Printed Circuit Board Design Techniques for EMC Compliance

Mark I. Montrose

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To
Margaret,
Maralena, and
Matthew
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Preface

This design guide is presented to assist in printed circuit board design and layout, with the intent of meeting North American and international EMC compliance requirements. Many different layout design methodologies exist. This technical guide illustrates generally applicable layout methods for EMC compliance. Implementation of these methods may vary for a particular printed circuit board design.

The intended audience for this guide is engineers who design electronic products that use printed circuit boards. These engineers may focus on analog, digital, or system-level boards.

Regardless of their specialties, all engineers must produce a design that is suitable for actual production. Frequently, more emphasis is placed on functionality of the design than on overall system integration. System integration is usually assigned to product engineers, mechanical engineers, or others within the organization. Design engineers must now consider other aspects of product design, including the layout and production of printed circuit boards for EMC, which includes cognizance of the manner in which the electromagnetic fields transfer from the circuit boards to the chassis and/or case structure.

Not only must a design work properly, it must also comply with international regulatory requirements. Engineers who specialize in regulatory issues must evaluate products based on different standards. This guide presents techniques that will alleviate existing conflicts among various layout methods.

A great deal of technical information related to printed circuit board design and layout is available commercially as well as from public-domain documents. Typically, these sources provide only a brief discus-
sion on how to implement a layout technique to solve an EMI problem (selected sources are listed in the Bibliography).

The guide itself is derived from lecture notes used to present EMC and printed circuit board layout information to engineers. The principles should prove useful for engineers in a variety of functions, including electrical and mechanical design, CAD/CAE, engineering and production test, manufacturing, and other fields.
Thanks to William (Bill) Kimmel and Daryl Gerke of Kimmel Gerke Associates, Ltd., St. Paul, Minnesota; Todd Hubing, University of Missouri; and Doug Smith, AT&T Bell Laboratories who provided technical review of the material for content and accuracy in addition to pointing out different aspects of printed circuit board design techniques not covered in my earlier drafts.

A special acknowledgment is given to Mr. W. Michael King of Costa Mesa, California, for his expertise, technical review, friendship, and encouragement without which I would never have achieved the technical knowledge to write this book.

My very special acknowledgment is to my wife, Margaret, and my two children, Maralena and Matthew, who tolerated my late night work and long hours at the keyboard. Without their understanding and support, this book could never have been written.

Mark I. Montrose  
Santa Clara, California
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Introduction

Printed Circuit Board Design Techniques for EMC Compliance is designed to help engineers minimize electromagnetic emissions generated by components (and circuits) to achieve acceptable levels of electromagnetic compatibility (EMC). It addresses both major aspects of EMC, which are

1. Emissions: Propagation of electromagnetic interference (EMI) from noncompliant devices (culprits), and in particular radiated and conducted radio frequency interference (RFI)

2. Susceptibility: The detrimental effects on susceptible devices (victims) of EMI in forms that include electrostatic discharge (ESD) and other forms of electrical overstress (EOS)

The engineer’s goal is to meet design requirements to satisfy both international and domestic regulations and voluntary industry standards.

The information presented in this volume is focused on “non-EMC” engineers who design and lay out printed circuit boards (PCBs). EMC engineers will also find the information helpful in solving design problems at the PCB level. This guideline is applicable as a reference document throughout any design project.

Circuit technology is advancing rapidly, and design techniques that worked several years ago are no longer effective in today’s high-speed digital products. Because EMC is insufficiently covered in engineering schools, training courses and seminars are held throughout the country to provide this information. As such, there is a widespread need for introductory material. With this in mind, Printed Circuit Board Design Tech-
Printed Circuit Board Design Techniques for EMC Compliance

is written for engineers who never studied applied electromagnetics in school or who have limited hands-on experience with high-speed, high-technology printed circuit board design as it specifically relates to EMC compliance.

A minimal amount of mathematical analysis is presented herein. It is the intent of this guideline to describe hands-on techniques that have been successfully applied to many real-world products. Data is presented in a format that is easy to understand and implement. Those interested in Maxwell’s equations or the more highly technical aspects of PCB design theory will find a list of appropriate materials in the bibliography.

