Design Techniques for EMC Part 2 - Cables and Connectors (first half of part 2)

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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.

2. Part 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.

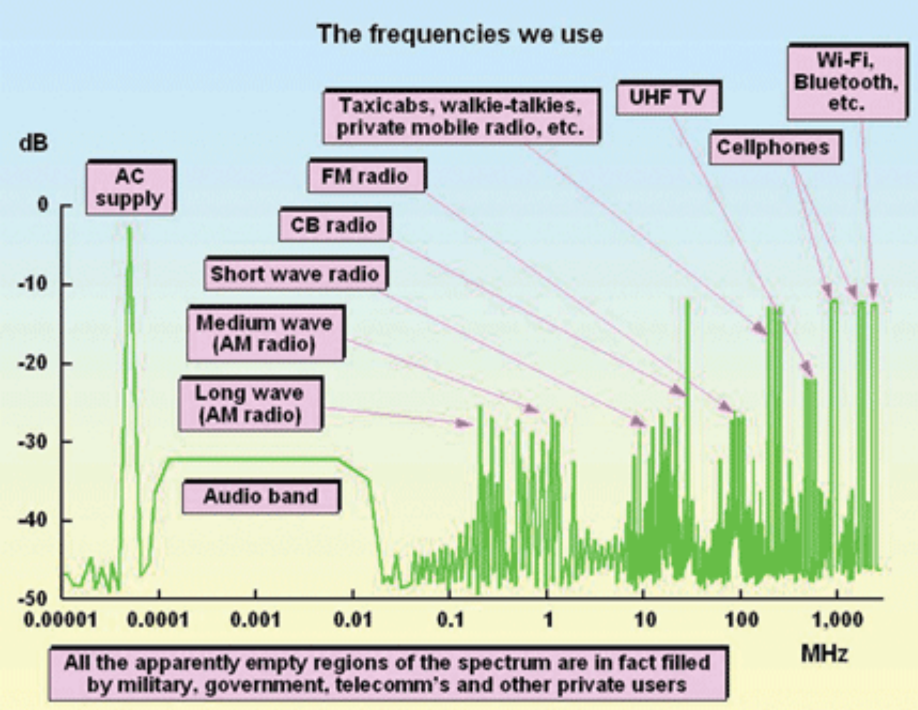

Figure 2A The frequencies we use

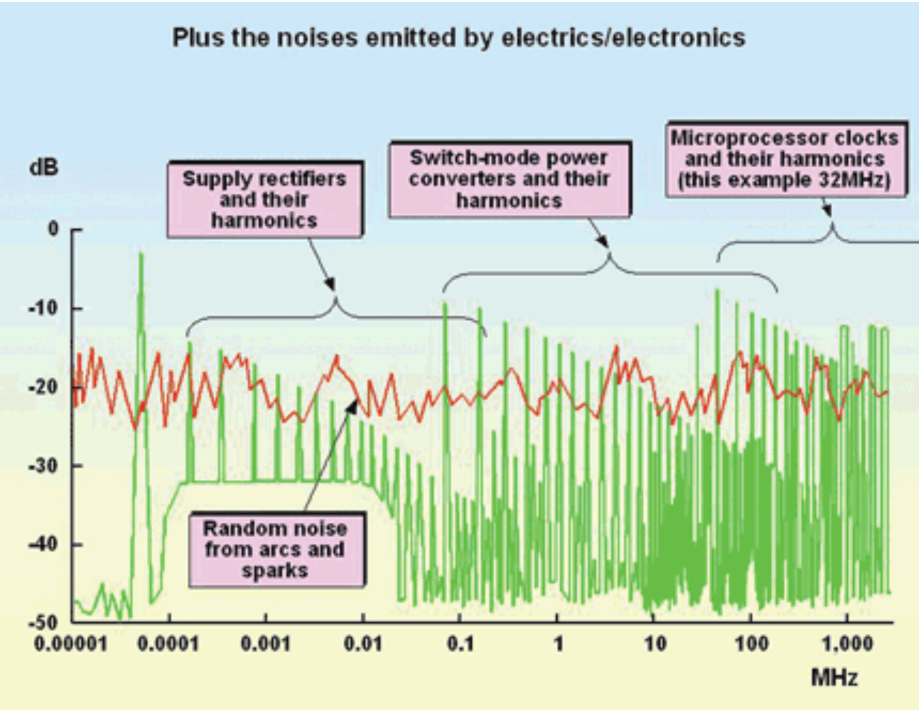

Figure 2B The noises emitted by electrical and electronic devices

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 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.

