Finding and Fixing Problems
Chapter 16

Abstract

In general, most reduced emission design fixes are really much simpler than hardware designers would expect. This chapter describes the required equipment and general techniques necessary to quickly enable inhouse engineering personnel to perform sensitive emission corrective actions.

Compromising Signals in the Real World

Compromising signals have their source in a circuit intended to carry the Red data. Basically, the semiconductor or integrated circuit pushes energy down a trace or wire and somehow this energy escapes through some other unintended path.

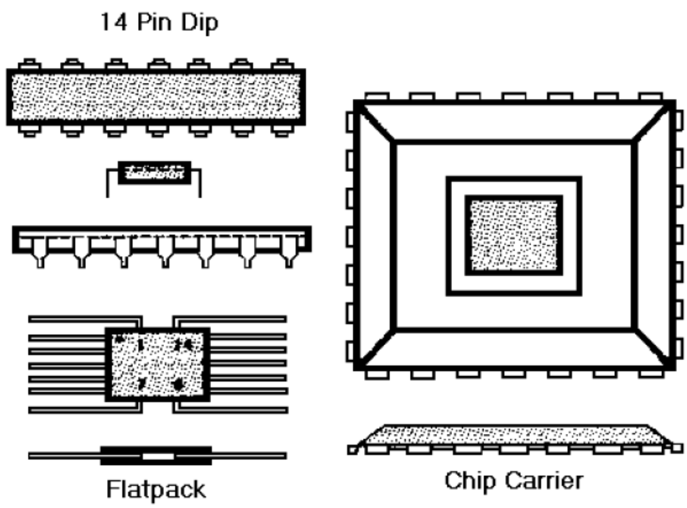
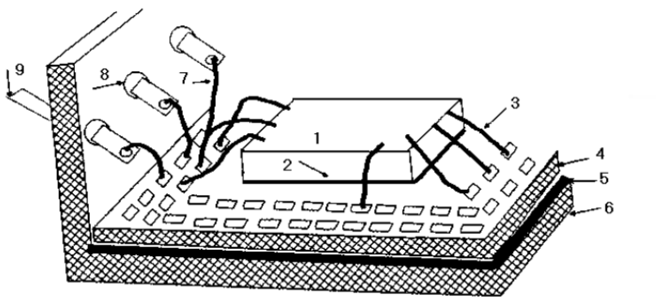


Figure 16-1 Adjacent pins are sufficiently Close to Enable Coupling

As can be seen in Figures 16-1 and 16-2, adjacent pins in Dip and Flatpack packages are sufficiently close that crosstalk coupling is possible, particularly at higher frequency harmonics. Unfortunately, the traditional Dip (Figure 16-2), with vertical pins, represents the worst offender. The layout of the package can also be a problem. Figure 16-3 is a standard inverter. In this case, a designer might inadvertently use two of the gates adjacent to each other, one for a RED protected signal and one for a BLACK control line that has little protection as it makes its way through the other circuitry in the box.



1. Chip
2. Die Attached Epoxy
3. Bond Wire
4. Programmable Silicon Circuit Board
5. Substrate Attached Epoxy
6. Package Base
7. Bond Wire
8. Glass Seal
9. Package Lead

Figure 16-2 DIP Package Substrate to Pin Interface

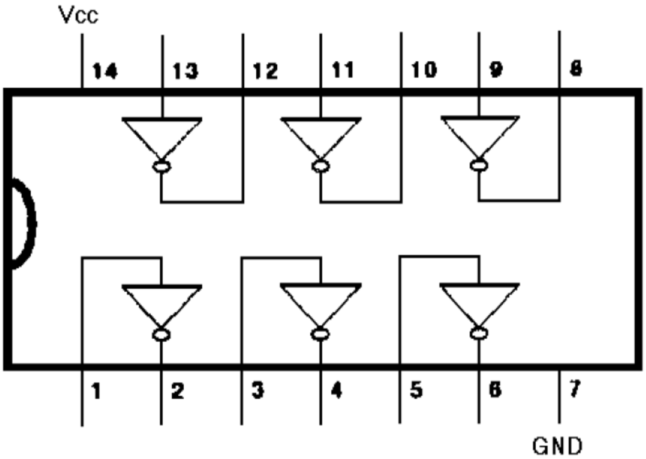


Figure 16-3 Inverter Gate Layout on DIP Package

The graph of Figure 16-4 shows the isolation between individual gates as frequency changes. Another unfortunate issue for TEMPEST engineers is that all digital pulses have significant harmonics at higher frequencies. This is particularly true with so called "saturating logic" or very fast rise and fall time logic.

