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Electromagnetic Compatibility

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29.1 Grounding and Shielding

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EMC (electromagnetic compatibility) is crucial to successful operation of industrial systems. Due to the increased electronic content of most industrial controls, electromagnetic interference (**EMI**) problems have increased dramatically in recent years. Two keys to EMC success are grounding and shielding. This section will briefly discuss how to implement these two crucial EMC strategies. It will also provide a general introduction to EMI problems in today's industrial electronic systems. The primary emphasis will be on practical insights and ideas gained in dealing with numerous industrial control problems.

Understanding EMI Problems

Here are three general observations on dealing with EMI problems in industrial electronics.

First, the industrial environment is harsh. The primary EMI threats are power disturbances, **RFI** (radio frequency interference), and **ESD** (electrostatic discharge). In addition, analog sensor circuits are often plagued with 50/60 Hz "ground loop" problems. Industrial electronics need more EMC care than most commercial electronics, and even more than many military systems.

Second, electronics often play a secondary role in electronics systems. Unlike a computer system, where electronics is the core technology, industrial electronics are often used to support another technology, such as chemical, mechanical, or process functions. This leads to EMC challenges when integrating the electronics to nonelectronic technologies.

Third, EMC rules and regulations are finally catching up to industrial electronics. For many years, industrial electronics were exempt from mandatory EMC rules, so unless there was an actual problem, EMC was often ignored. With the EMC directives of the European Union (**EU**) now in force, industrial electronics are no longer exempt.

Three Types of Problems

There are three aspects of the EMC problem: *emissions*, *susceptibility* (also known as immunity), and *self-compatibility.* **Emissions** originate within the equipment, and may upset other nearby equipment. On the other hand, external energy may upset equipment, leading to **susceptibility** (or a lack of immunity).

Finally, energy internal to the system may interfere with other internal circuits, resulting in a self-compatibility problem.

Problems with both emissions and susceptibility have led to EMC regulations. Two of the best known are the **FCC** (Federal Communications Commission) regulations for emissions in the U.S., and the EU regulations for both emissions and immunity in Europe. Industrial controls have always been exempt from the FCC regulations, but they are not exempt from the EU regulations which became mandatory in January 1996.

Four Major EMC Threats

Most industrial EMC problems fall into one of four key areas: *emissions, power disturbances, radio frequency interference,* and *electrostatic discharge.* In the past, industrial systems were usually only concerned with power disturbances. Today, all four threats must be considered.

Emissions.

Emissions refer to electric energy originating within equipment that can interfere with other equipment. The prime concern of this threat is jamming nearby television receivers, which is the basis for the now mandatory EU emissions regulations. Emissions problems between industrial electronic systems, however, are rare. While it is possible to interfere with any other nearby equipment, most industrial electronics generate only minute amounts of conducted and radiated interference, well below upset thresholds for digital or analog circuits.

Emissions are best addressed at the equipment design stage. Strategies include printed circuit board design techniques, high-frequency filtering on power and signal interfaces, shielded cables, and enclosure shielding. Fixes in the field are usually limited to shielded cables or enclosures, add-on filters, and ferrite clamps on cables.

Power Disturbances.

Power disturbances can take many forms, from short transients to long sags, surges, or complete power outages. The three most serious power threats to industrial controls are transients, voltage sags, and power outages. Stray 50/60 Hz currents can also cause problems with sensitive analog circuits, particularly due to ground loops (to be discussed later). Other power disturbances, like frequency or waveform variations, often have little effect on electronic systems.

Power disturbances are very common in industrial environments. As a result, most industrial systems are pretty robust against this threat, at least at low frequencies. High-frequency threats, such as fast transients or RF on the power lines, can still cause problems. The EU tests simulate these threats with the **EFT** (electrical fast transient) and injected RF tests.

Most power disturbances are caused by nearby equipment, rather than external sources. (One critical exception is lightning, which can result in some nasty voltage and current surges). Power disturbances solutions include grounding, power filters, transient protectors, and in extreme cases, uninterruptible power systems (UPS).

Radio Frequency Interference.

RFI deals with threats in the RF range. RFI is quite common in industrial environments, and will likely get worse with the proliferation of handheld radios and cellular telephones. It is expected that wireless LANs (local area networks) will also provide some interesting EMI challenges. There have been cases where handheld radios were banned from use due to repeated EMI problems with industrial electronics.

It turns out that the nearby handheld radio is a much bigger threat than a large commercial broadcast station several kilometers away. A key metric is electric field intensity, measured in “volts/meter.” This is a function of both transmitter power, and distance from the antenna, and can be quickly predicted by the formula:

$$E(V/m) = 5.5\sqrt{PA}/d$$

where P = transmitter power in watts, A = antenna gain, and d = distance from the antenna in meters. For example, the electric field from a 1 W radio with a zero gain antenna at 1 m is about 5 V/m, while the electric field from a 10,000 W broadcast station at 1 km is about 0.5 V/m. Since unprotected equipment can fail in the 0.1 to 1 V/m range, problems can and do occur. The EU "heavy industrial" limits of 10 V/m are clearly aimed at protecting against the nearby handheld radio.

Solutions to RFI problems include high-frequency filtering on power and signal cables, shielded cables, and shielded enclosures. Analog circuits are particularly vulnerable to RFI, so they often need extra protection. Do not overlook banning radio transmitters in the immediate vicinity. Often, maintaining a 3 to 10 m distance is enough to solve the problem.

Electrostatic Discharge.
ESD refers to the sudden discharge that can occur after a gradual buildup of electric charge. ESD is most commonly associated with humans (touching controls or keyboards), but ESD can also be caused by internal arcing due to the movement of paper, plastic, etc. Internal ESD problems are increasing in industrial systems.

Although the static buildup can take a long time (seconds or even minutes), the discharge is almost instantaneous (nanoseconds or less). Furthermore, it is the sudden current, not the voltage, that is the culprit. The effect is a bit like having a dam burst — the ESD current is like water running down a mountain, destroying anything in its path. Fortunately, the current surge does not last too long, so the energy levels are not high. They are high enough, however, to damage or upset electronic devices.

The extremely fast discharge results in high frequencies well into the UHF range. At 1 ns, the transient bandwidth is over 300 MHz. As a result, it does not take a "direct ESD hit" to cause a problem. ESD upsets 5 to 10 m away are not uncommon, due to the intense electromagnetic fields associated with an ESD event. These problems are particularly insidious, since the ESD event may be occurring on a different piece of equipment.

Solutions to ESD problems include transient protection, high-frequency filtering, cable shielding, and enclosure shielding. Grounding is a very important factor in ESD protection, but it must be designed for high frequencies. Since many times ESD causes "reset" problems, extra attention to microprocessor reset circuits is beneficial.

Sources, Paths, and Receptors

A common EMI problem is gathering and organizing data. This is particularly important when troubleshooting EMI in the field. The "source–path–receptor" model is popular. Simply stated, three elements are necessary for any EMI problem:

1. There must be a source of energy;
2. There must be a receptor that is upset by that energy;
3. There must be a coupling path between the source and receptor.

