Fundamentals of Electromagnetic Compliance

A Practical Overview of the Fundamentals of Electromagnetic Compliance

Introduction

Everyone enjoys the advantages of electronic devices and gadgets becoming smaller, lighter, and faster, while providing longer battery life and ever-improving processing ability. Smaller devices require smaller electronic components — an advantage in reducing electromagnetic interference (EMI). However, a compact design also means smaller spacing between components, circuit traces, and enclosures, which can lead to increased field interactions, current loops, ground loops, cross-talk, and other potential sources of EMI.

We benefit from the convenience of televisions, cell phones, digital tablets, notebook computers, and IoT devices, all operating at the same time while appliance motors, lights, fans, and HVAC units are operating in the background to keep us comfortable. With multiple electrical and wireless electronic devices operating at the same time, signals must remain reliable in electromagnetically-noisy environments.

The rapid growth of the electric vehicle (EV) and hybrid electric vehicle (HEV) market raises new electromagnetic compatibility (EMC) concerns as high-voltage batteries and chargers see increased use. High-voltage and high-frequency automotive electronics, if not properly designed, can lead to EMC compliance headaches. Focusing on design techniques that mitigate EMI will help ensure a low-emissions outcome.

High levels of electromagnetic (EM) noise leads to EMI, which is any undesired electrical disturbance (noise) that interferes with other circuits. Electromagnetic emissions occur when electrical or electronic equipment radiates or conducts EM noise that interferes with other devices. Electromagnetic compatibility is the ability of electronic equipment to function properly without interference from noise sources (immunity / susceptibility) and without causing disturbances to other electronic equipment (emissions).

EMC is verified by testing to industry standards developed by regulating agencies described later in this discussion. These standards define specific test conditions and limits of noise emissions that may vary by location, application, and operating environment.

Noise Sources

Noise might be of a transient or discontinuous nature, or it might be generated continuously. Potential sources of transient or discontinuous conducted emissions include automatic switches, temperature controllers, appliance controllers and other automatic controllers, motor controllers and any other non-constant or event-driven on/off switching of voltage. Potential sources of continuously conducted emissions include electric motors, unshielded or poorly-shielded data lines, switch-mode power converters, and any other constant steady-state switching of voltage. Improperly designed PCBs with power and signal areas too close together or having insufficient filtering can result in transient or steady state conducted emissions.

Modes of Electrical Noise Propagation

Noise is generally discussed as being either radiated or conducted. The solution to any noise problem requires identifying and understanding the nature of the noise. This can be complicated by interaction between radiating and conducting modes. After all, any conducted electricity has the potential to generate radiating fields, and likewise fields can cause electrical signals

Designing and testing for EMC involves understanding how electric fields (E-fields) and magnetic fields (B-fields) propagate and interact. A fundamental understanding of antenna theory provides insights into how the size and design of electronic components, PCB traces, pads, and grounds relate to various frequencies and their associated wavelengths. Understanding the modes of electrical noise propagation and the methods of testing for EMC leads to design solutions that greatly improve the probability of passing EMC compliance tests in the earliest stages. Failing to design for EMC often results in expensive redesigns and PCB re-spins.

Conducted Emissions

Electrical noise can be transferred to "victim" equipment by field-coupling from source "aggressor" equipment through conducting input lines, cables, connectors, or traces to the equipment circuits. This mode of noise propagation and its effects on power quality are referred to as conducted emissions. Conducted emissions can be conducted directly into the circuit on the input lines or they can be near-field energy that is capacitively-coupled (E-field) or magnetically-coupled (B-field) to a circuit unintentionally. Because conducted emissions may involve capacitively- or magnetically-coupled fields, they are essentially reactive (non-radiative) near-field effects that can generally be modeled using lumped resistive, inductive, and capacitive (RLC) elements. Conducted emissions are typically measured in the 150 kHz to 30 MHz frequency range.

Differential and Common Mode Noise

Conducted emissions consist of differential mode (DM) currents and common mode (CM) currents. The dominant mode depends on the source of the noise. Differential mode noise currents are superimposed on the intended current that powers the circuit, traveling in a loop from the power source, through the circuit, and returning to ground or the intended source return node for non-grounded circuits.

