EMI, RFI, and Shielding Concepts

INTRODUCTION TO ELECTROMAGNETIC COMPATIBILITY (EMC)

Analog circuit performance is often affected adversely by high frequency signals from nearby electrical activity. And, equipment containing your analog circuitry may also adversely affect systems external to it. Reference 1 (page 4) defines *electromagnetic compatibility* (EMC) based on the IEC-60050 definition:

EMC is the ability of a device, unit of equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

The term EMC therefore has two aspects:

1. *It describes the ability of electrical and electronic systems to operate without interfering with other systems.*
2. *It also describes the ability of such systems to operate as intended within a specified electromagnetic environment.*

So, complete EMC assurance would indicate that the equipment under design should neither produce spurious signals, nor should it be vulnerable to out-of-band external signals (i.e., those outside its intended frequency range). It is the latter class of EMC problem to which analog equipment most often falls prey. And, it is the graceful handling of these spurious signals that are emphasized within this section.

The externally produced electrical activity may generate noise, and is referred to either as *electromagnetic interference* (EMI), or *radio frequency interference* (RFI). In this section, we will refer to EMI in terms of both electromagnetic and radio frequency interference. One of the more challenging tasks of the analog designer is the control of equipment against undesired operation due to EMI. It is important to note that in this context, *EMI and or RFI is almost always detrimental*. Once given entrance into your equipment, it can and will degrade its operation, quite often considerably.

This section is oriented heavily towards minimizing undesirable analog circuit operation due to the *receipt* of EMI/RFI. Misbehavior of this sort is also known as EMI or RFI *susceptibility*, indicating a tendency towards anomalous equipment behavior when exposed to EMI/RFI. There is of course a complementary EMC issue, namely with regard to spurious *emissions*. However, since analog circuits typically involve fewer pulsed, high speed, high current signal edges that give rise to such spurious signals (compared to high speed logic, for example), this aspect of EMC isn't as heavily treated here. Nevertheless, the reader should bear in mind that it can be important, particularly if the analog circuitry is part of a mixed-signal environment along with high speed logic.

Since all of these various EMC design points can be critical, *references at the end of the tutorial are strongly recommended for supplementary study*. Indeed, for a thorough, fully competent design with respect to EMI, RFI and EMC, the designer will need to become intimately acquainted with one or more of these references (see References 1-6). As for the material following, it is best viewed as an introduction to this extremely broad but increasingly important topic.

EMI/RFI MECHANISMS

To understand and properly control EMI and RFI, it is helpful to first segregate it into manageable portions. Thus it is useful to remember that when EMI/RFI problems do occur, they can be fundamentally broken down into a *Source*, a *Path*, and a *Receiver*. As a systems designer, you have under your direct control the receiver part of this landscape, and perhaps some portion of the path. But seldom will the designer have control over the actual source.

EMI NOISE SOURCES

There are countless ways in which undesired noise can couple into an analog circuit to ruin its accuracy. Some of the many examples of these noise sources are listed in Figure 1.

- **EMI/RFI noise sources can couple from *anywhere***
- **Some common sources of externally generated noise:**
  - **Radio and TV Broadcasts**
  - **Mobile Radio Communications**
  - **Cellular Telephones**
  - **Vehicular Ignition**
  - **Lightning**
  - **Utility Power Lines**
  - **Electric Motors**
  - **Computers**
  - **Garage Door Openers**
  - **Telemetry Equipment**

Figure 1: Some Common EMI Noise Sources

Since little control is possible over these sources of EMI, the next best management tool one can exercise over them is to recognize and understand the possible paths by which they couple into the equipment under design.

EMI COUPLING PATHS

The EMI coupling paths are actually very few in terms of basic number. Three very general paths are by:

1. *Interference due to conduction (common-impedance)*
2. *Interference due to capacitive or inductive coupling (near-field interference)*
3. *Electromagnetic radiation (far-field interference)*

NOISE COUPLING MECHANISMS

EMI energy may enter wherever there is an impedance mismatch or discontinuity in a system. In general this occurs at the interface where cables carrying sensitive analog signals are connected to PC boards, and through power supply leads. Improperly connected cables or poor supply filtering schemes are often perfect conduits for interference.

Conducted noise may also be encountered when two or more currents share a common path (impedance). This common path is often a high impedance "ground" connection. If two circuits share this path, noise currents from one will produce noise voltages in the other. Steps may be taken to identify potential sources of this interference (see References 1 and 2, plus tutorial MT-031).

Figure 2 shows some of the general ways noise can enter a circuit from external sources.

◆ **Impedance mismatches and discontinuities**
◆ **Common-mode impedance mismatches → Differential Signals**
◆ **Capacitively Coupled (Electric Field Interference)**
   ● **dV/dt → Mutual Capacitance → Noise Current**
      (Example: 1V/ns produces 1mA/pF)
◆ **Inductively Coupled (Magnetic Field)**
   ● **di/dt → Mutual Inductance → Noise Voltage**
      (Example: 1mA/ns produces 1mV/nH)

Figure 2: How EMI finds Paths into Equipment

There is a capacitance between any two conductors separated by a dielectric (air and vacuum are dielectrics, as well as all solid or liquid insulators). If there is a change of voltage on one conductor there will be change of charge on the other, and a *displacement current* will flow in the dielectric. Where either the capacitance or the dV/dT is high, noise is easily coupled. For example, a 1-V/ns rate-of-change gives rise to displacement currents of 1 mA/pF.

