Class 366: Noise and Shielding

Kim Fowler

Noise can affect most devices. Designing adequate shielding does not have to be a black art – in fact, it should not be. Understanding some basic principles and applying appropriate measures will eliminate most problems. The references contain expositions on many possible situations for shielding. [1 – 3]

I first describe the various mechanisms of noise – understanding them will give you immediate insight into avoiding noise problems. Next I cover issues in grounding and electrostatic discharge. I then discuss provide basic design tips and techniques to diagnose problems and select the appropriate shielding. Finally, I apply these basic principles to circuit layout.

Part 1: Noise and Coupling

Disruption from noise requires three distinct components. All noise problems begin with a source and end with a susceptible receiver. Some sort of mechanism is the third component, which couples the noise from the source to the receiver. Figure 1 illustrates these components of noise.

Removing any one of these components eliminates the noise problem. Unfortunately, you typically cannot remove the sources; furthermore, the susceptible receiver is usually part of your instrument. This leaves us with dealing with the third component – the coupling mechanism.

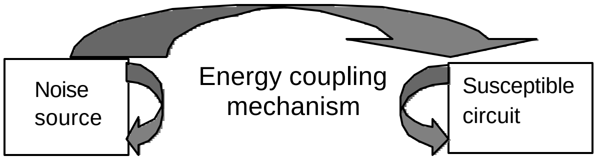


Fig. 1 Electromagnetic interference (EMI) always requires three distinct components: a noise source, a coupling mechanism, and a susceptible circuit. (© 2001 by Kim Fowler, used with permission.)

Sources

Some examples of sources are power lines, motors, high-voltage equipment (e.g. spark plugs, igniters), discharges and sparks (e.g. lightning, static electricity), and high-current equipment (e.g. arc welders). Clearly most of these sources either cannot move or are unpredictable in occurrence. You may be able to move the arc welder but not if your instrument is the robotic controller that positions it.

Receivers

You can usually trace susceptibility within a "receiver" to incorrect return paths or long, improperly shielded signal lines. Examples of susceptibility include crosstalk on inputs that flips bits in digital logic, radio interference and crackle, and static discharge that destroys components. Better understanding the coupling mechanisms will help you reduce susceptibility.

Coupling Mechanisms

Coupling mechanisms have four basic modes:

- conductive
- inductive
- capacitive
- electromagnetic.

Conductive coupling requires a continuous circuit path between source and receiver. This means it needs a complete circuit loop. While no absolute limit exists on frequency of operation, conductive coupling typically takes place between DC and 10 MHz.

Inductive coupling requires a current loop that generates a changing magnetic flux. The induced voltage is proportional to both the loop area and the time-rate of change in current. Reducing the loop area will reduce inductive coupling. Inductive coupling typically becomes a problem above 3 KHz.

Capacitive coupling requires both a changing voltage and proximity between circuits, i.e. a source and a susceptible receiver. The induced voltage is proportional to both the time-rate of change in voltage and inversely related to separation distance. Separating the source and susceptible receiver will reduce capacitive coupling, as will properly connecting a shield. Capacitive coupling typically becomes a problem above 1 KHz.

Electromagnetic coupling generally occurs when frequencies exceed 20 MHz and the length of the signal conductors exceeds 5% of the wavelength. Cables are the primary sources of electromagnetic interference and they typically are the receiver antennas.

Two Concepts in Energy Transfer

Before I discuss each coupling mechanism, I will introduce two simple concepts that will ease the diagnosis of noise problems. The first concept is that current follows the path of lowest impedance; knowing this will help you trace current paths. The second concept is “pseudo-impedance;” it provides an indication of the type of noise coupling.

Current Follows the Path of Lowest Impedance

Current follows the path of lowest impedance, not lowest resistance. Impedance has an inductive term and a capacitive term. Recall the formula for impedance:

$$Z = \sqrt{R^2 + [wL - (1/wC)]^2}$$

Most of us tend to think of current flowing through the minimum resistance – this is not necessarily so. Inductance or capacitance can dominate at higher frequencies. Figure 2 illustrates paths of lowest impedance.

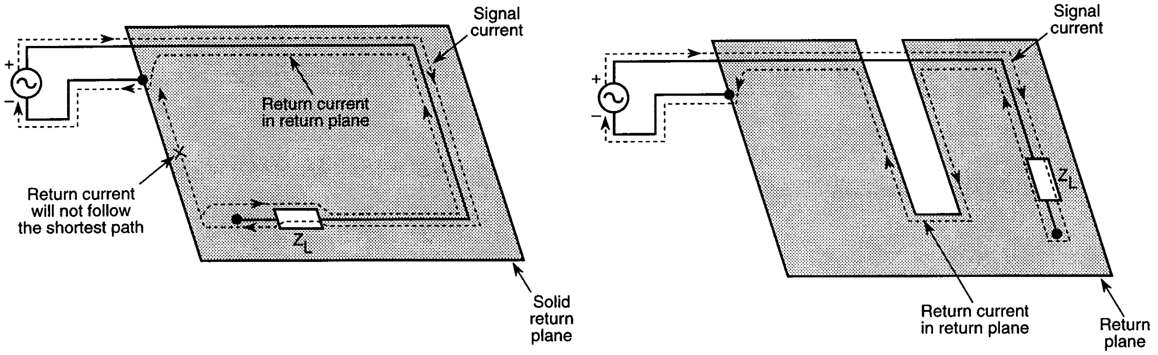


Fig. 2 Current follows the path of least impedance. (© 1996, Oxford University Press, Inc. Used with permission.)

Pseudo-impedance

Pseudo-impedance is a diagnostic ratio that helps point to possible noise coupling mechanisms. The ratio compares the time-rate of change of voltage to the time-rate of change of current, or (dv/dt)/(di/dt). Pseudo-impedance typically becomes useful when the frequency of operation exceeds 10 KHz.

For inductive coupling, the diagnostic ratio indicates a large change in current relative to the change in voltage. Therefore, $(dv/dt)/(di/dt) << 377\ \Omega$.

For capacitive coupling, the diagnostic ratio indicates a large change in voltage relative to the change in current. Therefore, $(dv/dt)/(di/dt) >> 377\ \Omega$.

For electromagnetic coupling, the diagnostic ratio begins to look like free-space impedance or approximately 377 Ω. Actually, any value between 100 Ω and 500 Ω may indicate electromagnetic coupling.

