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EMC techniques in electronic design Part 2 - Cables and Connectors

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Design Techniques for EMC
Part 2 — Cables and Connectors

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This is the second in a series of six articles on basic good-practice electromagnetic compatibility (EMC) techniques in electronic design, to be published during 2006. It is intended for designers of electronic modules, products and equipment, but to avoid having to write modules/products/equipment throughout – everything that is sold as the result of a design process will be called a 'product' here.

This series is an update of the series first published in the UK EMC Journal in 1999 [1], and includes basic good EMC practices relevant for electronic, PCB and mechanical designers in all applications areas (household, commercial, entertainment, industrial, medical and healthcare, automotive, railway, marine, aerospace, military, etc.). Safety risks caused by electromagnetic interference (EMI) are not covered here; see [2] for more on this issue.

These articles deal with the practical issues of what EMC techniques should generally be used and how they should generally be applied. Why they are needed or why they work is not covered (or, at least, not covered in any theoretical depth) – but they are well understood academically and well proven over decades of practice. A good understanding of the basics of EMC is a great benefit in helping to prevent under- or over-engineering, but goes beyond the scope of these articles.

The techniques covered in these six articles will be:

1) Circuit design (digital, analogue, switch-mode, communications), and choosing components
2) **Cables and connectors**
3) Filters and transient suppressors
4) Shielding
5) PCB layout (including transmission lines)
6) ESD, surge, electromechanical devices, power factor correction, voltage fluctuations, supply dips and dropouts

Many textbooks and articles have been written about all of the above topics, so this magazine article format can do no more than introduce the various issues and point to the most important of the basic good-practice EMC design techniques. References are provided for further study and more in-depth EMC design techniques.

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2. Cables and Connectors

2.1 Introduction

This article concerns the EMC design of metal interconnections for analogue and digital signals, and pulse-width modulated (PWM), AC or DC power. These interconnections can be between different circuits inside a product, or between different products in a system or installation.

Until a few years ago, it could generally be assumed that, for most products, most of the EMC problems at radio frequencies (RF) concerned their external cables, because they were long enough to act as reasonably effective 'accidental antenna' at the frequencies being employed by the electronics technologies of the time. Sometimes an internal conductor caused a problem for RF immunity above a few hundred MHz, in products with unshielded enclosures. However, internal conductors often caused problems due to electromagnetic coupling (e.g. crosstalk causing worsened signal/noise ratios) and transmission-line mismatch problems such as overshoot and ringing on digital signals. These 'internal electromagnetic compatibility' problems often required one or more additional design iterations to solve, and so delayed market introduction.

These days the frequencies being used by the digital devices found in almost all products are so high that internal conductors can be major sources of EMC problems (emissions and immunity), unless products have well-shielded and filtered overall enclosures – but ever-increasing cost pressures can make such enclosures too costly. And ever-reducing time-to-market pressures mean that design iterations must be avoided, so even if well-shielded and filtered product enclosures are used – electromagnetic coupling and mismatches in internal cables can no longer be left to be fixed during the development stage.

So the careful EMC design of conductors and their connectors during the earliest stages in the product design process is now very important indeed for both legal EMC compliance and successful, profitable products.

2.2 All conductors are 'accidental antennas'

Radio and television antennas are made of conductors, carefully dimensioned and arranged to efficiently transmit or receive electric (E), magnetic (H) or plane-wave electromagnetic (EM) fields in a given range of frequencies and/or polarisations. But the physical laws that govern the design of antennas mean that *all* conductors are what we might call 'accidental antennas', interacting with external E-, H- and EM-fields, often in complex ways not envisaged by designers using them as simple low-cost means of transferring electrical signals or power from one place to another. So this article could be said to be concerned mostly with how to use conductive interconnections whilst minimising their accidental antenna effects.

Figure 2A shows the frequencies we typically use for AC power, radiocommunications for radio and television broadcast, personal radio communications, data communications, etc., over the frequency range 10Hz to 2.5GHz.

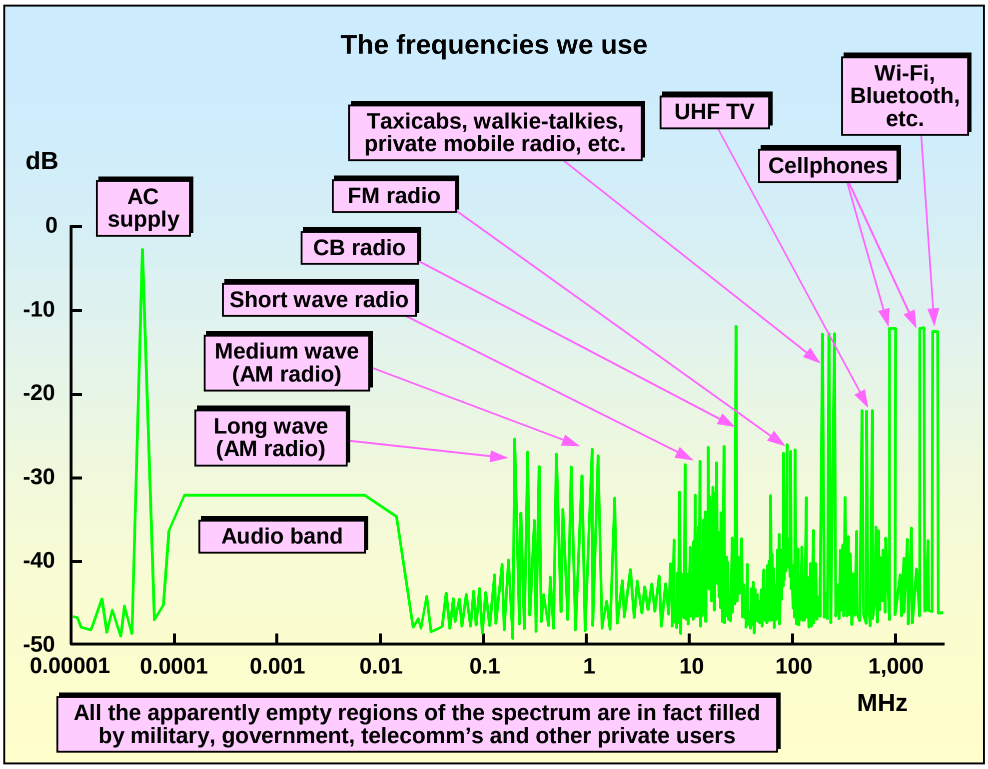

Figure 2A The frequencies we use

Figure 2B shows the same spectrum as Figure 2A but with some typical electrical and electronic noise spectra superimposed on top. This clearly shows that we have to keep our electrical and electronic noises contained within our products and cables, prevented from leaking into the wider environment, if we are to continue to use the electromagnetic spectrum for the myriad of useful, entertaining, and economically important purposes it is used for today.

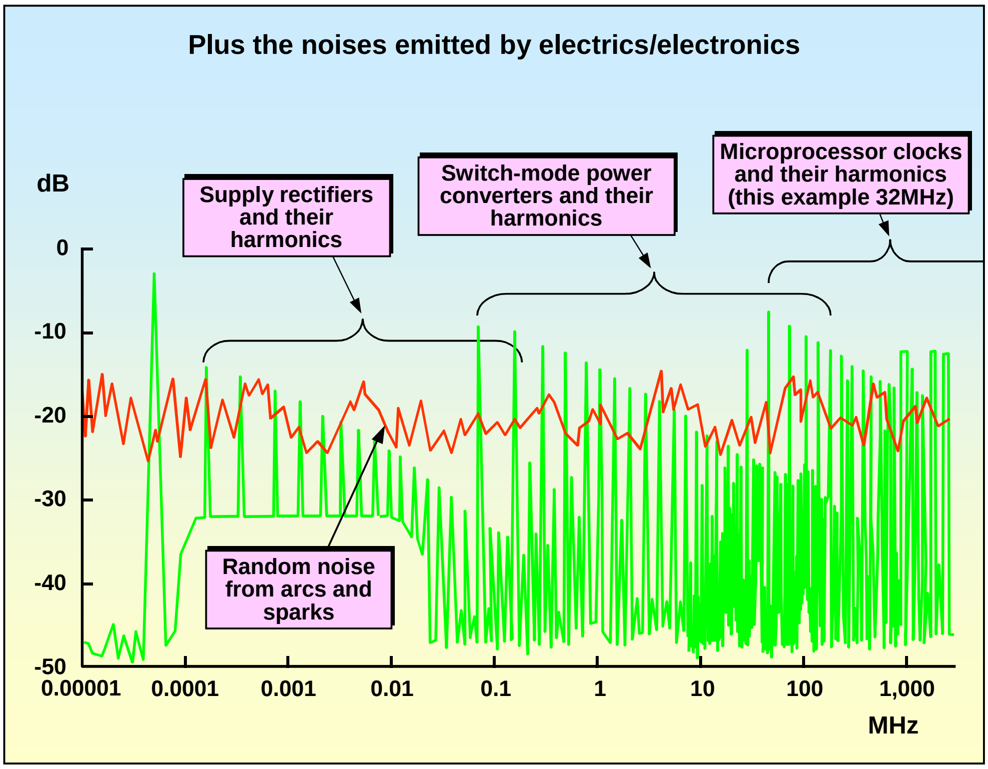

Figure 2B The noises emitted by electrical and electronic devices

Figure 2C shows the same spectrum as Figure 2B, but the vertical axis has been changed to metres and lines have been added to show the accidental antenna behaviour of a typical straight conductor in free space, driven at one end by a low-impedance source and with a high-impedance load at its other end. Such conductors resonate at frequencies at which their length is an integer multiple of a quarter-wavelength, and at those frequencies they are supremely efficient antennas. Indeed, almost all small portable radio transmitters and receivers rely on exactly such antennas, known as whip antennas.

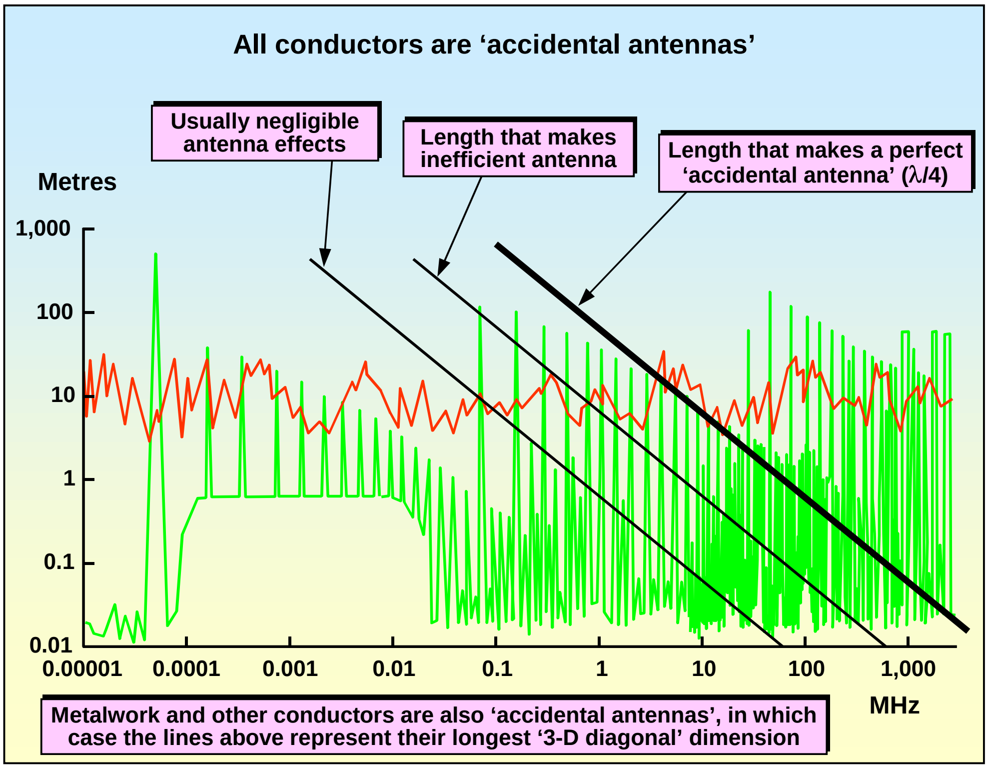

Figure 2C   The 'accidental antenna' behaviour of typical conductors

The bold line in Figure 2C shows the curve of length versus frequency for a conductor that is one quarter of a wavelength long. Below their first resonance, such conductors convert almost all of the signals they are carrying at their resonant frequency into electric fields launched into the air, which means there is little signal at that frequency left for the load – distorting waveforms and causing signal integrity (SI) problems. The E-fields launched turn into EM-fields in the far field (i.e. at distances greater than $\lambda/6$). Such conductors also convert electric fields in their environments (and the electric field components of EM-fields) into noise signals in themselves, causing signal integrity (SI) and EMC immunity problems for their circuits.

There are two other diagonal lines in Figure 2C, one indicating the length of conductor that makes a relatively poor antenna (approximately -20dB efficiency) at a given frequency, and another indicating the length that makes a very poor antenna (approx. –40dB efficiency). Note that this latter line crosses the axis at 10mm length at a frequency of around 70MHz, showing that for a 10mm long conductor (whether a piece of wire or a cable shield that is only terminated at one end) we might be able to ignore its accidental antenna behaviour at frequencies below 70MHz – *in typical commercial/industrial situations*, unless it was carrying atypically large RF currents. In especially sensitive applications, or in the very harsh EM environments of some military and aerospace applications, just 10mm of accidental antenna could cause interference problems at frequencies as low as 7MHz, and maybe even less.

The above analysis was for a straight conductor on its own, rather like the structure of a whip antenna, and a similar analysis can be applied to another common shape, the loop. Below its first resonance, a loop conductor with a low-impedance source and load emits and picks-up magnetic fields and also picks up the magnetic components of EM-fields. The H-fields it emits turn into EM-fields in the far field. For accidental loop antennas, the diagonal lines of accidental antenna efficiency in Figure 2C represent the radius of a circular loop, or half the loop's longest diagonal dimension.

Of course, few if any circuit conductors are ever simple whips or loops, but the simplistic graphs in Figure 2C show us that we should assume that any practical length of conductor can cause EMC problems over large areas of very important spectrum, hence the need for using the design techniques described in this article.

Conductors that employ controlled-impedance transmission line design techniques will have very much better EMC performance than the same conductors could otherwise. This is because their correctly matched resistive terminations considerably reduce the reflections at the ends, making them very poor accidental antennas. At the resonant frequencies of the conductors (with unmatched terminations), the reduction in emissions due to the matching resistors can be as much as 40dB.

2.2.1 All conductors should use EMC design

Designers often assume that only digital or high-frequency signal conductors have RF content and need to be carefully designed for EMC. But PWM power has a very high RF content, and all other AC and DC power carries fluctuating RF current noises, and their inevitable RF series impedances result in fluctuating RF voltage noises. And all conductors carry CM noise, whether caused by digital or high-speed processes occurring within a product (e.g. a microprocessor, power rectifier, local oscillator); or caused by picking-up E-, H- and EM-fields from their local environments.

All normal EM environments are now quite heavily polluted with frequencies from 50Hz to 2.5GHz, and in the near future the lower frequency will be extended downwards by the widespread use of variable-speed motor drives to save energy (this will also increase the levels of noise from 30kHz to at least 100MHz). Also, the upper frequency of the pollution will be extended to *at least* 8GHz by the rolling-out of Wi-Fi at 5GHz, Wi-MAX and UWB radio datacommunication systems.

Some designers of audio and DC instrumentation still seem to think that they do not need to use RF EMC techniques for their analogue cables, and still use design techniques that were developed to save money in the 1940s, such as single-point grounding and terminating cable shields at only one end. My experience and those of my customers in those industries over the last 25 years, has shown that applying EMC techniques appropriate to the local EM environment significantly improves signal/noise ratio, whilst also significantly reducing the functional testing times for complex products (such as audio mixing consoles) and considerably speeding up installation and commissioning [3]. See [4] for information on assessing EM environments.

2.2.2 It might be cost-effective not to use conductors at all

Conductors are always a problem for EMC, so for analogue or digital signals it can be more cost-effective to use fibre-optics or infrared instead. These are often not used in the initial design because of their higher component costs, and by the time the EMC problems with the cables are adding even more cost *overall*, it is too late to change the design. However, the costs of these alternative technologies are falling, especially for parts that are used in the automotive, cellphone or PC industries. For example, a 25Mb/s TX/RX pair for plastic fibre-optic cable in automotive applications cost £4.50 in 2004.

Wireless data links (e.g. Bluetooth, Wi-Fi, Zigbee, USB2-UWB, etc.) should also be considered as alternatives that could be less costly overall, but be aware of the possibilities for interference from the rest of the product to their receivers, and from their transmitters to the rest of the product. Adding radio communication devices to a product often benefits from the use of the advanced PCB design techniques for EMC described in [5].

Alternatives for delivering power include fibre-optics (up to a few watts), pneumatics and hydraulics. All of them are much better for EMC than metal conductors, and they also provide huge amounts of galvanic isolation and don't couple RF noise.

Conductors used for safety 'earthing' or 'grounding' are covered at the end of this article.

If using metal conductors: products that employ a single PCB with a 0V plane over the whole of its area, and no internal wires at all, are generally the most cost-effective. The 0V plane must underlie all of the components and traces and extend beyond them by *at least* 3mm on all sides (see Part 4 of [5] for more details).

Where multiple PCBs are required in a product, it can even be cost-effective to use flexi-rigid PCBs with an overall 0V plane, because of their EMC benefits. Flexi-rigid PCBs use one or more flexible PCB layers over all their area, plus rigid areas where components are mounted. The flexible areas are really just signal and power interconnections between the rigid areas, but the advantage over a number of PCBs connected by flexible jumpers, connectors, or cables is that the 0V plane can be continuous over the whole assembly. Flexi-rigid PCB assemblies generally cost more in themselves, but the EMC benefits of their continuous 0V planes can save development time and manufacturing costs *overall*, plus they do not have the cost, size, and unreliability problems associated with electromechanical connectors, and they can be much quicker to assemble in a product.

2.2.3 Controlling the DM <u>and</u> CM current paths

EMC design techniques for metal conductor interconnects are all about controlling the physical (i.e. geometrical) relationships between the send and return current paths, for both the differential-mode (DM) and common-mode (CM) currents. The DM currents and voltages are our wanted signals or power, whilst CM currents and voltages are associated with the accidental 'leakage' from our DM signals due to stray capacitance and inductance.

Conversion of DM into CM currents and voltages *always* happens in any real-life circuit, and in most applications is responsible for most of our EMC emissions problems above about 1MHz. The reverse process of CM-DM conversion is responsible for most immunity problems above about 1MHz. The exception is in applications where the metal chassis is used as the DM current return path, where DM currents and voltages can be significant above 1MHz. It is very bad EMC practice to use a chassis as a DM current return, but unfortunately this is exactly the method used for heavy loads in motor cars.

It would be ideal for EMC if we could use conductors in which the send and return path were physically identical, because their stray couplings to the rest of the world would then be identical and CM problems minimised. But of course this is physically impossible (the conductors would short-out), and the next section discusses practical cable types.

We can reduce the CM currents to some degree by filtering, and this is covered in Part 3 of [1] and of this new series. But there are always some CM currents and voltages, and we must control them to achieve good EMC. To do this, we use the conductive chassis or external 'earth/ground' as our CM return path. To reduce emissions and improve immunity, the CM current's send/return loop should have as small an area as possible, and we achieve this by routing our cables very close to metalwork or bonding conductors along their entire route, as shown in Figure 2D. The metalwork and conductors used for the CM return current must be electrically bonded along their lengths, and also bonded to the 0V of the circuits that generate the DM signals that cause the CM leakage.

Inside a product, if suitable metalwork or earth/ground bonding conductors do not exist, it is best to be prepared (by design) to add metalwork or conductors as necessary. Instead of metalwork, low-cost metal foil, conductively coated plastics, or thin sheets of metal-coated plastic or cardboard could be used instead.

Outside a product – in some applications (e.g. industrial, aerospace, military) it is usually possible to provide a nearby conductive path for CM return current, such as a metal conduit, cable tray or metal wall or floor. But in some others, such as portable computing devices, cellphones or domestic entertainment systems, adding CM return paths is usually not practical, although it is sometimes possible to use a parallel wire. Where there is no controlled close-proximity CM current return path, the CM currents will still flow, but in uncontrolled paths – causing increased emissions and worsened immunity. In such applications, greater control of the DM send/return loop to minimise the conversion to/from CM noise is often required. Higher-specification filtering and/or shielding may also be used to reduce the CM currents to levels that don't cause EMC problems.

Direct electrical connections are best but not necessarily essential for the CM current return path; capacitors of suitable types and values can be used in series with the CM return path to achieve galvanic isolation at the frequencies used by the electrical power supply whilst allowing the RF CM current to flow in the smallest loop area.

