ELECTROMAGNETIC COMPATIBILITY

Electromagnetic Compatibility (EMC) - the ability of a system to operate in its intended environment without

(1) suffering unacceptable degradation in performance due to coupling from other systems or
(2) causing unacceptable degradation in the performance of other systems via coupling.

Electromagnetic Interference (EMI) - undesirable signals coupled from one system (emitter) to another (receptor) which degrade the performance of the receptor. The emitter-receptor systems in an EMI problem are sometimes referred to as the threat-victim systems.

Effective EMC design has become a critical component in the design of most modern electronic devices. The electromagnetic interference environment is becoming increasingly cluttered as more small high-speed wireless devices are introduced into the marketplace. In order to reduce the amount of interference, EMC standards (commercial and military) have been introduced. These standards set prescribed limits on the amount of electromagnetic energy that a device can emit at specific frequencies. Some standards also prescribe the susceptibility levels for the operation of certain devices.

Manufacturers of electronic devices must certify that these devices meet the appropriate standards in order for these products to be marketed. In many cases, unforseen EMC problems are identified in the product testing phase. This requires modification of the product design (increasing the design complexity through the addition of components) which inherently decreases the product reliability. Correcting EMC problems after product testing also increases the time-to-market. The implementation of basic EMC design principles in the initial product design phase is a much more cost-effective approach to meeting EMC standards. Thus, the design engineer should be knowledgeable in the basic principles of effective EMC design.

The fundamental EMC coupling problem can be decomposed into three components as shown below in the *emitter-path-receptor EMC model*.

Emitter-Path-Receptor EMC Model

The identification of the three individual components of the emitter-path-receptor model in an EMC problem is not always trivial. The receptor itself may be a subsystem in a complex system. Note that the emitter and the receptor may be associated with two independent systems or both could be subsystems in a larger system (subsystems on a crowded printed circuit board). Once the receptor is identified based on its inability to function properly, the emitter can be located by analyzing the characteristics of the energy received by the receptor. The properties of the interference signals produced in the receptor are affected by the emitter characteristics (amplitude, spectrum, etc.) and the properties of the coupling path (the coupling path may act like a filter). The problem may be further complicated by the fact that there may be multiple coupling paths in a given EMC problem.

The three components of the emitter-path-receptor EMC model suggest that the effects of EMI can be reduced by

(1) suppressing emissions,
(2) reducing the efficiency of the coupling path, or
(3) reducing the susceptibility of the receptor.

The effects of EMI can be minimized by applying all three reduction techniques in concert. Depending on the EMC problem, some of these EMI reduction techniques may not be applicable. For example, the emitter may associated with an independent system producing intentional signals for that system.

The coupling paths encountered in an EMC problem (in the emitter-path-receptor model) can be classified according to the coupling mechanism.

Coupling Path Classifications

(1) *Conductive coupling* - a conductive path exists between the emitter and the receptor (power cords, ground returns, interface cables, cases, etc.)

(2) *Radiative coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the far-field of the emitter, the emitter "radiation field" decays as 1/R where R is the separation distance between the emitter and the receptor.

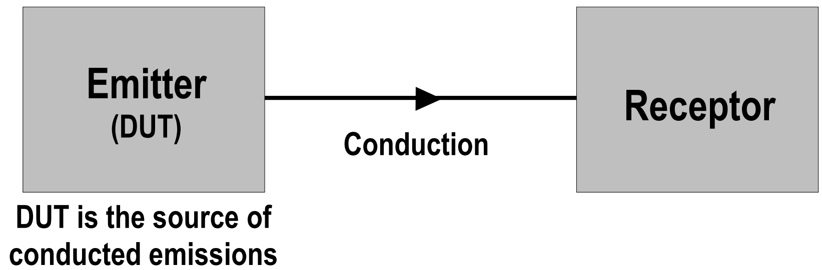
(3) *Inductive (magnetic) coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near-field of the emitter where the magnetic field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

(4) *Capacitive (electric) coupling* - no conductive path exists between the emitter and the receptor (electromagnetic coupling), the receptor lies in the near-field of the emitter where the electric field is dominant, the proximity of the emitter and receptor leads to "mutual coupling" (the emitter radiation is affected by the presence of the receptor).

