White Paper

# Immunity from Interference for Single Pair Ethernet (SPE) in Noisy Environments

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## Introduction

Ethernet has come a long way since its inception in the ‘70’s. Not only have data rates increased manyfold, its application has grown far beyond computer networking. Ethernet has been adopted in industrial automation and controls, medical equipment, automotive, avionics and more. In short, it is ubiquitous. The most widely deployed form of Ethernet uses multi-pair electrical transmission lines, and recent developments have introduced Single-Pair-Ethernet (SPE), which is finding increasing use in the automotive and industrial automation sectors.

One major difference between SPE and other twisted-pair systems is the common use of capacitive coupling (CC) instead of isolation transformers in the front-end. While there are some obvious advantages in capacitive coupling (for example where there are no high voltage isolation requirements to meet, a smaller size and lower cost are possible), some concerns with the performance of this approach have become evident in some applications.

Whereas earlier generations of 802.3 standards for Ethernet over twisted pairs set specific requirements for Common-Mode Rejection (CMR) at the Media Dependent Interface (MDI), recent xBASE-T1 specifications (for SPE) do not. This is entirely sensible, as it facilitates the use of SPE in environments where CAN or LIN systems are alternatives. However, SPE can be deployed in noisy environments, where capacitive coupling and Common-Mode Choke (CMC) front-end circuits may not offer sufficient CMR to protect the link. Communication drop-outs or complete signal blockage may occur due to interference that is readily found in noisy environments.

We demonstrate here that HALO’s high-speed SPE isolation transformers are effective in eliminating the susceptibility issues of capacitive coupling plus common-mode choke (CC+CMC) systems, and we note that transformers offer the most compact solution where there is also a requirement for high voltage isolation, as capacitors alone for this are rather bulky.

## Comparison of CMR Performance

The most common SPE front-end isolation circuit consists of a pair of capacitors and a CMC to combat received noise and to meet emission standards (Figure 1). It provides good common-mode noise suppression from 10 MHz and up, but it falls off somewhat below 10 MHz (Figure 3).

An isolation transformer on the other hand can provide vastly improved common-mode noise rejection right down to DC, and when combined with a CMC (Figure 2) the noise rejection is acceptable across the entire frequency band (Figure 3).

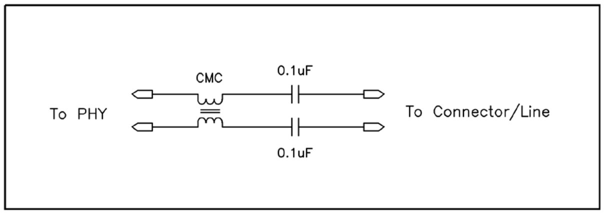


*Figure 1: CC + CMC Coupling Circuit*

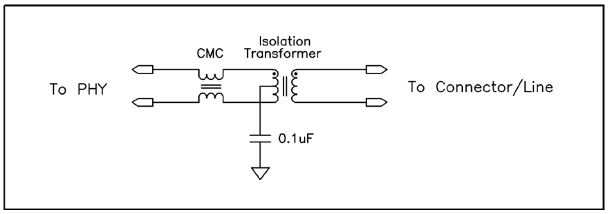


*Figure 2: Transformer + CMC Coupling Circuit*

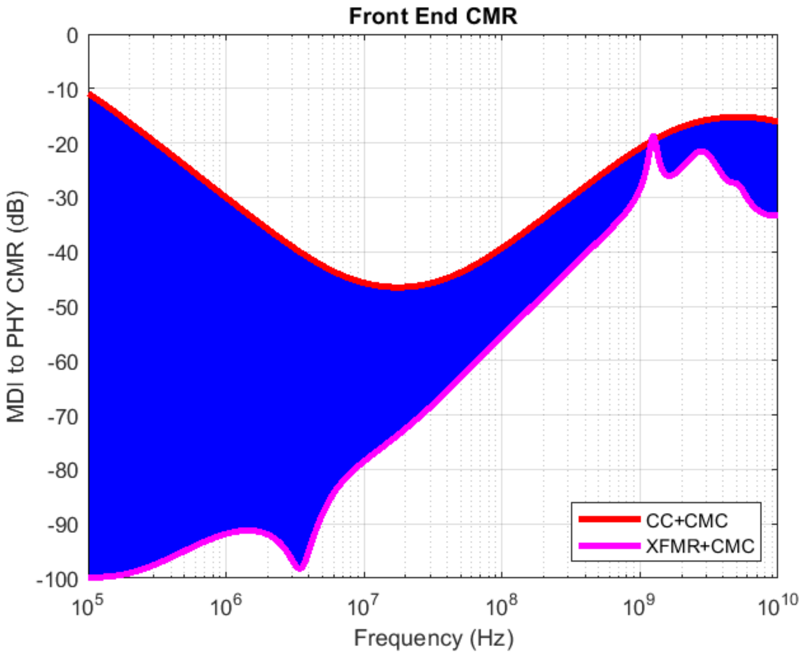


*Figure 3: Comparison of CMR of CC+CMC coupling circuit and transformer+CMC coupling circuit*

Figure 3 shows that the addition of a transformer greatly enhances the CMR at low frequencies precisely where CMR of CC+CMC coupling leaves a significant vulnerability.

## Interference Environments

Various interference environments are described in a number of Electromagnetic Compatibility (EMC) standards and can be a useful resource for gauging the hazards one is likely to encounter in a given circumstance. In environments in which large amounts of electrical power are generated, transported, consumed, or (especially) switched, a great deal of noise can be generated below 10 MHz. Examples of settings in which this can be the case include manufacturing lines, machine shops, air, sea, road, and rail vehicles, electrical generating, substations and switching rooms, to name a few. SPE for automation controls may encounter a great deal of noise below 10 MHz.