While CMOS (Figure 16-5) is quieter, saturating logic is often used at RED to BLACK interfaces so isolation can be achieved, particularly for the

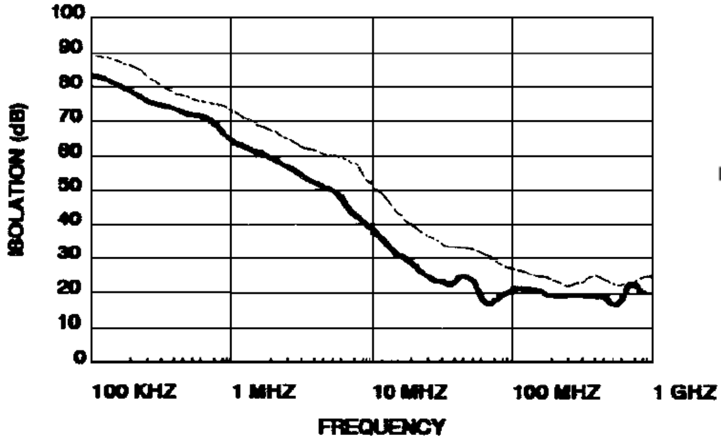


Figure 16-4 Adjacent Isolation between DIP Gates

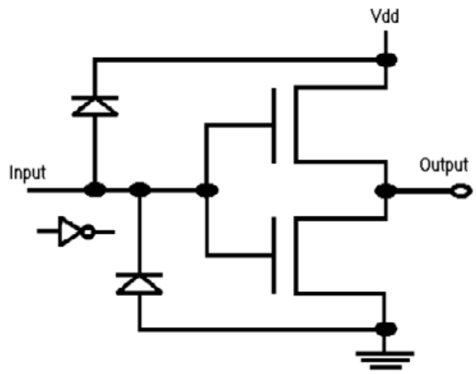


Figure 16-5 CMOS Internal Design

higher frequency harmonics. The digital filter depicted in Figure 16-6 is commonly used under these conditions. This is a digital filter with both forward and reverse isolation at a digital interface. In this case, very fast TTL logic might

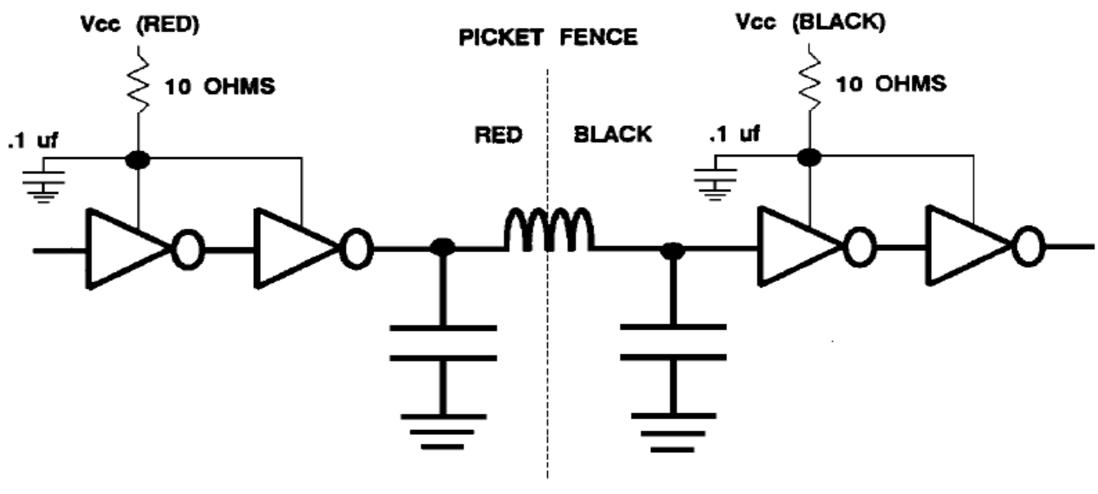


Figure 16-5 Saturating Logic Used to Provide Digital Filtering at a RED/BLACK Interface

be used for the driving and receiving logic with the passive filter used to provide higher frequency attenuation.

Setting Up a Troubleshooting Lab to Detect Signals

As sometimes happens, many equipment manufacturers don't perform inhouse emission reductions prior to sending their equipment to FCC test labs still pay premium costs for troubleshooting, but even these costs are considerably less than the cost associated with extensive laboratory troubleshooting. However, lessons learned from the FCC test industry can be applied by equipment manufacturers to greatly reduce their ultimate costs as well.

While not all emission related equipment problems will be identified with a comparatively inexpensive and simple inhouse test setup, the vast majority of problems can be quickly found and fixed with the approach proposed herein. First consider the cost of a basic set of test equipment as listed in the table below.