Conductive Coupling

The mechanism for conductive coupling requires a continuous circuit between source and receiver. Sneak circuits and ground loops often result from conductive coupling. Figure 3 illustrates the basic concept of conductive coupling. If connections A and B in Figure 3 are unintentional, then breaking either one or both will prevent conductive coupling.

If, however, connections A and B are intentional, such as in a simple transmission cable, then both could represent significant impedance in parallel paths. If any current paths "sneak" around connection A or B, then the unbalanced circuit can introduce noise. A ground loop has multiple ground connections that provide multiple return paths. These can cause significant current flow in the grounding structure parallel to either connection A or B. (More on ground loops later.)

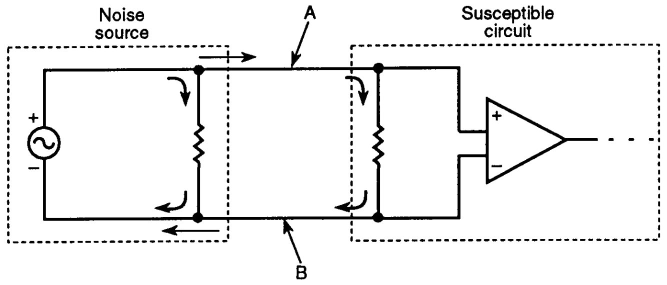


Fig. 3 Configuration of conductive coupling. If either connection A or B is removed, the conductive noise is eliminated. (© 1996, Oxford University Press, Inc. Used with permission.)

Inductive Coupling

The mechanism for inductive coupling requires several conditions:

- a current loop that generates a changing magnetic flux
- frequency > 3 kHz
- a large time-rate of change in current, (dv/dt)/(di/dt) << 377 Ω.

Induced voltage, in an inductive circuit, is proportional to both the time-rate of change in current (di/dt) and the loop area. **Important fact:** Reducing the loop area will reduce inductive coupling.

Straight wires create small loops that can magnetically couple. Twisted wire eliminates the effective loop area of the cables. Furthermore, twisting the wire and running it close to the ground will reduce the common-mode current, I_C, by reducing the loop area for inductive coupling. Figure 4 illustrates this coupling.

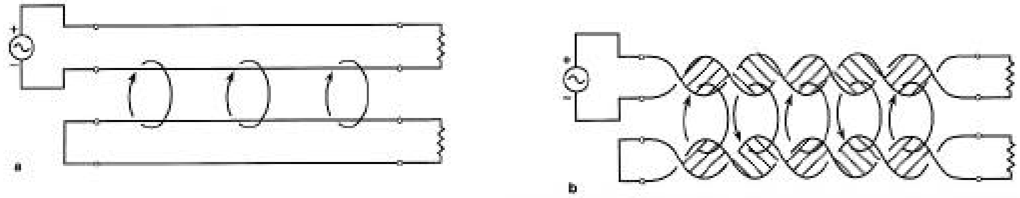


Fig. 4 Inductive coupling – bigger loops couple more effectively. Twisted wire eliminates both the effective loop area within cables and the magnetic coupling. (© 1996, Oxford University Press, Inc. Used with permission.)

Slots in the ground (or return) planes of circuit boards increase inductive coupling – hence greater noise problems. Figure 2 illustrates how a slot in the return plane can create a significant loop area that increases inductance. This is the reason why you should design ground and return planes with minimal penetrations, especially those that force current to flow in "loops" around slots.

Why would anyone cut slots in the ground (or return) planes of circuit boards? For various (bad) reasons, people cut slots either to run a row of vias through the ground plane or to separate analog and digital circuits. Figure 5 illustrates how a row of vias in a slot in the ground (or return) plane can create a significant loop area that increases inductance. You should make sure that the return plane encircles each via penetration. If a component manufacturer recommends separate analog and digital ground planes with a single point connection between the planes then follow the routing shown in Figure 6 if you need to run signal lines between the digital and analog circuits. DO NOT route signal traces over slots! [4] Slots in the ground planes help reduce interference from low-frequency noise such as derive from AC power (50 or 60 Hz). If your circuitry is never in proximity of AC power then a solid return plane most likely is fine, and it can reduce routing mistakes.

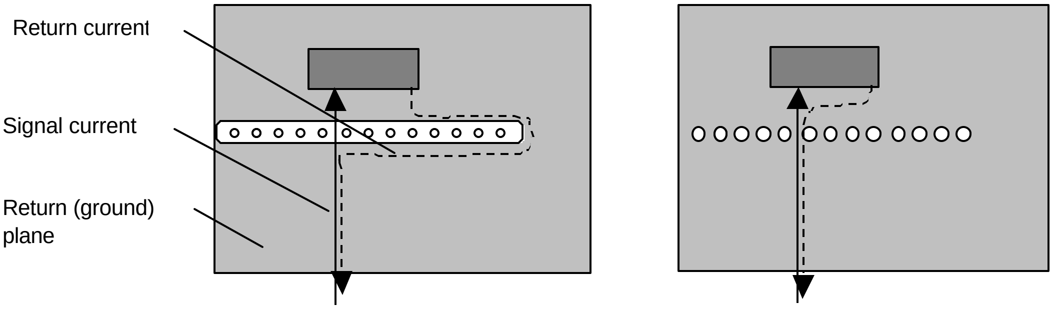


Fig. 5 Don't cut slots around rows of vias, make sure that the ground (return) plane encircles each via. (© 2002 by Kim Fowler, used with permission.)

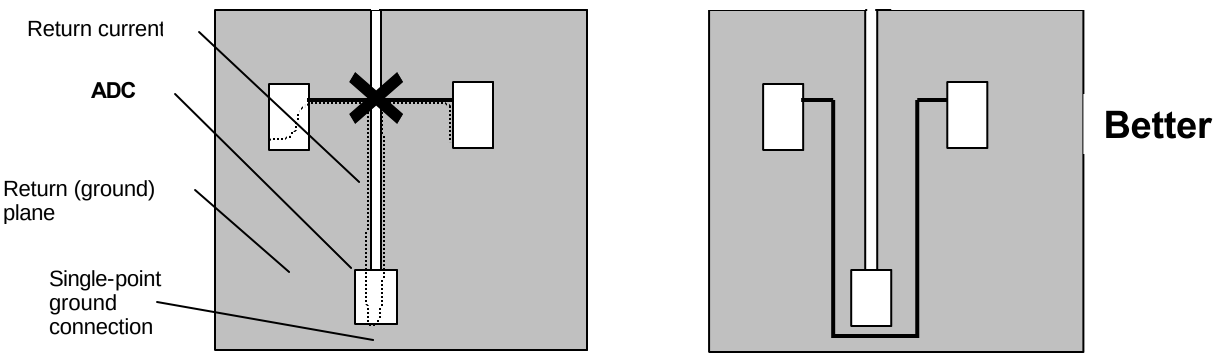


Fig. 6 Slots in a ground (return) plane separate analog and digital circuits and help isolate low-frequency noise. (© 2002 by Kim Fowler, used with permission.)