All three elements must exist at the same time, and if any one is missing, there is no EMI problem. Sometimes one can identify all three, and, other times, one can only guess. While this may seem simple, it is a useful tool to organize EMI information.

Figure 29.1 illustrates this model, giving typical sources, paths, and receptors. Several possible sources have been discussed: emissions from digital circuits, ESD, RFI from communications transmitters, and power disturbances (including lightning). Several different receptors have also been suggested: communications receivers, analog electronics, and digital electronics. Note the two types of paths: radiated and conducted. In both cases, the object is to block unwanted energy from reaching a receptor, which is done with shielding (for the radiated path) and filtering (for the conducted path).

Grounding

Grounding is probably the most important, yet least understood, aspect of EMI control. Every circuit is connected to some sort of "ground," so every circuit is affected by EMI grounding issues.

Any interference problem can be broken down into
- the SOURCE of interference
- the RECEPTOR of interference
- the PATH coupling the source to the receptor

Sources
- Microprocessors
- Video Drivers
- ESD
- Transmitters
- RF Generators
- Power Disturbances
- Lightning

Paths
- Radiated
  - EM Fields
  - Crosstalk
    Capacitive
    Inductive
- Conducted
  - Signal
  - Power
  - Ground

Receptors
- Digital
  - Microprocessors
  - Reset
  - Other logic
- Low level analog
- Receivers

FIGURE 29.1 The source–path–receptor model for assessing EMI problems. All three elements must be necessary for an EMI problem to occur.

TABLE 29.1 A Ground May Work Over Wide Frequency Ranges

Type	Frequency	Typical Current Levels	Typical Duration
Power	50/60 Hz	10–1000 A	Seconds or minutes
Lightning	300 kHz	100,000 A	Tens of milliseconds
ESD	300 MHz	10–50 A	Tens of nanoseconds
EMI	Dc–Daylight	μA–A	Nanoseconds to years

What Is a Ground?

A major problem with the subject of grounding is the ambiguity of the term. Our favorite definition is one popular in the EMC community, which says that a *ground is simply a return path for current flow.* These currents can be intended, or unintended. The unintended currents are often referred to as "sneak grounds," and can cause many kinds of EMI problems. Finally, a physical connection is not even necessary at higher frequencies, where parasitic capacitance or inductance may form part of a ground path.

Different Types of Grounds

Grounds are used for many reasons, including power, safety, lightning, EMI, and ESD. Although they may share common functions, they may vary widely when it comes to frequencies and current amplitudes. Recognizing these key differences is key to understanding grounding issues.

Table 29.1 shows some frequency and amplitude requirements of several different types of grounds. Note that power and safety grounds must handle high currents, but only at low frequencies. Grounds for EMI and ESD, on the other hand, must often handle high frequencies at relatively low current levels. Lightning grounds must handle extremely high currents, but at moderate frequencies.

The frequency of transient events is calculated using the formula $f = 1/(\pi t_r)$, where f is the equivalent frequency, and t_r is the transient rise/fall time. This relationship can be derived using Fourier analysis. For example, ESD has an equivalent frequency of about 300 MHz based on a typical 1 ns rise time, and lightning has an equivalent frequency of about 300 kHz based on a 1 μs rise time.

Note that of all these types of grounds, only one actually needs an Earth connection — lightning. Other grounds may be connected to Earth by convention or for other safety reasons. For example, power neutrals are connected to Earth in many parts of the world to help provide lightning protection. On the other hand, in many other parts of the world, the power systems do not have Earth connections. When dealing with power grounding, the local safety codes will determine the proper Earth grounding methods.

TABLE 29.2 Impedance Parameters for 10-cm-Length Wires

Gage	Ω/m	μH/m	*Z* @ 10 kHz	*Z* @ 1 MHz	*Z* @ 100 MHz
10	0.0033	1.01	0.006	0.63	63
12	0.0052	1.05	0.007	0.66	66
14	0.0083	1.10	0.007	0.69	69
16	0.0132	1.15	0.007	0.72	72
18	0.0209	1.19	0.007	0.75	75
20	0.0333	1.24	0.008	0.78	78
22	0.0530	1.29	0.009	0.81	81
24	0.0842	1.33	0.010	0.84	84
26	0.1339	1.38	0.012	0.87	87
28	0.1688	1.40	0.019	0.88	88
30	0.2129	1.43	0.022	0.90	90

TABLE 29.3 Impedance Values for Ground Plane Impedance

	Thickness		
Frequency	0.1 mm	1 mm	10 mm
60 Hz	172 μΩ	17.2 μΩ	1.83 μΩ
1 kHz	172	17.5	11.6
10 kHz	172	33.5	36.9
100 kHz	175	116	116
1 MHz	335	369	369
10 MHz	1.16 mΩ	1.16 mΩ	1.16 mΩ
100 MHz	3.69	3.69	3.69
1000 MHz	11.6	11.6	11.6

Ground Impedances

A good ground must have a low enough impedance to minimize voltage drop in the ground system, and must provide the preferred path for current flow. The key to success is maintaining that low impedance over the entire frequency range of interest. We cannot overemphasize this point. Most EMI grounding problems are due to using the wrong approach for a given range.

The impedance of a ground conductor consists of both resistance and inductance ($Z = R + j\omega L$). For frequencies from dc through about 10 kHz, the resistance is the major factor, so heavy-gage wires are often used for low-frequency ground conductors. As the frequency increases, however, the inductance becomes the limiting factor for impedance. As a rule of thumb, the inductance for round wires is in the range of 10 nH/cm.

Table 29.2 gives the resistance, inductance, and inductive reactance for typical wire sizes used in instrumentation power and signal circuits. It is apparent that at power and audio frequencies (dc to 10 kHz), resistance is the dominant factor in ground impedance. Thus, at low frequencies, look for ways to reduce resistance, typically by using larger wires. At frequencies above the audio range (>10 kHz), inductance becomes the dominant factor in ground impedance. Thus, at higher frequencies, look for ways to reduce the inductance of the ground path. This is accomplished by using ground planes, grids, and straps to lower the inductance.

Table 29.3 gives the impedances for solid ground planes at various frequencies. In this case, the impedances are in "ohms-per-square," which is a measure of impedance across a diagonal surface. By comparing this with Table 29.2, one can see that at high frequencies (such as 100 MHz) the ground plane impedance may be several orders of magnitude below the impedance of a wire. Furthermore, at high frequencies the thickness is not a factor, since the impedance is limited by the skin effect.

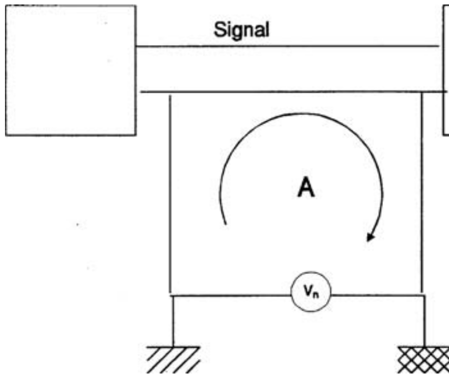

FIGURE 29.2 Typical industrial grounding situation, which also illustrates a ground loop.

