EMC and the Printed Circuit Board: Design, Theory, and Layout Made Simple. Mark I. Montrose
ISBN: 0-780-34703-X

1

EMC Fundamentals

This book seeks primarily to help engineers minimize harmful interference between components, circuits, and systems. These interferences include not only radiated and conducted radio frequency (RF) emissions, but also the influences of electrostatic discharge (ESD), electrical overstress (EOS), and radiated and conducted susceptibility (immunity). Meeting these requirements will satisfy legally mandated international and domestic regulatory requirements and governmental regulations. A companion book, *Printed Circuit Board Design Techniques for EMC Compliance,* presents design rules and layout concepts that assist in achieving an EMC-compliant product using suppression design techniques.

One of the engineer's goals is to meet design requirements in order to satisfy both international and domestic regulations and voluntary industrial standards related to EMC compliance.

The information presented in this book is intended for

- Non-EMC engineers who design and layout printed circuit boards (PCBs).
- EMC engineers and consultants who must solve design problems at the PCB level.
- Design engineers who want to understand fundamental concepts related to how electromagnetic interference (EMI) exists within a PCB.
- Those who want a comprehensive understanding of how PCB design and layout techniques work within a PCB.

This book is applicable for use as a reference document throughout any design project.

With these considerations in mind, the reader should understand that *EMC and the Printed Circuit Board* is written for the engineer who never studied applied electromagnetics in school, requires a refresher course, or has minimal hands-on experience with high-speed, high-technology product designs. As we well know, technology is advancing at a rapid rate. Design techniques that worked several years ago are no longer effective in today's products with high-speed digital design requirements. Because EMC may be insufficiently covered in engineering schools, training courses and seminars are now being held all over the country and internationally to provide this information.

Only a minimal amount of mathematical analysis is presented here because the intent of this book is to present *a basic understanding and analysis of how a PCB creates RF energy, and the manner in which RF energy is propagated.* The information presented is therefore in a format that is easy both to understand and to implement.

Since World War II, controlling emissions from a product has been a necessity for acceptable performance of an electronic device in both the civilian and military environment. It is more cost-effective to design a product with suppression at the source than to "build a better box." Containment measures are not always economically justified and may degrade as the life cycle of the product is extended beyond the original design specification. For example, the end user often removes covers from enclosures for ease of access to repair or upgrade. In many cases, sheet metal covers are never replaced, particularly those internal subassembly covers that act as partition shields. The same is true for blank metal panels or faceplates on the front of a system that contains a chassis or backplane assembly. As a result, containment measures become compromised. Proper layout of a PCB with suppression techniques also promotes EMC compliance with use of cables and interconnects, whereas box shielding (containment) does not. In addition to EMC compliance, signal functionality concerns exist. It does us no good if a product passes EMC tests and then fails to operate as designed.

This book provides details on why a variety of design techniques work for most PCB layout applications. It is impossible to anticipate every possible application or design concern. The concepts presented are *fundamental* in nature and are applicable to all electronic products. While every design is different, the basics of product design rarely change unless new components and materials become available.

Herein we discuss high-technology, high-speed designs that require new and expanded techniques for EMC suppression at the PCB level. Many traditional PCB techniques are not effective for proper signal functionality and compliance. Components have become faster and more complex. Use of custom gate array logic and application-specific integrated circuits (ASICs) presents new and challenging opportunities. The design and layout of a PCB to suppress EMI at the source can be realized while maintaining systemwide functionality.

Why worry about EMC compliance? After all, isn't speed the most important design parameter? Legal requirements dictate the maximum permissible interference potential of digital products. These requirements are based on experiences in the marketplace related to emission and immunity complaints. Often, suppression techniques on a PCB will aid in improving signal quality and signal-to-noise performance.

1.1 FUNDAMENTAL DEFINITIONS

The following basic terms are used throughout this book.

Electromagnetic Compatibility (EMC). The capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels or performance, without suffering or causing unacceptable degradation as a result of electromagnetic interference. (ANSI C64.14-1992)

Electromagnetic Interference (EMI). The lack of EMC, since the essence of interference is the lack of compatibility. EMI is the process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both). In common usage, the term refers particularly to RF signals, but EMI can occur in the frequency range from "DC to daylight."

Radio Frequency (RF). A frequency range containing coherent electromagnetic radiation of energy useful for communication purposes—roughly the range from 10 kHz to 100 GHz. This energy may be transmitted as a byproduct of an electronic device's operation. RF is transmitted through two basic modes:

Radiated Emissions. The component of RF energy that is transmitted through a medium as an electromagnetic field. Although RF energy is usually transmitted through free space, other modes of field transmission may occur.

Conducted Emissions. The component of RF energy that is transmitted through a medium as a propagating wave, generally through a wire or interconnect cables. LCI (Line Conducted Interference) refers to RF energy in a power cord or AC mains input cable. Conducted signals do not propagate as fields but may propagate as conducted waves.

Susceptibility. A relative measure of a device or a system's propensity to be disrupted or damaged by EMI exposure to an incident field of signal. It is the lack of immunity.

Immunity. A relative measure of a device or system's ability to withstand EMI exposure while maintaining a predefined performance level.

Electrostatic Discharge (ESD). A transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact. This definition is observed as a high-voltage pulse that may cause damage or loss of functionality to susceptible devices. Although lightning qualifies as a high-voltage pulse, the term *ESD* is generally applied to events of lesser amperage, and more specifically to events that are triggered by human beings. However, for the purposes of discussion, lightning is included in the ESD category because the protection techniques are very similar, though different in magnitude.

Radiated Immunity A product's relative ability to withstand electromagnetic energy that arrives via free-space propagation.

Conducted Immunity. A product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, and I/O interconnects.

Containment. A process whereby RF energy is prevented from exiting an enclosure, generally by shielding a product within a metal enclosure (Faraday cage or Gaussian structure) or by using a plastic housing with RF conductive paint. Reciprocally, we can also speak of containment as preventing RF energy from entering the enclosure.

Suppression. The process of reducing or eliminating RF energy that exists without relying on a secondary method, such as a metal housing or chassis. Suppression may include shielding and filtering as well.

1.2 EMC CONCERNS FOR THE DESIGN ENGINEER

Within the field of EMC, multiple design concerns exist. Most items identified here are *not* obvious. Past experience determines the amount of effort required to address these issues as they relate to EMC compliance along with signal functionality. Awareness of five key areas is mandatory for understanding why electromagnetic compatibility is required. With an understanding of these five areas, we can reduce difficult problems to simple applications of design techniques and implementations. About 95% of all EMC issues encountered are associated with the following. Each will be discussed separately [2].

1. Regulations
2. RFI
3. Electrostatic discharge
4. Power disturbances
5. Self-compatibility

1.2.1 Regulations

Part of the need for regulations stems from complaints regarding interference to electronic products used in both residential and commercial applications and part from the requirement to protect vital communication services. Without regulations, the "electromagnetic environment" in which we live would be crowded with interference and only a few electronic devices could survive and operate.

