Chapter 2

Basic EMC Concepts at IC Level

The FCC's Kansas City office received a complaint that the Search and Research Satellite Aided Tracking (SARSAT) system was experiencing interference from an unknown source. SARSAT is used by search-and-rescue teams to locate the radio beacon transmitters of crashed aircraft and distressed ships. Using mobile direction-finding gear, the FCC tracked the interference to a (presumably malfunctioning!) video display unit at a Wendy's restaurant.

—Quoted from [Arm07]

1 Introduction

Related to the design of practical electric and electronic appliances on one hand, and to the general electromagnetic principles and theory on the other hand, EMC is an interdisciplinary scientific domain that has introduced and maintained its own typical vocabulary, conventions, definitions and design guidelines over the years. As stipulated in the previous chapter, the major focus in this work lies on the design of analog integrated circuits exhibiting a high degree of immunity against electromagnetic interferences. This chapter therefore concentrates on the general EMC issues which appear at IC level.

Standardized measurement methods were developed in order to simulate as well as replicate in measurements the appearing EMC incompatibilities in integrated circuits. Using these measurement methods to evaluate the EMC behavior of IC's as such, does not require an in-depth knowledge of EMC or electromagnetism. Quite in the same way, numerous EMC-friendly design guidelines describe what should be done in order to eliminate or at least alleviate EMC problems in electronic circuits (although the vast majority of these guidelines are solely addressing the PCB level design). One may wonder if these design guidelines can not be used as such, without any theoretical EMC knowledge.

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The answer to this question is of course a matter of opinion: however, the bottom line is that using established measurement methods and corresponding design guidelines without any notion of where they're coming from or what restrictions they intrinsically contain, proves very often to be unfruitful and thought-constricting. Especially the latter is very undesirable since it impairs the flexibility and creativity which is required when designing electronic circuits. Electromagnetism is a scientific discipline which is unfortunately still commonly considered to be a standalone subject, dealing with antennas, transmission lines and radio waves, and therefore not directly tied to electricity and electronics. However, its impact on EMC is fundamental and profound, and its basic laws lie at the bottom of so-called rule of thumb EMC-friendly design guidelines as well as of the established and standardized measurement methods [Car95]. It is for this reason important to devote some attention to the links which exist between electromagnetism and EMC at IC level. Of course, this subject is in itself much too elaborate to be covered in full in this work. For this reason, the most basic concepts and tie-ins are discussed and presented in this chapter, offering a glimpse of what lies beyond the common rules of thumb and accepted measurement methods.

This chapter starts with a general classification of EMC terminology, and describes some frequent and palpable sources of electromagnetic disturbances. Next, a section is devoted to the link existing between electromagnetism and EMC-friendly integrated circuit design. Afterwards, the EMC issues in IC's are briefly discussed, and the main differences between digital and analog circuits are covered from a conceptual point of view where EMC is concerned. Finally, existing measurement methods for simulating and testing the electromagnetic susceptibility of integrated circuits are shortly reviewed.

2 Definition of EMC, EMI, EMS and EME

Many definitions are applicable in order to describe the principle of electromagnetic compatibility (EMC). The definition rendered here is the one offered in [Kei87], as it stands out because of its clearness and its unambiguity:

Electrical and electronic devices are said to be electromagnetically compatible when the electrical noise generated by each does not interfere with the normal performance of any of the others. Electromagnetic compatibility is that happy situation in which systems work as intended, both within themselves and within their environment.

When there is no EMC, this is due to electromagnetic interference (EMI). Quoted from [Kei87]:

EMI is said to exist when undesirable voltages or currents are present to influence adversely the performance of a device. These voltages or currents may reach the victim device by conduction or by electromagnetic field radiation.

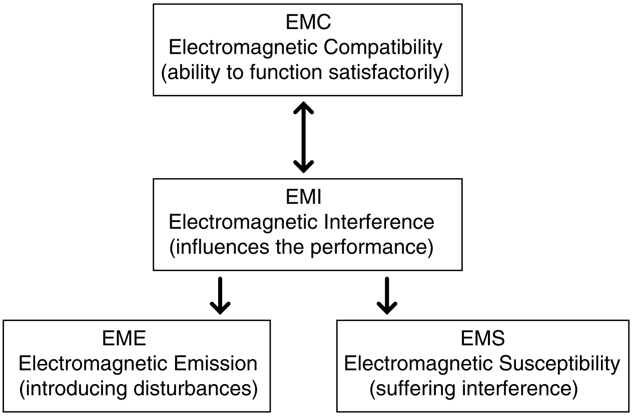


Figure 2.1. The used EMC terms in this work and their interrelationships, as represented in [Goe01].

This last precision is not superfluous, and a clear distinction between these two interference types must be made. To be precise, the term "radiated interference" in the above definition comprises two phenomena, namely near field coupling and far field radiation. This distinction is important and not a purely academic categorization, as will become apparent in Sect. 4.

When there is EMI, there is at least one EMI source causing an intolerable emission (be it conducted, near field coupled or far field radiated), and possibly one or more EMI victim(s) which for one or more reasons is (are) susceptible to the emanated disturbance. Electromagnetic emission (EME) is described by the International Electrotechnical Commission (IEC) as [IEV]:

The phenomenon by which electromagnetic energy emanates from a source.

In the same way, the IEC describes electromagnetic susceptibility (EMS) as [IEV]:

The inability of a device, circuit or system to perform without degradation in the presence of an electromagnetic disturbance.

Susceptibility is complementary to immunity, the latter describing to what extent EMI may be injected into a system before failures start to occur. Because the acronym for electromagnetic immunity would conflict with the one used for electromagnetic interference, this term is not abbreviated in this work: when used in the text, immunity always signifies the opposite of susceptibility. Care must be taken when using the concepts of immunity and susceptibility without distinction, since this easily leads to confusion. These four different phenomena and the way they are related to each other are represented schematically in Fig. 2.1, as in [Goe01].

3 Sources of electromagnetic interference

Nature contributes to electromagnetic pollution primarily by atmospheric noise (which is amongst others produced by lighting during thunderstorms) and cosmic noise [Wes01]). Lightning induces electromagnetic emissions which propagate over distances ranging up to several thousand kilometers, causing spikes or sharp random pulses in the electromagnetic spectrum. The spectral components of lightning span a wide range of frequencies, from a few Hertz to well over 100 MHz [Kei87]. Cosmic noise is a composite of noise sources comprised of:

- **Cosmic microwave background radiation:** discovered by Arno Penzias and Robert Wilson in 1965, the cosmic microwave background radiation confirms the Big Bang theory which has been predicted by George Gamow in cosmology, and it constitutes the radio remnant of the origin of our universe [Pen68]. The background radiation is isotropic, and it has a thermal black body spectrum at a temperature of 2.725 Kelvin. Its spectrum peaks at a frequency of 160.2 GHz [1] [Liv92].

- **Solar radio noise:** is proportional to solar activity and the generation of solar prominences and flares. Satellite observations have demonstrated that X-ray and ultraviolet emissions are especially intense in the heart of solar flares [Cha98].

- **Galactic noise:** with similar characteristics as thermal noise, it seems to come most strongly from the Sagittarius constellation [Kei87]. This complex radio source at the center of our Galaxy is identified as Sagittarius A, and it could equally be a plausible location for a supermassive black hole which astrophysicists believe is at the center of our galaxy [Cha98].