The details of the levels and spectrum of the interference that is expected to be encountered naturally depend on the specifics of the environment in which a system is to be deployed. However, the nature of the sources and mechanisms of coupling interference to signal lines appear as common themes time and again in EMC testing standards and recommendations. These include:

1. Radio transmission from intentional broadcast

2. Coupling from adjacent communications circuits

3. Coupling from nearby power circuits
    A. Continuous interference
    B. Switching transients
    C. Capacitive coupling
    D. Inductive coupling

4. Shared ground return paths

The first of these, intentional broadcast, includes not only Broadcast TV, Radio, and Radar transmission, but also emissions from portable radio equipment, such as cell phones, walkie-talkies, and radio control transmitters. As a threat to the integrity of a system, portable equipment poses something of a different challenge to that of public broadcast. It can come into very close proximity to an SPE link, and the resulting level of interference can be very high. The standards (Appendix B – Relevant EMC Standards) vary in their assessment of the spectrum and level of interference that a system should be able to withstand, and there are different means of introducing the interference to a system for test. Nevertheless, with care, a meaningful comparison can be made (Figure 4) and clearly illustrates the effects on requirements for CMR of different assumptions about the environment.

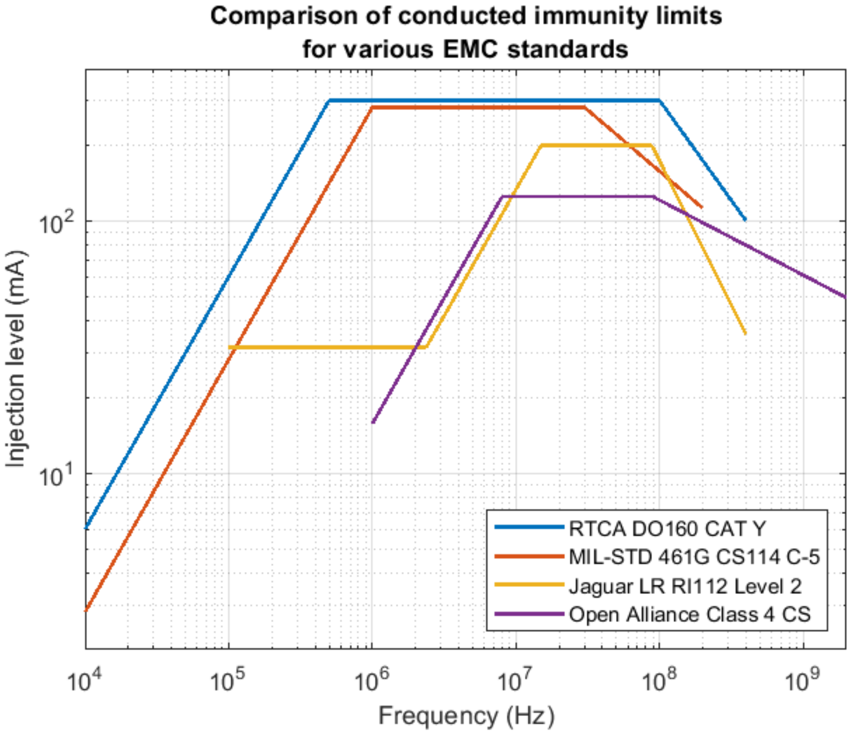


*Figure 4: Comparison of Conducted Immunity Limits for Various EMC Standards*

The above figure compares various recommendations for conducted immunity limits on signal lines to radio transmission (Appendix B - Relevant EMC Standards). To enable comparisons between tests, levels are referred to a current (in mA) that would be delivered to a 50 Ohm common-mode load at the MDI, i.e. the port for the Equipment Under Test (EUT). Most of the standards here recommend limits at 100 kHz of 30 mA or more. This level of interference would develop a modulation peak (for an 80% AM modulation depth) of 1.4 V RMS in the 25 Ohm common-mode impedance of a CC+CMC SPE front-end in that band. In contrast, a front-end that employs an isolation transformer would be entirely immune to interference at much higher levels than this.

However, the comparison above neatly side-steps important differences among the class of interference coupling mechanisms. Near-field magnetic coupling responds poorly to shielding with thin foils at low frequencies. Although it is effective at rejecting interference for far-field electromagnetic interference (EMI) and near-field electric interference, it is much less effective at low frequencies for a field that is substantially magnetic in nature. Such fields arise when large currents flow in conductors and extend for a small fraction (< 1/6) of a wavelength around the source. Nevertheless, this “small” fraction can be rather large for a long wavelength, for example at 10 MHz, the wavelength is 30 meters, and 1/6 of this is still 5 meters. A critical frequency occurs when the so called “skin-depth” exceeds the thickness of the shielding conductor. An aluminum conductor on a foil tape screening a twisted pair can be, for example, 10 microns in thickness, and the skin-depth exceeds 10 microns at a frequency of 67 MHz or less. The screen will be decreasingly effective with decreasing frequencies below this. Systems with screening can fail EMC tests that employ inductive coupling, such as a bulk current injection (BCI), at low frequency where they may pass a similar test at a seemingly equivalent level using a different coupling approach.

## Interference Immunity Tests

To demonstrate the impact of lower frequency interference to capacitively coupled SPE, a controlled comparison test was conducted between a system using capacitive coupling and one using isolation transformers. A Texas Instruments DP83TG720 1000BASE T1 Media Converter Evaluation Module was chosen for the test as it was a readily available higher speed device that could easily be modified to replace coupling capacitors with a HALO 2.5GBASE-T1 isolation transformer. Our test setup is depicted in Figure 5 below.

