An Introduction to Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI) for Audio System Designers*

PHILIP GIDDINGS

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PHILIP GIDDINGS

Toronto, Ontario M5A 3C3, Canada

Electromagnetic compatibility and electromagnetic interference engineering are well-developed fields, and many of the concepts and techniques used by professionals in this discipline are brought forward. This will allow audio system designers to begin to understand why many of the techniques used in audio engineering exist and will put them in a better position to make further use of these techniques in difficult situations and new designs.

0 INTRODUCTION

Electromagnetic compatibility (EMC) and electromagnetic interference (EMI) are not words commonly spoken by audio system designers. Many may not know what they mean or how they impact the audio field. On the other hand all of us are aware of electrical noise problems and have seen the hit-and-miss methods of solution, realizing that this process could be more scientific with, perhaps, less expense in time and materials.

To begin to tackle these challenges it is necessary to understand the basics of electromagnetic fields; how EMI is created, transmitted, and received; and what practices and techniques are available for its control. This paper discusses all of these topics.

The expense of dealing with potential EMI at the design stage is small compared to that resulting from remedial action needed in the field after installation. In fact, as it will be seen, many EMC procedures are nothing more than good practice and involve little time or cost for their implementation.

1 INTRODUCTION TO ELECTROMAGNETIC FIELDS

This section provides a brief introduction to how electromagnetic fields are created and interact with each other and will yield an appreciation useful in studying EMI and EMC.

The analysis of the propagation of electromagnetic fields may be divided into the near field and the far field. In the expanding wave front of the near field the electric and magnetic fields may be analyzed individually. As the field moves into the far field, the wave becomes a plane wave and the relationship of the electric and magnetic fields is established. The field is then analyzed as electromagnetic radiation.

1.1 Electric and Magnetic Fields

As the word electromagnetic implies, these fields are a two-part phenomenon consisting of an electric field and a magnetic field. It is helpful to have a physical model to visualize the behavior of these two types of fields.

The *electric* field can be modeled as "lines of force" emanating radially out from a wire (perpendicular from its surface), which has a voltage potential on it. They radiate out using the path of least resistance, naturally spacing themselves apart. If the wire has positive potential (due to an absence of electrons), the direction of the field lines is away from the wire, and it is toward the wire if there is a negative potential (Fig. 1). The density of the lines indicates the strength of the field, and moving away from the wire causes the field strength to diminish. In the case of a line source such as a wire, the field strength drops off at a rate of 3 dB per doubling of distance.

Just as a potential on a wire creates an electric field, an electric field creates a potential on a wire that the field lines strike. Wires couple in this manner. This

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coupling effect can be modeled perfectly as a capacitor between the two conductors. The capacitance between the source and the receiver is proportional to the area the source and the receiver share between each other (in the case of wire, determined by the gauge, length, and orientation), the frequency and the amplitude of the electrical source signal, and the permittivity (or dielectric constant) of the medium between the source and the receiver (victim). It is inversely proportional to the square of the distance between them.

If two wires with opposite potentials are placed parallel and near each other, they interact (and couple), as shown by the solid lines in Fig. 2. If an imaginary line is drawn perpendicular to the axis between the wires and dividing it into two equal parts, all the field lines pass through it at right angles, as illustrated. In a similar manner, if a ground plane is located at the imaginary line, the field lines will terminate on it at right angles, as shown in Fig. 3. A ground plane attracts the electric field.

The electric field is a voltage phenomenon and is often referred to as the high-impedance wave.

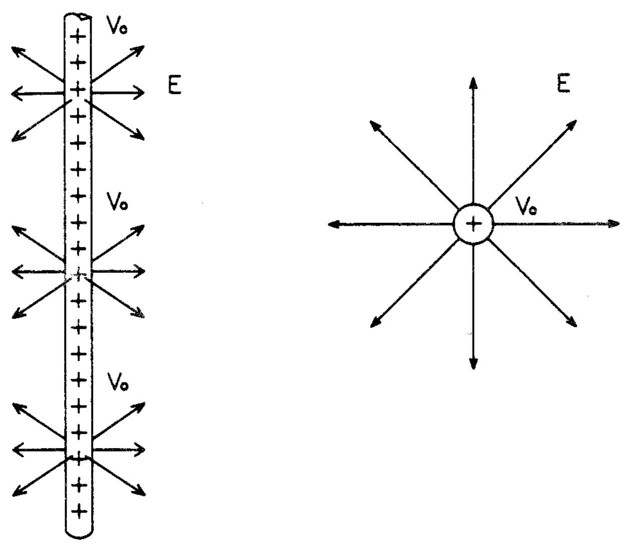


Fig. 1. Electric field of a conductor.

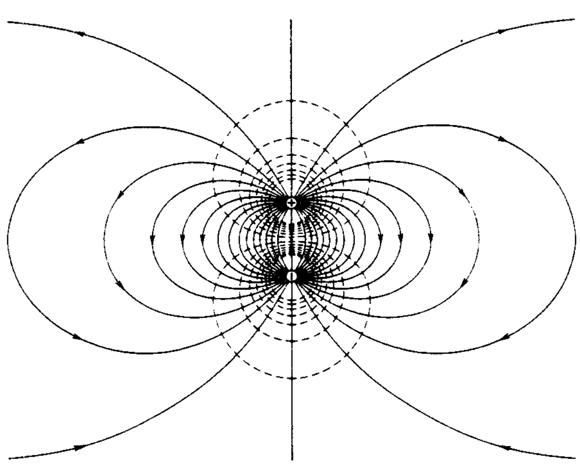


Fig. 2. Electric and magnetic fields of a pair of conductors oppositely charged. (Magnetic field dashed line.)

The *magnetic* field can be modeled as "lines of force" circling a wire that has a current (moving charge) on it. The lines of force surround the wire in circles that are at right angles to the electric field lines. A given contour represents a particular field strength (Fig. 4). The "right-hand rule" states that if the wire is grasped with the right hand with the thumb pointing in the direction of the current, the fingers will curl around the wire in the direction of the magnetic field. The density of the lines indicates the strength of the field, and moving away from the wire causes the field strength to diminish. In the case of a line source, such as a wire, the field strength drops off at a rate of 3 dB per doubling of distance.

Just as a changing current in a wire creates a field, a changing field creates a current in another wire when the field lines encircle it. This coupling effect can be modeled perfectly by the mutual inductance between two inductors in the source and receiving wires. The mutual inductance between the source and the receiver is a positive function of the loop area of the receiver circuit (as this determines the number of "lines of force," or field lines, which pass through it), the frequency (or rate of change), the current of the source, and the permeability of the medium between source and receiver. It is inversely proportional to the square of the distance between them.

If two wires with changing current in opposite directions are placed parallel and near each other, they

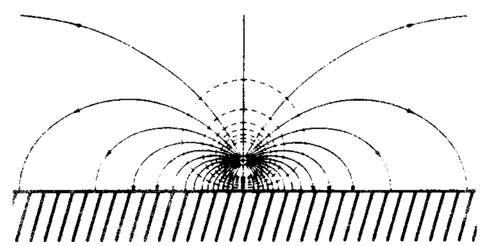


Fig. 3. Electric and magnetic fields of a conductor and ground plane. (Magnetic field dashed line).

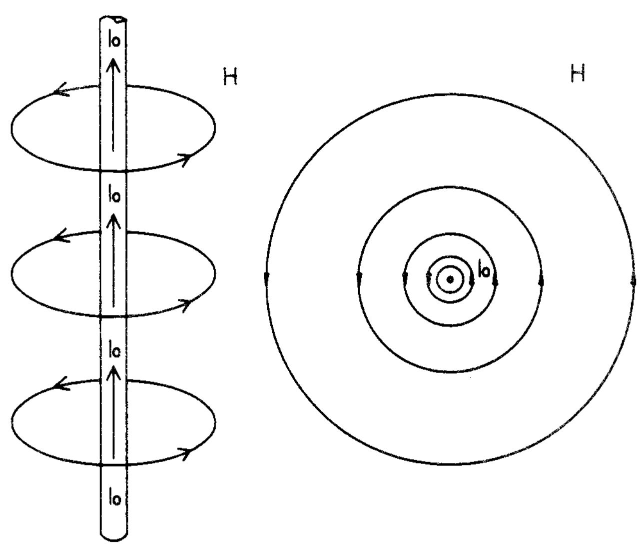


Fig. 4. Magnetic field of a conductor.

interact as shown by the dashed lines in Fig. 2. Unlike electric field lines, magnetic field lines are not attracted by a ground plane, as illustrated by Fig. 3.