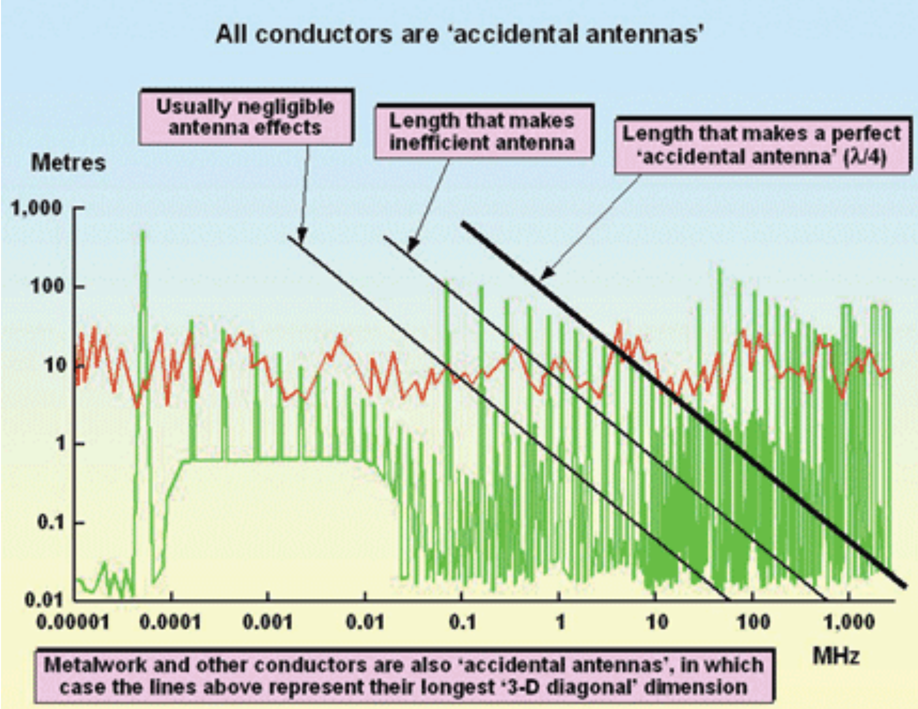

Figure 2C The 'accidental antenna' behaviour of typical conductors

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.

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 $\lambda/6$, λ being the wavelength). 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 1940's, 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 and 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.

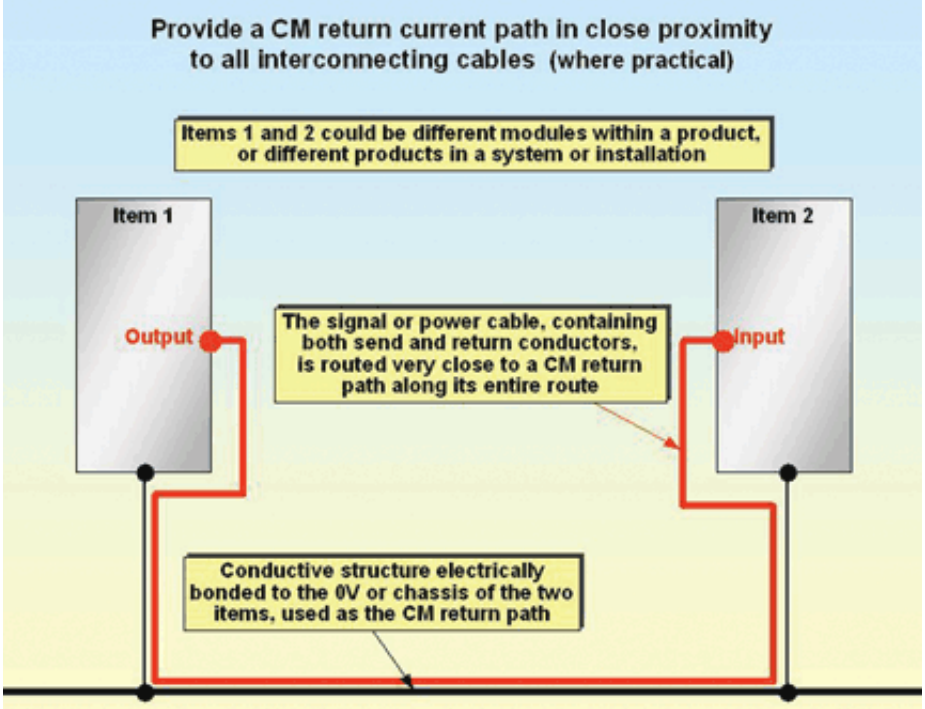

Figure 2D Provide a CM return current path in close proximity to all interconnecting cables

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.

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 2D.