Capacitive Coupling

The mechanism for capacitive coupling requires several conditions:

- proximity of circuits
- frequency > 1 kHz
- a large time-rate of change in voltage, $(dv/dt)/(di/dt) >> 377\ \Omega$.

Induced voltage in a capacitive circuit is proportional to the time-rate of change in voltage, dv/dt, and inversely related to separation distance. **Important fact:** Separating the source and receiver and properly connecting a shield will reduce or eliminate capacitive coupling.

Capacitive coupling provides a path for the injection of unwanted electrical charge. An appropriately placed shield prevents the coupling between circuits by shunting charge to ground. Figure 7 illustrates capacitive coupling. Unfortunately, an incorrectly placed or connected shield will increase capacitive coupling.

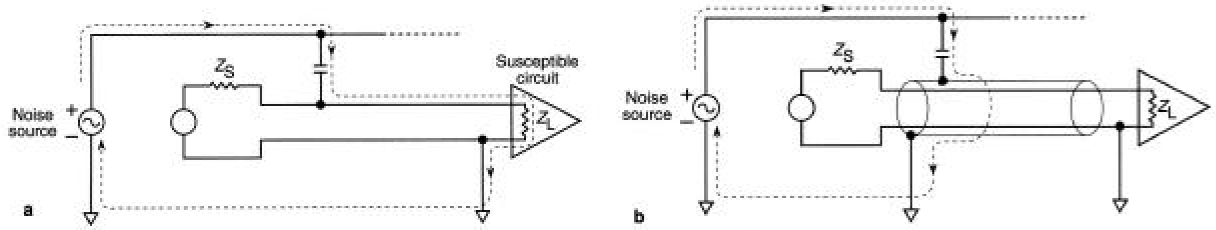


Fig. 7 Configuration of capacitive coupling. Without the shield, stray currents can disrupt the susceptible circuit. A properly connected shield will divert the capacitively coupled current away from the susceptible circuit. (© 1996, Oxford University Press, Inc. Used with permission.)

Electromagnetic Coupling

The mechanism for electromagnetic coupling mechanism:

- frequency > 20 MHz
- signal conductors must be > λ/20
- (dv/dt)/(di/dt) ≈ 377 Ω (actually any value between 100 Ω and 500 Ω)

Radiated electromagnetic energy requires an antenna in both the noise source and the susceptible circuits. The antenna must be an appreciable portion of the wavelength. Coupling is usually at high frequencies (> 20 MHz). Figure 8 illustrates electromagnetic coupling.

Electromagnetic interference (EMI) always begins conductive as current in wires, becomes radiative, and ends conductive where the E and H fields interact with the receiver circuitry. Remedies for EMI involve reducing both emissions and reception as follows:

- reduced bandwidth
- good signal routing
- shielded enclosures.

Important fact: A shielded enclosure should ideally be a completely closed conducting surface. Openings "leak" electromagnetic radiation. An effective enclosure is one that has watertight metallic seams and completely shielded penetrations and openings.

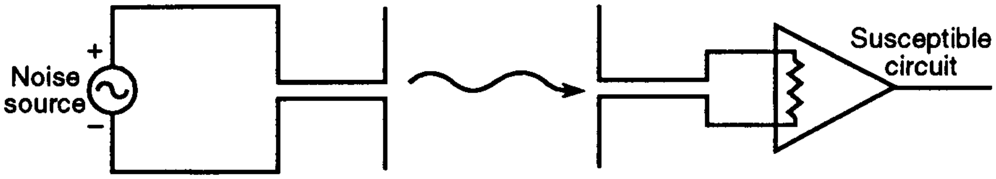


Fig. 8 Configuration of electromagnetic coupling. Radiated electromagnetic energy requires an antenna in both the noise source and the susceptible circuit. (© 1996, Oxford University Press, Inc. Used with permission.)

Part 2: Grounding

Shielding for noise has several possible configurations. Grounding is one of the concerns in designing an effective shield. Unfortunately, some folks think that picking a ground connection is the panacea for their noise problems. I hope that I can both dispel that notion and illustrate some principles for grounding and return configurations.

A proper ground minimizes the potential difference between a device and a reference point. This is the basic definition. Grounding, however, can have two very different functions, one for safety and the other for signal reference. Furthermore, it can have two different configurations, single-point connection and multi-point ground plane (or grid). I will introduce each of these areas.

Safety
A safety ground must be a permanent, continuous, low-impedance conductor with adequate capacity that runs from the power source to the load. It removes or reduces the shock hazard – electric current passing through a person's body – by reducing the voltage differential between external conducting surfaces.

Signal Reference
Grounding can also provide a base reference for low-level signals. Proper signal reference grounding minimizes inductive impedance, such as continuous ground (or return) planes.

Configurations for Grounding
Grounds can have one of two basic configurations, single-point connection or multi-point ground plane. Choosing one configuration over the other depends on current capacity and frequency.

A single-point ground is generally good for low current and low frequency. Grounds for signal reference typically have these characteristics:

- low current < 1 A
- low frequency < 1 MHz.

You must resort to a multi-point ground plane or grid when impedance in the ground structure becomes a factor and you need lower impedance than a single cable with a single-point connection. Typically, the situation has either high current or high frequency. Here are indications for a multi-point ground plane:

- high current > 1 A
- high frequency > 100 KHz.

Ground loop

A ground loop is a complete circuit comprising the signal path and part of the ground structure. Ground loops allow external currents in the ground structure to generate potential differences between the ground connections and to introduce noise in the signal circuit. Generally, the problem exists at lower frequencies (< 10 MHz). High frequencies follow the path of minimum impedance that often avoid higher-impedance ground loops. Figure 9 illustrates the general principle of a ground loop.