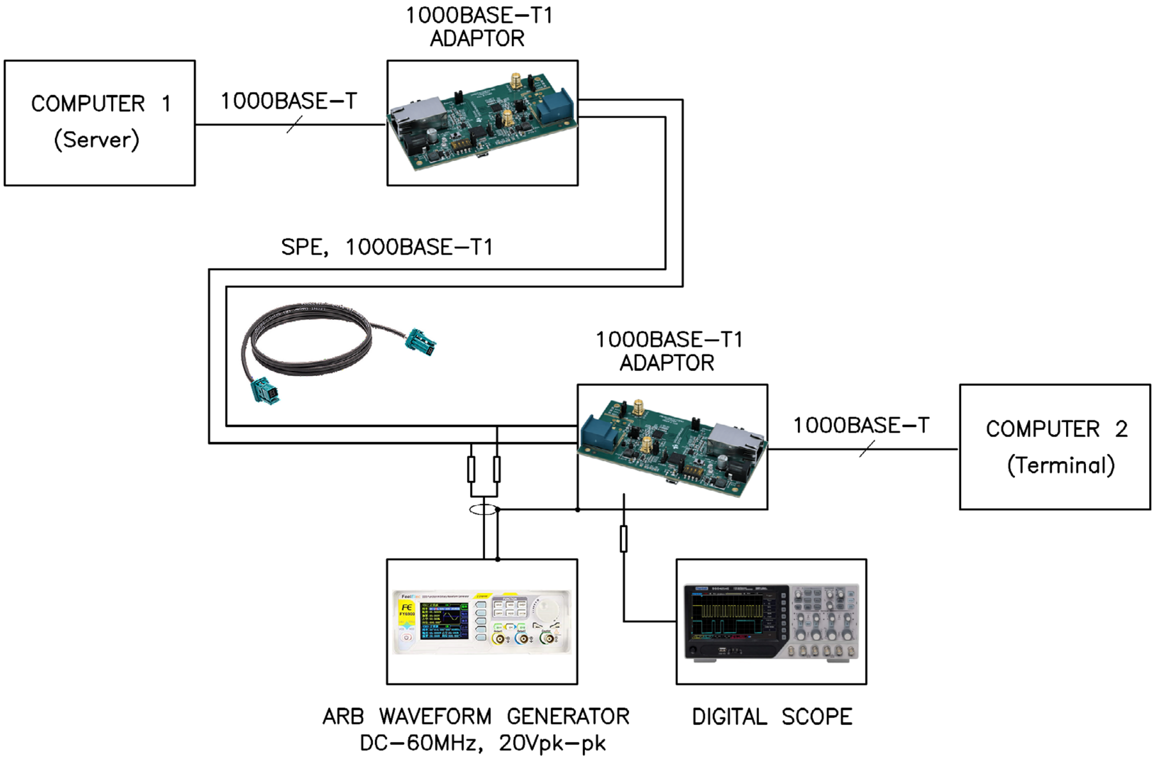


*Figure 5: Test Setup. We used IPERF3 server and client software on laptops to test a 1000BASE-T1 link between the TI media adaptors, and a FY6900-DDS Arbitrary Waveform Generator (AWG) to couple common-mode interference to the victim MDI through 120 Ohm resistors.*

We tested using the method of direct power injection (DPI) similar to what is described in the Open Alliance IEEE 1000BASE-T1 EMC Test Specification for Transceivers, Version 2.1, Section 3.1.3 Immunity to RF disturbances. However, as for the direct injection mechanism of IEC 61000-4-6, “Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields”, we omit any coupling capacitors. Other differences are that we tested over the frequency range DC – 60 MHz, and used a constant wave (CW) electromotive force (EMF) of up to only 8.5 V RMS at the 50 Ohm source (+25 dBm), as opposed to an EMF of up to 40 V RMS (+39 dBm) with a 1 kHz sine wave amplitude modulation (AM) of 80% depth on a carrier in the range 1 MHz – 2 GHz.

We found in our tests that communication was entirely blocked on a link between unmodified capacitively coupled + CMC adaptors by common mode interference as little as 0.7V RMS constant wave (CW) at the connector (a.k.a. the media dependent interface, MDI). In contrast, we found we could not interfere with communication at any frequency (DC - 60 MHz) or interference level (up to 8.5 V RMS at the MDI) available to us with the kit we used when an isolation transformer is in place of the coupling capacitors. See Appendix A for more test details.

Although a capacitively coupled front-end circuit can readily meet the Open Alliance recommendations, our demonstration shows that interference at lower frequencies, which are commonly covered by other EMC recommendations, will cause communication to be blocked. This is an issue that is exacerbated at higher speeds, as it becomes increasingly difficult to supply CMR at low frequencies with a CMC when it is simultaneously required for higher frequencies. See Interference environments for a schedule of EMC recommendations from various bodies.

We also explored what performance one might expect in tests for immunity to fast transients by simulation. This is the sort of interference that arises when power to electrical machinery is switched. We found that a CC+CMC front end would readily resonate with external capacitive coupling structures for this sort of interference, resulting in large amplitude oscillations that would be problematic. In contrast, it was evident that placement of an isolation transformer would inhibit such resonance from occurring. Our study also shows that a CMC might not be necessary for a screened system using an isolation transformer. See Appendix A – Tests and Simulations in More Detail for more information.

## Summary

Our tests clearly demonstrate a significant advantage for isolation transformers over capacitive coupling in its ability to tolerate low frequency interference that can be encountered in noisy environments. Although our tests did not cover higher frequencies and amplitudes, it is sufficient to confirm that isolation transformers can be used with SPE in the same way that they are for other forms of Ethernet over twisted pair, and their use typically remedies the susceptibility to interference that CC+CMC systems suffer. The ability to provide galvanic isolation that meets UL safety requirements for high voltage isolation in a compact package is another key advantage of transformers over capacitive coupling. For SPE with Power over Data Lines (PoDL) applications, DC blocking capacitors are needed between the isolation transformer and power injecting inductors, but this has no implications for CMR performance.

