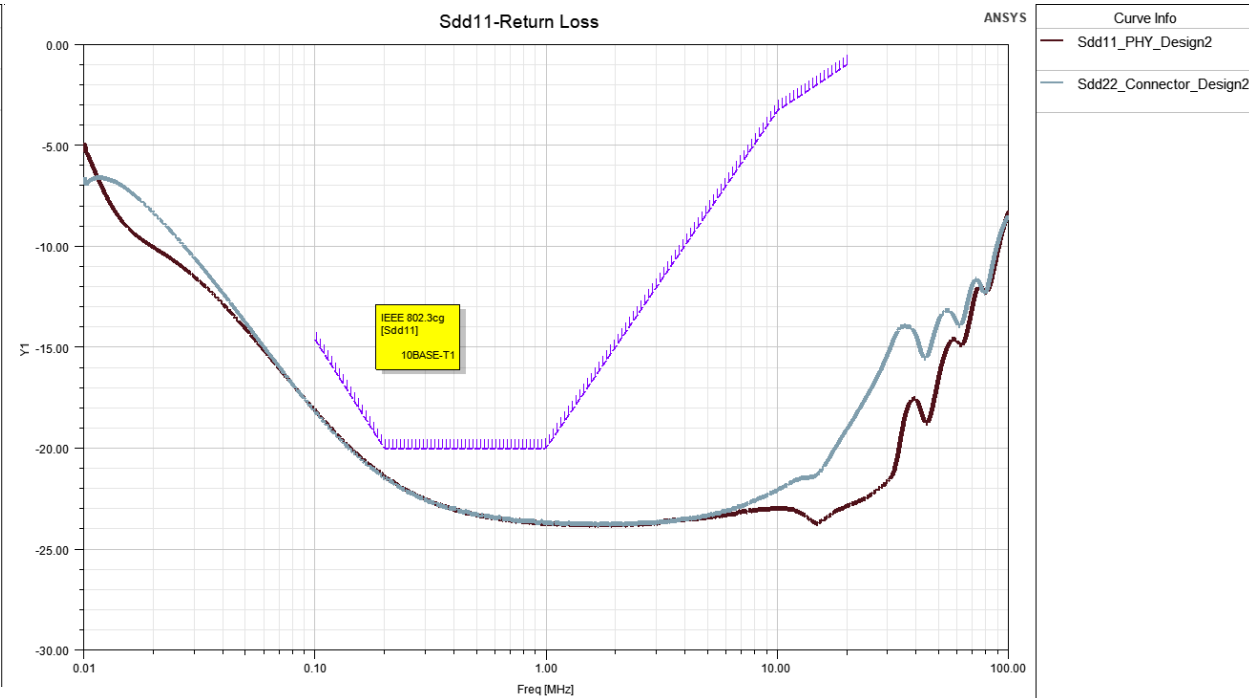


Design improvements (S_{dd11})