A ground loop has two characteristics. One, it has multiple ground connections that provide multiple return paths; these allow significant current flow in the grounding structure. Two, it unbalances the circuit.

Either circuit balance or isolation may remove problems caused by ground noise. Figure 10 illustrates several methods for eliminating ground loops. For short distances (< 30 m or 100 ft.), a balanced transmission line and single-point ground reduce noise and improve safety. For long distances (> 30 m or 100 ft.), an isolated signal transmission allows multiple safety grounds while eliminating ground loops.

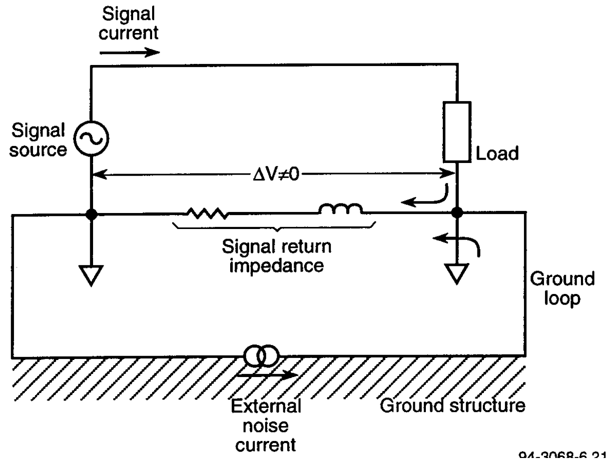
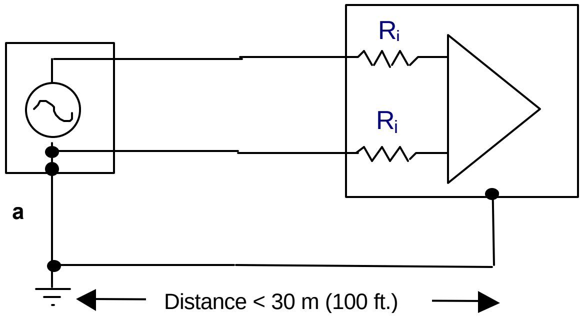


Fig. 9 Schematic for a ground loop. (© 1996, Oxford University Press, Inc. Used with permission.)



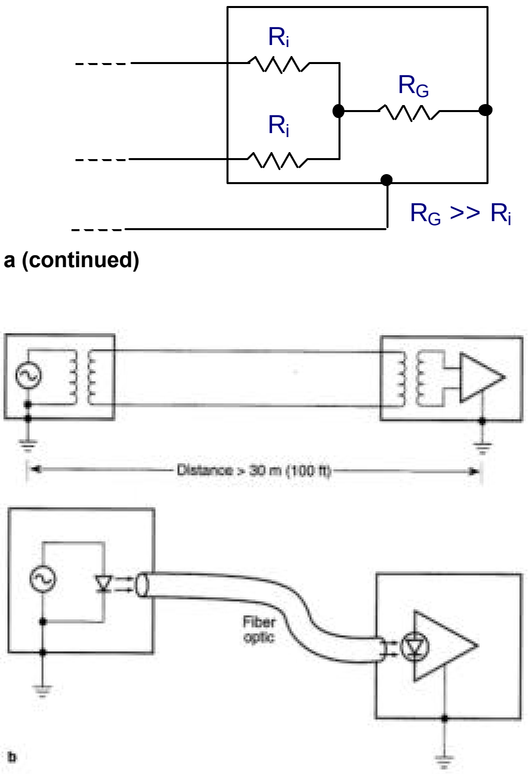


Fig. 10 Methods for eliminating ground loops. a) Balanced transmission is OK for < 30 m. b) Isolated transmission for > 30 m. (© 1996, Oxford University Press, Inc. Used with permission.)

Returns

OK, things get confusing and messy when we combine grounds and power return lines. This happens when many cards plug into a backplane or racks of equipment connect together. First, let's understand the difference in roles between ground and return lines, then let's examine some configurations for return lines.

The Difference between Grounding and Return

The primary physical difference between grounding and return is that of continuous current. A ground circuit should rarely, if ever, conduct current; it's there to maintain a zero potential between separate circuits. A ground is a safety measure. Conversely, a return should continuously conduct current from the load back to the power or signal source.

In small circuits, where the lengths of both the return and the ground lines are very short, they may be the same physical conductor. A good example of this is the ground plane in a circuit board. For many applications, it suffices to be the return current path while maintaining a (nearly) zero potential reference for grounding.

Return Configurations

When multiple circuits must draw power from a single source, then the configuration of the return lines becomes important. There are three main types of return configurations:

- series return connection
- single-point

- multi-point.

Some older backplanes used the series return connection. Low frequency operation and low currents allowed this configuration. But as frequencies and currents go up, the series return configuration generates significant potential differences between circuit cards that arise from the common impedance of the power and return lines.

The single-point configuration alleviates some of the problems encountered by series return. It removes the common impedances. If the lines are of equal length and routed similarly then the line impedances should be nearly identical. The disadvantage of this configuration is that it can complicate power distribution by the number of wires and its complex structure.

The multiple-point configuration compromises between the opposing constraints of grounding and return. Backplanes that use power and return planes are examples of multiple-point connections. The trick for the multiple-point configuration is to make sure that all power bus bars (or planes) run next to the return bus bars (or planes) and have sufficient current capacity. Don't separate the bus bars; it will only serve to greatly increase inductive impedance.

Part 3: Electrostatic Discharge

This part of the paper focuses on electrostatic discharge. It combines some specifics from noise mechanisms and grounding.

Electrostatic discharge (ESD) is an exchange of charge at very high voltage and current but very small total charge transfer. It requires three stages to occur: charge pickup, charge storage, and discharge. Removing any one of these stages will eliminate ESD.

If you eliminate activities and materials that create high static charge, then you will stop ESD. You can control ESD through techniques such as: grounding, careful handling, protective materials, and humidity.

Waveform

Figure 11 shows a typical waveform for an ESD pulse. Pulse amplitudes vary between 100s and 10,000s of volts. Simultaneously, the actual charge transferred is very small even though the effective current appears very high. The rise times are very fast (< 1 ns) but of short duration (~90 ns).