If changing magnetic flux from current flowing in one circuit couples into another circuit, it will induce an emf in the second circuit. Such *mutual inductance* can be a troublesome source of noise coupling from circuits with high values of dI/dT. As an example, a mutual inductance of 1 nH and a changing current of 1 A/ns will induce an emf of 1 V.

REDUCING COMMON-IMPEDANCE NOISE

Steps to be taken to eliminate or reduce noise due to the conduction path sharing of impedances, or *common-impedance noise* are outlined in Figure 3.

- ◆ **Common-impedance noise**
  - ● **Decouple op amp power leads at LF and HF**
  - ● **Reduce common-impedance**
  - ● **Eliminate shared paths**
- ◆ **Techniques**
  - ● **Low impedance electrolytic (LF) and local low inductance (HF) bypasses**
  - ● **Use ground and power planes**
  - ● **Optimize system design**

Figure 3: Some Solutions to Common-Impedance Noise

These methods should be applied in conjunction with all of the related techniques discussed in tutorial MT-031.

Power supply rails feeding several circuits are good common-impedance examples. Real world power sources may exhibit low output impedance, or may they not—especially over frequency. Furthermore, PCB traces used to distribute power are both inductive and resistive, and may also form a ground loop. The use of power and ground planes also reduces the power distribution impedance. These dedicated conductor layers in a PCB are continuous (ideally, that is) and as such, offer the lowest practical resistance and inductance.

In some applications where low-level signals encounter high levels of common-impedance noise it will not be possible to prevent interference and the system architecture may need to be changed. Possible changes include:

1. *Transmitting signals in differential form*
2. *Amplifying signals to higher levels for improved S/N*
3. *Converting signals into currents for transmission*
4. *Converting signals directly into digital form*

NOISE INDUCED BY NEAR-FIELD INTERFERENCE

Crosstalk is the second most common form of interference. In the vicinity of the noise source, i.e., near-field, interference is not transmitted as an electromagnetic wave, and the term crosstalk may apply to either inductively or capacitively coupled signals.

REDUCING CAPACITANCE-COUPLED NOISE

Capacitively-coupled noise may be reduced by reducing the coupling capacity (by increasing conductor separation), but is most easily cured by shielding. A conductive and grounded shield (known as a *Faraday shield*) between the signal source and the affected node will eliminate this noise, by routing the displacement current directly to ground.

With the use of such shields, it is important to note that it is always *essential* that a Faraday shield be grounded. A floating or open-circuit shield almost invariably increases capacitively-coupled noise. For a brief review of this shielding, see References 2 and 3 at the end of this section.

Methods to eliminate capacitance-coupled interference are summarized in Figure 4.

◆ **Reduce Level of High dV/dt Noise Sources**
◆ **Use Proper Grounding Schemes for Cable Shields**
◆ **Reduce Stray Capacitance**
   ● **Equalize Input Lead Lengths**
   ● **Keep Traces Short**
   ● **Use Signal-Ground Signal-Routing Schemes**
◆ **Use Grounded Conductive Faraday Shields to Protect Against Electric Fields**

Figure 4: Methods to Reduce Capacitance-Coupled Noise

REDUCING MAGNETICALLY-COUPLED NOISE

Methods to eliminate interference caused by magnetic fields are summarized in Figure 5.

◆ **Careful Routing of Wiring**
◆ **Use Conductive Screens for HF Magnetic Shields**
◆ **Use High Permeability Shields for LF Magnetic Fields (mu-Metal)**
◆ **Reduce Loop Area of Receiver**
   ● **Twisted Pair Wiring**
   ● **Physical Wire Placement**
   ● **Orientation of Circuit to Interference**
◆ **Reduce Noise Sources**
   ● **Twisted Pair Wiring**
   ● **Driven Shields**

Figure 5: Methods to Reduce Magnetically-Coupled Noise

To illustrate the effect of magnetically-coupled noise, consider a circuit with a closed-loop area of A cm^2 operating in a magnetic field with an rms flux density value of B gauss. The noise voltage V_n induced in this circuit can be expressed by the following equation:

$$V_n = 2\,\pi\,f\,B\,A\,\cos\theta \times 10^{-8}\ V \qquad\qquad \text{Eq. 1}$$

In this equation, f represents the frequency of the magnetic field, and θ represents the angle of the magnetic field B to the circuit with loop area A. Magnetic field coupling can be reduced by reducing the circuit loop area, the magnetic field intensity, or the angle of incidence. Reducing circuit loop area requires arranging the circuit conductors closer together. Twisting the conductors together reduces the loop net area. This has the effect of canceling magnetic field pickup, because the sum of positive and negative incremental loop areas is ideally equal to zero. Reducing the magnetic field directly may be difficult. However, since magnetic field intensity is inversely proportional to the cube of the distance from the source, physically moving the affected circuit away from the magnetic field has a very great effect in reducing the induced noise voltage. Finally, if the circuit is placed perpendicular to the magnetic field, pickup is minimized. If the circuit's conductors are in parallel to the magnetic field the induced noise is maximized because the angle of incidence is zero.