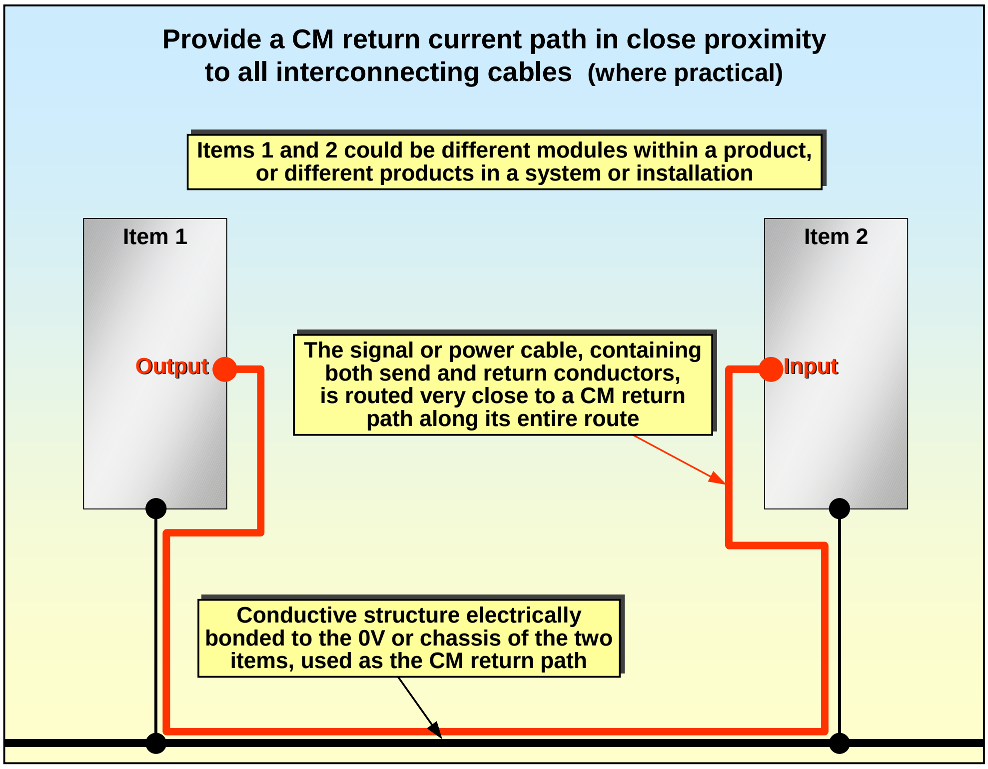

Figure 2D **Provide a CM return current path in close proximity to all interconnecting cables**

Appropriate cable shielding and connectors provides a very high-performance CM return path for the 'leakage' from a send/return pair of conductors (e.g. a shielded twisted-pair or 'twinaxial' cable). The shield of a coaxial cable does not act as a CM return path for its CM current leakage. In any case, no cable shields are ever perfect, so sometimes it is necessary to combine shielded cables with close-proximity metallic CM return paths for good EMC, and this is especially likely for Class 4 cables such as variable speed AC motor drive cables. Shielded cables are discussed below.

In conclusion: we design our metal interconnections to control our send/return current paths, to minimise DM to CM conversion and reduce CM currents and voltages; then we control the CM send/return current paths (wherever we can).

2.2.4 Coaxial and twisted-send/return conductors

Coaxial cable is the closest approach to coincident send/return conductors, because the averaged current flow in the coaxial shield across the cross-section lies along the centre line, where the centre conductor is routed. But flexible coaxial cables turn out to be less than ideal in practice, for reasons discussed later, and many manufacturers prefer to use unshielded cables to save cost.

We must always route each send conductor with at least one dedicated return conductor, and make them as close together as possible without compromising insulation requirements, as shown in Figure 2E.

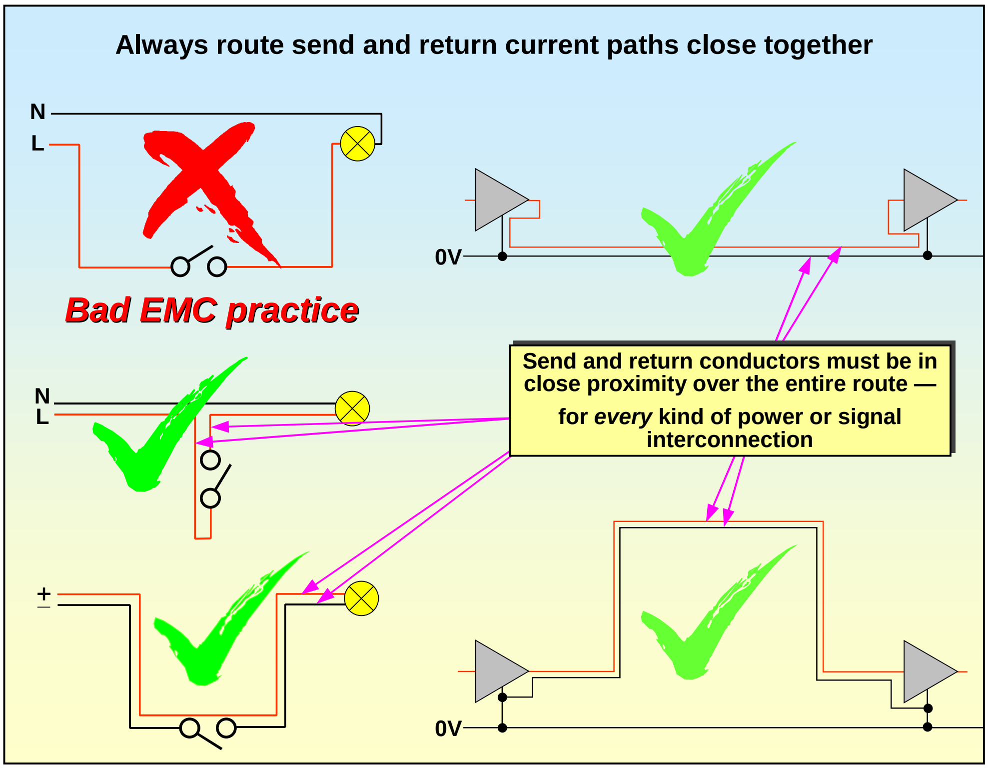

Figure 2E Always provide a return current path physically close to the send path

If we twist the send and return conductors together with a twist-pitch that is much less than one-tenth of a wavelength at the highest frequency of concern, the effects of stray capacitances and inductances tend to cancel out, reducing the rate of DM-CM conversion (and CM-DM). Better repeatability twist-to-twist means better cancellation and still lower conversion rates.

The return current associated with a given signal or power send conductor always takes the path of least impedance. At frequencies below a few kHz impedance is dominated by resistance, whilst at higher frequencies it is dominated by inductance. As Figure 2F shows, where the return conductors for two or more send/return pairs share a common plane (e.g. 0V) or chassis that has a low resistance – at low frequencies the return currents will tend to flow mostly in the plane or chassis, but at high frequencies they will tend to flow mostly in the return conductors that are physically closest to their send conductors. This is because the send/return conductor pair has the highest mutual inductance and the highest capacitance, hence the lowest loop impedance at frequencies above a few kHz.

This natural, automatic behaviour of the return current results in the best crosstalk and best EMC that is possible given a particular conductor structure. So all we have to do to make crosstalk, SI and EMC even better is provide lower-impedance return paths – and the return currents will automatically take them and achieve the benefits we want.

When using single-ended signals and power, all the low-impedance return paths appear in parallel with the reference voltage (typically 0V) on the circuit schematic, which looks like an unnecessary duplication and is prone to being simplified during ‘value analysis’ to save cost – so it is important to mark these on the drawing as an important EMC design issue, the removal of which will almost certainly add cost overall or cause non-compliance.

Sometimes the return current might flow in one or more DC power supplies as well as in the 0V system (e.g. in a ±12V analogue system), or might flow in all of the other phases and neutral of a three-phase mains electricity supply. So sometimes we may need to twist more than just a pair of conductors to provide the return current path, we might have to twist three, four or more wires. For example, a three-phase star-connected mains AC supply should twist five wires – the three phases, neutral and the earth or ground.

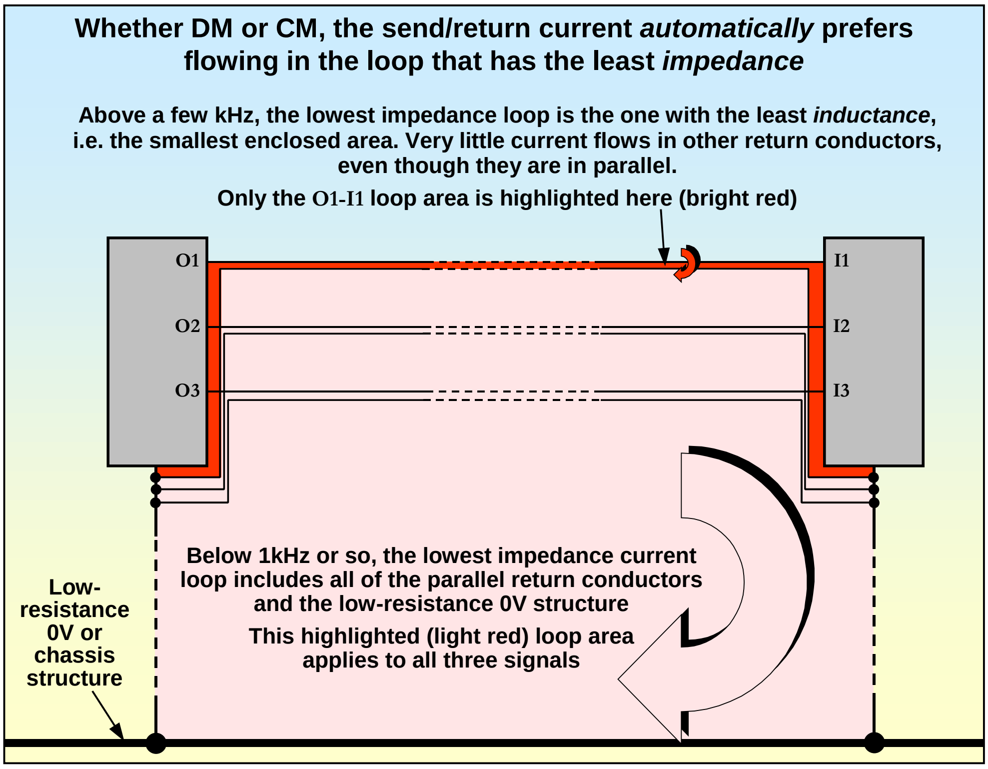

Figure 2F **The send/return current automatically flows in the loop that has the least impedance**

When very heavy currents are used (e.g. kA) it might not be possible to route the send and return conductors as close together as we would like for good EMC, because the physical and mechanical forces acting on the conductors themselves due to the very powerful magnetic fields between them can cause the conductors to damage their insulation. I had the experience of working on a steel rolling mill motor drive, where the motor currents were ±8kA. To prevent damage to the cables the send and return motor conductors were routed in steel cable trays about two metres apart. The magnetic fields in the nearby control room, resulting from the motor currents in the widely-spaced cables was over 100μT, which caused terrible distortion of the images on the cathode-ray type monitors, making the control room unusable.

The problem could have easily been foreseen by a few back-of-envelope calculations using the very simple Biot-Savart law, bearing in mind that most such monitors show image movement with more than 1μT. But the customer instead relied on the motor drive supplier's assurances that the drive passed all of the EMC Directive standards and was CE marked, and assumed this would guarantee no interference of *any* sort. But this article is not the place to discuss the difference between complying with EMC Directive listed standards, and actually complying with its EMC 'Protection Requirements'. In the end, the problem was solved by replacing the CRT monitors with liquid crystal flat-panel models. Now that the EMF Directive (1999/519/EC) is in force, and we have associated measurement standards, the human exposure in the control room should be measured and steps taken if it exceeds the limits, but this is also outside the scope of this article.

So the conclusion is that where the send and return path cannot be close together for some good reason, bad EMC effects must be expected and calculations or experiments undertaken to determine their scale and whether mitigation techniques (shielding, filtering, suppression, etc.) will be required.

2.2.5 Differential ('balanced') interconnections

So far we have assumed that signals and power are 'single-ended', i.e. generated with respect to some reference voltage (usually 0V). But when a closely-coupled pair of conductors are driven with antiphase signals or power, each one becomes the return current path for the other, the DM-CM and CM-DM conversion rates are reduced, and SI and EMC improve as a result. Figure 2G shows some examples of balanced interconnections.

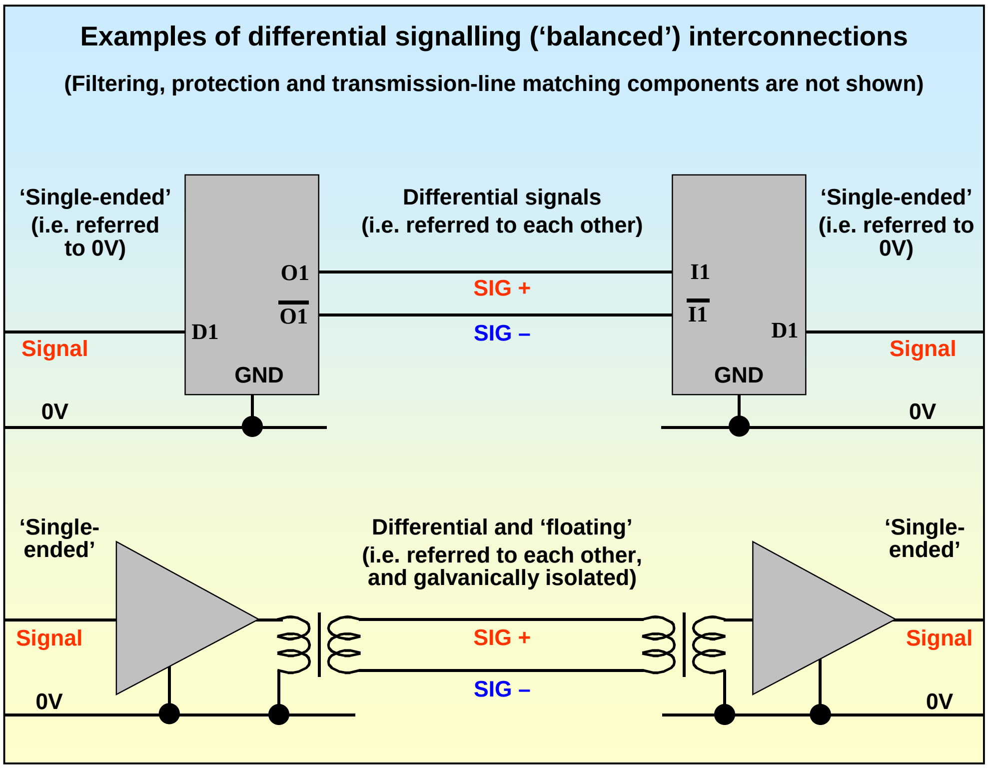

Figure 2G **Examples of differential signalling ('balanced') interconnections**

Differential signals and their conductor pairs are never *perfectly* balanced, so there is always some CM noise. Depending on the degree of balance achieved, the path taken by the CM currents may need to be controlled as described above, and CM filtering and/or shielding may be required as described in Parts 3 and 4 of [1] and of this new series.

2.3 Cable segregation

Segregation is a very powerful EMC design tool, and costs nothing at all if done early in the design process. But it is usually a very expensive technique to employ at the end of a project, so it is important to design the segregation early on. The aim is to segregate (i.e. separate) 'sensitive' circuits and products from 'noisy' circuits and products, by as much physical distance as is possible.

Examples of sensitive circuits and products include transducer amplifiers, radio receivers, and all low-voltage circuitry including analogue and digital signal processing. Sensitive equipment includes instrumentation and metering, computers and programmable logic controllers, audio, and radio receivers.

'Noisy' circuits and products include digital signal processing, switch-mode power conversion (DC power supplies, inverters, PWM, etc.), radio transmitters, RF processing of materials (e.g. plastic welders and sealers, induction heaters), and anything associated with electrical sparking or arcing, such as relays, contactors, switches, and commutator motors.

Notice that computer technology can be both sensitive and noisy. A variable speed motor drive can have a noisy output and also a sensitive input (e.g. from a tachogenerator or position sensor). Radio equipment can include a transmitter and a receiver.

To apply the principles of segregation to interconnecting cables, we first sort our cables into 'classes' according to the types of signals they carry….

Class 1: cables carrying very sensitive signals. This can usefully be split into Class 1a for very sensitive analogue signals, and Class 1b for very sensitive digital signals.

Class 2: cables carrying slightly sensitive signals.

Class 3: cables carrying slightly interfering signals (the 230VAC mains supply in a typical office or domestic building would generally be considered to be Class 3).

Class 4: cables carrying strongly interfering signals.

The above four classes are for power and signals at less than 1kVACrms or 1500VDC or peak. We could allocate Class 5 and 6 to high-voltage electrical supply cables with 1-32kV and above 32kV, respectively, but this article does not cover such high voltages.

Classes 1 and 4 should always use shielded cables and connectors along their entire route. Where this is not possible, EMC problems should be expected and mitigation measures may need to be applied.

Once we have the cables classified, we segregate their routes according to their class, always keeping them very close to a CM return path at all times as discussed earlier. There should be as much space as possible between each class (or sub-class) but it is very difficult indeed to specify what the spacing should be, because it depends upon the types, qualities and lengths of the cables, and the EMC performance of the electrical and electronic circuits connected to them.

However, a *very* crude guide for cables of 500mm long or more is to separate parallel runs of cables *inside* products by *at least* 100mm between classes 1-2, 2-3 or 3-4. This means 200mm between classes 1-3 or 2-4, and 300mm between 1 and 4, as shown in Figure 2H. For parallel cable runs *outside* a product up to 30m long and close to CM return path – use *at least* 150mm between classes 1-2 and 3-4, but 300mm between classes 2-3. For more than 30m, increase these spacings proportionally (e.g. doubling them for a run of 60m).

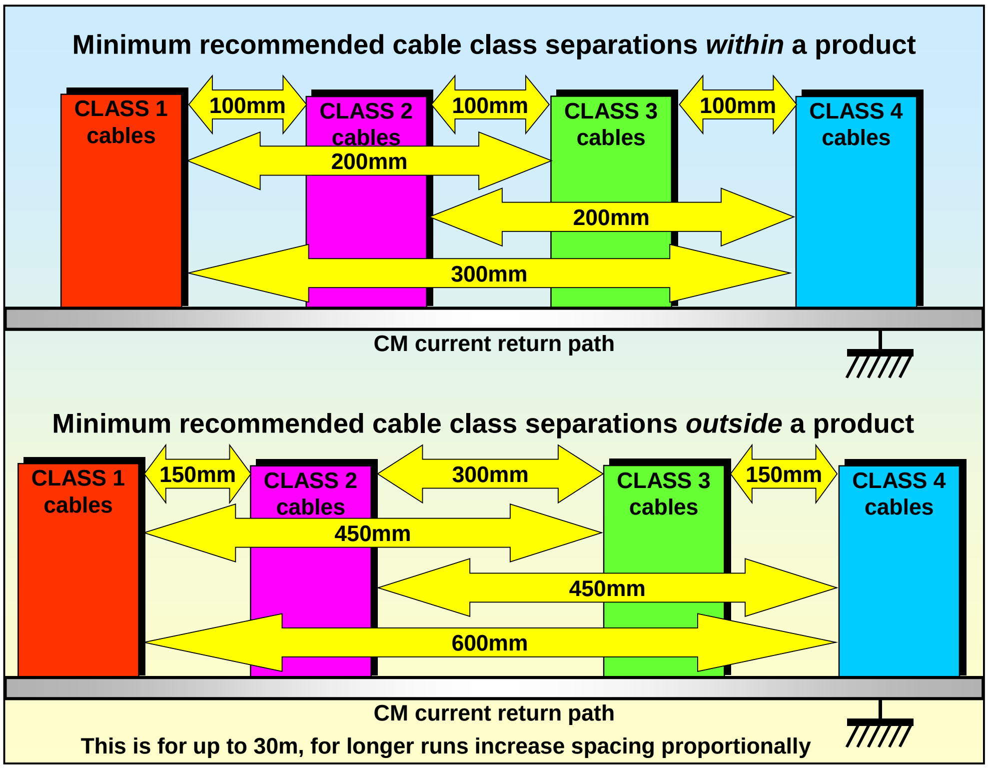

Figure 2H Minimum recommended cable class separations

All of the cables or wires in a bundle should of course be the same class (or sub-class) and should always be as close to their CM current return path (e.g. earth/ground-bonded metalwork) as possible along their whole length as shown in Figure 2D. Large diameter or tall bundles are therefore bad for EMC, because some of the conductors will not be close to the CM return path.

For the CM current return path to be effective it must have a low impedance current loop at the highest frequency to be controlled for EMC and SI. If it is ineffective, increase the above spacings considerably. When cable classes must cross over each other: preferably do it at 90° and try to achieve a good separation between the classes even so.

Because the above spacing guidance is so very crude, an investigation of cable-to-cable coupling is always recommended at a very early stage in a design. Rather than applying appropriate formulae, it is now more accurate, quicker and less costly overall to use a computer simulator. There are now several suppliers of these, but any simulator should have been calibrated by its manufacturer for its accuracy when solving cable-coupling problems by comparing its predictions with the results of actual experiments. An alternative to simulation is to carry out experiments early in a project, using the types of cables and connectors it is intended to use. If the hardware is not yet available to connect to the cables, appropriate load values should be used along with standard RF laboratory bench testing equipment.

Where the above spacings are difficult to achieve, investigations of cable-to-cable coupling at an early stage are strongly recommended, using calculations, simulations or experiments. Where spacings must be significantly closer than the above guides and cable lengths are significant, or where a potential problem is identified by investigation, it is possible to use higher-quality interconnections as described below, and/or employ the mitigation techniques (shielding, filtering, transient suppression, etc.) that are described in the other parts of [1] and of this new series.

Figures 2J and 2K give some simple examples of how the segregation technique might be applied inside a rack cabinet, and inside a product enclosure. For a discussion and examples of how segregation and CM return paths should be applied in systems and installations, see [6] and [7].