Patent US000008044747B2

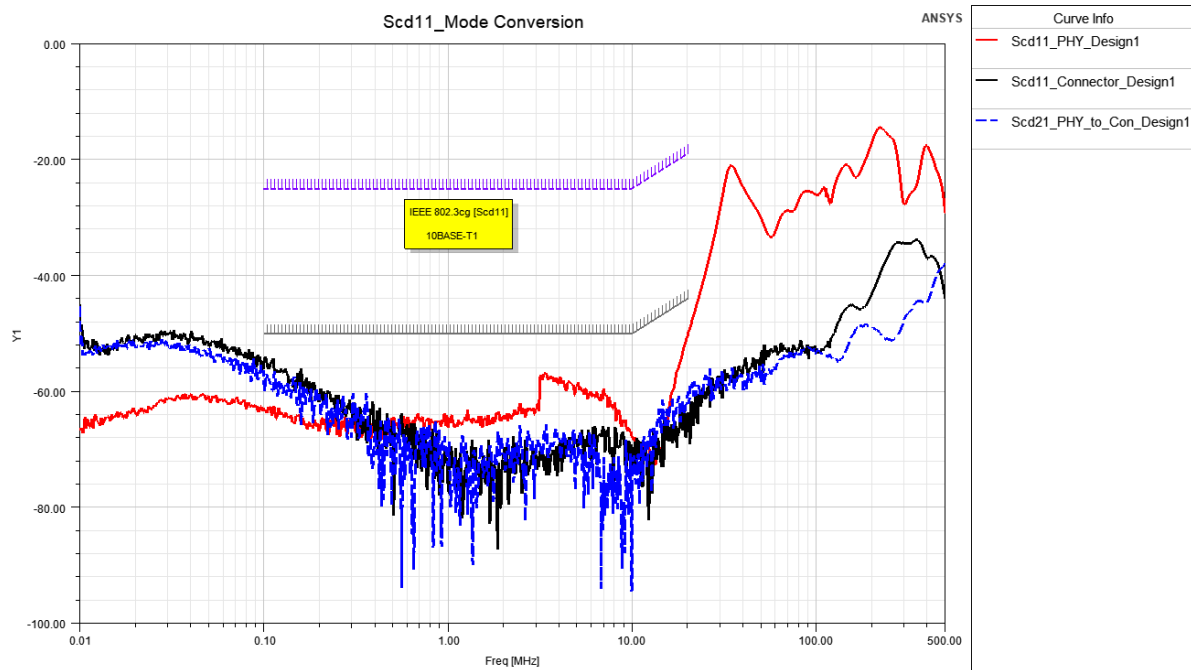


Alternative

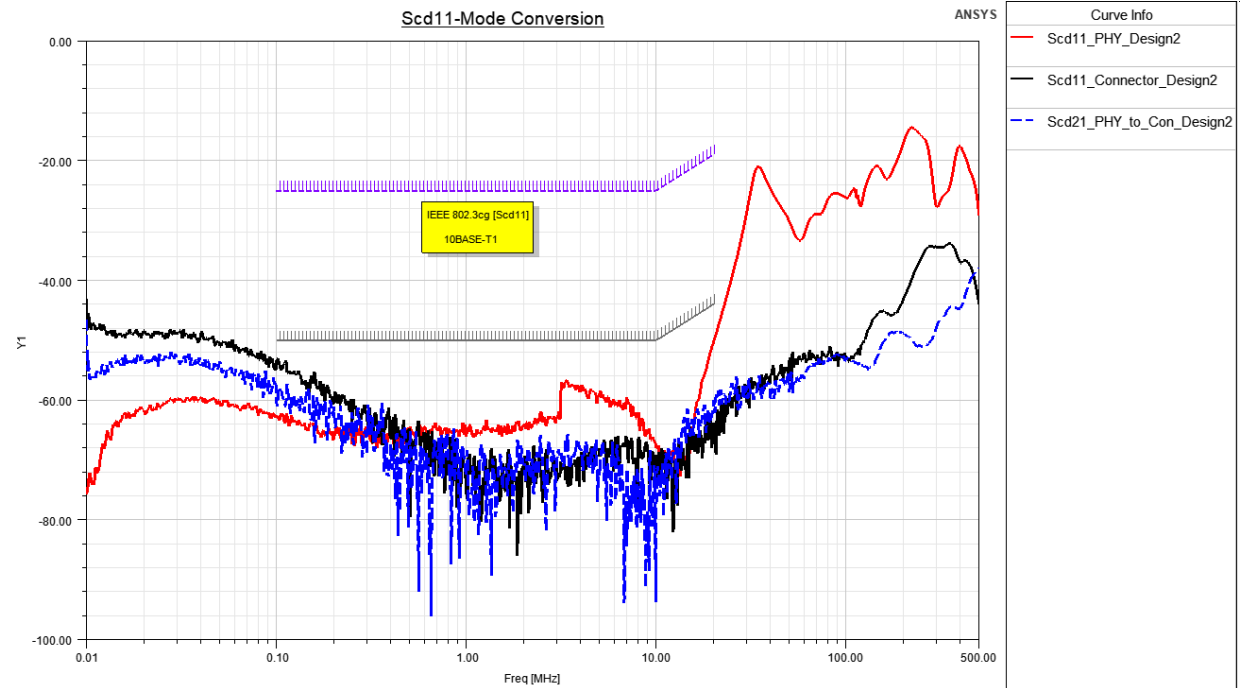


