

**COMMERCIAL-EMISSIONS LIMITS MAY BE INADE-  
QUATE FOR YOUR APPLICATIONS. YOU MIGHT NEED  
NEW DESIGN GOALS TO CONTROL EMISSIONS TO A  
SUITABLE LEVEL.**

# EMI and emissions: rules, regulations, and options

When most designers think of EMI, emissions are the problems they're usually concerned with. For almost 20 years, personal/commercial computers (and many computerlike devices) have been subject to mandatory EMI-emissions requirements. Although often perceived as nuisances, these regulations were necessary to keep the RF spectrum clean for legitimate licensed users.

Computers are often referred to as "unintentional radiators," but every computer is a potential RF polluter. Repetitive digital signals are rich with harmonics that can extend well into the gigahertz range. This unwanted energy can be radiated, using cables and wiring as antennas, or it can be conducted through the ac power system. If the levels are high enough, they can render nearby communications receivers unusable.

It was this problem that caused governments around the world to pass EMI regulations. But governments are driven by complaints (or votes), so it's the squeaky wheel that gets the grease. The biggest source of complaints for this type of interference came from the public, when television reception was disrupted. These complaints grew exponentially in the mid-1970s, fueled by the microprocessor revolution, and drove the FCC to initiate mandatory EMI testing of PCs and commercial computers in the early 1980s. The rules were patterned after regulations already in place in West Germany and administered by the Verband Deutscher Elektrotechniker (VDE). Later, the Japanese got into the act, as did the European Community (EC) with the EMC Directives of 1996.

All of these commercial-emissions regulations have one thing in common: They aim to prevent interference to a nearby television or broadcast-radio receiver and nothing more (see the side-

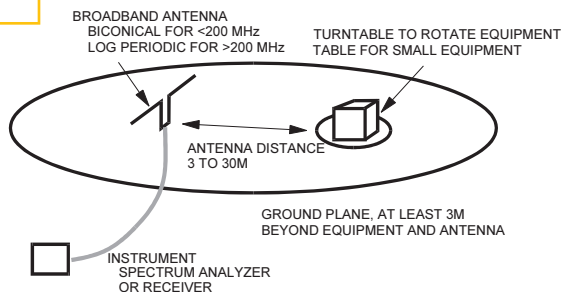
bar "Derivation of commercial EMI limits"). The limits work most of the time, but situations exist in which the limits aren't good enough. For example, they're not adequate to protect nearby sensitive communications receivers, such as military radios. That's why the military-emissions limits are about 30 times tougher than the commercial limits. Nor are they adequate to protect avionics or automobile radios, which is why the avionics and automotive industries have their own limits that can be more than 1000 times tougher than the commercial limits.

The bottom line is that the commercial-emissions limits may be inadequate for your applications. In one case, the emissions from a microprocessor-based control system was jamming a VHF land mobile radio that was also part of the system. In another case, a commercial product was widely used in fringe TV-reception areas and was interfering with the weak TV signals. In both of these cases, the products met the FCC limits but still caused problems. Sometimes, you need to establish new system limits (or design goals) to control the emissions to a suitable level.

## KEY EMISSIONS ISSUES

Before getting into design techniques, you need to be aware of several emissions issues. Some deal with definitions and others with better understanding the multiple mechanisms behind the emissions.

**Figure 1**



**Measure radiated emissions using existing antennas connected to a spectrum analyzer or a receiver.**

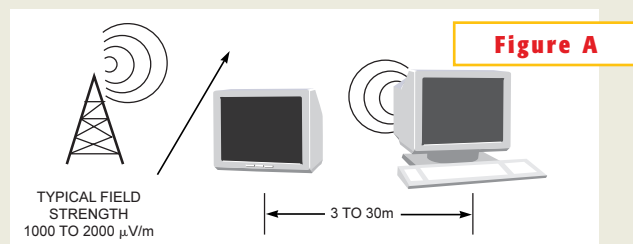
*This article is excerpted from the EDN Designer's Guide to Electromagnetic Compatibility, which is available from [www.ednmag.com](http://www.ednmag.com).*

## DERIVATION OF COMMERCIAL EMI LIMITS

Believe it or not, most EMI regulations have solid engineering behind them. Most are designed to solve real-world problems by providing adequate design margins. Although they can't eliminate every EMI problem, they can greatly decrease the probability of a problem in the field.

