Chapter 15

Shielding

This chapter looks at that classic of EMC design, the shielded enclosure. It is only too easy to say "the product's in a metal box, it must be shielded, that'll do". In fact there is much more to designing a shielded product than simply putting it in a metal box. This section explores the theory of ideal shields and the limits that this theory encounters when you look at the performance of real shields, and then the practical design measures that can be taken to deal with these limitations.

15.1 Shielding theory

Shielding and filtering are complementary practices. There is little point in applying good filtering and circuit design practice to guard against conducted coupling if there is no return path for the filtered currents to take. The shield provides such a return, and also guards against direct field coupling with the internal circuits and conductors. Shielding involves placing a conductive surface around the critical parts of the circuit so that the electric and magnetic fields which couple to it are attenuated by a combination of reflection and absorption. The shield can be an all-metal enclosure if protection down to low frequencies is needed, but if only high frequency (> 30MHz) protection will be enough then a thin conductive coating on plastic is adequate.

Will a shield be necessary?

Shielding is often an expensive and difficult-to-implement design decision, because many other factors – aesthetic, tooling, accessibility – work against it. A decision on whether or not to shield should be taken as early as possible in the project. Chapter 11, sections 11.2 and 11.3 showed that interference coupling is via interface cables and direct induction to/from the PCB. You may be able to calculate to a rough order of magnitude the fields generated by critical PCB tracks and compare these to the desired emission limit (see section 13.1.2). If the limit is exceeded at this point and the PCB layout cannot be improved, then shielding is essential. Shielding does not of itself affect common mode cable coupling and so if this is expected to be the dominant coupling path – generally only experience of similar products will tell this – a full shield may not be necessary. It does establish a "clean" reference for decoupling common mode currents to, but it is also possible to do this with a large area ground plate if the layout is planned carefully.

A description of shielding issues is best split into two parts:

- the theory of electromagnetic attenuation through a conducting barrier of infinite extent, and
- the degradation of theoretically achievable shielding effectiveness by practical forms of shield construction.

To shield or not to shield

- if predicted differential mode fields will exceed limits, shielding is essential
- if layout requires dispersed interfaces, shielding will probably be essential
- if layout allows concentrated interfaces, a ground plate may be adequate
- consider shielding only critical circuitry

15.1.1 Shielding theory for an infinite barrier

15.1.1.1 Reflection and absorption

An AC electric field E_0 impinging on a conductive wall of finite thickness but infinite extent will induce a current flow J_i in that surface of the wall, which in turn will generate a reflected wave E_R of the opposite sense. This is necessary in order to satisfy the boundary conditions along the wall, where the electric field must approach zero – although not reach it, since there will be a voltage along the length of the wall which is determined by the current density times the impedance of the wall, which is not zero. The difference between the impinging and reflected wave amplitudes determines the *reflection loss* of the wall. Because shielding walls have finite conductivity, part of this current flow penetrates into the wall and a fraction of it J_t will appear on the opposite side of the wall, where it will generate its own field E_t (Figure 15.1). The ratio of the impinging to the transmitted fields E_0/E_t is one measure of the shielding effectiveness of the wall. As with an optical mirror, the reflection loss is a surface effect only and is not affected by the thickness of the barrier.

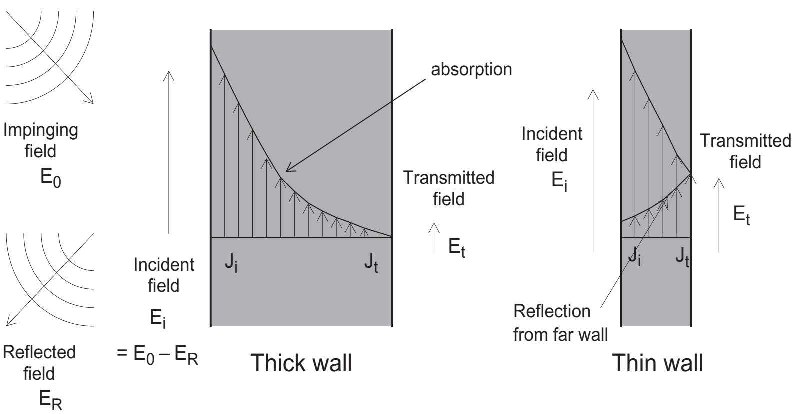

Figure 15.1 Reflection and absorption in an infinite barrier

The thicker the wall, the greater the attenuation of the current through it. This *absorption loss* depends on the number of "skin depths" through the wall. The skin depth (defined in Appendix D, section D.4.1) is an expression of the electromagnetic property which tends to confine AC current flow to the surface of a conductor, becoming less as frequency, conductivity or permeability increases. The current density is attenuated by 8.6dB (1/e) for each skin depth of penetration. For example, skin depth in aluminium at 30MHz is 0.015mm. This explains why thin conductive coatings are effective at high frequencies – the current only flows in a thin layer on the surface, and the bulk of the material does not affect the shielding properties.

Reflection loss

The reflection loss R depends on the ratio of wave impedance to barrier impedance. The concept of wave impedance has been described in section 11.1.4.2. The impedance of the barrier is a function of its conductivity and permeability, and of frequency. Materials of high conductivity such as copper and aluminium have a higher E-field reflection loss than do lower conductivity materials such as steel. Reflection losses decrease with increasing frequency for the E-field (electric) and increase for the H-field (magnetic). In the near field, closer than $\lambda/2\pi$, the distance between source and barrier also affects the reflection loss. Near to an E-field source, the electric field impedance is high and the reflection loss is also correspondingly high. Vice versa, near to an H-field source the magnetic field impedance is low and the reflection loss is low. When the barrier is far enough away to be in the far field, the impinging wave is a plane wave, the wave impedance is constant and the distance is immaterial. Refer back to Figure 11.9 on page 268 for the distinction in impedances between near and far field.

The re-reflection loss B is insignificant in most cases where absorption loss A is greater than 10dB, but becomes important for thin barriers at low frequencies.

Absorption loss

Absorption loss depends on the barrier thickness and its skin depth and is the same whether the field is electric, magnetic or plane wave: that is, it doesn't depend on the wave impedance, in contrast to reflection loss. The skin depth in turn depends on the barrier material's properties; steel, for instance, offers higher absorption than copper of the same thickness, at the lower frequencies where its relative permeability is high. At high frequencies, as Figure 15.2 shows, absorption becomes the dominant term, increasing exponentially with the square root of the frequency. Appendix D (section D.4) gives the formulae for the values of A, R and B for given material parameters.

15.1.1.2 Shielding effectiveness

Shielding effectiveness (SE) of a solid conductive barrier describes the ratio between the field strength without the barrier in place, to that when it is present. It can be expressed as the sum of reflection, absorption, and re-reflection losses, as shown in Figure 15.2 and given by equation (15.1):

$$\mathrm{SE(dB)} = \mathrm{R(dB)} + \mathrm{A(dB)} + \mathrm{B(dB)} \tag{15.1}$$

This is known as the "transmission line model" for shielding effectiveness, and among other things it makes the gigantic assumption that the coupling between the shield currents and the source of the incident field is negligible. In most shielding applications this is an unwarranted assumption, but it does at least simplify the model to the point at which it is comprehensible. The real problems are expanded in section 15.1.3.