Recent and planned developments in SPE for higher speeds make it more challenging to achieve adequate CMR for a noisy environment with a capacitive coupled + CMC circuit than was the case with lower speed systems. Although it can be a challenge to achieve the necessary bandwidth in isolation transformers for these high-speed systems, UWBX have developed patent pending technology that HALO uses under license for their range of higher-speed Ethernet isolation transformers, such as their 2.5GBASE-T1 (https://www.haloelectronics.com/2-5gbase-t1-isolation-transformers/) and 25/40GBASE-T isolation module (https://www.haloelectronics.com/25g-40g-isolation-transformer/).

# Appendix A - Tests and Simulations in More Detail

## Detailed Comparison of CMR Performance

Our test confirms that the improvement in CMR at low frequency using a transformer without a common-mode choke may very well be sufficient for most applications, particularly when a screen (shielded cable) is also used. Detailed comparison of CMR performance in different configurations is shown below.

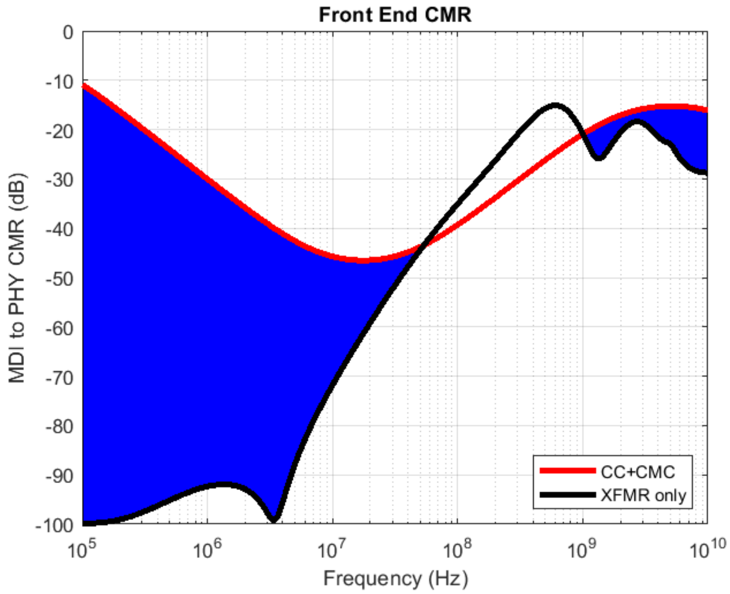


*Figure 6: CC+CMC vs. Transformer Only*

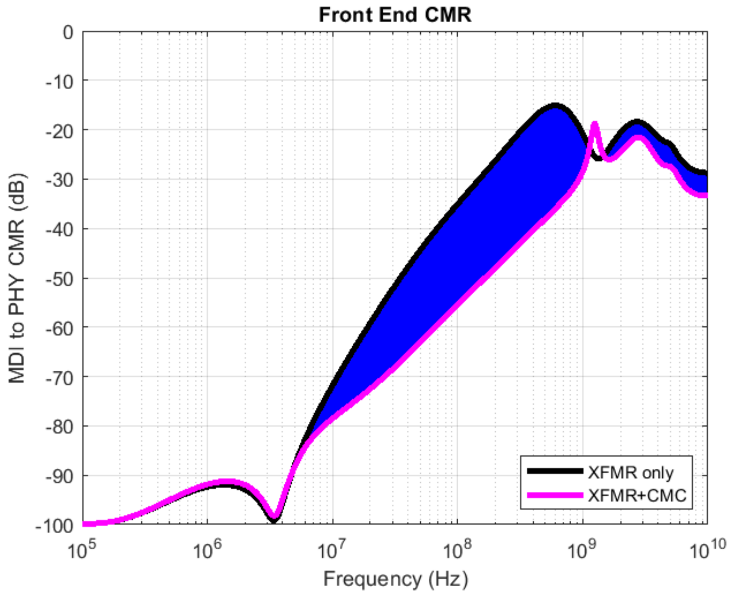


*Figure 7: Transformer Only vs Transformer+CMC*

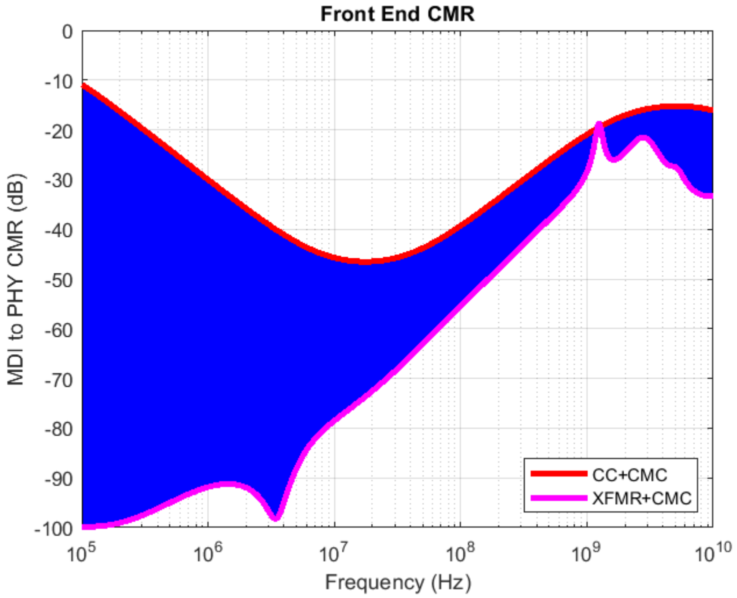


*Figure 8: Transformer+CMC vs. CC+CMC*

Another advantage of an isolation transformer is that by placing a transformer center tap to ground on the line side, one can reduce the number of components needed for common mode and ESD dissipation.