Several other natural noise sources and their corresponding emission spectra are enumerated in [Wes01]. Unsurprisingly, most pollution – be it environmental or electromagnetic – is man-made. Engine ignition in automotive devices, AC high-voltage power lines, microwave ovens, electric motors, communication transmitters, ... all these appliances, applications and systems contribute to an electromagnetically polluted radio spectrum [Mur03, Pat05]. These electromagnetic disturbances span a very broad frequency range, ranging from a few tens of Hz (typically 50–60, depending on the frequency of the power grid) to tens of GHz (frequency bands of modern communication systems). Extensive listings of man-made electromagnetic noise sources, intentional as well as

[1] Remarkably, the cosmic microwave background radiation contains more energy than has ever been emitted by all the stars and the galaxies that have ever existed in the history of the universe: the reason for this is that stars and galaxies (though very intense sources of radiation) occupy only a small fraction of space. When their energy is averaged out over the volume of the entire cosmos, it falls short of the energy in the microwave background by at least a factor of 10 [Cha98].

unintentional, functional as well as nonfunctional, are reported in [Wes01] and in [Kei87]. The threat associated to the criminal and covert use of intentional EMI has been discussed and illustrated with some examples and 'banana skins' in respectively [Wik00] and [Arm07].

4 Electromagnetism versus integrated circuit design

It is useful at this point to make a symbolic link between the elegant and complex theory of electromagnetism on one hand, and the intricate as well as exciting discipline of analog integrated circuit design on the other hand. Without doing so, the sense behind the accepted EMC measurement methods as well as widely recognized so-called EMC rule of thumb design rules is quickly lost, as has been motivated at the beginning of this chapter. A basic understanding of how both worlds tie into each other is quasi-mandatory. This is however not possible to accomplish without refreshing fundamental electromagnetic concepts, necessitating a vast array of calculations [Car95, Ida04, Sch02, Hea95]. In order to fit the present material on a few pages, the results of the computations are referred to but their derivation is omitted from the text: these exact analytical derivations can, however, be looked up in detail in the cited reference works.

Simply stated, all equipment which is using electricity or electromagnetic waves in its operation is fundamentally governed by physical laws which are elegantly merged and expressed in Maxwell's equations. In order to design and to understand the working of such equipment, Maxwell's equations or simplifications thereof (e.g. Ohm's law) are used, but only for the desired operation of the device. Indeed, owing to the huge amount of required calculations, it is usually not reasonable to examine all the possible electromagnetic interactions and couplings which are taking place in an arbitrary practical piece of equipment at the same time [Mar88]. Therefore, when considering and improving the EMC behavior of an electronic circuit, a set of design guidelines based on Maxwell's equations which minimize the likelihood of incompatibility occurrences must be used. The question of how these guidelines relate to the EMI frequencies is answered in the next paragraph.

4.1 Electrical length

An important step in understanding how electromagnetic waves influence a circuit's behavior is to introduce the *electrical length*, defined as the ratio of the physical length of a conductor, antenna, PCB track or device to the wavelength of the electromagnetic signal in question:

$$Electrical\ length = \frac{L}{\lambda} \tag{2.1}$$

Table 2.1. Electrical length of circuit components and basic physical connections for boundary EMI frequencies.

	Physical length	*EMI frequency*	*EMI wavelength*	*Electrical length*
IC tracks	10 µm–1 mm	150 kHz	2 km	0
		1 GHz	30 cm	0–0.003
IC bondwires, package leads, pins	1 mm–1 cm	150 kHz	2 km	0
		1 GHz	30 cm	0.003–0.03
PCB tracks	1 cm–10 cm	150 kHz	2 km	0
		1 GHz	30 cm	0.03–0.3
External wiring	10 cm–10 m	150 kHz	2 km	0–0.005
		1 GHz	30 cm	0.3–30

where L represents the length of the conductor, and λ stands for the wavelength of the electromagnetic signal. In general, any electric or electronic device whose electrical length is less than 1/20 or even 1/50 (in case of large impedance mismatches) can be considered as electrically short. Electrically short circuits can – depending on the desired accuracy – be fully described by basic circuit theory without having to worry about electromagnetism. On the other hand, the opposite is true for electrically long circuits: these require knowledge of electromagnetic theory in order to be solved and understood correctly [Sch02]. The major advantage of using the unitless electrical length relation resides in the fact that antennas and other radiating systems and coupling mechanisms become more easy to understand. Since the power of an antenna is proportional to its electrical length, a 50 Hz antenna, a 100 MHz antenna and a 1 GHz antenna all have the same radiation pattern and radiate with the same amount of energy if they have the same geometry with equal dimensions as measured by the electrical length, as well as identical material properties, as reported in [Sch02]. This property is rooted in the fact that Maxwell's equations are linear.

It is interesting at this point to observe how IC's, bondwires, package leads, pins, PCB tracks and external wires all relate to the electrical length, in order to check whether they are "electrically short", or "electrically long". As explained further in Sect. 8, EMC at IC level is currently measured between 150 kHz and 1 GHz. An overview enumerating the electrical length for both boundary EMI frequencies for typical circuit components and basic physical connections is presented in Table 2.1. Observe that taking the current EMC regulations into account, IC's themselves are electrically short. However, the interconnects lie very close to each other, and since the electric and magnetic field component are inversely proportional to the square of the distance in the near field as explained later on, parasitic coupling (crosstalk) may not be disregarded. Bondwires, package leads and pins start to behave as electrically long at larger EMI frequencies [Sic07b]. PCB tracks and external wiring, must be considered as being electrically long. The relevance of this will become more clear in a few paragraphs. Finally, it should be observed that the upper EMI frequency limit of 1 GHz is expected to be increased in the nearby future, meaning that IC tracks themselves will need to be considered as electrically long [Sic07c].

4.2 Near field versus far field

Although everybody is aware of the phenomenon of electromagnetic radiation, many misconceptions exist regarding this subject. This is mainly due to the confusing terminology as well as the fact that anything which is transmitted wirelessly using electromagnetic signals is commonly referred to as radiation. All this leads people to make basically inconsistent remarks like "disturbances owing to a 50 Hz radiation". As is explained in this section, far field radiation at 50 Hz is never encountered on Earth [Sch02].

Electromagnetic fields are basically divided into two types: near fields (storage fields) and far fields (radiating fields). Both are found mathematically when the magnetic and electric fields of an arbitrary moving point charge are developed using the Liénard-Wiechert potentials (directly originating from Maxwell's equations) [Hea95]. Extensive calculations yield that the electric ($\mathbf{E}$) and the magnetic ($\mathbf{B}$) field may be parsed into a velocity ($\mathbf{E}_v$, $\mathbf{B}_v$) and an acceleration ($\mathbf{E}_a$, $\mathbf{B}_a$) component, and that they are proportional to the distance (r) as follows [Hea95]:

$$\begin{aligned} \mathbf{E}_v, \mathbf{B}_v &\propto \frac{1}{r^2} \\ \mathbf{E}_a, \mathbf{B}_a &\propto \frac{1}{r} \end{aligned} \tag{2.2}$$

Integrating the Poynting vectors over the area of the sphere with radius r surrounding the moving point charge, yields the results that the energy which is associated to a static, or a constant velocity field remains attached to the charge, while the interplay of magnetic and electric acceleration fields constitute radiation, which detaches itself from the charge and travels off to infinity as an independent electromagnetic system. Both fields are now briefly clarified [Sch02, Hea95, Car95].