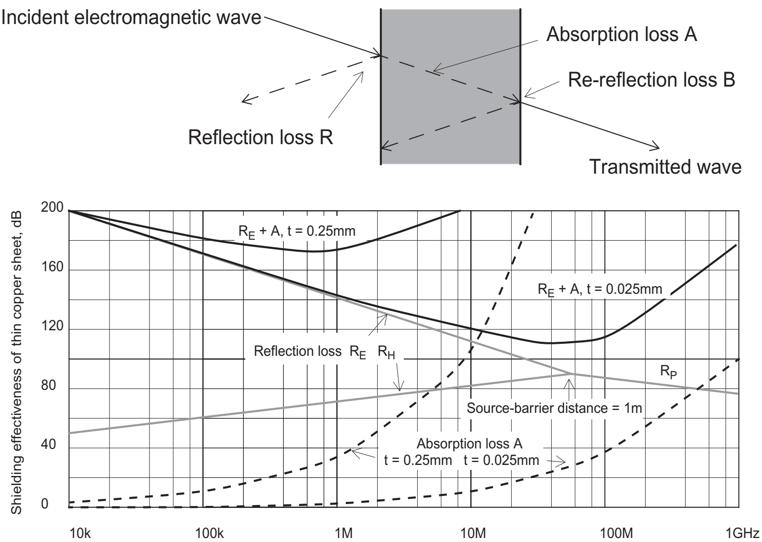

Figure 15.2 Shielding effectiveness versus frequency for a copper sheet of infinite extent

15.1.2 LF magnetic fields

LF magnetic shielding, in the sense of blocking the passage of the magnetic flux, is best accomplished with materials which exhibit a high absorption loss such as steel, mu-metal or permalloy. As the frequency rises these materials lose their permeability and hence shielding efficiency, while non-magnetic materials such as copper or aluminium become more effective. Around 100kHz shielding efficiencies are about equal. Permeable metals are also saturated by high field strengths, and are prone to lose their permeability through handling.

Shielding against magnetic fields at low frequencies is hard to achieve with purely conductive, non-permeable materials. This is because the reflection loss to an impinging magnetic field (R_H) depends on the mismatch of the field impedance to the barrier impedance. The low field impedance is well matched to the low barrier impedance, so there is little reflection, and the field is then transmitted through the barrier with only a few dB attenuation or absorption because of its low frequency. Fortunately, from the point of view of compliance the requirements of the EMC Directive and similar regimes generally don't extend to magnetic shielding at low frequencies, with the possible exception of some types of apparatus that may be susceptible to power frequency fields. But there are some applications where good magnetic field shielding is necessary for functional reasons: one example is CRT displays in high-field environments such as railway trackside locations, another is magnetically sensitive transducers such as electron beam microscopes.

A high-permeability material such as mu-metal or its derivatives can give LF magnetic shielding by concentrating the field within the bulk of the material, but this is a different mechanism to that discussed above, and it is normally only viable for sensitive (or noisy) individual components such as transformers. For an infinitely long cylinder in a DC field the shielding factor is:

$$S_M = (\mu_r/2) \times t/d \tag{15.2}$$

where μ_r is the material's relative permeability and t/d is the ratio of material thickness to cylinder diameter

Practically, there is a fall-off of shielding performance towards the ends, but for distances inside the cylinder greater than the diameter the shield can be regarded as infinitely long; alternatively a high-permeability end cap can be used. Both welded seams and high-intensity fields have the effect of reducing the material permeability μ_r. High flux densities will tend to saturate the material; if the expected flux density is greater than the material's saturation flux density then increase the material thickness or use a double shield with a "nested" construction, with a higher saturation flux density material facing the impinging field. For prototyping, you can use foil magnetic shielding material which can easily be worked by hand. Production shields should be properly fabricated and this needs to be done by a specialist.

You should be aware that this form of shielding is specifically for low frequencies. Permeability of all high-mu materials falls off at frequencies above a few tens of kHz. But as the frequency increases, so does the wave impedance at the barrier and therefore simple metal barriers become increasingly effective. If for some particular application you need extremely wideband shielding effectiveness, then you will use a combination of high-mu metals for the low frequency magnetic effects and conductive but non-magnetic metals for everything else.

Having said this, conductive but non-magnetic materials *can* reduce the amplitude of magnetic fields, through the mechanism of the "shorted turn". Rather than the classic reflection-absorption mechanism, the shorted turn relies on Lenz's Law, which says that a changing magnetic flux coupling with a conducting loop induces a current in the loop which tends to oppose the flux. If the loop is made into a three-dimensional enclosure – a shielded box – then the fields impinging on the box from outside are reduced inside it by partial cancellation, and vice versa. For best effect the conductivity of the box material needs to be high.

15.1.3 The effect of apertures

The curves of shielding effectiveness in Figure 15.2 suggest that upwards of 200dB attenuation is easily achievable using reasonable thicknesses of common materials. In fact, the practical shielding effectiveness is not determined by material characteristics but by necessary apertures and discontinuities in the shielding. You will need apertures for ventilation, for control and interface access, and for viewing indicators; seams at the joints between individual conductive members act as apertures too. Also, shielding is almost invariably applied in the near field of the circuits inside an enclosure. The theoretical material- and field impedance-related attenuation is merely an upper bound on what is achievable, and much lower values are found in practice.

There are different theories for determining SE degradation due to apertures. The simplest assumes an incoming plane wave, and that SE is directly proportional to the ratio of longest aperture dimension L and frequency, with zero SE when $L = \lambda/2$: $SE = 20 \cdot \log_{10}(\lambda/2L)$. Thus the SE increases linearly with decreasing frequency up to the maximum determined by the barrier material, with a greater degradation for larger apertures. A correction factor can be applied for the aspect ratio of slot-shaped apertures. This simple approximation finds favour in evaluating design options, since it doesn't require any knowledge of the actual mechanical structure or field parameters, but neither does it correctly predict the actual value of attenuation that is obtained.

15.1.3.1 Transmission line theory of a rectangular box with a single aperture

Work done in the later 1990s by the universities of York and Nottingham [129][50] has refined a theory which does show good correlation with actual results, under certain well-controlled conditions. This theory treats the case of a rectangular shielding box with a single slot in one of its faces (Figure 15.3(a)), as if it were a length of shorted waveguide. The slot is modelled as a length of transmission line shorted at either end, and the incident field is represented as a voltage source with an impedance equivalent to that of free space (Figure 15.3(b)). To determine the shielding effectiveness, the incident voltage is compared to the voltage at the desired location along the inside of the waveguide. By including some loss in the waveguide propagation the effect of the enclosure contents can also be represented: loading the box with PCBs, for instance, which needs an accurate model for these loss effects.