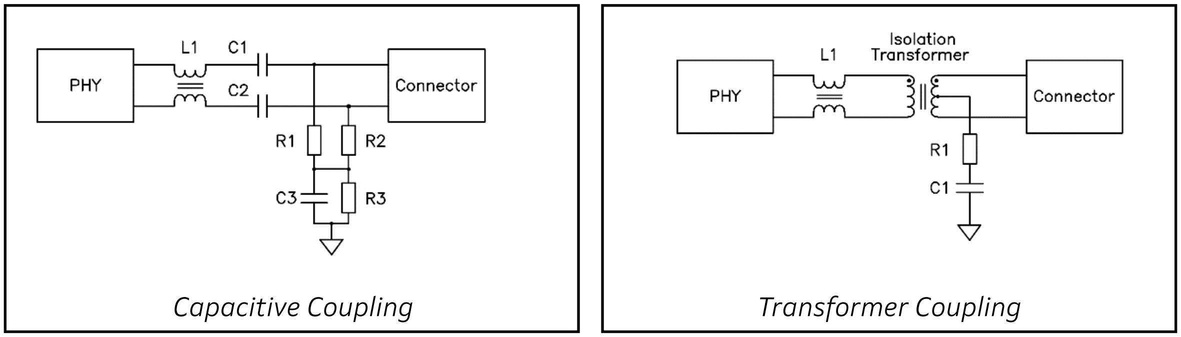


*Figure 9: Comparing ESD Protection Circuits for Capacitive Coupling and Transformer Coupling*

## Test by Direct Power Injection (DPI) in More Detail

We assessed the noise immunity of a Texas Instruments DP83TG720 1000BASE T1 Media Converter that uses CC+CMCs to supply isolation and CMR and compared with a units modified by replacing the coupling capacitors with isolation transformers.

We found that the introduction of a transformer significantly improved the interference immunity of the device. Communication was entirely blocked on a link between unmodified CC+CMC adaptors by common mode interference as little as 0.7 V RMS at the connector (MDI). In contrast, we found we could not interfere with communication at any frequency (DC - 60 MHz) or interference level (up to 8.5 V RMS at the MDI) available to us with the kit we used. This is shown in the chart below in terms of the interference power of the 50 Ohm source in dBm (Figure 10).

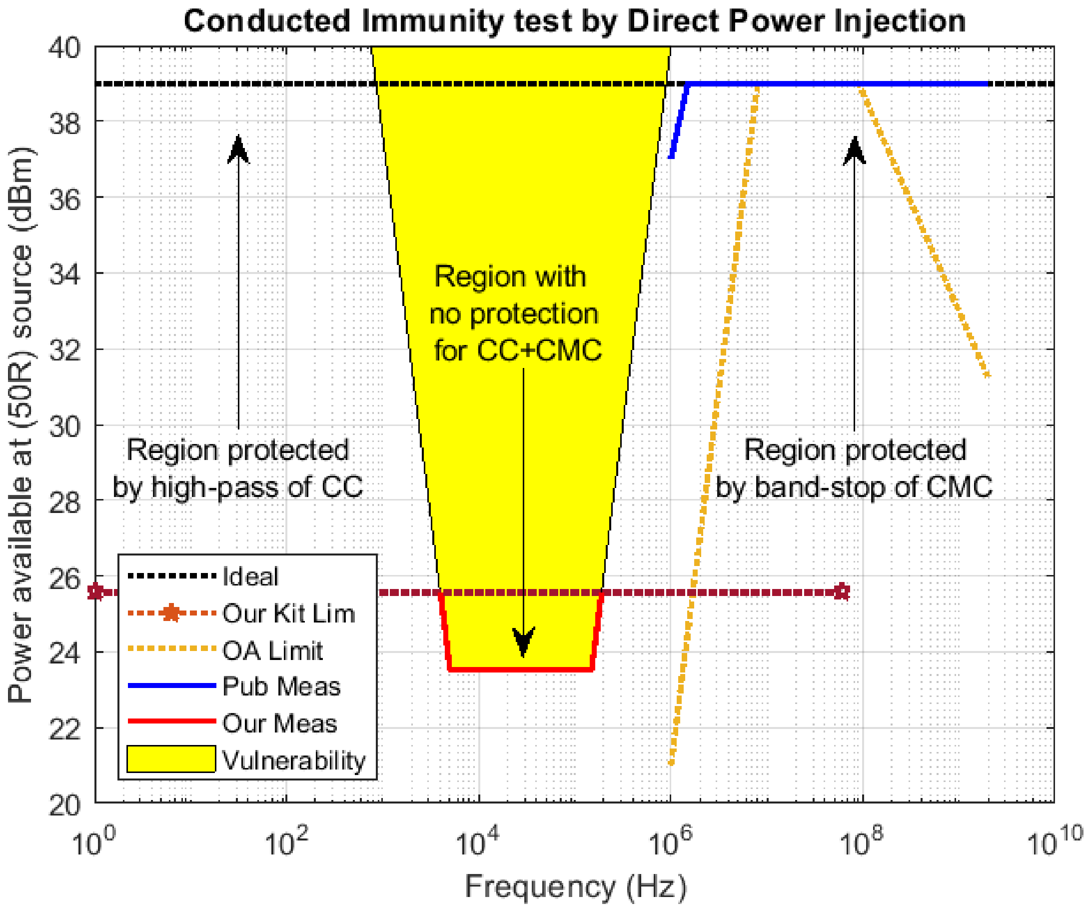


*Figure 10: DPI Test Results*

While the CC+CMC performance in the published results (blue line) meets the Open Alliance recommendations, our measurement shows that below 1MHz there is a large region (solid yellow) that is vulnerable to noise. The effectiveness of using an isolating transformer is strikingly clear.