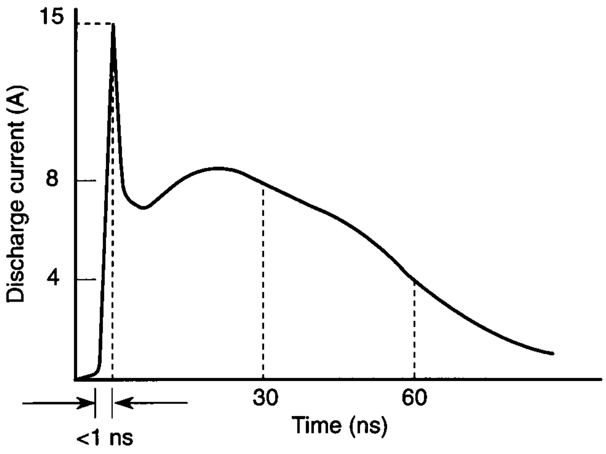


Fig. 11 A standard ESD waveform. (© 1996, Oxford University Press, Inc. Used with permission.)

Table 1. Some possible static voltages generated by casual activity. (© 1996, Oxford University Press, Inc. Used with permission.)

Static generation	10% relative humidity	65% relative humidity
Walking across carpet	35,000	1,500
Walking over vinyl floor	12,000	250
Common plastic bag picked up from bench	20,000	1,200
Work chair padded with polyurethane foam	18,000	1,500

Sources, pick up and storage
The general mechanism for ESD is mechanical friction. Dry, insulated materials when rubbed together will transfer charge. These materials are both the source and storage of charge.

Sources include plastic work surfaces, carpeted floors, wool, cotton or synthetic garments, vinyl or fiberglass chairs, common plastic bags, bubble wrap, spray cleaners, and electrostatic copiers. The amount of charge stored depends on the conductivity of the environment. If the humidity is high, then charge drains away from the storage materials and voltages drop quickly. Table 1 gives some values of ESD voltages.

ESD Avoidance

You can protect your instrumentation two ways, control the environment and provide surge protection. You can control the environment by removing static-generating materials and draining charge to ground. Circuitry for surge protection provides a path to ground for charge that might enter sensitive circuitry.

Here is a checklist for eliminating ESD:

- Use a static-free workstation and wear a wrist ground strap.
- Discharge static before handling devices.
- Keep parts in their original containers.
- Minimize handling components.
- Pick up devices by their bodies not their leads.
- Never slide a semiconductor over any surface.
- Use conductive or antistatic containers for storage and transport of components.
- Clear all plastic, vinyl, and Styrofoam from the work area.

Part 4: Fixes and Solutions

The previous three parts described mechanisms of noise, issues in grounding, and electrostatic discharge. This final part presents some diagnostics, shielding methods, and examples of fixes based on these foundational principles.

Diagnosis

Remember that noise has four types of coupling mechanisms. Understanding these mechanisms will provide the basis for diagnosing noise problems.

Each mechanism deals with both the path and the dynamics of current or charge transfer. First list or draw the path of current flow. Then determine the relative changes in voltage and current in the source. You can calculate the pseudo-impedance to help diagnose the coupling once you know the relative changes in voltage and current. Comparing the value of pseudo-impedance to the impedance of free space (377Ω) provides some insight into the coupling mechanism. Table 2 summarizes some clues for diagnosing the mechanism of noise coupling.

Shielding

Shielding is more than wrapping metal around a problem. You must understand the mechanism of noise coupling to select the most effective technique for shielding. For example, you can minimize inductive noise problems by eliminating the area of current loops within circuits. Reduce and reroute electrical charge to minimize capacitive noise problems. Suppress electromagnetic coupling by reducing emissions and reception through reduced bandwidth, good signal routing, and shielded enclosures (OK, here you can wrap metal around the problem – but seal the seams tightly!).

Table 2. Diagnostic clues of the four different mechanisms of noise coupling. (© 1996, Oxford University Press, Inc. Used with permission.)

Coupling mechanism	Frequency range	Diagnostic clues
Conductive	DC to < 10 MHz	Complete conductive path (such as multiple ground connections)
Inductive	> 3 KHz	1. (dv/dt)/(di/dt) << 377 2. Ringing on pulse edges 3. Low source impedance and high load impedance 4. Laying conductive foil over cable decreases noise level (acts as an eddy current shield) 5. Large circuit loops
Capacitive	> 1 KHz	1. (dv/dt)/(di/dt) >> 377 2. Rounding of pulse edges 3. High source impedance and high load impedance 4. Laying conductive foil over cable increases noise level (acts as a coupling capacitor
Electromagnetic	> 20 MHz	Distance between noise source and susceptible circuit > ë

Common-mode Choke

Common-mode noise injects equivalent currents flowing in the same direction in both the signal and return lines (I_C in Figure 13). A simple common-mode choke, Figure 12, can block this common-mode current.

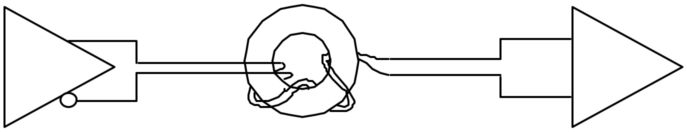


Fig. 12 Example common-mode choke. (© 2002 by Kim Fowler, used with permission.)

Inductive shielding

Twisting the wire and running it close to the ground will reduce the common-mode current, I_C, by reducing the loop area for inductive coupling. Figure 13 illustrates shielding for inductive coupling.

Ribbon Cable

Ribbon cable is suitable for low-frequency operation (< 1 MHz) of single-ended signals. Pair each signal conductor with a return conductor or use a return plane; this is critical for low-level signals or higher frequencies (Figure 14). Connectors with a return plane are expensive and difficult to find.

Capacitive shielding

Capacitive coupling provides a path for the injection of noise charges. An appropriately placed shield prevents the coupling between circuits by shunting charge to ground. Figure 15 illustrates shielding against capacitive coupling.

Twisted Pair vs. Coax

Twisted-pair cable is usually effective up to 1 MHz, above which it becomes lossy. Coax has low loss and less variance in its characteristic impedance from DC to very high frequencies (>200 MHz). Twisted-pair is cheaper and mechanically more flexible than coax. Consequently, twisted-pair is preferable for cheap, low-frequency applications. Coax is preferable for high fidelity or high frequency applications.

Carefully terminate the shield in coax cables. A pigtail connection is OK for very low frequency applications (<<1 MHz). You must, however, completely terminate the shield with a 360° conducting seal for high frequencies (> 1 MHz). The wiring and cabling in Figures 16 and 17 illustrate these concepts.