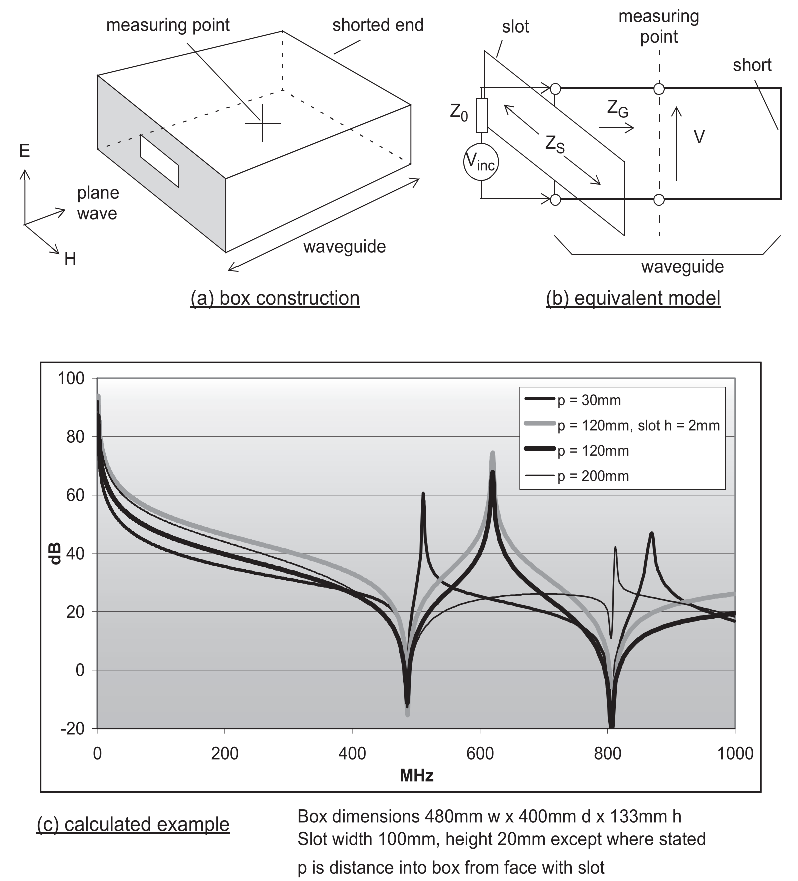

Figure 15.3 Modelling a rectangular box with a slot

Figure 15.3(c) shows the use of this model to calculate the shielding effectiveness of a box of a size typical of rack-mounted enclosures, with a display window in the front. This shows that shielding effect differs, as one might expect, depending on how far into the box the measuring point is located, and it also shows that the slot height does not have a large effect. Most noticeable, though, is that the shielding effectiveness becomes *negative* – that is, the field inside the box is higher than the incident field – at the box resonances. The ability of the enclosure to reduce the coupling of its contents with the environment is seriously compromised at these frequencies. How do they arise?

Enclosure resonance

As mentioned in section 11.3.1.3, a shielded enclosure can form a resonant cavity; standing waves in the field form between opposite sides when the dimension between the sides is an integer multiple of a half-wavelength. The electric field is enhanced in the middle of this cavity while the magnetic field is enhanced at the sides (Figure 15.4). For an empty cavity, resonances occur at:

$$F = 150\cdot\sqrt{(k/l)^2 + (m/h)^2 + (n/w)^2} \text{ MHz} \qquad (15.3)$$

where l, h and w are the enclosure dimensions in metres
k, m and n are positive integers, but no more than one at a time can be zero

For approximately equal enclosure dimensions the lowest possible resonant frequency will be given by equation (15.4):

$$F \approx 212/l \approx 212/h \approx 212/w \text{ MHz} \qquad (15.4)$$

The effect of resonances is to worsen the shielding effectiveness at the resonant frequencies. At these frequencies the field distribution within the cavity peaks, maximum current flows within the walls and hence maximum coupling occurs through the apertures of an imperfect enclosure, as can be seen in Figure 15.3(c). The resonances become more and more closely spaced as the frequency increases and higher order modes (k, m and n) are supported, so that actual shielding effectiveness tends to become extremely variable.

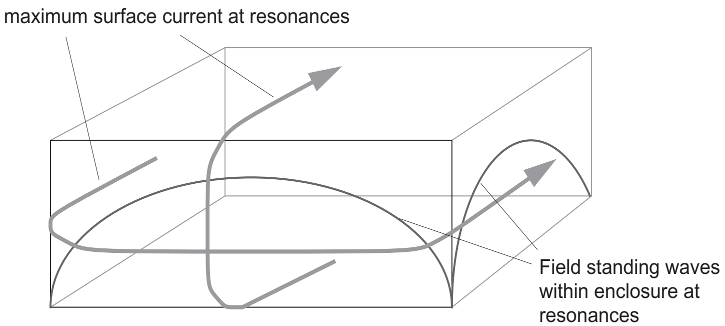

Figure 15.4 Resonances degrade shielding effectiveness

The above equations are accurate for a totally empty enclosure, but loading the enclosure with components, conducting structures and PCBs will detune the resonances and reduce their amplitude, often quite significantly [143]. This can have helpful consequences: for instance, if you have a particular emission or immunity problem at a box resonance, changing the dimension of the resonant cavity inside the box by adding, say, an internal screen or tie-bar may shift the resonance far enough away from the problem frequency to cure the effect. Conversely, if making such a modification doesn't bring relief, this is also a diagnostic hint. It means that you haven't addressed the particular mode that is causing the resonance, or that the problem is not related to resonant modes in the first place.

Exploring the effect of the slot

The worst shape for shielding is a long thin slot, especially if it is perpendicular to the E-field vector, which produces the maximum disturbance in the surface currents. The best shape is a round hole, but squares and hexagons are almost as good. Dividing a long slot into two shorter ones improves both the magnetic and electric shielding by about 6dB. The distance across the slot has only a second-order effect on the result. The slot's length also shows resonances, theoretically at every odd multiple of a half-wavelength established along its length. In practice, coupling between the slot resonances, the box resonances, and the content of the box detunes all of the resonances, so that the simple theory doesn't accurately predict what really happens. If you need to be able to evaluate the full impact of different enclosure design options before committing to tooling, the only way to do it with any confidence is to use electromagnetic modelling software [62].

15.1.3.2 The effect of seams

An electromagnetic shield is normally made from several panels joined together at seams. Unfortunately, when you join two sheets the electrical conductivity across the joint is imperfect. This may be because of distortion, so that surfaces do not mate perfectly, or because of painting, anodizing or corrosion, so that an insulating layer is present on one or both metal surfaces. Even if the surfaces appear conductive, when they are placed together contact is only created at points of pressure between one and the other.

Consequently, the shielding effectiveness is reduced by seams almost as much as it is by apertures (Figure 15.5). The fastener spacing d is critical in determining how much the shielding effectiveness is degraded, just as if the separation between fasteners was an actual aperture. The problem is especially serious for hinged front panels, doors and removable hatches that form part of a shielded enclosure. It is mitigated to a small extent if the conductive sheets overlap, since this forms a capacitor which provides a partial current path at high frequencies. Figure 15.6 shows preferred ways to improve joint conductivity. Conductive gaskets are discussed in section 15.2.1.