- **The velocity field** is commonly referred to as near field, reactive field or storage field, because it stores and transports energy in the near area of its source. Storage fields equally disappear when their source is turned off. Consider as an example an ideal inductor L_1 which is driven by an AC source. Ideally, no energy is lost in this inductor, since it generates a storage field, pumping power into this field which at the same time returns power to the circuit. This energy cycling is responsible for the 90 degrees phase shift between the voltage and the current. However, the moment a second inductor L_2 is placed in the near vicinity of the first one, the field from L_1 couples into L_2. If L_2 is shunted with a load resistor R_L, current flows through this resistor, and the reactive field allows energy to be transferred from the AC source to the resistor. Not surprisingly, this circuit behaves like a transformer, whereby energy is sapped from the AC source driving L_1 and dissipated in load resistor R_L. Note that the same effect could be achieved using ideal capacitors. A reactive field can therefore store energy, transport energy, or do both at the same time [Sch02].

- **The acceleration field** is commonly referred to as far field, or radiating field, because it radiates energy. As stated previously, these radiating fields propagate forever, even after their source is turned off. Antennas are focused on launching those fields, so that they propagate from the source, regardless of a receiving antenna [Sch02]. This energy loss appears as an energy dissipation across a resistor which is connected to the source: this resistance is called the radiation resistance. Observe that since acceleration can be positive or negative, energy is equally radiated upon deceleration. In the particular case when electrons are projected into a material in which they are stopped or slowed down, radiation results (as with X-ray beams) [Sch02].

The boundary between the near field and the far field is generally considered to lie around $2D^2/\lambda$, where D is the size of the transmitting antenna [Ben06]. For a dipole antenna, the reactive field becomes typically negligible at distances varying from 3λ to 10λ of the dipole [Sch02]. This explains why ordinary optical sources (e.g. a light bulb) appear as radiating sources and not as reactive sources, unless they are approached closer than a few µm. Referring to the beginning of this section, it is equally clear that a “disturbance owing to a 50 Hz radiation” is not possible on Earth because the disturbed appliance should be situated at a distance of more than thousand kilometers from the source to even get to the edge of the near field. However, disturbances associated to the 50 Hz power lines are possible (and in fact, occur quite often) as a result of a near field coupling [Sch02]. This differentiation is important when studying and deriving the basic concepts to reduce these disturbances [2].

[2] This explanation cultivates and sustains the impression that radiation is not present in the near field, while coupling does not occur in the far field. This practical approach is not mathematically complete, as is explained here. The electromagnetic field which is emanated by a transmitting antenna is expressed by the Poynting vector $\mathbf{E} \times \mathbf{H}$, in which $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field. Since an antenna is modeled

4.3 Radiation of a conductor

Recall from the previous paragraph that only accelerated charges radiate in the far field. In the near–constant velocity–field, electromagnetic energy is stored, transported and coupled. When a charged particle moves in a circle, or in any oscillatory manner, it experiences a sinusoidal acceleration. When a constant DC voltage V is connected across a conductor with resistance R, the current through the wire is defined by Ohms law ($I = V/R$). Although the net electron flow in the conductor is traveling at a constant speed, individually, the electron movement is quite random, and multiple collisions happen in-between the electrons, causing heat radiation [3]. The larger the current, the more collisions, and the more the conductor dissipates and radiates heat. Some of this heat radiation is propagated at lower energies, in the microwave and radio bands: this is the troublesome thermal white noise that is impeding the design of low noise circuits and low noise IC's. But, except for the heat, there is no radiation because the net current flow is constant [Sch02].

Assume now that the voltage source slowly oscillates in time. As long as the wavelength associated to the oscillating frequency is much larger than the length of the conductor, the electrical length is very small as expressed in (2.1), meaning that the acceleration (and the corresponding radiation) is small. This explains why electrically short antennas are not very efficient radiators [Sch02]. Mathematically, the radiated power (P_{rad}) of a conductor is found by calculating the time-averaged power density in the far field, and surrounding it by a sphere of radius r to calculate the total power traversing the outer surface of the sphere [Ida04]. As an example, for an electrically short Hertzian dipole antenna, the result of this calculation yields:

$$P_{rad} = I^2 \frac{\eta \cdot \pi \cdot (l')^2}{3 \cdot \lambda^2} \tag{2.3}$$

where l' is the length of the Hertzian dipole antenna, λ the wavelength and η represents the *far field wave impedance* of an electromagnetic wave, which is the ratio of the transverse components of the electric and magnetic fields in the far field. This ratio is equal to $\sqrt{\mu/\epsilon} \approx 377\ \Omega \approx 120 \cdot \pi\ \Omega$ in a lossless

by a RLC circuit, the generated electromagnetic field can be subdivided into a real field (generated by the resistive component) and a reactive field (generated by the capacitive and inductive components). The latter is predominant in the close proximity of the antenna, causing electromagnetic coupling: although the reactive field decays exponentially with increasing radius from the antenna, it is nevertheless present in the far field. Conversely, the real field, causing radiation, is expressed by the real part of the Poynting vector: it is dominant in the far field, but equally present in the near field. However, the near field is dominated by the reactive field (responsible for the electromagnetic coupling), while the opposite is true in the far field, which is pervaded by the real field (responsible for radiation). Strictly speaking, therefore, radiation at 50 Hz *is* encountered on earth: however, it can largely be neglected since its near field coupling largely dominates.

[3] Corresponding to radiation in the infrared region.

medium [4]. The far field wave impedance is a constant, which describes the physical transmission properties of a homogeneous medium. Observe that the radiation power is proportional to the current squared and the antenna length squared. It also depends on the intrinsic impedance of the medium in which the antenna radiates, and it is inversely proportional to the square of the wavelength [Ida04]. Using the definition of electrical length in (2.1), the radiated power is therefore proportional to:

$$P_{rad} \propto I^2, \quad (electrical\ length)^2 \tag{2.4}$$

Not surprisingly, previous expression indicates that high frequency signals radiate more readily than lower frequency ones over the same PCB track or conductor.

When the voltage source oscillation is increased even more, the AC current causes destructive interferences in the conductor: the radiation power is from then on no longer directly proportional to the antenna length squared, but follows more complex patterns [Sch02]. The associated integrals are quite difficult to resolve, but can be integrated numerically using integration methods. A full account of these calculations is provided in [Ida04]. The same calculations also explain why the well-known half wave dipole antenna is made slightly shorter than half a wave in practice [5] [Set97].

4.4 Basic EMC antenna concepts

Antenna theory and design is a very complex and elaborated research field, as can be duly appreciated in the quote at the beginning of this chapter. The object of this paragraph is to identify how unwanted and parasitic antennas appear in practical PCB and IC design. In this context, the two most basic types are studied, namely an electric dipole (Hertzian) antenna and a magnetic dipole (loop) antenna. As observed further on, the derived principles can be applied to reduce unwanted EMI coupling and pick-up from near and far fields. An electric dipole antenna and a magnetic loop antenna are depicted respectively in Figs. 2.2a and 2.2b. Observe that the magnetic field is not shown in the electric dipole antenna representation, and that the electric field is not drawn on the magnetic dipole antenna illustration: they have simply been omitted in order to not overload the figure unnecessarily. Furthermore, in the near field, the coupling is electrical for an electric dipole antenna, while solely magnetic for a magnetic dipole antenna as will be shown later on.