The magnetic field is a current phenomenon and is often referred to as the low-impedance wave.

1.2 Electromagnetic Radiation

Electromagnetic radiation by definition occurs in the far field where the wave front has become a plane wave transmitting through the medium with a specific electric-field to magnetic-field ratio. The ratio, it will be shown, is determined by the characteristic impedance of the medium.

Electromagnetic radiation is a two-part phenomenon consisting of an electric field and a magnetic field traveling as a transverse electromagnetic wave (TEM). An electromagnetic oscillation is electric and magnetic fields operating together by transferring energy back and forth. It is possible to model this relationship with a capacitor (the electric field) and an inductor (the magnetic field) wired together, as shown in Fig. 5. This circuit will oscillate between a charge on the capacitor with the associated electric field and a current through the inductor with its associated magnetic field. When there is maximum energy stored in the electric field, there is no energy in the magnetic field, and vice versa. In other words, when there is maximum current there is maximum magnetic field, and when there is maximum voltage there is maximum electric field. When there are both a current and a voltage present, there are both an electric and a magnetic field at something less then full potential. If the circuit had no resistive losses it would, once excited, oscillate forever. [This relationship can be likened to longitudinal sound waves traveling through air where the air pressure (potential energy) and the air velocity (kinetic energy) at a given point are always 180° out of synchronization with each other.]

The model illustrates that it is not possible to have

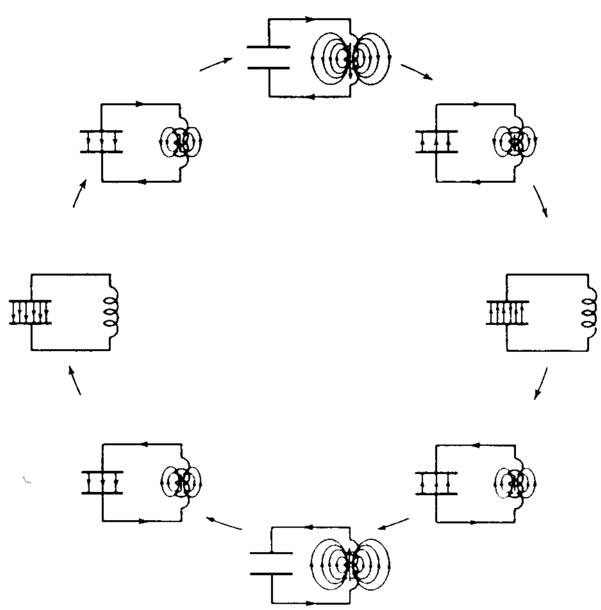


Fig. 5. Electromagnetic oscillation model.

a changing electric field without having a changing magnetic field, and vice versa.

It is possible to model electromagnetic radiation traveling in free space as an electric circuit of inductors and capacitors hooked together in a series–parallel arrangement, as shown in Fig. 6. This model will be familiar to some readers as that of a transmission line. Transmission-line theory can also be used to describe how electromagnetic radiation travels through the air. When a signal is applied to one end of the transmission line, the energy begins to move through the line by transferring energy from capacitor to inductor down the line, and so waves of energy are transmitted as oscillations through the medium.

The speed of propagation of a signal down a transmission line is determined by the values of its capacitance and inductance, which also determine the characteristic impedance of the transmission medium. For a given transmission medium, such as air, the value of the capacitance is given by its permittivity (e in farads per meter) and the value of the inductance is given by its permeability (μ in henrys per meter). The speed of electromagnetic waves is given by

$$V = \frac{1}{\sqrt{\mu e}} .$$

For free space (air) this is

$$\frac{1}{\sqrt{(1.26 \times 10^{-6})(8.85 \times 10^{-12})}} = 3 \times 10^{8} \text{ m/s} .$$

This is the speed of light and all other forms of electromagnetic radiation, in free space.

In order for a transmission line to exist, the medium must be sufficiently long that the fields emanating into it have an opportunity to establish themselves as traveling plane waves. This distance is about one-sixth (0.15) of a wavelength at the frequency of concern. The wavelength and the frequency of a propagating wave in a medium are related to the speed of transmission in the medium by the formula

$$\text{speed of transmission} = \text{wavelength} \times \text{frequency} .$$

In the 1000-kHz AM radio wave region, electromagnetic fields in free space (air or vacuum) traveling at the speed of light have wavelengths on the order of 300 m. They can be modeled as traveling over a transmission line where distances of 45 m or more are involved.

At about one-fifth of a wavelength or more away from the radiator the ratio of the strengths of the electric

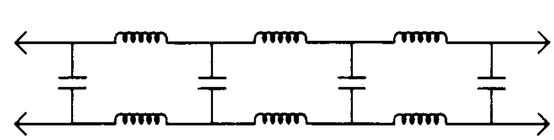


Fig. 6. Electromagnetic transmission line.

and magnetic fields is determined by a constant, the characteristic impedance of the medium, given by the formula

$$\text{characteristic impedance} = \sqrt{\frac{\text{inductance}}{\text{capacitance}}}$$

$$Z_{0\ \text{free space}} = \sqrt{\frac{\text{permeability}}{\text{permittivity}}}$$

$$= \sqrt{\frac{1.26 \times 10^{-6}}{8.85 \times 10^{-12}}} = 377\ \Omega\ .$$

In the far field the wave is electromagnetic radiation having a fixed ratio of electric to magnetic fields and a plane (flat) wave front.

2 SOURCE–TRANSMISSION MEDIUM–RECEIVER PATH

In order for EMI to exist there must be a source of electrical noise interference, a path for the interference to travel on, and a receiver that is susceptible to the level and nature of EMI being generated. EMC occurs when any one of these three elements is missing. Therefore EMC can be accomplished in several ways.

2.1 Sources of EMI

Electrical noise is any unwanted signal and has many sources. Some common ones are shown in Table 1.

In practice, while many electrical noise sources exist, most can be dismissed because they are of insufficient strength at the victim circuit's location to pose a threat.

In audio the most common sources of EMI include line-frequency ac power, broad-band electric noise on ac power lines, radiated electromagnetic waves (RF), and intercable crosstalk. For this reason EMI can manifest itself as hum, gurgles, buzzes, chirps, whistles, or intelligible voice signal interference.

In the case of clean ac power as a noise source, the noise frequency spectrum is simply that of the ac line (60 Hz in North America) and perhaps some harmonics (120 and 180 Hz) at lower levels. If the ac power feeds

Table 1. Sources of electrical noise.

Major sources
Fluorescent and neon lights
Thyristors and other semiconductors used in switching mode
Switched inductive loads, such as motors, switch gear, or switched HVAC equipment
Welding equipment and numerous industrial processes
Automobile ignitions
High- and low-voltage ac power lines
Computers
RF transmitters
Minor sources (not discussed here)
Thermal voltages between dissimilar metals
Thermal noise of resistors
Chemical voltages due to electrolyte between poorly connected leads

a motor or an electronic dimmer, there may be spikes and oscillations on the line which result in a much broader spectrum of noise, at higher frequencies than the ac line frequency.

Where inductive circuits are being switched, large voltages (on the order of 10 times nominal) and arcing can be created. The spike may be the result of the inductance in either the load or the transformer supplying the load. This is because, when the current in an inductor is halted by opening the circuit, a large voltage results from the current created by the collapsing magnetic fields in the coil. In an electric motor with brushes, switching occurs hundreds of times a second, whereas in the switch gear used to operate large (and inductive) transformers, switching may only occur once or twice per day or even per week.

2.1.1 Classification of Noise

Noise in its broadest definition is any undesired signal. The telecommunications industry uses the following classifications.

Thermal noise is a form of noise resulting from the random motion of electrons and is characterized by uniform energy distribution over the frequency spectrum (white noise).

Impulse noise is noncontinuous, short-duration, irregular pulses of relatively high amplitude. Sources of impulse noise include switched relay and control circuits, transients in power circuits, and crosstalk into other switched communications circuits.

Crosstalk is interference from other similar type circuits and may be intelligible or unintelligible.

Tone interference is due to single tones such as ac line frequency or complex periodic waveforms.

Miscellaneous noise is that interference which does not fall into any of the preceding categories.