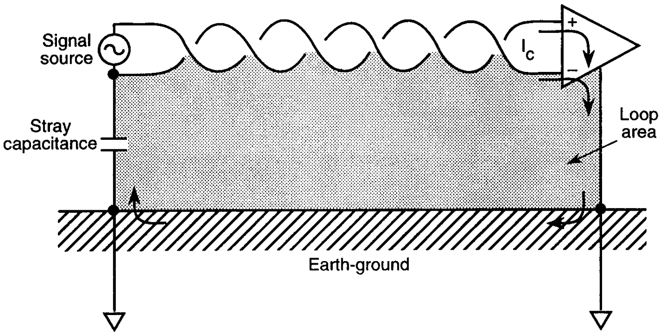


Fig. 13 Shielding for inductive coupling. (© 1996, Oxford University Press, Inc. Used with permission.)

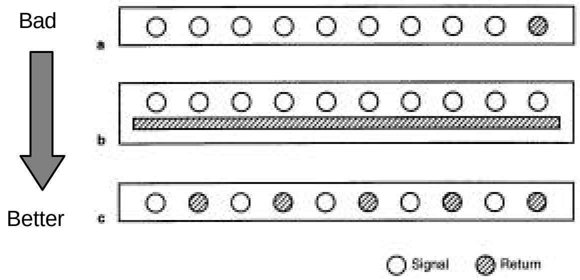


Fig. 14 Ribbon cable with single-ended signals is OK for lower frequencies (< 1 MHz). A ground (or return) plane must have continuous connection across its width through the connectors on both ends – these tend to be hard-to-find and expensive. (© 1996, Oxford University Press, Inc. Used with permission.) (See LVDS cabling for differential signals.

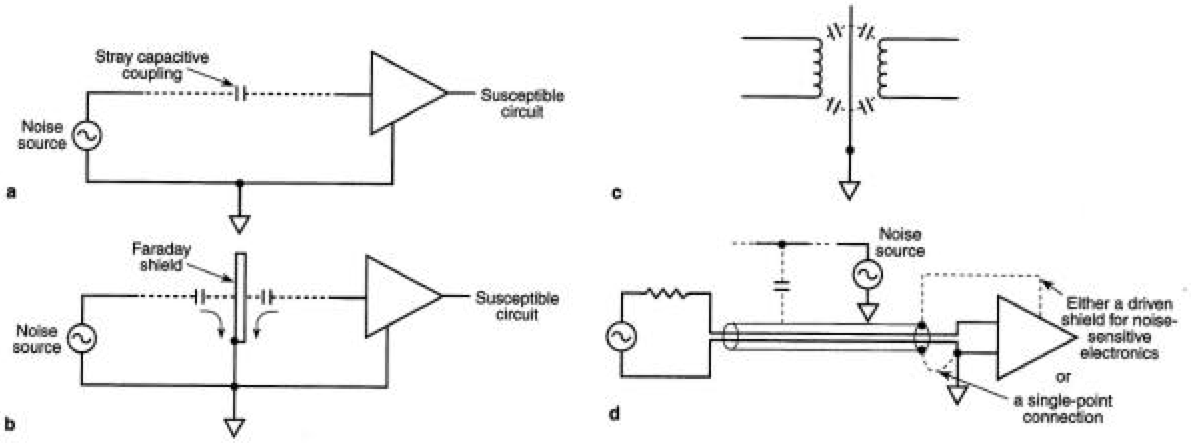


Fig. 15 Shielding for capacitive coupling. (a) Schematic outline of capacitive coupling. (b) Proper placement of a shield to shunt noise charge. (c) A shielded transformer prevents capacitive coupling between windings. (d) A cable shield usually should be connected at only one place to prevent coupling or to shunt charge. (© 1996, Oxford University Press, Inc. Used with permission.)

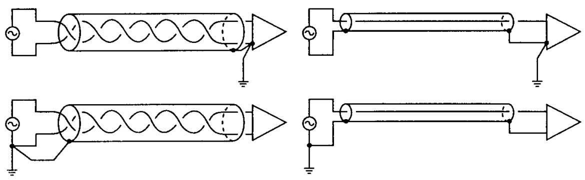


Fig. 16 These are cable configurations that best attenuate low frequency noise (< 1 MHz). (© 1996, Oxford University Press, Inc. Used with permission.)

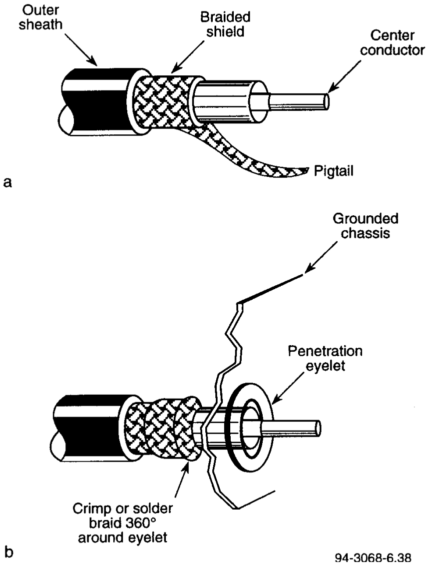


Fig. 17 Coaxial cable terminations. (a) The pigtail connection is OK < 1 MHz. A pigtail connection forms a loop that becomes a large inductive impedance at higher frequencies. (b) The complete 360° conducting seal is necessary > 1 MHz. (© 1996, Oxford University Press, Inc. Used with permission.

Enclosures

A shielded enclosure should ideally be a completely closed, conducting surface. An effective enclosure is one that has watertight metallic seams and openings. Openings "leak" electromagnetic radiation. Figure 18 points out problem areas for electromagnetic "leaks."

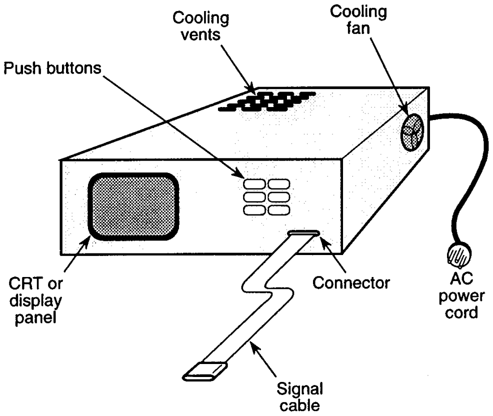


Fig. 18 Places where electromagnetic radiation can leak in or out of an enclosure. (© 1996, Oxford University Press, Inc. Used with permission.)