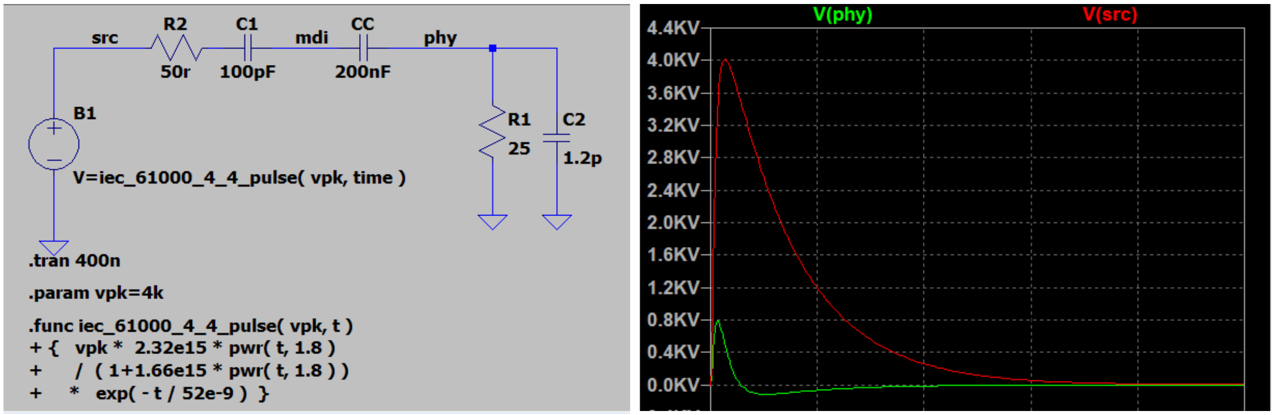
## Simulation of Susceptibility to Transients

We simulated the performance of a CC+CMC front end in a typical EMC recommendation for immunity to transient disturbances. We based our simulation on IEC 61000-4-4 Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test.

IEC 61000-4-4 describes the application of a burst of 75 large amplitude (240V – 3.8kV) impulses each with a rise time nominally of 5ns and width nominally 50ns repeatedly (every 300ms) capacitively coupled (circa 100pF) to a cable assembly, via a capacitive clamp, or directly to the screen or in common to each leg of a twisted pair through discrete capacitors, from a 50 Ohm source. We simulated coupling directly to each leg of a twisted pair through discrete 100 pF capacitors from a 50 Ohm source and observed the response to a single pulse.

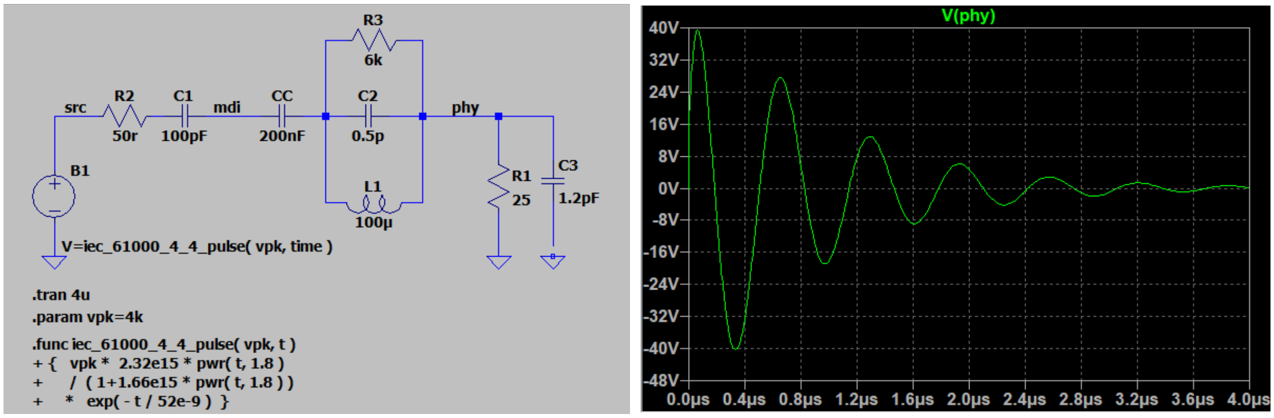
We found that if the twisted pair is unscreened, as in our simulation, neither a CMC alone nor a transformer alone adequately protect the circuit from interference of this nature. In either case excursions of the interfering signal at the PHY pins exceed the clipping level, and as a result, would block communications, at least temporarily. However, the interference that breaks through to the silicon (i.e., pins of the PHY or external protection diodes) for a CC+CMC (Figure 12) differs substantially from that of a transformer alone (Figure 13). In the case of a CC+CMC front-end, a substantial charge can be dumped into the supply rails over the course of a transient burst, and it is not inconceivable that an unmanaged PHY peripheral reset may ensue that would require a power cycle or system reset to clear.

In contrast, the excursions with a transformer are unlikely to cause anything worse than some packet errors throughout the course of the transient. The spectrum of the residual interference in the case of a CC+CMC front-end centers on a much lower frequency than for a front-end that includes an isolation transformer. As a result, the residual interference of a CC+CMC front-end may not be significantly improved by screening the twisted pair. In contrast, a screen would be effective at eliminating the residual interference when an isolation transformer is used.



```
.tran 400n
.param vpk=4k
.func iec_61000_4_4_pulse( vpk, t )
+ {  vpk *  2.32e15 * pwr( t, 1.8 )
+     / ( 1+1.66e15 * pwr( t, 1.8 ) )
+    *  exp( - t / 52e-9 ) }
```

*Figure 11: A transient applied to a device with no CMC obviously causes a problem. We simulate with a single maximal amplitude interfering pulse from the waveform proscribed by IEC 61000-4-4. When applied to a device with no CMC the interference would reach 0.8 kV at the PHY pins if it were not clamped.*