The focus of this guideline is strictly on the printed circuit board. Discussion of containment techniques (box shielding), internal and external cabling, power supply design, and other system-level subassemblies that use printed circuit boards as subcomponents will not be thoroughly discussed. Again, excellent reference material is listed in the bibliography on these aspects of EMC system design engineering.

Controlling emissions has become 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 on the printed circuit board than to “build a better box.” Containment measures are not always economically justified and may degrade as the EMC life cycle of the product is extended beyond the original design specification. For example, end users often remove covers from enclosures for ease of access during repair or upgrade. Sheet metal covers (particularly internal subassembly covers that act as partition shields) in many cases are never replaced. 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 are compromised. Proper layout of a printed circuit board with suppression techniques also assists in EMC compliance at the level of cables and interconnects, whereas box shielding (containment) does not.

While it is impossible to anticipate every application or design concern possible, this book provides details on how to implement a variety of design techniques for most applications. The concepts presented are fundamental in nature and are applicable to all electronic products. While every design is different, the basic fundamentals of product design rarely change, and EMC theory is constant.

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 experience in the marketplace related to emission and immu-
nity complaints. Often, these same techniques will aid in improving signal quality and signal-to-noise performance.

This text discusses high-technology, high-speed designs that require new and expanded techniques for EMC suppression at the PCB level. Many techniques that were used successfully several years ago are now less that effective for proper signal functionality and compliance. Components have become faster and more complex. Use of custom gate array logic and ASICs presents new and challenging opportunities for EMC engineers. The design and layout of a printed circuit board for EMI suppression at the source must always be optimized while maintaining system-wide functionality.

### 1.1 FUNDAMENTAL DEFINITIONS

The following basic terms are used throughout this book:

*Electromagnetic compatibility (EMC)—The ability of a product to coexist in its intended electromagnetic environment without causing or suffering functional degradation or damage.*

*Electromagnetic interference (EMI)—A 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)—The frequency range within which coherent electromagnetic radiation is useful for communication purposes—roughly from 10 kHz to 100 GHz. This energy may be generated intentionally, as by a radio transmitter, or unintentionally as a byproduct of an electronic device’s operation. RF energy is transmitted through two basic modes:

- *Radiated emissions (RE)—The component of RF energy that is transmitted through a medium as an electromagnetic field. RF energy is usually transmitted through free space; however, other modes of field transmission may occur.*

- *Conducted emissions (CE)—The component of RF energy that is transmitted through a conductive medium as an electromagnetic field, generally through a wire or interconnect cables. Line conducted interference (LCI) refers to RF energy in a power cord.*

*Susceptibility—A relative measure of a device or system’s propensity to be disrupted or damaged by EMI exposure.*
Immunity—A relative measure of a device or system’s ability to withstand EMI exposure.

Electrical overstress (EOS)—Damage or loss of functionality experienced by an electronic device as a result of a high-voltage pulse. EOS includes lightning and electrostatic discharge events.

Electrostatic discharge (ESD)—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 this text, lightning will be included in the overall ESD category because the protection techniques are very similar, although differing in magnitude.

Radiated susceptibility—The relative inability of a product to withstand EMI that arrives via free-space propagation.

Conducted susceptibility—The relative inability of a product to withstand electromagnetic energy that reaches it through external cables, power cords, and other I/O interconnects.

Containment—Preventing RF energy from exiting an enclosure, generally by shielding a product within a metal enclosure (Faraday cage) or by using a plastic housing with RF conductive paint. By reciprocity, we can also speak of containment as preventing RF energy from entering the enclosure.

Suppression—Designing a product to reduce or eliminate RF energy at the source without relying on a secondary method such as a metal housing or chassis.

The next section discusses the nature of EMC, its relation to printed circuit boards, and the legal mandates for EMC compliance.