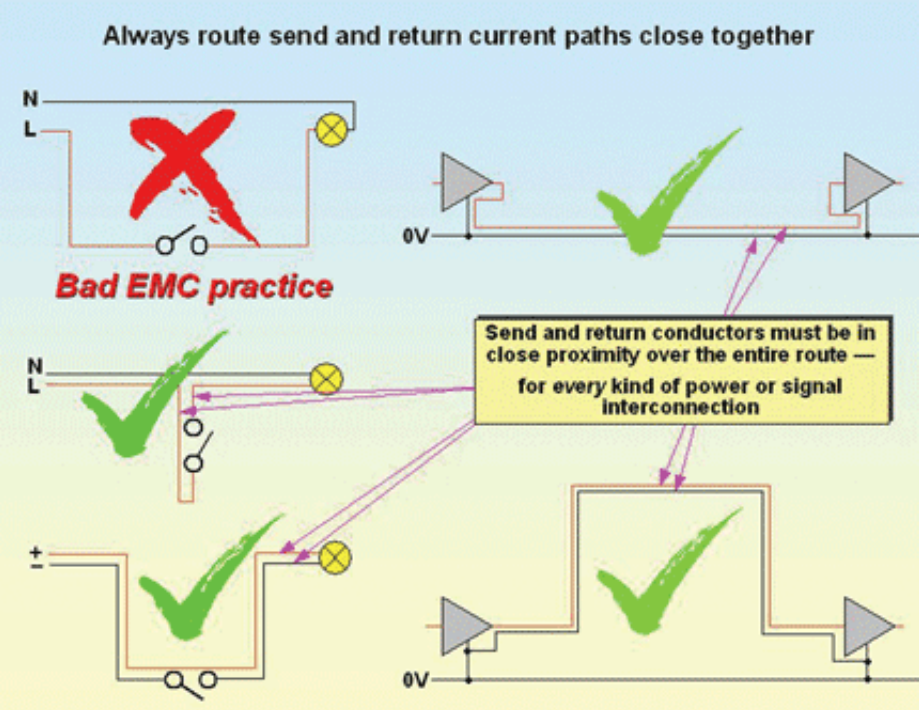

Figure 2E Always provide a return current path physically close to the send path

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.

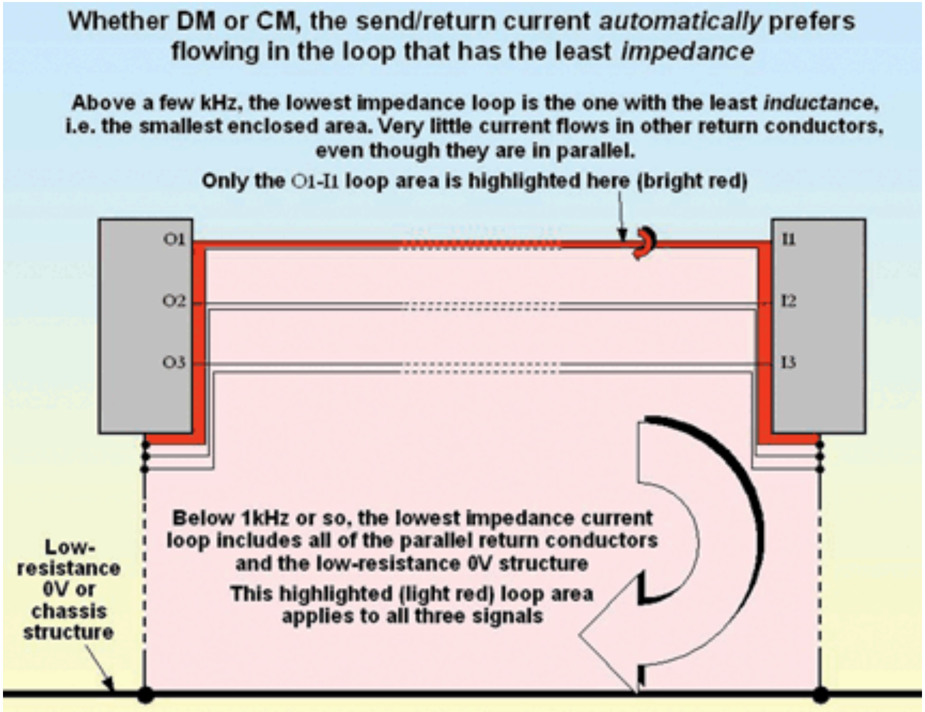

Figure 2F The send/return current automatically flows in the loop that has the least impedance

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.

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 1æT. 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.