You can see a good example of this engineered approach in the radiated-emission limits for commercial and personal computers. Anyone who has failed an FCC or EU radiated-emission test has probably questioned these limits, but they do make a lot of sense. The primary goal of these commercial limits is to prevent interference to nearby television and radio receivers. By making several assumptions, you can obtain a reasonable set of limits. **Figure A** shows the model for these assumptions.

The first assumptions are that interference above 30 MHz is through electromagnetic radiation and that low-frequency interference below 30 MHz is through power-line conduction. These



**In the model for commercial-radiated-emission limits, the goal is to keep interference to less than one-tenth the desired signal strength.**

assumptions are reasonable: The higher the frequency, the more likely radiation will occur, because cables act as efficient antennas at higher frequencies. They're also reasonable assumptions because most TV reception is above 30 MHz.

Another assumption is that the typical electric-field strength for a good picture in an urban setting is around 1000 to 2000  $\mu\text{V}/\text{m}$ . This assumption is also reasonable and consistent with FCC and other broadcast guidelines. These guidelines increase slightly with increasing frequency to account for additional path losses.

Another assumption is that a computer will reside within about 3m of a television receiver in the home and 10 to 30m in a commercial situation. The commercial situation will also likely have a wall between the two, which provides additional shielding.

Another assumption is that by keeping the signal strength of the interference less than one-tenth of the desired signal strength, the interference effects will be minimal.

That's the whole basis of the FCC and EU radiated-emission limits—keep the emissions to less than one-tenth of the typical desired television-receiver-signal strengths. The test distances for the two test categories (Class A—30m and Class B—3m) are based on the above assumptions on distance. The intervening wall for the commercial cases provides the 10-dB relaxation of the Class A limits, when the two are scaled to the same separation distance.

The increasing “stair-step” with frequency is to accommodate the increasing broadcast guidelines for desired signal strength. These regulations are sensible engineering guidelines.

**Hidden antennas and transmitters.** External cables and shielding discontinuities are the most common, but secondary antennas, such as internal cables or even pc boards, can contribute to emissions. All of these are particularly vexing when a resonance occurs, which can greatly amplify radiated emissions.

The primary hidden transmitters for emissions are clocks and other highly repetitive signals, which contain high harmonic content. Three key parameters drive harmonics: repetition rate, duty cycle, and edge rate. Thus, clocks (and clocklike signals) are often the main culprits in emissions, generating harmonic energy throughout the spectrum. (For more details, see the sidebar “The EFFT, or extremely fast Fourier transform”).

A clue in identifying these hidden transmitters is a precise numerical relationship to the fundamental clock (that is, 2 $\times$ , 5 $\times$ , 10 $\times$ , 11 $\times$ , and so on). Because many systems divide the clock internally, there may be a fractional relationship to the fundamental as well (2.5 $\times$ , 3.75 $\times$ , 11.25 $\times$ , and so on).

For example, emissions at 200, 210,

215, and 220 MHz could all be related to the same 20-MHz clock.

We're starting to see secondary hidden transmitters in the form of parasitic oscillations. Years ago, this was a vacuum-tube problem, and it is finally coming back in silicon. We've seen it with voltage regulators and high-frequency amplifiers. A clue is an emission at one frequency that is not an exact multiple of any system clock. (The problems we have seen were all in the 200- to 400-MHz range, but that situation could change.) These problems are still a bit rare but seem to be on the increase.