[4] The *far field wave impedance* is often defined as the wave impedance in the specialized literature. The reason why it is identified as "far field wave impedance" in this work, stems from the fact that a "near field wave impedance" is commonly distinguished as well: confusingly, both wave impedances describe different physical properties while being very often identified by the same term, which easily leads to confusion.

[5] In the strict sense, a half wave dipole antenna has a radiation impedance of $(73 + \mathrm{j}40)\ \Omega$: making the antenna slightly shorter cancels out the reactive component.

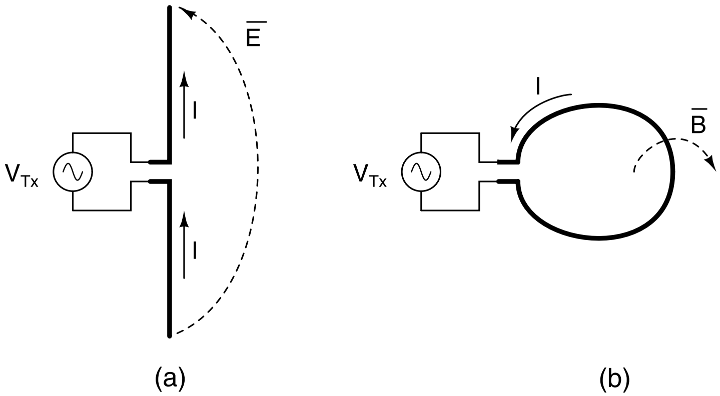
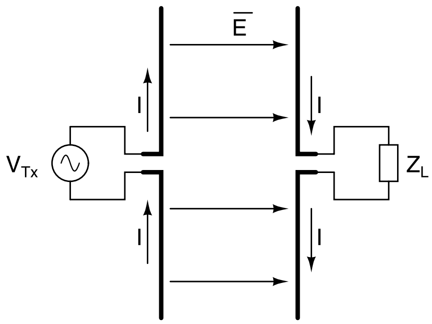


Figure 2.2. (a) Electric dipole (Hertzian) antenna. (b) Magnetic dipole (loop) antenna.

In the far field, radiation occurs for both antennas. In the first case, the electric dipole antenna generates an electric field. Consequently, this electric field produces a magnetic field, and the two fields propagate from the antenna. Similarly, in the second case, the loop antenna produces a magnetic field around the conductor: this magnetic field generates an electric field, and the two propagate away from the antenna. Upon arrival at the receiver, currents are induced on the receiving antenna: if the receiving antenna is an electric dipole antenna, it will receive the electric field, and the opposite is true for a loop antenna, which will receive the magnetic field mostly [Set97]. An ideal electric and magnetic dipole antenna with the same dimensions have the same radiation impedance and radiate the same power. Electric and magnetic components of far field waves are fixed by their far field wave impedance [Sch02]. The far field wave impedance is equal to the ratio of the magnitudes of the transversal electric and magnetic fields components, as defined anteriorly, and is approximately equal to 377 Ω in free space [Hea95].

This situation changes in the near field. The electric power of a transmitting electric dipole antenna is coupled on a nearby electric dipole antenna through its electric field, in the same way as capacitor plates (Fig. 2.3a). Parallelly, a nearby magnetic dipole antenna picks up the electric power which is coupled from an emitting magnetic dipole antenna through its magnetic field (Fig. 2.3b). Taking the ratio of the electric and magnetic field components in the near field, results in a quantity which has the same dimensions as the far field wave impedance, although it is a function of the distance to the antenna, while the far field wave impedance is a constant. Confusingly, this former parameter is equally defined as the wave impedance in most of the EMC related literature. In this work, this function is identified as the *near field wave impedance*, in order to distinguish it from the far field wave impedance. The near



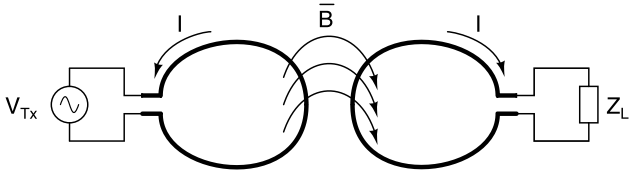


Figure 2.3. (a) Coupling between electric dipole (Hertzian) antennas. (b) Coupling between magnetic dipole (loop) antennas.

field wave impedance depends on the structure of the source, namely, on the antenna (or parasitic antenna type structure) which is generating the electromagnetic field. In particular, in the near field of an electric dipole antenna, the near field wave impedance (Z_E) increases, while in the near field of a magnetic dipole, the near field wave impedance (Z_H) decreases [Goe01]:

$$Z_E = \frac{|E|}{|H|} = \frac{1}{2 \cdot \pi \cdot \epsilon \cdot f \cdot r}, \qquad Z_H = \frac{|E|}{|H|} = 2 \cdot \pi \cdot \mu \cdot f \cdot r \tag{2.5}$$

where $|E|$ and $|H|$ are the electric and magnetic field components which are perpendicular to the propagation direction, r represents the distance to the respective electric and magnetic dipole antenna, and ϵ, μ equal the permittivity and permeability of the transmission medium, respectively. These relationships have led to the use of terms *high impedance electric field* and *low impedance magnetic field* [Goe01].

4.5 Radiated, induced and conducted disturbances

Throughout EMC regulations and corresponding literature, two types of disturbances are distinguished, namely conducted and radiated disturbances. In view of previous paragraphs, this is not correct, since both near field coupling as far field radiation have been lumped under the term "radiated". However, many authors prefer to talk about radiated disturbances, and make the near field and far field approximations ulteriorly. They define radiated disturbance as any interference which is transferred through a non-metallic (or simply non-conductive) medium by an electromagnetic field. Even the IEV (International Electrotechnical Vocabulary) adopted by the IEC in all their standards defines electromagnetic radiation as [IEV]:

1 *The phenomenon by which energy in the form of electromagnetic waves emanates from a source into space.*

2 *Energy transferred through space in the form of electromagnetic waves.*

Clearly, no difference is distinguished between near field coupling and far field radiation. This easily leads to confusion and misplaced observations, since there are many practical differences between near field coupling and far field radiation. As described previously, near field waves are usually dominated by either the electric either the magnetic component. As an example, the symmetrical design of a half wave loop antenna (resembling a magnetic dipole) generates a high magnetic field around the loop. On the other hand, a classic Hertzian half wave dipole antenna (resembling an electric dipole) generates a strong electric field perpendicular to the dipole. In this work, the same notations and definitions as in [Sch02] are followed, and the electromagnetic disturbances are grouped into three distinct categories:

- **Induced interferences (near field coupling):** unlike radiated interferences, near field waves are very often dominated by either the magnetic, either the electric component. Circuits pick up radiated energy if they contain electric or magnetic antenna-like elements, like dangling conductors and loops. It has previously been illustrated that long conductors are susceptible to electric fields, while large conductive loops are especially susceptible to magnetic fields. In addition, the better the receiving antenna's impedance is matched to the near field wave impedance at that particular distance from the transmitting antenna, the more energy is transported. As expressed in (2.5), electric near fields have a high near field wave impedance while magnetic near fields have a low near field wave impedance. Therefore, *high impedance circuits or nodes are particularly susceptible to electric near fields, while low impedance circuits or nodes are particularly susceptible to magnetic near fields* [Sch02]. Finally, near field interferences increase with larger fields, higher frequencies and shorter distances. Induced interferences are often referred to as capacitive and inductive crosstalk, depending on the coupling being electric or magnetic.

