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AES-X13 and Interference-Free Pro-Audio Systems

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AES-X13 and Interference-Free Pro-Audio Systems

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Abstract

The design of large professional audio systems was never trivial, but the recent increases in the use of digital, switch-mode and wireless technologies have worsened their interference problems.

This situation, increasing EMC regulation, and the poor EMC practice of single-point grounding commonly used in the pro-audio industry, encouraged the Audio Engineering Society (AES) to set up working group SC-05-05 to create a standard on cable shield termination.

Two shield termination methods for EMC are discussed in this paper – direct bonding at one end with capacitive bonding at the other, and direct bonding at both ends.

The effects on the EMC performance of a large professional audio system of applying single-ended, capacitive, and both-end shield bonding are discussed and test results given. Practicality and costs are also discussed.

INTRODUCTION

Professional audio systems such as those used in cinemas, concert halls, theatres and open-air concerts have always suffered from interference. But the great expansion in the last two decades in microprocessor control, phase-angle power control, switch-mode power conversion, digital signal processing, cellular and other wireless communications have very greatly increased their interference problems.

This has caused many problems for pro-audio manufacturers and their users, many of whom are members of the AES (www.aes.org). Another EMC issue has been the increase in world-wide EMC regulation, not least the European Union's (EU's) EMC directive with its requirements for emissions and immunity performance.

In response to these EMC pressures, the AES has begun to develop EMC standards under working group SC-05-05 [1]. Project reference AES-X13 covers the termination of

shielded, balanced audio cables. At the time of writing no drafts have been made available for public comment.

This paper discusses the regulatory and EMC issues peculiar to the pro-audio industry that created the need for a standard on terminating cable shields and considers the implications of the proposed shield bonding techniques.

Test results for a large pro-audio system are included, which cover traditional design techniques (e.g. single-ended shield grounding) and two methods of bonding cable shields for EMC – direct bonding to ground at one end with capacitive bonding at the other; or direct bonding of both ends as recommended by IEC 61000-5-2 [2].

The cost, time, and performance implications of practically implementing the two shield bonding techniques are considered and conclusions drawn about their relative merits.

EMC AND PRO-AUDIO SYSTEMS

Professional audio systems are used in public buildings, hotels and conference venues; in cinemas, concert halls, and theatres; in open-air concert venues; and in the entertainment media industry (music recording, films, videos, etc.). The active devices used in analog electronic equipment have intentionally non-linear characteristics which have the side-effect of demodulating radio frequency (RF) noise at much higher frequencies than their intended audio bandwidths (refer to [3] and section 7.2.5 of [4]).

Typical opamps for low-frequency use can demodulate RF signals at over 1GHz [5], with bipolar types usually being more effective RF demodulators than bifets. RF demodulation is also known as audio rectification, and is the principle by which early 'crystal radio' receivers operate. It is not a unique insight that we can consider all active devices to be 'crystal set' RF detectors, and all their interconnections (PCB traces, wires and cables) to be RF antennas.

The great expansion in the last two decades in the use of digital, switch-mode and wireless technologies have wors-

ened the electromagnetic environment up to at least 1.9GHz, and has significantly increased the interference problems experienced by pro-audio systems.

Modern pro-audio equipment also uses switch-mode power conversion, digital control and signal processing, and wireless communications, so it is now itself a significant emitter of electromagnetic noise. Modern pro-audio systems are as likely to suffer interference from a lack of electromagnetic compatibility between their own items of equipment as they are from their electromagnetic environment (see Figure 1).

The susceptibility of pro-audio equipment is often higher than other types of equipment, for the following reasons...

- Very low analog signal levels may be encountered, e.g. 10mV full-scale from some microphones.
- High-gain amplification, e.g. microphone amplifiers with gain of 60dB or more.
- Signal-noise ratios of over 100dB are commonplace.
- Long lengths of signal cables, often in excess of 30m.
- Single-point grounding construction means cable shields are only terminated at one end. This prevents them from being effective shields for wavelengths shorter than about six times the cable's length.