Ground Topologies

Now that we have looked at ground impedance vs. frequency, we are ready to look at ground topologies vs. frequency. The impedance limitations yield two different grounding approaches, dependent on frequency. For low-frequency problems (dc to 10 kHz), single-point grounds are preferred, while at high frequencies (above 10 kHz), multipoint grounds with planes or grids become the preferred approach.

This dichotomy often causes confusion with industrial controls, but this can be minimized by determining the frequency of the EMI threat and then selecting the appropriate grounding approach. In many cases, both approaches may be necessary at the same time, leading to "hybrid" grounds, which use capacitors and inductors to alter the ground topology with frequency.

Single-Point Grounds.

At low frequencies, one can usually steer current via wires. Since the inductance is low, the limiting factor is the wire resistance itself. Furthermore, capacitive coupling from the ground wires to adjacent wires or surfaces is small, so virtually all the current follows the wiring path.

Figure 29.2 shows a typical industrial grounding scheme. Note what happens if the system is grounded at both ends. Any common noise current in the common ground path is now coupled into the circuit via the "common ground impedance." This results in the dreaded "ground loop," which will be discussed shortly. A single-point ground eliminates the ground loop, since there is no common impedance across which a common-mode voltage can be generated. Thus, single-point grounding is a very practical way to limit "ground noise" problems with the threat of low-frequency ground currents. This is very typical of 50/60 Hz currents getting into sensitive analog instrumentation circuits.

Multipoint Grounds.

Unfortunately, as the frequency increases, the inductive reactance of the wires increases. At the same time, parasitic capacitive reactance to adjacent wires or surfaces decreases, and soon it is no longer possible to maintain a true single-point ground, even if the system is wired that way. The only option left is to lower the ground path impedance, and that is accomplished with planes or grids. Furthermore, single-point connections to a grid or plane are usually not adequate because of transmission line effects, so multipoint grounds (combined with planes/grids) become the preferred approach above 10 kHz.

Ground grids have been used for years in computer facilities, and are seeing increasing use in industrial facilities. The recommended spacing for grids is no more than 1/20 of a wavelength at the highest frequency of concern. Computer room grids are often spaced about 0.7 m (about 2 ft), which meets this criteria from dc to about 25 MHz. This is very beneficial in addressing ground noise due to lightning and other power transients, which are usually in the 1 MHz range and below. But a 0.7 m grid does not help with VHF/UHF radio problems or ESD. In those cases, solid surfaces may be necessary.

Ground Loops.

Ground loops are a serious problem for sensitive analog circuits facing low-frequency threats. At high frequencies, ground loops generally do not pose serious threats if proper high-frequency precautions are taken when designing the ground system.

A ground loop exists whenever multiple ground paths exist. Unwanted currents can take unwanted paths, resulting in unwanted noise voltages at unwanted places. The problem is particularly acute with sensitive analog systems, where even a few microvolts can jam intended signals. A classic example is 60 Hz ground currents causing hum in an audio system.

Figure 29.2 shows a typical ground loop problem. Note that there must be the three conditions of any EMI problem: a source, a path, and a victim. In this case, the source can be circulating power currents, the path the common ground impedance, and the victim is often the sensitive analog circuit. With many systems problems, one cannot do anything about either the source or victim, so the solution is with the ground path. As we have already seen, single-point grounding is effective at low frequencies, and ground planes/grids are effective at higher frequencies.

If one cannot change the ground paths, one can still attack the ground loop by "breaking" it in other places. For example, transformers or optical isolators (or even fiber optics) can be used in cable connections, which will block common mode noise currents while passing intended differential mode signals. Balanced input/output (I/O) circuits can be used to "cancel" the noise through common-mode rejection. All of these are most effective at 50/60 Hz, and become less effective at higher frequencies due to parasitic capacitance.

Grounding Guidelines

By now it should be apparent that there is no magic solution for grounding. Rather, different methods and approaches are necessary for different circuits and operating conditions. Two key parameters are the threat frequency (low vs. high), and the circuit operating levels. Here are some guidelines, but keep in mind that even these may need to be modified for a particular situation.

Analog Circuits.

Since most analog circuits operate at low frequencies and are subject to low-frequency threats, single-point grounds are preferred. Typical threats are 50/60 Hz power return currents, stray switching power supply currents, and perhaps digital circuit return currents (if separate analog and digital power and grounds are not provided). Low-level analog circuits are the most vulnerable, since the signal levels are small.

Keep in mind that high-frequency threats (such as a VHF radio) to low-frequency circuits may require high-frequency grounding solutions, such as multipoint grounds. Often, this can be accomplished by using small high-frequency capacitors (1000 pF typical) which appear as a short circuit at 100 MHz, yet still appear as a high impedance at 50/60 Hz.

Digital Circuits.

Most digital circuits today operate at relatively high frequencies, so multipoint grounds and ground planes and grids are preferred. The connections between the circuits and their grounds need to be short, fast, and direct to minimize inductance.

Digital circuits, particularly I/O circuits, are vulnerable to external high-frequency threats like RF and ESD. They are also a key source of high-frequency emissions and internal problems like cross talk. For digital circuits, multilayer boards with internal ground planes are preferred. These ground planes typically are connected to a metallic enclosure through multiple low-inductance connections.

Pay particular attention to where digital and analog circuits meet. A single-point connection is usually preferred to minimize ground loops, but installing a small resistor (1 to 10 Ω typical) or inductor (1 to 100 μH typical) at that point is often helpful in providing additional isolation. One may need to experiment with this to determine the optimum solutions.

Power Safety Grounding.

Entire books have been written about this subject, and rightly so; this is an extremely important safety issue. The key concern here is human safety and prevention of electric shock. In most parts of the world, exposed metal on line-powered equipment must be bonded to a safety grounding conductor. Furthermore, the electric wiring codes (such as the National Electrical Code in the U.S.) give very specific guidelines on how power grounding must be accomplished.

These guidelines must be followed when wiring any industrial control system, and must never be compromised by "isolated" power grounds or other similar foolishness. *Finally, if there is ever a conflict between EMI and safety grounding, the safety issues must always prevail!*

Shielding

Many systems today require at least some **shielding** for proper operation or to meet radiated emission or immunity requirements. Many engineers consider shielding purely a mechanical issue, but nothing could be farther from the truth. EMI shielding needs both an electrical and a mechanical understanding of key issues to assure success.

Two of these key issues are selecting the right material and maintaining the shielding integrity over the desired frequency range. While most people worry more about the selection, shield integrity is usually much more important. We will soon see that even very thin metallic coatings can be effective shields, yet even very small holes or penetrations can completely destroy a shield. Like grounding, shielding cannot be left to chance, and must be properly designed and implemented.

How Shielding Works

EMI shielding involves two independent mechanisms: *reflection* and *absorption*. In reflection, an electromagnetic wave bounces off the surface, just like light off a mirror. In absorption, the electromagnetic wave penetrates the material and is absorbed as it passes through, much like heat loss through an insulating wall.