Regulations protect the radio spectrum and limit "spurious" radiation from both intended radiators (such as transmitters) and unintended radiators (most electronic equipment). Numerous consumer complaints developed basically over interference to television and radio reception. In addition, aeronautical communication systems started to break down; police and fire units were unable to use their radios for emergency purposes; and commercial and residential electronic products were failing in the field owing to the presence of other electronic equipment located in the general vicinity. With these complaints, the Federal Communications Commission (FCC) developed a set of requirements for electronic equipment that would limit the amount of interference polluting the electromagnetic environment. The FCC followed the lead of Germany's Verband Deutscher Electrotechniker (VDE), which implemented mandatory requirements shortly after World War II. Other countries worldwide have followed the VDE and FCC in developing requirements for digital products.

Regulations control not only emissions but also susceptibility (or immunity). Europeans have taken the lead in mandating immunity tests; in North America, however, these same tests are only voluntary at the time of this writing.

1.2.2 RFI

Radio Frequency Interference (RFI) poses a threat to electronic systems due to the proliferation of radio transmitters that exist. Cellular phones, handheld radios, wireless remote control units, pagers, and the like are now quite widespread. It does not take a great deal of radiated power to cause harmful interference. Typical equipment failures occur in the electric field level range of 1 to 10 volts/meter. For example, a 1 watt radio transmitter at 1 meter distance from an electronic device has a field strength of approximately 5 V/m, depending on the frequency and antenna used for measurement purposes. Preventing RFI from corrupting a device has become legally mandatory for all products used within Europe, North America, and many Asian countries.

1.2.3 Electrostatic Discharge (ESD)

ESD technology has progressed to the point where components have become extremely dense along with small geometries (0.18 micron). The sensitivity of high-speed, multimillion transistor microprocessors is easily damaged by external ESD events. These events can be caused by either direct or radiated means. Direct contact ESD events generally cause permanent damage of the device or create a latent failure mode that will trigger permanent damage sometime in the future. Radiated ESD events (caused, for instance, by furniture moving in a room, reflected ESD energy off a structure, or a person walking across a carpet) can cause an upset in the device that may result in improper operation without leading to permanent damage to the system.

An ESD event is considered to be a broadband high-frequency problem with edge rates that are usually less than 1 nanosecond. This translates to a spectral bandwidth problem that can approach 1 GHz. It is not uncommon to observe ESD in the sub-nanosecond time period. This faster edge rate becomes a problem well into the gigahertz spectral bandwidth.

ESD is treated under the immunity requirements for compliance with the EU's (European Union's) EMC Directive. Most manufacturers worldwide recognize this problem. These manufacturers must design suppression and layout techniques into their products to guarantee that failure will not occur in the field.

1.2.4 Power Disturbances

With more and more electronic equipment being plugged into the power mains network, potential interference occurs. These problems include power-line disturbances, electrical fast transients (EFT), power sag and surges, voltage variations (high/low voltage levels), lightning transients, and power-line harmonics. Older products and power supplies were generally not affected by these disturbances. With newer, high-frequency switching power supplies, these disturbances are starting to become noticeable as the switching components consume AC voltage generally on the crest of the waveform, not the complete waveform.

Analog and digital devices respond differently to power-line disturbances. Digital circuits are affected by spikes on the power system (EFT and lightning), as well as failure due to excessively high or low voltage levels. Analog devices generally operate on voltage levels, which may be degraded by a disturbance changing the reference level of the system's power source.

Power-line harmonics have become a major concern, especially in Europe. Nonlinear loads (switching power supplies) consume AC mains power at the peak of the cycle rather than over the entire sine wave. This varying load generates harmonics and waveform distortions that affect the power distribution network. For example, it is common to see 230 VAC, 150 Hz (third harmonic), or 250 Hz (fifth harmonic) present in a power system that is intended to operate at 50 Hz consuming various levels of input current at these higher frequencies.

1.2.5 Self-Compatibility

A commonly overlooked issue is self-compatibility. A digital partition or circuit can interfere with analog devices, create crosstalk between traces and wires, or a fan motor may cause an upset with digital circuits. While most of these concerns are known to the system designer, these failures are not recognized as an EMI event. Recognition of this concern, along with design implementations that prevent internal system failures from occurring, will result in a less expensive and more robust system.

1.3 THE ELECTROMAGNETIC ENVIRONMENT

A product must operate within a particular environment compatible with other electronic equipment. To understand the need for compatibility in an environment where products must operate, we now examine this environment.

Any periodic signal (clock) generates a wide spectrum of RF energy when viewed in the frequency domain. Figure 1.1 illustrates a spectral plot of a nonsinusoidal oscillator in the frequency range between 30 and 200 MHz. In studying this plot, we observe not only the fundamental frequency of the oscillator (1.8432 MHz), but also all the harmonics created across the 170 MHz window. A low-frequency oscillator was chosen to illustrate this wide harmonic spectrum. The spectral bandwidth of the oscillator is determined by the "edge rate" of the oscillator, not the "clock rate." A detailed discussion of why the "edge rate" of the digital pulse signal is of more concern than operating "frequency" is presented in Chapter 3.

Using this same oscillator waveform, we examine a very narrow frequency range. Figure 1.2 shows that both even and odd harmonics of the primary oscillator in the frequency range of 88–108 MHz are present.

The FM radio band (88–108 MHz) is allocated to a specific range of pre-assigned frequencies. Many digital products produce unintentional radiated RF energy within this frequency spectrum, especially lower order harmonics. In Fig. 1.3, we observe two traces. The upper trace displays FM radio signals. For this example, the spectrum analyzer was configured to make the FM radio signal appear similar to the signature characteristics of our clock signal. To help differentiate between the clock harmonics and the FM radio signals, a 10-dB displacement is observed in Fig. 1.3 with the FM signals shown 10 dB higher above the oscillator. The lower trace is a narrow-band view of the oscillator in the same frequency range. Notice that the signals measured are harmonics from the 1.8432-MHz oscillator. With this situation, potential interference between the oscillator and FM signal may exist. This scenario can be applied to any communications system, such as between a nonintentional radiator (digital device) and aeronautical communications, or an emergency services broadcast.