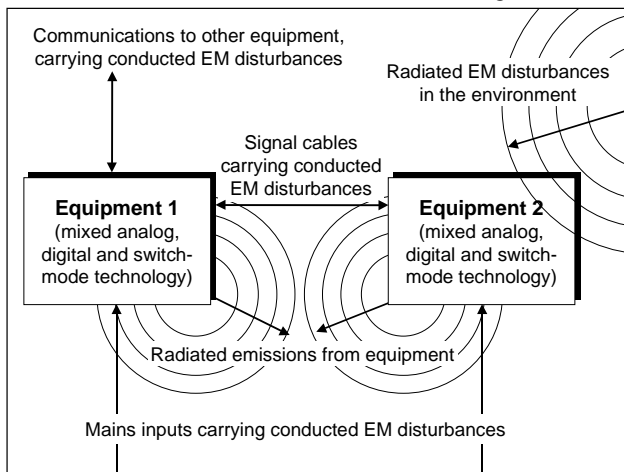


Figure 1 Electromagnetic (EM) interactions

The EU's EMC Directive (89/336/EEC, as amended) requires almost all electrical equipment, systems and finished installations supplied in the EU to have sufficiently low levels of electromagnetic emissions, and sufficiently high levels of electromagnetic immunity. The notified standards for the emissions and immunity of pro-audio equipment that must be used when self-declaring EMC compliance are EN 55103-1 and EN 55103-2 [6] [7].

Australia also applies EMC regulations to pro-audio equipment, and many other countries are increasing the scope/technical requirements of their EMC regulations.

TERMINATION METHODS FOR CABLE SHIELDS

Single-ended Shield Bonding

In the early days of pro-audio interference was quite rare, but there were always voltage differences between the chassis of different items of equipment at powerline-related frequencies. Single-point grounding and balanced (sometimes called differential) signaling became the favored way to reduce 'hum' in the audio signals. The standard pro-audio balanced signal connector became the 3-pin "XLR", with pin 1 dedicated to the shield connection and pins 2 and 3 for the signal pair.

Cable shield currents were found to be a frequent cause of hum noise. As we will show later, this was due to poor equipment design and not to the cables themselves, but it left the legacy of single-ended shield termination.

In large or complex pro-audio systems it is not often easy to specify which ends of which cables should have their shields bonded to ground, and which ends should be left open. The optimum solution for each cable often depends upon the exact system configuration, and can change if the system is altered. So a side-effect of single-ended shield bonding is the length of time it can take experts to install and commission a large pro-audio system.

Another side-effect of single ended shield bonding (and of the whole concept of single-point grounding) is that it exposes input and output ports to the full effects of voltage surges in the protective ground structure, such as can be caused by lightning activity or earth faults [8].

Single-ended shield termination condemns shields to only being effective at low RF frequencies. For example, the shield of a 30m (98ft) cable would not be expected to be effective at frequencies above 1.7MHz, and resonances at higher frequencies might cause worse EMC performance than if the cable was unshielded.

RF filtering all the input and output signals to the required degree is possible, but achieving the degree of attenuation that is generally required to meet pro-audio signal/noise ratios over the frequency ranges covered by [6] and [7] requires large and costly filters at both ends of every one of the hundreds of cables in a typical pro-audio system. It is more cost-effective to make better use of the existing cable shielding to minimize the cost and size of the signal filters.

Capacitive Shield Bonding at One End

Capacitive shield bonding is the method proposed by some in the pro-audio industry to preserve single-point grounding at powerline frequencies. It uses a capacitor between the shield and ground (protectively grounded chassis/frame/enclosure) at the end of the shield that would normally have been left unterminated. The high impedance of the capacitor resists the passage of shield current at powerline frequencies, whilst its low impedance at RF frequencies provides effective shield termination for RF.

This method has been used to cure interference problems in computer, pro-audio, and other systems but is relatively

unproven when it comes to complying with a test standard such as EN 55103-2.

As section 7.2.4.3 of [9] points out, capacitive bonding at one end is not a universal panacea. Real capacitors have series inductance internally (in their construction) and externally (in their leads and connections) and the resulting self-resonance stops them achieving low-impedances over wide frequency ranges. Low frequencies require large capacitance values with correspondingly low self-resonant frequencies, making them ineffective at high frequencies.

Figure 2 shows the performance of a proprietary product that adds capacitive filtering to standard connectors at reasonable cost. It inserts a ‘flexible circuit’ which connects surface-mounted ‘chip’ capacitors between the designated pins and the connector shell. Although the shortest possible lead lengths are achieved, the inherent trade-offs between size and frequency response are clearly visible.