2.1.2 Frequency Content of Noise

The frequency content of noise can be determined by use of a spectrum analyzer. A more available tool, however, is the oscilloscope, which is a time-domain instrument and does not readily reveal frequency content information. Using formulas developed through Fourier analysis it is possible to determine the approximate frequency content of a signal based on information obtained in the time domain (from an oscilloscope).

Two of the most common signals desirable to analyze are square waves, commonly used for digital control such as the SMPTE time code, and short spikes, which appear superimposed on ac power lines.

Square waves: The spectral content of a square wave is characterized by frequencies at the fundamental and at odd multiples of it (3, 5, 7, . . .) [1]. The relative levels of the frequency components are given in Table 2.

As the rise and decay times of the square wave increase, the high-order harmonics diminish at a rate of 40 dB per decade.

In the case of the time code that operates at 2.4 kHz, the 11th harmonic is at 26.4 kHz and is 18.7 dB down.

The time code, of course, varies with time and is not a steady-state signal. This example represents the case of all 1's, where the greatest number of transitions occurs.

Pulses: Noise caused by switched loads on a power line often results in spikes that occur once during each half-cycle of ac power. The shorter the duration of these transients, the broader will be their frequency spectra. As these are impulses in nature, their frequency spectra are more or less continuous and not represented by discrete multiples of a fundamental. In general, these signals will contain energy from low frequency to a frequency of 1 over the time duration ($1/t$) of the pulse. The energy content at any given frequency will be many times less than that of the impulse.

2.2 EMI Coupling (Transmission)

There are four means of transmission for electrical noise. Identifying how the noise is being transmitted to the receiver is a key factor in determining how it is most easily and effectively controlled. This is often the only area in an audio system where corrective measures can be made, since changes to the source or the receiver are not possible. Pursuing and eliminating the wrong transmission path can result in no improvement whatsoever.

Table 2. Square wave frequency content.

Frequency	Ratio	dB
Fundamental	1.27	+2.1
3rd harmonic	0.424	−7.4
5th harmonic	0.255	−11.9
7th harmonic	0.182	−14.8
9th harmonic	0.141	−17.0
11th harmonic	0.116	−18.7
110th harmonic	0.012	−38.7

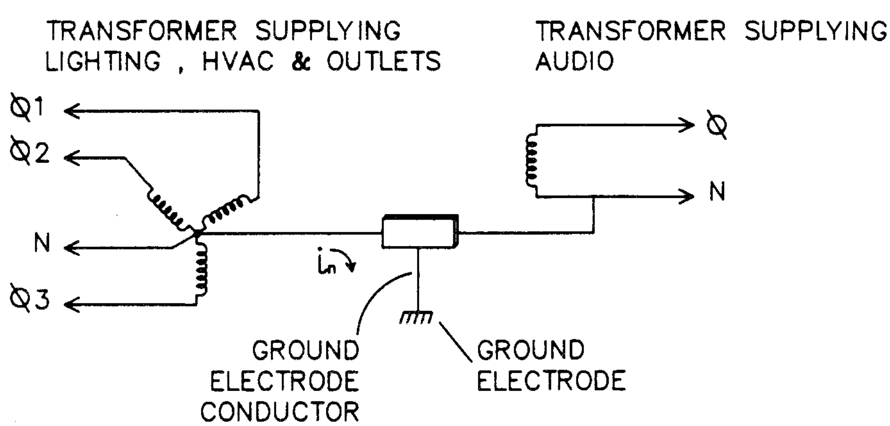
Note that the harmonics decrease at 20 dB per decade.

2.2.1 Common Impedance (or Conducted) Coupling

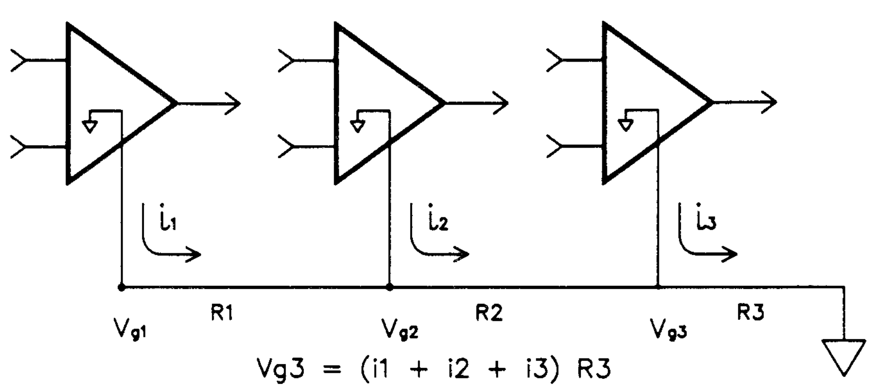
This type of coupling can occur whenever there is a shared conductor with impedance between the source and the receiver. (Fig. 7). Examples of this type of coupling are through ac power wiring (in particular the common neutral used in many ac power distribution systems), and where two pieces of equipment share the same technical ground wire. If a device is emitting electrical noise on a ground having impedance, a voltage is created, and this modulates the second device's ground reference. This type of coupling is a function of the impedance of the common wire and may also include the impedance to ground. Minimization of common impedance coupling is one of the prime reasons for use of the insulated low-impedance star grounding system.

The ac impedance of most wires is greater than their dc resistance (see Sec. 3.2). It is necessary to consider this when radio frequency interference (RFI) is expected or occurring.

There are many obvious paths for conducted coupling



(a)



(b)

Fig. 7. Common-impedance coupling through (a) ac-neutral; (b) shared-ground conductor.

which can usually be dealt with by proper wiring techniques, such as dedicated return wires, properly sized and insulated ground conductors, and other proper grounding techniques. There are many other paths which are less obvious and harder to deal with, for example, common power supplies and stray capacitance from enclosures to ground.

Common impedance coupling interference is the only type transmitted over wire conductors. The remaining types, discussed below, are transmitted through space (the air). It is often the case that a combination of coupling means make up the path for EMI. For example, noise can be generated by electronic dimmers and conducted throughout the ac power system, being retransmitted into the air by this large antenna.

2.2.1.1 Common- and Differential-Mode Noise

Electrical noise transmitted over a pair of wires (a circuit) can be either a common-mode or a differential-mode (normal) signal, as shown in Fig. 8. The mode of transmission is determined by how the noise is induced into the wires and how the circuit is balanced to ground. Whether it is common or differential mode will determine its effect on the victim circuit and how it should be dealt with.

Differences in the impedance to ground of either side of the balanced line will tend to convert common-mode signals to differential signals. This is known as common-mode to differential-mode conversion and can occur wherever there is imbalance. This is true for microphone lines through to ac power lines. The source driving the circuit, the cable as well as the victim's input, can all be sources of imbalance. Hence the common-mode rejection of an input, as measured "on the bench," may be reduced when in circuit.

In the case of balanced (tightly) twisted-pair audio lines, electrical noise generated from electric fields will tend to be common mode, while that from magnetic fields will tend to cancel, as explained later.

Common-mode noise will be reduced by the amount of the common-mode rejection ratio (CMRR) of the transformer or electronic input being driven. The CMRR decreases with increasing frequency due to circuit imbalance.

Differential noise, like the audio signal, passes through the input without being suppressed by the common-mode rejection. The only way to reduce differential noise, once in the circuit, is with a filter. If the frequency or frequency band of the noise falls inside the normal operating transmission band, then the noise filter will remove signal (data) as well. Therefore everything must be done to ensure that any noise picked up in the system will be common mode. This is, in fact, the reasoning for many interconnection standards, such as twisted wire and balanced circuits.

Ac power line noise is often conducted down the line from equipment that is powered by it. Radio, television, and radar signal noise, for example, may be induced into the line at some exposed point and then conducted down the line. Noise picked up by electromagnetic radiation tends to be common mode, while noise created by line-powered devices tends to be differential mode [2].

Since one side of all ac power circuits is well grounded at low frequencies (called the neutral), low-frequency noise is usually found on the phase (ungrounded conductor), making it differential mode. Theoretically any noise voltages created on the neutral (grounded) conductor are dissipated to ground. In practice there will be some inductance and resistance in the ground connection, and so this is not strictly true.

2.2.2 Electric Field Coupling

As discussed in Sec. 1, this type of coupling is determined by the capacitance between the source and the receiver and is proportional to the area that the source and the receiver share between each other (in the case of wire, their length and orientation), the frequency and amplitude of the noise voltage, and the permittivity of the medium between source and receiver. It is inversely proportional to the square of the distance between them.