DM currents include the typically lower-frequency desired fundamental signal and any higher-frequency harmonics. In some circuits, the fundamental frequency plus harmonics make up the desired waveform (AC), such as sine waves, square waves, or triangular waves. In others, the main current is DC and the AC portion is noise to be filtered out. The cutoff frequency of a low-pass filter inductor, choke, or LC filter must be designed to filter out the high-frequency noise without significantly attenuating the intended signal.

CM currents travel in the same direction through one or more conductors toward a common return point that closes the current loop (e.g. ground). When the return path is not intentional, the CM current may be the result of energy capacitively- or magnetically-coupled to the common point. Common mode chokes are designed to create high impedance to such CM noise (Figure 1) while presenting low impedance to the desired differential signal.

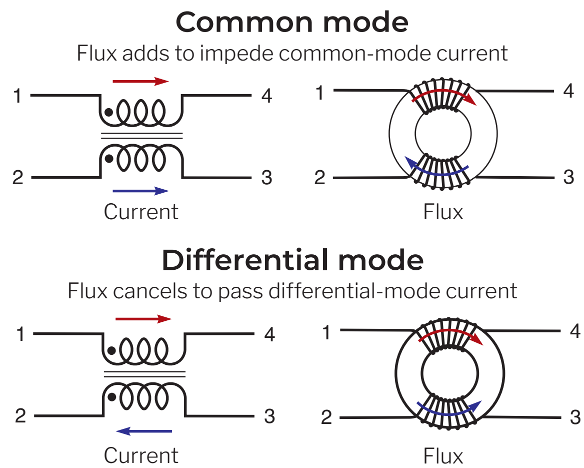

Figure 1. source: [*https://www.coilcraft.com/en-us/edu/series/a-guide-to-understanding-common-mode-chokes/*](https://www.coilcraft.com/en-us/edu/series/a-guide-to-understanding-common-mode-chokes/)

Radiated Emissions

Near-field and far-field are terms associated with antennas. Why mention antennas in an EMC discussion? Unintentional transmitters are circuit elements that unintentionally radiate or scatter radiation. These are in effect "antennas" that were not intentionally designed to transmit energy. Unintentional transmitters cause radiated emissions, that is, electromagnetic noise propagated through the air that is received by other parts of the circuit or other devices.

Radiated emissions are essentially far-field at approximately two or more wavelengths distance from the source. The maximum dimension of an optimized antenna is about 1/4 wavelength of the intended signal being transmitted or received. When the size of an unintentional circuit transmitter, such as a PCB trace cable or slot behaving as an antenna, approaches about 4x the wavelength the transmitted high-frequency energy can be modeled by distributed (transmission line) elements.

Wavelength and frequency have an inverse relationship, therefore at higher frequencies in which the corresponding wavelength approaches about 1/4 of the size of the unintended antenna or smaller, radiated emissions can be expected. Consequently, radiated emissions are tested at higher frequencies than conducted emissions, typically in the 30 MHz to 1 GHz range.

Potential sources of radiated emissions include switched wireless devices, iOT devices, radios, switching power supplies, electric motors, digital signal data lines, communications devices, motor drives, and any unshielded or radiating source with ineffective shielding. Some of these are also included as sources of conducted emissions, because they can interact both on power cables and data lines as well as via radiation over the air.

EMC Compliance Agencies and Test Methods

Following is a brief overview of EMC compliance agencies, test setups, methods, and standards. It also includes design hints for mitigating EMI and tips for EMC test troubleshooting.

EMC standards define specific test equipment, test set-ups, and pass/fail limits. EMC standards generally set limits on both peak (or quasi-peak) and average emissions levels vs. frequency range for the appropriate classification of the measured device. The equipment designed for measuring these levels is defined within the applicable product standard or within the referenced basic standard. EMC standards are continually under review due to new product types and applications. Therefore, the latest approved standard should be applied in any EMC test plan.

Figure 2 shows the test limits for FCC Part 15 (radio frequency devices) Subpart B radiated emissions limits for frequencies greater than 1 GHz for average measured values at 3 m and 10 m distance. Figure 3 shows the same for measured quasi-peak values.