Design improvements (S_{cd11})

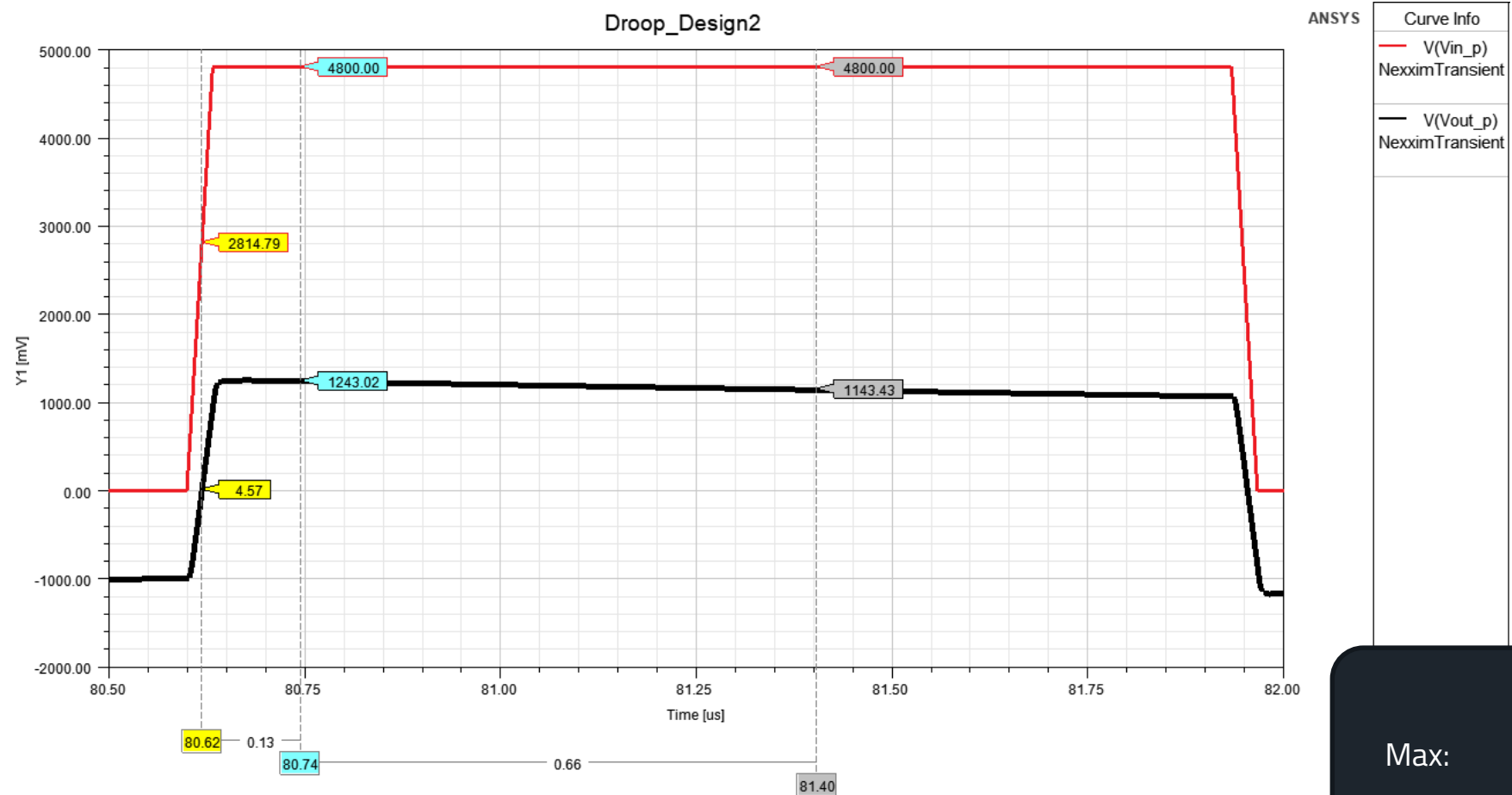
Patent US000008044747B2



Alternative



Droop Simulation



Droop:

Max: 10%

WE Design: 8%

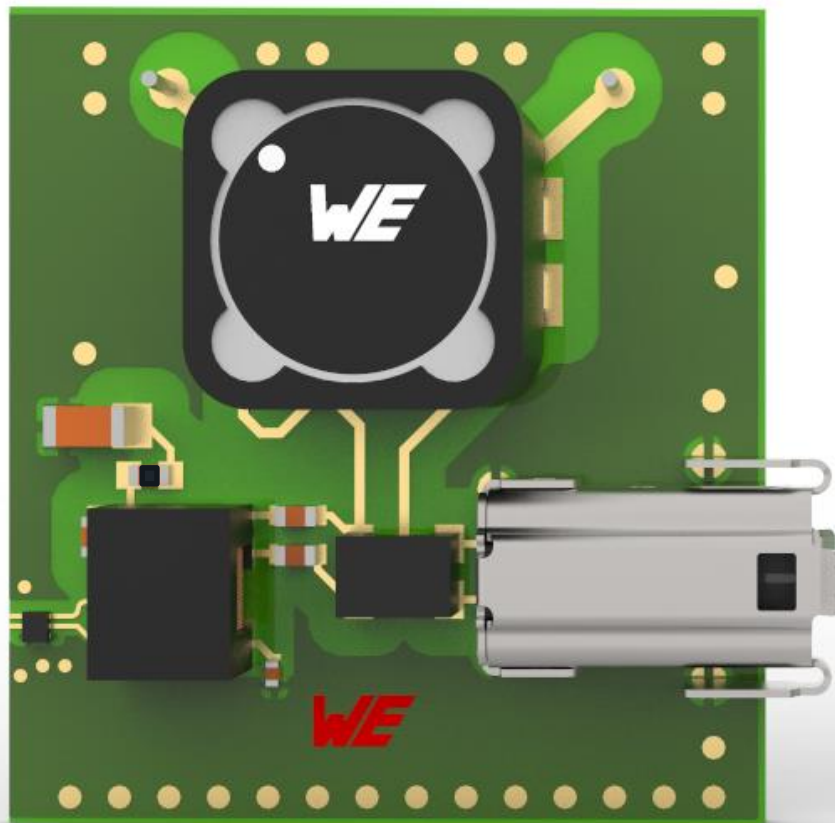
PoDL layout

PoDL Classes

0, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14

$I_{\max} = 700 \text{ mA}$

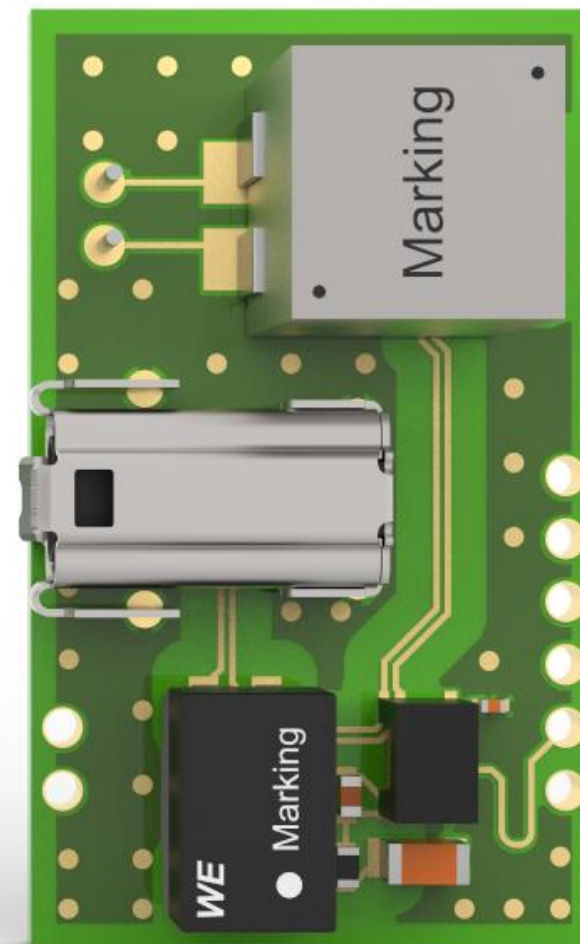
2021



All PoDL Classes

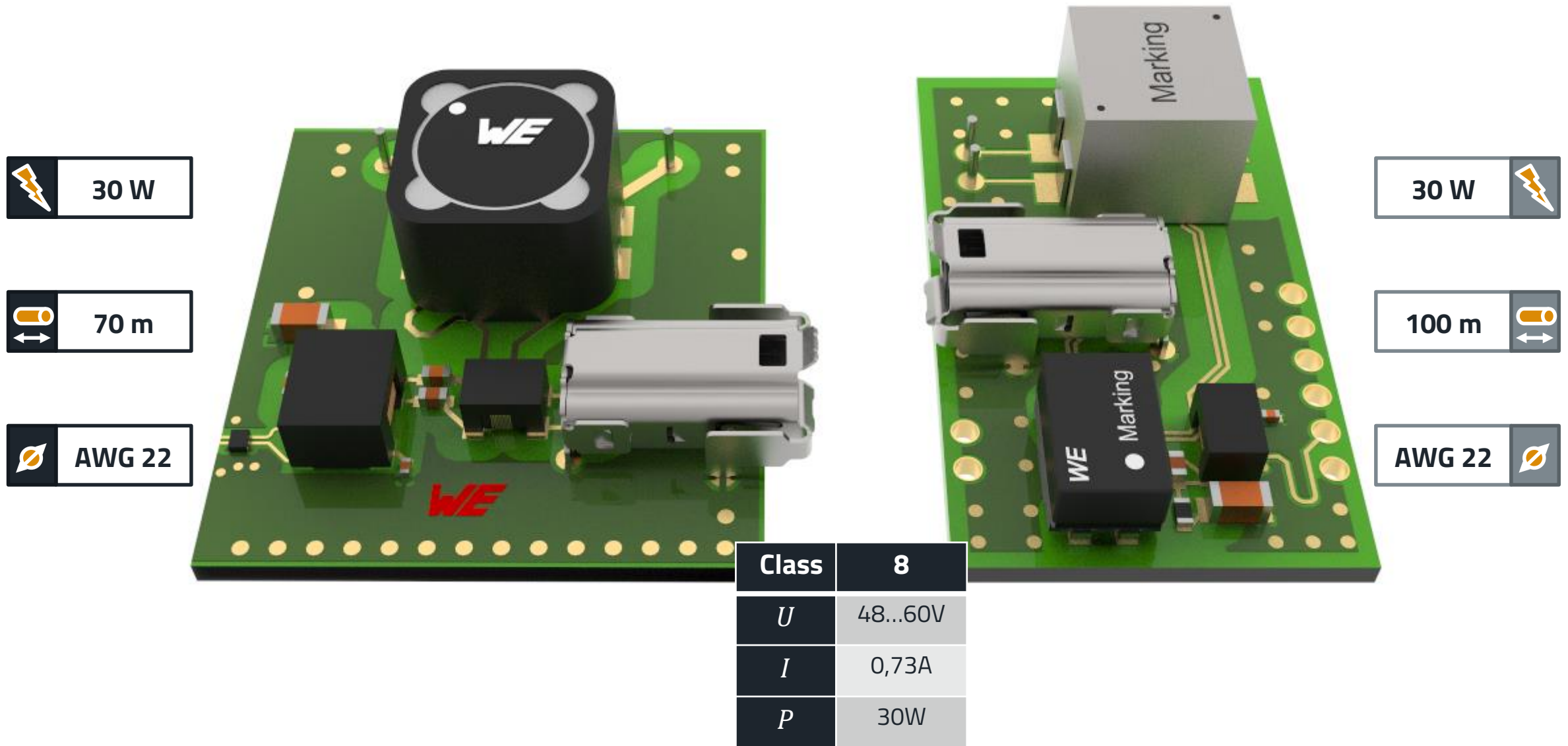
Class 0 - 15

$I_{\max} = 1600 \text{ mA}$

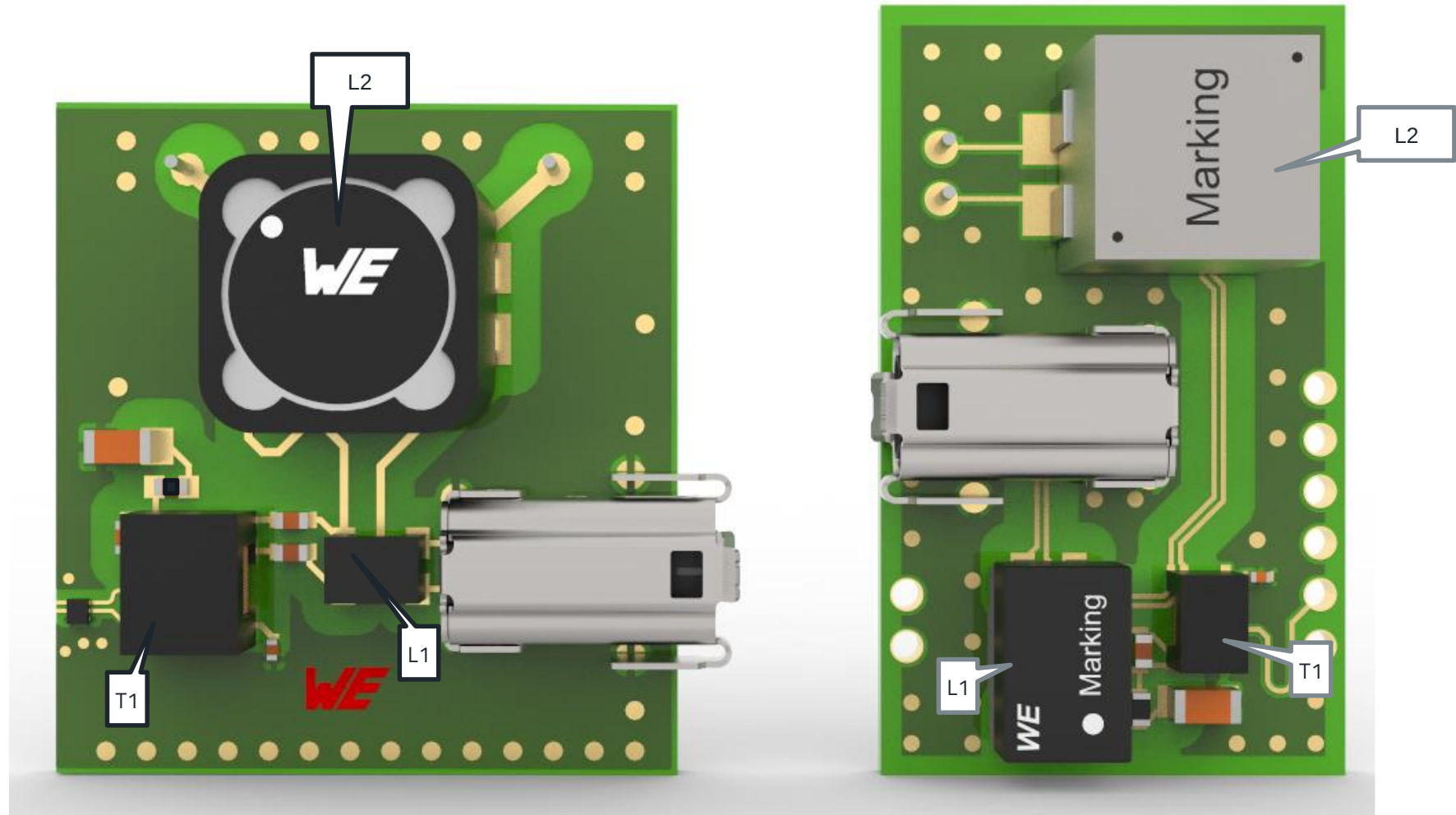


2022

PoDL layout



PoDL layout

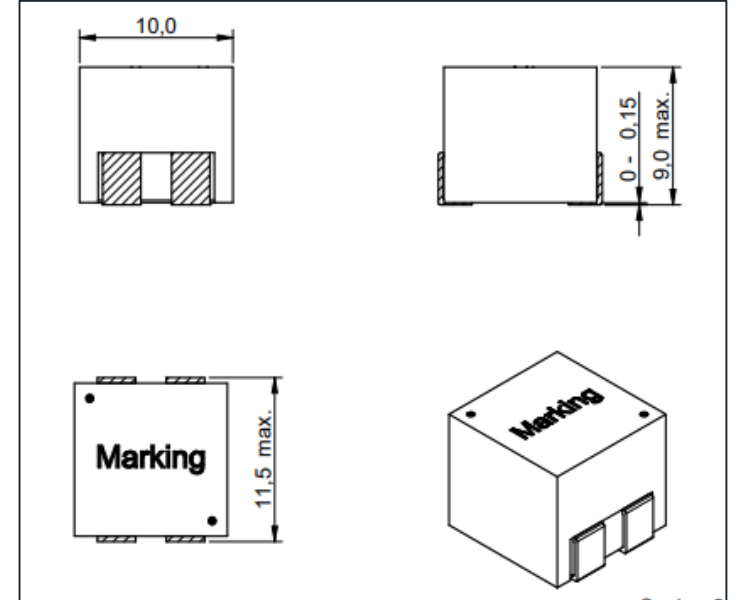


Power classes

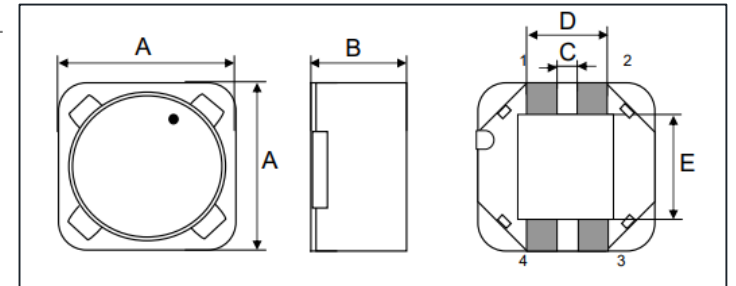
	12 V unregulated PSE		12 V regulated PSE		24 V unregulated PSE		24 V regulated PSE		48 V regulated PSE	
Class	0	1	2	3	4	5	6	7	8	9
$V_{PSE(max)} (V)^a$	18	18	18	18	36	36	36	36	60	60
$V_{PSE_OC(min)} (V)^b$	6	6	14.4	14.4	12	12	26	26	48	48
$V_{PSE(min)} (V)$	5.6	5.77	14.4	14.4	11.7	11.7	26	26	48	48
$I_{PI(max)} (mA)^c$	101	227	249	471	97	339	215	461	735	1 360
$P_{Class(min)} (W)^d$	0.566	1.31	3.59	6.79	1.14	3.97	5.59	12	35.3	65.3
$V_{ID(min)} (V)$	4.94	4.41	12	10.6	10.3	8.86	23.3	21.7	40.8	36.7
$P_{PD(max)} (W)^e$	0.5	1	3	5	1	3	5	10	30	50