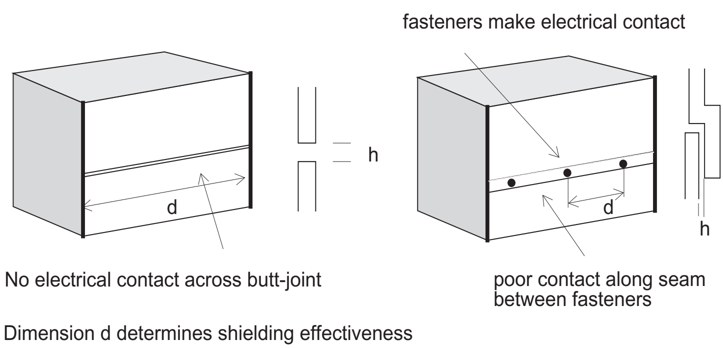

Figure 15.5 Seams between enclosure panels

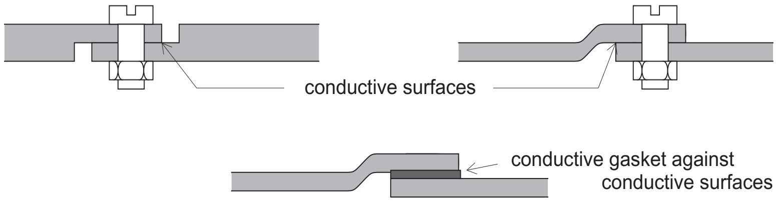

Figure 15.6 Cross-sections of joints for good conductivity

15.1.3.3 Seam and aperture orientation

The effect of a joint which creates a discontinuity is to force shield current to flow around the discontinuity. If the current flowing in the shield were undisturbed then the field within the shielded area would be minimized, but as the current is diverted so a localized discontinuity occurs, and this creates a field coupling path through the shield as described in section 15.1.3.1. The shielding effectiveness calculation assumes a worst case orientation of current flow. A long aperture or narrow seam will have a greater effect on current flowing at right angles to it than on parallel current flow†. This effect can be exploited if you can control the orientation of susceptible or emissive conductors within the shielded environment (Figure 15.7).

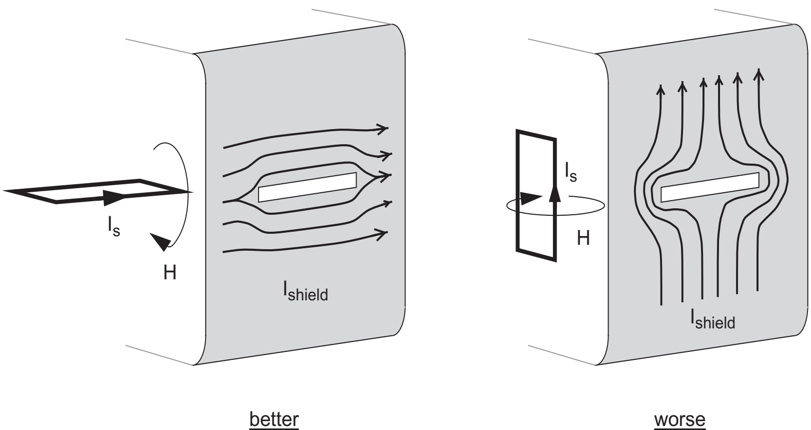

Figure 15.7 Current loop versus aperture orientation

The practical implication of this is that if all critical internal conductors are within the same plane, such as on a PCB, then long apertures and seams in the shield should be aligned parallel to this plane rather than perpendicular to it. Generally, you are likely to obtain an advantage of no more than 10dB by this trick, since the geometry of internal conductors is never exactly planar. Cables or wires, when routed near to the shield, should be run parallel to apertures rather than across them. But because the

† Antenna designers will recognize that this describes a slot antenna, the reciprocal of a dipole.

leakage field coupling due to joints is large near the discontinuity, internal cables should preferably not be routed near to apertures or seams at all. Where it's necessary for a cable to cross a seam, then you should provide a good bond between the two sides of the seam where the cable passes.

15.1.4 The shield as ground reference

A major advantage of a shielded enclosure is that the shield metalwork (or metallization) offers a low-inductance RF ground reference. This allows interfaces to be dispersed without suffering the penalty of high ground noise voltages developed by common mode noise currents flowing from one port to another. To achieve this, the interface cable screens must be bonded with low inductance directly to the shield as must any common mode decoupling capacitors. But, in using enclosure metalwork like this you can see that it is not absolutely essential that the shield be continuous in all dimensions around the circuit. The shield should be as complete (i.e. without apertures or seams) as possible *between the interface ports*, as any breaks will have the effect of diverting noise currents and thereby increasing the effective inductance of the ground reference. But this can quite easily be achieved with a U-shaped chassis (see Figure 15.8 for example, where a power supply comes in on one side of a circuit and the signal lines are connected on the other) without having to have a cover over the chassis.

You can choose to tie the circuit 0V to the shield in two ways. For good immunity of wideband analogue circuits it should be connected at the most sensitive part of the circuit to minimize noise coupling by the stray circuit-shield capacitances. On digital circuits on the other hand, multi-point grounding of the circuit 0V plane via several bonding points to the chassis will ensure the minimum common mode potential difference at any point in the circuit, and hence the best immunity to transient interference.

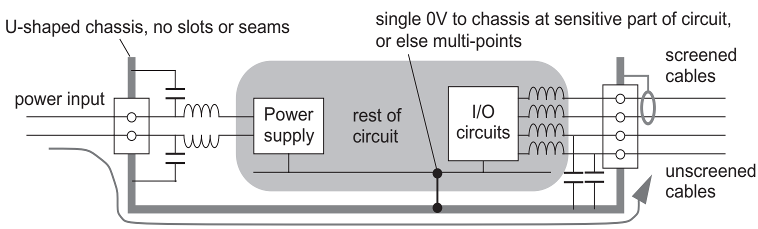

Figure 15.8 Shield metalwork as ground reference

15.1.5 The image plane

If you have a PCB which is poorly laid out and you are not in a position to revise the layout, a useful fix may be the image plane [74]. At first sight the image plane is a partial shield but in fact its mode of operation is distinct from that of a shield. The image plane is simply a flat conducting plane, typically made from a layer of foil laminated in plastic for insulation, placed as close as possible to the underside of the PCB (Figure 15.9). Alternatively, it could be a layer of metallization on the inner surface of the plastic enclosure on which the PCB is mounted. This plane should be at least the same size as the PCB and preferably larger so as to overlap the edges, especially those edges where (due to an oversight) there may be placed critical tracks. The criterion for overlap is that it should be greater than 10 · h, exactly as with PCB planes (section 12.2.3.3) and for the same reason: magnetic field coupling at the edges of the plane.

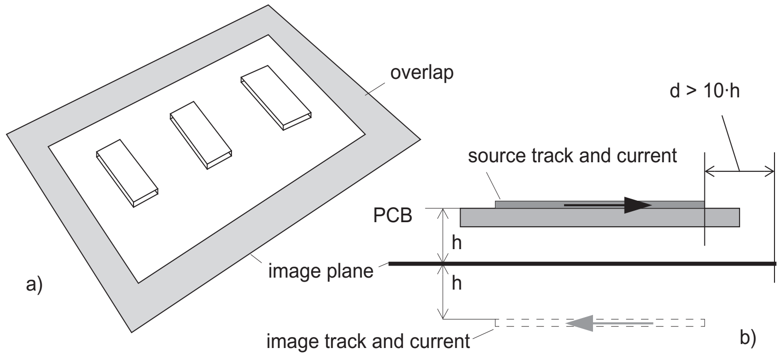

Figure 15.9 Image plane under a PCB

15.1.5.1 PCB with no external wires

If the PCB has no external connections, then the image plane can be electrically floating: there is no need to connect the PCB and the plane together. In this case the emissions radiated from the board on its own are principally due to common mode currents flowing on the various tracks. Adding an image plane creates a phantom reflection of these currents, effectively located at the "image" position on the opposite side of the plane (Figure 15.9(b)) – hence the name. These image currents are in the opposite polarity to the source currents. The effect of the ensemble is that the radiated emissions from the source currents are partially cancelled by the near-equal but opposite emissions from the image currents. The closer the plane is to the PCB (the distance h in Figure 15.9) then the more effective is this cancellation, since the separation of source and image is 2 · h.