- **Radiated interferences (far field radiation):** these interferences are constituted of purely electromagnetic transversal waves. They will therefore easily radiate (and parallelly, be received) on long loops (forming loop antennas) and long conductors (forming Hertzian antennas). Several theoretical analyses have been developed to describe the effect of radiation on e.g. an interconnecting cable or a transmission line [Kon94].

- **Conducted interferences:** this type of interferences comprises the unintended signal energy that leaves an integrated circuit through its outside connections and propagates through a conductor, e.g. a metal wire or a PCB track. Conducted interferences are in general caused by simultaneous switching noise (SSN), which generate fluctuations in e.g. a power bus. Because of these disturbances, the signals which are referenced to a particular power bus may exhibit high frequency voltage fluctuations if there is not enough decoupling or if these interferences are particularly important. The strongest currents are usually flowing in the power supplies and the ground pins [Ben06]. Consider the example of conducted electromagnetic noise which is generated on the power lines in a switched mode power supply (SMPS) [Car94]. These conducted interferences are usually dealt with using proper filtering and a good grounding strategy. When two or more current loops share a common conductor (e.g. the ground plane), one current loop may influence and alter the second current loop: this effect is identified as crosstalk via a common impedance. These issues are usually resolved by using adapted layout techniques, like point coupling (to each loop its own conductor) or a strip shaped reference (by providing all the tracks on one side of a circuit with a strip-shaped reference), and by keeping the common impedance at a low value [Goe01].

4.6 Practical example

In order to illustrate the implications enumerated in the previous paragraphs from a practical point of view, consider the PCB layout which is depicted in Fig. 2.4a. An arbitrary integrated circuit on this PCB is supplied by two tracks, connecting its positive (V_{dd}) and negative (V_{ss}) supply terminals to an ideal DC voltage source V_{DC} (e.g. a lithium battery). As observed in Fig. 2.4a, the PCB traces form a small square-shaped loop, with 2 cm side length. Assume that there is a time-varying, low frequency magnetic field, which is perpendicular to this loop (Fig. 2.4b). The parasitic EMI voltage generated between the supply terminals of the IC (V_{emi}), is expressed by the Maxwell-Faraday equation [Arc04]:

$$\oint \mathbf{E} \cdot dl = -\iint \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} \tag{2.6}$$

where **E** and **B** represent respectively the electric and the magnetic field. As long as the wavelength of the magnetic field is large compared to the length of the loop, then the magnetic flux is constant over the loop area, and previous

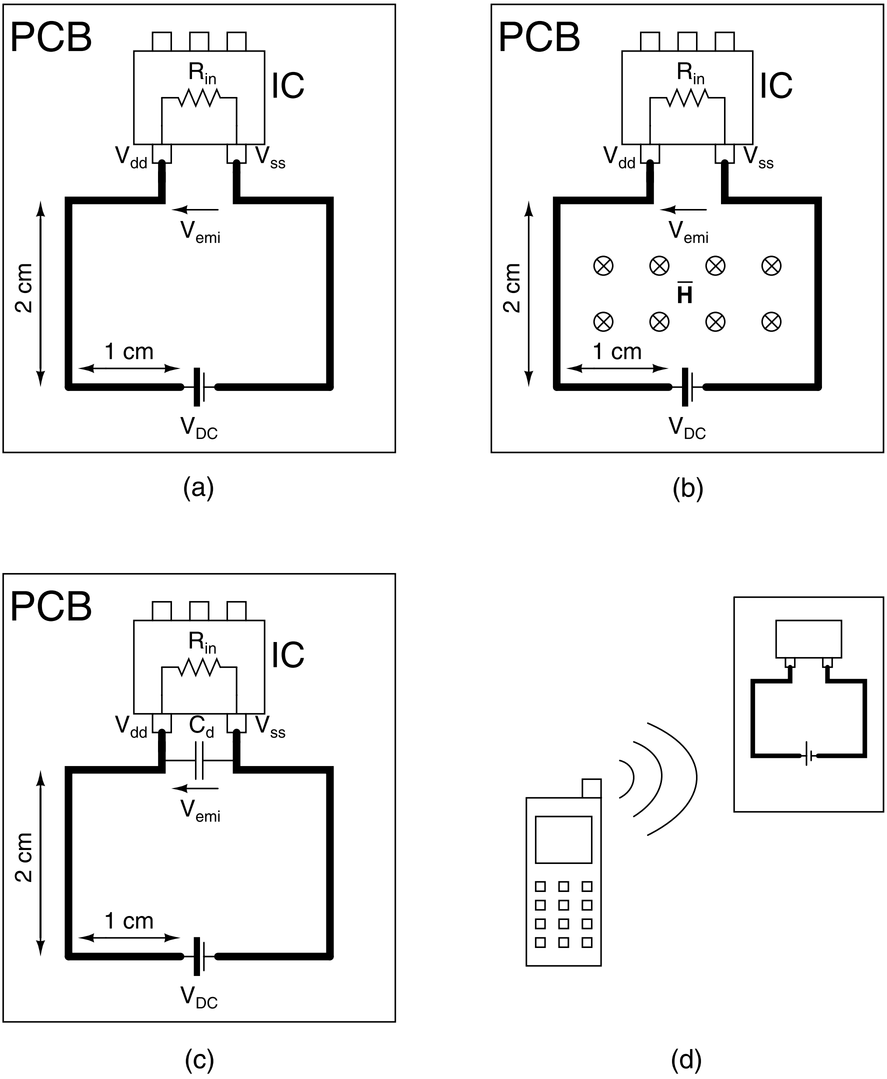


Figure 2.4. (a) PCB with the supply tracks connected to the IC forming a small loop. (b) With the presence of a magnetic field perpendicular to the loop. (c) With a decoupling capacitor. (d) Nearby a transmitting mobile phone.

equation can be rewritten as the Faraday's law of induction [Arc04]:

$$V_{emi} = \mathcal{E} = -\frac{d\Phi_B}{dt} = \omega \cdot \mu_o \cdot |H| \cdot A \tag{2.7}$$

where $\mathcal{E}$ is the electromotive force, Φ_B is the magnetic flux, ω is the angular frequency of the time-varying magnetic field, μ_o is the permeability of free space, $|H|$ is the magnitude of the magnetic field and A is the surface enclosed by the loop. Assuming that the frequency of the time-varying magnetic field is equal to 1 MHz and that its field strength is equal to 2 A/m, the induced EMI voltage at the supply terminals of the IC is derived as follows:

$$\begin{aligned} V_{emi} &= (2 \cdot \pi \cdot 10^6 \text{ [Hz]}) \cdot (4 \cdot \pi \cdot 10^{-7} \text{ [H/m]}) \cdot (2 \text{ [A/m]}) \cdot (0.02^2 \text{ [m}^2\text{]}) \\ &= 6.3 \text{ mV (RMS)} \end{aligned} \tag{2.8}$$

Unfortunately, this value increases with the frequency of the time-varying magnetic field, and can therefore attain considerable values. As an example, if the frequency of the magnetic field is increased to 10 MHz, the induced EMI voltage is equal to 63 mV. For this reason, it is important to decouple the supply lines very close to the IC pins (and preferably, add internal decoupling capacitors as well). Consider the case when a decoupling capacitor of 100 nF is placed close to the IC terminals, as illustrated in Fig. 2.4c. Assuming that the on-chip supply impedance between V_{dd} and V_{ss} (R_{in}) is negligible compared to this 100 nF capacitor, and assuming that the series inductances of the PCB tracks are approximated using the rule of thumb predicting 1 nH per mm conductor length [Goe01], yielding a total inductance of 80 nH for the full length of the loop, the voltage shunted across the supply terminals is reduced to 2 mV instead of 63 mV. Previous example illustrates the need of minimizing the occurrence of conductive loops, and highlights the necessity of placing decouple capacitors close to the IC pins.