Shielding effectiveness is usually expressed as follows:

$$\mathrm{SE}\left(\mathrm{dB}\right) = R\left(\mathrm{dB}\right) + A\left(\mathrm{dB}\right)$$

where SE is the total shielding effectiveness in dB, and R and A are the reflection and absorption losses expressed in dB. Reflection is the primary mechanism for high-frequency shielding (emissions, RFI, ESD), while absorption is the key mechanism for low-frequency magnetic field shielding. The actual formulas for calculating reflection and absorption losses are a bit complex, and beyond the scope of this chapter, but several sources are included in the further information section.

Three Types of Fields

It is customary when dealing with shielding to use three types of "fields" to explain shielding. These three fields account for differences in shielding performance due to differences in frequency and circuit impedance levels. They also explain why the same shield can behave differently for different energy sources. These are plane waves, magnetic fields, and electric fields. Figure 29.3 shows typical shielding curves for copper, with references to each type of field.

Plane Wave Fields.

If one is located greater than about 1/6 wavelength from a point source, the wave impedance (ratio of electric field intensity to magnetic field intensity) is a constant 377 Ω in free space. This field is known as the "far field" or "radiation field," since real energy predominates here and propagates as a "plane wave." Since reflection losses are due to a mismatch between the wave impedance (377 Ω) and a metallic shield surface impedance (typically milliohms or less), shielding effectiveness is usually very high for plane wave sources.

At frequencies 30 MHz and above, once one is more than about 1 m away, one is in the plane wave region. Thus, even very thin shields work well for emissions, ESD, and RFI problems, with reflection as the prime shielding mechanism.

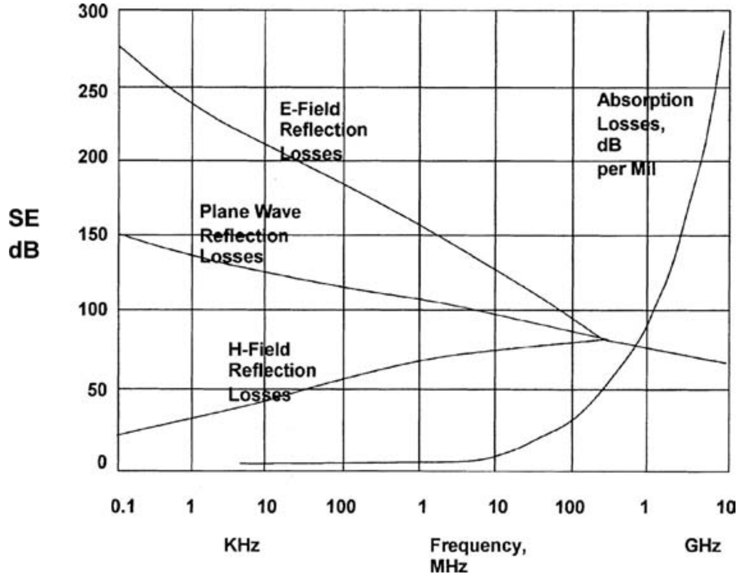

FIGURE 29.3 Typical shielding effectiveness curves for copper. Note two mechanisms (reflection and absorption) and three types of fields (electric, magnetic, and plane wave). Shielding for aluminum is almost the same as for copper.

Electric and Magnetic Fields.

If one is located less than about 1/6 wavelength from the source, then the wave impedance is dependent on the circuit impedance. This region is known as the "near field," since reactive energy predominates here. This region is further divided into "electric" and "magnetic" fields, both dependent on source circuit impedance. For high-impedance sources (electric fields), the reflection losses are still high, but for low-impedance sources (magnetic fields), the impedance can be quite low. In the latter case, the reflection losses can become minimal.

For power line frequencies, the near field almost always predominates. As a result, materials like aluminum or copper have no reflection losses and are virtually transparent to power line magnetic fields. (As a rule, remember that aluminum foil is transparent to 60 Hz magnetic fields.) To solve this problem, permeable materials are needed to boost the electric thickness for a given physical thickness. Steel or high-permeability mu-metals are usually used to absorb (not reflect) the magnetic fields. Even so, it can still be very difficult to shield for low-frequency magnetic fields.

Why Shielding Fails

While material selection is important, other factors must also be considered. For low-frequency/low-impedance threats (power supply or power line magnetic fields), steel or other high-permeability materials are needed. For high-frequency threats, however, even very thin materials like conductive paints provide high levels of shielding. Two problems at high frequencies, however, are shield openings and shield penetrations. Lack of attention to these areas can result in a loss of virtually all shielding effectiveness at high frequencies. Figure 29.4 illustrates these two high-frequency failure modes.

Intuition suggests that any opening in a shield can leak, much like an open window. The surprise is that for electromagnetic leakage it is not the area that is critical, but the longest dimension. For example, a 100 × 1 mm opening is about ten times more leaky than a 10 × 10 mm square hole. And that slot may not even be obvious. It could be a painted seam or a poorly fitting panel or door.

Slots act like small antennas. Because they are antennas, the longer they are, the better they radiate. While a half wavelength is very efficient, as a rule of thumb, we like to limit slots to 1/20 wavelength or less at the highest frequency of concern. For 100 MHz, this is 15 cm (about 6 in.); at 300 MHz (ESD

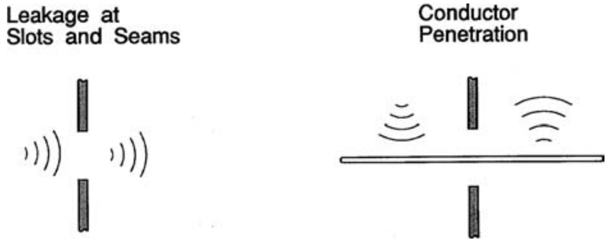

FIGURE 29.4 Two shielding failure modes, due to slots/seams and due to penetration of conductors. In both cases, the critical dimension is 1/20 wavelength for the highest frequency of concern.

frequencies), this drops to 5 cm (about 2 in.), and at 1000 MHz, it is only 1.5 cm (O in.). And even these dimensions may be too large, as they only assure 20 dB (tenfold) of shielding through the slot. Clearly, even small slots and other openings mean big shielding problems at high frequencies.

The other way to destroy a high-frequency shield is to pass unterminated metal through a shield. Hole dimensions do not matter here, and even a pinhole with an insulated wire passing through can carry large amounts across the shielding barrier. The dimension that does matter is how far the penetration extends on either side of the shield. Once again, the critical distance is 1/20 wavelength or more.

Shielding Guidelines

Now that we have looked at how shielding works (and fails), let us look at how to design good electromagnetic shields. Most of our focus will be on RF shielding in the 30 to 1000 MHz range, necessary for emissions, ESD, and RFI.

Material Selection.
We have already seen that for low-frequency magnetic interference problems, ferrous material like steel or mu-metals are necessary. Most instrumentation problems are either high impedance or high frequency in nature, so most of the time, thin conductive materials will work fine. For high frequencies, however, attention must be given to slots and penetrations.