The plane is most effective at reducing emissions if the original PCB suffered from bad layout, i.e. if it includes large loop areas (see section 12.2.1). Here the plane can often be brought much closer to the board than the distance that may separate signal and return paths on the PCB. There is therefore a worthwhile reduction in the effective radiating area, which is now determined by the separation between source and image locations rather than the original signal and return. On the other hand, with a well laid out PCB, especially one with a ground plane already incorporated, adding an image plane will have little effect unless for some reason there are large common mode currents flowing across the board.

15.1.5.2 PCB with connected cables

Another effect of the image plane is to reduce the inductance of each track, including the ground track(s), because of the mutual coupling of each track with its image. This leads to a reduction in the ground noise voltages developed along the tracks, and this in turn will reduce emissions due to common mode currents injected into connected cables (section 11.2.1.3). As before, the reduction is most worthwhile when the board has been badly laid out so that its initial ground track inductance is high; but even here the reduction is only a few tens of per cent, rarely more than 6dB.

If though, instead of floating, the image plane is connected to the ground return track on the PCB *at the same point as the connected cable*, then there is now a return path for the generated common mode current and the net current being fed into the cable is near zero. This will allow a significant drop in emissions. In practice, all wires in the cable must be decoupled to this point at the emission frequencies (unless it is a shielded cable) and therefore a capacitor between each signal line and ground at the interface is mandatory. In this application, the image plane acts in much the same way as a chassis and can be used as a surrogate for a chassis if one doesn't exist; or you can regard the chassis, or metallization on a plastic enclosure, as acting like an image plane. In the limit, you can implement the image plane as an extra plane layer on the bottom of a multilayer PCB, as long as there are no components on this bottom side, but the quality of the image plane will be compromised to some extent by its penetration by via holes.

15.2 Shielding practice

15.2.1 Shielding hardware

Many manufacturers offer various materials for improving the conductivity of joints in conductive panels. From the advertising hype, you might think that these are all you need to rid yourself of EMC problems for good. In fact such materials can be useful if properly applied, but they must be used with an awareness of the principles discussed above, and their expense will often rule them out for cost-sensitive applications except as a last resort. A further relevant difficulty is the EU's twin constraints on the materials used in products, the Restriction on Hazardous Substances (RoHS, 2002/95/EC) and Waste Electrical & Electronic Equipment (WEEE, 2002/96/EC) Directives. The second of these mandates a high degree of recyclability of products at their end of life, and the first limits the use of certain materials in any product's construction. The WEEE Directive may impact on techniques such as conductive coatings on plastic, or form-in-place gaskets. In cases where different materials are combined into one component, the recyclability of such components becomes very difficult.

The RoHS Directive places restrictions on the content of the following materials:

- lead;
- mercury;
- cadmium;
- hexavalent chromium;
- polybrominated biphenyls (PBB);
- polybrominated diphenyl ethers (PBDE).

Of these, really only hexavalent chromium has implications for EMC, since it is used in chromate conversions of aluminium; as long as you specify trivalent chromate conversion then you will stay clear of this restriction.

15.2.1.1 Gaskets and finger strip

Shielding effectiveness can be improved by reducing the spacing of fasteners between different panels. If you need effectiveness up to 1GHz and beyond, then the necessary spacing becomes unrealistically small when you consider maintenance and accessibility. In these cases the conductive path between two panels or flanges can be improved by using any of the several brands of conductive gasket, knitted wire mesh or finger strip that are available. The purpose of these components is to be sandwiched in

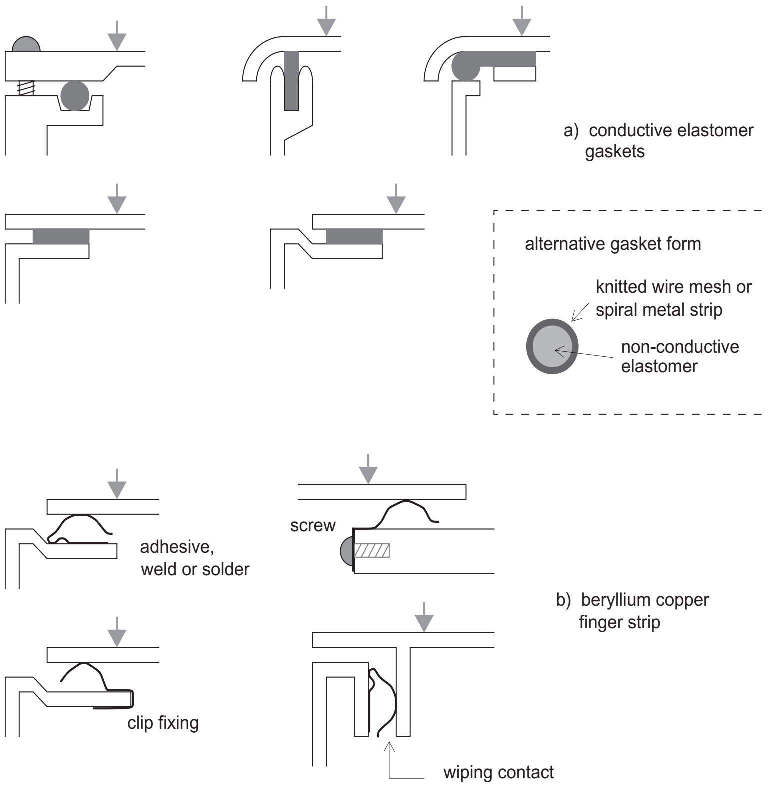

Figure 15.10 Usage of gaskets and finger strip

between the mating surfaces and conform with the irregularities of each surface, to ensure continuous contact across the joint, so that shield current is not diverted (Figure 15.10). Their effectiveness depends entirely on how well they can match the impedance of the joint to that of the bulk shield material.

You must bear in mind a number of factors when selecting a conductive gasket or finger material:

- its conductivity, which should be of the same order of magnitude as the panel material;
- compressibility and compression set, which should be matched to the mechanical deflection expected of the mating surfaces or mounting channel;
- ease of mounting: gaskets should normally be mounted in channels machined or cast in the housing, and the correct dimensioning of these channels is important to maintain an adequate contact pressure without over-tightening. Finger strip can be mounted by adhesive tape, welding, riveting, soldering, fasteners or by just clipping in place. The right method depends on the direction of contact pressure;

- galvanic compatibility with its host: to reduce corrosion, the gasket metal and its housing should be close together and preferably of the same group within the electrochemical series (Table 15.2, and see next section);
- environmental performance: conductive elastomers can offer combined electrical and environmental protection, but may be affected by moisture, fungus, weathering or heat. If you choose to use separate environmental and conductive gaskets, the conductive gasket should be placed *inside* the environmental seal, and also inside screw mounting holes.

There are a number of varieties of conductive gasket, and Table 15.1 describes their individual properties.