Source: IEEE802.3bu

7448990470



744870471

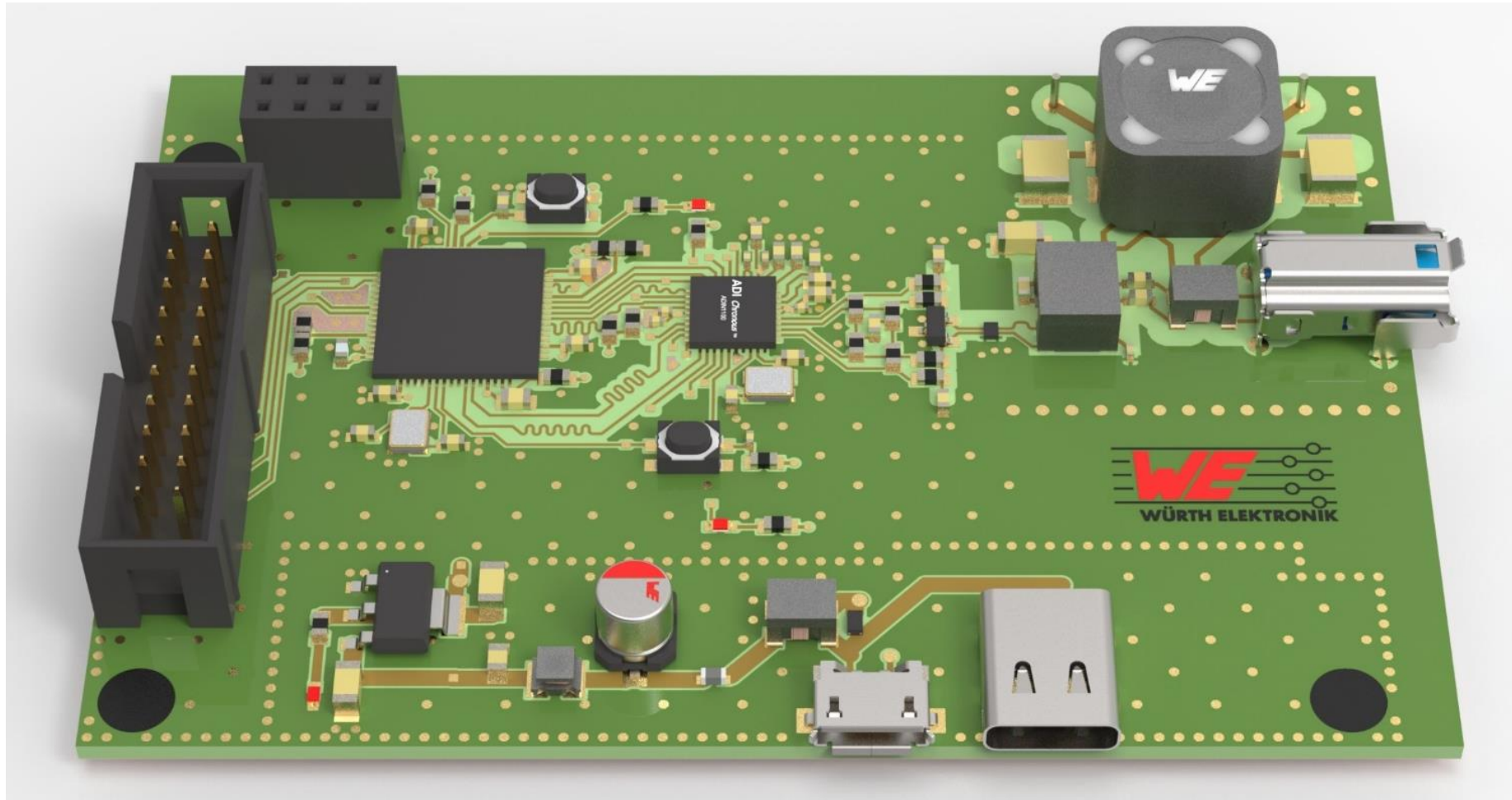


Power classes

Class	0	1	2	3	4	5	6	7	8	9
<i>U</i>	5,5...18V	5,5...18V	14...18V	14...18V	12...36V	12...36V	26...36V	26...36V	48...60V	48...60V
<i>I</i>	0,1A	0,22A	0,25A	0,47A	0,1A	0,34A	0,21A	0,46A	0,73A	1,3A
<i>P</i>	0,5W	1W	3W	5W	1W	3W	5W	10W	30W	50W

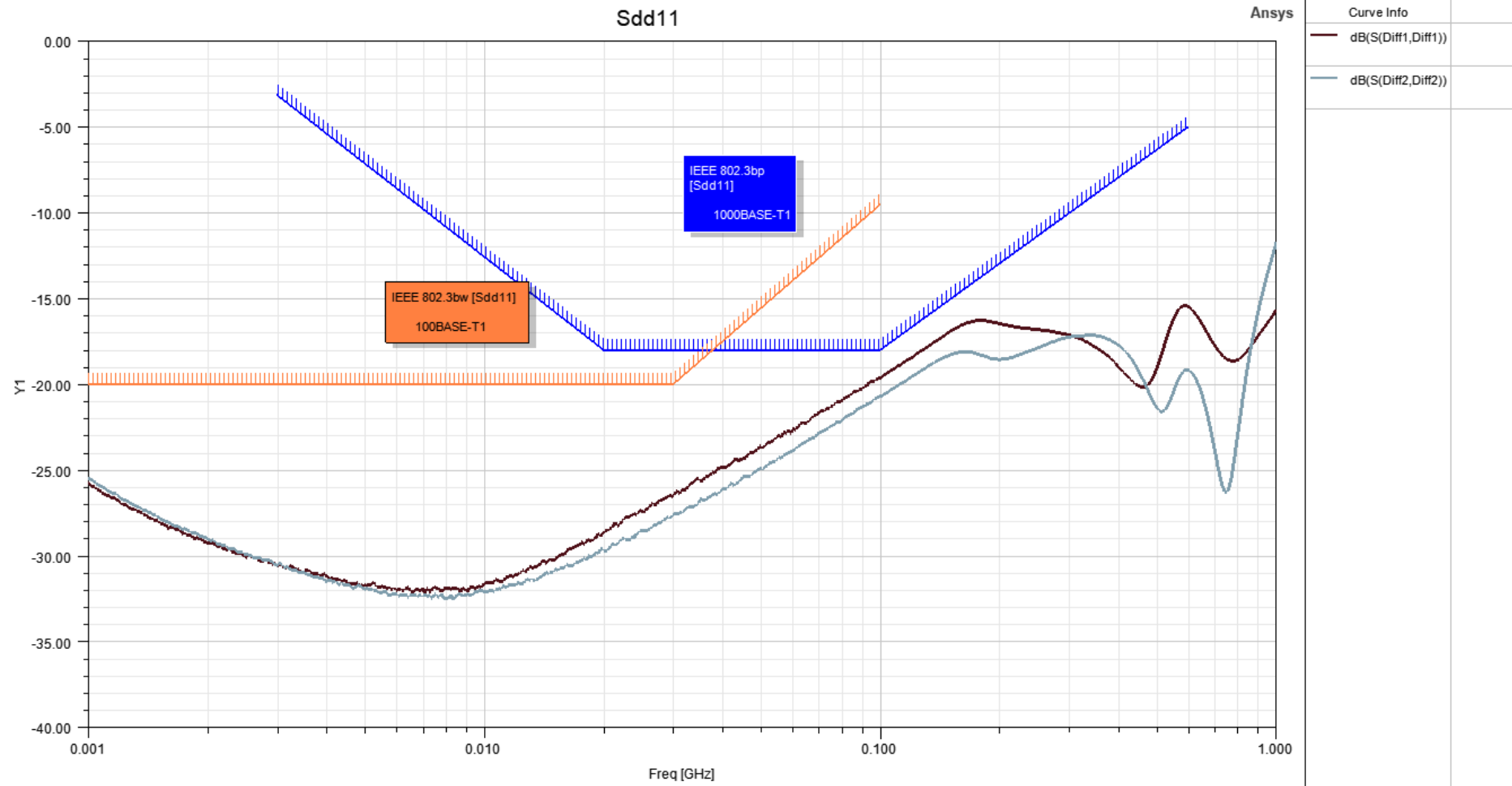
Class	10	11	12	13	14	15
<i>U</i>	20...30V	20...30V	20...30V	50...58V	50...58V	50...58V
<i>I</i>	0,092A	0,24A	0,632A	0,231A	0,6A	1,579A
<i>P</i>	1,32W	3,2W	8,4W	7,7W	20W	52W