Many enclosures today are made of plastic. For high-frequency shielding, conductive coatings also work quite well. Popular surface treatments include conductive paints, vacuum deposition, electroless plating, and even metal fabrics. Conductive plastics are also available, but they generally do not perform nearly as well as surface treatments for high frequencies.

Gasketing and Screening.
Large openings, such as ventilation ports or display areas, can be sealed with screening material. Seams or slots can be filled with conductive gaskets. In both cases, the secret is to provide complete and continuous metal-to-metal contact at all junctions. For high-frequency shielding, the connections must be almost watertight. Anything less is asking for problems.

For screening material, the smaller the openings, the higher the shielding. Window screen spacing is almost as effective as solid materials from dc to 1000 MHz, and even 5-mm (about 1/4 in.) openings are often acceptable at 1000 MHz. In any case, do not exceed 1/20 wavelength at the highest frequency of concern.

Cable Terminations and Filters.
Poor termination of shielded cables can cause big problems at high frequencies. If a shielded cable is not terminated directly at the shielding barrier, a lot of energy leaks, degrading both the cable and the enclosure shield. Pigtail connections, popular for terminating low-frequency cable shields, are particularly bothersome at high frequencies. In fact, this is a leading cause of EMI failures for RFI, emissions, and ESD. As a rule of thumb, pigtail connections should not be used on cable shields at frequencies above about 1 MHz.

Unshielded cables can also cause problems at high frequencies. In those cases, high-frequency filtering is needed directly at the interface to assure that the shield is not degraded at high frequencies. Common solutions are EMI filters on power and signal lines, or ferrite beads on the lines or cables. These must be installed as close to the shield penetration as possible. The best situation is to mount the filter directly in the shield itself, although this is not always necessary for moderate problems.

Internal Shields.
Finally, do not overlook using internal shields on critical circuits. Radio and television designers have been doing this for years, using selective shields on oscillators, power amplifiers, and the like. A classic example of this approach is the TV tuner, the most sensitive part of a television receiver. It is an inexpensive, yet highly effective shielding strategy.

Defining Terms

Conducted: Energy or interference that is propagated by a conductor, such as power, grounding, or signal interface wiring.

EFT: Electrical fast transient; a high-frequency burst of energy on power wiring.

EMC: Electromagnetic compatibility; the condition wherein electric and electronic equipment operate successfully in close proximity.

EMI: Electromagnetic interference; unwanted electric energy that may impair the function of electronic equipment.

Emissions: Electric energy emanating from an electronic source.

ESD: Electrostatic discharge; the rapid discharge that often follows a buildup of static charge.

EU: European union; formerly called the European Community.

FCC: Federal Communications Commission (U.S. government).

Ground: A return path for current.

Radiated: Energy or interference that is propagated by electromagnetic radiation through space.

RFI: Radio frequency interference; an older term for EMI, now usually used to describe interference caused by a nearby radio transmitter.

Shield: A metallic enclosure used to reduce electric or magnetic field levels.

Susceptibility: Vulnerability of electronic equipment to external sources of interference; often used interchangeably with immunity.

Further Information

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29.2 EMI and EMC Test Methods

Jeffrey P. Mills

Electric and magnetic fields must be measured for a variety of reasons. A radio or TV broadcast station is licensed to provide reliable coverage over a specified geographic area, and any properly operating receiver must pick up the signal and properly respond to it. This can be assured only if the broadcast signal is of a guaranteed minimum strength. Also, the signal must not be so strong that it interferes with a distant station sharing the same frequency. The broadcast field must be measured over its geographic area of coverage to be sure that it satisfies both criteria.

Many electric devices unintentionally radiate electromagnetic fields. Examples include

- Oscillators in superhetrodyne radio or TV receivers
- Digital logic circuits
- Switching contacts, particularly if unsuppressed
- Automotive ignition systems

Stray fields (**emissions**) from these devices can interfere with other devices, or even with the radiating device itself. This process is known as **electromagnetic interference**, commonly abbreviated EMI. Interference between two devices is known as **intersystem** EMI, whereas if a device interferes with itself it is **intrasystem EMI**. Intrasystem EMI is usually easy to spot because the device itself does not operate correctly. Intersystem EMI is usually more difficult to isolate. Its result might be a simple annoyance, such as noise on a radio and TV receiver caused by an electric vacuum cleaner or a power drill. It could, however, be much more serious; a portable radio receiver might affect aircraft navigation or critical communications.

It is also possible for a device to be **susceptible** to fields intentionally generated by a licensed transmitter such as a broadcast or mobile-radio transmitter. Examples include

- Public-address systems
- Music (high-fidelity) systems
- Telephone lines and instruments
- Digital logic circuits

Again, the result may be only an annoyance, or it could be much more serious; aircraft control surfaces have been observed to move uncontrollably due to strong electromagnetic fields. Since the fields themselves cannot be eliminated in these cases, the devices must be made immune to electromagnetic fields.

In the above cases, the interference is usually through electric and/or magnetic fields in space, so the process is known as **radiated coupling**. Another coupling path exists if two devices share the same power source. One device may generate undesired high-frequency voltages on its power leads, which then appear on the power leads of the other. The second device may then malfunction because of this high-frequency voltage. This is known as **conducted coupling**. So we must consider both radiated and conducted noise.

It is not practical to eliminate all interfering fields completely, so a compromise must be reached. A stray field will not cause EMI if it is very weak compared with the desired field, which might be the field of a broadcast signal. The permissible strength of the stray field depends on the strength of the desired field; the stronger the desired field, the more stray field can be tolerated. It also depends on the device that is being interfered with (the *victim*); some receivers can reject undesired signals better than others. Since there are many combinations of interference sources and victims, a worst-case scenario is sought that will protect most real-life situations. This occurs where the weakest legal radio or TV signal (in its licensed area of coverage) is received by the poorest available receiver.

The maximum stray field strength that causes no EMI for this worst-case scenario is incorporated into government regulations. The field actually radiated by every device must then be measured to be sure that it does not exceed this level at the nearest practical distance from it, usually 10 or 30 m. To specify and measure these field strengths accurately, the nature of electric and magnetic fields must be understood.

Unlike most electrical engineering topics, EMI control is not very precise because of the complexity of practical hardware. It is virtually impossible to predict interference more precisely than within a factor of three, and usually the margin of error is even worse. Measurements can vary significantly between two supposedly identical samples, due to slight variations in physical dimensions. If one measures the EMI resulting from two different designs, the design that exhibits less EMI is probably better, but not always. An engineer can often judge if an EMI problem exists, but one must never rely on the accuracy normally expected in other branches of electrical engineering.

Nature of Electric and Magnetic Fields

An electric field is generated by a distribution of electric charge. If the distribution changes with time, then so will the electric field. A magnetic field may be generated by a permanent magnet or by an electric current. If the permanent magnet or the current path moves, or if the current magnitude varies with time, the magnetic field will vary with time. A time-varying electric field creates a magnetic field, and conversely.