Consider now that a high frequency electromagnetic field (e.g. providing from a mobile phone) surrounds the PCB in question. Since the loop formed by the PCB tracks has a length which is equal to 8 cm, it behaves as a half wave loop antenna, receiving the GSM frequencies situated at 1800 and 1900 MHz:

$$\frac{\lambda}{2} \approx 8 \text{ cm} \rightarrow f \approx \frac{c}{\lambda} \approx 1.875 \text{ GHz} \tag{2.9}$$

The transmission equation developed by Friis, provides a straightforward way of calculating the power which is ideally received by an antenna (P_r), from another antenna some distance away, transmitting a known amount of power (P_t) [Set97]:

$$\frac{P_r}{P_t} = G_t \cdot G_r \cdot \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2 \tag{2.10}$$

where G_t, G_r express the antenna gains of respectively the transmitting and receiving antennas, and R is the distance between both antennas. Consider that a nearby mobile phone, which is situated at 1 m distance of the PCB, is transmitting at 1.875 GHz, with a peak transmitted power of 2 W, as depicted in Fig. 2.4d. Assuming out of simplicity that the mobile phone's antenna is a half wave dipole antenna, means that both antenna gains are equal to 1.64. Inputting the previous data in transmission equation (2.10), yields:

$$P_r = (2\ [\mathrm{W}]) \cdot (1.64)^2 \cdot \left(\frac{0.16\ [\mathrm{m}]}{4 \cdot \pi \cdot 1\ [\mathrm{m}]}\right)^2 = 0.87\ \mu\mathrm{W} \tag{2.11}$$

Ideally, a maximal power of 0.87 μW is received on the PCB tracks. Considering that at the frequency of interest, the internal resistance seen in the supply terminals on-chip (R_{in}) equals 75 Ω, and consequently matches with the loop antenna impedance, the EMI voltage between the supply pins is calculated as follows:

$$V_{emi} = \sqrt{P_r \cdot R_{in}} = \sqrt{0.87\ \mu\mathrm{W} \cdot 75\ \Omega} = 256\ \mathrm{mV\ (RMS)} \tag{2.12}$$

As is apparent from previous numerical examples, no big loops are necessary to generate significant interference levels at IC terminals. Maximal care must therefore be ensured while designing PCB and circuit layouts.

5 Intra-chip versus externally-coupled EMC

EMC issues associated with integrated circuits are generally classified as externally-coupled EMC or as intra-chip EMC [Ben06]:

- Externally coupled EMC problems result when noise which is generated externally interferes with the IC (EMS), or conversely, when noise generated in the IC, interferes with circuits and devices which are off-chip (EME). In this work, the former is considered, since this research is focused on the design of analog integrated circuits which have a higher degree of immunity against EMI. Owing to the small size of integrated circuits, they are in themselves not easily disturbed by radiated and induced disturbances because the on-chip interconnections they harbor are tiny and too small to function as effective antennas (refer to Table 2.1) [Mey03]. Bondwires, package leads, leadframe and pins may intercept radiated, induced and conducted high frequency disturbances. However, the main contribution comes from the noisy and relatively long PCB tracks to which IC's are ultimately connected [Fio01]. Depending on the total levels of conducted EMI which are present on such a PCB track, an unfortunate IC may not work correctly any longer: even worse, it may not work at all (Fig. 2.5). Adverse radiated and induced EMI effects can be alleviated by proper PCB layout and shielding techniques ([Goe01]), as observed previously. Preventing conducted EMI to access or emanate to or from a given IC pin, depends on the circuit to which the PCB track is connected. For instance, common-mode chokes and other discrete components (like decoupling capacitors)

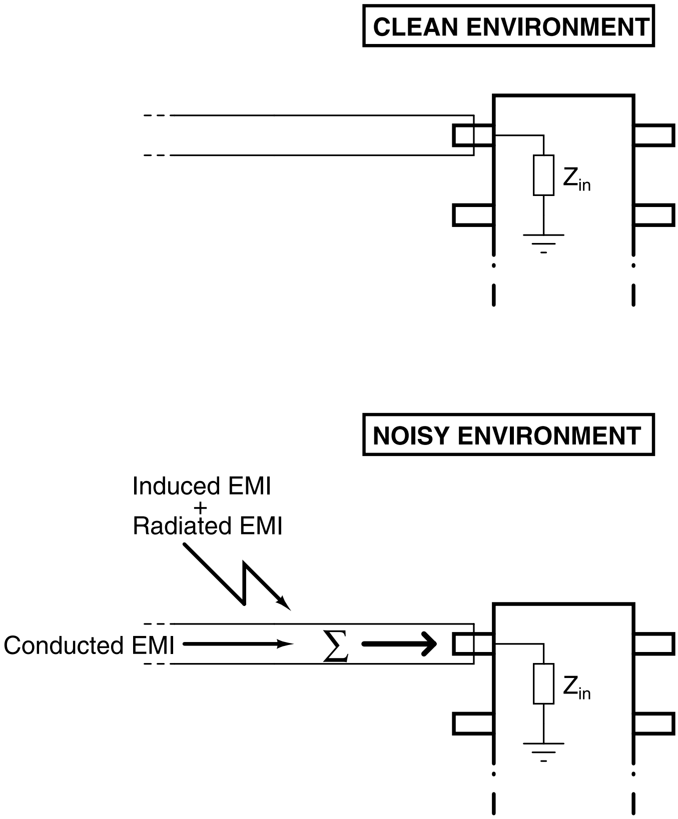


Figure 2.5. Schematic representation of induced, radiated and conducted EMI injected on a PCB track connected to an IC.

reduce conducted EMI on PCB tracks: however, their presence is not always wanted nor possible. Proper IC design should therefore focus on reducing the conducted EMI which is injected into PCB tracks (EME aspect). On the other hand, a certain robustness is required from integrated circuits themselves, meaning that they should be able to withstand a certain level of total conducted EMI before their correct operation is impaired. This is especially true when designing and processing IC's that are connected to unspecified PCB's, or to PCB's that are not EMC-wise characterized. Ideally, combining a proper PCB layout which reduces radiated and induced EMI, with IC's which produce less conducted EME and have a decreased EMS, leads to a full electronic system which is EMC. Conjunctively, previous sentence illustrates the necessity of including Sect. 2 and using indubitate definitions and abbreviations.