**Conducted versus radiated emissions.** Most EMI-emissions specifications include both conducted and radiated emissions. For commercial requirements (FCC or EU (European Union)), they break nicely at 30 MHz; with others (such as military), there may be overlap in frequency coverage.

You measure radiated emissions with an antenna connected to a spectrum analyzer or EMI receiver. You can do measurements in an open site (often referred to as an OATS, or open-area test site) or

in an anechoic room (a shielded room designed to minimize reflections). You measure emission levels in microvolts/meter, typically from 30 MHz to 1 GHz. (If your clock speeds are greater than 100 MHz, you may be required to test from 5 to 10 GHz and beyond.) See **Figure 1** for an example.

You measure conducted emissions on the power lines with a line-impedance stabilization network (LISN), a special network that isolates the power lines and ensures test repeatability. The LISN also connects to a spectrum analyzer or EMI receiver. You measure emission levels in microvolts, from 150 kHz (EU) or 450 kHz (FCC) to 30 MHz (**Figure 2**).

The commercial approach, with a break at 30 MHz, makes a lot of sense. At frequencies greater than 30 MHz, there's the potential for hidden antennas, so it's smart to measure the aggregate emissions from the system. At less than 30 MHz, just about the only potential hidden antenna is the power wiring. Even though test engineers could develop a complex fixture to simulate the power wiring, it's much easier and more repeatable to sim-

ply measure the RF voltage coupled at the power interface.

We have adopted (and slightly modified) this 30-MHz division as a rule of thumb for both emissions and RF immunity. The rule follows:

- Under 30 MHz, emissions or RF-immunity problems are probably conducted (and reradiated, or both) by the power lines.

- From 30 to 300 MHz, the emissions or RF-immunity problems are probably associated with external cables (acting as hidden antennas).

- Above 300 MHz, everything be-

comes a suspect hidden antenna (cables, seams/openings in enclosures, pc boards, and so on).

**Class A versus Class B.** The last issue to address before getting into fixing the problems is Class A versus Class B for commercial emissions. In general, Class A refers to equipment used in the industrial environment, and Class B refers to equipment used in the residential environment. The residential environment is assumed to have a nearby television receiver in the same room, so the measurement distances are shorter. Furthermore, even when the two limits are scaled for

the same distance, the residential Class B limits are about 10 dB tougher than the industrial Class A limits. This accounts for any additional attenuation through an anticipated wall or walls between the industrial source and the residential television receiver.

The Class A/B distinction extends to immunity requirements for the EU. (Because the FCC has no immunity requirements, this distinction does not apply in the United States.) For immunity, the industrial Class A limits are tougher than the residential Class B limits, reflecting the assumption that the industrial envi-

## THE EFFT, OR EXTREMELY FAST FOURIER TRANSFORM

First, there was the Fourier transform, then, the fast Fourier transform (FFT), and now, the extremely fast Fourier transform (EFFT). It is not only extremely fast, but also extremely useful when dealing with EMI problems, because it lets you move with ease between the time and frequency domains. It explains why both clock rates and edge rates (rise times) are so crucial for EMI control in digital systems.

Most of us live in a linear, time-domain world. We're used to viewing waveforms, digital or analog, as linear levels plotted against linear

of spectral lines that are bounded by the  $(\sin x)/x$  function. We make it simple in the EMI world, however, because we care only about the worst case. Set  $\sin x=1$ , and you now have a simple  $1/x$  curve. Better yet, plot this as a Bode plot (log frequency versus decibel amplitude), and you get a straight line with a 20 dB per-decade slope that has a breakpoint at  $1/(\pi t)$ . You can't get much simpler than that, can you?

Go through the same hocus-pocus for the triangular wave, and you end up with the harmonics that decrease as  $1/x^2$ . This gives a Bode plot with a 40-dB-per-decade slope and a breakpoint of  $1/(\pi t_r)$ . Obviously, the harmonics of a triangular wave decrease much faster than those of a square wave.