Table 1

Basic Troubleshooting Equipment Set

Suggested New or Used Equipment	Appx. Cost
Used Spectrum Analyzer to 1 GHz (HP 8568)	$15K to 25K
Used Pre-amps	$1200
Used Oscilloscope (400 GHz)	$5000 to 8000
E field antenna set	$3000
Tripod	$200
PLISN	$2500
Attenuator	$1000
Cables and Connectors	$500
Hand Probes	$400
Maximum Total (1990 Prices)	$44,800 (US)

In justifying the cost of the equipment described, extensively equipped test labs on the average charge about $1000 per day for test time. It’s a simple calculation to discover that savings of just under two months of development testing more then pays for the equipment needed to troubleshoot your own products. In addition, the equipment you purchase may qualify for a tax deduction, and can also be depreciated over time. It should also be noted that this suite of equipment can be rented for less then $10,000 per month. For the company that has only infrequent (less than 2 months/year) need of the equipment, rental may be the preferred (and also deductible) cost option.

Notice in the list above that some items commonly thought of as essential are not necessarily required for an emission troubleshooting lab. For instance, there is really no need for a shielded room (about a $20,000 cost) if no formal testing is to be performed. Unless your test laboratory is very noisy, simple testing can often be performed "around" the areas where ambient noise is a problem (and with a little practice "within" the noisy environment). Problem signals that appear at one frequency will normally show up all over the spectrum, allowing ample opportunity for detection elsewhere.

Another common problem encountered when purchasing test equipment is the concern often expressed that "none of my people know how to use the equipment for specialized emission testing." While this is true to some extent, remember that engineers troubleshooting equipment to reduce emissions don't need to perform a formal acceptability type test. If there is a major concern about using the equipment, hire a consultant to come in and show them how to use it.

Otherwise, remember all that is really required from engineering personnel is the ability to find, identify, and reduce problem signals, similar to what is done in the US for FCC emission suppression work. In addition, people who design the equipment 1) know how it works, 2) know how to use the unit specific test equipment, and 3) are the best suited to find and fix the problem, once they know what to look for.

If testing according to some protected formal techniques is desired, it would be a problem to test in an open lab environment. However, testing in a closed lab with restricted access, except for persons with the required need-to-know, is not too difficult to implement, and may be worth the effort to implement in the long run.

The final concern often expressed by non-emission designers is "I have no idea what to look for". If you know what your problem signal looks like on an oscilloscope, leave a scope probe connected directly to the data line, and use the spectrum analyzer at a wide bandwidth to find this same signal at some point in the frequency domain. Obviously, reducing the spectrum analyzer bandwidth will enable the tester to more clearly identify the signal. The detected data signal is the signal to be reduced, and it can show up in radiated form at almost any frequency.

What Do You Do

The easiest and least expensive way to support a redesign and trouble shooting effort is to start by building a finger wound antenna probe. To make a BNC trouble shooting H-field probe, using a barrel connector, solder a wire to the center pin, wrap the wire around your finger about 35 times, then remove your finger and solder the other wire end to the outside surface of the barrel. A large tip on your soldering iron is necessary to heat the barrel enough for solder to stick. Use masking tape to secure the loops from spreading out too far or unraveling. More sensitive probes are available commercially.

The troubleshooting method described here is nearly identical to the method described by Berger[1], and is based on the assumption that a noise signal that radiates an appreciable emission due to current flow can be readily detected at close range with an inefficient H-field probe. Also, a second assumption is that the radiated emission exists at many harmonics, and can probably be detected with a mid-range (biconical) type antenna at some measurable level by monitoring the spectrum analyzer and preamp output on an oscilloscope. The test equipment is shown in Figure 16-6.

[1] Berger, H. Stephen, Using an Oscilloscope and Sniffer Probe to Solve EMI Problems, Evaluation Engineering Magazine, February, 1987.