1.2 EMC AND THE PRINTED CIRCUIT BOARD

Traditionally, EMC has been considered an art of “black magic.” In reality, EMC can be explained by mathematical concepts. Some of the relevant equations and formulas are complex and beyond the scope of this design guideline. Fortunately, simple models can be formulated to describe how and why EMC can be achieved.

Many variables exist in the creation of EMI. This is because EMI is often the result of exceptions to the normal rules of passive component behavior. A resistor at high frequencies acts like a series combination of inductance with resistance in parallel with a capacitor. A capacitor at high
frequency acts like an inductor and resistor in a series-parallel combination with a capacitor. An inductor at high frequencies performs like an inductor and capacitor in parallel. An illustration [1] of these abnormal behaviors of passive components at both high and low frequencies is shown in Fig. 1.1.

These behavioral characteristics are referred to as the “hidden schematic.” Digital engineers generally assume that components have a single frequency response. As a result, passive component selection is based on functional performance in the time domain without regard to the real characteristics exhibited in the frequency domain. Many times, EMI exceptions occur if the designer bends or breaks the rules, as seen in Fig. 1.1.

To restate the complex problems that exist, consider the field of EMC as “everything that is not on a schematic or assembly drawing.” This statement is why the field of EMC is sometimes considered to be an art of black magic.

Once the hidden behavior of components is understood, it becomes a simple process to design products with circuit boards that pass EMC requirements. Hidden behavior also takes into consideration the switching speed of active components along with their unique characteristics, which also may have hidden resistive, capacitive, and inductive components.

Designing products that will pass legally required EMI tests is not as difficult as one might expect. Engineers strive to design elegant products, but elegance sometimes must give way to other engineering considerations such as product safety, manufacturing cost, and, of course, EMC. Such abstract problems can be challenging, particularly if the engineer is

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**Fig. 1.1** Component Characteristics at RF Frequencies (Source: Designers Guide to Electromagnetic Compatibility, *EDN*. © 1994, Cahners Publishing Co. Reprinted by permission.)
unfamiliar with the types and levels of compliance required. The general guidelines offered in this book will remove the mystery from the “hidden schematic.”

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

1. a source of energy
2. a receptor that is disrupted by this energy
3. a coupling path between the source and receptor

For interference to exist, all three elements must be present. If one of the three elements is removed, there is no interference. It therefore becomes our first task to determine which is the easiest element to remove. Generally, designing a printed circuit board that eliminates most sources of RF interference is the most cost-effective approach (called suppression). The second and third elements tend to be addressed with containment techniques. Figure 1.2 illustrates the relationship between these three areas and presents a list of products typically associated with each element.

A product must be designed for two levels of performance: one to minimize RF energy exiting an enclosure (emissions), and the other to minimize the amount of RF energy entering the enclosure (susceptibility or immunity). In both cases, there are considerations of radiated and conducted EMI. This relationship is shown in Fig. 1.3.

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

The higher the frequency, the greater the likelihood of a radiated coupling path; the lower the frequency, the greater the likelihood of a conducted coupling path.

There are five major considerations in EMI analysis, as enumerated below:

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 (clock signals), or does it exist only during certain cycles of operation (i.e., 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
5. **Dimensions.** What are the physical dimensions of the emitting device? RF currents will exit an enclosure through chassis leaks that equal fractions of a wavelength or significant fractions of a “rise-time distance.” Trace lengths on a printed circuit board are also transmission paths for RF currents.

Regarding impedance, if both source and receptor have the same impedance, one should expect greater emission problems than if the source and receptor have different impedances. This is because high-impedance sources have minimal impact on low-impedance receptors, and vice-versa. Similar rules apply to radiated coupling. High impedances
are associated with electric fields, whereas low impedances are associated with magnetic fields.

1.3 NORTH AMERICAN REGULATORY REQUIREMENTS

Electrical and electronic products generate RF energy. Emission levels are set by rules and regulations as mandated by national and international organizations. In the U.S.A., the Federal Communications Commission (FCC) regulates radio and wire communications. In Canada, the Department of Communication (DOC) performs the same function. Internationally, each country has a designated agency within its government to oversee all aspects of communication.