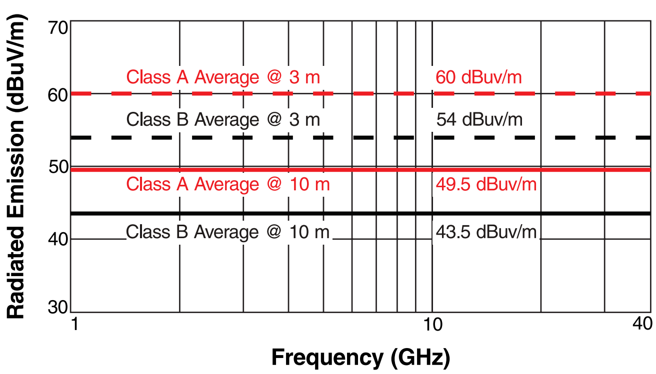

Figure 2. FCC Part 15. Subpart B Radiated Emissions Limits > 1 GHz - Average

Quasi-peak measurements apply a weighting factor based on the repetition frequency of the spectral components of the signal. Even if the emission is over a test limit when measured with peak detection, it can pass if the quasi-peak level is below the limit. For this standard, one must meet the limits for both average and quasi-peak measurements. Quasi-peak measurements require more time than peak measurements. If initial (faster) peak measurements pass, they will pass quasi-peak testing and the slower quasi-peak test is not needed.

Basic EMC publications include definitions of terms and specific test set-ups and equipment requirements, such as those for line impedance stabilization networks

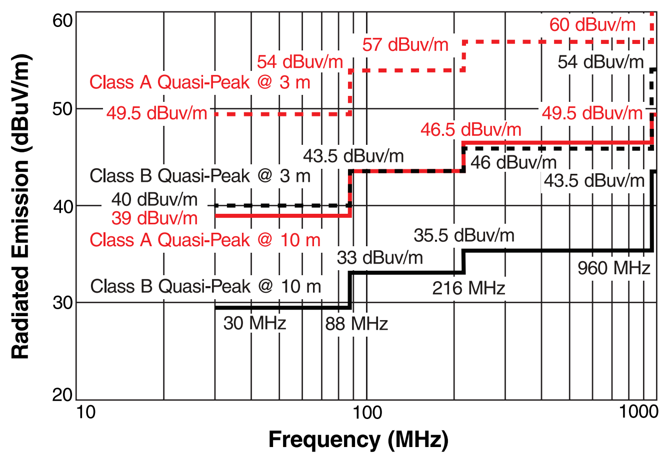

Figure 3. FCC Part 15. Subpart B Radiated Emissions Limits 30 – 1000 MHz - Quasi-Peak

(LISN) that stabilize the impedance of the source and provide isolation of the test equipment and circuit under test. EMC product standards and EMC product family standards refer to specific products and categories of products, while generic EMC standards apply where specific product or family categories do not exist. Product, product family, and generic EMC standards reference the more fundamental basic EMC standards.

Selecting appropriate EMC standards can be confusing, requiring a clear indication of the product category and markets, whether local, international, or both. Consulting an accredited EMC test laboratory can save much time and effort in determining the appropriate test standards and requirements for general or specific products and applications.

The following are the major EMC regulation agencies and examples of some of their basic, product, product family, and generic standards currently in effect.

Major US and Global EMC Regulating Agencies

The major regulating agencies that publish EMC standards include:

FCC — Federal Communications Commission (USA / North America)

Products designed for North American markets are generally tested to the basic compliance limits of the Federal Communications Commission (FCC) Part 15.

IEC — International Electrotechnical Commission (International)

CISPR — Comité International Spécial des Perturbations Radioélectriques (International)

CISPR is part of the IEC.

Basic EMC Standards

The major basic EMC standards cover a wide range of devices and include:

FCC Title 47 Part 15 — Radio Frequency Devices is a basic standard in the USA. Under this standard:

Class A digital devices are generally marketed for use in commercial, industrial, or business environments.

Class B digital devices are generally marketed for residential, but can include commercial, industrial, or business environments. Class B requirements are more stringent, therefore Class B devices can be used in Class A environments.

IEC 61000 Series Parts 1, 2, 4, 5, 6, and 9 define basic terminology, test and measurement methods, and installation and EMI mitigation guidelines.

IEC 61000-3 European (international) Standard for all electrical and electronic equipment that is connected to the public mains up to and including 16 A max.

CISPR 16 — Defines measuring apparatus and methods for radio disturbance and immunity testing from 9 kHz to 1 GHz.