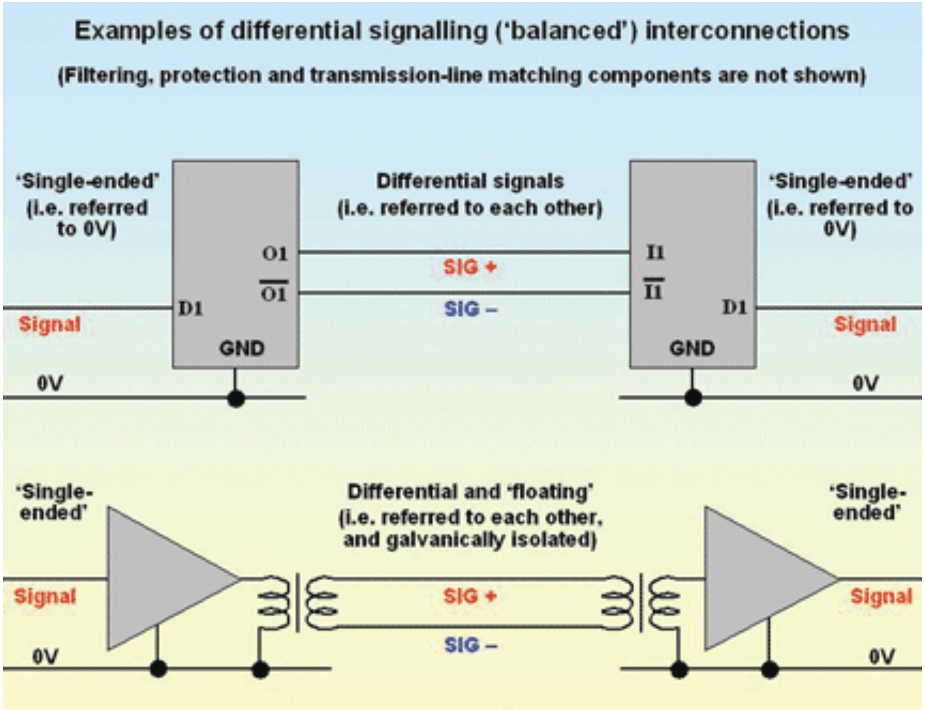

Figure 2G Examples of differential signalling ('balanced') interconnections

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.

>p>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).

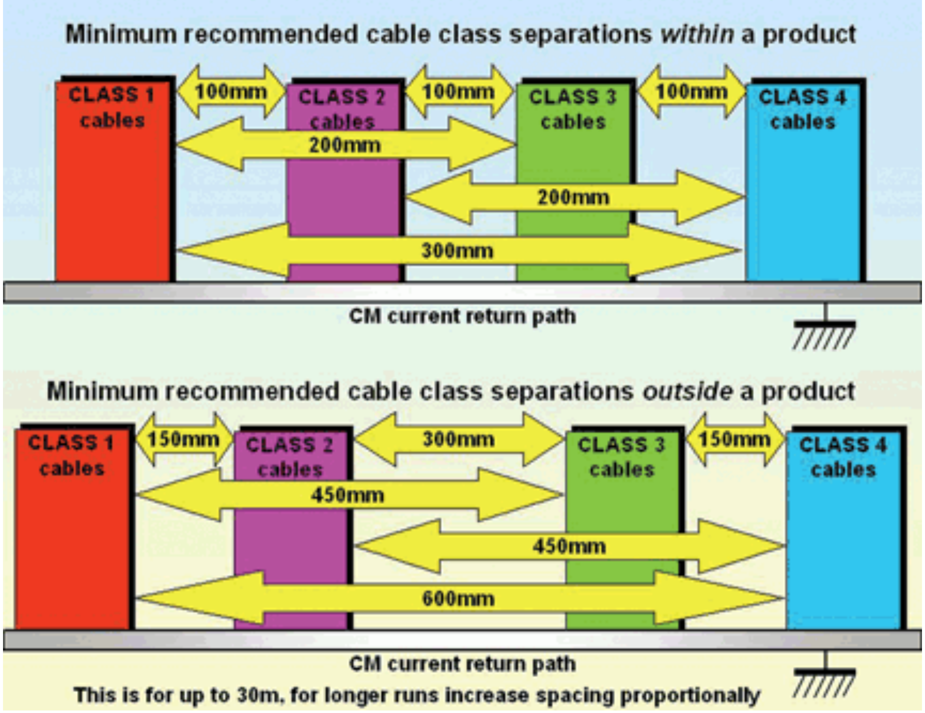

Figure 2H Minimum recommended cable class separations

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^{o} 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].