There are also techniques that can be used to reduce the amount of magnetic-field interference, *at its source*. In the previous paragraph, the conductors of the receiver circuit were twisted together, to cancel the induced magnetic field along the wires. The same principle can be used on the source wiring. If the source of the magnetic field is large currents flowing through nearby conductors, these wires can be twisted together to reduce the net magnetic field.

Shields and cans are not nearly as effective against magnetic fields as against electric fields, but can be useful on occasion. At low frequencies magnetic shields using high-permeability material such as Mu-metal can provide modest attenuation of magnetic fields. At high frequencies simple conductive shields are quite effective provided that the thickness of the shield is greater than the skin depth of the conductor used (at the frequency involved). Note—copper skin depth is $6.6/\sqrt{f}$ cm, with f in Hz.

PASSIVE COMPONENTS: YOUR ARSENAL AGAINST EMI

Passive components, such as resistors, capacitors, and inductors, are powerful tools for reducing externally induced interference when used properly.

Simple RC networks make efficient and inexpensive one-pole, low-pass filters. Incoming noise is converted to heat and dissipated in the resistor. But note that a fixed resistor does produce thermal noise of its own. Also, when used in the input circuit of an op amp or in-amp, such resistor(s) can generate input-bias-current induced offset voltage. While matching the two resistors will minimize the dc offset, the noise will remain. Figure 6 summarizes some popular low-pass filters for minimizing EMI.

In applications where signal and return conductors aren't well-coupled magnetically, a common-mode (CM) choke can be used to increase their mutual inductance. Note that these comments

apply mostly to in-amps, which naturally receive a balanced input signal (whereas op amps are inherently unbalanced inputs—unless one constructs an in-amp with them). A CM choke can be simply constructed by winding several turns of the differential signal conductors together through a high-permeability (> 2000) ferrite bead. The magnetic properties of the ferrite allow differential-mode currents to pass unimpeded while suppressing CM currents.

LP Filter Type	ADVANTAGE	DISADVANTAGE
RC Section	**Simple** **Inexpensive**	**Resistor Thermal Noise** I_B **x R Drop** $\rightarrow$ **Offset** **Single-Pole Cutoff**
LC Section **(Bifilar)**	**Very Low Noise at LF** **Very Low IR Drop** **Inexpensive** **Two-Pole Cutoff**	**Medium Complexity** **Nonlinear Core Effects Possible**
π Section **(C-L-C)**	**Very Low Noise at LF** **Very Low IR Drop** **Pre-packaged Filters** **Multiple-Pole Cutoff**	**Most Complex** **Nonlinear Core Effects Possible** **Expensive**

Figure 6: Using Passive Components Within Filters to Combat EMI

Capacitors can also be used before and after the choke, to provide additional CM and differential-mode filtering, respectively. Such a CM choke is cheap and produces very low thermal noise and bias current-induced offsets, due to the wire's low dc resistance. However, there is a field around the core. A metallic shield surrounding the core may be necessary to prevent coupling with other circuits. Also, note that high-current levels should be avoided in the core as they may saturate the ferrite.

The third method for passive filtering takes the form of packaged π-networks (C-L-C). These packaged filters are completely self-contained and include feedthrough capacitors at the input and the output as well as a shield to prevent the inductor's magnetic field from radiating noise. These more expensive networks offer high levels of attenuation and wide operating frequency ranges, but the filters must be selected so that for the operating current levels involved the ferrite doesn't saturate.

REDUCING SYSTEM SUSCEPTIBILITY TO EMI

The general examples discussed above and the techniques illustrated earlier in this section outline the procedures that can be used to reduce or eliminate EMI/RFI. Considered on a *system* basis, a summary of possible measures is given in Figure 7.

Other examples of filtering techniques useful against EMI are illustrated in Tutorial MT-070.

The section immediately below further details shielding principles.

- ◆ **Always Assume That Interference Exists!**
- ◆ **Use Conducting Enclosures Against Electric and HF Magnetic Fields**
- ◆ **Use mu-Metal Enclosures Against LF Magnetic Fields**
- ◆ **Implement Cable Shields Effectively**
- ◆ **Use Feedthrough Capacitors and Packaged PI Filters**

Figure 7: Reducing System EMI/RFI Susceptibility

A REVIEW OF SHIELDING CONCEPTS

The concepts of shielding effectiveness presented next are background material. Interested readers should consult References 4-9 cited at the end of the tutorial for more detailed information.

Applying the concepts of shielding effectively requires an understanding of the source of the interference, the environment surrounding the source, and the distance between the source and point of observation (the receiver). If the circuit is operating close to the source (in the *near*, or induction-field), then the field characteristics are determined by the source. If the circuit is remotely located (in the *far*, or radiation-field), then the field characteristics are determined by the transmission medium.