Which brings us to the trapezoidal wave. In the real world, all digital waveforms are trapezoidal, because there are always finite rise/fall times. The trapezoidal wave acts like a square wave at low frequency but then acts like a triangular wave at high frequency. The Bode plot for a trapezoidal wave has two breakpoints: the first at  $1/(\pi t)$  and the second at  $1/(\pi t_r)$ , where the slope changes from 20 to 40 dB per decade.

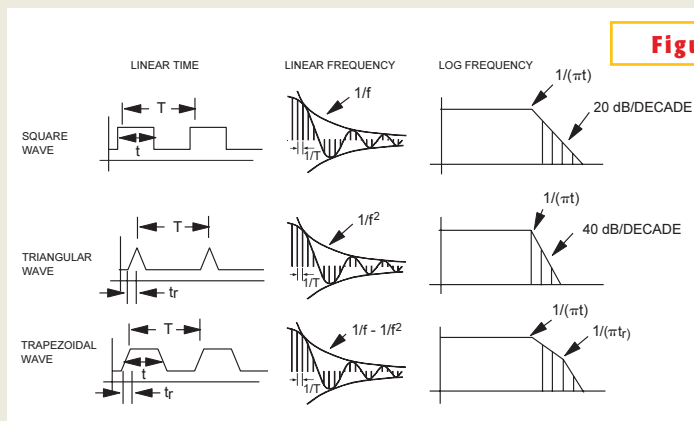
In the EMI world, this last frequency,  $1/(\pi t_r)$ , is a critical design frequency. This does several things:

- It establishes a reasonable upper-frequency limit for emissions due to harmonics. This frequency defines the point at which harmonics start to decrease at a rapid rate, 40 dB/decade.

- It establishes a reasonable EMI bandwidth for immunity. This frequency defines an upper frequency to which a digital or analog circuit responds. This is the same approach used by oscilloscopes—you need a 100-MHz scope to see 3-nsec rise times and a 300-MHz scope to see 1-nsec rise times, and so on.

- It demonstrates that rise-time control is a very effective tool in EMI control for both emissions and increased immunity at the same time. We believe in EMI-bandwidth conservation: Don't waste it if you don't need it. To paraphrase Will Rogers, "They ain't making it anymore."

One last piece of information: The EFFT also works with single events, such as transients. That is why we say an ESD event is a 300-MHz phenomenon (1 nsec=318 MHz) and lightning is a 300-kHz phenomenon (1  $\mu$ sec=318 kHz). Now we can quickly move between the time and frequency domains.



**Figure A**

The extremely fast Fourier transform is useful for EMI problems.

time. Many EMI issues, however, are easier to understand when you view them in the frequency domain, particularly when you also use logarithmic scales. Don't worry: We're just talking about some old friends, Bode plots, with their simple, straight-line approximations. You can gain a lot of insight just by looking at the breakpoints and slopes of some common digital waveforms. Figure A shows three views: linear time, linear frequency, and log frequency. It's very easy to move among them, because there are only two important parameters: pulse-repetition time (T) and rise/fall time ( $t_r$ ).

Start with the square wave. The Fourier series tells you that a square wave comprises a series of harmonically related sine waves. For a perfect square wave with a 50% duty cycle, the even harmonics cancel, and the odd harmonics decrease as the inverse of the harmonic number. That is, the third harmonic amplitude is one-third the fundamental; the fifth harmonic is one-fifth the amplitude, and so on. If you plot this on a linear-frequency scale, you end up with a bunch

ronment is dirtier from an EMI standpoint.

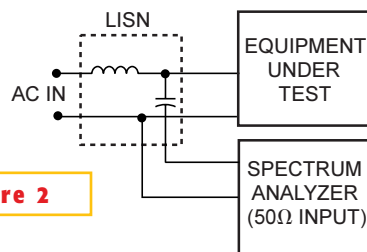
Finally, there is a subtle difference in definitions between the United States and Europe. In the United States, if the equipment will be widely used in homes, then it must be tested to the tougher Class B emissions limits. In the EU, if the equipment will be used in the home or the light industrial environment, then it must be tested to the Class B limits, which are tougher for emissions but less severe for immunity. If the equipment will be used in the heavy industrial environment, however, it must be tested to Class A limits, which are easier for emissions but more severe for immunity. A key point is that your test category may be different for the United States and Europe. If you have a question regarding the proper class, check with an EMI-test laboratory or a cognizant EMI-test engineer.