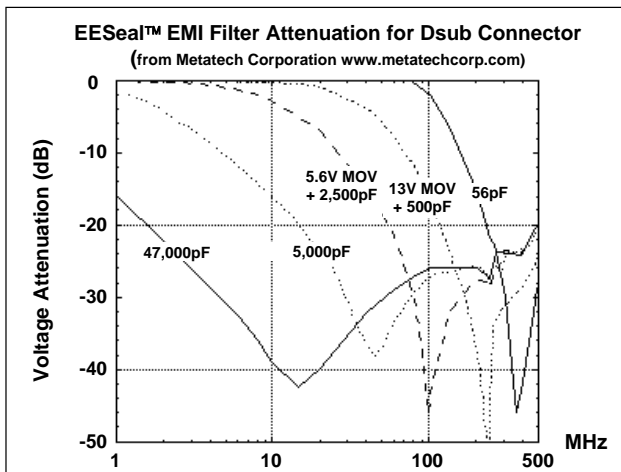


Figure 2 Capacitive connector pin bonding example

‘Filter-pin’ connectors can have more wideband performance at extra cost, but are not available in XLRs. But using a filter-pin to bond a shield to ground means ‘pigtailing’ – connecting the shield with a piece of wire (e.g. the drain wire of a spiraled foil shield) or unpicking a braid shield and retwisting it to solder to the pin. Unfortunately, pigtailing significantly reduces a shield’s effectiveness.

For good shielding performance a shield connection is required that does not disturb the shield but simply clamps all around it. This is known as ‘peripheral’ or ‘360°’ shield bonding, and is commonplace in RF and EMC connectors.

So what is required is a shield-terminating capacitor with one terminal that makes a 360° connection to the undisturbed cable shield, the other terminal making a 360° connection to the connector shell or body. The capacitor construction should also minimize internal and external inductances, even a 1mm (0.04”) lead length could be too long). Such shield-bonding capacitors are possible, but are likely to be very costly – BNC connectors using this type of capacitive shield bonding cost \$45 in the mid-1990s.

Capacitors terminating cable shields must also be overvoltage rated or protected by voltage clamping devices. ANSI/IEEE C62.41 recommends testing at 6kV (see [10]), but [7] only tests at up to 0.5, 1, or 2kV.

Finally, capacitive shield bonding does not avoid the time-consuming process of figuring out which end of the cable should be directly bonded and which should not, when testing, installing and commissioning a system.

Direct Shield Bonding at Both Ends

Direct grounding of cable shields to the equipment frame/chassis/ground at both ends is the method we favor. It is a well-proven EMC technique which helps to achieve the best shielding effectiveness from any cable shield, especially when 360° terminations are used. [2] and [9] describe how to reduce excessive shield currents by using ‘parallel earth conductors’ (PECs) with low resistance and a high mutual inductance with the cable in question.

At power frequencies ground loop currents can be large enough to heat cable shields where there are only a few cables, so a PEC might be needed. But pro-audio systems usually have numerous cables and bonding all their shields at both ends often means that PECs are not required to prevent heating – although they may still be useful for improving the system’s EMC performance.

We, and a number of pro-audio companies, have been using direct shield bonding at both ends and the other techniques recommended by [2] in pro-audio systems for a number of years. We have found that – when implemented thoughtfully – this not only achieves excellent EMC performance but also reduces audio noise levels.

Direct shield bonding at both ends is usually dismissed on the basis that ‘everyone knows’ that ground loop currents flowing in cable shields cause hum problems. The assumption is that there is an imbalance in the inductive coupling between the cable shield current and the balanced signal conductors, causing the common-mode (CM) shield current to be converted to differential-mode (DM) noise.

In October 2001 we conducted some experiments on a variety of pro-audio balanced cables including one that we deliberately designed to be worse than any possible audio cable ever could be, even in a legacy system. We tested these cables with shield currents strong enough to cause them to heat up. The results of our experiments are described in detail in [11], with the following conclusions:

- Any type of shielded balanced cable *naturally* achieves a very low inductive imbalance.
- Cable shield currents at powerline frequencies need not be a significant cause of balanced signal noise.
- Directly bonding cable shields at both ends (following [2]) reduces the voltage differences between equipment chassis, helping achieve good signal/noise ratios.
- Cable shield currents at powerline frequencies only cause noise where equipment does not connect cable

shields directly to its frame/chassis/enclosure at the point where the cable enters.

Not connecting cable shields to chassis at the point of entry is well-known as bad EMC practice. It was also identified as a poor pro-audio design technique called the “Pin 1 problem” by [12] in 1995.