The FCC regulates electronic products by specifying technical standards and operational requirements in the Code of the Federal Regulations (CFR), Title 47. The sections applicable to products discussed herein are Parts 15, 18, and 68. These regulations have been developed over many years and are based on complaints files with the Commission. The most prominent are listed below. In Canada, the specification equivalent to CFR 47, Part 15 is SOR 88/475.

1. Part 15 is applicable to unlicensed radio-frequency radiating devices (both intentional and unintentional). Information technology equipment (ITE) falls within Part 15.
2. Part 18 regulates industrial, scientific, and medical (ISM) equipment. These devices use radio waves for normal operation.
3. Part 68 regulates electronic equipment connected to a telephone
network. This Part provides a uniform standard to protect the tele-
phone network from harm caused by terminal equipment con-
nected to it.

The FCC and DOC define a digital device as:

An unintentional radiator (device or system) that generates and
uses timing signal pulses at a rate in excess of 9,000 pulses
(cycles) per second and uses digital techniques; inclusive of
telephone equipment that uses digital techniques or any device
or system that generates and utilizes radio frequency energy
for the purpose of performing data processing functions, such
as electronic computations, operations, transformation, record-
ing, filing, sorting, storage, retrieval or transfer.

Digital computing products are classified into two Categories: Class A and
B. The FCC and DOC use the same definitions:

Class A: A computing device that is marketed for use in a commercial,
industrial, or business environment, exclusive of a device which is
marketed for use by the general public or is intended to be used in the
home.

Class B: A computing device that is marketed for use in a residential
environment, notwithstanding its use in a commercial, industrial or
business environment.

If a product contains digital circuitry and has a clock frequency greater
than 9 kHz, it is defined as a digital device and is subject to rules and reg-
ulations of the FCC and DOC. Electromagnetic interference may occur
due to both time-domain and frequency-domain components of both digi-
tal and analog circuits. These products are subject to both domestic and
international regulations.

The FCC and DOC regulate conducted emissions on power cords (line
conducted interference) from 450 kHz to 30 MHz. Radiated emissions are
measured from 30 MHz to 1000 MHz.

1.4 WORLDWIDE REGULATORY
REQUIREMENTS

Harmonization of test requirements, standards, and procedures is being
implemented on a worldwide basis. Principles discussed herein will allow
regulatory compliance to be achieved with minimal development costs and shorter design cycles. The harmonization process is based on the work of an expert technical committee run by the Committee for European Electrotechnical Standardization (Comité Européen de Normalisation Electrotechnique, or CENELEC). CENELEC adopts standards developed by the International Special Committee on Radio Interference (Comité International Spécial des Perturbations Radioélectriques, or CISPR). CISPR is not a regulatory authority; it oversees the work of the International Electrotechnical Commission (IEC). The IEC is a subcommittee of CISPR. The IEC issues recommendations to CISPR for adoption. CISPR presents these recommendations to CENELEC which, in turn, sends them on to the European Parliament for adoption. Once adopted by the European Parliament, it is the responsibility of each member country of the European Union (EU) to adopt these requirements into their national law.

It is common to refer to international specifications as CISPR when, in fact, the real standards, after adoption and publication by the European Parliament, are prefixed with an EN number (European Normalisation). To summarize, the European Parliament places into law requirements developed by CISPR and other European working groups and committees under the auspices of CENELEC.

This book focuses on products that fall within the category of information technology equipment and are covered by EN 55 022. CISPR regulates conducted emissions on power cords from 150 kHz to 30 MHz. Radiated emissions are measured from 30 MHz to 1000 MHz.

The most commonly referenced CISPR test standards for products that contain printed circuit boards are listed below. This book is applicable to these commonly referenced standards. Many other test standards exist. This list is subject to periodic change due to continuing development in standards writing, along with continuing harmonization within the European Union (EU). The EU was formerly known as the European Community (EC) or European Economic Community (EEC). This list is current at date of publication.