Openings and penetrations are unavoidable in instrument enclosures. You can install honeycomb EMI filters over air intakes and exhaust vents. You can plate plastic enclosures internally with conductive coatings and apply EMI gasketing between all mating parts, including the front panels on circuit boards. [5, 6]

Part 5: Circuit Layout

The basic principles and techniques for suppressing noise and improving shielding also apply to circuit layout, particularly for high-speed, high-frequency circuits. I will cover several selected issues in circuit layout but there are many more. The references go into much more detail. [7 – 9]

Component placement

Component placement is important to controlling interference for both radiation and reception. Group analog circuits separately from digital circuits. This helps reduce crosstalk from digital transients from interfering with low-level signals in analog circuits. Group low-power or low-frequency circuits away from high-frequency and high-current circuits. The same reasoning applies; it helps reduce crosstalk from high-current or high-frequency transients from interfering with low-level signals. Place high-frequency circuits near connectors to reduce signal path length, crosstalk, and noise. Also place high-current circuits near connectors to isolate stray currents. Finally, place high-current circuits near the edge of the circuit board and close to a heat sink to remove heat. See Figure 19.

High-speed design

High-speed design begins for clock frequencies somewhere above 1 MHz. Transmission line effects come into play in high-speed design. Another concern is that harmonics of the signal edges are 20 to 30 times the fundamental frequency.

The basic rules of thumb that define when design crosses over into high-speed realms are as follows:

1. The signal length exceeds 5% of the wavelength of the clock frequency, $l > \lambda/20$.
2. The rise time (slew rate) of pulses is less than four times the propagation time, $t_r < 4\ t_p$.

Where l = length of signal path, λ = wavelength, t_r = rise time of signal edge, and t_p = propagation delay of signal path.

For a fundamental clock frequency of 10 MHz, the signal wavelength, λ, is about 30 m; five percent of this wavelength is 1.5 m. While a fundamental clock frequency of 100 MHz has a signal wavelength, λ, of about 3 m; five percent of this wavelength is 15 cm (or about 6 inches). For 100 MHz, the harmonics can reach to 2 or 3 GHz!

Guidelines

Basic guidelines for high-speed design require managing, among other things, bandwidth, decoupling, ground bounce, crosstalk, and impedance matching. You should limit bandwidth; select the slowest available logic family that still meets your requirements. Use this comparison of rise time versus propagation time to serve as a basic rule of thumb: $t_r / t_p < 4$. Another way to reduce high-frequency transients is to use decoupling capacitors carefully. You should always place them very near the IC to reduce LC resonance (remember that L is proportional to loop area). Ground bounce is an interesting phenomenon where multiple, simultaneous transitions cause glitches in the return plane. You can reduce ground bounce by reducing loop inductance and input gate capacitance. Also select a logic family that controls the transitions or use slower rise/fall times.

The impedance of signal conductors directly affects circuit operation. Impedance mismatch causes reflections and ringing or slow transitions in high-speed circuits. (See figure 20.) Impedance mismatches cause reflections that can delay switching and trigger logic falsely. One source of impedance mismatch is stubs, which cause signal reflections that result in ringing, overshoot, and undershoot. Here are some things to do to reduce impedance mismatch:

- Reduce the length of stubs.
- Terminate the ends of the transmission line.
- Remove or reduce sharp corners and vias.

Another area of concern is crosstalk. Crosstalk is where one signal couples into another using the mechanisms discussed earlier in this article. You can avoid crosstalk in a number of ways:

- Don't run parallel traces for long distances – particularly asynchronous signals.
- Increase the separation between conductors.
- Shield the clock lines with guard strips (see LVDS guidelines).
- Reduce the magnetic coupling by reducing the loop area of circuits.
- Sandwich signal lines between return planes.
- Isolate the clock, chip-select, chip-enable, read, and write lines because crosstalk in synchronous systems occurs on the pulse edges when data are sampled.

Obviously, these guidelines run counter to high trace densities. You will have to make the appropriate tradeoffs to balance noise, EMI, and trace density.

LVDS

High-speed data transfers are demanding different signaling strategies and architectures. Low Voltage Differential Signaling (LVDS) provides signaling rates beyond 400 Mbps. LVDS provides a good example of how to implement some of these guidelines.

Every LVDS signal line is paired with its complement. It uses a 3.5 mA current source to drive the differential pair lines, which have a characteristic impedance of about 100 (Figure 22). The voltage transitions are small, only about 300 to 350 mV, with relatively slow pulse edge rates of 300 mv/300 ps or about 1 V/ns. It limits EMI generation and susceptibility and rejects common-mode noise. It generally provides point-to-point communications of less than 15 m. [7]

You should follow a number of guidelines when laying out LVDS lines on a printed circuit board. Minimize the separation between the + and – traces of the differential pair. Isolate other logic traces, particularly single-ended signals, from the LVDS lines. Use at least four planes when incorporating LVDS: one for LVDS signals, one for ground, one for power, and one for other logic signals. Use proper termination, typically 100 , near the receiver; use surface mounted resistors for minimize size and separation; keep the resistor tolerance tight, 1 or 2%, to reduce impedance mismatch. Avoid or minimize discontinuities, sharp corners, vias, and improper terminations, because they cause signal reflections that degrade signals and show up as common-mode noise. Ground the trace guards to the ground plane at intervals that are at least every quarter of the dominant wavelength. [7, 8]

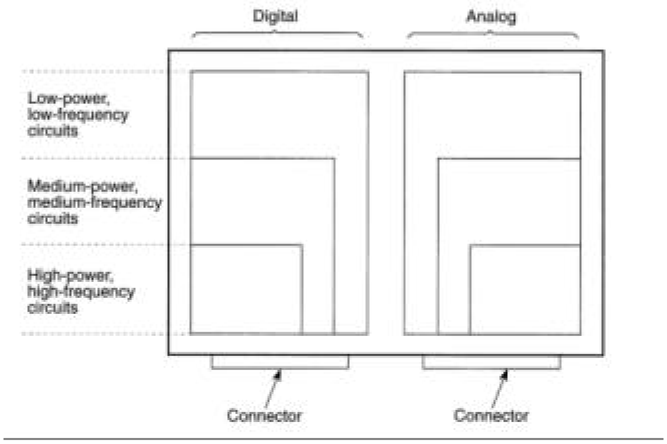


Fig. 19 Placement of components for maintaining signal integrity. (© 1996, Oxford University Press, Inc. Used with permission.)