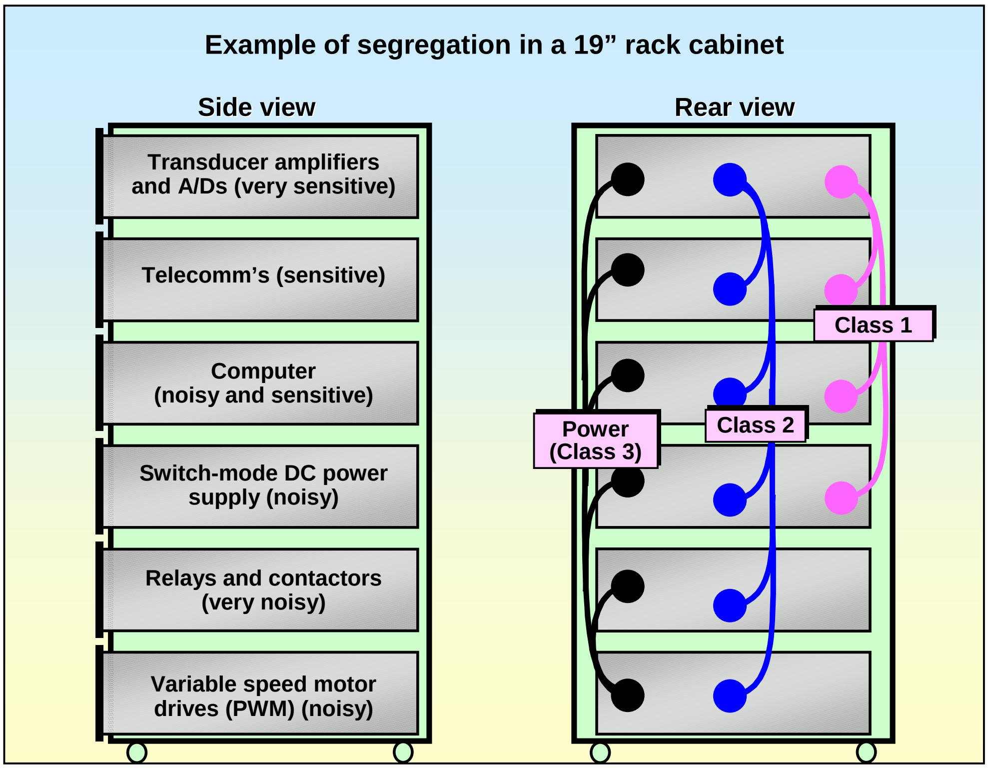

Figure 2J Example of segregation in a 19” rack cabinet

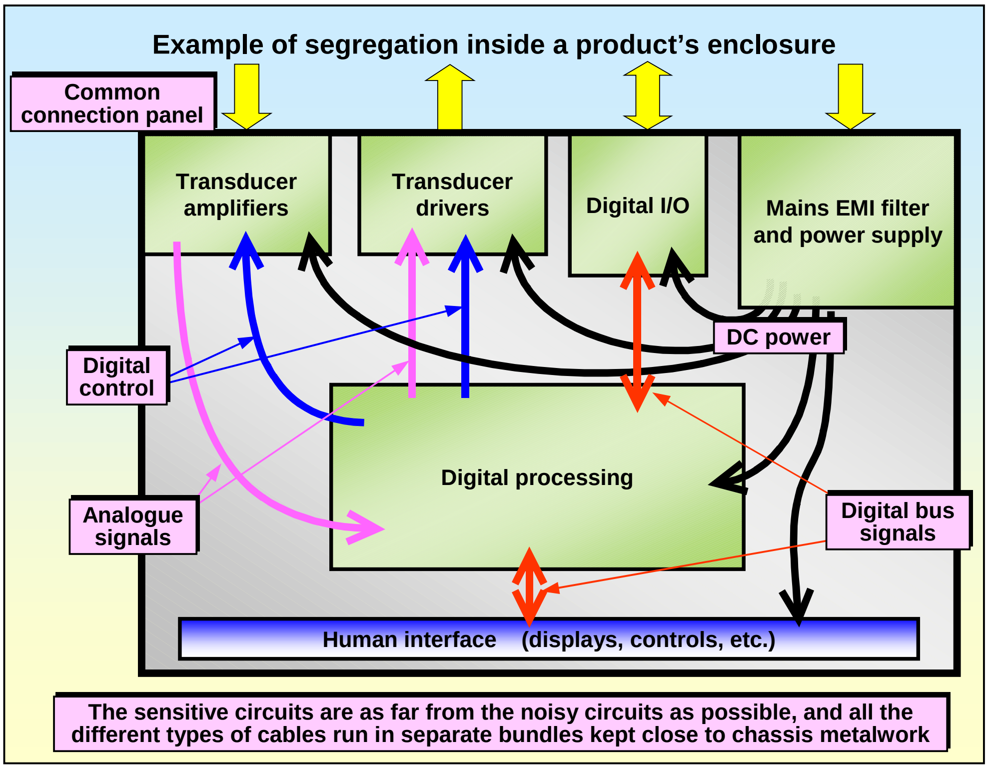

Figure 2K Example of segregation inside a product’s enclosure

Where ‘noisy’ and ‘sensitive’ circuits or products must interconnect, the sensitive one is at risk from conducted DM *and* CM noise from the noisy one. This is best avoided by using galvanic isolation techniques suitable for the frequency range of the noise, including:

- Isolating transformers
- Opto-isolators or opto-couplers

- Fibre-optics (using cables that contain no metal, e.g. for pulling strength, vapour barriers or armour)
- Infra-red communications
- Wireless communications
- Free-space microwave or laser communications

Any conductive interconnections between noisy and sensitive units will need to be mitigated (e.g. by shielding, filtered, transient/surge suppression, etc.) to reduce the potentially interfering DM *and* CM noises on the conductors to acceptable levels.

2.4 Unshielded interconnections

2.4.1 Unshielded wires and cables

Unshielded conductors can be quite good for EMC – *providing* they use the twisted-send/return technique described above, and have connectors that maintain close proximity between their send and return pins. But shielded twisted-pairs are better, and are discussed below.

Some manufacturers prefer to use bundles of single conductors, or ribbon cables that can be mass-terminated, because they require less time (hence costs) during assembly, and are more easily automated, than twisted-pairs. Although such conductors have poor EMC performance (for both 'internal' and 'external' EMC), they can be designed to obtain the best EMC performance they are capable of. This helps reduce the cost of the product by easing filtering and shielding requirements, and helps avoid delays by reducing the number of design iterations.

The EMC performance of bundles of single conductors can be improved considerably by including a number of additional return wires in the bundle, as shown in Figure 2L. These extra conductors must have low-impedance RF bonds (e.g. direct connections or series capacitors) to the reference planes (e.g. 0V) or chassis at both ends of the bundle. The additional wires should ideally be distributed regularly throughout the bundle, and with nearly as many additional wires as there are original signal or power wires the improvement in EMC can be more than 10dB up to at least 200MHz.

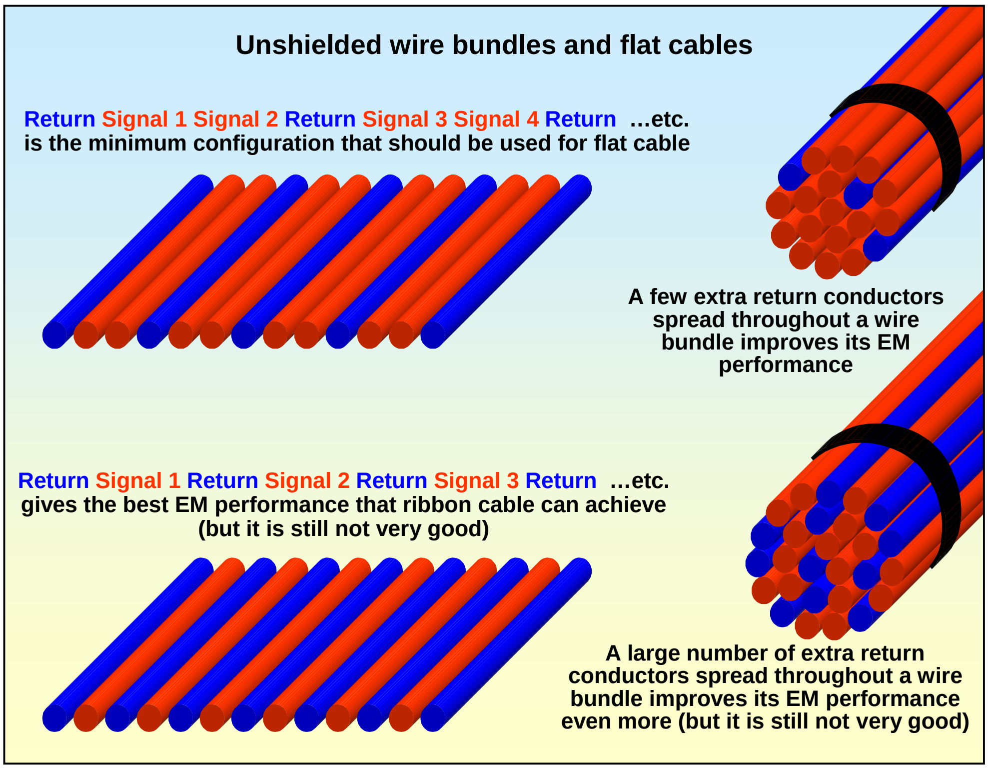

Figure 2L Improving wire bundles and flat cables

The EMC performance of ribbon cables can be improved markedly, by adding return conductors. Each signal or power conductor should have at least one return conductor adjacent to it, so the minimum implementation is: return, signal, signal, return, signal, signal, return, ….etc. as shown in Figure 2L. But the best implementation is: return, signal, return, signal, return, signal, ….etc., also as shown in Figure 2L Making the outermost two conductors in a ribbon cable return, not signal or power, can also help. Power conductors are treated as if they were signals.

Unshielded wires and cables that are implemented using correctly-matched controlled-impedance transmission lines will have very much better EMC performance than the same wires could otherwise. This is because their correctly matched resistive terminations considerably reduce the reflections at the ends, making them very poor accidental antennas. At the resonant frequencies of the (unmatched) conductors, the reduction in emissions due to matching can be as much as 40dB. Transmission-line design will be discussed in the second instalment of this article.

2.4.2 Unshielded connectors

Many types of unshielded connectors are available, and they generally have poor EMC performance. To improve their EMC performance they should use additional return conductors, following the guidance in the section on unshielded cables above.

In the case of an otherwise uncontrolled wire bundle (see Figure 2L) the pins allocated to the additional return conductors should be spaced throughout the connector so that no signal or power pin is too far from a return pin. For flat cable connectors used with mass termination connectors, the return pin assignment naturally follows the assignment in the cable. For twisted pair conductors the return pin must be the closest pin to the send pin. See Figure 2M for some examples.

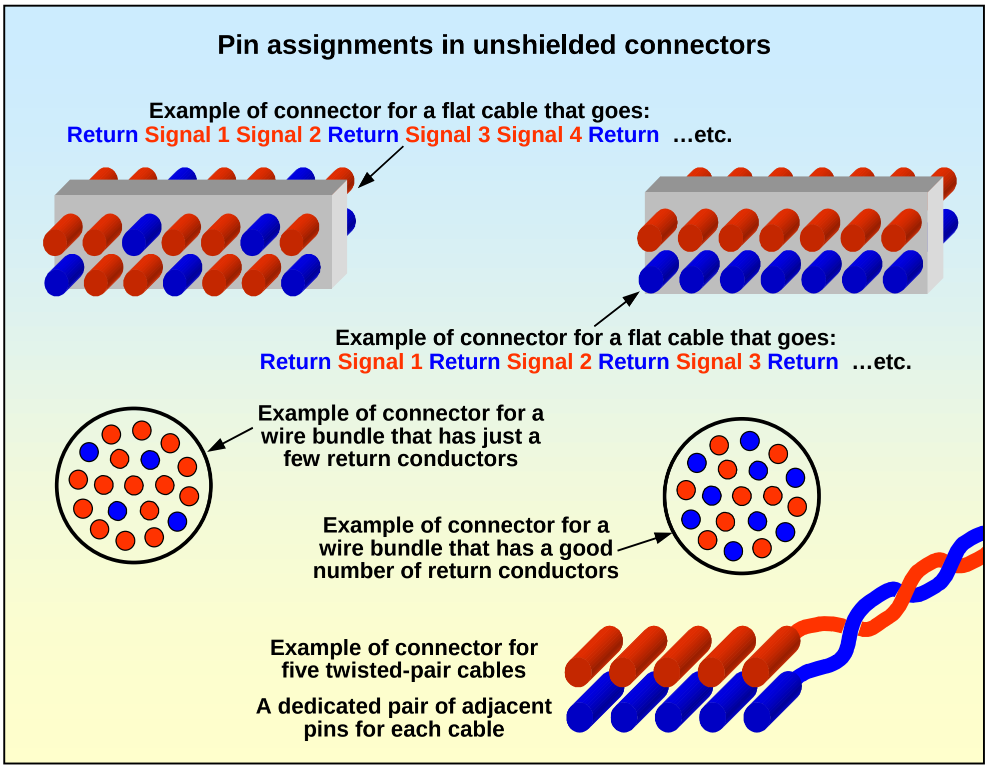

Figure 2M Pin assignments in unshielded connectors

Where multiple conductors are twisted (e.g. an analogue signals plus +12V, -12V and 0V as returns) all the pins should be the closest possible to each other, see Figure 2N for some examples.

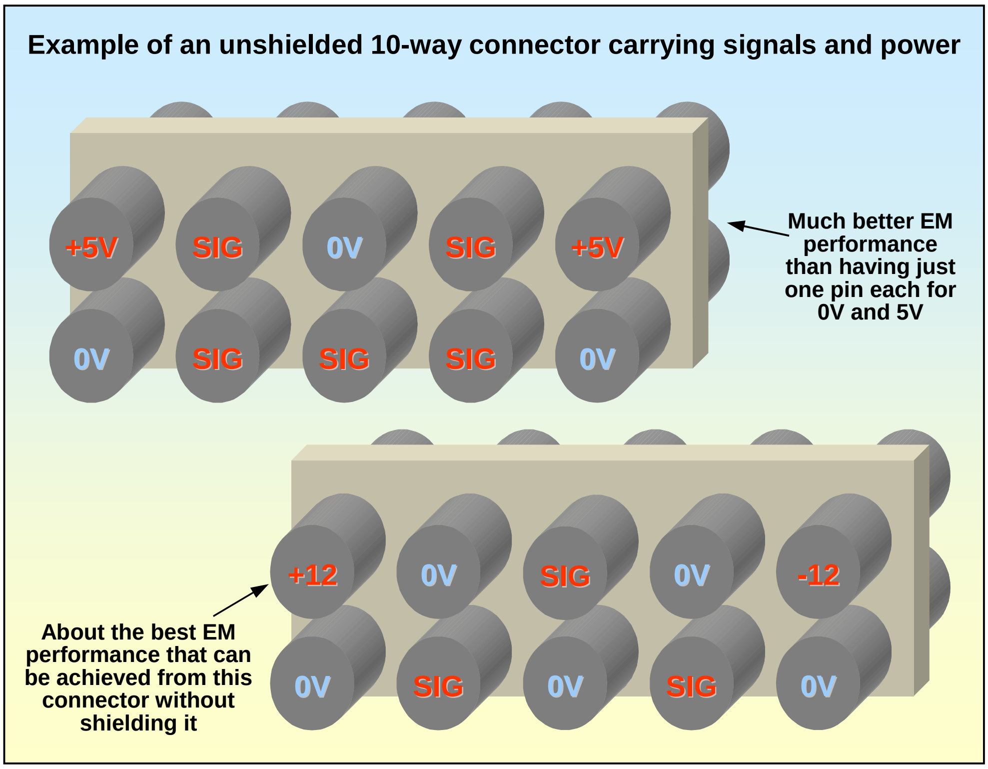

Figure 2N Example of an unshielded 10-way connector carrying signals and power

2.5 Earthing and grounding conductors

This article is about signal and power interconnections, but it is worth saying a few words about earthing and grounding, because this is usually done with conductors.

The purpose of earthing and grounding of products is to ensure personnel safety and protection of the installation against damage. The main consideration for safety earths and grounds are power system faults and lightning, with typical currents being 10kA or more.

To function as an effective earth/ground, the installation's earth/ground structure must have a low impedance at the highest frequency of concern. Traditional building installation earth/ground structures use long conductors to connect to a single point of connection (the main earth/ground terminal or bar). 10m (40 feet) of wire has an impedance of about 1Ω at about 16kHz, so we can see that such structures are generally ineffective for EMC above a few tens of kHz. Figure 2C also shows us that a 10m wire starts to behave as a significant accidental antenna above about 75kHz, which makes it no kind of earth/ground at all at such frequencies.

To have some useful effect on higher frequencies requires a meshed conductive earth/ground structure; for example, a 1m mesh size provides a low-impedance earth/ground structure up to about 1MHz. But sheet metal earth/ground structures, typical of traditional aircraft, ships, oil and gas platforms, etc., are even better than meshes, and can provide low impedance earths/grounds up to hundreds of MHz.

But the only effective RF earth/ground is a *local* one, so to be of any use at all for EMC a low impedance earth/ground structure in an installation should be closer to the product to be grounded than one-tenth of a wavelength at the highest frequency of concern. For a good quality earth/ground connection, the product should be even closer to the low-impedance ground structure, maybe one-hundredth of a wavelength or less.

Assuming that we had a perfect low-impedance earth/ground structure in the installation our product is intended for, and our product was close enough to it, we still need to make our connection between the product and the earth/ground with a low enough impedance, and without resonances in the frequency range of concern. For example, a 600mm square cabinet on insulated feet 10mm above a sheet metal earth/ground floor will have a stray capacitance of approximately 0.4nF between the cabinet and the floor. Bonding them together with 100mm of round wire, or 150mm of braid strap has an inductance approximately 100nH, resulting in a parallel resonance with the stray capacitance at around 25MHz – making its EMC worse around this frequency than if there was no connection at all between the cabinet and the installation's earth/ground. The only RF bonding that is truly effective up to 1GHz or more is direct metal-to-metal contact, preferably at multiple points, ideally seam-soldered or seam-welded.

So the EMC effects of connecting a product to the earth/ground in its installation depends on how the earth/ground structure is implemented and its impedance versus frequency characteristics; plus the stray capacitance between the product and the earth/ground and the inductance associated with the connection between the product and the earth/ground.

Typical building installations constructed using single-point earthing/grounding with long conductors are useless as EMC earth/grounds above a few tens of kHz. Meshed ground structures with multiple very short conductors or braids connecting to a product's chassis can be made to be effective up to tens of MHz, and large areas of sheet metal with the product's chassis bolted directly to it at multiple points can be a very effective ground up to hundreds of MHz. To be more precise than this requires a detailed analysis of the structures and conductors concerned, and the shape and location of the product.

2.6 Shielded (screened) cables

2.6.1 How do we shield a wire or cable?

Like any electromagnetic (EM) shields, shielded cables and connectors have a metal layer (the shield) around all of the conductors to be shielded. For good shielding performance, they need 360° shield coverage along their entire length, including at all connectors, glands or joints. The phrase: "360° shield coverage" is sometimes called 'peripheral' or 'circumferential' shield coverage, and these terms are applied to shielded cables of any cross-sectional shape, whether they are round, flat, or whatever. 360° shield coverage really means that there are no gaps or regions of high conductivity in the shield's material all around the cross-section of the cable, and all around any connectors or glands.

For good shielding performance the electrical bonding between a cable's shield and the shields of its connectors or glands and any shielded enclosures should have no gaps in it either. This means that there should be a seamless low-impedance electrical connection all around the perimeter or circumference of the electrical joint. This is often referred to as 360° shield bonding (even when the connector or gland isn't circular), and it applies between a cable shield and connector shield; the shields of two mating connectors; and between the shield of a connector and the metal chassis or structure it is mounted on.

It can help to think of shielding cables as plumbing with copper pipes – if there are any gaps in the 360° surface of the metal pipes or its connectors and glands, or in their soldered or metal-to-metal compression joints, the water will leak out. If we substitute EM-field leakage for water leakage we have a useful analogy. The higher the frequency, the higher the field leakage rate through a given shield imperfection, so we could make an analogy between higher frequencies and higher water pressures. But it doesn't do to stretch the analogy very far, because EM-fields also leak into a cable at its shield imperfections; and there is no EM analogy for preventing water leakage with a rubber washer.

The metal shielding layer is ideally made of a solid metal. This makes the cable inflexible, but this can be acceptable where cables lie in fixed routes, for example products often use 'microwave semi-rigid' cables for the fixed wiring for their microwave signals.

Flexible shielded cables either use a metallised plastic tape wound around the conductors to be shielded (usually called 'foil shielded'), or a braided wire tube ('braid shielded'). Multiple shields are also used, typically two braids in contact with each other, or braid and foil. Because common types of foil shields are wound as a helix, the metallised layers do not make contact between the turns, so a 'drain wire' is used to short each turn of the foil to its neighbouring turns. In a braid-and-foil shielded cable, it is best if the braid is on the metallised side of the plastic foil, because this makes very much better connections between foil's turns and results in better overall EM performance.

All flexible shielded cables have 'leakage' problems because they don't use a solid metal shield. The apertures that are inevitable in braid or foil shielded flexible shields have associated stray capacitances and stray inductances, although it is possible to 'optimise' a braid so that these effects cancel out to some extent over a limited frequency range.

Belden (and maybe others) offer a type of aluminium foil shielded cable in which the foil is aligned longitudinally along the cable, instead of spiral-wrapped. A longitudinal "Z-fold" electrically bonds the metallised surfaces of the foil along the cable, providing better shielding effectiveness than a spiral wrapped foil with a drain wire to short out the turns. But it will not be as flexible as a spiral wrapped foil cable, so is better suited to applications where the cable does not move.