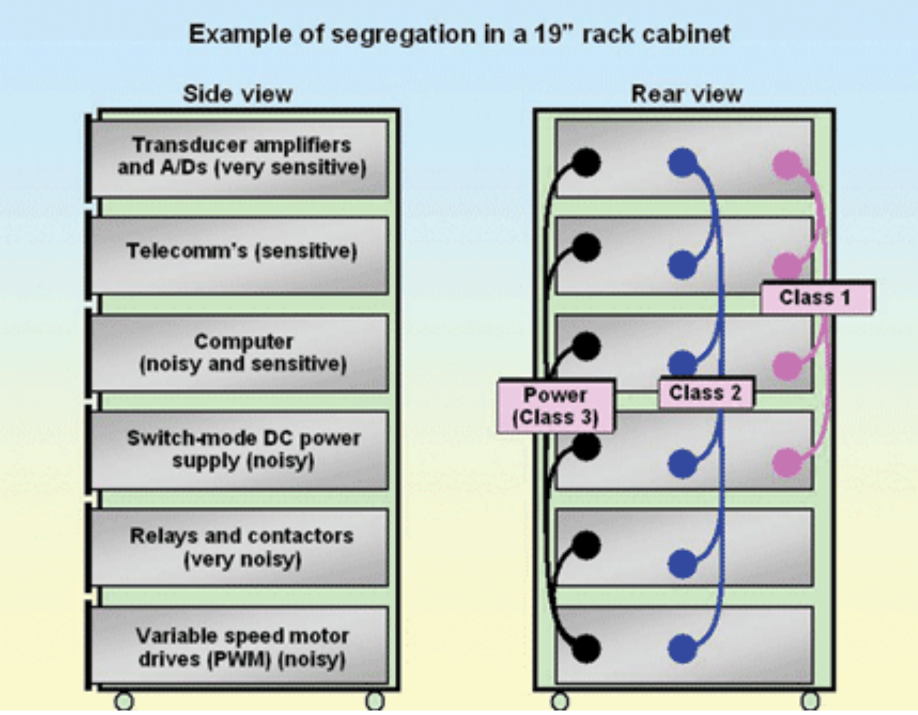

Figure 2J Example of segregation in a 19" rack cabinet

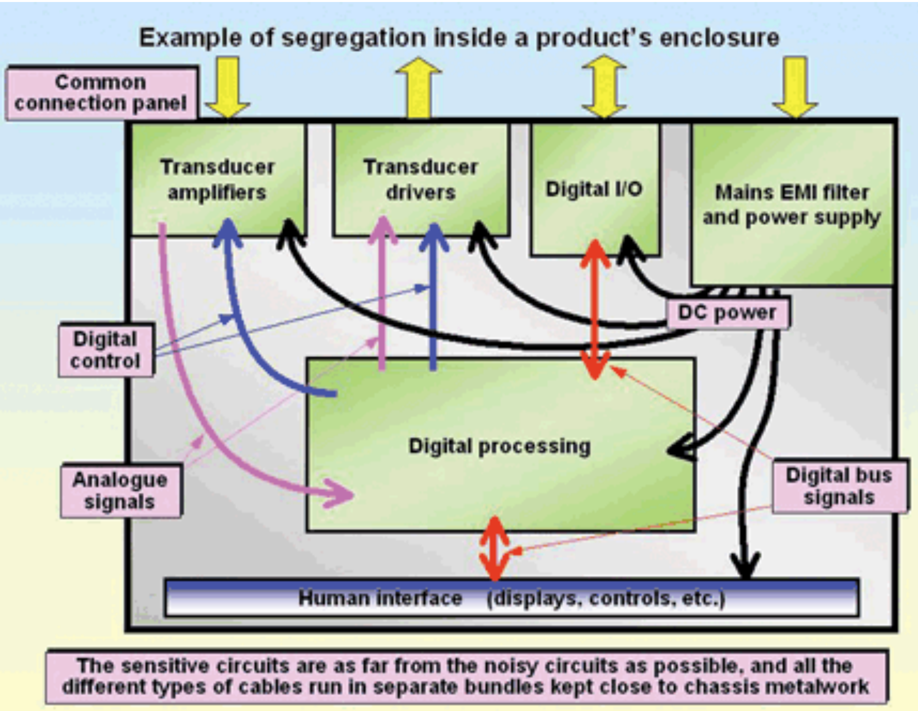

Figure 2K Example of segregation inside a product's enclosure

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.

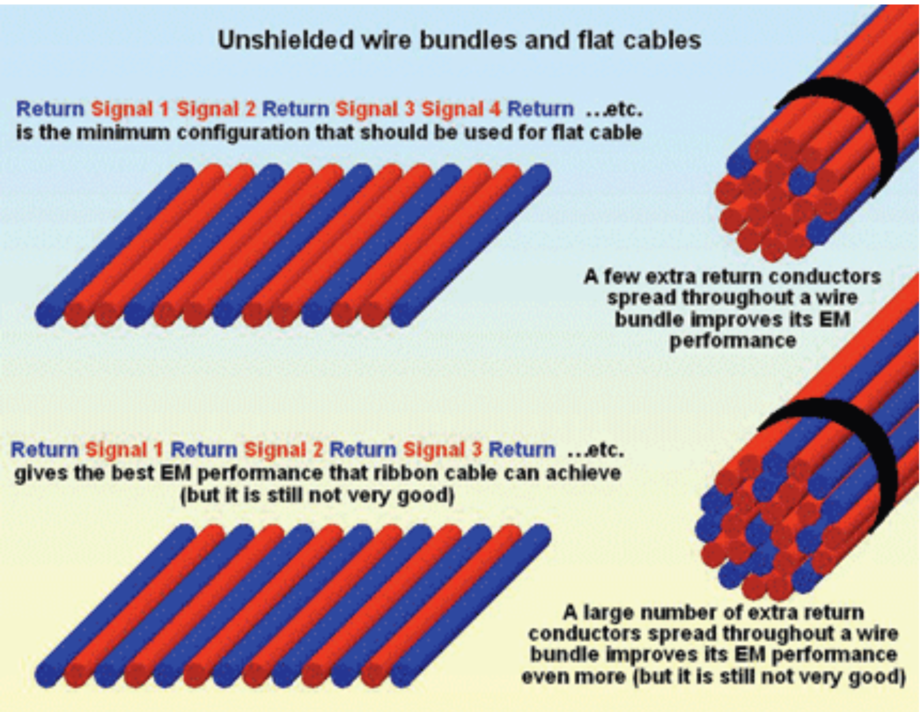

Figure 2L Improving wire bundles and flat cables

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.