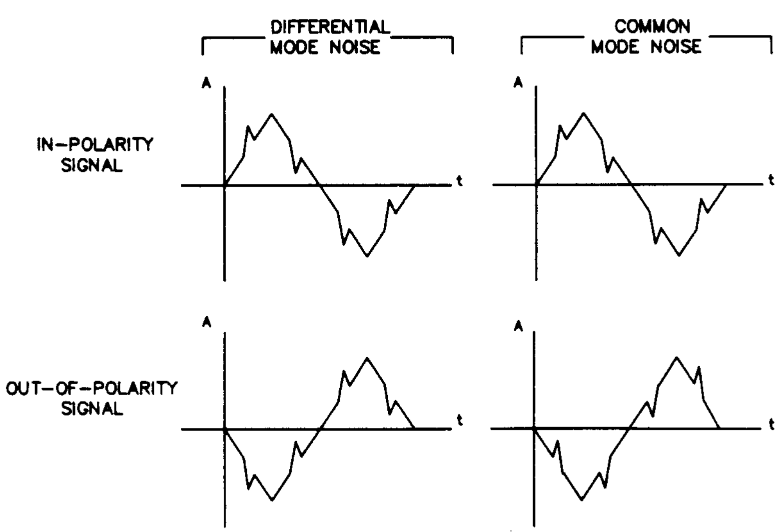


Fig. 8. Common and differential mode noise.

Electric coupling creates a voltage in the victim circuit. This results in a noise voltage at the load resistance. If a noisy circuit suspected of having electric coupling is short-circuited (at the output driving the line) and the noise is largely eliminated, this verifies electric (capacitive) coupling. If the coupling were inductive, the current would continue to flow.

In the case of an audio line adjacent to another audio line or to an ac power line, the noise voltage created in the victim load is determined by the source and load impedance of the victim circuit as well as by any capacitance to ground (stray or intentional) in the victim circuit, since these form a voltage divider with the coupling capacitance [3].

The inverse law relating the field strength to the distance between conductors means that significant decoupling can be achieved with initial small spacings, but that additional spacing must become large. In the case of 22 AWG wire, most decoupling occurs within a couple of centimeters of separation [4].

It was seen earlier that it is desirable to ensure that noise picked up on a balanced audio line be common mode. When a balanced line is located very close to an EMI source, the electric field strength at the two conductors may vary depending on their orientation to the source. If they are twisted together, over a given length, they will be subjected to equal field strengths or, in other words, they will have the same capacitance to the source. If the source is some distance away, then the field strength will be effectively equal at the two conductors, and twisting will not encourage common-mode pickup by the balanced line.

2.2.3 Magnetic Field Coupling

As discussed in Sec. 1, this type of coupling is determined by the mutual inductance between the source and the receiver. Therefore it is a positive function of the loop area of the receiver circuit, the frequency (or rate of change) and current of the source, and the permeability of the medium between source and receiver. It is inversely proportional to the square of the distance between them. It is also related to the orientation of the wires. The magnitude of the transmitted noise will be determined by this mutual inductance and the rate of change (frequency) of the noise current. In the case of an audio line adjacent to another audio line or to an ac power line we expect better coupling (more interference) when the loop created by the receiver is bigger (the receiver hot and return wires spaced apart) and when the source and the receiver are closer together or contain higher frequencies or transient signals.

Magnetic coupling creates a current in the victim circuit. This current results in a noise voltage as it passes through the load resistance. If a noisy circuit suspected of having magnetic coupling is open-circuited (at the source driving the line) and the noise ceases, this verifies magnetic (inductive) coupling. If the coupling were capacitive, the voltages would remain even when the circuit is opened.

The common and effective way to control magnetic coupling is to use a balanced transmission and to twist the wires together. When the send and return wires are twisted together, the area of the loop created by the circuit is reduced and the direction of the induced current alternates in each successive loop and so cancels. If the circuit is unbalanced and the return wire is in parallel with a ground return path, the inductive coupling is not necessarily reduced.

The unit distance per twist is known as the *lay* of the cable and has a direct effect on the degree of magnetic coupling, as shown in Sec. 3.3, Table 10. The shorter the twist increment (lay), the greater the number of turns per unit length, the better the decoupling, although a plateau exists at about a 25-mm lay, after which the rate of improvement slows as the cost of manufacture rises.

Shielding from magnetic fields is very difficult, as discussed in Sec. 3.1. Magnetic fields are attenuated by metals according to their permeability. The permeability relative to air is 1 for copper and around 1000 for steel, such as that used in EMT and IMC conduit. The permeability of a good magnetic shield such as Mumetal is 80,000. See Sec. 3.1, Table 5, for 60-Hz magnetic field reduction of raceway.

2.2.4 Electromagnetic Radiation

This type of coupling occurs when the source and the receiver are at least 0.15 (one-sixth) wavelength apart, placing the receiver in the far field. The far field is defined as where the wave front is a plane (no longer spherical) and the ratio of electrostatic to electromagnetic field strengths is a constant equal to the square root of permeability divided by permittivity of the transmission medium. As mentioned, this is known as the characteristic impedance of the medium, and it is equal to 377 Ω for air. This means that electromagnetic radiation has an electric field strength 377 times the strength of the magnetic field. The electric and magnetic coupling discussed in the preceding sections are considered near-field effects. Electromagnetic radiation is common from television, radio, and radar transmitters where these sources are of sufficient strength and of sufficient distance away to create the far field at the receiver's position, as given in Table 3.

Electromagnetic radiation is often of insufficient strength to have any effect in audio circuits. It can be difficult to conquer as it is not a localized effect and any shielding discontinuity or weakness will be subject to the fields. The techniques used to control electric fields are usually appropriate since the electric field is 377 times the strength of the magnetic field.

Table 3. Far field versus frequency for electromagnetic waves.

Frequency	Far field (0.15 wavelength)
100 kHz	500 m
1 MHz	50 m
10 MHz	5 m
100 MHz	0.5 m
1 GHz	50 mm

2.2.4.1 Field Strength

To determine the severity of incident radio waves the field strength can be approximated with the formula

$$FS = \frac{0.173}{D} \sqrt{P}$$

where

FS = field strength, volts per meter
P = radiated power, kilowatts
D = distance from source, kilometers.

In rough terms, if the field strength is below 0.01 V/m, there is normally little risk of EMI. From 0.1 to 3 V/m EMI is a potential problem, and from 3 V/m and up the EMI potential is great.

IEEE Std. 518-1982 suggests that whenever the field strength exceeds 1 V/m, a determination of susceptibility is advisable [5]. Examples of this are a 50-kW transmitter at 1.3 km or a 5-W transmitter at 13.1 m.

2.3 Receiver Susceptibility or Immunity to EMI

The ability of a receiver to differentiate between signal and noise and to attenuate or ignore the noise will determine to what levels of EMI it can be subjected.

When EMI is incident on a pair of twisted wires, it creates a common-mode signal as discussed in Sec. 2.2.3. For this reason balanced inputs, canceling the common-mode noise, have a distinct advantage over unbalanced inputs. Unfortunately balanced inputs tend to become unbalanced with increasing frequency due to the different inductances and capacitances (to ground) of the input leads and circuitry. This results in common-mode to differential-mode signal conversion. This signal can manifest itself in the audio band through "audio rectification."

Audio rectification occurs when noise signals enter an amplifier or digital circuit through any means of coupling and path (signal or power leads) and are demodulated by a nonlinear element, such as the detector of an AM radio or the first high-gain, wide-bandwidth transistor in the signal path [2], [6]. The term rectification is somewhat misleading; the word demodulation would be more appropriate as the out-of-band noise is frequency-shifted down. It often occurs at frequencies that are enhanced by parasitic circuit resonances. The signal is subsequently amplified by the following electronics. Bad solder joints can also cause rectification. The character of the interference can depend on the source, which can be amplitude modulated or frequency modulated. AM radio signals can be clearly audible, single-side-band and amateur radio may be audible but garbled. AM pulsed radar and television signals may produce buzzing. In [6] it is suggested that FM radio and television signals may cause volume changes.

For a given voltage resulting from capacitive coupling (electric fields), the higher the circuit impedance, the greater will be its effect. In a low-impedance circuit the voltages are drained away with little effect, and currents induced by inductive coupling (magnetic fields) become more significant. Consequently circuit impedances have a large effect on the type of coupling that can be expected.