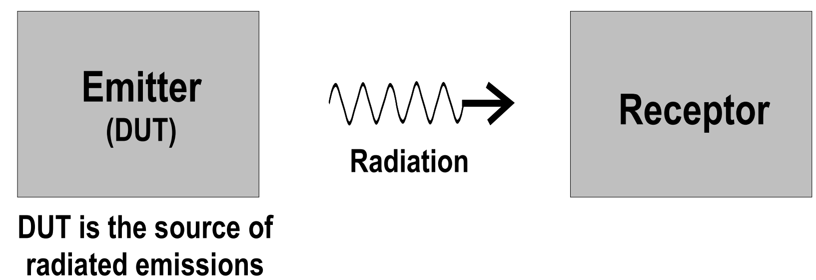
Note that the coupling mechanisms described above can be generalized into two simple classifications: conduction or radiation (radiative, inductive and capacitive coupling are all due to radiated fields, only the emitter-receptor separation distance and emitter field characteristics are different). Using the general coupling classifications of "conducted" and "radiated", we may classify the general EMC problem into one of four subgroups, based on whether the device under test (DUT) is the emitter of conducted or radiated coupling or the receptor of conducted or radiated coupling. The DUT is also referred to as the equipment under test (EUT).

<u>EMC Problem Classifications</u>

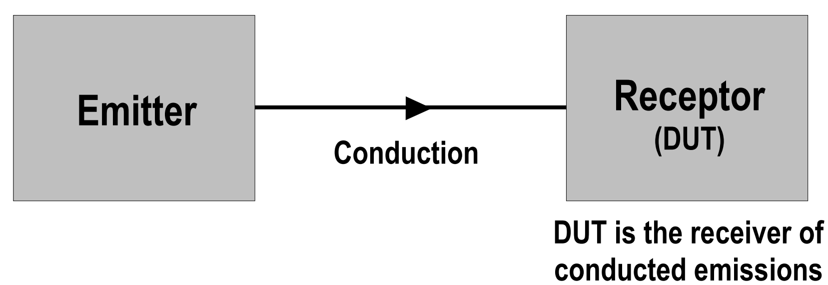
1. Conducted Emissions



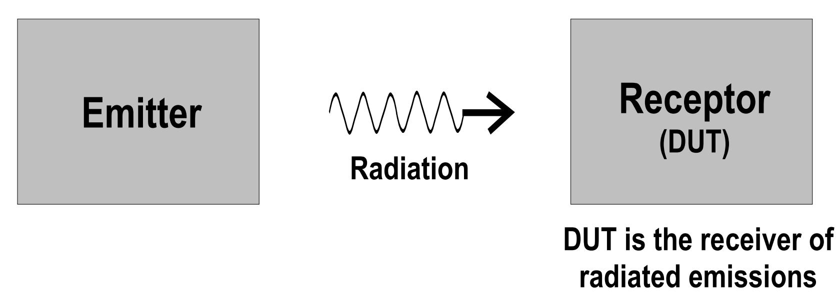
2. Radiated Emissions



3. Conducted Susceptibility



4. Radiated Susceptibility



Examples (EMC Problem Classifications)

A switched-mode power supply generates noise signals at the supply switching frequency and its harmonics. These noise signals are conducted onto the AC power line. (conducted emissions)

A DC-DC converter must operate in an environment where the signal at the input connection is characterized by a DC signal plus AC noise at a particular frequency. The DC-DC converter must provide an AC rejection level of 50 dB at the noise frequency. (conducted susceptibility)

The DC motor of a kitchen blender generates wideband noise due to the arcing that occurs as the motor brushes make and break contact. (radiated emissions)

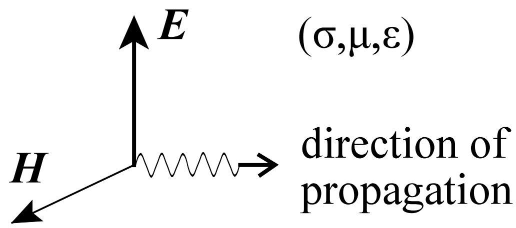
A carrier-based military aircraft is illuminated by the high-power search radar of the carrier under normal operations. The missiles mounted under the wings of the aircraft must not activate. (radiated susceptibility)

PHYSICAL AND ELECTRICAL DIMENSIONS OF COMPONENTS IN EMC PROBLEMS

The ability of an EMC component to operate as a radiator (emitter) or a receiver (receptor) of electromagnetic energy depends on the *electrical dimension* of the component. The electrical dimension of an EMC component depends on the physical size of the component and the frequency of operation (wavelength). Thus, the electrical dimension of a component is measured in wavelengths. The wavelength of an electromagnetic wave actually depends on the type of wave. We choose the wavelength of a uniform plane wave as the standard measure since its wavelength is representative of most electromagnetic waves .