Product EMC Standards

Product EMC standards apply to specific products, such as electric vehicle conductive charging systems, power electronic converter systems, cables and connectors, or medical electrical equipment.

Examples of product-specific EMC standards include:

IEC 61851-21 — Electric vehicle conductive charging system - Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply

IEC 62477-1 — Safety requirements for power electronic converter systems and equipment - Part 1: General

IEC 61726 — Cable assemblies, cables, connectors and passive microwave components - Screening attenuation measurement by the reverberation chamber method

IEC 60601-1-2 — Medical electrical equipment - Part 1-2: General requirements for basic safety and essential performance - Collateral standard: Electromagnetic compatibility - Requirements and tests

Product Family EMC Standards

Product family EMC standards apply to wider general product categories, such as vehicles, information technology equipment, industrial, scientific, and medical equipment.

Examples of product CISPR EMC standards include:

CISPR 25 — Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers. This is the go-to standard for automotive applications.

CISPR 22 — Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement - High frequency conducted emissions standard

CISPR 11 — Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement - High frequency conducted emissions standard

CISPR 15 — Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment

Generic EMC Standards

Generic EMC standards are grouped as either residential, commercial, and light industrial, or as industrial. Industrial includes higher-power industrial, and scientific and medical equipment. When a specific EMC standard does not exist for new products, a simplified generic EMC standard may be invoked. As with other product standards, they may refer to basic EMC standards for specific test methods.

Generic EMC standards examples include:

IEC 61000-6-3 — Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments

IEC 61000-6-4 — Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments

Designing to Mitigate EMI

Because higher-frequency harmonics are considered noise in conducted emissions testing, low-pass filters are purposely designed into electronic equipment to reduce this high-frequency noise to below the defined limits of the conducted emissions test. Series inductors, and capacitors between line and neutral lines, such as X-caps between the power and neutral lines, are employed to reduce the high-frequency DM currents. Common mode chokes and Y-caps between the lines and chassis ground are used to reduce the CM noise.

When the source includes significant conducted noise as with switching power supplies, additional elements may be needed to create higher-order LC filters that further reduce the DM and CM noise. Some good news is that the use of small surface mount (leadless) components reduces connection inductance and the length of traces that may contribute to higher EMI.

Design Hints for Passing EMC Pre-compliance and Compliance Tests

These design hints for passing EMC pre-compliance and compliance testing do not comprise an exhaustive list, however following these guidelines will help assure minimal generation of EMI.

1. Minimize the length of circuit traces to avoid making unintentional emitters / antennas. This is listed as #1 because it is most critical in preventing EMI. Minimizing trace length decreases the total stored reactive energy of the trace and reduces ringing due to parasitic inductance. This is especially critical in switched power converters.
2. Consider EMC in the earliest stages of the design process. It can save considerable time and help prevent time-consuming PCB redesigns.
3. Use simulation programs to design and simulate noise filters, and use real measurements to verify them. Even accurate models may not fully capture some important parasitic interactions.
4. Use magnetically shielded inductors to minimize B field coupling, unless your design requires purposeful interaction with the inductor field (e.g. NFMI or RFID). Magnetic shielding is created by surrounding the inductor with a high-permeability, low-reluctance material (e.g. ferrite) creating a “closed” magnetic path. The purpose of magnetic shielding is to reduce the amount of magnetic flux generated outside the inductor, in turn reducing the likelihood of radiating energy to nearby components or circuit board traces causing electro-magnetic interference (EMI).
5. Avoid electrically-conducting (metal) materials directly above, next to, or below inductors or high-frequency switches (e.g. switched power converters). When this can’t be avoided, use raised inductors to increase the distance between inductor and conductors below.
6. Place the start winding of inductors closest to the high dv/dt side of switches.
7. Maintain spacing between components, generally 1.5x the largest x-y dimension.
8. Avoid or slow down sharp rising-edge and falling-edge waveforms (slew rate control). This can lead to reduced efficiency, so there are trade-offs and a balance must be struck.
9. Route clock lines and other high-speed traces away from power sources.
10. Avoid running high-speed lines across gaps in return lines.
11. Consider ground loops or return paths of reference planes as potential EMI sources.
12. Avoid discontinuous signal return paths e.g. gaps in ground planes.
13. Utilize filtering or shielding to block coupling paths from energy sources.
14. Engage filter reference designs with proven performance and to save design time.
15. A single pole (L or C) filter provides -20 dB/decade of frequency filtering. A two-pole (LC) filter has a more rapid attenuation rate of -40 dB/decade. A three-pole filter (e.g. LCL) gives -60 dB/decade attenuation. Therefore, a sharp cutoff frequency requires a high order filter.
16. Consider spread-spectrum control methods to spread noise energy to lower levels over a range of frequencies.
17. Slope compensation requires a certain level of ripple current to maintain stability. If the ripple is too high, it can cause EMI. When using slope compensation, check that the ripple current is not a source of EMI.