PoDL board



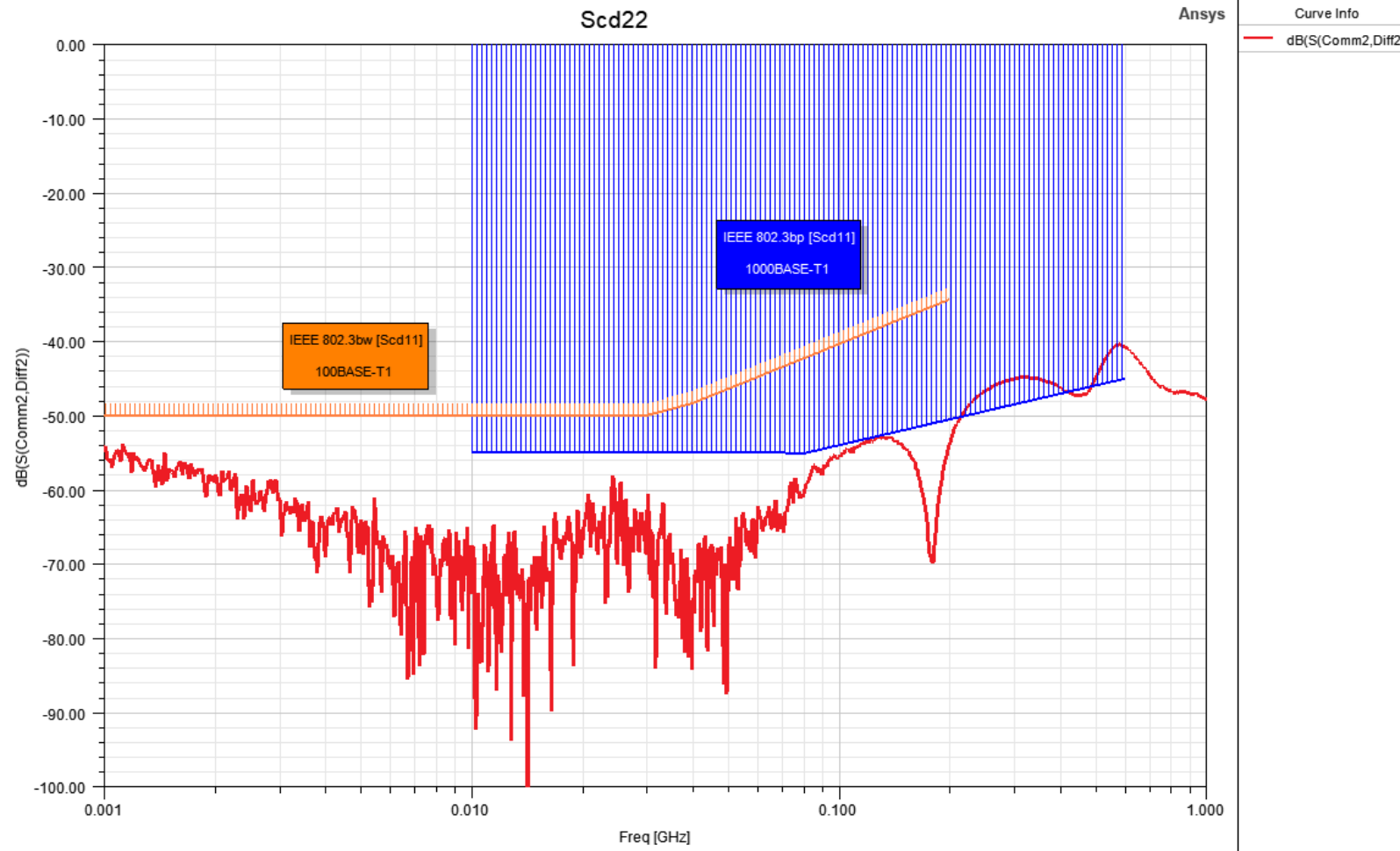
1000BASE-T1

Return Loss



1000BASE-T1

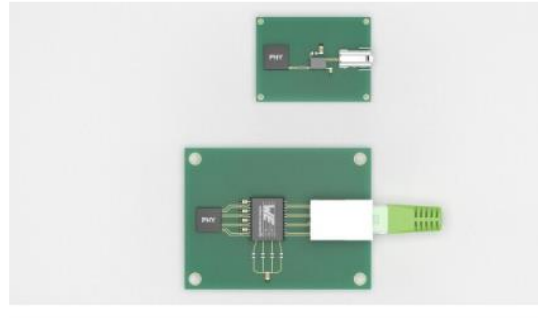
Mode Conversion



Landing Page

Compact design

By using only one pair of wires, the number of passive components on the PCB is considerably reduced. Together with the very compact connector, Single Pair Ethernet can save up to 75 % PCB space, compared to current Ethernet over RJ45.

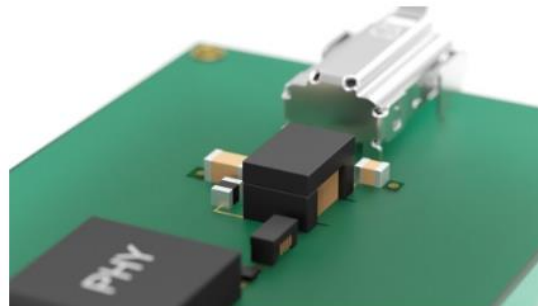


Insulation voltage according to IEC 62368-1

Similar to Ethernet over four-pair wires, isolation in accordance with IEC 62368-1 (formerly IEC 60950) is also specified for Single Pair Ethernet. Capacitors with 50 Volt galvanic isolation apply almost exclusively to automotive Ethernet applications and are not sufficient for industrial applications.

The good news is that the electrical isolation in Single Pair Ethernet can be easily solved by a signal transformer. Our **WE-STST** transformer series combines excellent performance with a very compact size of only 4.5 x 3.2 mm.

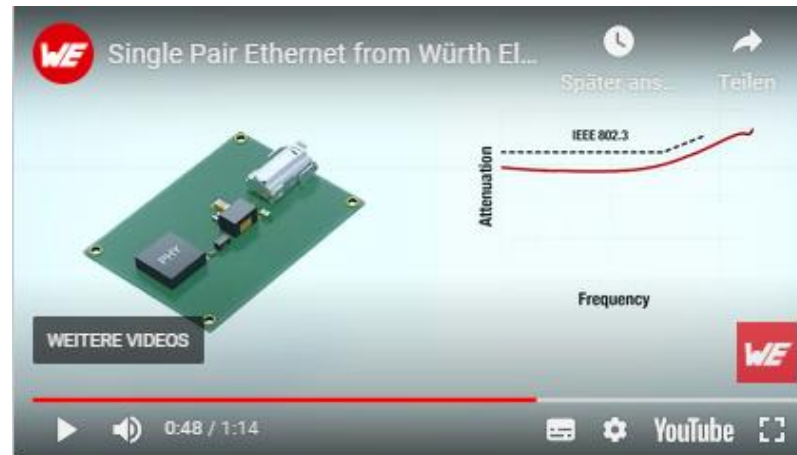
Through connection of the centre tap to GND, common mode signals are also effectively attenuated



Webinar



Video



Application Note

Single Pair Ethernet for Industrial Applications



mode choke 74472222 not only provides common mode suppression but also has a positive influence on return loss and mode conversion loss. Due to the low cut-off frequency, the dimensions (10 mm x 8.7 mm) and inductance value ($2 \times 2200 \mu\text{H}$) of the common mode choke are correspondingly large. The common mode rejection for 74472222 is illustrated in figure 15.