Uniform Plane Wave

(1.) ***E*** and ***H*** lie in the plane ⊥ to the direction of wave propagation.
(2.) ***E*** and ***H*** are ⊥ to each other.
(3.) ***E*** and ***H*** are uniform in the plane ⊥ to the direction of wave propagation.



The wavelength of the uniform plane wave depends on the electrical characteristics [σ - conductivity (S/m), μ - permeability (H/m), and ε - permittivity (F/m)] of the media through which the wave travels. The wave propagation characteristics of the wave are defined by the wave *propagation constant* (γ). The propagation constant of a uniform plane wave at a given frequency f traveling through an arbitrary medium is given by

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta$$

where $\omega = 2\pi f$ is the radian frequency (rad/s) of the wave, α is the *attenuation constant* of the wave (Np/m), and β is the *phase constant* of the wave (rad/m). The attenuation constant and the phase constant of the wave may be written as

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right]}$$

The *velocity of propagation* v and the *wavelength* λ of the uniform plane wave are both defined in terms of the wave phase constant.

$$v = \frac{\omega}{\beta} \qquad\qquad \lambda = \frac{2\pi}{\beta}$$

The wavelength is the distance (m) the wave travels as the fields of the wave experience 2π radians of phase shift (one cycle). Note that the velocity of propagation and the wavelength are both inversely proportional to the phase constant β. Given uniform plane waves at a particular frequency propagating through two media (medium 1 and medium 2) with phase constants β_1 and β_2 such that $\beta_1 > \beta_2$, the waves in medium 1 will travel at a slower velocity of propagation and a shorter wavelength than the waves in medium 2.

For the special case uniform plane wave propagating in a lossless medium ($\sigma = 0$), the phase constant reduces to

$$\beta = \omega\sqrt{\mu\varepsilon} = 2\pi f\sqrt{\mu\varepsilon}$$

while the velocity of propagation and wavelength reduce to

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}}$$

$$\lambda = \frac{2\pi}{\beta} = \frac{1}{f\sqrt{\mu\varepsilon}} = \frac{v}{f}$$

The overall permeability and permittivity of the medium are defined as

$$\mu = \mu_r \mu_o$$

$$\varepsilon = \varepsilon_r \varepsilon_o$$

where (μ_o, ε_o) are the permeability and permittivity of free-space (vacuum) [$\mu_o = 4\pi\times10^{-7}$ H/m, $\varepsilon_o = 8.854\times10^{-12}$ F/m] and (μ_r, ε_r) are the relative permeability and permittivity (unitless). The velocity of propagation for a uniform plane wave in free space is the speed of light.

$$v_o = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \approx 3 \times 10^8 \text{ m/s}$$

The velocity of propagation and the wavelength of the uniform plane wave in a general lossless medium can be written in terms of the free space velocity of propagation.

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{v_o}{\sqrt{\mu_r \varepsilon_r}}$$

$$\lambda = \frac{1}{f\sqrt{\mu\varepsilon}} = \frac{v_o}{f\sqrt{\mu_r \varepsilon_r}}$$

For any media with $\mu_r > 1$ and/or $\varepsilon_r > 1$, uniform plane waves propagate at speeds slower than the speed of light and wavelengths shorter than those found in free space.

The electrical dimension of an EMC component located in a particular lossless medium is determined by taking the ratio of the largest physical dimension ($\mathscr{L}$) to the wavelength.

$$\frac{\mathscr{L}}{\lambda} = \frac{\mathscr{L} f \sqrt{\mu_r \varepsilon_r}}{v_o}$$

The component is electrically small if the largest physical dimension is much less than the wavelength ($\mathscr{L}/\lambda \ll 1$). As a rule of thumb, we choose the maximum value of $\mathscr{L}/\lambda$ to be 0.1 in order for the component to be classified as *electrically small*.

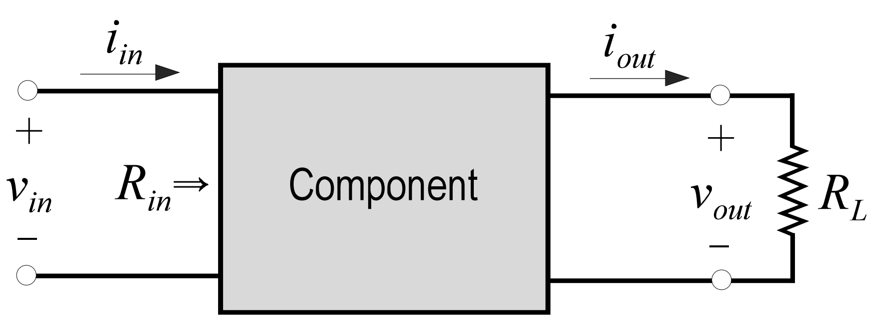
$$\frac{\mathscr{L}}{\lambda} = \frac{\mathscr{L} f \sqrt{\mu_r \varepsilon_r}}{v_o} \le 0.1 \qquad \text{(electrically small)}$$