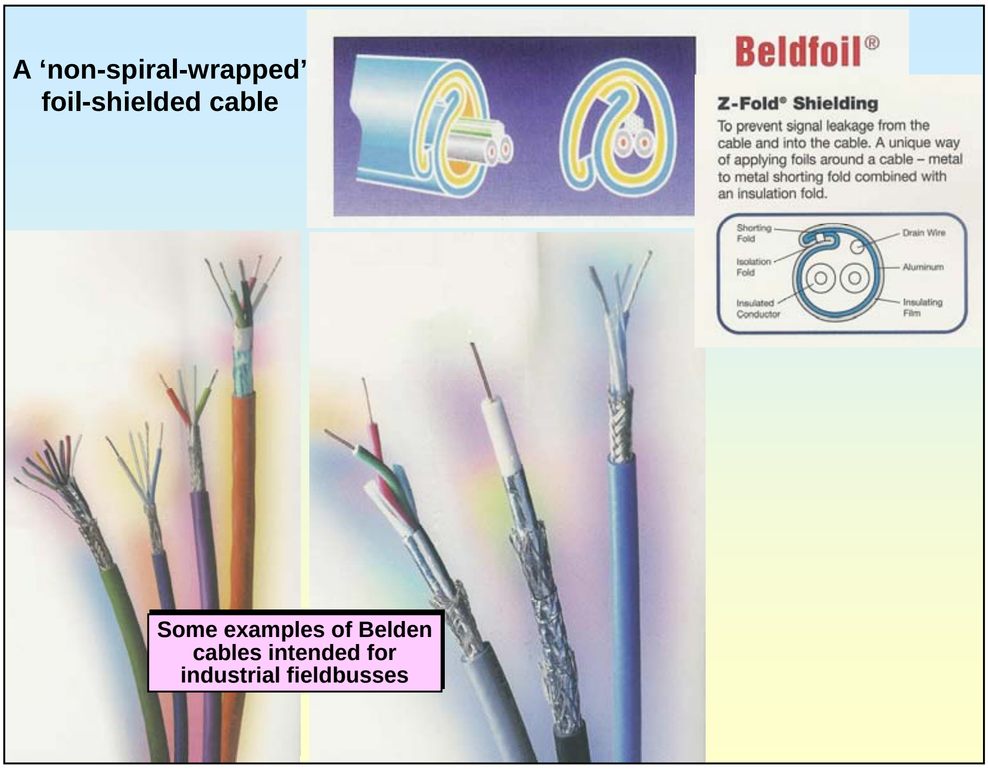

Figure 2ZZ Example of a 'non-spiral-wrapped' foil-shielded cable

Special cables are also available with multiple *insulated* shields, in which the different shields do not make contact with each other (e.g. Triaxial). Even more exotic (and expensive) are 'superscreened' flexible cables, which combine one or more metal shields with one or more high-permeability metal tapes wound around the conductors.

Some connectors use multi-point bonding for their shields, instead of 360° bonding. The more bonding points there are, the better the shielding will be, with continuous bonding around the whole circumference being the best.

2.6.2 How shielded interconnections work

When a shield interacts with an EM-field, currents flow in the shield. 'Skin Effect' makes RF currents travel on the surface of a shield, with current density diminishing with depth into the shield's metal by 36% for every 'skin depth'. The higher the frequency, or the more conductive the metal of the shield, the smaller is the skin depth. For good shielding effectiveness the shield should have many skin depths of thickness at the *lowest* frequency to be shielded. Skin effect is not described further here, but a useful reference is [8]. Figure 2P shows that providing we achieve our 360° shield coverage and 360° electrical bonding at shield joints, and have enough thickness in our shield's metal given the frequency, the skin effect tends to force the 'external' surface currents to flow on the *outside* of the shield, and the 'internal' surface currents on the *inside*. Understanding how the internal and external surface currents flow in shielding systems is key to understanding how to design shielding that functions well.

The external surface currents shown by Figure 2P are created by the interaction of the shield with its external EM environment, and they are CM currents. For good immunity we must ensure that their current density in the shield material is very low indeed by the time they reach its inner surface.

Still referring to Figure 2P, the internal surface currents are created by the CM currents leaking from the DM signals, or from RF noise in the send/return conductor twisted pair. For low emissions we must ensure that their current density in the shield material is very low indeed by the time they reach its outer surface.

The inner surface of the shield makes an ideal low-impedance CM return path for the interconnection, and it is important to complete the loop by connecting the shield to the electronic circuit where the DM signals or RF noise originated. This is shown in Figure 2P as a direct connection between the PCB's reference plane (usually a 0V plane for analogue or digital signals) and the chassis that the shielded connector is mounted upon. As mentioned earlier, the CM current path can be completed by series capacitors instead of direct connection, where galvanic isolation is required (e.g. for automotive applications, or off-line mains power supplies).

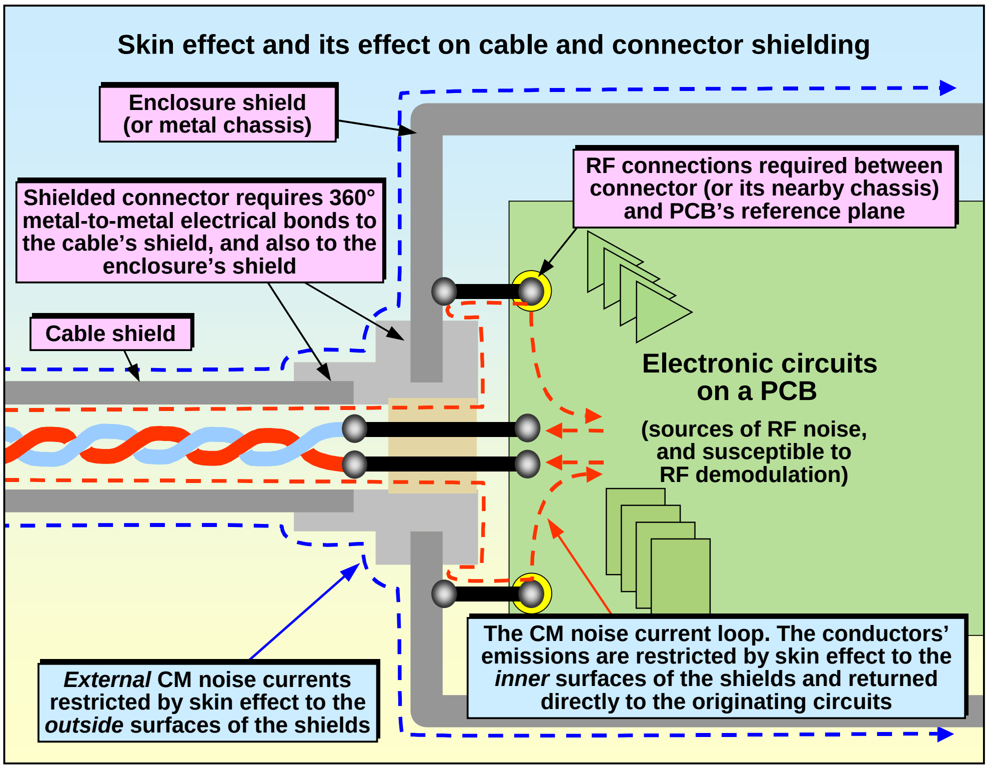

Figure 2P Skin effect and its effect on cable and connector shielding

Figure 2Q shows an example of this direct connection between connector shield, enclosure shield, and PCB 0V plane in a 2002 model of Dell personal computer. This is also an example of good design for EMC *and* low-cost assembly: the connectors are automatically placed and soldered onto the PCB along with the other components, then the assembled PCB is placed inside its enclosure where the die-cut conductive gaskets automatically make a 360° electrical bond between the PCB connectors and the PC's enclosure shield.

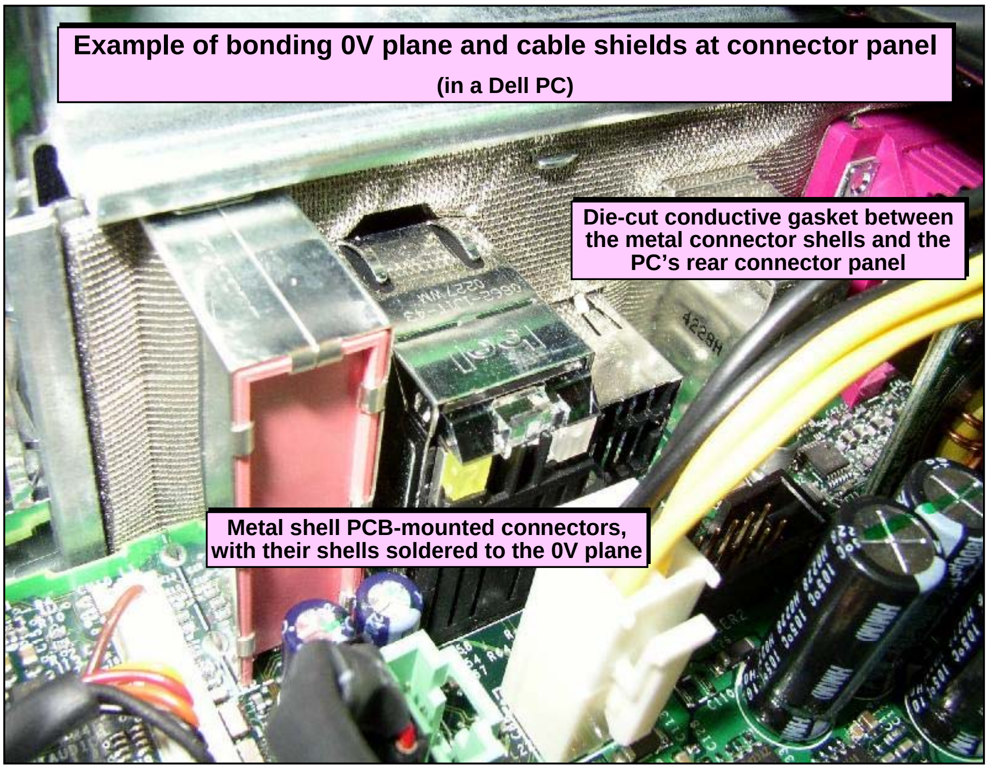

Figure 2Q Example of bonding 0V plane and cable shields at PC rear panel

Figure 2R shows some examples of die-cut conductive gaskets intended for exactly the application described above, for low-assembly-cost and good EMC. Traditional die-cut gaskets like this use a non-conductive soft foam core with metal-plated fabric on both sides, and the resulting insulation around the die-cut holes does not allow the surface currents on the insides of the cable and enclosure shielding to follow their optimum paths, so the resulting EMC performance is not the best. However, in recent years, so-called ‘Z-axis conductive’ versions have been developed based on a conductive foam core, which will help improve EMC.

Some examples of die-cut conductive gaskets

(from Schlegel)

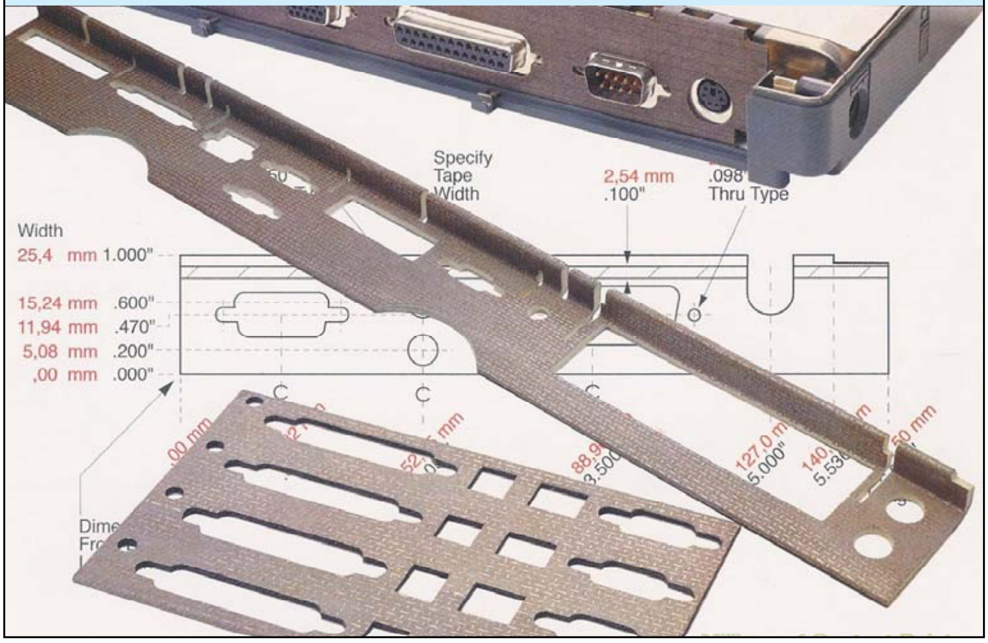

Figure 2R Some examples of die-cut conductive gaskets

2.6.3 Why coaxial cables aren’t very cost-effective for EMC

In the shielded twisted-pair of Figure 2P, the shield only carries CM currents, which are typically 100 to 1000 times smaller than the DM currents, depending on the ‘balance’ of the twisted-pair. But in coaxial cables the DM return current itself flows on the inside surface of the shield, so the resulting ‘leakage’ current density on the outer surface of the shield, responsible for creating the emissions, is much larger than it would be for a twisted-pair with the same type of shield.

Also, in a coaxial cable the current density on the inside surface of the shield resulting from the diffusion of the external CM currents adds a noise voltage in series with the return path of the DM signal, which is the same as adding the same noise voltage into the send path of the wanted signal. So coaxial cable is not as good for immunity as the same shield over a twisted-pair either.

Coaxial cables with solid and thick metal shields have very good EMC performance indeed, for both emissions and immunity, but they are not flexible so are not generally used. There are some types of flexible coaxial cables that achieve good EM performance by using double-layer shields and other techniques, such as ‘superscreening’, but at a price. So coaxial cables are *not* preferred when we need good EMC at a low cost – shielded twisted-pairs are better.

2.6.4 The Z_T and Shielding Effectiveness (SE) of various types of cable

SE is defined as the ratio (in dB) of the field emitted without the shield, compared with the field emitted with the shield. Measuring this accurately can be quite tricky, so it is more usual to measure the surface transfer impedance: Z_T. Z_T is measured in test jigs that inject a surface current into the cable’s shield, and measure the noise voltage resulting on the inner conductors. The ratio of the measured noise voltage to the injected shield current is Z_T, in Ω. These tests are more easy to set up to give accurate results, so when we want a cable with a good SE, we choose one with a low value of Z_T over the frequency range we are concerned about.

One formula relating Z_T to SE is: $SE = 36 - 20\log_{10}L - 20\log_{10}Z_T$, where L is the cable’s length in metres and Z_T is in Ω/m. But because of the variety of definitions and measuring methods for SE, this simple equation might not predict the SE actually measured.

Figure 2S shows some test results for different types of coaxial cable, taken from figure A2 of Def Stan 59-41 Part 7/1 Annex A. I would expect a shielded twisted-pair to have a usefully lower Z_T (higher SE) than a coaxial cable with the same design of shield.

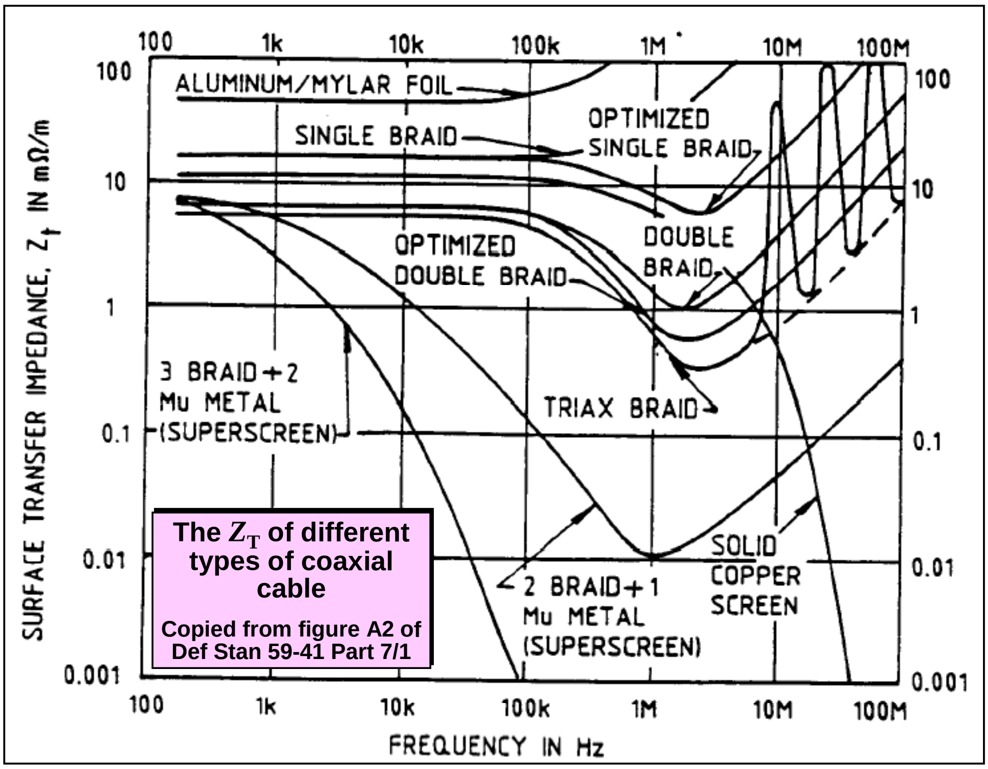

Figure 2S **The Z_T of different types of coaxial cable**

As Figure 2S shows, a lower shield resistance (more metal in the shield) reduces Z_T and hence improves SE at frequencies below 1MHz. Above 1MHz, it is clear that all flexible shielded cables suffer from 'leakages' that increase their Z_T (reduce their SE) above a frequency that generally lies somewhere between 1 and 100MHz. Even 'superscreened' cables show this behaviour, except for the more costly types. [9] has a lot more information on the SE and Z_T of various cables.

However, cables with solid metal shields (e.g. microwave 'semi-rigid', and solid metal circular conduit with 360º bonds at all joints and both ends) have a Z_T that continually reduces as the frequency increases. This is because with solid metal shields, skin effect can work to its fullest extent, keeping internal CM surface currents inside, and external CM surface currents outside.

2.6.5 Shielded connectors and glands for shielded cables

To obtain the full EM performance that a shielded cable is capable of, it is important to electrically bond the shield correctly *at both ends of the cable*. Figure 32-3 on page 32-7 of [10] gives some useful comparisons between the SEs of different types of shielded cables with their shields terminated at one or both ends. (Many people who are not EMC engineers and have never tried to get a product through EMC compliance tests will be horrified by the idea of the 'ground loops' that will result from bonding cable shields at both ends, but in fact if the good modern electronic design techniques described in this series are used, ground loops do not cause problems even with the most sensitive circuits, as discussed later.)

As was mentioned earlier, correctly terminating a shield requires 360° shielding to be maintained right through all connectors or glands, to another shielded cable or a metal (or metallised) enclosure. This means that a metal or metallised shell must be provided, to keep the internal and external surface currents separated right through from one cable's shield to the shield of another cable, or to the shield of a metal enclosure as shown in Figure 2P above. Figure 2T shows an example of a well-shielded military-style circular connector, which uses a conductive O-ring to connect the cable's braid in 360° to its outer metal shell, and maintains 360° bonding to its mating connector using another circular conductive gasket (sometimes using a circular arrangement of spring finger gaskets).

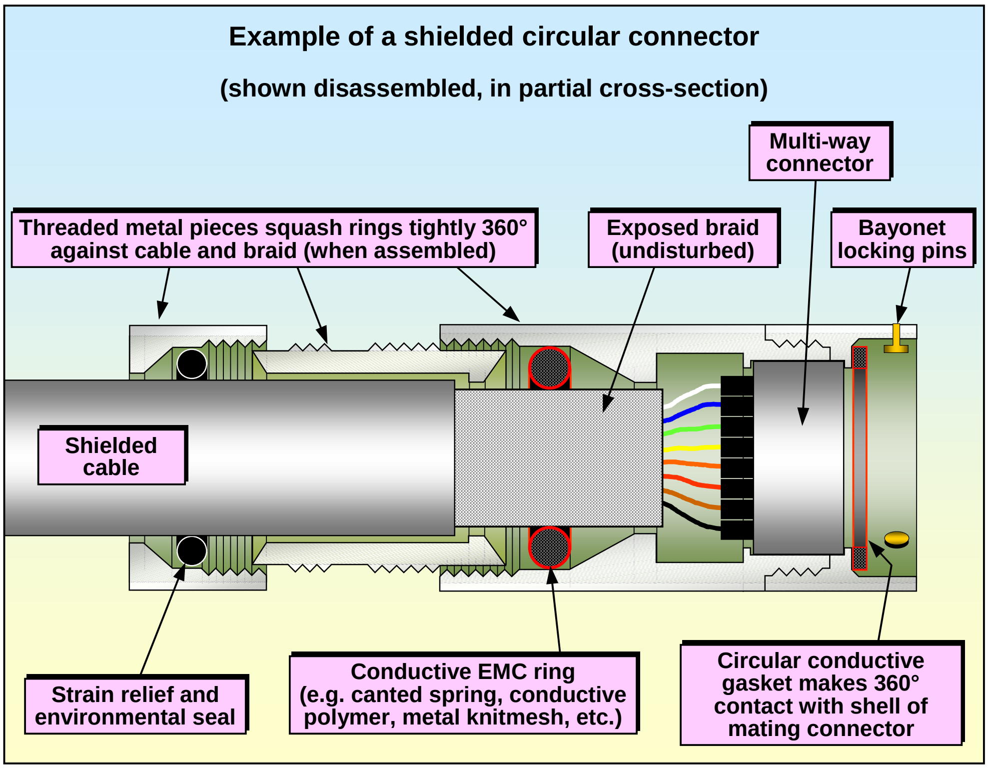

Figure 2T Example of a shielded circular connector

Figure 2U shows an example of a low-cost metallised-plastic D-type shielded connector. A variety of such connectors are available – this type uses a metal 'saddleclamp' to bond the shield to the metallised surface of the connector's backshell. The backshell then makes multiple bonds to the metal body of the connector itself, and the multiple dimples in the socket part make multiple connections to the mating connector. Although such connectors are not as good as the proper 360° shield bonding shown in Figure 2T, either for high levels of SE or for frequencies above 1GHz, they are often adequate for less-demanding requirements.