Weston [3, sec. 4.2] suggests that a rough guideline for determining which mode of coupling predominates between cables in close proximity is:

> If the emitter circuit and receiver circuit impedance products are less than 300 Ω^2 the coupling is primarily magnetic, but when the products are above 10,000 Ω^2, the coupling is primarily electric.

When the impedance products are between these two, then either can predominate, depending on geometry and frequency.

3 CONTROLLING EMI

Many of the techniques used in interconnecting audio systems today are taken for granted, with little appreciation of why they exist and what type of EMI they specifically deal with. This section explains the many tools available and their uses and limitations.

3.1 Shielding (High and Low Frequencies)

Shielding is a technique used to control noise by preventing transmission of EMI from the source to the receiver. It can be done at the source or at the receiver and is a positive function of the shield material's thickness, conductivity, continuity, and percentage coverage for the case of electric fields, where it is most effective.

Simplified, the basic mechanism in shielding occurs when an electromagnetic field strikes a conductive surface. This incident field creates a current on the surface of the conductor, which in turn creates a reflected field and a surface field. The surface field exactly cancels the incident field. If the conductor is not perfect, then current will penetrate the surface by an amount known as the skin depth (a function of frequency), and the reflection is not perfect. The current on the far side of the shield reradiates the field. The total shield effectiveness will be due to the amount of reflection, the attenuation of the current, and, to a much lesser extent, the reflection on the far wall of the shield.

Anything that prevents the current from flowing in the shield, such as poor conductivity, holes and other discontinuities, contact resistance, or poor or no grounding, will invite fields on the protected side. For racks and cases, holes and discontinuities on the order of one-tenth of a wavelength of the electromagnetic noise are to be avoided. Shielding without grounding is for the most part ineffective.

Magnetic fields, being of low wave impedance, are not reflected by shields, and shielding is the result of attenuation, which is much less effective. Electric fields of high wave impedance are reflected and attenuated by shields. When the shield is less than one-quarter of the wavelength of the field in the shield, then shielding is due to reflection.

Low-frequency magnetic shielding (below 10 kHz) is not usually possible without shields of very great thickness or high-permeability material such as Mumetal, Supermalloy, or Permalloy. Consequently foil, braid, and served cable shields, all thin and having a relative permeability of 1, provide little magnetic shielding.

Tables 4 and 5 document results published in IEEE Std. 518-1982 [5].

As the bandwidth of a signal increases beyond 100 kHz, the best method of cable shield grounding becomes more difficult to define. As the wavelength of the signal to be shielded from either inside or outside the cable approaches one-quarter to one-thirtieth of the cable length, the shield effectiveness is reduced due to standing waves on the shield. (Older references use a ¼ wavelength maximum length, while one new publication [2] suggests 1/30.) Table 6 summarizes shield-length criteria.

As audio signals are limited to 20 kHz, the shield is normally best grounded in one place and at one end only. Where digitally encoded audio or other high-speed control signals are to be contained by a shield, or RF frequency fields are to be excluded by a shield, better shielding may be obtained by multiple shield grounds—the cable shield is broken at several locations and each section grounded appropriately.

It is a misconception that a cable that has "100% shield coverage" provides perfect shielding. This statement merely indicates the physical coverage of the shield.

3.2 Grounding and Bonding (High and Low Frequencies)

Grounding and bonding are fundamental techniques used in the control of EMI. This is done by minimizing common impedance coupling and by grounding shields, which can be critical to proper performance. The ideal ground is a zero-potential body with zero impedance capable of sinking any and all stray potentials and current. Sec. 3.1 illustrated how grounding improves a shield's performance. Low-impedance insulated grounding also minimizes common impedance coupling, while providing a steady ground reference regardless of what ground current might be flowing.

In general, grounded shields or other conductive parts (racks, panels) act as sinks to electric fields. Therefore all metal parts should be effectively grounded.

A subset of grounding is bonding. Bonding is a term for special measures taken to ensure that various components are electrically connected together by a low-impedance connection, thus ensuring that they are effectively of the same potential. (The term bonding is also used by the National Electrical Code of the United States, where it has a special meaning, somewhat different from that of EMI specialists.) Grounding is the connection to earth of all those points requiring a stable reference, and in doing so makes use of bonding. Bonding is one means of controlling common impedance coupling.

Technical ground systems are insulated from other building grounds to minimize noise pickup due to stray and circulating currents. A common difficulty with technical grounding systems is maintaining their electrical isolation from other building ground systems. This is true at dc and low frequencies, but it is particularly true at high RF frequencies where capacitive coupling becomes significant. Any inadvertent short circuit between the technical ground and other ground systems creates a ground loop. Ground loops result in

Table 4. Electrostatic noise test results.

Shield*	Noise reduction (ratio)	(dB)
Copper braid (85% coverage)	103:1	40.3
Spiral-wrap copper tape	376:1	51.5
Aluminum-mylar tape with drain wire (100% coverage)	6610:1	76.4

* No shield = 0 dB.
From IEEE Std. 518-1982 [5], with permission.

Table 6. Maximum ungrounded shield distance versus frequency of EMI waves.

Frequency	0.25 Wavelength	0.033 Wavelength
10 kHz	7500 m	1000 m
100 kHz	750 m	100 m
1 MHz	75 m	10 m
10 MHz	7.5 m	1 m
100 MHz	7.5 cm	1 cm
1 GHz	7.5 mm	1 mm

Table 5. Raceway shielding.

Raceway type	Thickness (in)	60-Hz magnetic field attenuation (ratio)	(dB)	100-kHz electric field attenuation (ratio)	(dB)
Free air		1:1	0	1:1	0
2-in aluminum conduit	0.154	1.5:1	3.3	2150:1	66.5
No. 16 gauge aluminum tray	0.060	1.6:1	4.1	15,550:1	83.9
No. 16 gauge steel tray	0.060	3:1	9.4	20,000:1	86.0
No. 16 gauge galvanized ingot iron tray	0.060	3.2:1	10.0	22,000:1	86.8
2-in IPS copper pipe	0.156	3.3:1	10.2	10,750:1	80.6
No. 16 gauge aluminum tray*	0.060	4.2:1	11.5	29,000:1	89.6
No. 14 gauge galvanized steel tray	0.075	6:1	15.5	23,750:1	87.5
2-in electric metallic tubing (EMT)	0.065	6.7:1	16.5	3350:1	70.5
2-in rigid galvanized conduit	0.154	40:1	32.0	8850:1	78.9

From IEEE Std. 518-1982 [5], with permission.
* Sic. We assume this should be No. 14.

current and voltage fluctuations in the ground reference by two distinct means. Differences in ground potentials often exist in building grounds due to stray currents. Induced currents from inductive coupling cause circulating currents and a resultant voltage in the ground (Fig. 9). Ground loops can also be formed within a technical ground system by internal short circuits (Fig. 10).

Less-understood and discussed challenges in providing good grounds include the inductance and the skin effect of wire, which cause increasing impedance with frequency.

Factors that increase the inductance of a wire are the number of bends and loops. Ground wires should be run in as short and direct a path as possible. The incremental inductance of a straight piece of wire is given by [7, p. 35]

$$L = 0.002 \times l \left[\ln\left(\frac{2l}{r}\right) - 0.75 \right]$$

where

l = length, in centimeters
r = wire radius, in centimeters
ln = natural logarithm.

Table 7 lists the inductance of different gauges and lengths of wire as predicted by this formula.

The skin effect is due to the internal inductance of a wire. Magnetic fields inside the conductor are more dense toward the center and hence make it easier for current to flow at the surface. The resistance from the skin effect for a solid conductor is, in part, determined by the ratio of surface area to volume of the cross section. Round conductors, having the least surface-area-to-volume ratio, exhibit the greatest skin effect. Highly rectangular cross sections, such as strap and foil-type conductors, are preferred, although these are awkward to use. Litz (Litzendraht) wire is insulated strands, connected in parallel at the cable ends, which are braided in a pattern that causes each conductor to occupy every position in the cable (over a given length), with the result of minimum skin effect. Unfortunately the impact of skin effects is covered poorly and inconsistently in the references to this paper, and so it is difficult to draw firm conclusions. In [8, pp. 6–8] and [4, p. 129] it is suggested that R_{ac} is related to R_{dc} as follows:

$$R_{ac} = (0.096 d\sqrt{f} + 0.26) R_{dc}$$

where

d = conductor diameter, in inches
f = frequency.