A circuit operates in a near-field if its distance from the source of the interference is less than the wavelength (λ) of the interference divided by 2π, or $\lambda/2\pi$. If the distance between the circuit and the source of the interference is larger than this quantity, then the circuit operates in the far field. For instance, the interference caused by a 1-ns pulse edge has an upper bandwidth of approximately 350 MHz. The wavelength of a 350-MHz signal is approximately 32 inches (the speed of light is approximately 12"/ns). Dividing the wavelength by 2π yields a distance of approximately 5 inches, the boundary between near- and far-field. If a circuit is within 5 inches of a 350-MHz interference source, then the circuit operates in the near-field of the interference. If the distance is greater than 5 inches, the circuit operates in the far-field of the interference.

Regardless of the type of interference, there is a characteristic impedance associated with it. The characteristic, or wave impedance of a field is determined by the ratio of its electric (or E-) field to its magnetic (or H-) field. In the far field, the ratio of the electric field to the magnetic field is the characteristic (wave impedance) of free space, given by $Z_O = 377\ \Omega$. In the near field, the wave-impedance is determined by the nature of the interference and its distance from the source. If the interference source is high-current and low-voltage (for example, a loop antenna or a power-line transformer), the field is predominately magnetic and exhibits a wave impedance which is less than 377 Ω. If the source is low-current and high-voltage (for example, a rod antenna or a high-speed digital switching circuit), then the field is predominately electric and exhibits a wave impedance which is greater than 377 Ω.

Conductive enclosures can be used to shield sensitive circuits from the effects of these external fields. These materials present an *impedance mismatch* to the incident interference, because the impedance of the shield is lower than the wave impedance of the incident field. The effectiveness of the conductive shield depends on two things: First is the loss due to the *reflection* of the incident wave off the shielding material. Second is the loss due to the *absorption* of the transmitted wave *within* the shielding material. The amount of reflection loss depends upon the type of interference and its wave impedance. The amount of absorption loss, however, is independent of the type of interference. It is the same for near- and far-field radiation, as well as for electric or magnetic fields.

Reflection loss at the interface between two media depends on the difference in the characteristic impedances of the two media. For electric fields, reflection loss depends on the frequency of the interference and the shielding material. This loss can be expressed in dB, and is given by:

$$R_e(dB) = 322 + 10\log_{10}\left[\frac{\sigma_r}{\mu_r f^3 r^2}\right]$$

Eq. 2

where σ_r = relative conductivity of the shielding material, in Siemens per meter; μ_r = relative permeability of the shielding material, in Henries per meter; f = frequency of the interference, and r = distance from source of the interference, in meters

For magnetic fields, the loss depends also on the shielding material and the frequency of the interference. Reflection loss for magnetic fields is given by:

$$R_m(dB) = 14.6 + 10\log_{10}\left[\frac{f r^2 \sigma_r}{\mu_r}\right]$$

Eq. 3

and, for plane waves ($r > \lambda/2\pi$), the reflection loss is given by:

$$R_{pw}(dB) = 168 + 10\log_{10}\left[\frac{\sigma_r}{\mu_r f}\right]$$

Eq. 4

Absorption is the second loss mechanism in shielding materials. Wave attenuation due to absorption is given by:

$$A(dB) = 3.34t\sqrt{\sigma_r \mu_r f}$$

Eq. 5

where t = thickness of the shield material, in inches. This expression is valid for plane waves, electric and magnetic fields. Since the intensity of a transmitted field decreases exponentially relative to the thickness of the shielding material, the absorption loss in a shield one skin-depth (δ) thick is 9 dB. Since absorption loss is proportional to thickness and inversely proportional to

skin depth, increasing the thickness of the shielding material improves shielding effectiveness at high frequencies.

Reflection loss for plane waves in the far field decreases with increasing frequency because the shield impedance, Z_s, increases with frequency. Absorption loss, on the other hand, increases with frequency because skin depth decreases. For electric fields and plane waves, the primary shielding mechanism is reflection loss, and at high frequencies, the mechanism is absorption loss.

Thus for high-frequency interference signals, lightweight, easily worked high conductivity materials such as copper or aluminum can provide adequate shielding. At low frequencies however, both reflection and absorption loss to magnetic fields is low. It is thus very difficult to shield circuits from low-frequency magnetic fields. In these applications, high-permeability materials that exhibit low-reluctance provide the best protection. These low-reluctance materials provide a magnetic shunt path that diverts the magnetic field away from the protected circuit. Examples of high-permeability materials are steel and mu-metal.

To summarize the characteristics of metallic materials commonly used for shielded purposes: Use high conductivity metals for HF interference, and high permeability metals for LF interference.

A properly shielded enclosure is very effective at preventing external interference from disrupting its contents as well as confining any internally-generated interference. However, in the real world, openings in the shield are often required to accommodate adjustment knobs, switches, connectors, or to provide ventilation. Unfortunately, these openings may compromise shielding effectiveness by providing paths for high-frequency interference to enter the instrument.