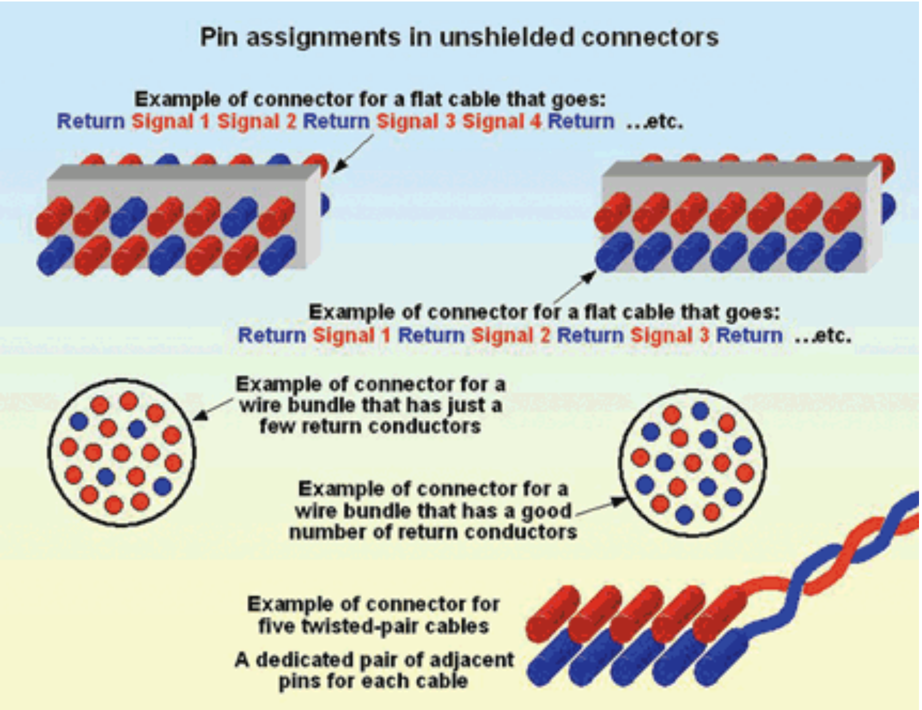

Figure 2M Pin assignments in unshielded connectors

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.

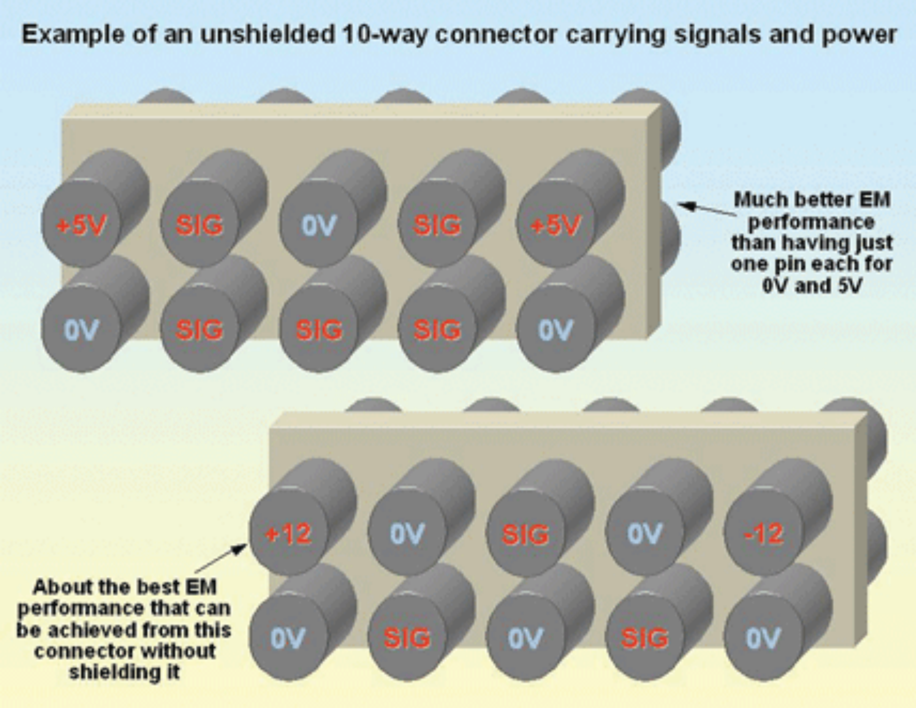

Figure 2N Example of an unshielded 10-way connector carrying signals and power

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 1W 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^{o} shield coverage along their entire length, including at all connectors, glands or joints. The phrase: "360^{o} 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^{o} shield coverage 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 its 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^{o} shield bonding, and it applies between a cable shield and connector shield, the shields of two mating connectors, and also 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^{o} 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 the foil shield is 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 neighbour. In a braid and foil shielded cable, it is best if the braid is on the metallised side of the plastic foil, because this connects the foil's turns to each other better.