For $d\sqrt{f} > 10$ the formula is accurate to within a few percent, although for $d\sqrt{f} < 10$ R_{ac} is less then it should be. Table 8 lists skin effects as predicted by this formula.

Another issue that is often overlooked in grounding and bonding is the long-term reliability of the electrical connections from ground conductors to bus bars, terminals, and chassis. When dissimilar metals are joined, the possibility of corrosion exists. The further apart on the electrochemical series the metals are, the more distinct is the problem (Table 9). There must be some impurities and moisture or other liquid to act as an electrolyte. Outdoor and oceanside sites deserve close attention.

In general, bus bars should be copper, all hardware of stainless steel or brass, and all wire termination lugs of copper or copper plated with nickel or tin. To ensure long-term reliability of ground connections, machine screws should be highly torqued. In humid or damp locations, the entire assembly should be coated with a moisture-proof barrier. Aluminum wire terminations, hardware, and bus bars should not be used.

The topic of grounding is so extensive and important to EMC that an additional paper is required for proper coverage.

3.3 Balancing and Twisting

Balancing and twisting work together to provide substantial immunity to EMI. Balancing allows differential-mode signals to pass through, but common-mode (noise) signals to be stopped. Twisting of wires causes electric fields to induce common-mode signals on the wire. Twisting reduces magnetic EMI pickup by effectively reducing the loop area of the cable to zero, and in this regard it is vastly more effective than shielding. The greater the number of turns per unit length (the lay), the higher will be the frequency up to which this will be true. Fig. 11 illustrates the progressive steps in balancing and loop-area reduction (twisting). Table 10 documents the effectiveness of twisting on reducing magnetic interference [5].

In [4], [9], and [10] test results showing inductive coupling for an unbalanced circuit versus balanced and shielded circuits is given. The procedures were only slightly different, although in some cases the results disagree. The following conclusions seem relatively reliable.

1) Going from a 50-mm lay to a 17-mm lay resulted in 30 dB less inductive coupling at 100 kHz.

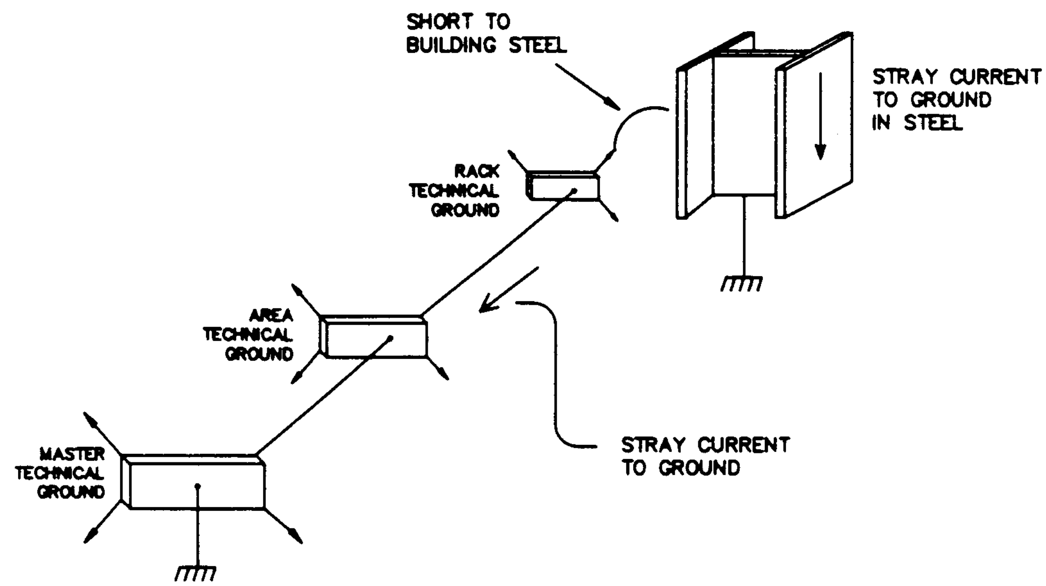
2) Going from an unbalanced system with the return through the ground plane to a balanced twisted pair where the load is floating yields about 50–80 dB of improvement.

3) Little improvement in an unbalanced circuit is achieved by adding a return wire in parallel to the ground.

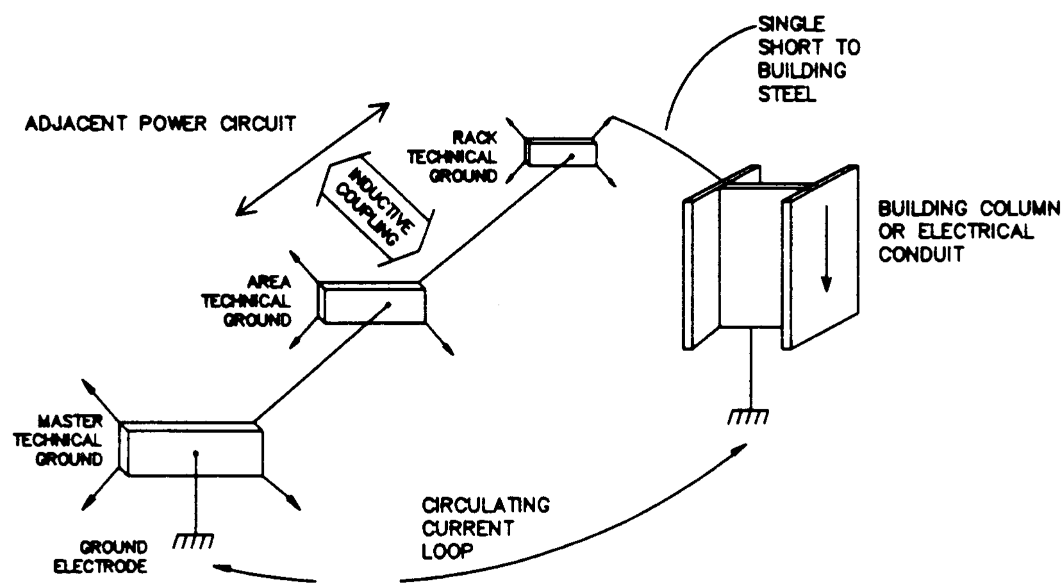
4) For a coaxial cable with one end completely floating, and with send on the center conductor and return on the shield, results similar to those for the twisted pair can be expected.

3.4 Separation and Routing

Physical separation of cables has a significant effect on their interaction with each other. (Where the EMI



(a)



(b)

Fig. 9. Ground loop due to (a) short-to-stray current; (b) single short-to-ground and inductive coupling.

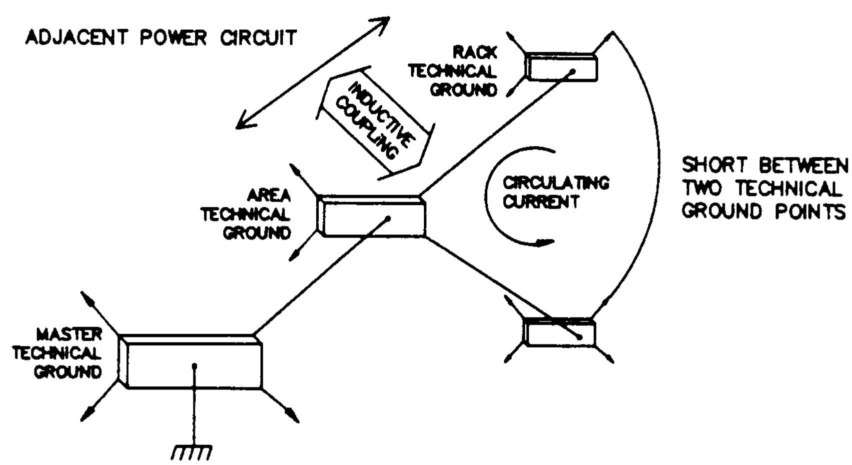


Fig. 10. Ground loop due to double-shield ground and inductive coupling.

Table 7. Wire inductance for isolated straight wire, $l >> r$.