Table 15.1 Conductive gaskets

Material	Features
Form in Place (FiP)	A conductive elastomer paste is dispensed by numerically controlled machine as a continuous strip or semi-circular profile bead onto a metal or metallized part and then cured, creating a single piece part before assembly and eliminating waste; generally a high volume process, conductivity depends on filler
Mould in Place (MiP)	Conductive elastomer ribs are moulded directly onto a substrate instead of being mechanically attached; a rib pattern can be moulded onto any metal or plastic substrate, creating a multi-compartment shielded enclosure, usually used in conjunction with PCBs
Fabric over foam	Metallized textile formed over urethane foam core, various profiles, flame retardant; good for applications requiring low mating pressure and large deflection, high conductivity
Conductively loaded urethane foam	Like fabric over foam, with low closure force and compression set, but with conductive fibres dispersed through the foam
Conductive elastomer	Can be extruded in various profiles including hollow for increased deflection or die cut from flat sheet, variety of elastomer compounds and metallic fillers, can provide electrical and environmental seal in one part if carefully applied, mostly used in bolt-down applications; conductivity depends on filler, can be quite expensive
Spring finger stock	Historically the original conductive gasket, wide range of configurations available from many suppliers, high conductivity, good for repeated cycle applications such as doors with wiping or compression action, wide temperature range but relatively susceptible to damage; available in beryllium copper, stainless steel and phosphor bronze
Spiral wrap	Similar to finger stock in application, only mounted in a groove, usual material stainless steel, may be combined with elastomer
Oriented wire	Monel or aluminium wire bonded into flat silicone sheet provides a multiple spring effect with individual contact points cutting into metal surfaces; can be die cut, provides environmental seal
Knitted wire mesh	Monel, steel or aluminium wire knitted into various cross-section profiles, high conductivity, economical and resilient but only suited for occasional cycling, can be sheathed over elastomer core

15.2.1.2 Surface treatment

Apart from actually ensuring physical contact, the difficulty with the conductivity of metal surfaces is twofold:

- they will oxidize in contact with air, and some oxides are non-conductive;
- in contact with other metal surfaces, they may suffer electrochemical corrosion.

Any mating surfaces should be conductively finished to prevent insulating oxides from forming – alochrome or alodine for aluminium, nickel or tin plate for steel. (It should be blindingly obvious that mating surfaces should never be painted! Where you have a painted metal enclosure, the surfaces which are to be in contact should be masked from the paint and conductively finished.) For surfaces which will be subject to repeated wear, the hardness of the plating which is used is important. Bright tin and nickel offer an adequate combination of conductivity and hardness for general applications. For best conductivity combined with low wear, use gold or rhodium; silver has the highest conductivity, but the poorest wear resistance.

Corrosion is a significant factor in contact resistance. The by-products of corrosion are usually effective insulators. Corrosion occurs continually at any surface, but you can slow down its rate enough to avoid problems within the lifecycle of the unit that is being shielded. To control it, you need to select mating metals to have similar electrochemical potentials, within adjacent or preferably the same groups in the electrochemical series (Table 15.2); and you need to create a barrier between the mating faces and the atmosphere, to starve the chemical reaction of oxygen and electrolytes such as atmospheric salts. This can mean painting the assembled piece parts, which precludes separating them again, or ensuring a gas-tight joint, which means tightening fasteners adequately and providing an environmental seal.

Table 15.2 The electrochemical series

Anodic – most easily corroded ⟶				
Group I	Group II	Group III	Group IV	Group V
Magnesium	Aluminium + alloys			
	Zinc	Carbon steel		
	Chromium	Iron	Nickel	
	Galvanized iron	Cadmium	Tin, solder	Copper + alloys
			Lead	Silver
			Brass	Palladium
			Stainless steel	Platinum
				Gold
		⟶	Cathodic – least easily corroded	
Corrosion occurs when ions move from the more anodic metal to the more cathodic, facilitated by an electrolytic transport medium such as moisture or salts				

15.2.2 Conductive coatings

Many electronic products are enclosed in plastic cases for aesthetic or cost reasons. These can be made to provide a degree of electromagnetic shielding by covering one or both sides with a conductive coating [35][125]. Normally, this involves both a moulding supplier and a coating supplier. You might consider using conductively filled plastic composites to obtain a marginal degree of shielding (around 20dB); it is debatable whether the extra material cost justifies such an approach, considering that better shielding performance can be offered by conductive coating at lower overall cost [42]. Conductive fillers affect the mechanical and aesthetic properties of the plastic, but their major advantage is that no further treatment of the moulded part is needed. Another problem is that the moulding process may leave a “resin rich” surface which is not conductive, so that the conductivity across seams and joints is not assured. As a further alternative, metallized fabrics are available which can be incorporated into some designs of compression moulding.

15.2.2.1 Shielding performance

The same dimensional considerations apply to apertures and seams as for metal shields; an added factor is that any scratch or crack which breaks through the coating acts as an aperture and degrades the shielding effectiveness. Thin coatings will be almost as effective against electric fields at high frequencies as solid metal cases but are ineffective against magnetic fields. The major shielding mechanism is E-field reflection loss (Figure 15.2, R_E) since absorption is negligible except at very high frequencies, and re-reflection (B) will tend to reduce the overall reflection losses. The higher the resistivity of the coating, the less its efficiency. For this reason nickel paints, which have a resistivity of around 1Ω/square, make poorer shields than silver or copper paints or the various types of metallization (see Table 15.3) which offer resistivities below 0.1Ω/square.

15.2.2.2 Enclosure design

Resistivity will depend on the thickness of the coating, which in turn is affected by factors such as the shape and sharpness of the moulding – coatings will adhere less to, and abrade more easily from, sharp edges and corners than rounded ones. Ribs, dividing walls and other mould features that exist inside most enclosures make application of sprayed-on coatings (such as conductive paint or zinc arc spray) harder and favour the electroless plating methods. Where coatings must cover such features, your moulding design should include generous radii, no sharp corners, adequate space between ribs and no deep or narrow crevices (Figure 15.11). As with metallic enclosures, good conductivity across seams is vital, although clever moulding design can create an approximation to a conductive gasket.

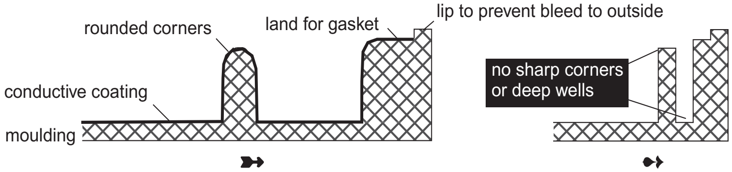

Figure 15.11 Moulding design for conductive coatings

15.2.2.3 Coating properties

Environmental factors, particularly abrasion resistance and adhesion, are critical in the selection of the correct coating. Major quality considerations are:

- will the coating peel or flake off into the electrical circuitry?

- will the shielding effectiveness be consistent from part to part?
- will the coating maintain its shielding effectiveness over the life of the product?

Adhesion is a function of thermal or mechanical stresses, and is checked by a non-destructive tape or destructive cross-hatch test. Typically, the removal of any coating as an immediate result of tape application constitutes a test failure. During and at completion of thermal cycling or humidity testing, small flakes at the lattice edges after a cross-hatch test should not exceed 15% of the total coating removal.

Electrical properties should not change after repeated temperature/humidity cycling within the parameters agreed with the moulding and coating suppliers. Resistance measurements should be taken from the farthest distances of the test piece and also on surfaces critical to the shielding performance, especially mating and grounding areas.