EN 50 081-1: 1992
Electromagnetic compatibility generic emission standard—Part 1: Residential, commercial and light industry

EN 50 081-2: 1994
Electromagnetic compatibility generic emission standard—Part 2: Heavy industrial environment
EN 50 082-1: 1993
Electromagnetic compatibility generic immunity standard—Part 1:
Residential, commercial and light industry

EN 50 082-2: 1994
Electromagnetic compatibility generic immunity standard—Part 2:
Heavy industrial environment

EN 55 011: 1991
Limits and methods of measurements of radio disturbance character-
istics of industrial, scientific and medical (ISM) radio-frequency
equipment (CISPR 11: 1990 ed. 2)

EN 55 013: 1993
Limits and methods of measurements of radio disturbance character-
istics of broadcast receivers and associated equipment (CISPR 13: 1975 ed. 1 + Amendment 1: 1992)

EN 55 014: 1993
Limits and methods of measurements of radio disturbance character-
istics of household electrical appliances, portable tools and similar
electrical apparatus (CISPR 14: 1993 ed. 3)

EN 55 020: 1993
Limits and methods of measurements of radio disturbance character-
istics of broadcast receivers and associated equipment (CISPR 20: 1990 ed. 2 + Amendment 1: 1990)

EN 55 022: 1987
Limits and methods of measurements of radio disturbance character-
istics of information technology equipment (CISPR 22: 1985 ed. 1)

Products are classified into two categories of emissions: Class A and Class B. CISPR defines these categories as:

Class A: Equipment is information technology equipment if it satisfies
the Class A interference limits but does not satisfy the Class B limits. In
some countries, such equipment may be subjected to restrictions
on its sale and/or use.
(Note: The limits for Class A equipment are derived for typical com-
mercial establishments for which a 30 m protection distance is used. The
class A limits may be too liberal for domestic establishments and
some residential areas).

Class B: Equipment is information technology equipment if it satisfies the
Class B interference limits. Such equipment should not be subjected
to restrictions on its sale and is generally not subject to restrictions on
its use.
(Note: The limits for Class B equipment are derived for typical domestic establishments for which a 10 m protection distance is used).

Limits for European standards are similar but different from the North American requirements. Appendix B illustrates the specification limits for FCC/DOC (Part 15/SOR 88/475) and various international standards in both tabular and graphical format.

European standards for susceptibility (immunity) are provided in the IEC 1000-4-X series. This series describes the test and measurement methods of basic standards. Basic standards are specific to a particular type of EMI phenomenon. It is not limited to a specific type of product. Internal to this series are the following:

- terminology
- descriptions of the EMI phenomenon
- instrumentation
- measurement and test methods
- ranges of severity levels with regard to the immunity of the equipment

The IEC 1000-4-X series is based on the well known IEC 801-X requirements. The main difference is in the title and publication number. Future changes in technical requirements may be significant between the IEC 1000-4-X and the IEC 801-X series. IEC requirements were officially withdrawn from circulation and replaced with a newly designated series. The subparts of IEC 1000-4-X are listed below. As of the date of writing, only IEC 1000-4-2/3/4 are legally required for EMC compliance. It is anticipated that in the future, additional test standards and requirements will be mandatory. Currently, immunity tests are mandated in Europe, only recommended in North America, and optional worldwide.

- IEC 1000-1 General Considerations
- IEC 1000-2 Environment
- IEC 1000-3 Limits/Generic Standards
- IEC 1000-4 Test and Measurement Techniques
  - IEC 1000-4-1 Administrative Aspects of the Directive
  - IEC 1000-4-2 Electrostatic Discharge
  - IEC 1000-4-3 Radiated Susceptibility
  - IEC 1000-4-4 Electrical Fast Transients
IEC 1000-4-5 Surge Voltage Immunity
IEC 1000-4-6 Conducted Disturbance Induced by RF Fields Above 9 kHz
IEC 1000-4-7 Harmonics, Interharmonics and Instrumentation for Power Supply Systems
IEC 1000-4-8 Power Frequency Magnetic Field Immunity
IEC 1000-4-9 Pulsed-Magnetic Field Immunity
IEC 1000-4-10 Damped Oscillatory Magnetic Field
IEC 1000-4-11 Voltage Dips, Short Interrupts and Voltage Variations Immunity
IEC 1000-4-12 Oscillatory Waves