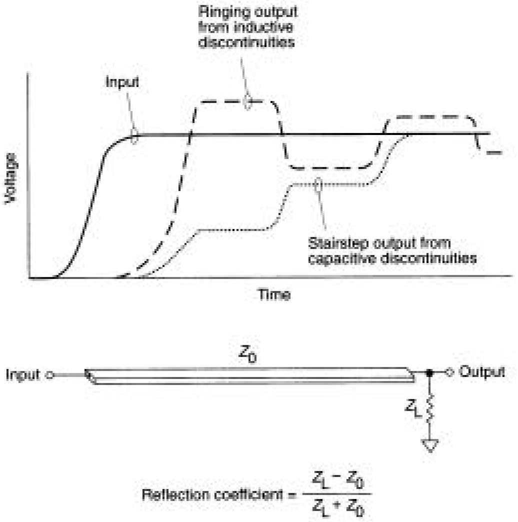


Fig. 20 Impedance matching or mismatching affects the signal propagation and can result in ringing or slow transitions. (© 1996, Oxford University Press, Inc. Used with permission.)

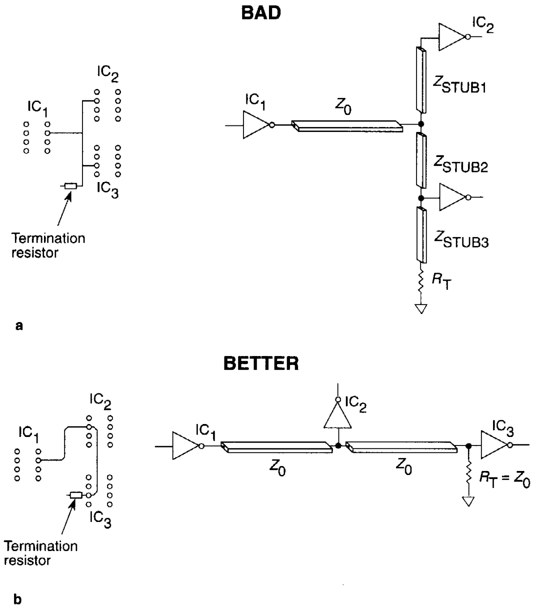


Fig. 21 Some suggestions for circuit layout to improve impedance matching. (© 1996, Oxford University Press, Inc. Used with permission.)

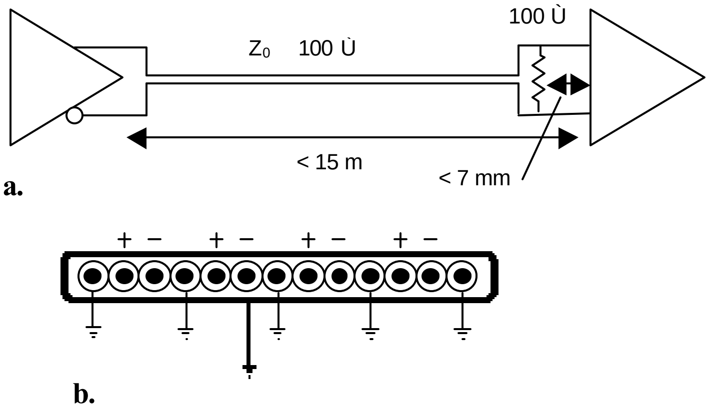


Fig. 22 Recommended configuration for LVDS a) differential pair driver and receiver with termination, and b) ribbon cable. Make sure that each differential signal pair is separate from other pairs by a grounded guard line. A grounded, foil shield should encase the entire cable. (© 2002 by Kim Fowler, used with permission.)

Part 6: General Rules for Design

From this background, you can synthesize some general rules for design. First characterize the system, and then apply the appropriate design techniques to eliminate problems. Characterize the system:

- Establish the grounding options, source and load impedances, and frequency bandwidth.
- Determine the predominant mechanisms for coupling.
- Diagram the circuit paths.

Good design techniques include:

- Reducing frequency bandwidth to the minimum necessary.
- Balancing currents in long lines.
- Reducing loops, both ground loops and inductive loops, and routing signals for self-shielding: return (ground) plane and short traces.
- Using appropriately sized decoupling capacitors near ICs.
- Wrapping metal enclosure around the problem only when necessary.

Reciprocity

There is a general rule of reciprocity in shielding. Anything that reduces emissions usually makes the circuit less susceptible to disruption. If you decrease the inductive loop of a circuit to reduce emission, then you will also reduce the mutual coupling that could receive noise.

I did not cover all topics in-depth that are closely related to these principles and techniques. They include power concerns – filtering of power input lines and power factor correction, signal line layout, and high-speed design. The references can help you with these topics. [1, 2, 8 – 10]

References

[1] R. Morrison, *Grounding and Shielding Techniques,* Fourth Edition, Wiley, New York, 1998.
[2] H. W. Ott, *Noise Reduction Techniques in Electronic Systems,* Second Edition, Wiley, New York, 1988.
[3] K. R. Fowler, *Electronic Instrument Design,* Oxford University Press, New York, 1996, pp. 181 - 229.
[4] T. Hubing and T. Van Doren, "Designing for EMC: The Top 4 Guidelines," *Printed Circuit Design & Manufacture,* June 2003, pp. 22, 23, 26, 27, 47.
[5] E. Eacueo, "What Should You Look For When Specifying An Electronics Enclosure?" *Electronic Design*, June 14, 1999, p. 68.
[6] L. H. Hemming, *Architectural Electromagnetic Shielding Handbook,* IEEE Press, New York, 1992.
[7] LVDS Owner's Manual, 2nd Edition, Spring 2000, National Semiconductor, (based on ANSI/TIA/EIA-644 and IEEE 1596.3) www.national.com/appinfo/lvds/.
[8] M. I. Montrose, *Printed Circuit Board Design Techniques for EMC Compliance, A Handbook for Designers,* 2nd Edition, IEEE Press, New York, 2000.
[9] H. W. Johnson and M. Graham, *High-Speed Digital Design: A Handbook of Black Magic,* PTR Prentice Hall, Englewood Cliffs, New Jersey, 1993.
[10] *IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment,* 1992.