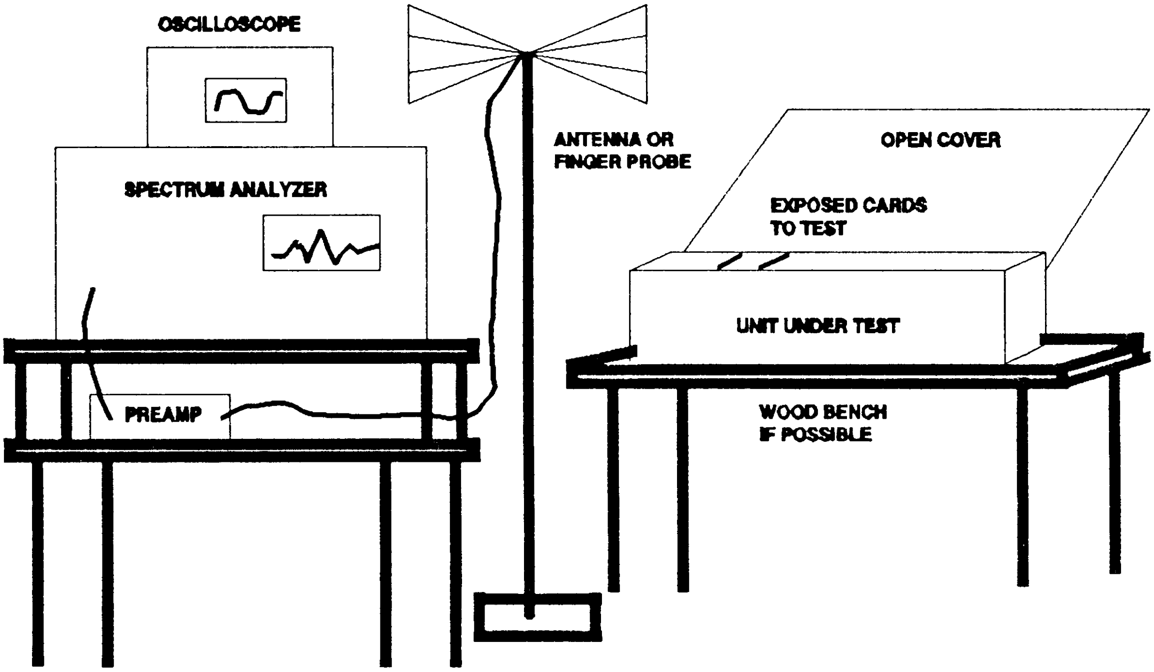


Figure 16-6 Equipment Test Set-up

In nearly every case, the radiated condition will become observable when the unit containing the signal source is exposed by opening its cover. Therefore, by reducing this easily detectable signal at its source initially, an engineer can greatly enhance the chances of passing accreditation testing the first time through.

Open the cover on the box to be tested shown in Figure 16-7, and first, using an oscilloscope and preamp while looking at the schematic diagram and layout drawing, find one of the noisy data lines to be emission controlled. Next, determine the RF spectrum of this signal with a preamp connected to the input of the spectrum analyzer if necessary. Connect your finger probe to the spectrum analyzer and move the probe around the board to locate and map where the highest readings are for the signal being analyzed. Your goal will be a complete mapping of the

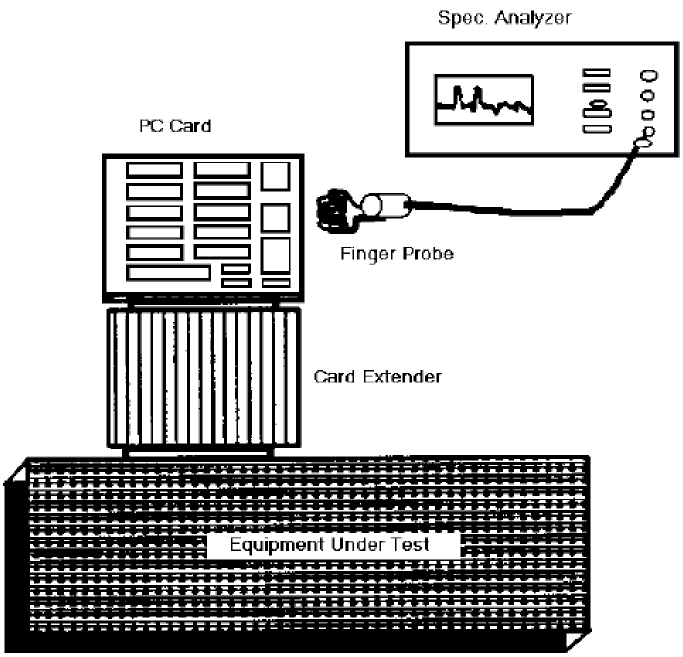


Figure 16-7 Open Box Signal Probing

card as shown in Figure 16-8. Remember that you may be observing a frequency domain signal that can show up at various harmonics. You will need to also see the time domain signal pulse (clock or signal related) that can be wide or narrow depending on the bandwidth setting.

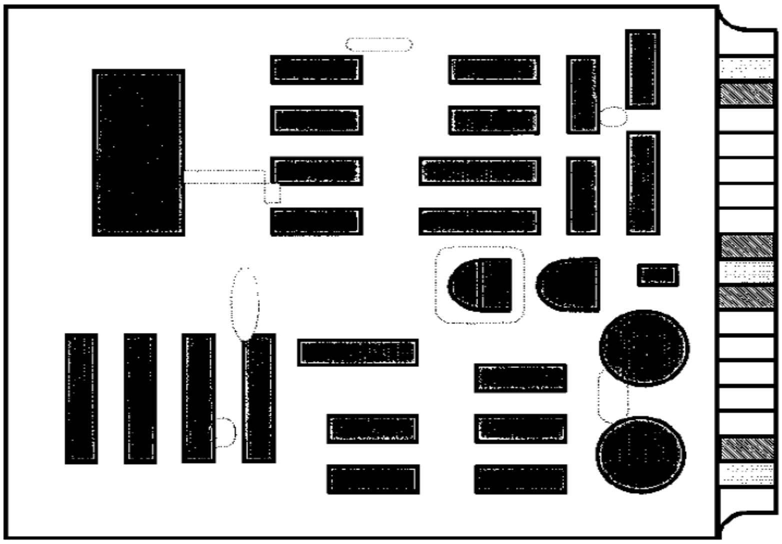


Figure 16-8 PC Card Emission Hot Spot Mapping

At each point where a high H-field level is detected, measure the signal amplitude using the spectrum analyzer and a fixed commercial E-field antenna located at some point near to the unit under test, exactly as would be done in a FCC troubleshooting test lab. The E-field is measured at a fixed location since it is easier to identify and measure its corresponding H-field using a home made uncalibrated or commercial but still less sensitive finger probe. The measured E-field signal should be easily identified since it will look nearly identical to the signal located with the finger probe. Repeat this procedure for each of the other signal lines to be analyzed.