## TWO STRATEGIC CONCEPTS

General design techniques exist to control and prevent emissions problems, both conducted and radiated. The first concept is to treat all cables as antennas. Cables usually have the largest physical dimensions in a system, so they're the most efficient at radiating or intercepting electromagnetic energy. You can generally assume any conductor that is more than one-twentieth of a wavelength is an effective antenna. At 100 MHz, this amounts to 15 cm, or about 6 in.; at 1 GHz, it's only 15 mm, or about 0.6 in. Of course, at one-fourth of a wavelength or longer, cables become efficient antennas. Table 1 illustrates this critical relationship.

Incidentally, don't ever assume that a shielded cable won't radiate. It's very common for high-frequency current to be coupled onto the shield, causing the entire cable shield to behave as an antenna. In fact, this common-mode cable radiation is a key reason for failing radiated-emissions tests. Furthermore, keep in mind that it's not necessarily the intended signals on a cable that cause problems—often the unintended signals cause the problems. We have seen many problems when an engineer told us, "Don't worry about that cable—it contains only slow signals."

The second concept is to determine the most critical circuits. These are the circuits that are acting as those hidden transmitters. Once again, the most powerful hidden transmitters are the highly



**Figure 2**

**Measure conducted emissions on power lines with a line-impedance stabilization network.**

repetitive signals, such as clocks, but watch out for parasitic oscillations.

## PROTECTION AT THE CIRCUIT LEVEL

Like RFI protection, good emissions protection begins at the circuit level. If possible, suppress critical circuits right at the devices, augmented by filtering on external I/O lines. You should also liberally use ferrites and multilayer pc boards when emissions are issues.

Clocks deserve special attention. Be sure all clocked circuits are well-decoupled for high frequencies. (By clocked circuits, we mean circuits that are clock sources, buffers, and destinations.) You should also have provisions for filtering the clock with ferrites, small capacitors, or both. Of course, for very-high-speed clocks, that provision isn't possible, but slower systems, such as embedded controllers, can often stand significant clock filtering without adverse effects on the system performance. Clock location and trace layout are also important. Avoid placing a clock next to an I/O port; otherwise you're just asking for emissions problems.

Power regulators and high-speed amplifiers also deserve special attention. As mentioned earlier, these circuits can support parasitic oscillations. Regulators are particularly prone—they're already feedback devices. Remember, the criterion for an oscillator is simply an amplifier with positive feedback (phase shift of 180°) at a specific frequency combined with a gain greater than one. Phase shift often results from poor high-frequency decoupling, making good high-frequency decoupling of these circuits critical. Most of these parasitic oscillations occur in the 200- to 400-MHz range.

I/O circuits are connected directly to the hidden-antenna cables, so high-frequency filters are often a last line of defense for radiated emissions. The filters

can be on individual lines or even common-mode chokes, such as clamp-on ferrites. In either case, the objective is to electrically isolate the system electronics from the cables.

Ferrites are your friends for emissions, just as they are for ESD. EMI ferrites are most effective in the 50- to 500-MHz range. Below 50 MHz, they have too little inductance and resistance, and above 500 MHz, the lead capacitance becomes a limiting factor. (Surface-mount ferrites work well into the gigahertz range because they have no exposed leads.)

Be careful when using ferrites. First, be sure to use EMI ferrites, not low-loss ferrites. Second, be sure to use the ferrites in a low-impedance load. (A shunt capacitor of 100 to 1000 pF works well. Keep the capacitor leads short to minimize unwanted lead inductance.) Third, watch out for saturation due to dc or low-frequency currents. As a rule of thumb, small beads are good from about 100 to 500 mA before they saturate.