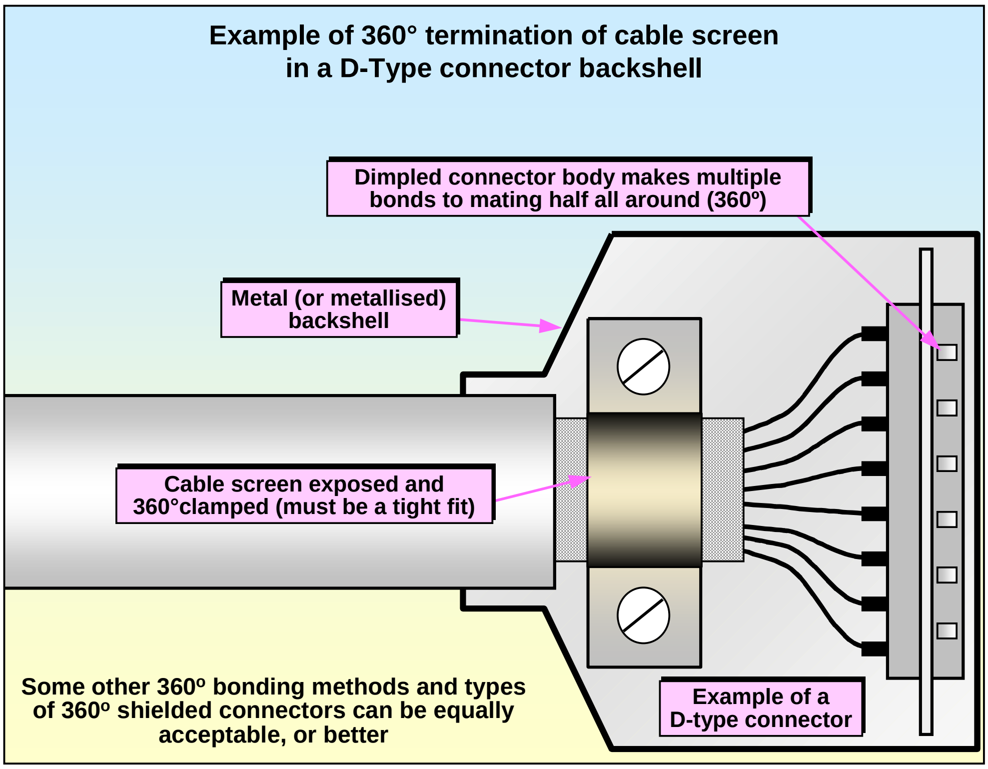

Figure 2U Example of 360° cable shield termination in a D connector backshell

The saddleclamp is an approximation to 360° shield bonding, and has the significant advantage that braided shields need not be disturbed at all during assembly. Any connector or cable that requires the shield to be worked on (e.g. unpicked and formed into a pigtail for trapping under a spring or clamp), or relies upon making connection to a drain wire, is not going to provide very good EMC performance.

Figures 2T and 2U show braided cable shields being used. Foil-wrapped cables can be used, but the metallised surface of the plastic foil must be on the *outside* of the foil wrap so that the conductive O-ring or saddleclamp makes a good connection all around it. Cables in which the metallised surfaces are on the *inside* of their plastic foil wraps (which will also have their drain wires on the *inside* of their foil wraps) are difficult to use to achieve good EMC at higher frequencies, because it is impossible to achieve a good 360° bond to their shielding surfaces. So when using foil-shielded cables with their metallisation (and any drain wires) on the *inside* surfaces of their foils, the EMC performance is not the best and can vary considerably depending on the quality of the workmanship.

Figure 2V shows some types of cable glands that provide 360° shield termination to a shielded enclosure. One type (the example from KEC) uses a conductive O-ring like the connector sketched in Figure 2T, and achieves a very good EMC performance. This type of gland also allows the shield to be carried through the wall of the enclosure without a break, so that it can be connected directly to the reference plane for the electronics (e.g. the PCB's 0V plane) to make an ideal return path for its internal surface currents. (The external surface currents not penetrating the enclosure wall, and remaining on the outside of the shielded enclosure due to skin effect, as shown by Figure 2P.) A similar type is shown by the example from Lapp Kabel, using a multiple spring finger contact to approach 360° shield bonding instead of a conductive O-ring.

Figure 2V includes an example of a shielded gland from Hummel, which should cost less to purchase than the two examples discussed above, but requires careful workmanship in cutting the cable shield and spreading it around the perimeter of a plastic or metal part before it is assembled. The EMC performance of this type of gland (or similar shield termination methods in connectors) depends upon the quality of the workmanship, especially when foil-wrapped cables are used, and it does not allow the shield (with its internal surface currents) to be carried through the gland to the PCB.

Figure 2V also shows an example of a mass shield termination system from Holland Shielding Systems. Essentially, this is an arrangement of two strips of soft conductive gaskets in some sort of clamp – cable shields are exposed, laid on one of the gaskets, and the cables held in place by plastic ties or some suitable method. When all the cables are in place the other strip of conductive gasket is clamped over them all, and the deformation of the soft gaskets ensures close-to-360° shield bonding. Of course, this method only works where the cables use metal braids or externally-metallised foils.

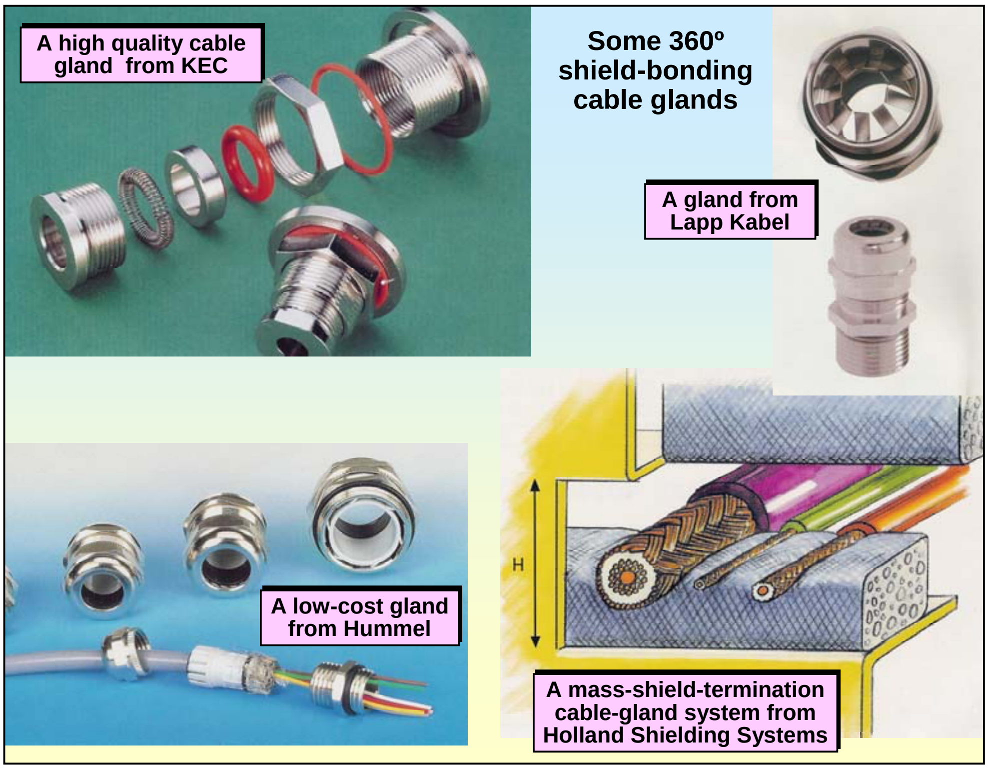

Figure 2V Some 360º shield-bonding cable glands

It is quite easy for any mechanical engineer to design similar shield termination systems into electrical/electronic control panels, cabinets or cubicles, but a little more difficult to achieve 360° shield bonding to the wall of the panel, cabinet or cubicle. Where the best EMC performance is not required, 360° bonding might not be necessary, but it is always very important to bond cable shields metal-to-metal and not to use a pigtail, as discussed later.

Figure 2W shows two D-type connectors and a cable gland connecting shielded cables to the wall of a shielded enclosure. The important point being made here is that chassis-mounted shielded connectors and glands <u>must</u> make a direct metal-to-metal electrical contact with the metal or metallised wall of the enclosure they penetrate. This requires the wall of the enclosure to present a high conductivity metal surface to the mating surface of shielding connectors and glands, usually achieved by appropriate plating.

The high conductivity metal, metallised or plated surfaces must be resistant to oxidation or other surface effects over their life, to help ensure that good SE is maintained. This is why plain aluminium is not preferred – aluminium is very reactive and always forms a skin of aluminium oxide, which gets thicker with time. Aluminium oxide is a very hard material, requiring immense contact pressure to break through to the conductive metal underneath, making plain or anodised aluminium a bad choice for shielded enclosures.

Another important point is that the metal or plating used for the enclosure must be galvanically compatible with the metal or plating of the connector or gland bodies, and with any conductive gaskets used. This is to help ensure that the inevitable metal corrosion over the lifetime of the product does not degrade EMC performance by too much. Good manufacturers of EMC gaskets will provide all the necessary assistance with minimising corrosion, including accelerated lifecycle test results to provide the necessary confidence in metal and gasket selection.

Where the EMC requirements are not very high, metal-to-metal bonding between connectors, glands and the chassis they are mounted on may be sufficient. But where high levels of SE are required, or where frequencies of over 300MHz are to be shielded, multi-point bonding and/or conductive gaskets will be required to approach or achieve 360° termination between the cable shield and the enclosure shield. If it is hoped to be able to avoid the use of gaskets, the design should still permit them to be employed, so as not to delay the project if it is found that they are needed.

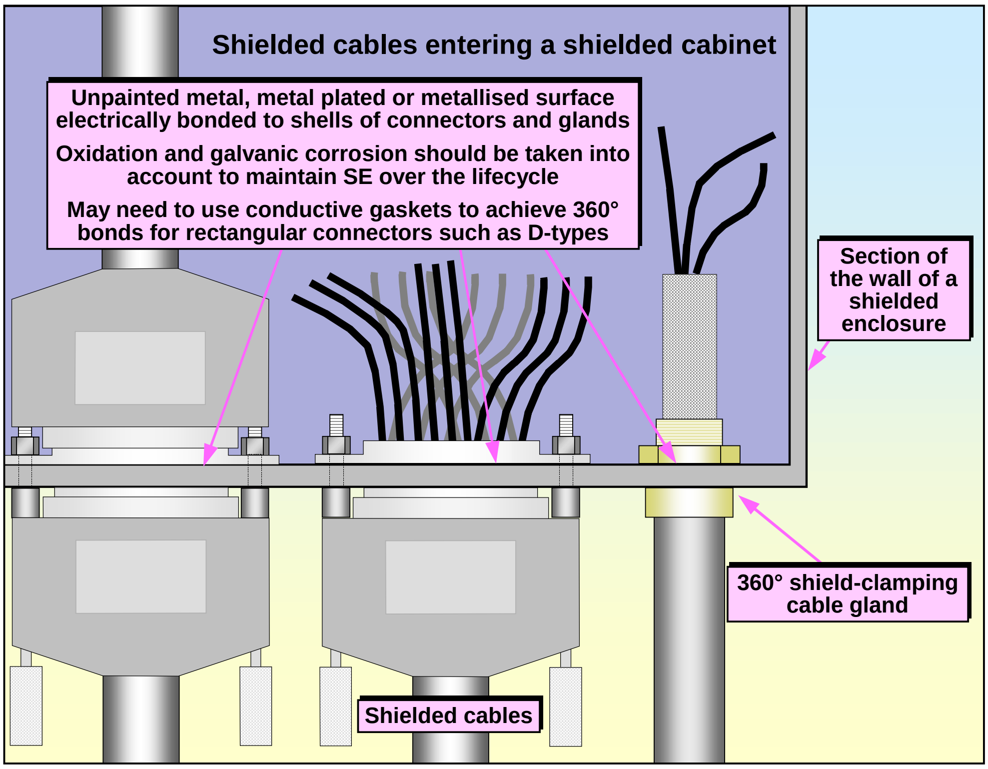

Figure 2W Shielded cables entering a shielded cabinet

Figure 2X provides an overview of interconnecting two shielded enclosures with both shielded and unshielded cables. This issue is discussed in more detail in Part 4 of [1] or Part 4 of this series, but it is important to note that to maintain the shielding of the enclosures, *all* of the conductors that enter them must either be shielded or filtered at the walls of the enclosures (and 'grounded' conductors such as the PEC must be directly connected to the wall) at their point of entry. There can *never* be any exceptions to this rule, for *any* types of wires or cables whatever the signals or power they are carrying. This rule even applies to anything metal that penetrates the wall of a shielded enclosure – such as cable armour; metal draw-wires or armour in some types of fibre-optic cables; or metal pipes carrying hydraulic fluids, pneumatic power, or ventilation ductwork.

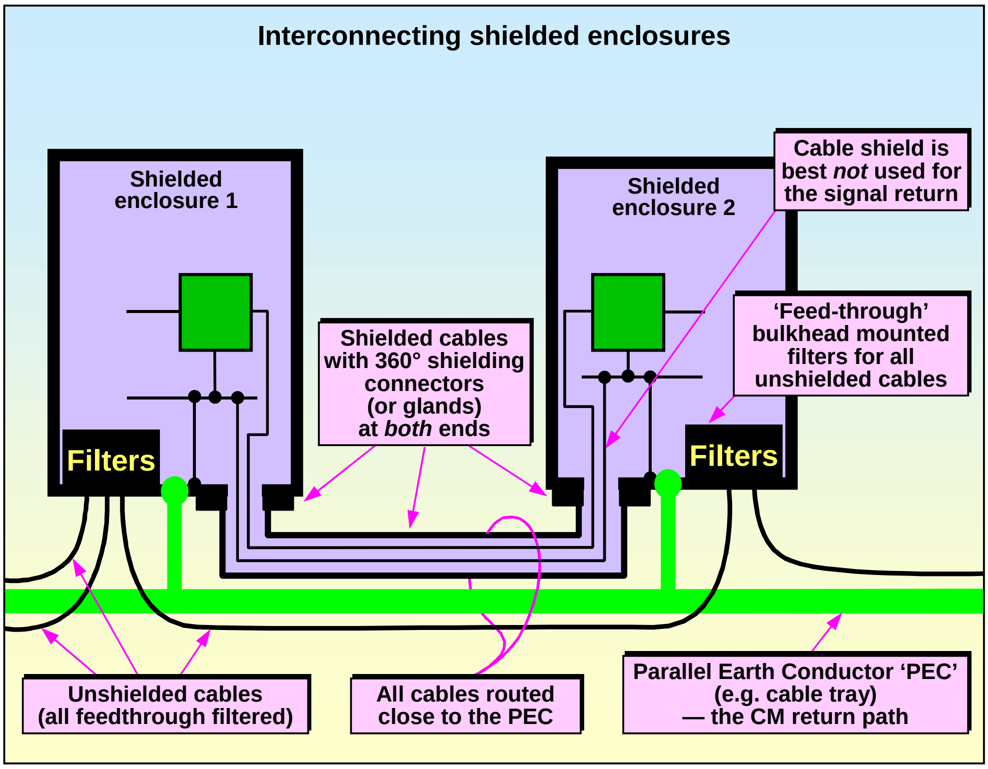

Figure 2X Interconnecting shielded enclosures

Some types of shielded connector (e.g. BNC) can be supplied with a choice of characteristic impedances, for use in matched transmission-line interconnections (see later). Although such connectors might look identical, their different characteristic impedances mean that they have different dimensions internally. So when using a given type of connector it is important not to mix impedances, because this can cause problems with contact reliability, or even actual damage to one or both mating connectors.

2.6.6 Problems with some traditional connector types

Digital processing devices and switch-mode power converters are emitting increasingly higher levels of CM noise at increasingly higher frequencies. And the environment is also suffering increasing levels and frequencies of RF noise due to the huge growth in wireless communications for voice and data (Bluetooth, Wi-Fi, Zigbee, etc.). As a result, wherever cable shielding is required, 360° shield termination methods are increasingly necessary to maintain functional performance characteristics (e.g. signal/noise ratio) and prevent interference.

Unfortunately, many of the shield terminating practices that became established in some industries and application areas in previous decades do not maintain the SE of the cables. For instance, some connectors and glands require shields to be connected using a short length of wire or twisted braid, or the drain wire in a foil-wrapped cable. Such a shield connection is often called a 'pigtail', and it completely ruins the RF shielding performance of the cable, allowing external surface currents (see Figure 2P) to access internal circuits and devices (causing problems for immunity), and allowing internal surface currents to access external surfaces (causing problems for emissions).

It has been the habit in some industries in the past to classify cables as 'Low Frequency' or 'RF' according to the DM signals they are intended to carry, and applying shield terminations at one end (usually with a pigtail) or at both ends accordingly. But in the world we are creating for ourselves, CM noise and/or RF noise in the environment mean that <u>all</u> cables now need to be treated as RF cables, and use appropriate shield bonding techniques.

It has also been standard practice in certain industries for decades to terminate a cable shield by routing it through one of the pins in the connector to connect it to the shield of another cable or enclosure, rather than using the outer metal shell to make that connection. These pins require cable shields to be pigtailed, and are themselves extensions of pigtails. Any length of pigtail ruins the shielding performance of cable shields at RF, as Figure 2Y shows using the example of a 25-way subminiature D-type, and is taken from [9].

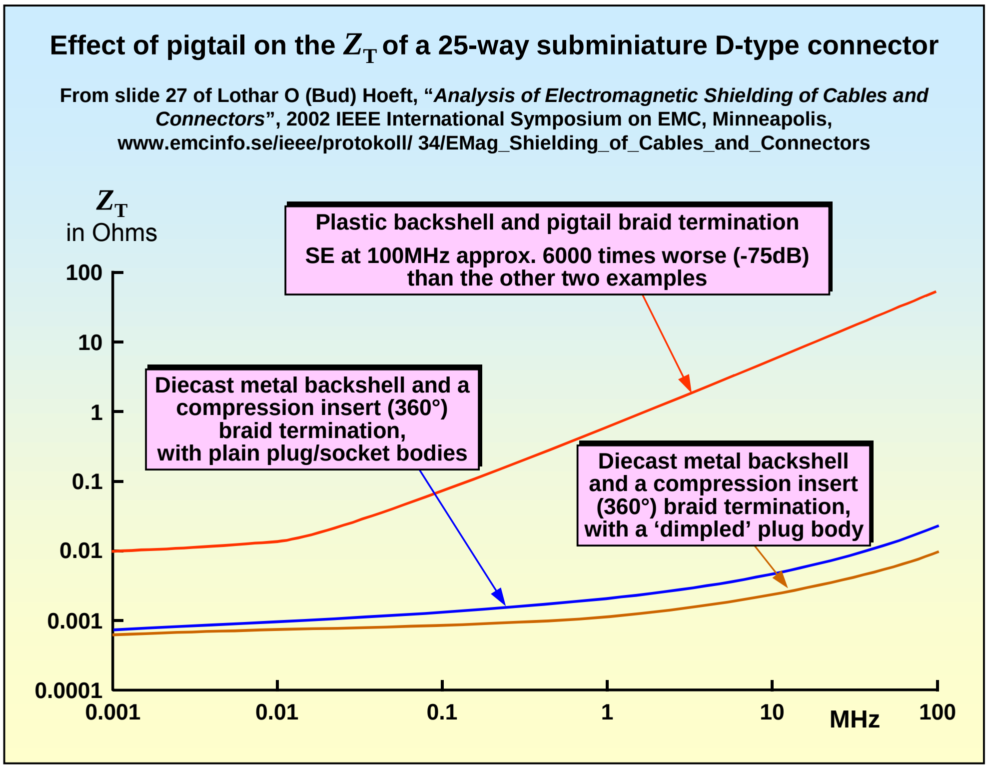

Figure 2Y An example of the effect of a pigtail on the Z_T of a connector

Some traditional types of shielded cable connectors also cannot make a 360° bond to their product's enclosure, creating more EMC problems. Figure 2Z shows some gaskets that have been developed to help achieve reasonable levels of SE when using DIN and D-type connectors in modern equipment.

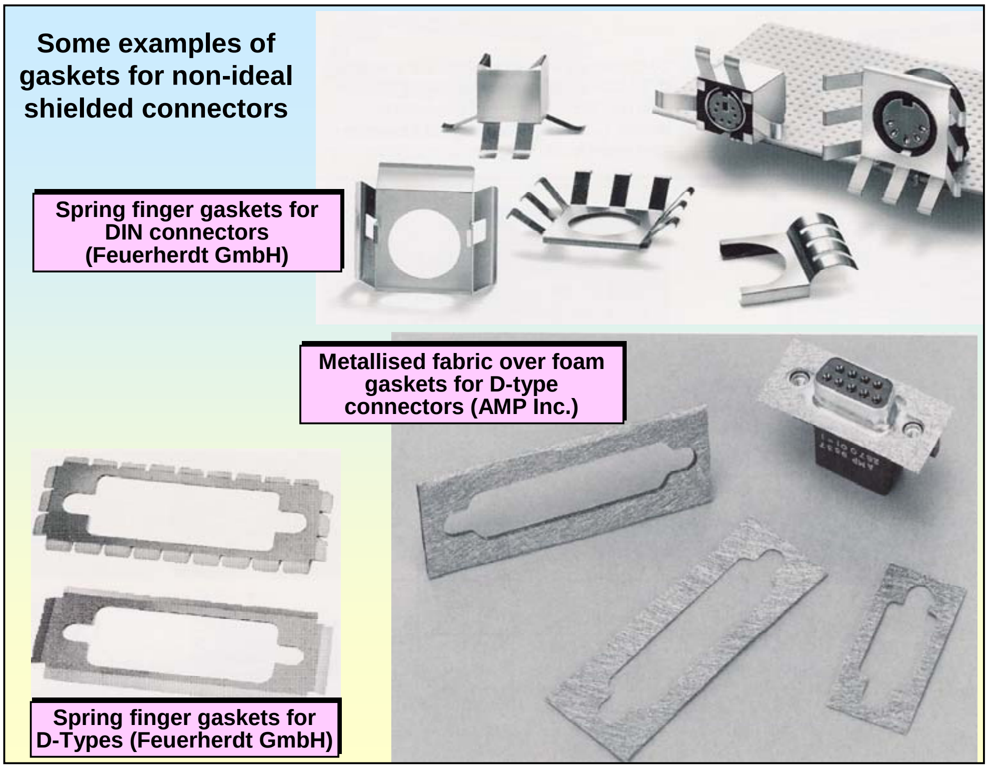

Figure 2Z Some examples of gaskets for non-ideal connectors

Products need to use standard connectors to maintain compatibility with legacy systems and installations, but where these connectors do not allow 360° shield termination it prevents the achievement of good EMC performance. A typical example is the use of 'phono', 'jack' and 'XLR' connectors in the audio and professional audio industries. This situation is best solved by connector manufacturers designing and manufacturing versions of their decades-old connector types to permit correct 360° shield termination to the cable and to mating connectors or metal enclosures. In the case of the venerable XLR connector, at least one manufacturer

(Neutrik) has started to produce versions that allow 360° shielding, advertised by them as being suitable for digital signals. In fact they are much better for the EMC of *all* types of signals, including microphones and low-voltage power, than the traditional designs of XLR connectors.