Once the radiated E-field emissions from each of the problem signals has been measured, the next step is to systematically reduce these radiated emission levels using source suppression components mounted directly to the pc card. Many sources[2] are available describing card level noise reduction techniques and noise testing techniques. If a manufacturer can correct emission problems during the design stage of a program, it is a simple matter to incorporate these fixes within the overall product development program. However, if a laboratory finds problems and recommends fixes after a product has been built and delivered to the test lab, both schedule delays and redesign costs increase dramatically.

If a detected signal is closely associated with a specific integrated circuit, and not just an output pin, the initial suppression technique could include a ferrite pad under the entire integrated circuit (IC). This fix often works with F series logic operating at high data rates. Another approach at the integrated circuit level which does not affect the output waveform is to add a resistor (try 10 ohms) in series with the IC power input (DC bus), and increase the value of the decoupling capacitor (appx. 1 μF) located between the resistor and the IC. The preferred capacitor for high frequency DC decoupling is a ceramic disk.

Often the detected signal follows a printed circuit board trace and is greatest at the location of the line driver for the trace. Therefore, beginning with an uncovered operating board and the largest emission detected, and using a schematic and pc board layout drawing,

[2] Compliance Engineering Magazine and Application Notes, Boxborough, MA; EMC Technology Magazine, Gainesville, VA; ITEM Magazine, West Conshohocken, PA; etc

observe the signal waveshape on the trace using an oscilloscope. Chances are that the signal waveform will have ringing and overshoot as shown in Figure 16-9.

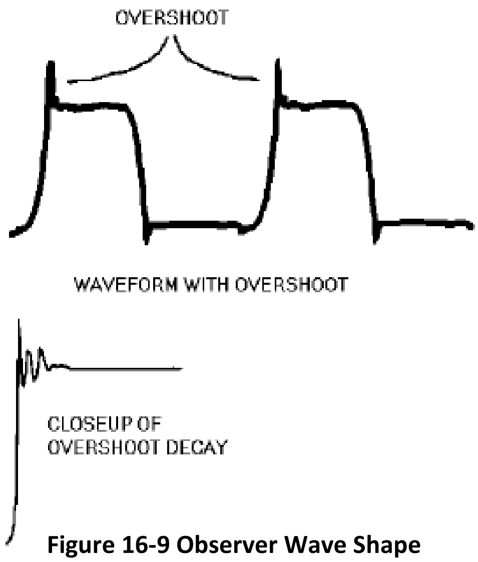


Figure 16-9 Observer Wave Shape

To reduce the trace ringing, begin by adding simple wave shaping (loading) components adjacent to their source while monitoring the amplitude of the emission under investigation. Start with a series RC filter of 410 pF and 50 ohms as the loading components. Adding a capacitor only is not a good idea as it has the effect of shunting noise into the ground plane, and will increase the radiated antenna farm effect from common mode noise in the ground plane.

Once the waveform appears clean from loading, again measure the radiated level of the data line with your fixed antenna and spectrum analyzer. The detected emission level should be greatly reduced. However, if the emissions are higher, then you have increased the problem associated with antenna farm effects from the ground return, and absorption rather than a loading component is required. In this case, a series ferrite bead', or a series ferrite filter (shown in Figure 16-10) should be added, with a size and value proportional to the frequency being detected. However, since the addition of ferrites can sometimes cause harmonics to be generated, it is important to investigate this possibility with the spectrum analyzer before finalizing your design.

If the ferrite bead can't be tolerated by the circuit, the next approach is to add a small series resistor in the data line itself. In this case, insure the voltage drop across the resistor is not enough to affect the logic operation. The value of the resistor can be determined by the logic family, i.e. the source current provided.