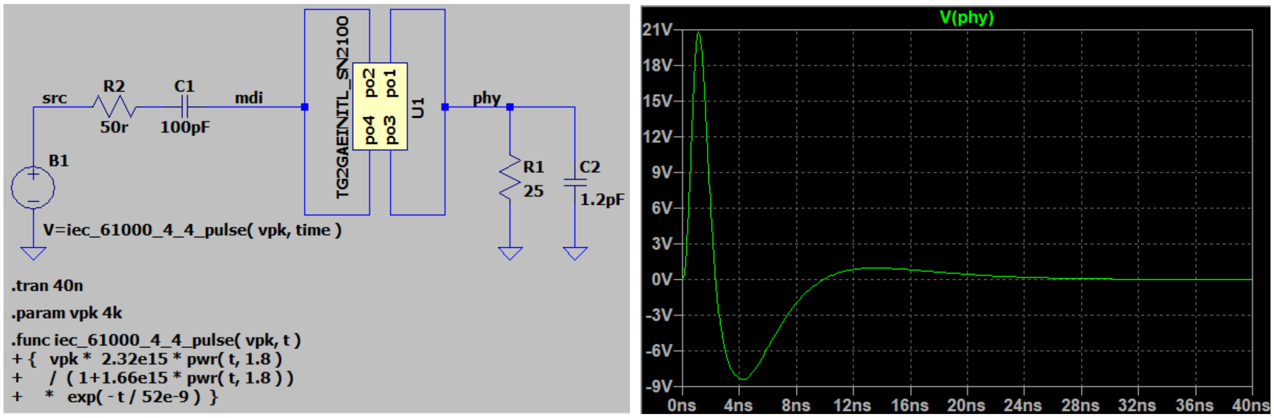


```
.tran 4u
.param vpk=4k
.func iec_61000_4_4_pulse( vpk, t )
+ {  vpk *  2.32e15 * pwr( t, 1.8 )
+     / ( 1+1.66e15 * pwr( t, 1.8 ) )
+    *  exp( - t / 52e-9 ) }
```

*Figure 12: Transient interference applied to a device with CC+CMC is still problematic. If unclipped excursion would reach 40 V at the silicon. When coupled to a front-end with a 100 μH CMC but no isolation transformer the 100 pF source capacitance and CMC inductance form a series resonant circuit with 1⁄((2 π√(L C))=) 1.6 MHz. This resonance may be too slow to be adequately attenuated by a thin screen.*

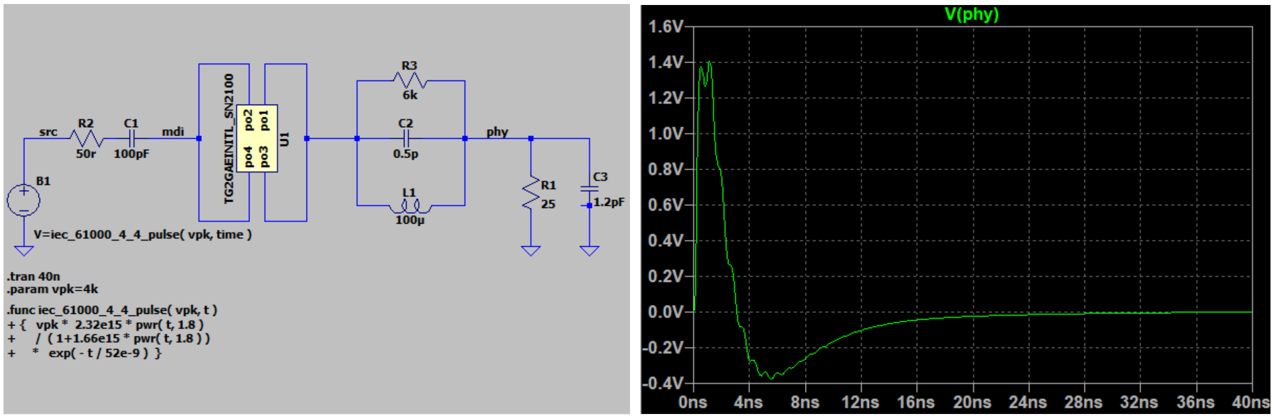
For a CC+CMC front-end there is little to no attenuation at any frequency of series resonance between a coupling structure external to the device and the CMC within the device. A common-mode impulse that excites this natural resonance would lead to disruption of communications – either by causing packet errors, or by otherwise disrupting the proper functioning of the device (i.e. by inducing a spurious and unrecovered peripheral hardware reset).

Substituting a transformer for the CC+CMC in the front-end prevents this resonance. Although there is still a significant excursion, albeit of very short duration. A screen, when functioning properly, would attenuate this high-speed pulse very well.



```
.tran 40n
.param vpk 4k
.func iec_61000_4_4_pulse( vpk, t )
+ {  vpk *  2.32e15 * pwr( t, 1.8 )
+    / ( 1+1.66e15 * pwr( t, 1.8 ) )
+    *  exp( - t / 52e-9 ) }
```

*Figure 13: A transformer alone is insufficient to prevent the repeated loss of packets during a transient burst. However, the presence of a functioning screen would attenuate this high-speed residual interference very well.*