To illustrate the effects of a design change, the lower trace in Fig. 1.4 represents a compliant product. Changing just one component, moving a single trace, or using an alternate manufacturer of a logic family for the same function (74Fxx in place of a 74LSxx)

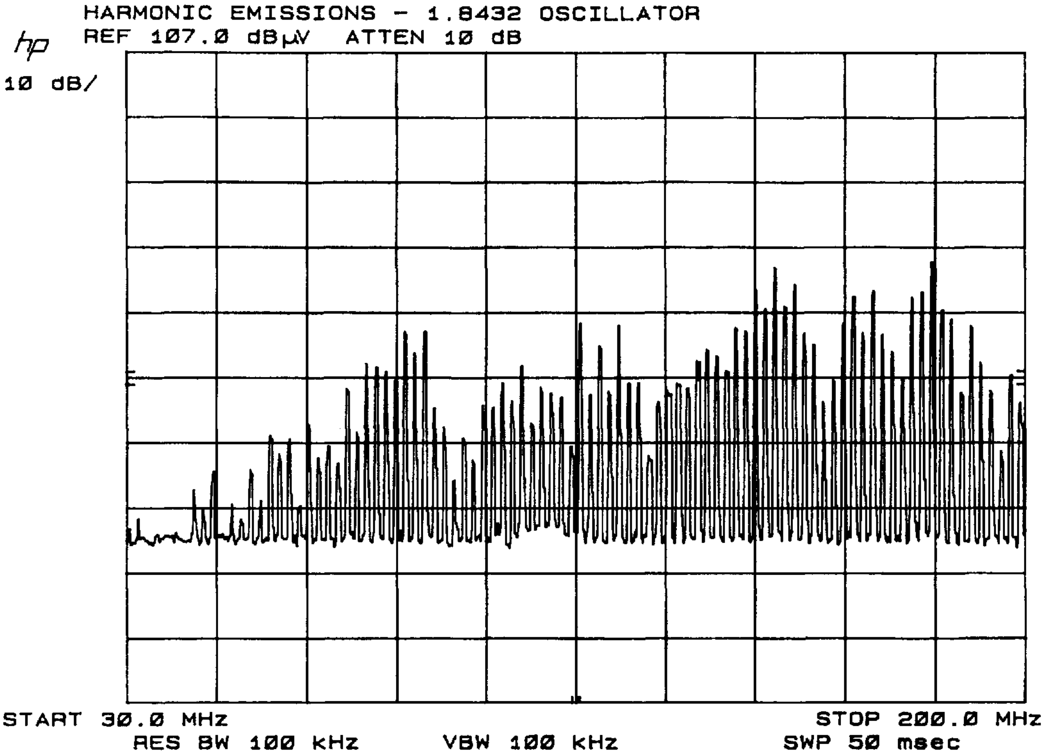

Figure 1.1 Oscillator and related harmonics (30–200 MHz).

now makes a compliant product noncompliant. This plot should enlighten those skeptics who believe that an alternate device that is identical in form, fit, and function can be easily substituted. Although the component may be functionally 100% compatible, its effects on changing the overall EMC characteristics may be radically different. The edge rate of the source driver may differ between vendors, although functionality remains the same. Not all components are the same, EMI considered. Chapter 3 provides details on how and why different components with the same function can cause functionality and EMI concerns.

Although difficult to observe in Fig. 1.4, we are able to distinguish the effects of a simple change to the circuit, especially in the middle frequency range of the plot.

Designing products that will pass legally required EMI tests is not as difficult as one might expect. Engineers often strive to design elegant products, but elegance sometimes must give way to product safety, manufacturing, cost, and, of course, EMC. Such abstract problems can be challenging, particularly if the engineer is unfamiliar with compliance or manufacturing requirements. We must remove the mystery from the "Hidden Schematic" syndrome.

When an EMI problem occurs, the engineer should approach the situation logically. A simple EMI model has three elements:

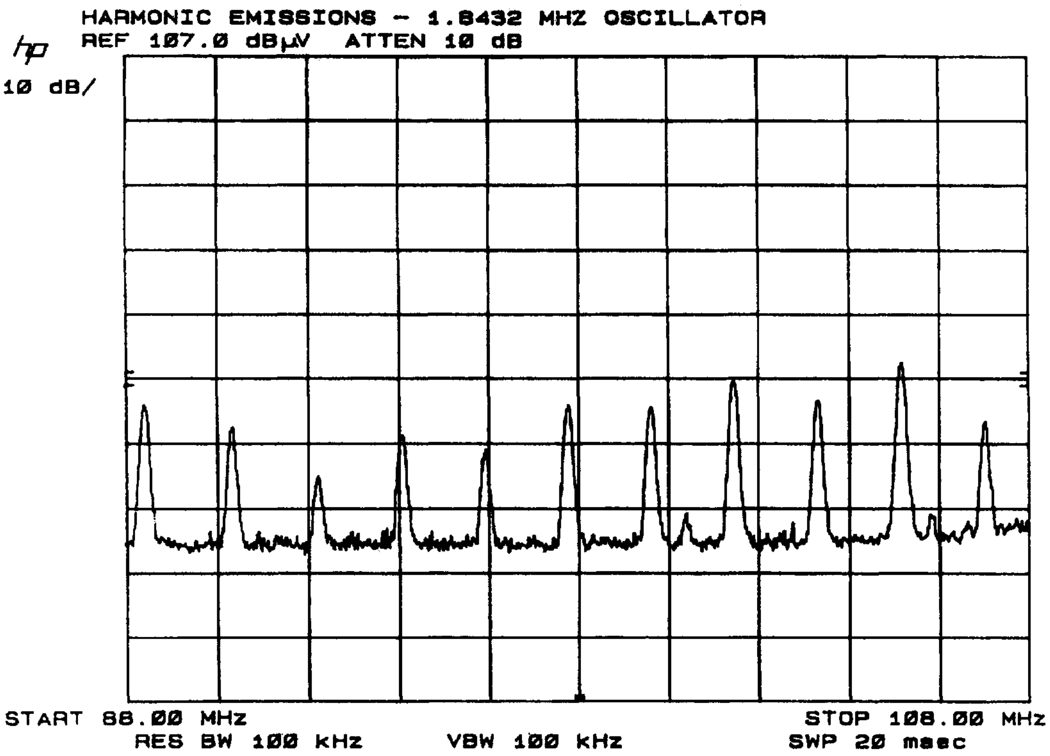

Figure 1.2 Oscillator and harmonics within a narrow frequency range (88–108 MHz).

1. There must be a source of energy.
2. There must be a receptor that is upset by this energy when the intensity of the electromagnetic interference is above a tolerable limit.
3. There must be a coupling path between the source and receptor for the unwanted energy transfer.

For interference to exist, all three elements have to be present. If one of the three elements is removed, there can be no interference. It therefore becomes the engineer's task to determine which is the easiest element to remove. Generally, designing a PCB that eliminates most sources of RF interference is the most cost-effective approach (called suppression). The source of interference is the active element producing the original waveform. What is required is to design the PCB to keep the RF energy created to only those sections of the board which require this energy. The second and third elements tend to be addressed with containment techniques. Figure 1.5 illustrates the relationship between these three elements and presents a list of products associated with each element.

With respect to PCBs, we observe the following.

- Noise sources are clock generation circuits, component radiation within a plastic package, incorrect trace routing, electrically long trace lengths, poor impedance control, internal cable interconnects, and the like.