Length l (cm)	Radius r (cm)	Inductance (μH)	Resistance at 60 Hz (Ω)	1 kHz (Ω)	20 kHz (Ω)	100 kHz (Ω)
100	0.0322	1.597	0.001	0.010	0.201	1.003
1000	0.0322	20.573	0.008	0.129	2.585	12.927
10 000	0.0322	251.786	0.095	1.582	31.640	158.201
100 000	0.0322	2978.372	1.123	18.714	374.273	1871.365
100	0.1026	1.365	0.001	0.009	0.172	0.858
1000	0.1026	18.256	0.007	0.115	2.294	11.470
10 000	0.1026	228.608	0.086	1.436	28.728	143.639
100 000	0.1026	2746.598	1.035	17.257	345.147	1725.737
100	0.2057	1.226	0.000	0.008	0.154	0.770
1000	0.2057	16.864	0.006	0.106	2.119	10.596
10 000	0.2057	214.696	0.081	1.349	26.980	134.898
100 000	0.2057	2607.482	0.983	16.383	327.666	1638.328
100	0.4126	1.087	0.000	0.007	0.137	0.683
1000	0.4126	15.472	0.006	0.097	1.944	9.722
10 000	0.4126	200.775	0.076	1.262	25.230	126.151
100 000	0.4126	2468.270	0.931	15.509	310.172	1550.858
100	0.5842	1.017	0.000	0.006	0.128	0.639
1000	0.5842	14.777	0.006	0.093	1.857	9.285
10 000	0.5842	193.820	0.073	1.218	24.356	121.781
100 000	0.5842	2398.717	0.904	15.072	301.431	1507.157

100 cm = 3.2 ft		22 AWG	= 0.0322-cm radius
1000 cm = 32 ft		12 AWG	= 0.1026-cm radius
10 000 cm = 320 ft		6 AWG	= 0.2057-cm radius
100 000 cm = 3200 ft		0 AWG	= 0.4126-cm radius
		0000 AWG	= 0.5842-cm radius

Table 8. Skin effect for copper wire.

Frequency (Hz)	R_{ac}/R_{dc} for a given wire diameter (cm) 0.0322	0.1026	0.2057	0.4126	0.5842
5000	1.37	3.80	7.35	14.49	20.41
12 500	2.02	5.85	11.48	22.76	32.11
25 000	2.74	8.17	16.12	32.08	45.31
50 000	3.77	11.45	22.69	45.25	63.97
100 000	5.23	16.08	31.98	63.89	90.35
200 000	7.28	22.64	45.12	90.25	127.67
500 000	11.36	35.64	71.19	142.54	201.72
1000 000	15.96	50.30	100.58	201.48	285.16
10 000 000	49.92	158.49	317.49	636.56	901.20

22 AWG = 0.0322-cm radius
12 AWG = 0.1026-cm radius
6 AWG = 0.2057-cm radius
0 AWG = 0.4126-cm radius
0000 AWG = 0.5842-cm radius

Table 9. Electrochemical series.

Anodic end	Most corroded
	Magnesium and alloys
	Zinc, aluminum, aluminum alloys, cadmium
	Carbon steel, iron, lead, tin, tin–lead solder
	Nickel, chromium, stainless steel
	Brass, copper, bronzes, Monel
	Silver, gold, platinum, titanium, graphite
Cathodic end	Least corroded

is another similar signal, this interaction is often called crosstalk.) The effects of the separation of parallel wires are governed by the 3-dB per doubling of distance rule, and they work for both electric and magnetic fields. For example, when spacing cables from 1 unit of distance to 2, 4, 8, or 16 units, there is 3 dB less coupling per step. Once the small initial separation has been achieved, much greater separations are needed for further improvement.

The types of signals that require separation are given in Table 11.

When routing cables, if it is necessary to cross wires of different levels, doing so at right angles will totally cancel the magnetic coupling, but not the electric coupling. It is not possible to eliminate electric coupling by orientation, although it may be minimized. Consequently a high-impedance victim circuit might still be affected by the electric coupling.

3.5 Isolation

Electrical isolation (not physical isolation, discussed under separation) prevents the possibility of common impedance coupling by electrically isolating, usually through transformers, a circuit that has more than one ground reference (Fig. 12). It is a means of controlling common impedance coupling and ground loops. Transformers are often used to provide high- and low-frequency isolation.

3.6 Other Techniques

3.6.1 Transformers

All transformers that provide dc isolation between primary and secondary windings are isolation transformers. This terminology is somewhat meaningless. Shielded isolation transformers make use of various techniques to control the interwinding capacitive coupling and may be power or audio types.

The intrinsic common-mode rejection of the power transformer will reduce only low-frequency common-mode noise. High-frequency noise is capacitively coupled across the windings. The differential response of power transformers drops with frequency, making them low-pass filters to some extent (as are power lines that have self-inductance and capacitance). A (faraday) shielded isolation transformer will prevent high-frequency differential and common-mode noise from being passed through, although in the case of power transformers the mandatory grounded neutral allows electrical noise to be transmitted through a poor ground.

Installing a transformer to take advantage of its common-mode rejection when the noise is differential mode and low frequency in nature will have little effect and is not worthwhile. The real solution is to install a line filter capable of suppressing the differential noise. An oscilloscope can be used to determine the nature of the noise. Ac line power monitors are available, which indicate noise voltages and mode of transmission.

3.6.2 Capacitors

Ceramic disk capacitors can be used to ac ground the end of a shield cable that would normally be left insulated (floating). This improves the shield effectiveness at higher frequencies, which becomes important in areas of strong RF fields. These capacitors can also be put across a differential input to attenuated RF inputs. Due to self-inductance they can resonate, and so several different values are often used in parallel. Typical values used on shields are around 0.01 μF.

3.6.3 Ferrite Beads

A ferrite bead is a doughnut-shaped piece of ferrite which increases the inductance of the wire passing through it. It is a simple means of attenuating high-

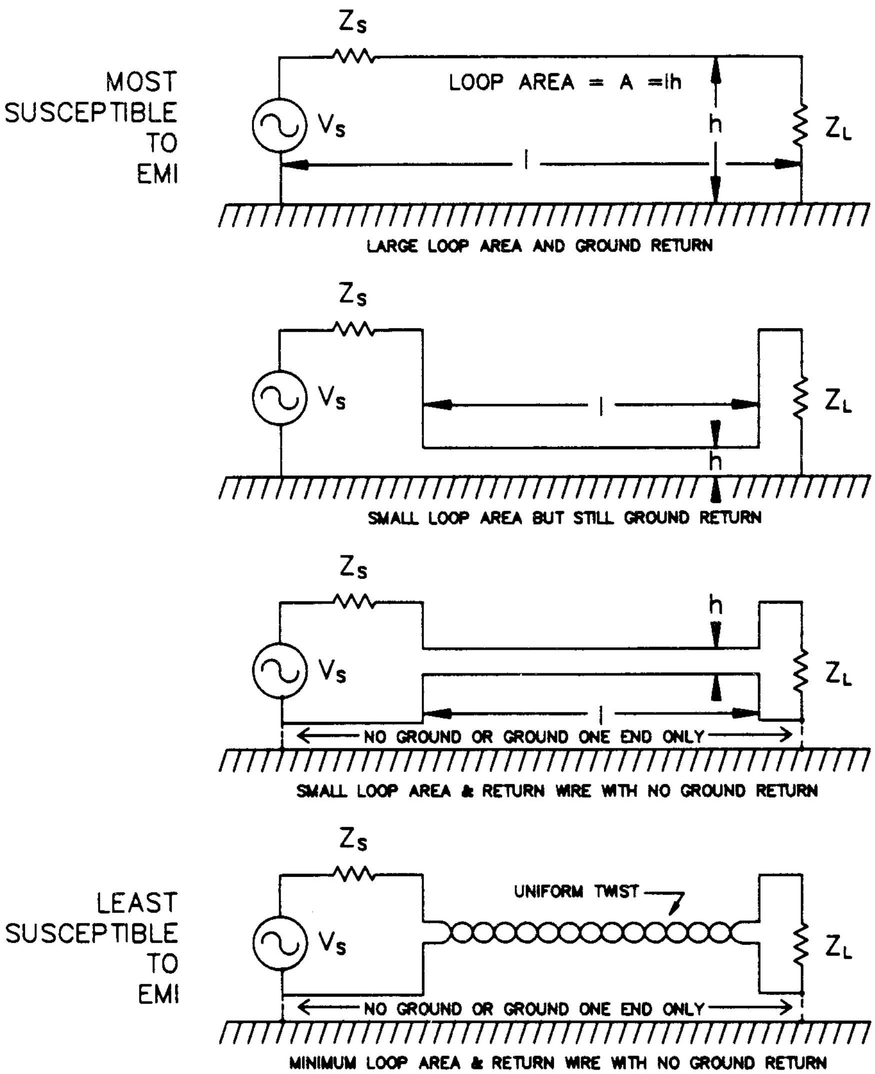


Fig. 11. Progressive step for controlling noise through balancing and twisting.

frequency (RF) signals. If beads are placed around each wire or a balanced pair, they reduce differential-mode and common-mode noise. If placed around a balanced line, they only reduce common-mode noise. A single large ferrite doughnut can be placed around a number of balanced lines for common-mode control. Manufacturers of ferrite beads include Ferronics Inc. (Fairport, NY) and Ferroxcube (Saugerties, NY). Experimenter kits are available.