If the EMC component is electrically small, the operation of the component can be accurately defined using circuit concepts (Kirchoff's voltage law, Kirchoff's current law, etc.). The lumped-element circuit equations are simply a special-case of Maxwell's equations based on low-frequency approximations for the circuit elements. An electrically small EMC component consisting of current carrying conductors will be an inefficient emitter or receptor of electromagnetic energy. For EMC components which are not electrically small ($\mathcal{L}/\lambda \geq 0.1$), we must use field equations (Maxwell's equations) rather than circuit equations to characterize the component operation.

COMMON EMC UNITS

The quantities most often encountered in EMC applications are circuit values of voltage (V) and current (A) as seen in conducted emissions problems or field values of electric field (V/m) and magnetic field (A/m) as seen in radiated emissions problems. In addition to these quantities, we are frequently interested in the overall circuit power (W) or overall field power density (W/m^2). In a typical EMC problem, these quantities may range over several orders of magnitude. For this reason, these quantities are normally expressed on a logarithmic scale using *decibels*.

Given a component operating with an input power P_{in} and an output power P_{out}, the power gain of the device is defined as the simple ratio of the output power to the input power (we will assume RMS quantities).



$$\text{Power Gain} = \frac{P_{out}}{P_{in}} = \frac{v_{out}\, i_{out}}{v_{in}\, i_{in}} = \frac{v_{out}^2 / R_L}{v_{in}^2 / R_{in}} = \frac{i_{out}^2\, R_L}{i_{in}^2\, R_{in}}$$

The power gain in decibels is defined as

$$\text{Power Gain}_{\text{dB}} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

According to the power gain definition in decibels, every 10 dB of power gain represents an order of magnitude in the actual power ratio. If we assume that the input and output powers are delivered to equivalent resistances ($R_{in} = R_L$), then the voltage and current gains in dB can be made equal to the power gain in dB by choosing the scaling constant to be 20 rather than the value of 10 used for the power gain.

$$\begin{aligned}
\text{Power Gain}_{\text{dB}} &= 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \\
&= 10\log_{10}\left(\frac{v_{out}^2 / R_L}{v_{in}^2 / R_{in}}\right) = 10\log_{10}\left(\frac{i_{out}^2\, R_L}{i_{in}^2\, R_{in}}\right) \\
&= 20\log_{10}\left(\frac{v_{out}}{v_{in}}\right) = 20\log_{10}\left(\frac{i_{out}}{i_{in}}\right) \\
&= \text{Voltage Gain}_{\text{dB}} = \text{Current Gain}_{\text{dB}}
\end{aligned}$$

Thus, the general formulas for power, voltage and current gain in dB are

$$\text{Power Gain}_{\text{dB}} = 10\log_{10}\left(\frac{P_2}{P_1}\right)$$

$$\text{Voltage Gain}_{\text{dB}} = 20\log_{10}\left(\frac{v_2}{v_1}\right)$$

$$\text{Current Gain}_{\text{dB}} = 20\log_{10}\left(\frac{i_2}{i_1}\right)$$

Note that the power, current and voltage gain are always expressed as a ratio of two quantities. The magnitude of EMC quantities such as voltage, current, power, electric field and magnetic field are commonly expressed in units of dB referenced to a convenient base value.

Voltage

$$v_{\text{dBmV}} = 20\log_{10}\left(\frac{v}{1\text{ mV}}\right)$$

$$v_{\text{dB}\mu\text{V}} = 20\log_{10}\left(\frac{v}{1\ \mu\text{V}}\right)$$

Current

$$i_{\text{dBmA}} = 20\log_{10}\left(\frac{i}{1\text{ mA}}\right)$$

$$i_{\text{dB}\mu\text{A}} = 20\log_{10}\left(\frac{i}{1\ \mu\text{A}}\right)$$

Power

$$P_{\text{dBmW}} = 10\log_{10}\left(\frac{P}{1\text{ mW}}\right)$$

$$P_{\text{dB}\mu\text{W}} = 10\log_{10}\left(\frac{P}{1\ \mu\text{W}}\right)$$

Electric field

$$E_{\text{dBmV/m}} = 20\log_{10}\left(\frac{E}{1\text{ mV/m}}\right)$$

$$E_{\text{dB}\mu\text{V/m}} = 20\log_{10}\left(\frac{E}{1\ \mu\text{V/m}}\right)$$

Magnetic field

$$H_{\text{dBmA/m}} = 20\log_{10}\left(\frac{H}{1\text{ mA/m}}\right)$$

$$H_{\text{dB}\mu\text{A/m}} = 20\log_{10}\left(\frac{H}{1\ \mu\text{A/m}}\right)$$

A value of 83 dBµV is expressed as “83 dB above a microvolt” while a value of −35 dBmA is expressed as “35 dB below a milliamp”. One special case is the unit of dBmW which is commonly denoted as dBm.