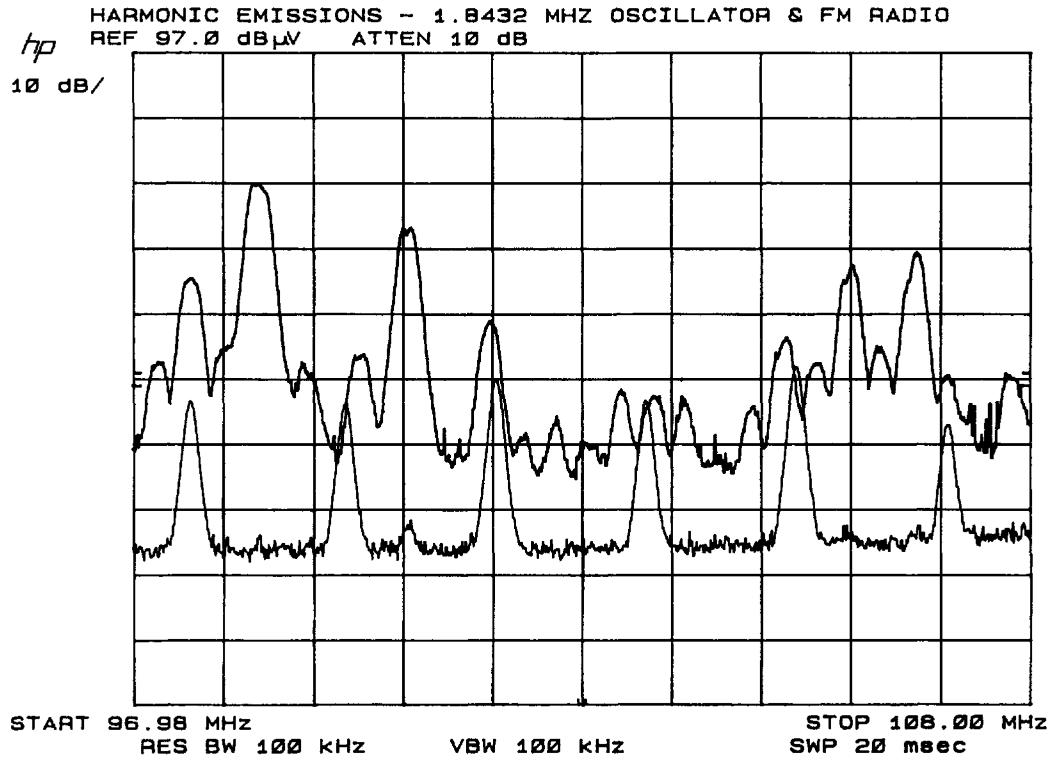

Figure 1.3 Oscillator's harmonics and FM radio signals superimposed. *Note:* FM radio stations are plotted 10 dB above oscillator for clarity.

- The propagation path is the medium that carries the RF energy, such as free space or interconnect cabling (common impedance coupling).
- Receptors can be components on the PCB that easily accept harmful radiated interference from I/O cables and transfer this harmful energy to circuits and devices susceptible to disruption.

1.4 THE NEED TO COMPLY (A BRIEF HISTORY OF EMI)

In North America, interference to communication systems became a concern in the 1930s, whereupon the United States Congress enacted the Communications Act of 1934. The Federal Communications Commission was created to oversee enforcement and administration of this act. Harmful effects were being observed with the technology of this time period, enough to cause the U.S. government to take action.

EMI was also recognized as a problem during World War II with vacuum tubes. The terminology used was Radio Frequency Interference (RFI). During this period, spectrum signatures of communication transmitters and receivers were developed along with radar systems. Because of the size and expense of these devices, the military owned the

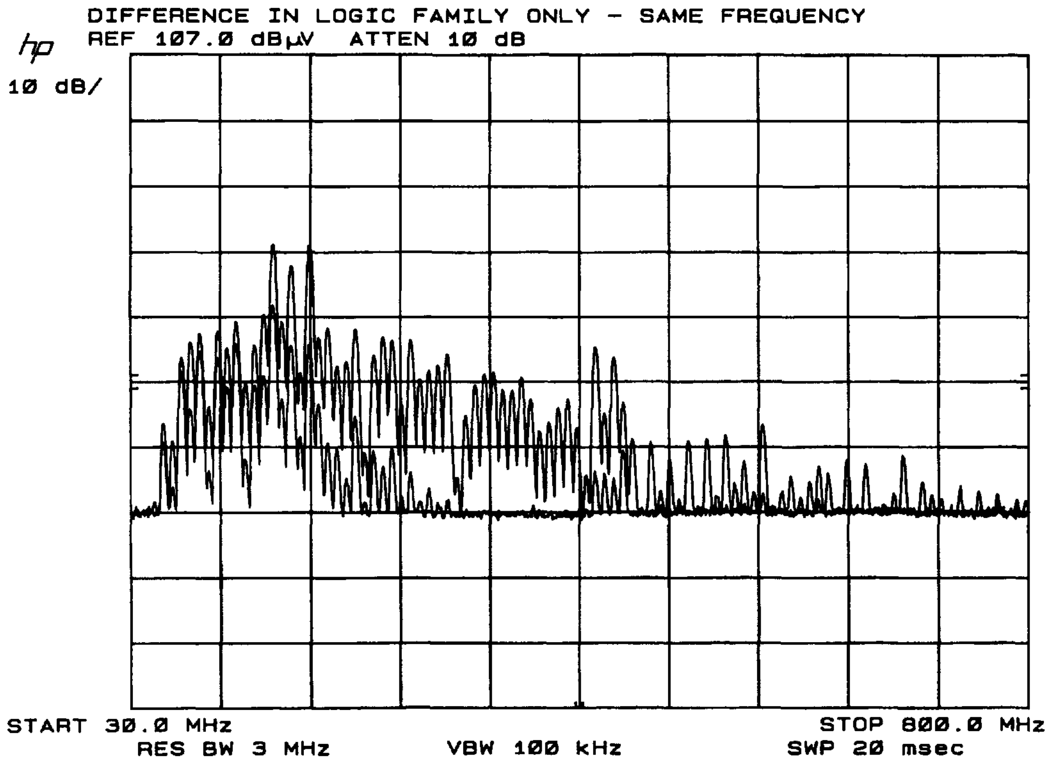

Figure 1.4 Effects of a single change to a circuit related to RF emissions.

majority of high-technology electronic systems. Research and information on EMC was kept from the general public under the guise of national security.

Following the Korean War, most EMC work was not classified unless it dealt with the specifics of a particular tactical or strategic system such as the Minuteman rocket, B-52 bombers, and similar military and espionage equipment. Conferences on EMI began to be held in the mid-1950s where unclassified information was presented. The first conference on EMI (RFI) was held in 1956 sponsored by the IEEE (Institute of Electrical and Electronic Engineers) and the IRE (Institute of Radio Engineers). During this time frame, the Army Signal Corps of Engineers and the United States Air Force created strong ongoing programs dealing with EMI, RFI, and related areas of EMC.

In the 1960s, NASA (National Aeronautical and Space Administration) began stepped-up EMI control programs for their launch vehicles and space system projects. Governmental agencies and private corporations became involved with combating EMI in equipment such as security systems, church organs, HI-FI amplifiers, and the like. All of these devices were analog-based systems.