Electric fields, designated E, are normally expressed in volts per meter (V/m). Magnetic fields are designated H and expressed in amperes per meter (A/m). More often, magnetic fields are perceived as magnetic flux density, which is designated B and expressed in webers per square meter (W/m^2), also known as *teslas* (T). A non-SI unit, sometimes found in older literature, is the *gauss*, equal to 10^{-4} T. Of course, any unit may be preceded by a scaling prefix such as micro or pico. In free space, B is equal to $\mu_0 H$, where, μ_0 is equal to 0.4π (approximately 1.257) μT·m/A (equivalent to μH/m).

Near a time-varying electric field source such as a charge distribution, the magnetic field is relatively weak, but it becomes stronger when observed from farther away. At a great enough distance, the ratio of E to H approaches $\sqrt{\mu/\epsilon}$, which in free space is equal to 120π (approximately 377) Ω. For a sinusoidal function of time with a frequency f, this occurs at any distance that is large compared with $\lambda/2\pi$ (approximately $\lambda/6$). Here, λ is the wavelength corresponding to f, equal to $3 \cdot 10^8/f$ m if f is specified in hertz. Distances much greater than $\lambda/2\pi$ are considered to be in the **far-field region**; nearer distances are in the **near-field region**. For a nonsinusoidal function of time, each Fourier frequency component must be considered separately, and the far-field region begins closer to the source for its higher frequency components.

Near a time-varying magnetic field source such as a current loop, the electric field is weak, becoming stronger when observed from a greater distance. At distances that are large compared with $\lambda/2\pi$ (the far-field region), the ratio of E to H again approaches 120π Ω.

Since $H = \sqrt{\epsilon/\mu}E$ and $B = \mu H = \sqrt{\mu\epsilon}E$ in the far-field region for either type of source, only E or B must be measured, and the other can easily be calculated from it. In free space, $\sqrt{\mu\epsilon} \approx 10^{-8}/3$ T·m/V (equivalent to s/m), so, if E is expressed in volts per meter, $B \approx 3.33E$ nT. By choice of a suitable antenna, either field can be measured. Far-field strengths are normally specified in terms of the E field, no matter whether the E or B field is measured.

Alternatively, the far-field strength may be specified in terms of **power density**, expressed in watts per square meter. This denotes the amount of radiated power passing through each square meter of a surface perpendicular to the direction away from the source. The *peak* power density P is equal to EH, and, for a sinusoidal source, the *average* power density is half this value. For a nonsinusoidal source, each frequency component must be considered separately, and the total average power is the sum of the average powers for all frequencies. Since $H = \sqrt{\epsilon/\mu}E$, it follows that $P = E^2/377$ Ω.

In regions other than the far field, the ratio of E to H varies greatly, approaching infinity for an electric field source or zero for a magnetic field source. A source may generate both electric and magnetic fields; for example, a charge moving between two electrodes causes a current to flow between them. Then the ratio of E to H may be any value at all. Therefore, at distances less than $\lambda/2\pi$ from a field source, both the E and B fields must be measured separately.

In the far-field region, both the electric and magnetic fields are perpendicular to the direction that an electromagnetic wave is propagating, and they are also perpendicular to each other. This still usually allows the fields to be oriented at many different angles with respect to the surface of the Earth. The direction of the electric field is called the **polarization** of the wave, which may be vertical, horizontal, or somewhere between. Or the wave may be **elliptically polarized**, which results from two waves that are not exactly in phase, one polarized vertically and the other horizontally. If the waves are equal in magnitude and exactly 90° out of phase, the wave is *circularly* polarized. To account for all these cases, all fields must be checked separately for vertically and horizontally polarized waves.

Measurement Antennas

Most electronic components and instruments are designed to respond to voltages or currents, not fields. To measure a field strength it is necessary to convert its effect to a voltage or a current. This is achieved by an antenna. Although many antennas are simple conductor shapes, they must be analyzed carefully if accurate quantitative measurements are desired.

A straight conductor immersed in a time-varying electric field will develop a current in it. If the conductor material is linear (the usual case), the current will be proportional to the applied electric field, so their ratio will be constant. This ratio, however, depends greatly on the geometric dimensions of the conductor and the frequency of the electric field. It must be known to calibrate the antenna.

Similarly, a closed conductive loop immersed in a time-varying magnetic field will develop a current in it. Again, if the conductor is linear, the ratio of the current to the magnetic field strength is constant but depends on the dimensions of the loop and the frequency of the magnetic field.

The easiest way to calibrate an antenna is to immerse it in a known electric or magnetic field and measure the current or voltage at the antenna terminals. The principal problem is generating the known field. To find its strength, one must use a "standard" antenna for which the current-to-field ratio can be calculated.

To calculate the required ratio, Maxwell's equations must be solved subject to the boundary conditions of the antenna conductor. For most antennas an exact closed-form solution is impossible. However, for a sinusoidally varying field encountering a straight cylindrical conductor called a **dipole antenna**, such a solution is possible, though difficult [1]. Once the solution is obtained, the required ratio becomes a simple expression if the antenna is *resonant* or *tuned*. This occurs for a precise length that is slightly less than one half the wavelength, λ, of the time-varying field. Obviously, the antenna will be resonant at only one frequency, so the ratio will be valid only for a field varying sinusoidally at that frequency. For nonsinusoidal fields, each Fourier frequency component must be measured separately, and the antenna length must be changed as different frequencies are measured. To simplify changing its length, two telescoping rods, mounted end to end, are normally used to make the dipole antenna. The measuring instrument is connected between these two rods via a transmission line.

For a given frequency, at any point on the antenna, there is a certain current I flowing in it, and there is also a certain voltage V on it with respect to ground. The ratio of these phasors, V/I, is known as the **driving-point impedance**. The precise resonant antenna length is that for which V and I are exactly in phase, i.e., for which the driving-point impedance is purely real. As mentioned above, this length is slightly less than half the wavelength, λ, and it also depends on the thickness of the telescoping rods (pp. 547–548 of Reference 1). For a rod thickness of $\lambda/400$, the resonant length is 0.476λ. The driving-point impedance of a dipole antenna of these dimensions is 64 Ω. If a voltage-measuring instrument such as a radio receiver or spectrum analyzer is connected to the antenna terminals via a transmission line, and is properly matched to the 64 Ω impedance, the measured voltage V_m will be equal to $0.148\lambda E$, where E is the applied field strength and λ is the wavelength at the frequency being measured. The ratio V_m/E, equal to 0.148λ, is known as the **effective length** (l_e) of the antenna, since it relates the field strength in volts per meter to the measured terminal voltage in volts. Obviously, it is not equal to the physical antenna length but is instead approximately one third of that value. With this ratio known, the electric field strength E that causes a certain terminal voltage V_m can easily be calculated.

To simplify calculations, E is often expressed in decibels with respect to a reference field of 1 μV/m and is designated E_d. Similarly, V_m is expressed in decibels with respect to a reference voltage of 1 μV and is designated V_d. The **antenna factor** (AF) is defined as the effective length expressed in negative decibels, or AF = $-20 \log(l_e)$. Then the multiplication becomes an addition, i.e., $E_d = V_d + \text{AF}$.