Table 15.3 compares the features of the more commonly available conductive coatings (others are possible but are more expensive and little used). These will give shielding effectiveness in the range of 30–70dB if properly applied. It is difficult to compare the shielding effectiveness figures from different manufacturers unless they specify very clearly the methods used to perform their shielding effectiveness tests; different methods do not give comparable results. Also, laboratory test methods may not correlate with the performance of a practical enclosure for a commercial product, for the reasons discussed in section 15.1.3.

Table 15.3 Comparison of conductive coating techniques

	Performance	Advantages	Disadvantages
Conductive paint	Silver, Hybrid: 30-50mΩ/☐ Copper: 0.2-0.5Ω/☐ Nickel: 1-2Ω/☐	Water or solvent based 5-80μ typical thickness Flexible application, manual (low volume) or robot (high volume) Wide availability, easy scaleability to volume	Requires line of sight, can be masked Silver gives good conductivity but expensive
Electroless plating	Copper: 10-30mΩ/☐	1-10μ per layer, can coat multiple layers, e.g. Cu/Ni, can be thickened with electroplating Consistent thickness No need for line of sight	If masked, extra catalytic base coat needed, extra process
Vacuum metallization (sputtering)	Aluminium: 100-200mΩ/☐	2-10m layer, typically aluminium but also Cu, Ni, Cr Suitable for large volume, small, simple geometries	Batch process, requires line of sight, mask tool required for each part in the batch

Finally, be sure if you specify conductive coatings on an existing product that in doing so you are not compromising safety requirements. Particular issues are:

- the stability of adhesion of the coating – make sure as above that it cannot flake and bridge safety isolation paths or cause a fault;
- the effect of the coating on the flame retardant properties of the enclosure;
- the effect on creepage and clearance distances for safety insulation. A conductive coating applied without thought could reduce the isolation between safe parts and hazardous live parts by providing a new conducting path which is close to each of these.

15.2.3 Windows and ventilation slots

Viewing windows normally involve a large open area in the shield and you have to cover the window with a transparent conductive material, which must make good continuous contact to the surrounding shield, or accept the penalty of shielding at lower frequencies only. You can obtain shielded window components which are laminated

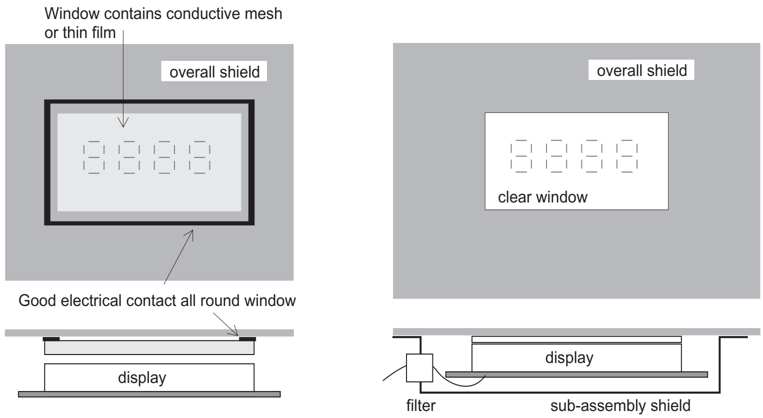

Figure 15.12 Alternative ways to shield a display window

with fine blackened copper mesh, or which are coated with an extremely thin film of gold or indium tin oxide (ITO). In either case, there is a trade-off in viewing quality versus a clear window, due to reduced light transmission (between 60 and 80%) and diffraction effects of the mesh. Shielding effectiveness of a transparent conductive coating is significantly less than a solid shield, since the coating will have a resistance of a few ohms per square† and attenuation will be entirely due to reflection loss. This is not the case with a mesh, but shielding effectiveness of better than 40–50dB may be irrelevant anyway because of the effect of other apertures. Shielded windows are certainly costly and rarely suited to consumer applications.

An ITO layer thickness of 1 micron will have a sheet resistance of about 10 ohms per square and a visible light transmission of around 80%. A simple and very approximate equation for the far field shielding attenuation versus frequency of such a layer is given by [63]

$$SE = 20 \log [(7 \cdot 10^{11}) / (f \times R)] \quad (15.5)$$

Where f = frequency (Hz)
R = sheet resistance (Ohms/square)
SE = far field shielding effectiveness (dB)

15.2.3.1 Using a sub-enclosure

An alternative method which allows you to retain a clear window, is to shield behind

† The resistance across two sides of a square is independent of the size of the square, and hence the units of "ohms per square" are entirely reasonable and not a misprint. This and surface resistivity (ohms) are just two conventions for specifying the same thing, and are numerically equivalent.

the display with a sub-shield (Figure 15.12), which must make good all-round contact with the main panel. The electrical connections to the display must be filtered to keep the shield's integrity, and the display itself is unshielded and must therefore not be susceptible nor contain emitting sources. This alternative is often easier and cheaper than shielded windows. It can also be applied to other apertures besides windows: for example, a large number of connections may be made to the equipment via terminal blocks, and it is not effective to have these mounted within a shielded enclosure since the incoming cables breach the shielding. Instead, you can mount the terminal blocks in a compartment outside the primary shielding, and have the connections between the terminal blocks and the main circuit taken through the shielding at a filtered or isolated interface (Figure 15.13). This partitioning of the shielded enclosure is sometimes referred to as the "clean box/dirty box" approach. It has the advantage that the shielded enclosure need not be the same as the overall product enclosure but can sit within it.

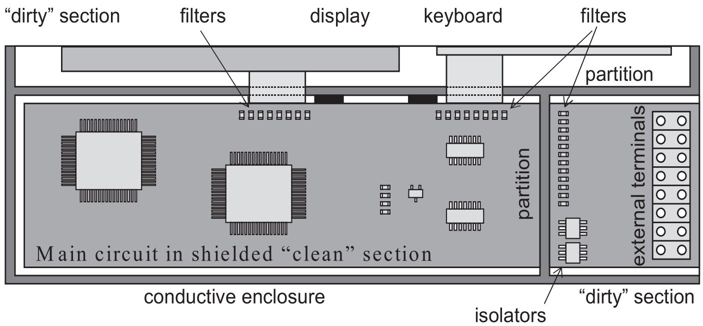

Figure 15.13 Terminals and user interface in unshielded compartments

15.2.3.2 Mesh and honeycomb

Ventilation apertures are frequently a cause of difficulty for shielded enclosures. They can be covered with a perforated mesh screen, or the conductive panel may itself be perforated. If individual equally sized perforations are spaced close together (hole spacing $<< \lambda/2$) then the reduction in shielding over a single hole is approximately proportional to the square root of the number of holes. Thus a mesh of 100 4mm holes would have a shielding effectiveness 20dB worse than a single 4mm hole. On the other hand, *for a fixed open area*, the shielding effectiveness *improves* proportionally to the square root of the number of holes: in other words, ventilation is always better provided by a mesh of many small holes rather than a few large ones. Two similar apertures spaced greater than a half-wavelength apart do not create any significant extra shielding reduction over a single aperture.

Wire mesh rather than perforated holes can be similarly treated, provided that the wires make good electrical contact at each crossover or intersection, and provided that the mesh is bonded to the main panel all around its edge. If the wires are corroded or loose at each intersection, the mesh will not provide the expected shielding results.