As digital logic devices were developed, EMI became a greater concern. In approximately 1970, research was started to characterize EMI in consumer electronics, which included TV sets, common AM/FM radios, medical devices, audio and video recorders, and similar products. Very few of these products were digital but were becoming so. Analog

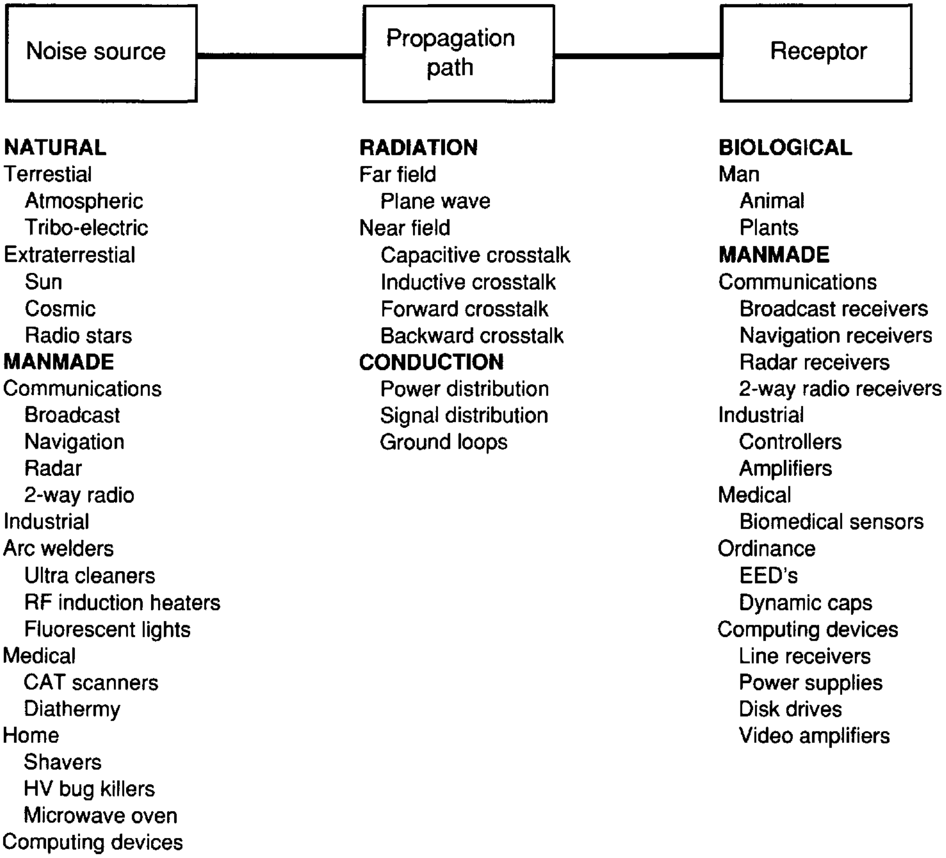

Figure 1.5 Items associated with the three elements of the EMI environment.

systems are more susceptible to problems than digital equipment because the threshold of susceptibility in a switch or control circuit is higher than that of a high gain amplifier.

In the late 1970s, problems associated with EMC compatibility became an issue for products that were beginning to be used within the commercial marketplace. These products include home entertainment systems (TVs, VCRs, camcorders), personal computers, communication equipment, household appliances with digital logic, intelligent transportation systems, sophisticated commercial avionics, control systems, audio and video displays, and numerous other applications. During this time period, the general public became aware of EMC and the threats associated with it.

After the general public became involved with EMI associated with digital equipment used within residential areas, the Federal Communications Commission (FCC) in the mid- to late 1970s began to promulgate an emissions standard for personal computers and similar equipment. Since personal computers comprised such a huge market, commercial entities became involved in the field of EMC. This was due in part to military and space funding being tapered off during this time period. Now almost all electronic equipment is digital, whether or not it needs to be.

The focus of electronic equipment has now shifted from analog to digital. Another factor that pushed digital devices into regulation status was that in the early days of digital, the prevailing wisdom was that digital devices were "not susceptible" to EMI. Because of this perception, the commercial community was totally shocked that digital devices were actually susceptible to disruption.

If it had not been for the personal computer, commercial manufacturers would not be paying much attention to the threat of EMI. The Food and Drug Administration (FDA), however, recognized the threat posed by EMI. The issue of compliance became a concern when the European Union (EU), through its EMC Directive 89/336/EEC, imposed emissions and immunity requirements. Another forcing function of EMC compliance is the increasing role played by electronics in power conversion, communications, and control systems where electromechanical systems once were primarily used. Since a lot of things are now done electronically that once were not, the opportunities and consequences of EMC are much greater. Because of this issue, a lot of people have had to deal with EMC for only 20 years, whereas the military, NASA, and RF engineers have been dealing with this issue from day one.

EMC is now a major factor in the design of all electrical products; emissions, and immunity. Digital logic has fallen below the 1-nanosecond edge rate, while clock frequencies approach 1 GHz.

1.5 POTENTIAL EMI/RFI EMISSION LEVELS FOR UNPROTECTED PRODUCTS

The complexity of a product is dependent on processing speed and other factors. The more complex a product is, the more likely it will both radiate and be susceptible to RF energy. This is shown in Table 1.1. This table defines a matrix in which product size and complexity are plotted against processing speed.

In the upper left corner of the table, products with processing speeds of less than 10 MHz are commonly found. As we proceed toward the bottom right corner, systems are much faster and more complex. These high-technology systems include RISC (Reduced Instruction Set Computing) CPUs, Pentium[1] processors, and similar products. Most of these products have edge rates in the sub-nanosecond range and operate above 100 MHz.

1.6 METHODS OF NOISE COUPLING

A product must be designed for two levels of performance: one is to minimize RF energy exiting an enclosure (emissions), and the other is to minimize the amount of RF energy entering the enclosure (susceptibility or immunity). Both emissions and immunity travel by either radiated or conductive paths. This relationship is shown in Fig. 1.6.

---

[1] Pentium is a registered trademark of Intel Corporation.

TABLE 1.1 Matrix of Potential Emission Levels for Various Products

	Product size/complexity		
Processing speed	Low Single board	Medium Mother/daughter board	Large Multiple modules
Slow < 10 MHz	Low	Medium	Large
Medium 10 MHz < f < 100 MHz	Medium	Medium to high	High to very high
High > 100 MHz	High	High to very high	Very high

To further examine coupling paths, it must be realized that the propagation path contains multiple transfer mechanisms. These are detailed in Fig. 1.7 and include

1. Direct radiation from source to receptor (path 1).
2. Direct RF energy radiated from the source transferred to AC mains cables or signal/control cables of the receptor (path 2).
3. RF energy radiated by AC mains, signal, or control cables from source to receptor (path 3).
4. RF energy conducted by common electrical power supply lines or by common signal/control cables (path 4).

In addition to the four coupling paths, there are four transfer mechanisms that exist for each coupling path. These four mechanisms are [5]

1. Conductive.
2. Electromagnetic.
3. Magnetic field (subset of electromagnetic identified separately in Fig. 1.7).
4. Electric field (subset of electromagnetic identified separately in Fig. 1.7).