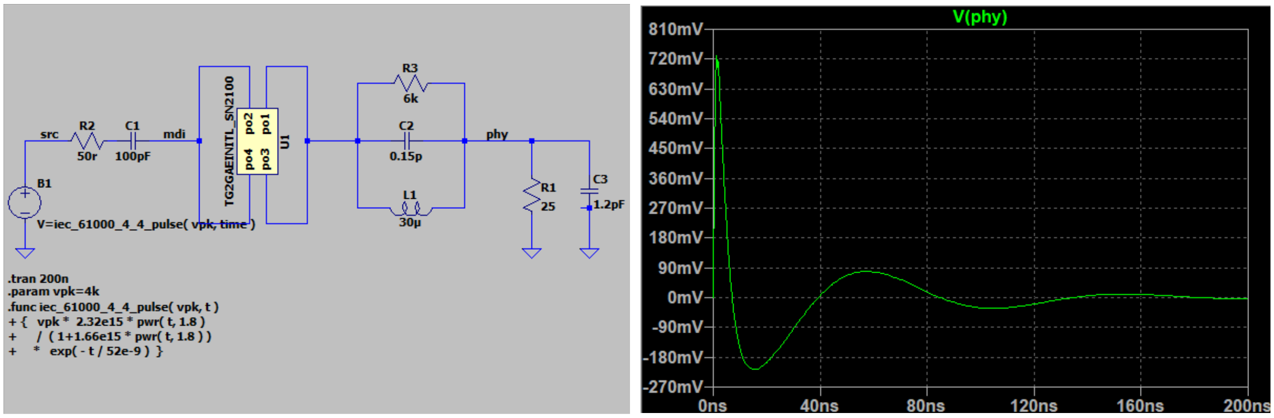


```
.tran 40n
.param vpk=4k
.func iec_61000_4_4_pulse( vpk, t )
+ {  vpk *  2.32e15 * pwr( t, 1.8 )
+    / ( 1+1.66e15 * pwr( t, 1.8 ) )
+    *  exp( - t / 52e-9 ) }
```

*Figure 14: Placing a transformer between the MDI and CMC (resulting in a transformer+CMC configuration) prevents the external coupling structure resonating with the CMC, and is effective in further attenuating the interference.*

For a transformer+CMC the remaining interference at the PHY is certainly small enough to be effectively eliminated by screening the twisted pair. However, the CMC design has not been optimized for use in combination with a transformer and there is room to improve the combined performance.

A simple tweak to the CMC model (reducing L and C by a factor of 3) yields some indication of what should be possible simply by modifying the CMC design parameters.



```
.tran 200n
.param vpk=4k
.func iec_61000_4_4_pulse( vpk, t )
+ {  vpk *  2.32e15 * pwr( t, 1.8 )
+     / ( 1+1.66e15 * pwr( t, 1.8 ) )
+    *   exp( - t / 52e-9 ) }
```

*Figure 15: A small change to the CMC design would be sufficient to prevent packet loss even when a screen is not present or fails.*

## Appendix B - Relevant EMC Standards

Our demonstration shows that, although SPE systems that do not employ isolating transformers may pass some EMC recommendations, they would fail others.

| | |
|---|---|
| IEEE 802.3 | **IEEE STANDARD FOR ETHERNET** |
| | 12.5.3.2.5 Common-mode rejection – 1BASE5, +/- 20 V pk sq wave : 40+ kHz |
| | 14.3.1.3.5 Common-mode rejection – 10BASE-T, 25 V pp sq wave @ < 500 kHz |
| | 32.6.1.3.6 Common-mode rejection – 100BASE-T2, 25 V pp sq wave @ < 500 kHz |
| | 40.6.1.3.3 Common-mode rejection – 1000BASE-T, 1 V rms @ 1 – 250 MHz CC |
| | 55.5.4.3 Common-mode rejection – 10GBASE-T, +6 dBm 80 – 1000 MHz CC |
| | 113.5.4.3 Rejection of External EM Fields – 25/40GBASE-T 80 – 2000 MHz CC |
| | 126.5.4.3 Rejection of External EM Fields – 2.5/5GBASE-T 80 – 2000 MHz CC |
| | |
| ISO 7637-3 | Road vehicles — Electrical disturbances from conduction and coupling — Part 3: Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines |
| ISO 11442-4 | Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 4: Harness excitation methods |
| | |
| IEC 61000-4-4 | Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test |
| IEC 61000-4-6 | Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields |
| IEC 61000-4-12 | Part 4-12: Testing and measurement techniques - Ring wave immunity test |
| IEC 61000-4-16 | Part 4-16: Testing and measurement techniques - Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz |
| | |
| IEC 62132-4 | Integrated circuits - Measurement of electromagnetic immunity 150 kHz to 1 GHz - Part 4: Direct RF power injection method |
| IEC 62215–3 | Integrated circuits - Measurement of impulse immunity - Part 3: Non-synchronous transient injection method |
| | |
| MIL-STD-461G | **REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT** |
| | CS114, Conducted susceptibility, bulk cable injection |
| | CS115, conducted susceptibility, bulk cable injection, impulse excitation |
| | CS116, conducted susceptibility, damped sinusoidal transients, cables and power leads. |

| | |
|---|---|
| RTCA DO-160G | **ENVIRONMENTAL CONDITIONS AND TEST PROCEDURES FOR AIRBORNE EQUIPMENT** |
| | 19.3.3, Audio Frequency Magnetic Fields Introduced Into Interconnecting Cables |
| | 19.3.4, Audio Frequency Electric Fields Introduced Into Interconnecting Cables |
| | 19.3.5, Spikes Induced Into Interconnecting Cables |
| | 20.4, Radio Frequency Susceptibility – Conducted Susceptibility (CS) Test |
| | |
| JLR-EMC-CS | **JAGUAR LAND ROVER – ENGINEERING STANDARD – ELECTROMAGNETIC COMPATIBILITY SPECIFICATION FOR ELECTRICAL/ELECTRONIC COMPONENTS AND SUBSYSTEMS** |
| | 10.0, RI 112, RI 114, RI 115 – Radio Frequency Immunity 100 kHz – 3.1 GHz |
| | 12.0, RI 140 – Magnetic Field Immunity, 20 Hz – 150 kHz |
| | 13.0, RI 130 – Coupled Immunity – Transient disturbances |
| | 14.0, RI 150 – Coupled Immunity – Continuous disturbances |
| | 17.0, CI 250 – Immunity to Ground Voltage Offset |

*Table 1: Schedule of some relevant EMC recommendations. CC+CMC systems would typically fail a significant number of these, whereas transformer+CMC systems would provide significantly improved performance.*

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HALO Electronics is a leading electromagnetic component supplier
https://www.haloelectronics.com

UWBX is a technology company that specializes in the development of IP for electromagnetic devices
https://uwbx.co.uk