- Intra-chip EMC problems occur on the same IC, when a signal or noise created in one or more (sub)circuits interferes with the operation of another circuit block. Because on-chip distances are small, radiated intra-chip interferences are not occurring, because the far field stretches outside the IC itself. However, induced and conducted interferences are likely to occur. This results in two common IC problems, namely crosstalk and simultaneous switching noise [Ben06]:
  - **On-chip crosstalk** between two circuits or circuit elements is defined as the ratio between the unintentional signal voltage appearing across a load impedance to the signal voltage in the source circuit. Basically, three types of parasitic coupling may result in crosstalk: electric field coupling, magnetic field coupling and common impedance coupling [Goe01]. Common impedance coupling occurs when multiple current paths share the same conductor. The finite impedance of the latter generates a voltage drop which appears in the current loops sharing this conductor, and which is proportional to the total current flowing through it, as well as to its impedance. Electric field coupling can be represented by a capacitor between two tracks: in the same way, magnetic field coupling can be modeled by coupled inductors. On-chip crosstalk can be reduced by a good routing strategy [Cat95b].
  - **Simultaneous switching noise** (SSN) is a particular case of common impedance crosstalk when subcircuits on a same IC share the same power distribution bus. It is also known as ground bounce, power bounce or di/dt noise. It can be reduced by using on-chip decoupling capacitors and by observing a consistent grounding strategy [Ben06]. Distortion measurement results on the output waveform of an integrated opamp owing to substrate noise generated by surrounding logical circuitry have been presented in [Cat95a].

6 Analog versus digital integrated circuits

Digital integrated circuits are inherently less susceptible to EMI than their analog counterparts: this stems from the fact that digital circuits have the benefit of using thresholds between logic levels, and are hereby predisposed to have a natural resistance against interferences. However, it should be pointed out that although digital integrated circuits exhibit a lower susceptibility to EMI, this does not mean that they are completely immune to it. EMI has been observed to have two distinct effects on digital devices, namely false switching (static failure) which occurs when the EMI level is large enough to change the logic state of a digital signal, and EMI induced delay, which is the change of propagation delay owing to the EMI. It has been illustrated that the latter occurs at much lower amplitudes of EMI than the former [Lau95, Cha97]. In

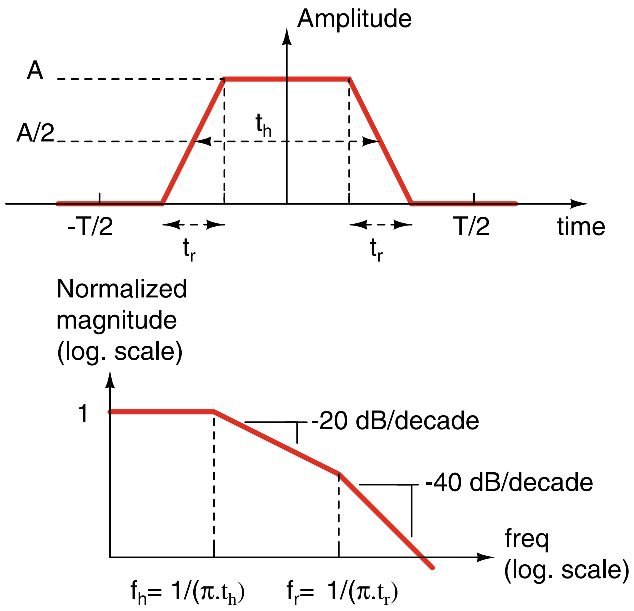


Figure 2.6. Shape and corresponding emission spectrum of a trapezoidal signal.

a worst case situation, depending on the total EMI level, digital integrated circuits can botch a complete data operation because some significant bits were permanently flipped into another state owing to a particularly strong EMI injection. This evidently may lead to a completely false information processing from which the system can not recover easily, and that may even require a reset [Tro85]. Conversely, the same disturbance would have barely caused a brief "crackle" in an analog circuit [Goe01]. Nevertheless, as long as realistic EMI levels are considered and if some basic precautions are taken in order to reduce and prevent the injection EMI into a particular digital integrated circuit, digital integrated circuits exhibit a higher immunity to EMI than analog ones, because of their threshold levels.

Additionally, digital circuits typically have a very fast switching behavior: this causes sharp transients, which induce a lot of high-frequency components in the electromagnetic spectrum, consequently increasing the EME. Since analog circuits process the signals in a continuous way, they tend to have a much smaller emission spectrum. As an example, Fig. 2.6 depicts the approximated spectrum of a periodic normalized trapezoidal signal, using the "three-straight-line" approximation described in [Goe01]. Observe that at frequencies above f_h, the asymptotic amplitude of the spectral components is inversely proportional to frequency (-20 dB/decade) and at frequencies above f_r it is inversely proportional to the square of the frequency (-40 dB/decade). This underlines the necessity of reducing fast switching times, in order to achieve a smaller EME spectrum. Other design possibilities to reduce the EME in IC's include a reduction of the clock frequency, and the use of a small resistor in the power supply lines in order to dampen the oscillations generated by fast switching [Loc04]. Dedicated design techniques are used to alleviate EMI in digital IC's: as an example, logic family comparisons show that the enhanced current steering logic (ECSL) constitutes the best compromise in terms of performance and induced power supply noise [Zho08].

7 EMC in automotive applications

The automotive industry is particularly interested in increasing the EMC performances of electronic circuits and systems, since the automotive electromagnetic environment can be very severe and (owing to the inherent mobility of automotive applications), most unpredictable [IET]. In order to ensure that vehicle accidents are not caused as a result of EMC incompatibilities, vehicle manufacturers as well as electronic sub-assembly (ESA) companies go to enormous lengths (driven by severe product liability legislation) to ensure that their vehicles do not suffer from EMC problems. It has been claimed that occasional and untested EMI events that could cause a safety incident only once during a 10-year vehicle life, can still expose drivers to safety risks comparable with those of the world's most dangerous occupations [Arm08] [6]. In the next few years, the importance of EMC-proof applications within a vehicle is bound to increase even more, since fully electronic braking, steering and anti-collision systems are likely to be introduced in the present and nearby future. This implies that electromagnetic compatibility is of paramount importance in order to assure the correct functioning of an automobile [Ale08].

8 Immunity measurement methods for IC's: IEC 62132

Clearly, no equipment can sustain gracefully unlimited levels of electromagnetic aggression, without suffering an impaired or reduced operation at a certain point. When designing to achieve an increased EMC behavior, a realistic assessment of the threat levels during normal operation must be made [Mar88]. EMC measurement setups for automotive electronic systems are defined in standards such as in the International Special Committee on Radio Interference

[6] Quoting from [Arm08]: *"A simple analysis based on reasonable assumptions for a 6-cylinder engine at 2000 rpm with spark-ignition transients lasting 50 ns, shows that in each minute there is a 0.001% likelihood of an overlap of at least 50% with a 100 ns transient that occurs once every minute (on average, for example due to the actuation of an electric motor or solenoid). If the vehicle is driven for 1 hour/day, 5 days/week, 40 weeks/year, the likelihood of such an overlapping pulse event is 12% per year. And if the overlapping pulses caused an electronic sub-assembly (ESA) to malfunction with a 1% chance of death, the driver would have a risk of death of 0.12% per year. This compares with a death rate of about 0.1% per year for very hazardous occupations (e.g. oil industry divers)".*

(Comité International Spécial des Perturbations Radioélectriques) (CISPR) 25 for parasitic emissions, and in the International Organization for Standardization (ISO) 11452 for susceptibility to EMI [Ram09]. Since IC's are generally the main cause of EMI related malfunctioning and disturbance in electronic equipment, there has recently been considerable demand for simple, reliable, and standardized measurement methods focusing only on IC's.