XLR connectors that achieve 360° direct shield bonding are available, although not yet widely used for analog signals. Their extra cost is modest [11].

A major benefit of direct shield bonding at both ends is that it is no longer necessary to spend time figuring out which end of the cable should have its shield bonded to ground. Pro-audio systems constructed using this method quickly achieve excellent sound quality with much less expert attention needed during installation/commissioning. Where equipment suffers from the ‘Pin 1 problem’, it should either be modified to provide direct ground bonding, or else capacitive shield bonding used.

So we can see that using optimum EMC techniques results in optimum audio signal quality and helps to significantly reduce lengthy installation and commissioning timescales.

EMC TESTING AN AUDIO SYSTEM

This section describes the experience of one of the authors when modifying a traditionally-designed audio mixing console so that it complied with the EMC Directive’s notified harmonized standards [6] [7].

Radiated Emissions

A 32-input 8-output analog audio mixing console was measured for radiated emissions, with its audio input and output cables connected and terminated to represent a typical installation and operating mode. The emissions were indistinguishable from the background noise because the console used ‘plain old analog’ signal processing and a linear power supply.

In this 1994 production model the shields of the balanced audio cables were connected to the analog circuitry’s signal reference ground (0V) in every module, and the chassis was isolated from signal reference ground except at a single “star point” – all traditional pro-audio design practices used throughout the industry but now known to be very poor EMC practice.

The same console was then stripped of its analog-only modules and re-populated with 32 channels and group module versions containing digital control circuits. This version of the console allows switch routing, level control and MIDI functions to be saved and recalled using an external computer. A Central Control module is added, containing one interface processor (for the console) and one communications processor (between the console and the external PC). The clock speed of the processors was 16MHz, console data was collected and delivered via two 500b/sec serial data busses. Such a system would normally

be used with an external PC, but not in this test. All the console’s external cable shields were terminated as before.

This time, the scans revealed high levels of emission from 30MHz to 300MHz, as shown in Figure 3. Peaks associated with the 16MHz clock were very obvious and many had amplitudes well in excess of the relevant EMC standard’s limit line.

Conducted Emissions

It was clear from the radiated emissions tests that if any circuits in the console were generating any RF energy, unwanted RF noise could appear at the analog input and output ports, where they could cause failure to meet regulatory emissions limits and could also be passed on to other equipment via the interconnecting cables.

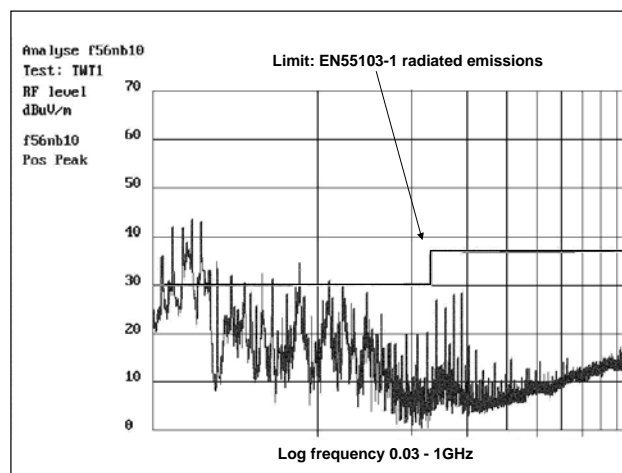


Figure 3 Radiated emissions, digital modules fitted

The console’s linear power supply was replaced with a switch-mode model and a conducted emissions measurement made on its mains port. Figure 4 shows the high levels of interference measured, because the power supply did not have a mains filter fitted.

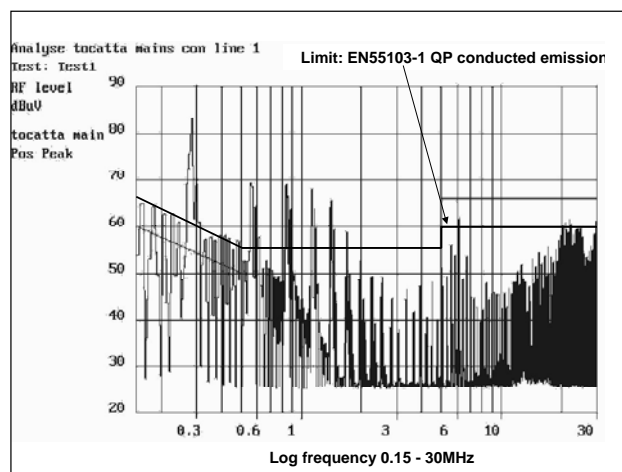


Figure 4 Conducted emissions, digital modules fitted

The harmonics of the power-supply’s switching frequency can be clearly seen right across the frequency range, with

some additional peaks and nulls at the low frequency end (150kHz to 400kHz) due to rectifier switching. Some of the energy above 1MHz was attributable to digital noise from the console passing through the switch-mode supply.