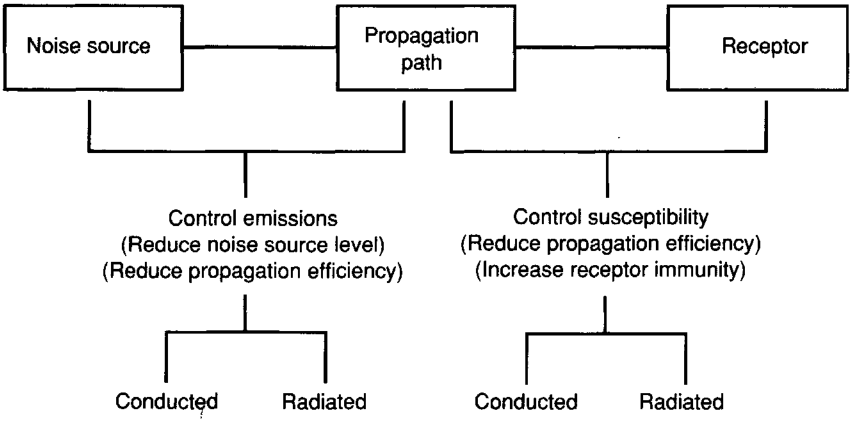

Figure 1.6 Coupling paths.

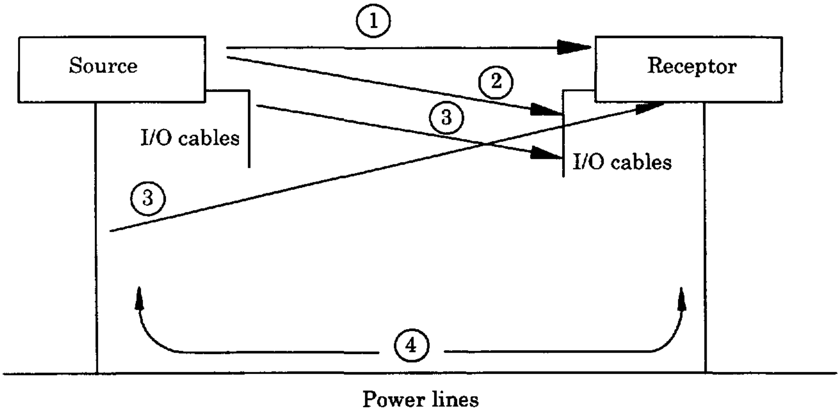

Figure 1.7 Coupling path mechanisms.

If the noise coupling mechanism can be ascertained, a logical solution can be determined to reduce the coupling.

Conductive coupling is identified as common impedance coupling. This coupling occurs when both noise source and susceptible circuits are connected by a mutual impedance. A minimum of two connections is required. This is because the noise current must flow from a source to load and then return to the source. Figure 1.8 illustrates two circuits and a power source. Current from each circuit flows through both the shared impedance of the power subsystem and interconnect wiring, all caused by shared metallic connections. For this figure, the shared connection is the return line.

Magnetic coupling occurs when a portion of magnetic flux created by one current loop passes through a second loop formed by another current path. Magnetic flux coupling is represented by mutual inductance between the two loops. The noise voltage inducted in the second loop is $V_2 = M_{12}dI_1/dt$, where M_{12} = mutual coupling factor and dI_l/dt = the time rate of change of current in the trace. Magnetic flux coupling is shown in Fig. 1.9.

Electric field coupling occurs in low-impedance circuits. The effects are small relative to other coupling that may occur. In a circuit there is mutual capacitance if we have high Z_S in parallel with Z_L (see Fig. 1.10). Capacitive coupling occurs when a portion of the electric flux created by one circuit terminates on the conductors of another circuit. Electric flux coupling between two circuits can be represented by mutual capacitance. The noise current injected into the susceptible circuit is approximately $I = CdV/dt$.

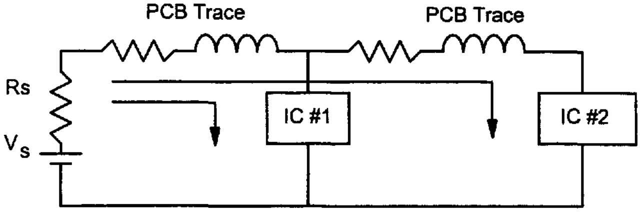

Figure 1.8 Conductive transfer mechanism.

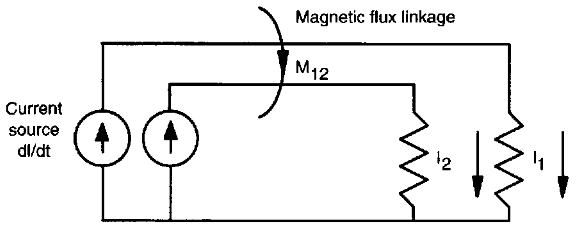

Figure 1.9 Magnetic field coupling.

Electromagnetic field coupling is a combination of both magnetic and electric fields affecting a circuit simultaneously. Depending on the distance between source and susceptor, the electric field (***E***) and magnetic field (***H***) effects may be different, depending on whether we are in the near field or far field. This is the most common transfer mechanism observed.

When dealing with emissions, the general rule of thumb is:

> The higher the frequency, the greater the efficiency of there being a radiated coupling path; the lower the frequency, the greater the efficiency that a conducted coupling path will be the cause of EMI. The probability of coupling is "1." The extent of coupling depends on frequency.

The most overlooked noise coupling method is through a conductor, a wire, or a PCB trace. This conductor may pick up RF noise from a culprit device and transfer this noise to a victim circuit. The easiest way to prevent this transfer from occurring is either to remove the noise from the culprit trace or to prevent the victim trace from receiving this RF energy.

What happens to a signal that is propagating down a PCB trace from source to destination? Figure 1.11 illustrates a model of one propagation path. The signal line connects directly between a source and a destination. With this circuit we have both inductive coupling (L) and capacitive coupling (C) between adjacent circuits.

Looking at Fig. 1.11, notice that the output capacitance siphons off a certain percentage of output drive current. The inductance of the line attenuates the signal, which also couples to adjacent traces. The capacitance between signal traces also shunts RF energy in addition to corrupting the signal through crosstalk. Finally, the capacitance of the load shunts energy away from the input source. The load capacitance thus couples the electromagnetic signal energy to ground.

If the signal trace is long compared to the rise time of the signal, distributed effects are observed.[2] Energy, which has been propagating down the trace with a characteristic

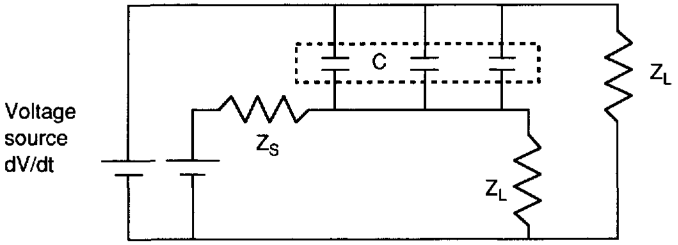

Figure 1.10 Electric field transfer coupling.