2.6.7 Terminating cable shields when not using shielded connectors or glands

Sometimes 360° shield termination is not practical, and/or is not required for reasons of EMC performance. For example, in the industrial control industry it is common practice for industrial control products to provide screw-terminals even for shielded cables. Nevertheless it is possible to obtain some useful SE performance at RF from the shielded cables, by minimising the impedance between their shields and the 'reference plane' by using metal-to-metal bonding. Even where a product or equipment enclosure is not a shielded type (e.g. the typical industrial cabinet) – metal-to-metal cable shield bonding can improve EMC performance hugely.

The reference plane of a product is the metal frame, chassis or enclosure that carries or contains the electronic units or circuits or devices that the cables connect to. In the industrial control industry, it can be the metal backplate upon which the industrial control products are mounted (see Part 3 of [6] and Chapter 6 of [7] for more on this). Such frames, chassis or enclosures should be metal-to-metal bonded to the reference planes of the electronic units or circuits (e.g. the 0V plane in their PCBs) to help provide a low-impedance return path for their CM currents (see Figure 2P) to help reduce emissions.

A typical method for connecting cable shields to the reference plane is the saddleclamp or P-clip, as shown in Figure 2AA. At one time suitable components had to be purchased from suppliers of plumbing, hydraulic or pneumatic components, but now some EMC component manufacturers supply suitable parts, such as the plated plastic P-clips from Kitagawa also shown in Figure 2AA.

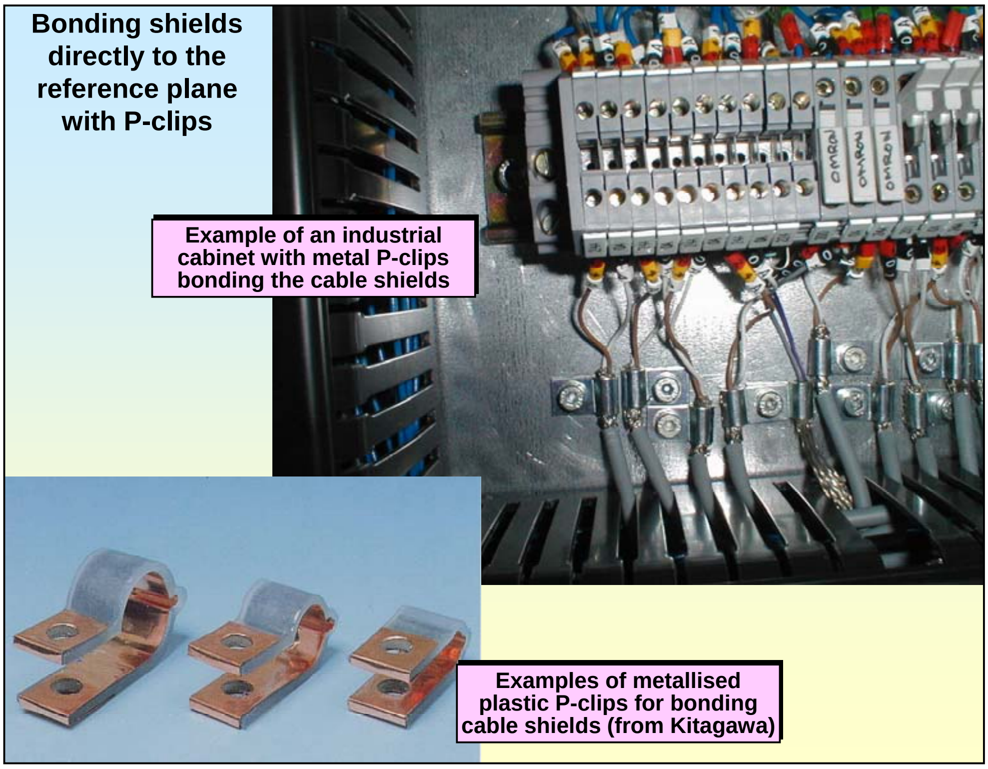

Figure 2AA Example of bonding cable shields with P-clips

My experiences with EMC testing over the last 16 years have been that wherever a product uses metal enclosures and shielded cables, and if the cables shields use pigtails, poor RF emissions or immunity performance can usually be significantly improved by modifying the shield terminations at the connectors to achieve a direct metal-to-metal bond between shield and chassis. If a 360° bond can be achieved, the performance is even better.

In one recent instance the shielding of a 2m long foil-wrapped cable was completely ruined at frequencies above about 30MHz by pigtails of 25mm length or longer, causing an emissions test to be failed. The emissions from that shielded cable alone were enough to cause the whole unit to fail the compliance test, but replacing the pigtail with a metal saddleclamp that clipped the cable shield directly against the backplate reference plane, although not a proper 360° termination to a shielded enclosure, reduced the shield's termination impedance by enough to cause the cable's emissions to fall below the test's noise floor.

(Interestingly, the cable concerned in the above example was connected to the 'volt-free' inputs and outputs of a popular programmable logic controller (PLC). Despite having no electrical connection to the PLC's circuits, the volt-free contacts and their attached conductors had sufficient stray capacitance and mutual inductance to the PLC's circuits to pick-up, conduct, and re-radiate noise at sufficient levels to fail the 'Class A' limit line.)

There are many ways of bonding a cable shield metal-to-metal to a chassis, limited only by the imagination of the designer. Examples include the P-clips of Figure 2AA and the mass cable shield termination system sketched in Figure 2AB. Other low-cost methods include strapping exposed cable braids or externally-metallised foils with metal or metallised cable ties or band-clamps. Beware: some manufacturers of industrial cabinets and/or the fittings for them offer shield-terminating components or systems that do *not* minimise the RF impedance between the cable shields and the reference plane by ensuring direct metal-to-metal bonding, and are often little (if any) better than pigtails.

Some supplier's EMC installation instructions require that shielded cables only be terminated at one end. This can be a sign of bad EMC practices in electronic design, and should be considered a possible warning that the supplier's products could cause EMC problems for the product, equipment or installation that employs them. It is fair to say that some suppliers write such installation instructions because they are afraid that 'ground loop' cable shield currents might overheat their cables, but in this case they would be better advised to recommend the use of the good installation practices of IEC 61000-5-2 [11], especially its 'parallel earth conductor' (PEC) technique, which is discussed in Part 4 of [6] and Chapter 7 of [7].

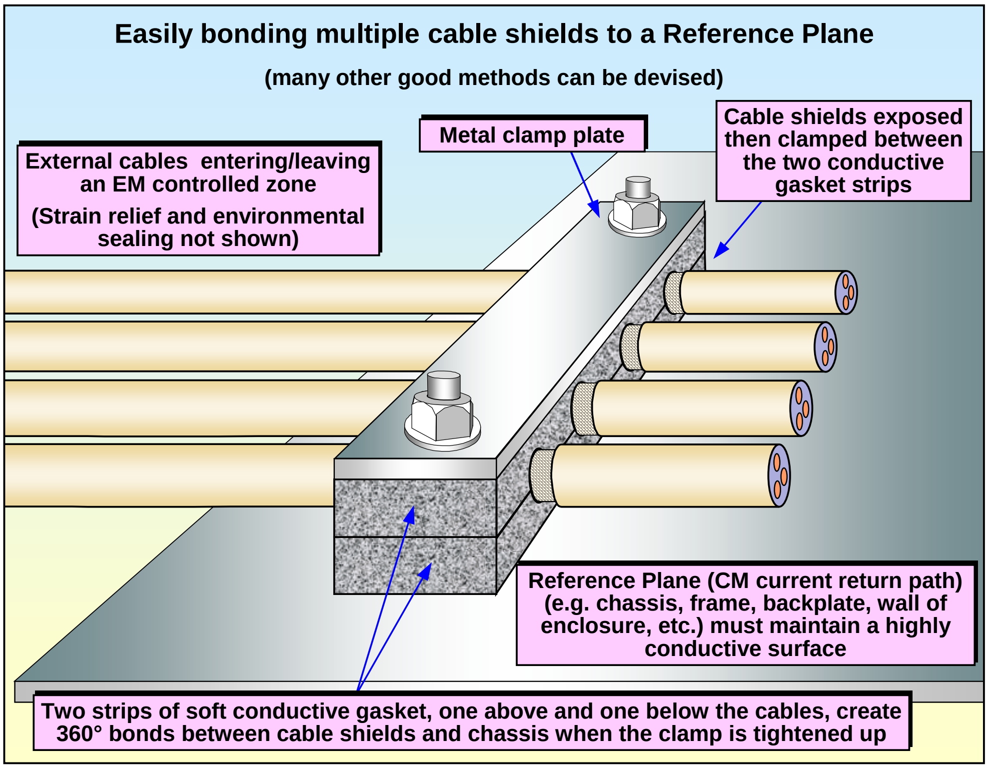

Figure 2AB Example of method for bonding multiple cable shields to a chassis

A problem sometimes arises with such suppliers' equipment, when it is necessary for its shielded cable(s) to interconnect two shielded enclosures. As Figure 2X showed, when interconnecting two shielded enclosures, shielded cables must be 360° terminated as they penetrate the walls of each of the enclosures – for their SE not to be degraded. This conflicts with the supplier's instructions to only bond the shield at one end.

Figure 2AC shows one way around this problem – using a double-insulated-shield cable (two shields insulated from each other). Terminating the outer shield at both ends preserves the SE of both enclosures, whilst the inner shield can be terminated according to the device supplier's instructions. Now, if the device does not work to specification, the supplier cannot claim that his installation instructions were not followed.

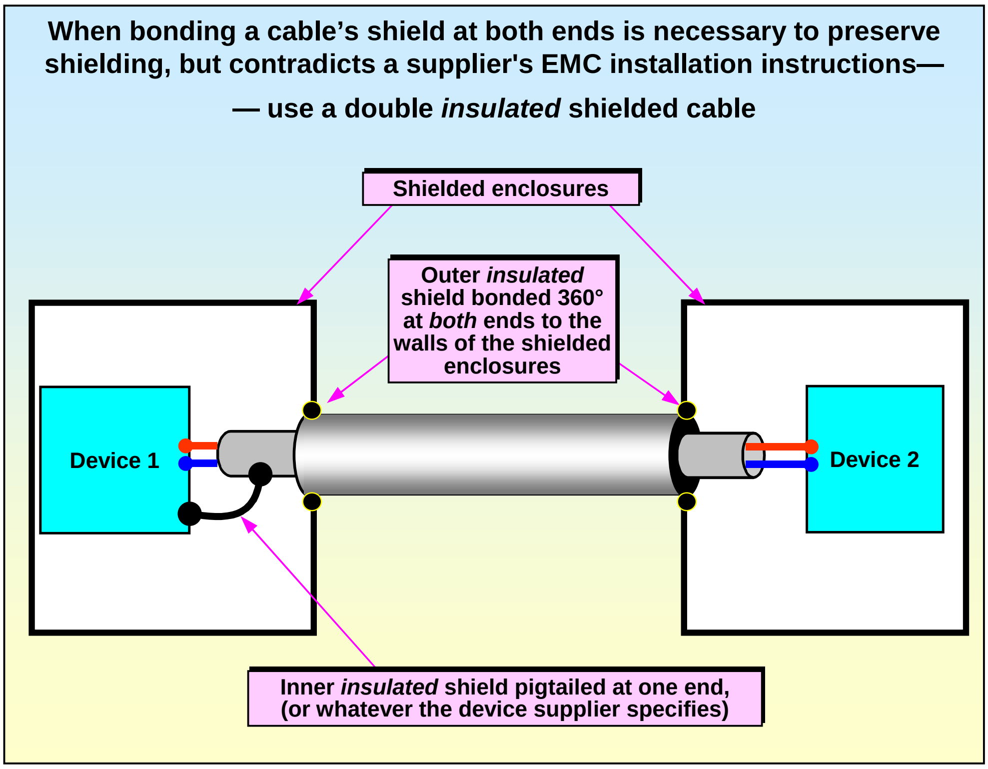

Figure 2AC When suppliers insist on bonding cable shields at one end

2.6.8 Why 'ground loops' are not a problem for correct design

'Ground loops' or 'earth loops' are sometimes called 'hum loops' because of the noise they can make in poorly-designed audio systems. Traditional installation practice uses single-point earthing/grounding and cable shield termination at only one end, to avoid creating ground loops, but the ground loop problem is in fact caused by poor electronic design practices.

On an electronic test bench it is usually found that it is easiest and lowest-cost to obtain the best signal-to-noise ratio (SNR) for a low-frequency amplifier circuit, by connecting the 0V from the DC power supply, and the input cable shield, at a single point on the circuit – usually somewhere near the most sensitive amplifier stage. Attempts to make this type of design give good SNR in the real world of systems and installations resulted in the policy of single-point grounding and isolating DC power supplies (although DC power supply isolation was needed for safety reasons anyway).

Every mains-powered product suffers from ground-leakage current, and – since every product had its own ground wire (with unavoidable impedance) back to some 'star point' common ground connection – with respect to the star point each product had a different 'ground' voltage on its chassis. So if any shield was connected at both ends, the ground potential difference between the two products resulted in a 'ground loop' current in the shield, which was of course connected directly into the reference voltage of the most sensitive electronic circuits. As this current flowed through the traditionally high-impedance 0V systems used in non-RF amplifiers, it gave rise to noise voltages that degraded the SNR.

Hence the bogey of 'ground loop currents' was created by the original mistake, which was to try to force the lowest-cost test bench solution for individual PCB assemblies into the real world of systems and installations. Over time, that mistake has resulted in an overall cost to industry that is at least an order of magnitude higher (maybe two or three orders) than it would have cost if the circuits had been properly designed in the first place to cope with real-world ground potential differences. In the professional audio industry, for example, costly high-specification isolation transformers are often employed to counteract the effects of poor electronic design.

In fact, ground loops are a problem of the CM impedance coupling of single-sided signals using single-point earthing. It is rarely an issue for shielded signals in a well-designed system [12].

An unavoidable fact about the modern environment is that it is badly polluted with RF noise, which is getting higher in amplitude and frequency all the time. But another problem with the single-point grounding method is that it is impossible to use it to control RF currents – the ground wires have too much impedance to be effective, and behave as accidental antennas just as shown in Figure 2C, allowing the RF currents to flow uncontrolled, causing interference problems. As has been shown above, the best connections for an RF shield are 360° terminations at both ends, and anything else has worse EM performance.

A cable shield that is only terminated at one end is an accidental antenna as shown in Figure 2C, just like any other conductor, and not a shield at all for frequencies at which the cable is longer than one-sixth of a wavelength. And a shielded enclosure penetrated by a cable that is neither shielded nor filtered is no longer a shielded enclosure (see Figure 2X).

Since we now have no option but to control real-world RF, we have two choices – filtering and shielding. Cost-effective design uses both techniques, either separately or combined, but where shielded cables are already used the best cost-effectiveness is generally achieved by allowing the cables to provide the SE they have always been capable of, instead of wasting their SE by employing the 'traditional' approach of only terminating the shield at one end (and that using a pigtail).

Effective shielding will of course create 'ground loops', but there are simple and relatively low-cost techniques for dealing with them. The first is to always connect the shield to the chassis of the product – the low impedances in the product's metalwork will divert most of the current away from the sensitive circuits and into the ground structure. The 360° shield termination method described in Figure 2P is ideal for this purpose.

The next step is to recognise that there are noisy potential differences between the chassis of different items, and so to interconnect them using balanced (differential) signalling circuits as shown in Figure 2G and also as discussed in Part 1 of both [1] and [13]. The better the common-mode rejection ratio (CMRR) of the circuits at the power supply frequency, the lower will be the resulting noise due to the chassis voltage differences.

In a well-designed balanced signalling circuit, screen currents (which are CM) do not cause significant DM signals, even when using very poor quality unbalanced cables, even with 50Hz currents high enough to heat up the cable, as shown by the tests described in [14]. The only significant cause of the DM interference that causes the hum noise is the potential difference between the earths (grounds) of the equipment at both ends of the cable, and the CMRR of the sending and receiving circuits.

Terminating all of the cable shields at both ends creates a 'meshed ground' (what [6] [7] and [11] call a MESH-CBN, for Meshed Common Bonding Network), and the more such a structure is meshed, the more the potential number of paths for ground current, the lower its ground impedance. Since earth/ground leakage currents mostly cause potential differences between items of equipment, the lower ground impedance of a MESH-CBN results in lower hum noise and better SNR, not worse.

Another traditional worry is that damage to cables might occur due to high levels of shield currents in some high-power installations, or during a surge caused by a thunderstorm or power distribution fault. In general, when an installation has been correctly earth-bonded for safety reasons, the current that will flow in the relatively high-impedance cable shields cannot be high enough to damage them. But the grounding/earthing structures in some legacy installations are very poor, and sometimes cables are routed where there is no low-impedance ground structure common to the equipment at both of its ends. In such cases, adding a PEC as recommended in [11] will protect the shield from overcurrent damage, and will also help protect the electronics at both ends from overvoltage damage during thunderstorms, see [15] for more on this. Care should be taken when routing a PEC between two separate installations, to avoid injecting power-fault currents from one installation into parts of the other that cannot handle them.

Where very high performance signals are required (e.g. in Professional Audio), it may be necessary to improve the CMRR by using high-CMRR balanced transformers, or high-CMRR electronic circuits. Another technique is to add a PEC in parallel with the cable shield, as recommended in [11]. This will considerably reduce the low-frequency shield currents, but for balanced interconnections shield currents cannot cause significant levels of noise in any case, and the main benefit of the PECs is in reducing the potential differences between the chassis of the products at each end of the cable, see [14] for simple tests that can quickly demonstrate this.

Some industries use very long coaxial cables, for example for '75Ω' video (e.g. in broadcasting studios). These are very prone to ground loop current noise because of the tradition amongst video designers of using single-ended signalling and connecting the coaxial cable shields directly to their circuits' 0V references. Single-ended signalling is also commonplace in the computer industry, for example for data connections between servers, because it results in the lowest cost electronics (but not the lowest overall cost of ownership). But as well as injecting external surface current noise into the reference voltage of the most sensitive circuits as mentioned earlier, this also results in the ground potential differences between the items of equipment appearing directly in series with the DM return path of the signal. In single-ended signalling, any voltage noise in the 'ground' return has exactly the same noise effect as if it appeared in the signal conductor.

Where single-ended signalling cannot be replaced by the much better technique of balanced (differential) signalling, the techniques described earlier of connecting the shields directly to the product's reference plane (as well as to the circuit 0V, as shown in Figure 2P) and reducing the ground impedance by the MESH-CBN and PEC techniques described in [3] [6] [7] [11] [14] and [15] are very effective ways of reducing the noise whilst also helping to achieve good EMC.

Creating a low-impedance mesh-bonded ground is easy to justify and achieve for a dedicated server room, where it is often called the System Reference Potential Plane (SRPP) or 'Bonding Mat'. In the 1970s IBM's guide for ground potential differences between opposite corners of a computer room was around 1.5V, but the guides for modern server farms require a few tens of milliVolts. But mesh bonding is usually not easy to achieve in the legacy installations that many video systems have to contend with. As a result, the 75Ω video industry often finds it necessary to use devices variously called Ground-Loop Breaking, Hum-Bucking, Anti-Hum and Hum Suppressor Transformers. Some of these are CM chokes optimised to create a high CM impedance to power line frequencies, and some are 75Ω isolating transformers.

From this analysis, we see that having a great many ‘ground loops’ actually reduces the levels of power supply noise in the interconnections – providing we design our circuits so that their cable shields always connect directly to the product or equipment’s reference plane (chassis, frame, backplate, metal enclosure, etc.) as shown in Figure 2P – as they should to help achieve good EMC anyway.

2.6.9 When galvanic isolation is a requirement

Where true galvanic isolation is needed, bonding a cable’s shield at both ends is not possible. In such cases isolating transformers, infra-red, fibre-optics, wireless and free-space microwave and laser techniques should be considered instead for communicating signals of all types (analogue, control, data, etc.). There are now commercially-available products for passing up to 5 Watts of isolated electrical power over a fibre-optic link (e.g. from the Photonic Power division of JDSU, http://www.jdsu.com).

Of course, the transformers, transmitters and receivers should not degrade the EMC. Unfortunately this is not easy to achieve when using isolating transformers, because of the break they create in the shielding, and the fact that their interwinding capacitance makes an excellent path for CM currents at RF.