The longest dimension (not the total area) of an opening is used to evaluate the ability of external fields to enter the enclosure, because the openings behave as slot antennas. Equation 6 can be used to calculate the shielding effectiveness, or the susceptibility to EMI leakage or penetration, of an opening in an enclosure:

$$\text{Shielding Effectiveness (dB)} = 20 \log_{10}\left(\frac{\lambda}{2 \cdot L}\right) \qquad \text{Eq. 6}$$

where λ = wavelength of the interference and L = maximum dimension of the opening

Maximum radiation of EMI through an opening occurs when the longest dimension of the opening is equal to one half-wavelength of the interference frequency (0-dB shielding effectiveness). A rule-of-thumb is to keep the longest dimension less than 1/20 wavelength of the interference signal, as this provides 20-dB shielding effectiveness. Furthermore, a few small openings on each side of an enclosure is preferred over many openings on one side. This is because the openings on different sides radiate energy in different directions, and as a result, shielding effectiveness is not compromised. If openings and seams cannot be avoided, then conductive gaskets, screens, and paints alone or in combination should be used judiciously to limit the longest dimension of any opening to less than 1/20 wavelength. Any cables, wires,

connectors, indicators, or control shafts penetrating the enclosure should have circumferential metallic shields physically bonded to the enclosure at the point of entry. In those applications where unshielded cables/wires are used, then filters are recommended at the shield entry point.

GENERAL POINTS ON CABLES AND SHIELDS

Although covered in detail elsewhere, it is worth noting that the improper use of cables and their shields can be a significant contributor to both radiated and conducted interference. Rather than developing an entire treatise on these issues, the interested reader should consult References 2, 3, 5, and 6 for background.

As shown in Figure 8, proper cable/enclosure shielding confines sensitive circuitry and signals *entirely within the shield*, with no compromise to shielding effectiveness.

SHIELDED
ENCLOSURE A

SHIELDED
INTERCONNECT
CABLE
LENGTH = L

SHIELDED
ENCLOSURE B

FULLY SHIELDED ENCLOSURES CONNECTED BY FULLY
SHIELDED CABLE KEEP ALL INTERNAL CIRCUITS AND
SIGNAL LINES INSIDE THE SHIELD.
● TRANSITION REGION: 1/20 WAVELENGTH
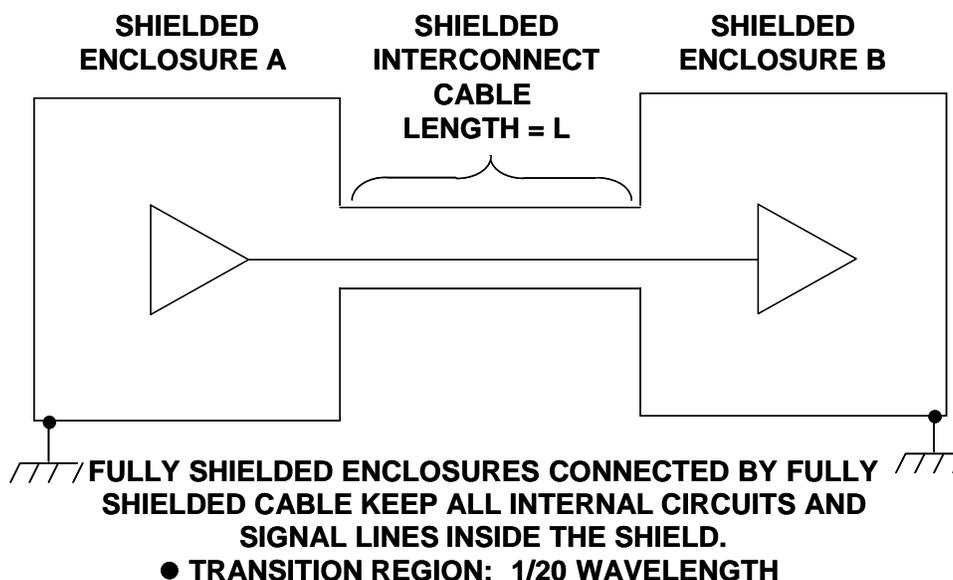
*Figure 8: Shielded Interconnect Cables Are Either Electrically Long or Short,
Depending Upon the Operating Frequency*

As can be noted by this diagram, the enclosures and the shield must be grounded properly, otherwise they can act as an antenna, thereby making the radiated and conducted interference problem worse (rather than better).

Depending on the type of interference (pickup/radiated, low/high frequency), proper cable shielding is implemented differently and is very dependent on the length of the cable. The first step is to determine whether the length of the cable is *electrically short* or *electrically long* at the frequency of concern. A cable is considered electrically short if the length of the cable is less than 1/20 wavelength of the highest frequency of the interference. Otherwise it is considered to be electrically long.

For example, at 50/60 Hz, an electrically short cable is any cable length less than 150 miles, where the primary coupling mechanism for these low frequency electric fields is capacitive. As such, for any cable length less than 150 miles, the amplitude of the interference will be the same over the entire length of the cable.