Examples (EMC units)

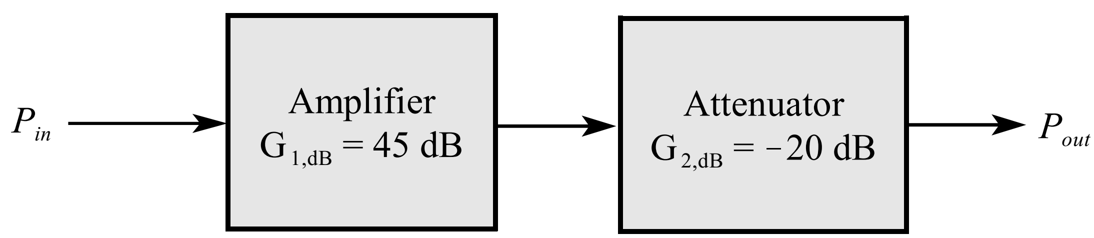
1. Convert $v = 250$ mV to $v_{\mathrm{dB\mu V}}$.

$$v_{\mathrm{dB\mu V}} = 20\log_{10}\left(\frac{v}{1\ \mu\mathrm{V}}\right) = 20\log_{10}\left(\frac{0.25}{10^{-6}}\right) = 107.96\ \mathrm{dB\mu V}$$

2. Convert $P = 56$ dBm to P in watts.

$$P_{\mathrm{dBm}} = 10\log_{10}\left(\frac{P}{1\ \mathrm{mW}}\right) \qquad \Rightarrow \qquad P = 10^{-3}\times 10^{56/10} = 398.11\ \mathrm{W}$$

3. Determine P_{out} for the system shown below if $P_{in} = 1$ μW.



The output power of the cascaded amplifier/attenuator system can be determined using the actual gains (not dB) of the amplifier and attenuator.

$$P_{out} = G_1\, G_2\, P_{in}$$

$$G_1 = 10^{45/10} = 31{,}623 \qquad\qquad G_2 = 10^{-20/10} = 0.01$$

$$P_{out} = (31{,}623)(0.01)(10^{-6}) = 316.23\ \mu W$$

Alternatively, we can express the power terms on both sides of the equation above in terms of dB.

$$10\log_{10} P_{out} = 10\log_{10}(G_1\, G_2\, P_{in})$$

$$P_{out,\mathrm{dB}} = 10\log_{10} G_1 + 10\log_{10} G_2 + 10\log_{10} P_{in}$$

$$= G_{1,\mathrm{dB}} + G_{2,\mathrm{dB}} + P_{in,\mathrm{dB}}$$

The input and output power terms in the equation above can be expressed using any appropriate base. There is no need to manipulate the amplifier and attenuator power gains since these terms are based on ratios of like units. Using dBμW gives

$$P_{out,\,\mathrm{dB\mu W}} = G_{1,\mathrm{dB}} + G_{2,\mathrm{dB}} + P_{in,\mathrm{dB\mu W}}$$

$$P_{in,\,\mathrm{dB\mu W}} = 10\log_{10}\frac{10^{-6}}{10^{-6}} = 0\ \mathrm{dB\mu W}$$

$$P_{out,\,\mathrm{dB\mu W}} = 45 + (-20) + 0 = 25\ \mathrm{dB\mu W}$$

$$P_{out} = 10^{-6} \times 10^{25/10} = 316.23\ \mu W$$

Using dBmW gives

$$P_{out,\,\mathrm{dBmW}} = G_{1,\mathrm{dB}} + G_{2,\mathrm{dB}} + P_{in,\mathrm{dBmW}}$$

$$P_{in,\,\mathrm{dBmW}} = 10\log_{10}\frac{10^{-6}}{10^{-3}} = -30\ \mathrm{dBmW}$$

$$P_{out,\,\mathrm{dBmW}} = 45 + (-20) + (-30) = -5\ \mathrm{dBmW}$$

$$P_{out} = 10^{-3} \times 10^{-5/10} = 316.23\ \mu W$$