For RFI emissions, you can use ferrites in clock lines and sometimes in micro-processor or clock-driver  $V_{CC}$  lines. In the latter case, the ferrite is installed on the power-supply side of the decoupling capacitor, forming a small LC or RC filter on the  $V_{CC}$  line. One or two well-placed ferrites can be very effective against RFI emissions by killing high-frequency noise right at the source.

Multilayer boards are effective weapons in the war against emissions. We've seen emission reductions of 10 to 100 (20 to 40 dB) when changing from a two- to a four-layer board. Multilayer boards also increase RFI and ESD immunity at the same time.

These improvements are due to several effects (Figure 3). First, the loop areas of signal and power traces that can act as small transmitting antennas are reduced. At high frequencies, opposing currents induced in a nearby plane cause fields to cancel, spoiling the unwanted antenna effects. Second, high-frequency ground bounce is reduced due to much lower ground impedance. Third, the power-distribution impedance lowers at high frequency due to the distributed capacitance of the power and ground plane, which reduces high-frequency power-line ringing.

Incidentally, you don't always need multiple planes. A major miracle occurs with the addition of the first plane. The

real secret is to get the plane as close to the traces as possible to improve the cancellation effects. We've added ground planes to two-layer boards with copper tape and seen significant improvements. We've also had success by

adding a small local ground plane under individual microcontrollers on two-layer boards.

### CONNECTOR AND CABLES

The higher the frequency, the better the cable and connector must be. Cables act as unintended antennas (both transmitting and receiving) for RF energy. Connectors provide unintended leakage points to and from the cable shield, and poor connectors render even the best cable ineffective. Cable/connector problems are a major reason for failing commercial radiated-emission tests.

You need to consider cables and connectors together as a system and not as individual components. Think of your cables as a garden hose. The connections to the faucet (and between the connectors and the hose) are just as important as the hose material itself. In fact, the best hose in the world will leak if the connections aren't tight. So it is with cables and connectors for RFI problems. Here are some recommendations.

**Use high-quality shielding above 10 MHz.** Below approximately 10 MHz, most cable shielding works pretty well, but above 10 MHz, leakage through the shield becomes a problem. In fact, the higher the frequency, the leakier the shield becomes due to a shield property known as transfer impedance.

You need to determine the highest frequency at which the shield must perform. If all of your RF sources or problems are below 10 MHz (don't forget harmonics), then simple braid shielding should work well. At higher frequencies,

| FREQUENCY | WAVELENGTH | 1/4 WAVELENGTH | 1/20 WAVELENGTH |
|-----------|------------|----------------|-----------------|
| 10 kHz    | 30 km      | 7500m          | 1500m           |
| 100 kHz   | 3 km       | 750m           | 150m            |
| 1 MHz     | 300m       | 75m            | 15m             |
| 10 MHz    | 30m        | 7.5m           | 1.5m            |
| 100 MHz   | 3m         | 75 cm          | 15 cm           |
| 1 GHz     | 30 cm      | 7.5cm          | 1.5cm           |

use high-coverage braids or braid-over-foil shielding. Incidentally, solid foil works well at high frequencies, as long as it remains intact. If a foil shield is flexed, however, it may rupture, and the shielding is lost. That's why a braid-over-foil is preferred to a simple metal-foil shield.

**Use high-quality connectors.** This is good advice at any frequency but very important at frequencies above 10 MHz. The objective is to provide full 360° coverage all the way from the cable shield to the cabinet. Every joint must be watertight: shield to connector, connector to connector, and connector to chassis.

Don't use pigtails or drain wires to make a connection between the shield and connector or chassis. The impedance of such a connection is inductive and can be very high at even low radio frequencies. We have seen 30 to 40 dB increases in radiated-emission levels due to this problem—it's very important! Even a loose connection in a connector is enough to cause a problem at 100 MHz and higher.