In applications where the length of the cable is electrically long, or protection against high-frequency interference is required, then the preferred method is to connect the cable shield to low-impedance points, *at both ends*. As will be seen shortly, this can be a direct connection at the driving end, and a capacitive connection at the receiver. If left ungrounded, unterminated transmission lines effects can cause reflections and standing waves along the cable. At frequencies of 10 MHz and above, circumferential (360°) shield bonds and metal connectors are required to main low-impedance connections to ground.

In summary, for protection against low-frequency (<1 MHz), electric-field interference, grounding the shield at one end is acceptable. For high-frequency interference (>1 MHz), the preferred method is grounding the shield at both ends, using 360° circumferential bonds between the shield and the connector, and maintaining metal-to-metal continuity between the connectors and the enclosure.

However in practice, there is a caveat involved with directly grounding the shield at both ends. When this is done, it creates a low frequency ground loop, shown in Figure 9.
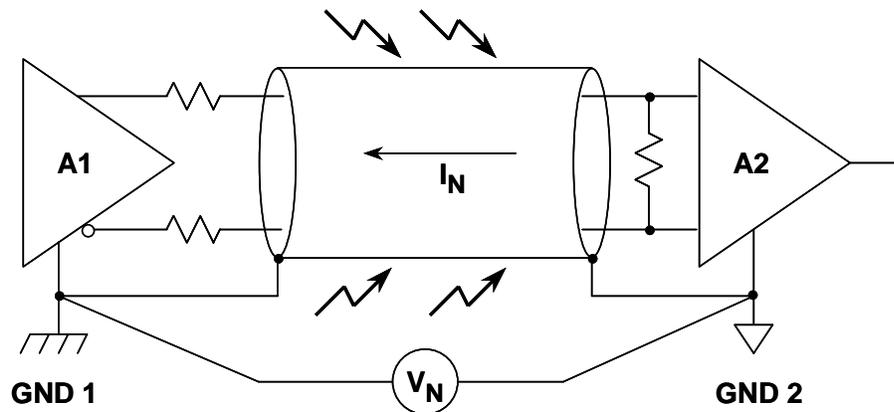
◆ V_N Causes Current in Shield (Usually 50/60Hz)

◆ Differential Error Voltage is Produced at Input of A2 Unless:
  ● A1 Output is Perfectly Balanced and
  ● A2 Input is Perfectly Balanced and
  ● Cable is Perfectly Balanced

Figure 9: Ground Loops in Shielded Twisted Pair Cable Can Cause Errors

Whenever two systems A1 and A2 are remote from each other, there is usually a difference in the ground potentials at each system, i.e., V_N. The frequency of this potential difference is

generally the line frequency (50 or 60 Hz) and multiples thereof. But, if the shield is directly grounded at both ends as shown, noise current I_N flows in the shield. In a perfectly balanced system, the common-mode rejection of the system is infinite, and this current flow produces no differential error at the receiver A2. However, perfect balance is never achieved in the driver, its impedance, the cable, or the receiver, so a certain portion of the shield current will appear as a differential noise signal, at the input of A2. The following illustrate correct shield grounding for various examples.

As noted above, cable shields are subject to both low and high frequency interference. Good design practice requires that the shield be grounded at both ends if the cable is electrically long to the interference frequency, as is usually the case with RF interference.

Figure 10 shows a remote passive RTD sensor connected to a bridge and conditioning circuit by a shielded cable. The proper grounding method is shown in the upper part of the figure, where the shield is grounded at the receiving end.
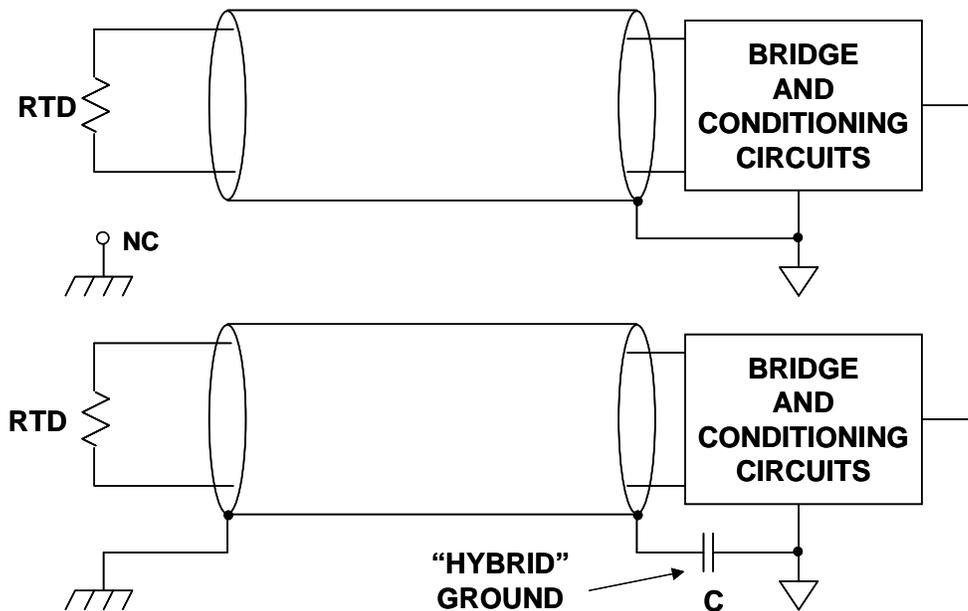
Figure 10: Hybrid Grounding of Shielded Cable With Passive Sensor

However, safety considerations may require that the remote end of the shield also be grounded. If this is the case, the receiving end can be grounded with a low inductance ceramic capacitor (0.01 µF to 0.1 µF), still providing high frequency grounding. The capacitor acts as a ground to RF signals on the shield but blocks low frequency line current to flow in the shield. This technique is often referred to as a *hybrid ground*.