Where a shielded cable is used despite a requirement for galvanic isolation at powerline frequencies, it may be possible to use a capacitor to bridge across the necessary gap in the cable shield, at one or both ends or at some point along the cable (e.g. where an isolating transformer is fitted). These capacitors should be rated for the maximum voltage they will be exposed to over their life, which could be several kV due to surges and other transients, and in many cases they will need to be safety-rated (preferably safety approved) types too, possibly with limitations on their maximum value to limit leakage currents at power frequencies. But unless special coaxial or annular capacitors, or radial arrays of multiple capacitors are used – such shield-linking capacitors will degrade the RF shielding performance of the cable.

2.6.10 Intermodulation in RF connectors

Oxides formed on metal surfaces, and corrosion products formed between dissimilar metals, can cause small but non-linear impedances to arise where connectors are used in the return current paths of cable shields. Mostly, these cause problems in RF power applications such as cellphone basestations, where a number of different frequencies are transmitted from the same antenna, using coaxial cable so the return currents in the cable shield and mating connector shells are high. The result is intermodulation, generating numerous new noise frequencies from the sums and differences of the wanted frequencies. Another cause of intermodulation is the non-linear B-H curve of any magnetic materials in such connectors.

Screwed backshell connectors (e.g. N-type) are the most suitable types of connectors to use in such applications, and additional precautions include using connectors made from non-magnetic metals, white bronze or silver plated, with soldered rather than crimped connections. It is also important to ensure that the connectors used are not damaged, and are clean when assembled.

2.6.11 Checking connectors after assembly, and in the field

Bad workmanship, oxidation and corrosion can affect the shielding performance of connectors and glands. Following training in correct shield termination practices, there is a tendency for assembly personnel to revert to earlier assembly methods, causing problems for EMC compliance and increasing warranty claims due to interference incidents in real life.

However, almost all modern products and equipment include digital processing ands/or switch-mode power conversion, and as a direct result *all* of their power and signals interconnections carry CM RF noise. Leakage of this noise at badly assembled or otherwise poor connectors and glands is very easy to detect very quickly with low skill requirements using low-cost portable spectrum analysers and home-made close-field probes.

Three examples of portable spectrum analysers are shown in Figure 2AD, with the PSA1301T being the least costly at just under £800. Suitable designs for very low-cost close-field probes are given in Part 1 of [16]. I use small unshielded loop probes like those in Figure 2AD – merely a single-turn of enamelled copper wire soldered to a BNC or SMA connector – making a probe that is sensitive to both electric and magnetic fields at the same time, handy for saving time when one doesn’t know which type of field might be leaking.

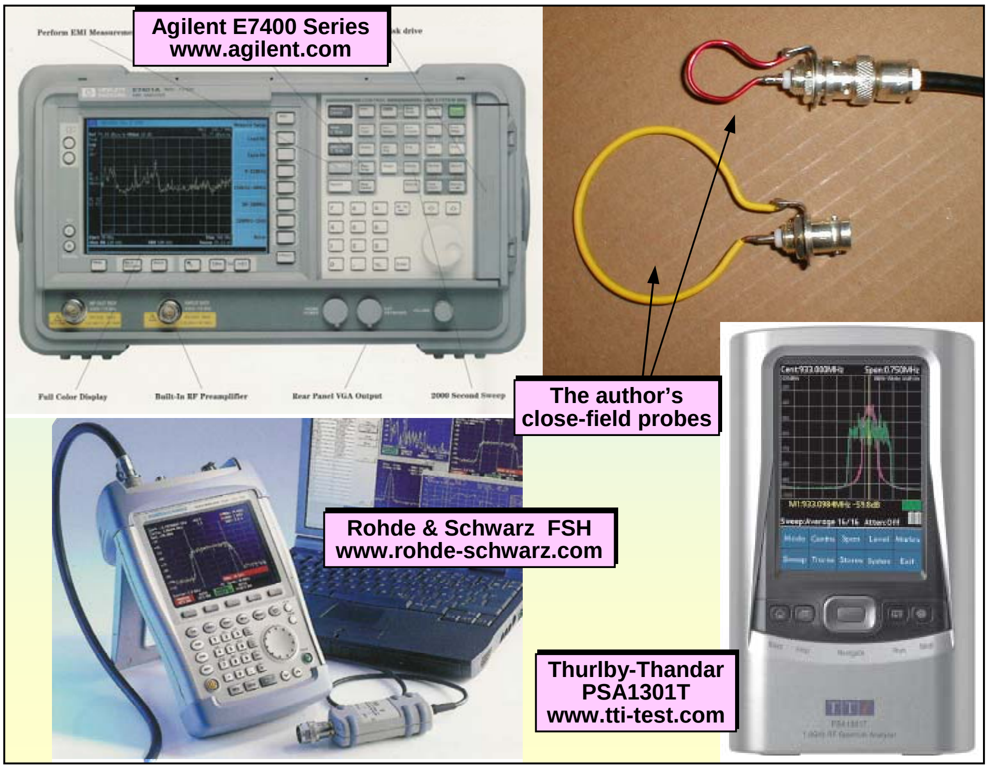

Figure 2AD Three portable spectrum analysers, two home-made close-field probes

Checking a connector or gland requires that the spectrum analyser be set to its greatest sensitivity and to repetitively scan the frequency range of the CM RF noise (where this is unknown: scan from 1MHz to1GHz). Then simply holding the close-field probe against the surface of a connector or gland will reveal any leakage within one scan of the spectrum, typically just a few seconds. Properly 360° bonded cable shields do not show any leakage at all on this test, but pigtails (for example) do.

Close-field probes are not very sensitive to ambient EM fields in their environment, but will often pick up some noise, especially when held close to the metal chassis or enclosure. So it is necessary to learn which of the noises displayed on the spectrum analyser screen are due to the ambient, and which are due to imperfect shielding – but this is not difficult.

This close-field probe test is of course a quick, crude and low-cost test for revealing gross problems, but nevertheless it is very useful indeed. It can be used to check products in serial manufacture to help maintain regulatory compliance and keep warranty costs low – and it can also be used to quickly check other workmanship aspects, such as errors in filter bonding and enclosure shielding (see Parts 3 and 4 of [1], or Parts 3 and 4 of this series). It can also be used at intervals throughout a product's life to check whether oxidation, corrosion or misuse has degraded a correctly-assembled connector or gland.

Another use for close-field probing with a portable spectrum analyser is at Goods Inward, to check the 'RF signatures' of ICs and complex sub-assemblies (such as computer cards and switch-mode power supplies). This can be a useful part of a procedure to help ensure that 'bad' or counterfeit parts do not become assembled into products – but this is outside the scope of this series.

It is of course possible to perform more searching tests on assemblies of shielded cables, connectors and glands, often using a tracking signal generator and suitable coupling device to put voltage or current noise onto a cable, and a suitable current or voltage probe connected to a spectrum analyser to analyse the shielding performance more accurately, and with better rejection of ambient noise.

2.7 Transmission line interconnections

2.7.1 What are they?

The send/return current loops of all types of conductors have a 'characteristic impedance', which we call Z_0. This is determined by the stray inductances (partial and mutual) and stray capacitances in the conductors, according (approximately) to the following equation –

$$Z_0 = \sqrt{\frac{L}{C}}$$

where: C = capacitance per unit length (e.g. F/m), and L = inductance per unit length (e.g. H/m)

The stray inductances and capacitances associated with a conductor depend upon the geometry of the metal structures carrying the send and return current paths; the relative permittivity (i.e. dielectric constant) and relative permeability of the medium filling the space around the conductors, and their proximity to other conductors or conductive objects or surfaces.

In normal wiring, cables and connectors, the stray inductances and capacitances are not intentionally controlled, so their Z_0 will vary from point to point along the interconnection. RF signals and noises experience reflections whenever Z_0 changes, resulting in worsened SI (e.g. eye patterns more closed), increased emissions and increased pick-up of noise from external E, H and EM fields. When the distance between two Z_0 changes is a quarter or half a wavelength (depending on the type of Z_0 change at each end) that portion of the interconnect becomes resonant, and the resonant gain significantly amplifies the effects on SI, emissions and immunity. The largest impedance changes usually occur at the ends of the conductor, where there is a large mismatch between the conductor's Z_0 and the impedances of the source and/or the load, making the whole length of the cable resonate. Knowing this can help during EMC fault-finding, as it can allow the peak emissions or worst immunity frequencies to be related to cable length, to help identify which cable is causing the problem.

But when the Z_0 of an interconnection is controlled so that it remains closer to the same value all along its length, right from the source to the load, then the effects on SI, emissions and immunity are reduced. This is called 'controlled-impedance transmission line design' and it has many benefits for SI and EMC. It is important to note that a controlled-impedance transmission line requires the impedance of the signal or noise source to be a close match with the characteristic impedance of the interconnecting cable, and also with the impedance of the load. All joints and connectors along the path must also have a closely-matched characteristic impedance.

A well-matched transmission-line exhibits minimal resonance effects, avoiding the resonant gain at particular frequencies that causes 'accidental antenna' problems for all other types of conductive interconnection. Transmission lines can use unshielded or shielded cables, but the shielded types (ideally shielded twisted pairs) generally provide significantly better EM performance for both emissions and immunity.

Some cable construction topologies are more vulnerable than others to suffering changes in Z_0 along their length when they are bent at too sharp an angle, squashed, or run close to metal objects.

2.7.2 Why and when are matched transmission lines needed?

Where Z_0 varies along a line, or when the source or load impedances don't match Z_0, the forward propagating electromagnetic energy (which is what all signals and power really are) suffers from reflections. Reflections create an undesirable backwards-propagating wave, and when the cable length is some integer multiple of the wavelength this results in resonance, manifested as 'standing waves' on the line. Resonant amplification of the currents and voltages cause the EMC performance to be very much worse at the resonant frequencies

Oscilloscopes show that reflections create overshoot, undershoot and other waveform distortions which can cause mis-operation of digital circuits, for example double-clocking. Network analysers show that they create a non-flat frequency response (some frequencies attenuated, others amplified).

From an EMC point of view, resonances and standing waves make conductors behave like efficient antennas, increasing emissions. Such unintentional antennas are also good at picking up EM fields in their environment and converting them into conducted noise in the signals they carry, worsening immunity.

When a conductor length is shorter than one-seventh of the wavelength at the highest frequency of concern, it is said to be 'electrically short' and Z_0 is generally not considered to be important for SI reasons. For example, imagine that a digital signal repeating at 20MHz needs harmonics up to its 5th (100MHz) to be square enough for circuit functionality, so the higher harmonics are filtered out to prevent them causing problems for SI and EMC. At 100MHz the wavelength in air is $3.10^8/100.10^6$ = 3 metres, but because the dielectric constant of cable insulation increases capacitance per unit length it slows the velocity of propagation, so 2 metres is a more realistic estimate for one wavelength of 100MHz in a cable. One-seventh of this is 285mm, so cables longer than this are 'electrically long' for this 20MHz digital signal and should use matched transmission line techniques to maintain a sufficiently accurate waveform for SI.

But the 'one-seventh of the wavelength at the highest frequency of concern' guideline still results in conductors that are relatively efficient accidental antennae at 100MHz, as shown by Figure 2C. For good EMC, matched transmission-line techniques should be used for cables longer than about $^1/_{28}$ of the wavelength (71mm in the above example) – maybe even shorter, depending on the EMC performance required.

Digital circuit designers tend to work in the time domain rather than the frequency domain, so their version of the above 'one-seventh of the wavelength at the highest frequency of concern' guideline is to say that a conductor is 'electrically long' when the time that the signal edges take to travel from its source to its furthest receiver exceeds half of its rise or fall time (whichever is the shorter). Some SI experts (e.g. Dr Howard

Johnson) use a one-third of the rise or fall time instead. As above, these half or third rise/fall time guides are only for SI – for good EMC matched transmission-line techniques should be used for cables with propagation times longer than about ⅛ of the rise or fall time – maybe even shorter, depending on the EMC performance required.

But these guides based on rise/fall times can lead to problems if their assumptions are not understood. For example, the rise or fall times used should be the *real* values, not databook specifications. Device data only gives rise/fall times as *maximum* values; so that the semiconductor manufacturers can shrink their silicon dies whenever a new silicon chip manufacturing process becomes cost-effective. Shrunk silicon devices switch faster, but because the databooks only publish maximum values, they are not reissued, giving a false idea about the switching speeds likely to be met in practice.

For instance, when HCMOS devices first became available in the 1980s, their switching speed was around 5ns, and SI and EMC problems above 60MHz were rare. But purchasing HCMOS devices with the same part numbers and package styles as in the 1980s now gets you a very much smaller silicon die, which can have SI and EMC problems up to at least 800MHz, implying rise/fall times of around 0.4ns.

So when using rise/fall time based rules for deciding whether matched transmission line techniques are required, we need to know the real-life rise/fall times – measured with oscilloscopes and probes that have a combined bandwidth of at least 5GHz. Alternatively, measure the noise created by the IC up to the highest frequency of concern using a spectrum analyser and tiny close-field probe, and use the wavelength-based guidelines instead.

Another assumption in the rise/fall time based guides is that the propagation time of the cable can be had from the cable's velocity factor data – but this is only true for point-to-point interconnections. Where a cable supplies multiple devices along its length, the capacitive loading of the connectors and device inputs slows the velocity of propagation along the cable below what is achieved by the cable alone.

2.7.3 Matching transmission lines

'Matching' means that the termination resistance at the end of the transmission line equals the transmission-line's Z_0. When choosing matching resistor values, the effects of the internal impedances of the source and load devices must be taken into account.

Classical or 'both-ends' transmission-line matching

Matched resistances terminate classical transmission lines at both ends – the signal's source and its final load – as shown in Figure 2AE. This is an ideal and sometimes necessary technique, and is often used for long cables between products, and for RF signals inside products.

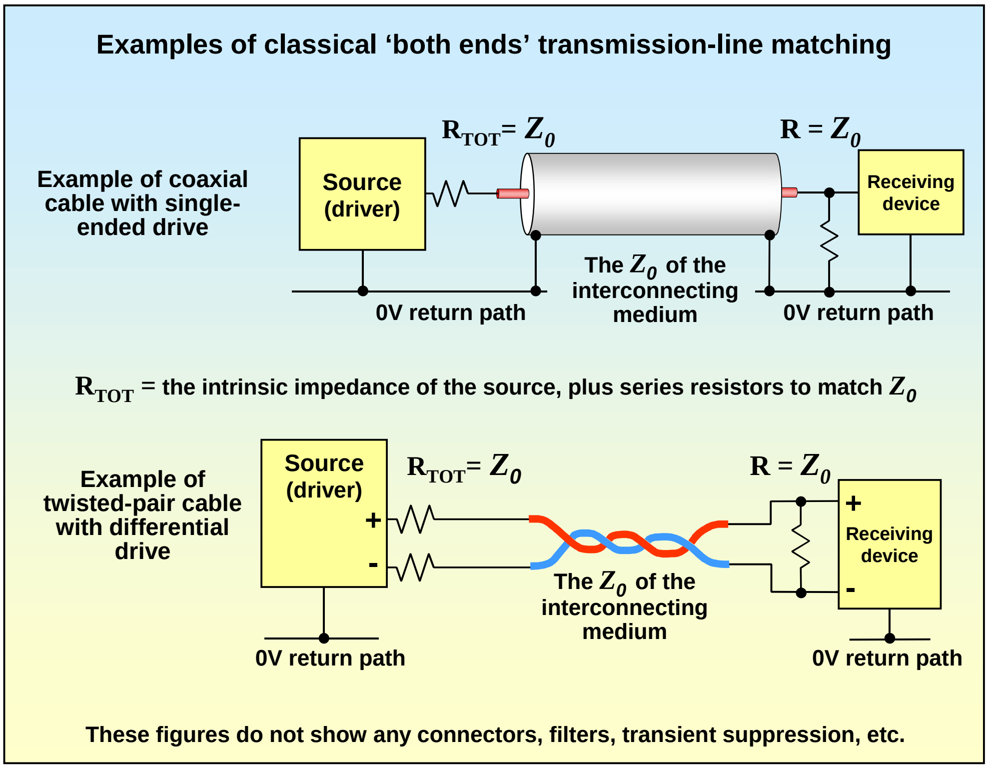

Figure 2AE Classical transmission-line matching examples

But classical matching halves the received voltage, so has not generally been used in the past for digital circuits communicating within a product, to save the cost of the extra amplification that would be needed. However, the present trend for replacing parallel busses with asynchronous serial interconnections operating at high speed is making classical termination more commonplace. Some LVDS receivers have high sensitivity, so function quite happily with signal voltages halved by classical line matching.It can be difficult to achieve accurate line matching at the driver end, when using drivers whose source impedance varies between their high and low output states, as ordinary TTL and CMOS 'glue logic' devices do. Accurate line matching, hence good SI and improved EMC, requires drivers that are designed for transmission-line driving, with low-impedance outputs (lower than Z_0) that are the same whether driving high or low.

Series and shunt transmission-line matching

To avoid losing half the signal voltage by using classical transmission-line matching, most digital signals communicated within the same product with TTL or CMOS devices use low-impedance drivers and high-impedance loads, with the transmission line terminated in a matching resistor at one end only. Two basic methods are available, called 'series' and 'shunt', each of them using just one of the end terminations of the classical termination method described above.

Series (source) termination uses a matched resistor at the driver's end only, as shown in Figure 2AF. Signals launched into the line by the driver are attenuated by the series resistor and propagate down the line at 50% of their amplitude. Eventually they are reflected in-phase at the mismatched high-impedance load, and the reflected signal then propagates back down the line, adding to the incoming signal along the way, creating the desired 100% amplitude as it does so. When the reflected signal edge reaches the matching resistor at the source it is fully absorbed by the matched series resistor, so no further reflections occur. This reliance on signal reflection at the load to create 100% amplitude is why this technique is also known as 'reflected wave switching'.

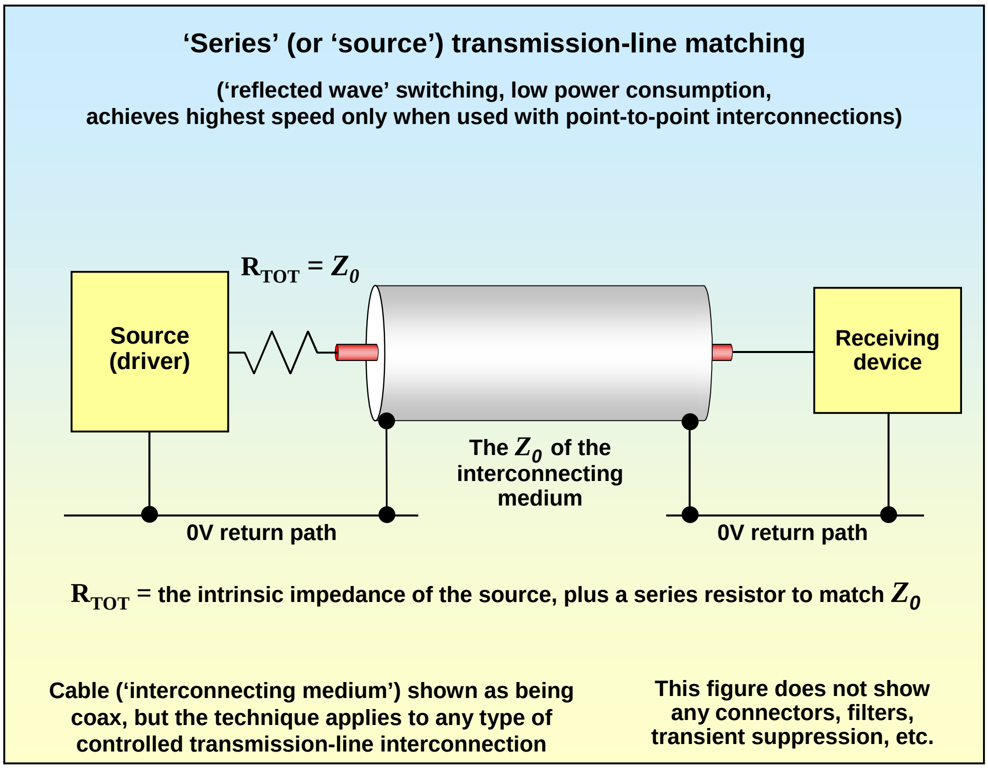

Figure 2AF Series or source transmission-line matching

Series termination is most suitable for lines with a single load device at their far end, often called point-to-point interconnections. Where other loads exist along the length of the line they experience 'reflected wave switching' as the forward wave going past at 50% amplitude, followed a little while later by the reflected wave reaching them at 100% amplitude. The response of devices along a series-terminated line might need to be slowed to prevent double clocking.

Series termination consumes very little power, and (as for classical termination above) accurate line matching (hence good SI and improved EMC) requires drivers that provide low-impedance outputs that are the same impedance whether driving high or low.

Parallel (shunt, or load) termination uses a matched resistor at the furthest receiver. The mismatch at the source might result in a little higher dissipation in the driver, but the signal is launched into the transmission line with 100% amplitude. There are no reflections from the load because it is impedance-matched, so it achieves what is called 'incident wave switching'. It is most often used where high data rate is important and there are a number of receivers spread along the length of the transmission line.

Figure 2AG shows the matching resistor connected to the 0V plane, but some logic families use other reference voltages (e.g. ECL uses the positive supply rail). Problems with parallel termination include high dissipation in the load resistors, and a driver DC current requirement that might be too high for some drivers.

Figure 2AG also shows RC termination – an attempt to reduce shunt termination's power dissipation and DC loading problems. It typically uses capacitor values between 10 and 620pF, and only matches the line at high frequencies (e.g. when a digital signal is changing state). Some care is needed to choose the correct capacitance value, which will depend upon the length of the transmission line and type of data expected. The RC time constant must be greater than twice the propagation delay of the loaded transmission line. And to achieve power dissipation savings when compared with plain resistive shunt termination, the RC time constant must be shorter than the data period.