The above antenna factor assumes that the antenna is perfectly matched to the receiver, which implies maximum power transfer. A mismatch would change the antenna factor. Therefore, since the antenna driving-point impedance usually is not equal to the receiver input impedance, a matching circuit must be inserted between the antenna and receiver. Another essential consideration is antenna balance. Most receivers and spectrum analyzers have one input terminal grounded. If this grounded terminal is connected to one of the dipole antenna terminals, the impedances connected to the two antenna terminals will be unequal with respect to ground. This also will upset the antenna factor, since one side of the antenna will not be properly matched to the receiver. To prevent this, a balanced-to-unbalanced (**balun**) network must be inserted between the antenna and receiver. Such a circuit provides a high impedance *with respect to ground* for both input terminals, while providing the correct input impedance (such as 64 Ω) *between* its input terminals. Normally, a single network provides both the matching and balancing functions.

Unfortunately, unless the dipole antenna is precisely the correct length, its antenna factor is much more complicated. Even if the frequency being measured differs only a few percent from the antenna resonant frequency, the antenna factor becomes unpredictable and the driving-point impedance becomes complex. Thus, the electric field cannot be easily calculated from the measured terminal voltage. To achieve the simple antenna factor described above, the frequencies must be measured one at a time and the dipole antenna length properly adjusted for each frequency. It is impossible to sweep the spectrum rapidly, as when using a spectrum analyzer, unless the antenna length can somehow be varied also. This leads to mechanical difficulties and is usually impractical.

Other types of antennas, however, are less sensitive to frequency. Examples are the biconical antenna and the log-periodic antenna. A biconical antenna can perform acceptably over a range of 20 to 300 MHz, and a log-periodic antenna is useful from 300 to 1000 MHz. Their antenna factors are relatively constant, usually varying by no more than 20 dB, over their useful frequency ranges. The antenna factors are usually too difficult to calculate, but they may easily be measured simply by observing the terminal voltage resulting from a sinusoidally varying field of known strength. The known field is first measured using a tuned dipole antenna, for which the antenna factor can be calculated. The antenna factor is measured in this manner at several frequencies throughout its useful range, and the results are plotted for use with the antenna.

Unlike the tuned dipole, the biconical and log-periodic antennas do not exhibit constant driving-point impedances over their useful frequency range. Since the receiver input impedance cannot be made to follow the variation of driving-point impedance with frequency, an exact match is impossible. This affects the antenna factor just as it would for a mismatched tuned dipole. To compensate for this, the antenna factor must be measured with the antenna terminated into a known impedance, which must then be used for all measurements made with that antenna. Then the mismatch is accounted for in the antenna factor itself. The mismatch does cause the antenna to reradiate the received signal, but this effect may be minimized by performing the measurements in an open-field site, which will be discussed later.

Tuned dipole, biconical, and log-periodic antennas are *linearly polarized* antennas because they respond to only one polarization component of a propagating wave. If the antenna is oriented horizontally, only the horizontally polarized component of the wave will affect it. Similarly, only the vertically polarized component will affect a vertically oriented antenna. Thus, with two measurements, any linearly polarized antenna will detect any type of field polarization. Other types of antennas, such as the spiral antenna, are designed to detect a circularly polarized wave. They will detect vertically and horizontally polarized waves, but they could miss a wave that is circularly polarized in the reverse direction (counterclockwise instead of clockwise, for example). Consequently, circularly polarized antennas are forbidden for many types of field measurements.

All antennas discussed above respond to the electric field, E. As mentioned earlier, in the far-field region, the magnetic field, B, is simply 3.33 nT times the value of E expressed in volts per meter. In any other region, however, B is not so simply related to E and must be measured separately, using an antenna that responds to magnetic fields. A circular loop or coil of wire is such an antenna. The loop is cut at one point and the radio receiver or spectrum analyzer is connected between its two ends. For quantitative measurements, its antenna factor must be known. The factor can be measured by immersing the antenna in a known magnetic field and measuring its terminal voltage. To find the known magnetic field strength, the electric field is first measured, in the far-field region, using a tuned dipole antenna for which the factor is known. The magnetic field is then 3.33 nT times this value expressed in volts per meter. With the magnetic field thus determined, the antenna factor of the loop may be calculated, as required.

Measurement Environment

A major difficulty with electromagnetic field measurements is repeatability of results. Electromagnetic fields are affected by any materials in their vicinity, even by poor conductors and dielectrics. The measurement environment must therefore be carefully defined, and similar environments must be used for all comparable measurements.

The ideal environment would be one where (1) the only electromagnetic field source is the equipment under test (EUT) and (2) there is no "foreign" material at all that could affect the fields being measured. Unfortunately, the only natural location where this could be achieved is in outer space, since the Earth itself affects electromagnetic fields. Since this is impractical, attempts are made to simulate this environment on Earth.

A large outdoor open area simulates a hemisphere of free space. Such a test site is appropriately called an **open-field site**. If the conductivity, permittivity, and permeability of the Earth were constant, every open-field site would have the same effect on the electromagnetic fields radiating from the EUT. The Earth's parameters do vary, however. To compensate for this variation, a large conductive floor, or ground plane, is laid under the EUT. This causes all electromagnetic waves to be totally reflected from the ground plane, so that the Earth's properties have no effect. The ground plane must be large enough so that it appears infinite with respect to the EUT and the associated test equipment. Acceptable dimensions are $1.73d \times 2d$, where d is the distance between the measurement antenna and the EUT, normally 3 or 10 m. Radiated emissions must be measured in all directions from the EUT, and at various angles of inclination. This is most easily achieved by placing the EUT on a turntable, which is then rotated during the test. To allow measurement at various inclination angles, the receiving antenna height must be varied, and this is accomplished by mounting it on a halyard. A typical open-field site appears in Figure 29.5.

An open-field site provides repeatable data only if there are no nearby trees or structures that could cause undesirable reflections. Before it can be reliably used, it must be tested. This is done by generating a known electromagnetic field and measuring it. The field is normally generated by a radio frequency oscillator driving a tuned dipole antenna, for which the radiation can be calculated (pp. 237–238 of Reference 2). This radiation is then measured as though it were generated by a typical device being tested. The ratio of the voltage at the transmitting antenna terminals to that at the receiving antenna terminals is known as the **site attenuation**. If the site attenuation is within 3 dB of its calculated value, the test site is deemed acceptable.

Although an open-field site eliminates reflections, external field sources, such as licensed transmitters, still cause problems. Since electromagnetic radiation can travel thousands of miles, no open-field site will be completely free of electromagnetic fields. To eliminate the effects of these stray sources, testing must be performed inside a shielded enclosure. There, however, severe reflections occur, and measurements become inaccurate and unrepeatable.