---

[2] An electrically long trace is defined as a routed trace containing a signal with an edge rate that is faster than the time it takes for a signal to travel from source to load, and return from load to source, causing functionality concerns that include ringing and reflections.

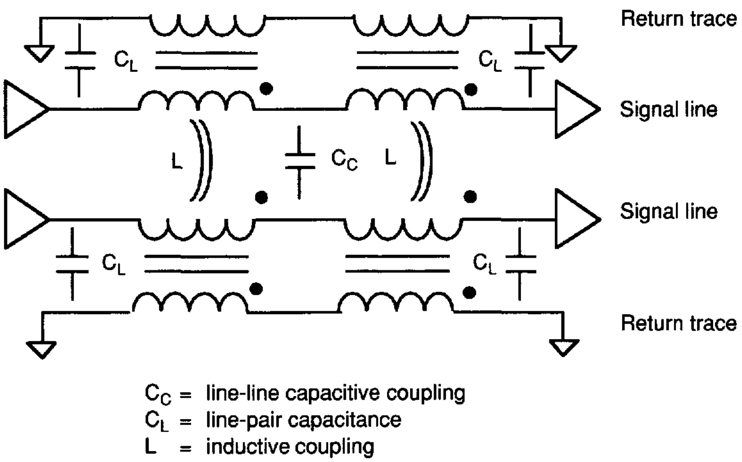

Figure 1.11 Coupling model for traces.

impedance Z_o, will arrive at the load. If the load impedance, Z_o, is the same as the source impedance, all energy will be absorbed in the load. If the load impedance is high, the signal will reflect back to the source since the signal cannot be consumed by the circuit. This reflection can be identified as ringing or over/undershoots. Transfer impedance, both inductive and capacitive, also exists inside components (Chapter 3). Internal ground bounce further degrades the quality of the transmitted signal (Chapter 7).

1.7 NATURE OF INTERFERENCE

Interference can be grouped into two categories, internal and external. The internal problem can be due to signal degradation along the transmission path along with parasitic coupling between adjacent circuits, in addition to field coupling between internal subassemblies, such as a power supply to a disk drive. Stated more specifically, the problems are signal losses and reflections along the path and crosstalk between adjacent signal traces.

External problems are divided into emissions and susceptibility concerns. Emissions are primarily from harmonics of clocks or other periodic signals. Remedies concentrate on containing the periodic signals to as small an area as possible and blocking the parasitic coupling paths to the outside world.

Susceptibility to external influences, such as ESD or radio frequency interference, are related primarily to energy which couples onto I/O lines and then becomes transferred to the inside of the unit. The principal recipients are high-speed input lines and sensitive adjacent traces, particularly those terminated with edge-triggered devices.

There are five major considerations in EMC analysis [2].

1. *Frequency.* Where in the frequency spectrum is the problem observed?
2. *Amplitude.* How strong is the source energy level, and how great is its potential to cause harmful interference?

3. *Time.* Is the problem continuous (periodic signals), or does it exist only during certain cycles of operation (e.g., disk drive write operation)?
4. *Impedance.* What is the impedance of both the source and receptor units and the impedance of the transfer mechanism between the two?
5. *Dimensions.* What are the physical dimensions of the emitting device that can cause emissions to occur? RF currents will produce electromagnetic fields that will exit an enclosure through chassis leaks that equal significant fractions of a wavelength or significant fractions of a "rise-time distance." Trace lengths on a PCB have a direct relationship as transmission paths for RF currents.

Whenever an EMI problem is approached, it is helpful to review the above list based on product application. Understanding these five items will remove much of the mystery of how EMI exists within a PCB. Applying these five major considerations teaches that design techniques make sense in certain contexts but not in others. For example, single-point grounding is excellent when applied to low-frequency applications but is completely inappropriate for radio frequencies, which is where most of the EMI problems exist. Many engineers blindly apply single-point grounding for all product designs without realizing that additional and more complex problems are created using this grounding methodology.

How does one make use of the above list? It is common to think of a current source being created from a voltage applied across an impedance (Thevenin equivalent). It is, however, more advantageous to consider voltage as a result of current traveling through an impedance (Norton equivalence). Using the Norton network, many EMI questions are answered as it is easier to visualize EMI using the Norton configuration. *E*-field coupling involves the induction of common-mode voltage sources, whereas *H*-field coupling can end up with either common- or differential-mode currents (depending on victim wiring).

Current is preferable to voltage for a simple reason: current always travels around a closed-loop circuit following one or more paths. It is to our advantage to direct or steer this current in the manner that is desired for proper system operation. To control the path that current flows, we must provide a low-impedance RF return path back to the original source of interference. We must also divert interference current away from the load. For those applications that require a high-impedance path from source to the load, we must consider all possible paths through which the return currents may travel.

1.7.1 Frequency and Time (à la Fourier: time domain ⇔ frequency domain)

It is common for design engineers to think in terms of the time frame. EMI is generally viewed in a frequency frame. RF energy is a periodic wave front that propagates through various mediums. Different wavelengths of the sine wave are recorded as EMI for those products that are not designed to be intentional radiators. It is difficult to understand an EMI problem in the time domain alone. (Conversion between the time and frequency domain is detailed in Appendix B using Fourier analysis.)

Baron Jean Baptiste Joseph Fourier (1768–1830), a French mathematician and physicist, formulated a method for analyzing periodic functions. Fourier proved that any periodic waveform can be decomposed into an infinite series of sine waves, each at an integral multiple or harmonic of a fundamental frequency. The composition of the harmonics is determined during a mathematical operation known as a Fourier transform. Fourier transforms can easily be calculated for simple waveforms and displayed with modern instrumentation.

1.7.2 Amplitude

The impact of amplitude is obvious. The higher the amplitude, the more interference one may encounter. It becomes important to limit the peak amplitude of the RF energy to only that necessary for circuit, device, and system performance.

1.7.3 Impedance

If both source and receptor are not the same impedance, one should expect greater interference problems than a source and receptor with identical impedance. This is because, for example, high-impedance sources can have minimal impact on low-impedance receptors and vice versa. Similar rules apply to radiated coupling. High impedances are associated with electric fields. Low impedances are associated with magnetic fields.

1.7.4 Dimensions

Physical dimensions play a significant factor related to the wavelength of an RF wave. When dealing with physical dimensions of a PCB trace, or the slot (aperture) opening of an enclosure, this aspect of EMC comes into view. Circuit analysis can no longer be assumed with lumped circuit parameters if numerical modeling is used during the design cycle.

The need to minimize the physical length of a trace or aperture opening relates to the electrical parameters of high-speed digital devices. When the speed of propagation becomes a significant portion of the propagational delay from source to load, we start to observe effects where field coupling becomes noticeable. When the trace length becomes physically long relative to a wavelength of a particular frequency, or in time domain terms, when the rise time becomes less than the propagational delay between source and load, the trace assumes the characteristics of a transmission line. All transmission lines must be terminated in their characteristic impedance for optimal transfer of the signal. While this practice is related primarily to preserving signal integrity, it also helps to control EMI.