RF Immunity

We have found that using the IEC 61000-4-6 conducted RF immunity test method up to 1GHz, using the EM-Clamp method on each of the console’s input and output cables, is quicker and easier to do than radiated immunity testing to IEC 61000-4-3. For our products, a pass on this extended conducted test corresponds to a pass on a radiated RF immunity test. So the conducted RF tests reported here can be taken to indicate the conducted and radiated RF immunity performance of the console tested.

Testing the above audio console design for RF immunity was disappointing. The analog audio circuitry demodulated the RF test signal at 16 different frequencies, as shown in the second column of Table 1.

Table 1 Conducted RF immunity results

Tested frequency	Original build	1nF shield bonds	Direct shield bonds
10.000 kHz	P = Pass	P	P
14.000 kHz	P	P	P
19.600 kHz	P	P	P
27.440 kHz	P	P	P
38.416 kHz	Fail	P	P
53.782 kHz	Fail	P	P
75.295 kHz	Fail	P	P
105.414 kHz	Fail	P	P
147.579 kHz	Fail	P	P
206.610 kHz	Fail	P	P
289.255 kHz	Fail	P	P
404.956 kHz	Fail	P	P
566.939 kHz	Fail	Fail	P
793.715 kHz	Fail	Fail	P
1.111 MHz	P	Fail	P
1.556 MHz	Fail	P	P
2.178 MHz	P	P	P
3.049 MHz	Fail	P	P
4.269 MHz	Fail	P	P
5.976 MHz	P	P	P
8.367 MHz	Fail	P	P
11.714 MHz	P	P	P
16.399 MHz	Fail	P	P
22.959 MHz	P	P	P
32.142 MHz	Fail	P	P
44.999 MHz	P	P	P
62.998 MHz	P	P	P
88.198 MHz	P	P	P
123.477 MHz	P	P	P
172.867 MHz	P	P	P
242.014 MHz	P	P	P
338.820 MHz	P	P	P
474.348 MHz	P	P	P
664.087 MHz	P	P	P
929.722 MHz	P	P	P
1.000 GHz	P	P	P

EMC Compliance Solutions

While we knew that we had to redesign the console system in order to pass the EMC Directive, the solutions proposed were not very palatable to many audio designers...

- All signal and control cable connectors mounted on a metal backplate and all cable shield connections bonded directly to the backplate. This backplate also provides a low impedance ground for signal reference.
- Large audio consoles are constructed using modular techniques, creating structures which are not ideal for shielding purposes. So the above backplate was bonded to the console frame so that when all modules were in place their internal circuitry was provided with an effective shield.
- Console frame bonded to protective ground conductor.
- Internal ground conductors bonded to the above backplate at multiple locations.
- All signal and control I/O ports filtered.
- Both the mains input and DC output of the power supply filtered.
- All printed circuit boards re-designed to segregate noisy and sensitive circuits. Wherever possible, a continuous ground plane was included. Particular attention was given to decoupling and trace routing around all ICs. Four-layer printed circuit boards were often necessary, with one layer used as a solid ground plane.

Despite the objections of the seasoned audio designers, these changes were made and the console system re-tested. The radiated emissions were reduced to the levels shown in Figure 5 – a startling improvement.