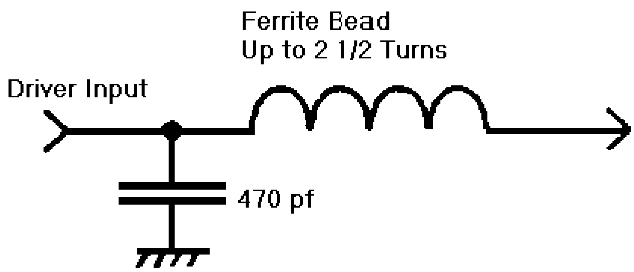


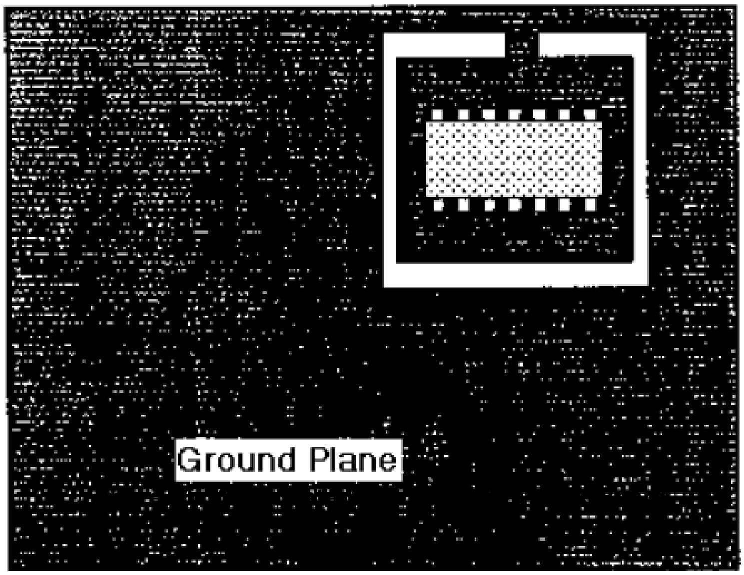
Figure 16-10 Ferrite Filter

What's often encountered, a particular emission seems uniformly distributed over the entire card, and only detected at higher or lower values depending on probe location. In this case, the date related emission is likely being modulated on a noise source, such as the system clock, and is widely distributed throughout the circuitry by the power system or ground plane (or trace). To reduce a widely distributed signal, either the signal must be localized and controlled, or the carrier must be reduced and/or localized.

Controlling Widespread Signal Problems

One of the easiest methods of localizing an emission was mentioned previously by using power source decoupling. Normally a resistor or ferrite on the IC's power input line, plus a larger decoupling capacitor effectively isolates the IC source. In addition, locating the signal source (such as the clock circuit) near the card interface connector during board layout, and then placing a ground plane under the IC with the conductive connection to the rest of the ground plane at only one point, as shown in Figure 16-11, is also effective.

Controlling a carrier, especially a wideband noise source like the system clock, involves a combination of all the techniques described above. In addition, the carrier ground returns may need to be controlled by isolated branching, as shown in Figure 16-12, to insure the noisy ground does not contaminate all other grounds on the pc board.



Putting it All Together

After all identified problem emissions have been reduced as much as possible using the techniques previously described, choose the largest emission detected, close up your box, and see if the signal is still detectable. If it is, chances are that your box leaks or a ground loop exists within your box, and its inherent shielding is having no effect.

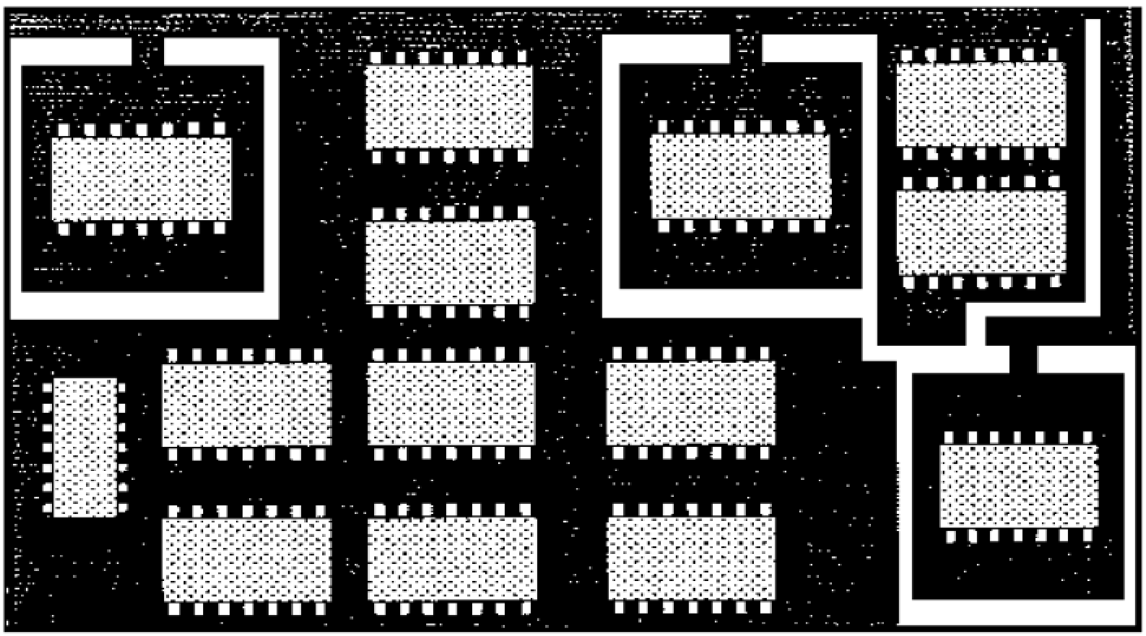


Figure 16-12 PC Card Showing Isolated Ground Plane Branching

The Ground Plane

With the box closed, again use your finger probe and move around the box to find out if a leak is present. Leaks can usually be fixed with finger stock, sanding to insure good metal to metal contact, or gasketing. In some cases, a mechanical redesign is your only alternative.