Regarding EMI, we must concern ourselves with preventing creation of an antenna by having a PCB trace (or wire) approach a dimension that is the same as the offending source. When the trace approaches a particular wavelength of the offending signal (or portion of a wavelength), an efficient antenna will exist.

1.8 PCBs AND ANTENNAS

A PCB can act as an antenna to radiate RF energy through free space or couple through a cable interconnect. When we talk about the PCB acting as an antenna, what exactly do we mean? An antenna is an efficient and integral part of radio frequency communication. We need antennas to operate as intentional radiators. Most PCBs act as an unintentional radiator and are regulated by international EMC requirements unless design requirements include it as being a transmitter. Transmitters are regulated by regulatory requirements. If the PCB is an efficient unintentional radiator and suppression techniques cannot be implemented, containment measures must be provided.

Antennas exhibit various efficiencies as a function of frequency, whether intentional or accidental. When an antenna is driven by a voltage source, its impedance varies dramatically. When an antenna is in resonance, its impedance will be high and mostly reactive. The resistive portion (R) of the impedance equation ($Z = R+j\omega L$) is called "radiation resistance." This radiation resistance is a measure of the antenna's propensity to radiate RF energy at a specific frequency.

Most antennas are efficient radiators at a specific frequency spectrum. These frequencies are typically below 200 MHz, because I/O cables are approximately 2 to 3 meters in length and are sometimes long relative to a wavelength. At higher frequencies, significant radiation is generally observed directly from the unit due to the contribution of apertures in the enclosure.

When it is possible to isolate where the antenna exists, as in common-mode cable radiation, a reduction in the drive voltage is the easiest suppression technique to implement. RF voltages exist because of

- Impedance of circuit traces (which in turn is derived from lead inductance).
- Ground bounce (a point of uniform potential).
- Bypassing or shielding with respect to ground to reduce the drive voltage available to the unintentional antenna.

A schematic representation of an antenna is shown in Fig. 1.12. The antenna presents a specific impedance to the source driver that varies with frequency. At resonance, the reactive components, L and C, cancel out. Radiation resistance is maximum. RF energy is thus radiated.

To minimize the effects of an unwanted antenna existing in a PCB, EMC design and suppression techniques are required. These include establishing a good ground system in the layout in addition to the use of a Faraday cage (to contain RF emission). RF filters also reduce unwanted RF signals with minimal effects on the desired data, as long as the filter is properly chosen for its intended function.

1.9 CAUSES OF EMI—SYSTEM LEVEL

This book deals with the concepts that cause or are related to the creation of EMI within a PCB. A product is not complete without mentioning other aspects of a design that affects compliance. These other aspects are associated with system-level design. Detailed discus-

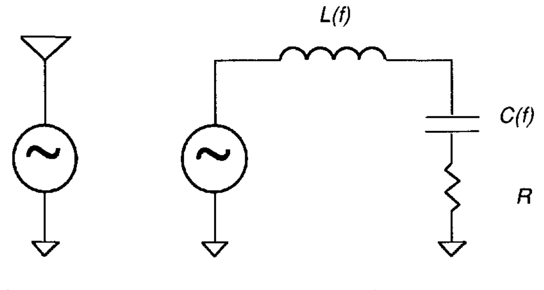

Figure 1.12 Representation of an antenna. Antenna Equivalent circuit of an antenna

sion of the following is beyond the scope of this book; the focus is on PCBs. Excellent reference material is provided in the References sections for those interested in other aspects of EMC system-level design.

The most common areas of concern for system-level EMC compliance involve

- Improper use of containment measures (metal versus plastic housing)
- Poor design, implementation, and grounding of cables and connectors
- Incorrect PCB layout (includes)
    1. clocks and periodic signal trace routing
    2. stackup arrangement of the PCB and signal routing layer allocation
    3. selection of components with high spectral RF energy distribution
    4. common-mode and differential-mode filtering
    5. ground loops
    6. insufficient bypassing and decoupling

To implement system-level suppression, the following techniques are generally required:

- Shielding
- Gasketing
- Grounding
- Filtering
- Decoupling
- Proper trace routing
- Isolation and separation
- Circuit impedance control
- I/O interconnect design
- PCB suppression techniques designed internal to a component package

Even with all of these items, multiple techniques of both suppression and containment to achieve a compliant product can be required. Depending on the complexity of the system, speed of operation, and EMC requirements where shielding is needed, proper PCB layout will minimize shielding requirements.

1.10 SUMMARY FOR CONTROL OF ELECTROMAGNETIC RADIATION

In order to reduce or eliminate the potential for electromagnetic radiation, several basic concepts must be understood. These are listed below and detailed in later chapters.

1. Reduce the intensity of the RF source (voltage and current drive levels).
2. Provide differential- and common-mode filtering for high-speed signals or use balanced differential pairs with impedance-matched signals.

3. Reduce the energy being coupled to the antenna structure; use self-shielded trace routing and reduce differential-mode to common-mode conversion.
4. Reduce the effectiveness of the antenna's propensity to radiate RF energy.

High-frequency currents on an antenna are necessary to cause electromagnetic radiation. These RF currents can be reduced by differential-mode filtering and slowing down the edge rate of digital logic devices. We can reduce the conversion of differential-mode (DM) to common-mode (CM) currents by improving the impedance balance of the circuit. Since we generally cannot control the length of an external I/O cable, reducing the length of one-half of the antenna will make this radiator less efficient.

For RF energy to exist, there must be a voltage reference difference between two circuits. As a result, maintaining all metal structures (ground planes, ground traces, chassis, etc.) at a uniform or equivalent potential eliminates this voltage reference difference. This voltage reference difference is often due to inductance within the circuit and structure. Regardless of how well we design a product, a finite amount of inductance will always be present. If this inductance is added to the antenna structure, along with mutual capacitance, the antenna becomes an efficient radiator. A few nano-Henries (nH) of inductance or a few pico-Farads (pF) of capacitance are significant at higher frequencies, related to RF emissions.

REFERENCES

[1] Montrose, M. I. 1996. *Printed Circuit Board Design Techniques for EMC Compliance.* Piscataway, NJ: IEEE Press.

[2] Gerke, D., and W. Kimmel. 1994. "The Designers Guide to Electromagnetic Compatibility." EDN (January 20).

[3] Mardiguian, M. 1993. *Controlling Radiated Emissions by Design.* New York: Van Nostrand Reinhold.

[4] Van Doren, T. 1995. *Circuit Board Layout to Reduce Electromagnetic Emission and Susceptibility.* Seminar Notes.

[5] Hartal, O. 1994. *Electromagnetic Compatibility by Design.* W. Conshohocken, PA: R&B Enterprises.

[6] Ott, H. 1988. *Noise Reduction Techniques in Electronic Systems.* 2nd ed. New York: John Wiley & Sons.