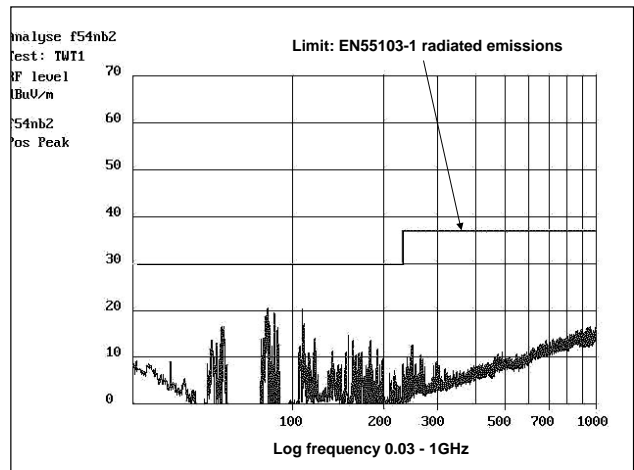


Figure 5 Radiated emissions after modifications

The reduction in the conducted emissions were just as startling, and are shown in Figure 6. But the emissions were still too high from 1-6MHz, eventually traced to the lack of filtering on the cables to the mouse and keyboard used to program the console’s VCA fader automation.

No failures were found on a radiated immunity test of the modified console, but the conducted immunity re-test was more interesting. There was so much opposition to bonding audio signal cable shields to ground that capacitors between the XLR connectors' pins 1 (the cable shield) and the new backplate were tried at first. But there was no capacitor value that would give the required EMC results over the whole frequency range. The best results were with 1nF capacitors, shown in the third column of Table 1.

It is possible that advanced capacitive-shield-bonding connectors might have achieved the necessary EMC performance, but they didn't exist at the time (they still don't) and the EMC Directive still had to be met.

Only terminating the cable shields directly to the new backplate (the console chassis and protective ground) using the shortest possible links allowed the system to pass the conductive immunity test specified by EN 55103-2. These results are shown in the fourth column of Table 1.

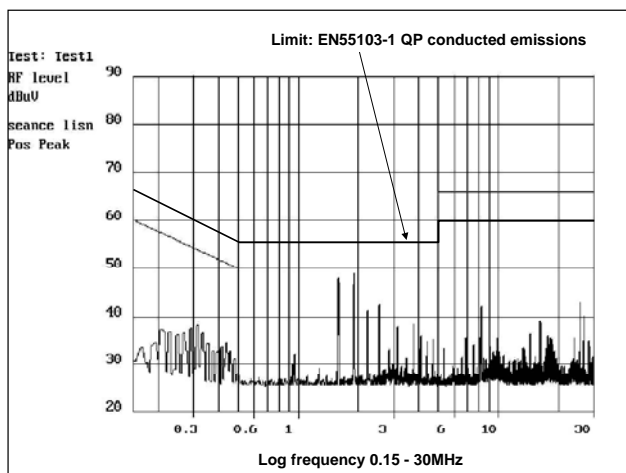


Figure 6 Radiated emissions after modifications

Audio performance improvements

Far from increasing the noise by creating 'ground loops' as claimed by many in the pro-audio industry, we have found that directly bonding cable shields to chassis ground (or frame or enclosure grounds) at both ends and following the other recommendations in [2] has had a beneficial effect on the audio signal/noise performance of our consoles.

Eliminating the need to figure out which shield ends of the hundreds of audio cables in a typical system should be bonded, and which left open, has saved us a great deal of time. There is no doubt that what sold the EMC design changes to the management was the greatly reduced costs in final test procedures, installation and commissioning.

We now spend much less time 'fire-fighting' audio noise problems in our pro-audio systems around the world than we used to do before we made these EMC changes, and it is noticeable how much more resistant our consoles are to real-world sources of interference. Where other suppliers' equipment suffers from the "Pin 1 problem" it is usually possible to modify it to achieve direct shield bonding.

But just as important as all this was that our EMC changes permitted our company's Founder and Chief Executive to realize his greatest desire – extending the audio frequency response of our consoles from 40kHz to 80kHz.

CONCLUSIONS

Single-ended shield termination bonding of balanced cables requires lengthy testing/installation/commissioning time-scales and does not permit EMC Directive compliance without expensive filtering on all signal ports.

Capacitive termination at one shield end is unproven as far as compliance with EN 55103-1 and EN 55103-2 is concerned, and will probably require special connectors to be designed containing special capacitor constructions.

This technique does nothing to reduce the lengthy testing/installation/commissioning timescales typical of the single-ended shield bonding method. However, shield bonding with leaded capacitors can be used successfully to reduce interference over narrow frequency bands.

Direct shield bonding at both ends as recommended by [2] is a very effective EMC technique and the resulting ground loop currents do not increase systematic powerline-related noise for equipment that is designed correctly (or modified) so as not to suffer from the "Pin 1 problem". Furthermore, this technique dramatically reduces testing/installation/commissioning timescales and saves cost.

References

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