EMC Filter Simulations

Computer programs for designing noise filters speed up the design and analysis phase of electronic product development. Free programs are useful for designing and verifying the performance of LC filters. Physics-based three-dimensional EM (3D EM) simulation programs that use more advanced computational solver methods, such as FEM, FDTD, MoM are higher-priced and require more advanced knowledge, however, these advanced solver programs provide more geometry- and materials-related insights when attempting to understand EM field interactions.

Cost free passive component filter simulation programs

These no-cost programs help engineers design and simulate lumped-element filters and their effects on circuit behavior. It typically takes much less time to model and simulate a proposed circuit than to build and test the physical circuit, especially when performing “What-if?” analyses that involve many iterations. Thus, SPICE-based and other circuit design and synthesis simulation programs provide fast insights while saving time in the initial stages of design and analysis.

Analog Devices

LTspice

LTpowerCAD Includes EMI Filter Design Module)

Coilcraft

Coilcraft LC Filter Designer Software: Create elliptic low pass filters using actual Coilcraft inductor values, not just ideal components.

Coilcraft LC Filter Reference Designs

WA4DSY.NET

Design LC Filters: Filter design calculations for designing multi-pole filters

3D Electromagnetic Simulations

The major advanced 3-dimensional electromagnetic (3D EM) programs for simulating printed circuit boards (PCBs), electronic components, and circuits include Ansys - HFSS, AWR Axiem / Analyst, CST Studio Simulia, and Cadence Clarity. These programs use physical models that include materials and geometry details and advanced computational techniques for a better understanding of the effects of materials and spacings at various operating conditions.

Pre-Compliance Testing

Even the best design simulations can miss unanticipated field or wave interactions. Intertek Testing Services NA, Inc, an accredited EMC test lab has found that about 50% of EMC tests fail on the first try (note 5). Some failures may be unavoidable, but many are due to preventable design oversights, such as failure to apply EMC principles or to simulate predictable interactions between circuit components. Pre-compliance testing allows engineers to pre-verify EMC standard compliance so that no such surprises delay release of a product due to necessary re-designs. When un-predicted EM noise is made visible by pre-compliance testing, there are methods that can be employed to identify the source and remediate the problem.

Tips for EMC Test Troubleshooting

1. Use E-field and B-field probes to locate sources of EMI on a PCB.
2. If inductors or capacitors are suspected, rotate inductors by 180 degrees, and place nearby inductors and capacitors 90 degrees to each other. If available, replace inductors having side terminations with bottom-terminated inductors.
3. Use a spectrum analyzer to determine the frequency range and amplitude of noise sources.
4. Set the resolution bandwidth of the spectrum analyzer to that specified in the applicable emission standard.
5. Slower voltage rise times create higher-order harmonics of lower magnitude and faster rise times lead to higher-magnitude, higher-order harmonics.
6. Lower duty cycle leads to lower-magnitude, higher-order harmonics and higher duty cycle leads to higher-magnitude, higher-order harmonics.
7. Determine whether the noise is DM or CM. If the noise is suspected to be CM, select a CM choke for the offending frequencies. If the noise is reduced, the noise was CM (unless the choke is a combination choke). If the noise is not reduced, it is more likely DM noise.
8. If changing EMI filter components does not change the EMC test results, this points to a possible PCB layout issue.
9. A combination of too many circuit elements can lead to resonances that amplify unwanted harmonics. In such cases, removing a component, such as a capacitor, may improve EMC test results. This may seem counter-intuitive, however, sometimes more is not better.
10. Is ringing in your switched mode power supply switching edges causing EMI? Use a simulation program to design an RC snubber circuit to reduce the ringing. Higher resistance dampens the ringing but can affect efficiency, so use simulation to optimize the trade-offs.
11. If the source issue is a strong E-field, a metal "Faraday cage" shield connected to ground provides a closed field path that shunts noise to ground.
12. Wrap thin copper completely around a noisy transformer and connect the copper to ground to create a Faraday cage shield.
13. Use copper tape in closed loops to create prototype shielding. Test with and without the shielding to determine whether it is needed.
14. Review the design hints above for additional insights into possible solutions.