**If you can't shield, then filter.** For cables with data rates under 1 MHz, you can often use filtering in lieu of shielding. At 1 MHz, a wavelength is 300m, and most cables are not very efficient antennas at these frequencies and wavelengths. Even though the intended signals are at 1 MHz or less, you must provide filtering to prevent unintended higher frequency energy from sneaking into (or out of) the system via the cables. Even a simple RC filter with a corner frequency of 1 MHz provides 30 dB of filtering at 30 MHz and 40 dB at 100 MHz.

Small, high-frequency filters consisting of ferrites and bypass capacitors work well. Keep the leads short and connect bypass capacitors directly to circuit ground. This situation is different from RF or immunity, in which we recommend connecting the capacitors directly to chassis ground. To deal with both problems, you may need separate capacitors, or you may need

to solidly ground the chassis and signal ground together at the I/O area, which actually has other advantages and is usually recommended for high-frequency systems.

**Don't forget internal cables.** Internal cables can

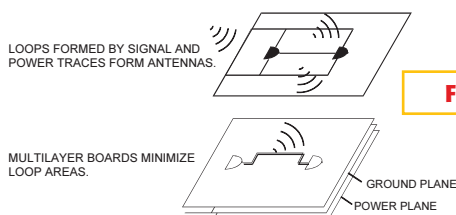
also act as unwanted antennas, and they deserve your attention. Be careful with routing, and keep cables away from seams and slots in enclosures. We've seen numerous FCC emission failures due to cables close to seams, as the RF jumps from the internal cable to the slot antenna formed by seams or slots, which then radiates the unwanted energy. Common-mode ferrites that clamp over the entire cable can also be a big help in taming RF energy on internal cables.

If you're using ribbon cables, use the maximum number of ground returns and spread them throughout the cables, which minimizes loop areas that can also act as unwanted loop antennas. The best situation is a dedicated return line for each signal line. But our experience has shown that we often go as high as a 5-to-1 ratio of signal lines to return lines, as long as the returns are spread throughout the cable and as long as the edge rates are greater than 5 nsec. With 3-nsec edge rates, we generally recommend no more than a 3-to-1 ratio of signal lines to return lines, and with 1-nsec edge rates, 1-to-1 is definitely preferred.

### RF-GROUNDING GUIDELINES

**Inductance is the killer in RF grounding.** When dealing with grounding, most engineers get hung up on resistance and ignore inductance, which leads to all kinds of problems when dealing with RF energy. In fact, inductive effects predominate throughout the RF range, even at the low end of approximately 10 kHz.

As a rule, a round wire has a self-inductance of about 10 nH/cm. This rule is good for most wires used in equipment design, because the inductance is insensitive to wire size. For most wire, the inductive reactance per length exceeds the resistance per length at frequencies above 10 kHz. By 100 MHz, the inductive reactance can be several orders of magnitude greater than the resistance. For example, a 4-in. #12 wire has an inductive reactance of about 50Ω at 100 MHz, and its resistance is only milliohms.



**Figure 3**

**Multilayer boards often reduce emissions by 10 to 100 times.**

One way to reduce the inductance is to use a wide strap rather than a wire. In theory, an infinite plane is the best, but from a practical standpoint, it's the aspect ratio (length to width) that is important. For many years, the military has recommended using a maximum ratio of 5-to-1 (length to width) for bond straps in radio and radar systems, but sometimes that's still not good enough. Therefore,

use 3-to-1 for bonds between boards and chassis. Flat wire or braid alone doesn't work its miracles unless the aspect ratio is favorable. Keep those high-frequency grounds short, fat, and flat!

**Where you ground is as important as how you ground.** When dealing with RF emissions, you usually use signal ground to intercept RF currents so that they go back to their source and divert them

from cables acting as unwanted antennas. Thus, onboard filters should be grounded to the signal ground to optimize emission reduction.