A case of an active remote sensor and/or other electronics is shown Figure 11. In both of the two situations, a hybrid ground is also appropriate, either for the balanced (upper) or the single-ended (lower) driver case. In both instances the capacitor "C" breaks the low frequency ground loop,

providing effective RF grounding of the shielded cable at the A2 receiving end at the right side of the diagram.

There are also some more subtle points that should be made with regard to the source termination resistances used, R_S. In both the balanced as well as the single-ended drive cases, the driving signal seen on the balanced line originates from a net impedance of R_S, which is split between the two twisted pair legs as twice $R_S/2$. In the upper case of a fully differential drive, this is straightforward, with an $R_S/2$ valued resistor connected in series with the complementary outputs from A1.

In the bottom case of the single-ended driver, note that there are still two $R_S/2$ resistors used, one in series with both legs. Here the grounded dummy return leg resistor provides an impedance-balanced ground connection drive to the differential line, aiding in overall system noise immunity. Note that this implementation is only useful for those applications with a balanced receiver at A2, as shown.
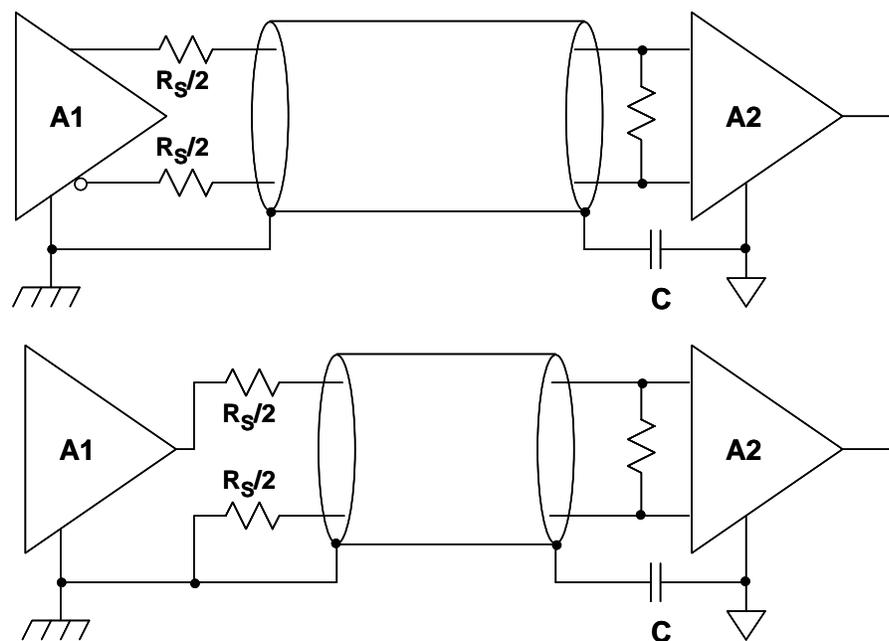

Figure 11: Impedance-Balanced Drive of Balanced Shielded Cable Aids Noise-Immunity With Either Balanced or Single-Ended Source Signals

Coaxial cables are different from shielded twisted pair cables in that the signal return current path is through the shield. For this reason, the ideal situation is to ground the shield at the driving end and allow the shield to float at the differential receiver (A2) as shown in the upper portion of Figure 12. For this technique to work, however, the receiver must be a differential type with good high frequency CM rejection.

However, the receiver may be a single-ended type, such as typical of a standard single op amp type circuit. This is true for the bottom example of Figure 12, so there is no choice but to ground the coaxial cable shield at both ends for this case.
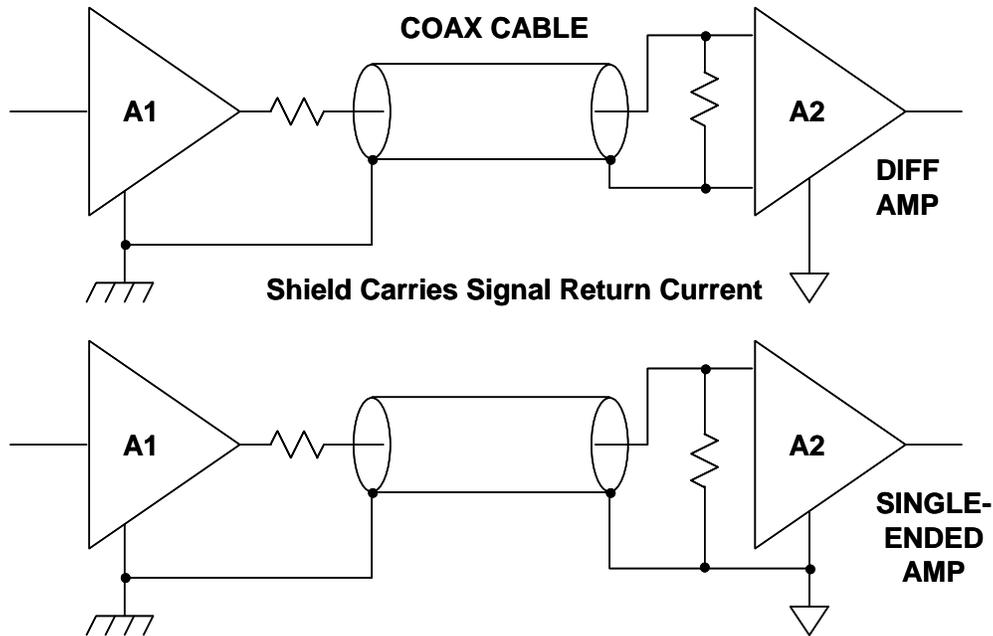