4 GUIDELINES FOR MINIMIZING AND CONTROLLING EMI

This section discusses the practical techniques that can be used to control noise inputs into audio systems. It is written as a general guide for the wire person and installer.

From a wiring standpoint the best approach is to assume that all the techniques listed should be done on a regular basis to prevent EMI. Most techniques are good practice and require little extra time and materials. If these practices are followed routinely, then problems that do occur in the early stages of operation will be the result of some other shortcoming. Eliminating the wiring and installation techniques as a source for concern greatly simplifies the troubleshooting process. Proper wiring and installation also increase the mean time between EMI problems.

4.1 Cable Shields

1) When terminating shield cable, always keep the unshielded portion as short as possible (normally less than 25 mm).

2) Never terminate the shield of a balanced audio line at both ends. This author recommends connecting the shield at the load (input) end of the line.

3) Always terminate the insulated (floating) end of a shielded cable with an insulating sleeve that ensures that it cannot become inadvertently grounded (to the connector shell, for example).

5) The shield must be completely insulated and not become grounded or short-circuited to another cable shield (except where it is intentionally grounded at one end) as ground loops will be created.

6) In the case of very long cables [over 1000 ft (300 m)] it may be desirable to break the shield and ground it in two places to reduce the length of shield.

7) An alternative to 6) where a shield is only slightly longer than recommended is to ground one end normally and use ceramic disk capacitors to ground the other end. This provides high-frequency grounding without introducing a dc ground loop. In areas of extreme EMI levels this technique can also be used regardless of cable length.

8) Avoid or minimize the breaks in shields, such as at junction boxes, and always maintain shield continuity and isolation from ground, through all boxes or multipin connectors, unless system design documentation states otherwise.

9) Use shielded cable on digital control or audio lines to contain signals as well as to shield from them.

10) Use shielded cables that have a continuous conductive path around the circumference. This is not the case in some cheaper cables where the foil wraps around the cable and the mylar insulation lies against the aluminum foil. Generally a fold in the foil is needed to ensure conduction at the overlap. The drain wire should

Table 10. Magnetic interference reduction.*

Type	Noise reduction (ratio)	(dB)
Parallel wires	0	
Twisted wires		
4-in lay	14:1	23
3-in lay	71:1	37
2-in lay	112:1	41
1-in lay	141:1	43
Parallel wires in 1-in rigid steel conduit	22:1	27

From IEEE Std. 518-1982 [5], with permission.
* The frequency at which these results were obtained and the distance between parallel wires were not given in the reference.

Table 11. Signal classifications for audio EMI purposes.

Class	Description	Example
1	Very low level and current	Microphone
2	Low level and current, analog	Line-level audio
3	Low level and current, digital	Digital control–time code
4	Medium level and current, analog	Loudspeaker level
5	Medium level and current, digital	Relay control
6	High level and current	Ac power circuits

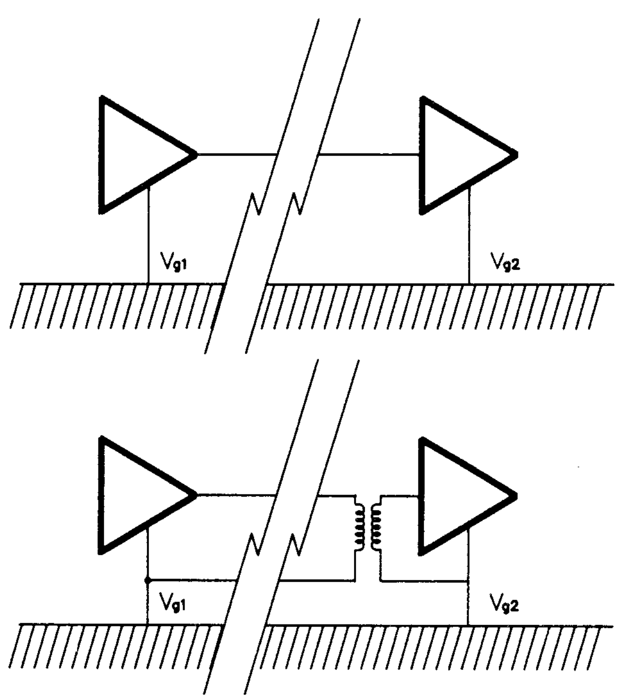


Fig. 12. Isolation provided by transformer.

also lie against the foil side of the mylar, making electrical contact.

11) Multiconductor shielded twisted-pair cable should have individual insulated shield and drain wires for each shield.

4.2 Twisting

1) Twist all balanced lines to control magnetic coupling.

2) When terminating twisted-pair cable, always keep the untwisted portion as short as possible. In an XLR connector consider connecting the hot and the return, giving them a twist, and then connecting the shield.

3) Twisting the hot and the return ac power and relay control wires will reduce the effect of their fields on other circuits.

4.3 Grounding

1) All grounding must be done via excellent electrical connection between the ground reference and the item to be grounded. Grounding joints of dissimilar materials must be avoided.

2) In multiconductor cables ground all unused lines at one end.

3) Ground the shell of all connectors in high-EMI areas.

4) If ground potentials exist between distant areas to be interconnected and cannot be removed by use of grounding techniques, consider using a transformer for isolation.

5) Junction and terminal boxes, like conduit, should be grounded (usually to building steel). This is particularly true where they contain open splices.

6) Running ground wires in the most direct route with as few bends and loops as possible will minimize self-inductance and improve the ground.

4.4 Separation and Routing

1) For audio purposes cable types should be divided into classes as outlined in Table 11.

2) Always separate cables carrying different signal levels and types, particularly where they run for any distance parallel to each other. A minimum separation is 100 mm; 300–600 cm is recommended for runs over 4 m.

3) Keep the hot and the return wires in ac power cables as close together as possible. This minimizes the radiated fields. Use individual returns for each hot wire rather than a common return, and twist the pairs together.

4) Never transmit signals of differing characteristics (level and bandwidth) over the same multi-conductor cable if interchannel crosstalk cannot be tolerated.

5) Cable routing should be utilized in all aspects of installation from conduit routing to assembly wiring, with the goal of maximizing the distance between differing signal types.

6) Routing cables near a ground plane (ground metal parts) will reduce the crosstalk due to electric fields with nearby cables.

7) Do not route audio cabling near main (feeder) power lines or switch gear, even when contained in conduit. Consider using a localized magnetic barrier if necessary.

5 ACKNOWLEDGMENT

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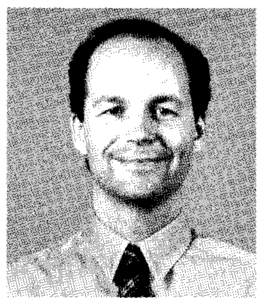
THE AUTHOR



Philip Giddings graduated with a Bachelor of Electrical Engineering degree from Montreal's McGill University in 1979 and became a registered engineer in the province of Ontario, Canada, in 1981. Since graduation he has worked with several sound-system contracting and engineering firms as well as equipment manufacturers. These include Strand Century Ltd., Engineered Sound Systems Ltd., and Gerr Electro Acoustics Ltd. He has worked in the broadcast, recording, postproduction, and sound reinforcement fields and in all areas from conceptual design to manufacturing and project management. He has managed the development of several custom computer-controlled audio products and has provided acoustical consulting services. He is presently self-employed, providing independent engineering services from Toronto.

Mr. Giddings has served terms as chairman, vice chairman, treasurer, and committeeman of the Toronto Section of the Audio Engineering Society and was the speakers' chairman for the AES Audio Overview 85 held in Toronto. He is a member of the Audio Engineering Society, Society of Motion Picture and Television Engineers, United States Institute of Theater Technology, Canadian Acoustical Association, and International Institute of Connector and Interconnection Technology.