An ideal test environment would be a shielded enclosure lined with material that does not reflect electromagnetic waves. Such an enclosure is called an *anechoic chamber*, with the understanding that the name refers to *electromagnetic* echoes. Until recently, such chambers were not practical except at very high frequencies, but improvements are constantly being made. Such an enclosure is acceptable for testing

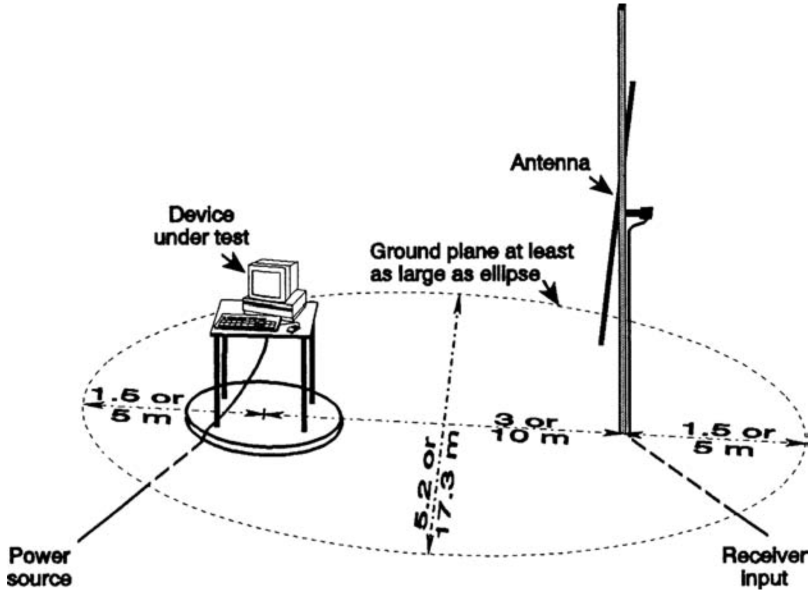

FIGURE 29.5 An open-field test site. Power and antenna cables are run under the ground plane so that they will not affect measured fields. The area outlined by the ellipse must be free of everything except the device under test, the table on which it rests, and the measuring antenna. To facilitate measuring radiation in all directions from the device, it is placed on a turntable. By rotating it during testing, and simultaneously varying the height of the receiving antenna, the direction of maximum radiation is found.

if it meets the site-attenuation requirements of a true open field. The site attenuation must be measured at several points inside the chamber, to assure that the proximity of the chamber walls has no effect. Unfortunately, such chambers are at present very expensive.

Another type of test chamber is the **transverse electromagnetic (TEM) cell**. This consists of an enlarged section of waveguide, in which the electromagnetic fields can be accurately predicted [3,4]. They are suitable only for testing small devices at relatively low frequencies. The TEM cell can be no larger than a wavelength at the frequency being tested. For example, to test at 200 MHz, the cell could be no larger than 1.5 m, or 5 ft, and the device itself must not exceed 1/6 of this value, or 10 in. For small devices, however, the TEM cell is very accurate and is unaffected by stray field sources.

If a suitable anechoic chamber is not available, a device may be tested in an ordinary shielded enclosure to learn what frequencies it emits. The field strengths will be inaccurate due to the internal reflections. Then the device is tested in a true open-field site, and the suspected frequencies are measured quantitatively. Any field that exceeds the acceptable limits is then observed while the device is shut off. If it does not disappear, it is obviously not being generated by the EUT. This procedure is acceptable, although not as simple as testing inside an anechoic chamber.

Preliminary measurements may even be performed in an ordinary room. They will not be comparable with similar measurements made anywhere else, because of the effects of nearby conductors and dielectrics. Here, also, the device must be shut off to decide if any emissions are from stray external sources instead of from the EUT. This procedure provides a rough estimate of the emissions from the EUT, and it usually saves time during any later testing at a true open-field site. The various measurement methods appear in Table 29.4.

Permissible emission levels appear in the *Code of Federal Regulations* [5]. These rules assume open-field measurements, which are the most accurate possible. Even there, variations of ±6 dB are typical. Therefore, a manufacturer should allow a safety factor when performing measurements intended to assure compliance with government regulations. Otherwise, a device may pass when tested by the manufacturer

TABLE 29.4 Comparison of EMI Measurement Methods

Method	Equipment Required	Space Required	Accuracy	Outside Influence	Cost	Comments
Ordinary room	Antenna and receiver	3 or 10 m radius around EUT	Medium, affected by structure, ±20 dB	May be severe, depending on location	Minimum	Usually acceptable for preliminary tests
Shielded room	Shielded room, antenna, and receiver	4 to 6 m radius around EUT	Poor, ±30–40 dB due to reflections	Usually none	Moderate	Use for preliminary tests in noisy areas
TEM cell	TEM cell and receiver	1 to 3 m^3	Very good, ±10 dB	Usually none	Moderate	Unusable for large EUT due to high-order modes
Open field	Antenna and receiver	17 × 20 m open field with no nearby structures	Excellent, usually ±6 dB	May be severe, depending on location	High, due to logistics of site (power, weather, etc.)	Standard test method
Shielded anechoic chamber	Anechoic chamber, antenna, and receiver	6 to 15 m radius around EUT	Very good, ±10 dB	Usually none	Very high	Use for accurate tests in noisy areas

but fail if later tested by the government using a supposedly identical test procedure. Since the government's measurements then prevail, the manufacturer's integrity could be questioned.

Further details on measurement techniques are available in the References 2 and 6.

Defining Terms

Antenna factor: Its effective length expressed in negative decibels.

Balun: An interface device used to isolate a dipole or other balanced antenna from the effects of a receiver having one grounded terminal.

Conducted coupling: Coupling due to voltages imposed on a shared power source.

Dipole antenna: An antenna consisting of two collinear rods with the feed line connected between them.

Driving-point impedance: The ratio of voltage to current at the driving point (normally the center) of an antenna.

Effective length: The ratio of the voltage observed at the driving-point of an antenna to the strength of its received electric field.

Electromagnetic compatibility (EMC): The capability of two or more electrical devices to operate simultaneously without mutual interference.

Electromagnetic interference (EMI): Any undesired effect of one electrical device upon another due to radiated electromagnetic fields or due to voltages imposed on a shared power source.

Elliptical polarization: Polarization of an electromagnetic wave consisting of two perpendicular electric fields of differing phase.

Emissions: Fields or conducted voltages generated by an electrical device.

Far-field region: Any location that is much farther than $\lambda/2\pi$ from an electric or magnetic field source, where λ is the wavelength at the frequency of concern.

Intersystem EMI: Electromagnetic interference between two or more systems.

Intrasystem EMI: Electromagnetic interference between two or more parts of the same system.

Near-field region: Any location that is much nearer than $\lambda/2\pi$ to an electric or magnetic field source, where λ is the wavelength at the frequency of concern.

Open-field site: A test location free of any conductors which would affect electromagnetic fields and taint the results.

Polarization: The direction of the electric field, *E*, of an electromagnetic wave.

Power density: Radiated power per unit of cross-sectional area.

Radiated coupling: Coupling due to radiated electric, magnetic, or electromagnetic fields.

Site attenuation: A measure of the degree to which electromagnetic fields at a test site are disturbed by environmental irregularities, obtained by comparing calculations with measured experimental results.

Susceptibility: The degree to which an electrical device is affected by externally generated fields or conducted voltages.

Transverse electromagnetic (TEM) cell: A relatively small test chamber in which fields can be accurately controlled by its geometric properties.

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