Honeycomb

You can if necessary gain improved shielding of vents, at the expense of thickness and weight, by using "honeycomb" panels in which the honeycomb pattern functions as a waveguide below cut-off (Figure 15.14). In this technique the shield thickness is several times that of the width of each individual aperture, and the honeycomb is a cluster of waveguides. Each aperture is less than a half-wavelength in dimension w at the highest frequency which must be blocked. Thus for instance below 1GHz any tube of diameter less than 15cm will function as such a cut-off waveguide.

Under these circumstances and for frequencies several times less than the cut-off, field propagation down each aperture is attenuated at a rate of about 27dB (for rectangular cross-section, 32dB for circular) over each distance w in the direction t, through the thickness of the panel. A common t/w ratio is 4:1 which offers an intrinsic shielding effectiveness of over 100dB. This method can also be used to carry insulated control spindles (*not* conductive ones, or cables!) or other non-conductive services such as optical fibres through a panel.

In the construction of honeycomb vent panels, the foil strips making up the cells are treated so that the individual cells make good electrical contact with each other and with the mounting frame in all directions. Shielding effectiveness of honeycomb material is significantly improved when the complete panel is plated with a conductive material, such as tin. For these panels, with many waveguides in parallel, the loss down a single waveguide is reduced by a factor $10 \cdot \log_{10}(n)$ related to the total number of openings n in the panel. Thus a panel with 100 individual cells will perform 20dB worse than a single individual cell.

15.2.4 Shields on the PCB

Carrying on from the idea of shielding only part of an enclosure, it is logical to go one step further and apply a sub-shield as a single component on a PCB. This allows you to shield only those components or sections that need it, and if necessary to create multiple shielded sections on one PCB with a single formed part. This practice is not just for external EMC – maybe there is a wireless interface on the board which needs its own shielding regime; or it may be necessary for purely functional reasons to protect a low-level radio receiver from local microprocessor noise.

In virtually all cases the shielding component will work in conjunction with the circuit's 0V plane. It is very rare, though not impossible, to apply shields to a board

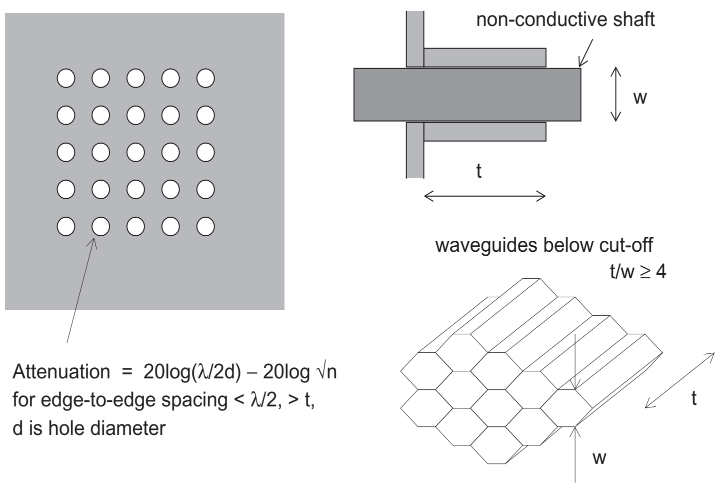

Figure 15.14 Mesh panels and the waveguide below cut-off

without a 0V plane. The plane is normally expected to provide the bottom face of the shield, which then itself prevents E-field coupling to or from the components and upper surface tracking. For this to work into the GHz range, the connection between the shield and the plane must have a very low inductance. This, as ever, means multiple connections all around the sides of the shield. The equivalent circuit for such an arrangement, assuming that various ICs are the source of E-field noise, can be viewed as shown in Figure 15.15.

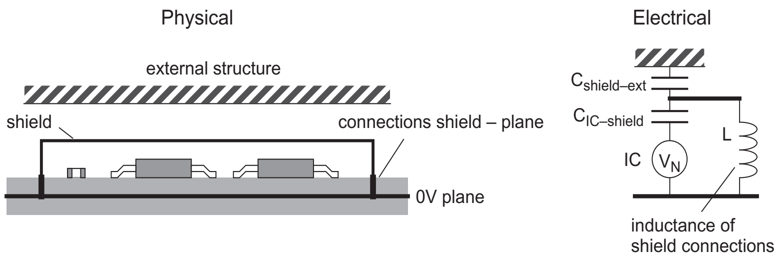

Figure 15.15 Equivalent circuit for E-field shield on a PCB

What we are normally trying to prevent is coupling of V_N to external structures, so that unwanted disturbance currents don't flow in these structures. The shield will couple it instead back to 0V, but only provided that the mounting inductance L is negligible. Purely for illustration, consider two sets of figures (Figure 15.16): with coupling capacitance of 10pF on both sides of the shield, the mounting inductance may be 5nH (poor) or 0.5nH (relatively good). The result is a peak in coupling (zero shielding effect) well below 1GHz for the high inductance, but reasonably above it for the low.

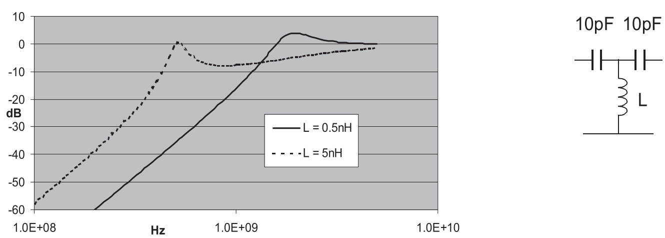

Figure 15.16 Attenuation through a shield with mounting inductance L

The best form of mounting is to have a surface land on the PCB that mates with a lip on the wall of the shield, all around its perimeter, with many vias through to the 0V plane, so that the shield wall is soldered all along its length. Mounting with individual pins through the board is a second best; if you're going to use it, as a through-hole component, there should be as many pins as possible around the perimeter.

With this fundamental requirement addressed, actually designing the shield is usually simple. If you will need access to the top of the PCB later, for testing or rework, then a two-part shield is necessary: a wall or fence which is soldered to the PCB, and a lid which is subsequently clipped to the wall and is removable. Alternatively a five-sided box permanently soldered to the PCB can be used if no access is needed. Usually, tin plated steel is more than adequate for the purpose, both electrically and mechanically. Depending on volume, the part can be photochemically machined or stamped, and supplied ready for surface mounting in pick-and-place waffle packs. As is to be expected, the cost of the part will depend on its size and the complexity of forming.

15.2.5 Standardization of enclosure SE

A departure in the IEC 61000 series of standards has been to publish a method for the description of shielding effectiveness of commercial enclosures, similar to the IP rating scheme for environmental protection. IEC 61000-5-7 [174] specifies the "EM" rating, in which the designator EM*ABCDEF* specifies the shielding performance in each of six frequency ranges. Table 15.4 gives the meaning of each of these designators. The standard also specifies the SE test methods to be employed for each frequency range. It will be interesting to see how popular this designation becomes in the future.

Table 15.4 The IEC 61000-5-7 EM shielding code

Frequency range	Shielding designator	Shielding performance (dB)	Designator value
10kHz–100kHz	*A*	Untested	x
100kHz–1MHz	*B*	<10	0
1MHz–30MHz	*C*	≥10	1
30MHz–1GHz	*D*	≥20	2
1GHz–10GHz	*E*	≥30	3
10GHz–40GHz	*F*	≥40	4
		≥50	5
		≥60	6
		≥70	7
		≥80	8
		≥100	9

Example: EM66644x provides ≥60dB SE from 10kHz to 30MHz, and ≥40dB from 30MHz to 10GHz