Common-mode currents in the signal ground can also contribute to emissions. In that case, it is advantageous to make a solid connection between the signal ground and chassis ground (assuming you're using a metal chassis) at the I/O connectors. (The objective is to short any voltage signal ground and chassis ground at the cable connection.) Better yet, ground your high-speed boards as often as you can, through multiple short, fat, flat connections, which helps minimize resonances due to the board size.

#### **RF-SHIELDING GUIDELINES**

Most high-speed systems need at least some shielding to control radiated emissions. Although the exact values necessary vary from system to system, here are some typical values for today's equipment:

- Commercial equipment: 30 to 60 dB typical (reduces fields by 30 to 1000 times)
- Military equipment: 60 to 90 dB typical (reduces fields by 1000 to 30,000 times)
- Special situations: you may need 90 to 120 dB (reduces fields by 30,000 to 1,000,000 times.)

Generally, 120 dB is a practical upper limit for most equipment enclosures. Even though the materials may be capable of higher levels, the openings and penetrations limit the overall shield performance.

**Thin materials work fine.** Thin conductive coatings provide high levels of shielding over 10 kHz to 10 GHz and beyond. Aluminum foil provides at least 90 dB over this frequency range. Thin metal coatings, such as nickel or copper paints, provide 40-to-60 dB of shielding, and vacuum plating and electroless deposition are good to 80 dB or more. Thus, these processes are usually more than adequate for commercial designs.

Thin shields are not effective for low-frequency magnetic fields, such as those from a power supply or magnetic-deflection circuit. In those cases, you need thick steel or other ferrous materials. Generally, this is not an issue above approximately 20 kHz. For emissions, steel works fine for high frequencies and is rarely needed only for magnetic-field emis-

sions at low frequencies. Low-frequency emissions are not concerns for commercial equipment, but they can be for certain types of military equipment.

For now, just remember that thin, highly conductive materials work well for most of your RF-emissions (and RF-immunity and ESD) problems.

**Slots and seams destroy RF shields.** A major problem with RF shielding is leak-

age due to slots and seams. These discontinuities act as slot antennas and actually reradiate high-frequency energy. Thus, you want to keep internal cables away from slots and seams because they're hot with RF energy.

In addition, it's the longest dimension, not the area, that is critical. A long thin slot is like a long thin wire antenna, and both radiate equally well. A rule of

thumb in the EMI world is to limit the longest dimension of any opening to one-twentieth of a wavelength or less at the highest frequency of concern. For 100 MHz, that distance is about 6 in.; at 1 GHz, it's only about 1/2 in. Even that amount may not be enough, because the one-twentieth rule provides only 20 dB of attenuation through the slot. You may get away with these dimensions on a low-frequency commercial design, but for higher frequencies (clocks over 100 MHz) or commercial designs, even 1/200 of a wavelength may be marginal. Those types of systems usually need gaskets and filters to maintain the necessary shielding integrity.

**Unfiltered penetrations also destroy RF shields.** Any isolated conductor passing through a shield can carry high-frequency energy right through the shield. All penetrations must be bonded to the cabinet or decoupled with high-frequency filters. (Obviously, you can't short out power and signal lines, so you filter them as they pass through the shield barrier.)

We can't emphasize this point enough. We've seen high-performance shield rooms with more than 120 dB of shielding turned into 20-dB shielding wimps due to a single unterminated cable penetrating the shield. Fortunately, it's easy to fix if it's only one cable—you just add a bulkhead connector, and the shielding is restored.

For RF shielding, use a continuous metal coating with minimal seams. Filter or bond all penetrations to the shield. Keep the longest dimension of any opening at less than 1/2 in. if you need to go to 1 GHz, and keep all internal cables and critical circuits at least 2 in. away from seams and openings. You may need gasket material for seams and slots for higher speed systems (or military designs), so you should design your enclosures to add gaskets if necessary. □

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#### AUTHOR'S BIOGRAPHIES

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