The International Electrotechnical Commission (IEC) is one of the international standards organizations which are addressing the need for standardized IC EMC test methods. The IEC's IC EMC standards are sponsored by the IEC sub-committee (SC) 47A (integrated circuits), which is a part of the IEC technical committee (TC) 47 (semiconductor devices). SC 47A created working group (WG) 9 to prepare international standards for test procedures and measurement methods to evaluate the EMC of ICs [Car04]. Where possible, WG 9 coordinates the preparation of its standardized test methods with methods standardized or in progress with industry and national standards bodies including, but not limited to, the Society of Automotive Engineers (SAE) in the United States and the Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE) in Germany [Car04]. SC 47A, WG 9 has released two main standards for measuring the EMC of integrated circuits: the first one (released in 2001) for measuring radiated and conducted emission [IEC 61967], and the second one (released in 2003) for measuring immunity [IEC 62132]. A short but very comprehensive overview describing previous standardized immunity measurements at IC level is given in [Car04] and in [Ben06]. Nowadays, the upper EMI frequency used in the actual EMI immunity measurement methods is limited to 1 GHz. Owing to the higher process integration, higher switching speeds and higher circuit complexity, the demands for measurements at higher EMI frequencies grow stronger, and it is very likely that this upper limit will be stretched to 3 GHz in the near future [Sic07c]. Following the requirements set by the International Technology Roadmap for Semiconductors (ITRS) for the coming years [ITRS], it is expected that even higher EMI frequencies will need to be addressed in the measurements. Future trends about IC technology and a corresponding tentative EMC roadmap until 2020, with a strong focus on embedded system-on-chips (SOC) for automotive and consumer electronics applications, is presented in [Sic07c]. Promising research results addressing the EMI frequency-band between 3 and 10 GHz results have been published: one of these is the near field scan immunity (NFSI) measurement method [Boy07]. Above 10 GHz, dedicated IC measurement methods do not exist yet [Sic07c]. Future plans include EMC measurements up to 40 GHz, but much research is still needed in this area [Sic07c].

- **TEM cell and GTEM cell:** The transverse electromagnetic mode (TEM) cell, as well as its high frequency variant – Gigahertz TEM (GTEM) cell – are used for measuring the IC immunity to electromagnetic fields [Ben06].

The TEM cell is nothing else than an expanded rectangular waveguide with an inner conductor which is called the septum. Electromagnetic interference is injected in the septum, and a test PCB containing the IC to be measured is inserted in an aperture on the outer wall of the TEM cell, with the chip inside the cell. The maximum frequency that can be used in the TEM cell is set by the resonance of the lowest higher order mode, which is dependent on the size and the shape of the cell. Typical TEM cell dimensions can handle a 200 to 300 MHz cut-off frequency. The GTEM cell was designed to overcome the frequency limitations of the TEM cell, and so it stretches up to frequencies of several GHz (typically 18 GHz). Since the TEM cell is a radiative measurement method, it is quite cumbersome to use this method as such in circuit simulations. For many integrated applications, the TEM/GTEM cell measurements constitute the final EMC compliance tests.

- **Workbench Faraday cage (WBFC):** The workbench Faraday cage is a standard method for carrying out conducted immunity measurements [Ben06]. However, the scope of this measurement setup is very restricted, since it is only applicable to electronic products that are connected to external wiring: it is therefore not a suitable measuring method to measure e.g. small wireless appliances. Finally, it is again not practical to use this method as such in circuit simulations.

- **Bulk current injection (BCI):** The measurement reproduces the induced current that is generated in the real world by electromagnetic fields which are coupling into the wires of a system [Ben06]. Two current probes are used: one for injecting the disturbance in the wire, and the other one for measuring the level of injected current. The EMI frequency to be measured ranges from 10 kHz to 1 GHz according to the IEC standard, although in practice, the upper EMI frequency does not exceed 400 MHz [Ben06]. The main problem which prevents this measurement method to be used in circuit simulations is the fact that the magnetic coupling between the current probe and the wire is not exactly known. The typical BCI measurement configuration is represented in Fig. 2.7. For many integrated applications, the BCI measurements are used for EMC pre-compliance testing.

- **Direct power injection (DPI):** In this measurement setup, the EMI disturbance is injected into the pin of a component through a decoupling block [Ben06]. In practice and by default, this decoupling block is a capacitor (C_c) of 6.8 nF. The source impedance of the EMI source R_s is set to 50 Ω. The default value of protection resistor R_p is 0, although it may be increased up to 100 Ω if the application requires it. The EMI frequency to be measured ranges from 150 kHz to 1 GHz. The DPI measurement setup

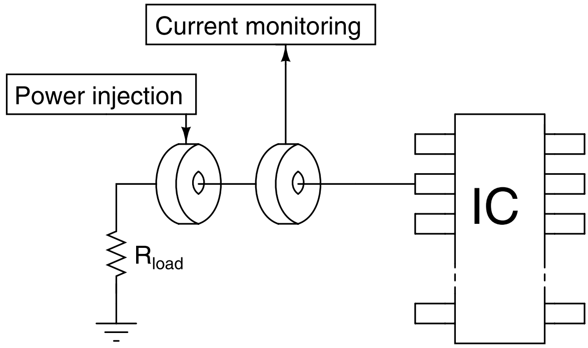


Figure 2.7. Bulk current injection measurement setup.

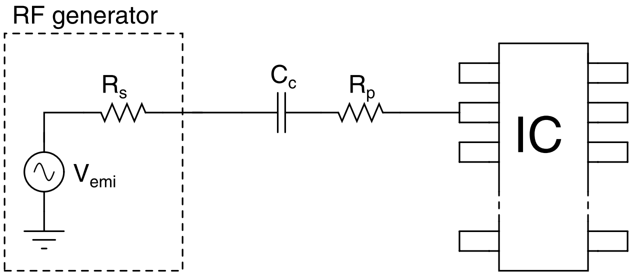


Figure 2.8. Direct power injection measurement setup.

Table 2.2. DPI injected power levels.

Zone	*Forward injected EMI power (W)*	*EMI source voltage amplitude (V)*	*Notes*
1	1 to 5	20 to 44.7	Direct connection of the I/O to the environment (e.g. LIN)
2	0.1 to 0.5	6.3 to 14.1	Direct connection of the I/O to the environment, but some R-L-C low-pass filtering is available (e.g. sensor interfaces)
3	0.01 to 0.05	2 to 4.5	No direct connection of the I/O to the environment (e.g. interfacing with IC's mounted on the same module)

is depicted in Fig. 2.8. The nature of this measurement makes it very suitable to be incorporated directly in circuit simulators. The DPI specification further states that a forward power is injected through the coupling block in the IC pin no matter whether it is reflected or absorbed. The forward injected power level depends on the application of the IC and on the IC pin itself: a summary is presented in Table 2.2 [Mey03]. Observe that the relation between the forward injected EMI power (P_{f_EMI}) and the EMI source voltage amplitude (V_{emi}) is expressed as follows:

$$V_{emi} = 2 \cdot \sqrt{2} \cdot \sqrt{P_{f\_EMI} \cdot R_s} \tag{2.13}$$

For many integrated applications, the DPI measurements are used for EMC pre-compliance testing.

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