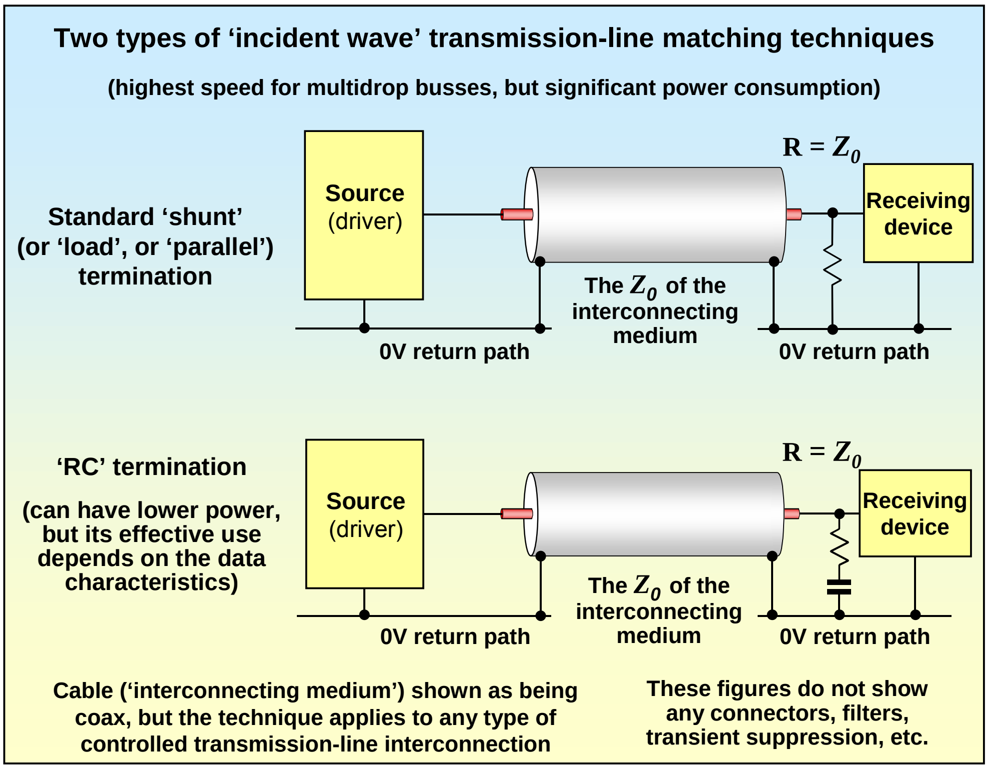

Figure 2AG Shunt, parallel or load transmission-transmission-line matching

Thévenin transmission-line matching

An alternative type of shunt line termination is called 'Thévenin', shown in Figure 2AH, with the aim of reducing power consumption and the DC loading on the driver. It uses resistor values designed so that their parallel resistance equals Z_0, and also so that if disconnected from the line they would provide a DC voltage at their junction equal to the average line voltage of the data, to minimise power dissipation and the DC current loading in the driver. Another design issue is that when undriven (e.g. a tristated driver, or a broken or disconnected line) the receiver's input should have a defined voltage that is either a logic 0 or 1 – unfortunately this often prevents the achievement of minimum power dissipation.

Thévenin termination is very useful for 'weak' drivers (such as ordinary TTL or CMOS glue logic), and for long lines, as it helps them achieve good switching waveforms at the receiver. Note that the positive power rail requires a very low impedance at the highest frequency of concern, so will probably need to have a power decoupling capacitor nearby, at least (not shown in Figure 2AH).

Proprietary Thévenin and RC termination devices are available from a number of component manufacturers (e.g. California Micro Devices) usually as arrays of 8 or more in very small surface mount packages which have good characteristics to over 1GHz.

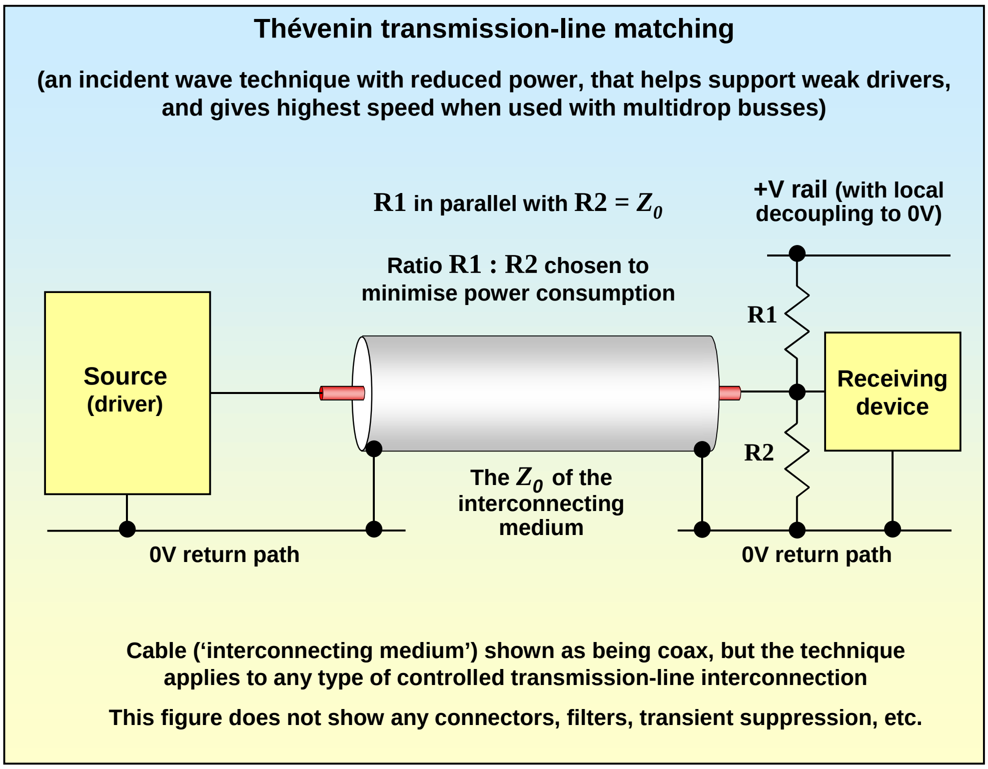

Figure 2AH Thévenin transmission-line matching

Active transmission-line matching

'Active termination' is a shunt termination method that connects the matching resistor to a bias voltage, instead of to the 0V plane. At the point where a matching resistor connects to the bias voltage rail, the impedance at the highest frequency of concern must be very low. The bias voltage source must be able to source as well as sink current.

The main aim is to set the bias voltage to the average value of the digital signals, to minimise power consumption and/or suit the line to the pull-up and pull-down currents available from the driver. But (as for Thévenin line-matching above) it may be necessary to set the bias to a different voltage so that if the line becomes undriven (e.g. a tristated driver or a broken or disconnected line) the receiver's input has a defined voltage that is either a logic 0 or 1 – but this can prevent the achievement of minimum power dissipation.

Active line matching is a different way of achieving Thévenin termination, and so is very useful for 'weak' drivers (such as ordinary TTL or CMOS glue logic), and for long lines, as it helps them achieve good switching waveforms at the receiver. But it can reduce the power consumption below that of the electrically equivalent Thévenin method, if the bias voltage generator operates in Class AB mode, so that it only consumes maximum currents when needed.

'Diode termination'

This is not a transmission-line matching technique at all, but is mentioned here to avoid confusion. It helps to prevent device damage or latch-up due to signal overshoots or undershoots that go beyond the power rails. It also helps prevent damage due to transient disturbances such as ESD or fast transient bursts. However, it has little if any other benefits for SI, and no benefits for EMC.

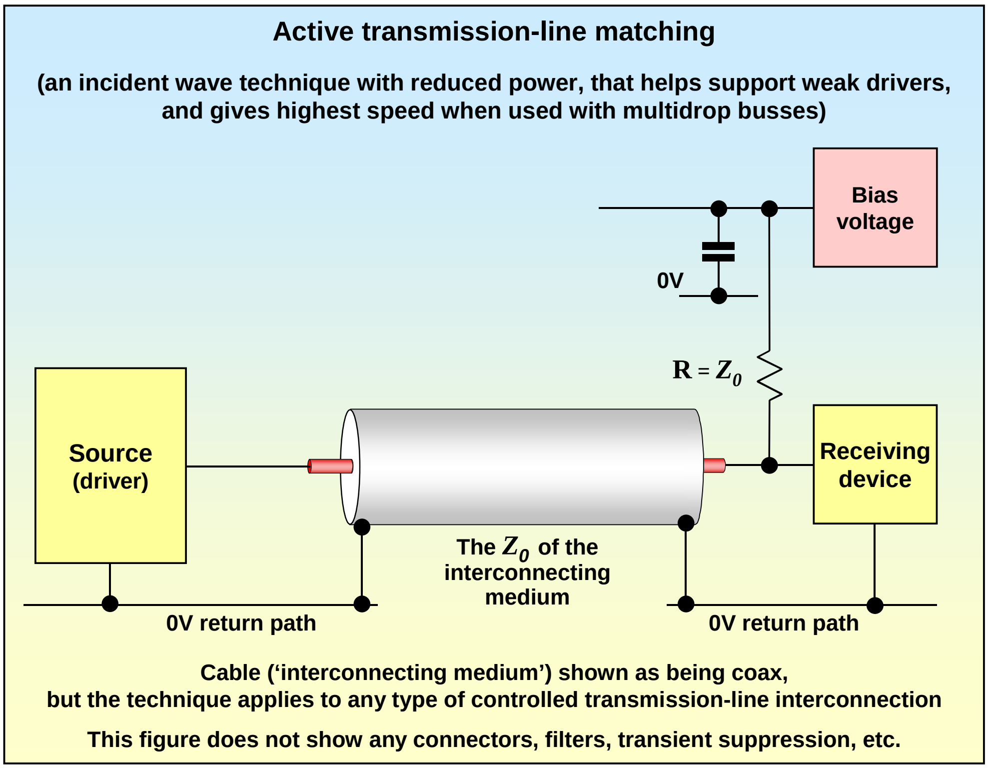

Figure 2AJ Active transmission-line matching

2.7.4 Matching the characteristic impedances of differential (balanced) lines

Differential transmission lines are being used a great deal more these days for high-speed clocks and data, for SI reasons, but they can also help achieve good EMC. They use two conductors to carry antiphase signals, and might also have a common reference conductor, such as a third conductor in the cable or a shield.

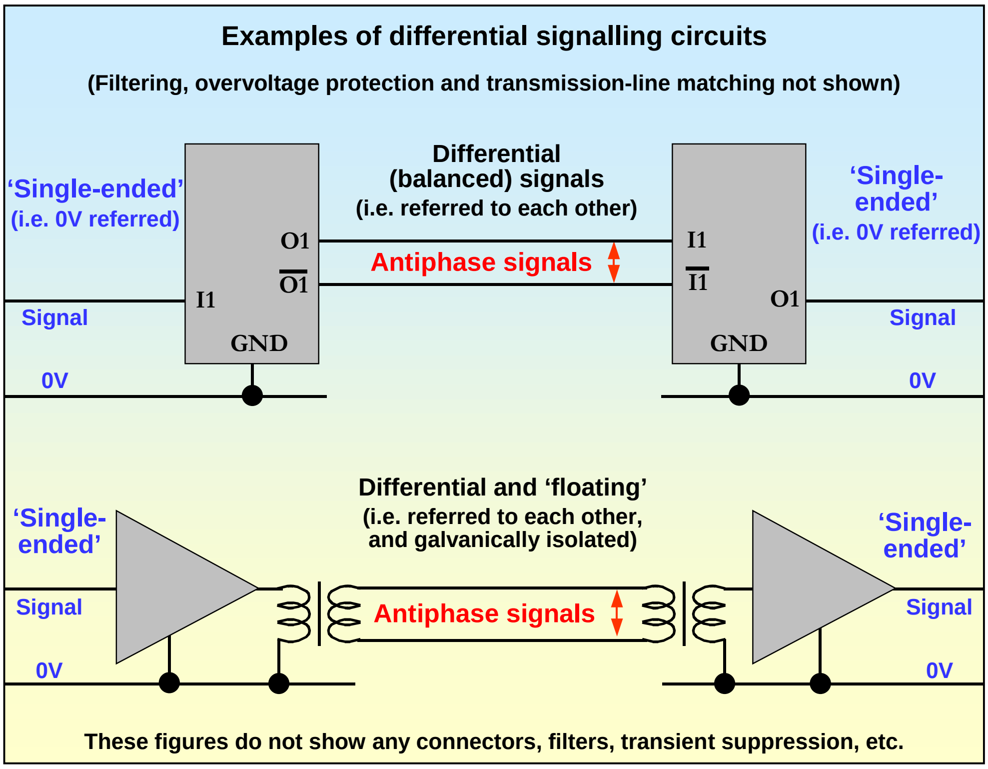

Figure 2AK Some examples of differential transmission lines

But differential transmission lines have several different Z_0s:

- The Z_0 of each conductor when driven individually with respect to the reference conductor
- Their balanced Z_0 when both conductors are driven with DM signals (pure antiphase signals)

- Their CM Z_0 when both conductors are driven together, with CM signals (with respect to the reference conductor)

Real differential drivers never have perfectly balanced output signals, so all the above three modes experience signals. For SI, it is usually sufficient to match the impedance of the balanced Z_0, but to help improve EMC each one should be terminated correctly so that none of the modes can experience standing wave resonances.

It is common to find differential transmission lines for which only the DM Z_0 is matched, often because there is no common reference connection between the source and receive ends, for example Ethernet using unshielded twisted pair (UTP) cable. Such transmission lines usually need CM chokes at their source to reduce their CM currents and improve their EMC performance.

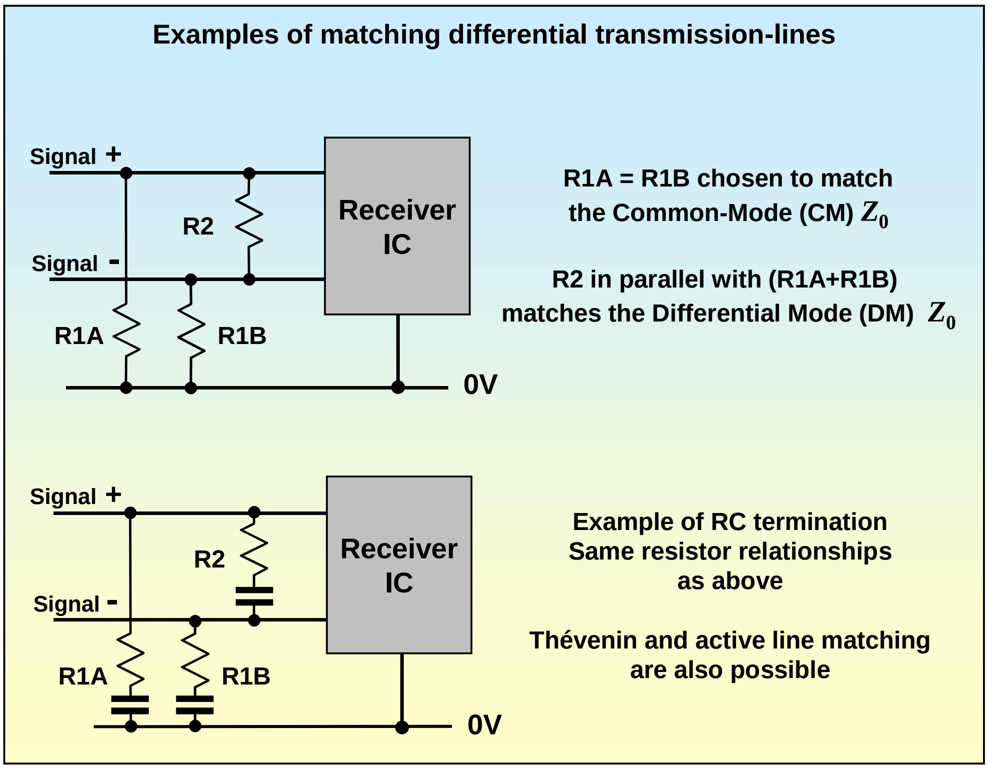

Figure 2AL Some examples of differential line matching

2.7.5 Matching resistors must be resistive at the highest frequency of concern

Transmission-line matching resistors must behave resistively up to the highest frequency of concern, which may need to be a higher frequency for EMC reasons than for SI. Cable terminators use resistors integrated into the bodies of controlled-impedance connectors, so they can easily be plugged into a cable connector. They are fitted internally with the correct value of resistor, using a resistor type and assembly method that matches the impedance of the transmission line from DC up to a frequency specified by their manufacturer. Some cable terminators can handle high power dissipations, using high-power resistors and finned heatsinks.

When terminating transmission lines with resistors mounted on PCBs, there are a number of design issues to be taken into account. Leaded resistors suffer from the inductance of their leads and the stray capacitance of their end-caps, often limiting them to frequencies below 100MHz. Surface mount resistors (but not MELF types) are much better, and providing the PCB trace routing is done well (see Part 5 of [1], or Part 5 of this series) even ordinary low-cost types can match a transmission line to over 1GHz.

Resistors in smaller surface-mounted package styles will generally have better performance at higher frequencies than large ones (e.g. 0603 will be better than 0805), and arrays of resistors in small surface mount packages are available from a number of suppliers to help save space on PCBs. At microwave frequencies above a few GHz, RF resistors in controlled-impedance packages and/or special assembly techniques may be needed.

Some PCB suppliers can provides embedded terminating resistors, created by selectively etching a layer of resistive material laminated inside the PCB.

2.7.6 Impedance matched transmission-line connectors

Connectors used with transmission-line cables must have a Z_0 that matches the Z_0 of the cable they are to be used with, otherwise the resulting impedance discontinuity can cause reflections leading to resonances and standing waves along the cable, hence poor EMC and possibly also degraded SI.

Impedance-matched connectors are common in RF applications, and we are all familiar with coaxial types such as the 50Ω BNC. Shielded transmission-line cables and connectors will generally be better for EMC, even within a product where they help improve SI by reducing crosstalk, and also help avoid the need for enclosure shielding/filtering, or at least save cost by reducing their specifications.

Don't forget that, as mentioned earlier, connectors of apparently the same type but with a choice of Z_0s might look identical, but their different Z_0s mean they have different internal dimensions. So when using a given type of connector it is important not to mix Z_0s, because this can cause problems with contact reliability, or even actual damage to their pins.

2.8 References:

[1] Keith Armstrong, "*Design Techniques for EMC*", UK EMC Journal, a 6-part series published bimonthly over the period February – December 1999. An improved version of this original series is available via the "Publications & Downloads" page at http://www.cherryclough.com

[2] "*EMC for Functional Safety*", The IET, 2008, a 180-page practical guide suitable for all industries and applications, available for free download from www.theiet.org/factfiles/emc/index.cfm or as a colour printed book for £27 from: http://www.emcacademy.org/books.asp

[3] The articles in the "*EMC for Pro-Audio*" section of the "Publications & Downloads" page at http://www.cherryclough.com

[4] Keith Armstrong, "*Assessing an EM Environment*", includes informative tables, an example of an initial questionnaire, guidance and useful references, available via the "Publications & Downloads" page at http://www.cherryclough.com

[5] Keith Armstrong, "*EMC for Printed Circuit Boards – Basic and Advanced Design and Layout Techniques*", February 2007, www.emcacademy.org/books.asp, £47 plus p&p, perfect bound: ISBN 978-0-9555118-1-3, spiral bound (lays flat): ISBN 978-0-9555118-0-6

[6] Keith Armstrong, "*EMC for Systems and Installations*", a 6-part series published in the EMC+Compliance Journal, January-December 2000, also available via the "Publications & Downloads" page at http://www.cherryclough.com

[7] Tim Williams and Keith Armstrong, "*EMC for Systems and Installations"*, Newnes 2000, ISBN 0 7506 4167 3, www.newnespress.com, RS Components Part No. 377-6463.

[8] Skin Depth formula and material properties:
http://www.rfcafe.com/references/_spreadsheets/skin_depth_calc_ss.htm

[9] Lothar O (Bud) Hoeft, "*Analysis of Electromagnetic Shielding of Cables and Connectors (keeping currents/voltages where they belong)*", 2002 IEEE International Symposium on EMC, Minneapolis,

www.emcinfo.se/ieee/protokoll/ 34/EMag_Shielding_of_Cables_and_Connectors

[10] John R Barnes, "*Robust Electronic Design Reference Book, Volume I*", Kluwer Academic Publishers, 2004, ISBN: 1-4020-7737-8

[11] IEC 61000-5-2:1997 "*Electromagnetic Compatibility (EMC) – Part 5: Installation and Mitigation Guidelines – Section 2: Earthing and Cabling*", http://www.iec.ch

[12] R H Entwistle, "*Practical Experience of EMC Engineering in Avionics*",

[13] Keith Armstrong, "*Design Techniques for EMC, Part 0 – Introduction and Part 1 – Circuit Design and Choice of Components*", The EMC Journal, January 2006 pp 29-41, plus March 20906 pp 30-37.

[14] Tony Waldron and Keith Armstrong, "*Bonding Cable Shields at Both Ends to Reduce Noise*" EMC + Compliance Journal, May 2002, pages 14-27, available from the "Publications & Downloads" page at http://www.cherryclough.com

[15] Keith Armstrong, "*The Benefits of Applying IEC 61000-5-2 to Cable Screen Bonding and Earthing*", IEE seminar: "EMC – its nearly all about the cabling", Savoy Place, London, U.K., January 22nd 2003. The same paper was repeated by invitation at Euro-EMC 2004 in Eindhoven, The Netherlands. Available from the "Publications & Downloads" page at http://www.cherryclough.com

[16] Tim Williams and Keith Armstrong, "*EMC Testing*", a 7-part series published in the February 2001 – March 2002, available via the "Publications & Downloads" page at http://www.cherryclough.com

2.9 Acknowledgements

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