Conclusion

The continual increased use of electronics and electrical products has led to an environment filled with many signal and noise sources over a wide range of frequencies. Understanding how fields interact to create intentional and unintended transmitters and receivers, and applying EMI mitigation techniques when designing and testing, can lead to positive outcomes in electromagnetic compliance testing.

Definitions

CISPR — Comité International Spécial des Perturbations Radioélectriques

Common mode current (noise) involves currents flowing in the same direction to circuit ground at higher frequencies. It is also called asymmetrical or longitudinal current.

Conducted emissions are unintentionally conducted, capacitively coupled (E-field), or magnetically coupled (B-field), to the circuit. They are typically measured in the 150 kHz to 30 MHz frequency range.

Crosstalk occurs when a high-frequency (e.g. clock) signal couples into nearby analog circuits.

Differential mode (normal) noise involves currents flowing in opposite directions at lower frequencies, also called symmetrical or transverse current.

Electromagnetic (EM) field — A field of force that consists of both electric and magnetic components, resulting from the motion of an electric charge and containing a definite amount of electromagnetic energy.

Electromagnetic (EM) noise a.k.a. electrical noise is any unwanted electrical disturbance, not necessarily in the audible frequency range (audible noise).

EM Emissions occur when equipment radiates or conducts electromagnetic noise.

EM Immunity is the ability of the equipment to withstand outside sources of EM noise without adversely affecting functionality.

EM Susceptibility is the sensitivity of equipment to function within an environment of EM noise.

- An **aggressor** is equipment that emits EM noise. Aggressors conduct or radiate EM emissions.
- A **victim** is equipment that is adversely affected by EM noise. Victims are susceptible to EM emissions.

EMC is **electromagnetic compatibility**. EMC is verified by testing to industry global and local standards.

EMI is **electromagnetic interference**. If EMI exists at a level that exceeds the applicable EMC testing standards, the equipment is not EMC-compliant.

Far-field — Involving a distance from the source in which the distributed element models are needed for high-accuracy far-field simulations.

The transition from near-field to far-field exists at about 1/6 the wavelength of the signal (or noise).

FCC — Federal Communications Commission (USA)

FCC Title 47 Part 15 — Radio Frequency Devices is a basic EMC standard in the USA applicable to electromagnetic energy at any frequency in the radio frequency (RF) spectrum between 9 kHz and 3 GHz.

FDTD — Finite Difference Time Domain - A powerful method of solving Maxwell's equations directly without requiring physical approximations.

FEM — Finite Element Method - An advanced method of numerically solving differential equations that, for example, define physical relationships over a geometric space.

IEC — International Electrotechnical Commission

Intentional transmitters (antennas) purposely transmit EM waves for wireless charging and communications.

LISN — Line Impedance Stabilization Network - Pi filter networks that stabilize the impedance of the test source and provide isolation of the test equipment and circuit under test.

MoM — Method of Moments - Efficient full-wave numerical technique for solving open-boundary electromagnetic problems.

Near-field — Involving capacitively-coupled E fields or magnetically-coupled B fields. Lumped element models can be sufficient for near-field simulations.

Radiated emissions are the result of unintentional current loop paths that radiate EM noise from the circuit. They are typically measured in the 30 MHz to 1 GHz frequency range.

SMPS — Switched Mode Power Supply (switching converter).

Unintentional radiator — A device that intentionally generates radio frequency energy for use within the device, or that sends radio frequency signals by conduction to associated equipment via connecting wiring, but which is not intended to emit RF energy by radiation or induction.

Unintentional transmitters unintentionally transmit EM waves as noise. The FCC defines this as an "incidental radiator" - A device that generated radio frequency energy during the course of its operation although the device is not intentionally designed to generate or emit radio frequency energy.

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