If an obvious leak is not detected) and the signal is higher in some places and low but detectable in others, a more serious system related problem exists. In this case, take a look at how the pc board is grounded, and reduce the ground to either a single point ground, or as in the case of a pc, the processor board might need multiple grounds, with only the problem signal grounds controlled to a single point.

Check to make sure the power supply is isolated, and also well grounded to the primary central point ground. This is normally the case near the processor ground for metal enclosed electronic units. If the signal is still detectable, go back to the signal source and further reduce it. If further reduction is difficult or impossible, the only alternative may be to add a ground plane to the outer layers of the pc card in a sandwich approach. This is usually the final alternative when all else fails, but it also usually works to fix the problem.

Conducted Problems

So far we have only discussed radiated problems. Attacking an emission at its source using decoupling at the IC's power input pin also works to reduce conducted emissions. In addition, choosing a less efficient (and usually less noisy) power supply, such as a shunt or series-shunt regulator, and mechanically partitioning your chassis to provide separation between the power supply and the rest of the electronics, including associated cabling, will greatly reduce your chances of encountering a conducted problem.

Once you have identified a radiated emission, the same technique can be used to identify the noise emission on your powerlines , except that you need a Powerline Impedance Stabilization Network (PLISN) to match the spectrum analyzer input to the powerline.

If the noise source can be detected on your powerline, in most cases it coupled around your filtering or partitioning and contaminated the power supply primary. In this situation, if you can't go back and isolate the signal at its source further, and maximum power supply isolation has been mechanically implemented, either add or increase powerline filtering first at the power supply secondary, and finally at the power supply primary. If the signal is still detectable, call in a consultant.

EMI Hand Probes

The availability of hand-held “sniffer” probes since the 1990s has significantly enhanced the engineer’s ability to detect problem noise sources. The previously used finger probes were less sensitive as well as prone to directional detection problems. E-field or H-field probes, such as shown in Figure 16-13, have become a required item in most designer’s equipment suites.

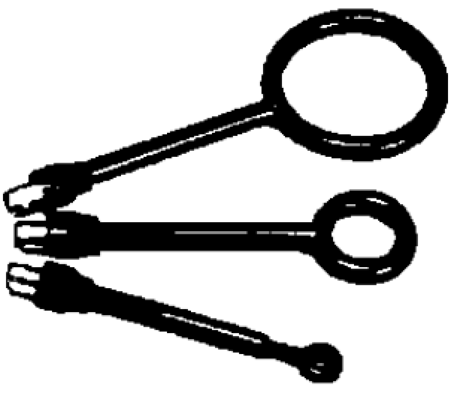


Figure 16-13 Hand-held "Sniffer" Probes

Using Preamps with Spectrum Analyzers

A few words about pre-amps. Preamplifiers improve spectrum analyzer sensitivity by decreasing the noise figure of the pre- amplifier/analyzer combination. As preamplifier gain increases and noise figure decreases, analyzer sensitivity increases. To achieve maximum sensitivity without significantly degrading dynamic range, gain must be optimized. To determine the optimum gain, the overall system noise figure must first be evaluated, as follows:

$$\mathbf{F}_{tot} = F_1 + (F_2 - 1)/G_1$$

F_{tot} = the total noise figure of the spectrum analyzer and preamplifier combination,
F_1 = the noise figure of the pre- amplifier
F_2 = the noise figure of the spectrum analyzer, and
G_1 = the power gain of the preamplifier.

The first criteria for using the preamplifier approach is clearly a preamplifier noise figure much lower than that of the spectrum analyzer. Second, the equation shows that the total noise figure decreases when G_1 increases and approaches F_1 that is, when G_1 becomes very large compared to F_2. Therefore, because the spectrum analyzer's noise level is proportional to F_2.the lowest total noise level- or best sensitivity-is obtained with the highest preamplifier gain.

However, inherent problems exist. The use of any preamplifier results in the reduction of the spectrum analyzer's dynamic range. A preamplifier with gain of G1 reduces the input 1-dB compression point level by G1. However, the decrease in noise level is not proportional to G1, as shown in the equation. Therefore, there must be an optimum gain G1 at which the increase in sensitivity is significant without an objectionable loss of dynamic range.