All flexible shielded cables have 'leakage' problems because they don't use a solid metal shield. The imperfections in flexible shields have associated stray capacitance and stray inductance, and it is possible to 'optimise' a braid so that these effects cancel out to some extent.

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*.

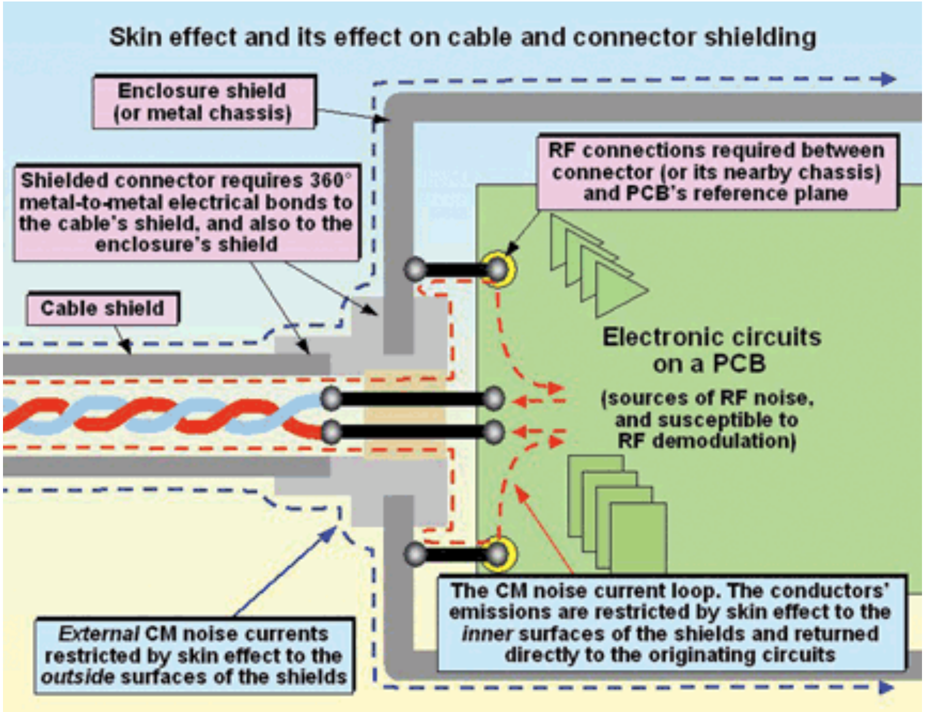

Figure 2P Skin effect and its effect on cable and connector shielding

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 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 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^{o} electrical bond between the PCB connectors and the PC's enclosure shield.

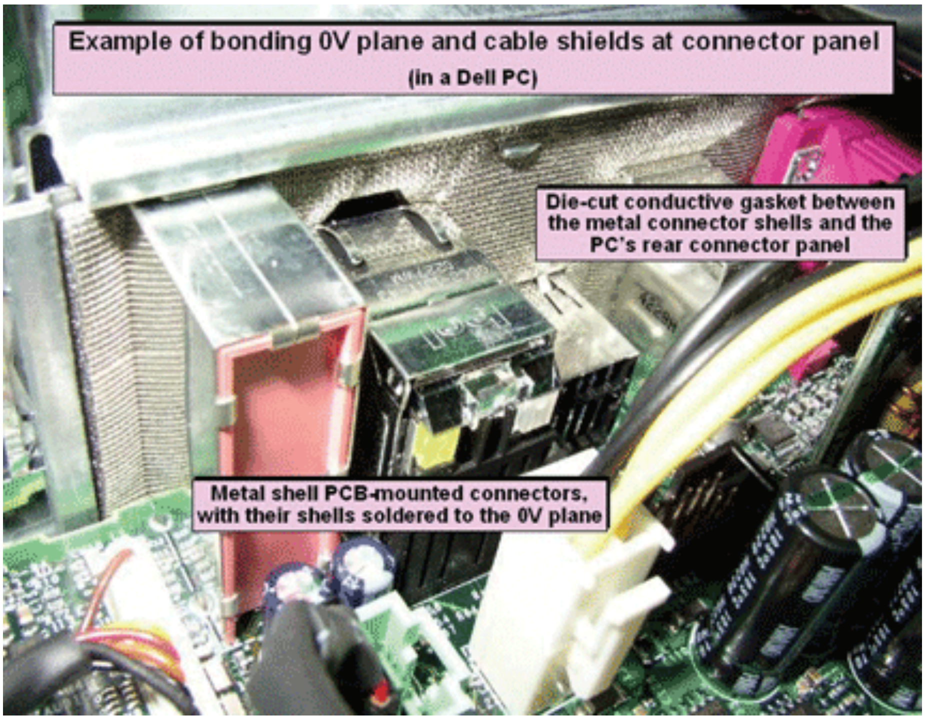

Figure 2Q Example of bonding 0V plane and cable shields at PC rear panel

Figure 2R shows some examples of die-cut conductive gaskets intended for exactly the application described above, for low-assembly-cost and good EMC.