- IEC 1000-5 Installations and Mitigation Guideline
- IEC 1000-9 Miscellaneous

To summarize, the standards that are required now and in the future for compliance with the EMC Directive 89/336/EEC, amended in 1992, are contained in Table 1.1, even though some of these test standards have not yet been adopted and published. Until the test requirements are officially published in the European Official Journal, compliance is optional.

1.5 ADDITIONAL NORTH AMERICAN REGULATORY REQUIREMENTS

Table 1.1 International Emissions and Immunity Standards

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Immunity</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 55 022 (ITE) Information technology equipment</td>
<td>IEC 1000-4-2 ESD</td>
</tr>
<tr>
<td></td>
<td>IEC 1000-4-3 Radiated susceptibility</td>
</tr>
<tr>
<td></td>
<td>IEC 1000-4-4 Electrical fast transients</td>
</tr>
<tr>
<td>EN 55 014 (HHA) Household appliances, hand tools, and similar apparatus</td>
<td>IEC 1000-4-5 Lightning on power lines</td>
</tr>
<tr>
<td></td>
<td>IEC 1000-4-6 Conducted continuous wave</td>
</tr>
<tr>
<td></td>
<td>IEC 1000-4-8 Magnetic radiated fields</td>
</tr>
<tr>
<td>EN 55 011 (ISM) Industrial, scientific, and medical equipment</td>
<td>IEC 1000-4-11 Sags, surges, dropouts</td>
</tr>
<tr>
<td>EN 60 555-2 Power line harmonics</td>
<td></td>
</tr>
<tr>
<td>EN 60 555-3 Power line flicker</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates that the standard, as of the date of writing, is in draft form, published but not official, or not yet legally required as part of the EMC directive. The reader should verify the existence and status of a particular IEC 1000-4-X documents before implementing tests.
Other agency requirements in North America include those listed in Table 1.2. These standards are very specific and for the most part beyond the scope of this design guideline. The list is presented for completeness only, given that printed circuit boards are used in products covered by these standards.

### 1.6 SUPPLEMENTAL INFORMATION

In addition to compliance for EMC, requirements exist for product safety. These requirements include energy hazards and flammability. Many printed circuit boards are subject to high voltage and current levels that pose a possible shock hazard to the user. In addition, extensive current flow on traces generates heat, which can cause the fiberglass material used in the construction of the printed circuit board to burn and/or melt, with an associated risk of fire. Components and interconnects on a printed circuit board may also provide a source of fuel (combustible material) that may contribute to a fire hazard under abnormal fault conditions.

An important part of this design guide is the Appendix. Much technical information is contained in all the chapters. To assist during the actual layout of a printed circuit board, Appendix A, Summary of Design Techniques, provides a brief overview of items discussed, cross-referenced to their respective chapters. This summary may be used for quick review during the layout and design stage.

Appendix B is provided as a quick reference guide to international EMC specification limits for the United States and Canada (FCC/DOC), Europe, and worldwide, in addition to the European immunity limits.

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**Table 1.2 Additional North American Standards**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Subject Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDS-201-0004 FDA Standard for Medical Devices</td>
<td>Emissions and susceptibility in medical electronics</td>
</tr>
<tr>
<td>SAE J 551</td>
<td>Radiated EMI from vehicles and associated devices</td>
</tr>
<tr>
<td>NACSIM 5100 (a.k.a. TEMPEST)</td>
<td>Classified standard limiting emissions from certain products to be sufficiently low to prevent interception and deciphering data streams that contain intelligence</td>
</tr>
<tr>
<td>MIL-STD-461/462</td>
<td>U.S. military emission standards and test procedures, both radiated and conducted</td>
</tr>
</tbody>
</table>