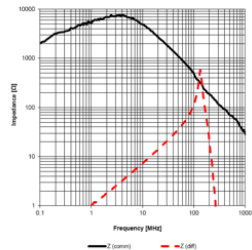


Figure 15: Common mode and differential mode impedance 74472222 for 10BASE-T1

A more compact and electrically at least equivalent solution is the design with a transformer. Figure 16 shows the transformer design for 10BASE-T1. In contrast to chapter 4, no common mode choke is required for the 10 Mbit/s design. The reason is the good interference suppression of the transformer at low frequencies. Another difference is the capacitor C_1 on the two center pins which extends the transformer bandwidth up to 35 kHz and thus helps to improve the return loss in low frequencies.

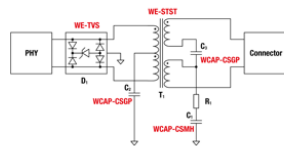


Figure 16: 10BASE-T1 transformer design

Since it is not possible to split the center pin on all transformer types, two capacitors can be used on the outer transformer pins as an alternative to C_3 between the transformer center pins. This design enlarges the circuit minimally, but has the advantage, that the similar circuit can be used for Power over DataLink (PoDL) applications. For PoDL, the voltage on both capacitors drops only half, thus preventing DC saturation. If only data is transmitted, capacitors with an isolation voltage of 25 V are sufficient, whereas with PoDL an isolation voltage of 100 V is necessary.

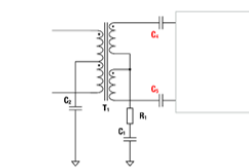


Figure 17: Capacitors C_1 and C_2 on the outer transformer pins as alternative to C_3

In addition to the insulation voltage of the capacitors, their capacitance is important for both circuit diagrams. Simulations and measurements result in a minimum value of 100 nF to meet the limits of IEEE802.3cg. However, the section "148.5.4.2 Transmitter output droop" mentions a maximum voltage drop of 10% between 133.3 ns and 800 ns for a test signal of the PHY chip. To meet this requirement, two changes can be made. Either the inductance of the transmitter is increased, which also goes along with the increase in size or capacitors with larger capacitance values are used. The second possibility is more space-saving, cheaper and easier to implement. In this case 470 nF capacitors are used to achieve the best compromise between the droop and return loss requirements. As figure 18 and the following equation shows, this circuit design achieves a voltage drop of about 8.3% and is therefore within the standard.

Application Note

Single Pair Ethernet for Industrial Applications



frequency ranges. Due to the lower cut-off frequency at 100BASE-T1 of 1 MHz, the impedance of the choke must be high in low frequencies and, if possible, also cover higher frequencies up to 200 MHz. The number of windings and core size is correspondingly larger.

The GND termination typically consists of three resistors, where the first two 1 kΩ resistors are responsible for signal termination, and the 100 kΩ resistor together with the capacitor decouples common-mode components in the signal.

The coupling capacitors have capacitances of typically 100 nF and come with 50 V isolation voltage. They are comparatively small and cost-effective, which is why they are used in automotive applications with low-voltage environments and a maximum cable length of 15 m.

3.2 Isolation requirements

Outside the automobile, the IEEE 802.3 standard for signaling systems stipulates the insulation requirement according to IEC 62368-1, which corresponds to 1500 V AC for 60 seconds. A DC voltage of 2250 V DC for 60 seconds or certain test voltage pulses are also permitted. These high insulation voltages cannot be maintained by the 50 V capacitors, so alternative solutions must be sought. The following chapter therefore describes a solution with transformer. Detailed measurements and a comparison with capacitors with 2000 V insulation voltage follows in the chapter Performance Comparison SPE automotive vs. SPE industrial Solutions

At 1 – 66 MHz, the frequency range for SPE 100BASE-T1 is in the Gigabit Multipair Ethernet (1 - 62.5 MHz) range. It is therefore obvious to design a circuit for SPE that is based on the circuit diagram of Gigabit Ethernet, see figure 8.

The central element of the circuit is a signal transformer, which provides the galvanic isolation and ideally does not influence the data signals. The transformer is terminated at its center pins with capacitors to GND. A common mode choke is used for common mode interference suppression. To ensure protection against ESD pulses, a TVS diode is placed between the common mode choke and the PHY chip. ESD suppression is even better if the TVS diode is located between the connector and the transformer. However, in order not to cause a short circuit between

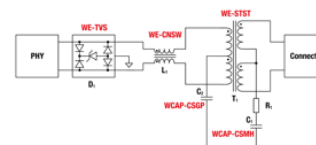


Figure 8: SPE schematic with a transformer solution

The following chapter describes the individual components of the circuit in more detail.

3.3 Galvanic isolation with a transformer

For SPE a signal transmitter of the WE-STST series is selected. Its compact design compared to conventionally manufactured LAN transformers, together with high inductance of 350 μH, offers good signal characteristics even at lower frequencies. In addition, it is SMT mountable and is manufactured 100 % automatically.

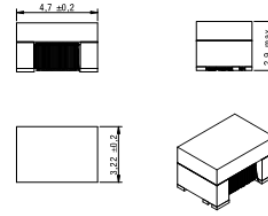


Figure 9: WE-STST shapes and dimensions

The transformer consists of a core of MgZn, which is wound bifilarly from two sides, i.e. windings of primary and secondary side are on top of each other for signal coupling. Insulation is provided by a plastic sheathing of the wires, both on the primary and secondary side. Due to the direct coupling and the transmission ratio of 1:1, differential signals are transmitted. Direct voltage components are blocked.

Besides the galvanic isolation, a signal transformer needs to transfer data in a determined frequency range of 1 – 66 MHz for 100BASE-T1 Single Pair Ethernet. For

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