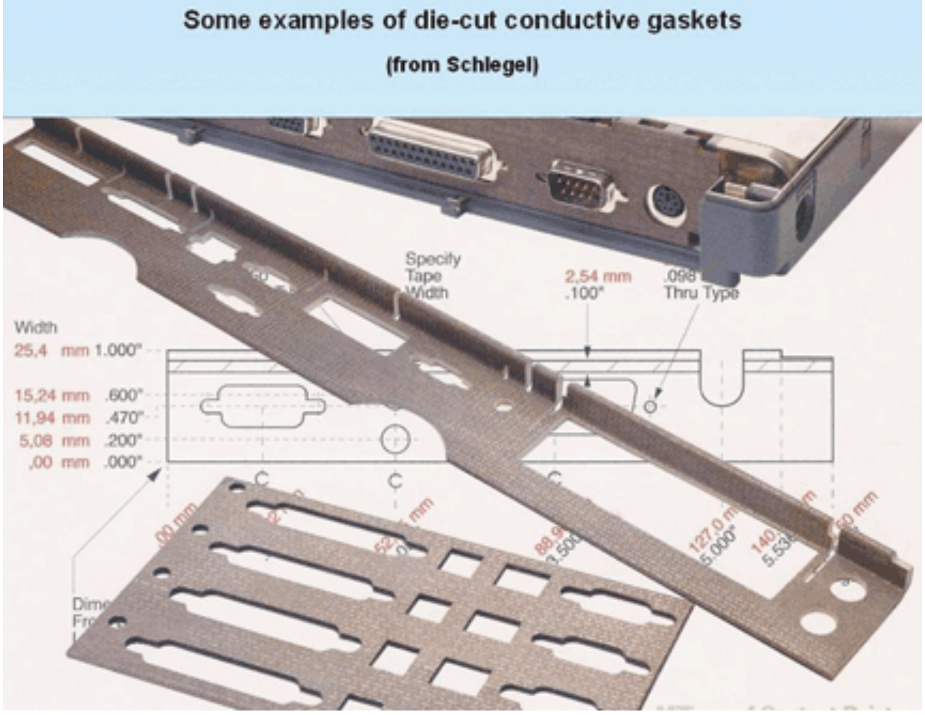

Figure 2R Some examples of die-cut conductive gaskets

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.

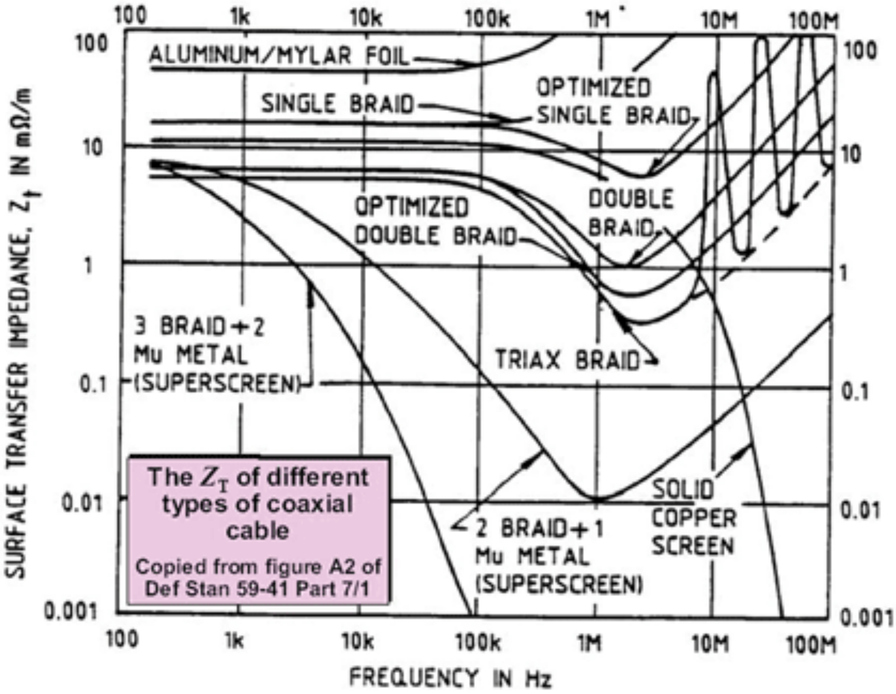

Figure 2S The Z_T of different types of coaxial cable

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 ZT of various cables.

However, cables with solid metal shields (e.g. microwave 'semi-rigid', and solid metal circular conduit with 360^o 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 More on designing shielded interconnections

The 2nd Instalment of this article will continue discussing the design of shielded interconnections.

2.7 Transmission line interconnections

This topic will be covered in the 2nd Instalment of this article.

2.8 References

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