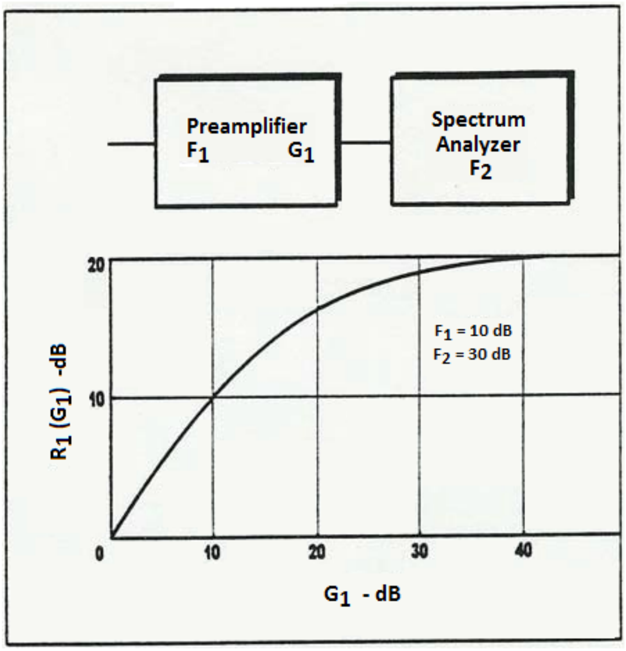


Figure 16-14 Noise Level Improvement Function

A basic setup of the spectrum analyzer with an internal noise figure of F_{21} and a preamplifier with noise figure of F_1 and gain of G_1 is shown in Figure 16-14. The figure shows the noise-level improvement function R_1G_1 as a function of G_1 expressed in decibels, for a preamplifier with a noise figure F_1 equal to 10 dB and a spectrum analyzer with a noise figure F_2 equal to 30 dB. The preamplifier gain is variable. The ratio of the input noise of the spectrum analyzer without a preamplifier to the input noise with a preamplifier (shown in the plot) indicates the result of increasing preamplifier gain. As the gain G1 increases, sensitivity increases significantly until the gain reaches 20 dB. The curve indicates that gains higher than 20 dB, the sensitivity does not increase significantly.

Another function of interest is the ratio $R_1(G_1)$ of the dynamic range of the spectrum analyzer alone to the dynamic range of the spectrum analyzer with a preamplifier. Figure 16-15 shows a plot of the $R_1(G_1)$ in decibels, versus the preamplifier gain, G_1. The curve indicates that for gains less than 20 dB, degradation is very small. Dynamic range degradation increases rapidly (and the dynamic range decreases) as the increasing preamplifier gain.

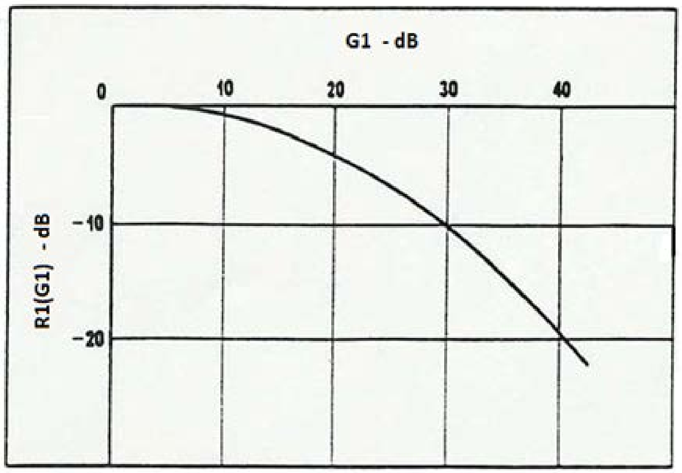


Figure 16-15 Dynamic Range Degradation with Gain

Expression of Merit

The product of the two functions R1(G1) and R2(G2) is defined as R(G1), the preamplifier's expression of merit. In essence, R(G1) is the ratio of the increase in sensitivity and the decrease in dynamic range, as a function of G1.. When evaluating R1(G1) and R2(G2), it is evident that the merit function R(G1) increases at low gain, indicating that the sensitivity increases without sacrificing dynamic range. However, as preamplifier gain increases, the merit function decreases. This decrease indicates that sensitivity improves only slightly, but there is a severe reduction in dynamic range.

In summary, the overall noise figure of the preamplifier/analyzer system, using the optimum preamplifier gain, is 3 dB higher than the noise figure of the preamplifier alone. In summary, when a preamplifier is used with a spectrum analyzer, its optimum gain will decrease dynamic range by only 3 dB, but will increase the sensitivity by the difference in noise figures of the spectrum analyzer and the preamplifier, minus 3 dB.

Conclusions

This chapter provides suggestions to TEMPEST engineers on how to quickly find and correct emission problems as well as greatly reduce their costs associated with testing emission suppressed equipment.