**Figure 12: Coaxial Cables Can Use Either Balanced
or Single-Ended Receivers**

REFERENCES:

1. Tim Williams, *EMC for Product Designers, 2nd Ed.*, Newnes, Oxford, 1996, ISBN: 0 7506 2466 3.

2. Henry Ott, *Noise Reduction Techniques In Electronic Systems, 2nd Ed.*, John Wiley & Sons, New York, 1988, ISBN 0-471-85068-3.

3. Mark Montrose, *EMC and the Printed Circuit Board*, IEEE Press, 1999, ISBN 0-7803-4703-X.

4. Ralph Morrison, *Grounding And Shielding Techniques in Instrumentation*, *3rd Ed.*, John Wiley & Sons, New York, 1986, ISBN 0-471-83805-5.

5. Daryl Gerke and William Kimmel, "Designer's Guide to Electromagnetic Compatibility," *EDN*, January 20, 1994.

6. *Designing for EMC* (Workshop Notes), Kimmel Gerke Associates, Ltd., 1994.

7. Daryl Gerke and William Kimmel, "EMI and Circuit Components," *EDN*, September 1, 2000.

8. Alan Rich, "Understanding Interference-Type Noise," *Analog Dialogue*, Vol. 16, No. 3, 1982, pp. 16-19 (also available as application note AN-346).

9. Alan Rich, "Shielding and Guarding," *Analog Dialogue*, Vol. 17, No. 1, 1983, pp. 8-13 (also available as application note AN-347).

10. James Wong, Joe Buxton, Adolfo Garcia, James Bryant**,** "Filtering and Protection Against EMI/RFI" and "Input Stage RFI Rectification Sensitivity", Chapter 1, pg. 21-55 of *Systems Application Guide*, 1993, Analog Devices, Inc., Norwood, MA, ISBN 0-916550-13-3.

11. Adolfo Garcia**,** "EMI/RFI Considerations"**,** *Chapter 7, pg 42-80 of High Speed Design Techniques,* 1996, Analog Devices, Inc., Norwood, MA, 1993, ISBN 0-916550-17-6.

12. Walt Kester, Walt Jung, Chuck Kitchen, "Preventing RFI Rectification"**,** Chapter 10, pg 10.39-10.43 of *Practical Design Techniques for Sensor Signal Conditioning,* Analog Devices, Inc., Norwood, MA, 1999, ISBN 0-916550-20-6.

13. Charles Kitchin and Lew Counts, *A Designer's Guide to Instrumentation Amplifiers, 3rd Edition*, Analog Devices, 2006.

14. *B4001 and B4003 common-mode chokes*, Pulse Engineering, Inc., 12220 World Trade Drive, San Diego, CA, 92128, 619-674-8100, http://www.pulseeng.com

15. *Understanding Common Mode Noise*, Pulse Engineering, Inc., 12220 World Trade Drive, San Diego, CA, 92128, 619-674-8100, http://www.pulseeng.com

16. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as *Linear Circuit Design Handbook*, Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 11

17. Walt Kester, *Analog-Digital Conversion,* Analog Devices, 2004, ISBN 0-916550-27-3, Chapter 9. Also available as *The Data Conversion Handbook*, Elsevier/Newnes, 2005, ISBN 0-7506-7841-0, Chapter 9.

18. Walter G. Jung, *Op Amp Applications*, Analog Devices, 2002, ISBN 0-916550-26-5, Chapter 7. Also available as *Op Amp Applications Handbook*, Elsevier/Newnes, 2005, ISBN 0-7506-7844-5. Chapter 7.

SOME USEFUL EMC AND SIGNAL INTEGRITY RELATED URLS:

1. Kimmel Gerke Associates website, http://www.emiguru.com

2. Henry Ott website, http://www.hottconsultants.com

3. IEEE EMC website, http://www.ewh.ieee.org/soc/emcs

4. Mark Montrose website, http://www.montrosecompliance.com/index.html

5. Tim Williams website, http://www.elmac.co.uk

6. Eric Bogatin website,http://www.bethesignal.com

7. Howard Johnson website,http://signalintegrity.com