Jean-Michel Redouté
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EMC of Analog Integrated Circuits

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Preface

Environmental electromagnetic pollution has drastically increased over the last decades. The omnipresence of (wireless) communication systems, new and various electronic appliances and the use of ever increasing frequencies, all contribute to a noisy electromagnetic environment which acts detrimentally on sensitive electronic equipment. Integrated circuits constitute the beating heart of almost any given electronic system nowadays: luckily, owing to their small sizes, they are not easily disturbed by radiated disturbances, because their tiny on-chip interconnections are much too small to function as effective antennas. However, the ultimate contribution comes from the conducted interferences which are present on the noisy and relatively long printed circuit board tracks, used to connect and interconnect the integrated circuits in question.

Aside from a polluted electromagnetic spectrum, integrated circuits must be able to operate satisfactorily while cohabiting harmoniously in the same appliance, and not generate intolerable levels of electromagnetic emission, while maintaining a sound immunity to potential electromagnetic disturbances. As different electronic systems are compactly integrated in the same apparatus, the parasitic electromagnetic coupling between these circuits sharing the same signal, power and ground lines, is a critical design parameter that can no longer be safely excluded from a product design flow. This dense integration level links the electromagnetic compatibility (EMC) issue of integrated circuits to the graceful coexistence between systems: as an example, Bluetooth, GSM and WiFi services have to coexist and operate in harmony within the crammed confinement of a modern mobile phone.

Distinct frequency allocations provide a shield against electromagnetic interferences by separating the signal spectra of different systems from each other: nevertheless, the intrinsic nonlinearity of active devices may cause the demodulation of interfering out of band signals, whereby spurious signals tend to appear in the frequency band of the exposed circuit. Furthermore, these out of band disturbances may induce a severe distortion of the wanted signals (which is certainly not recommended), and DC shift errors on sensitive nodes in the respective circuit, hereby possibly driving the latter out of its correct operation mode (which is even less acceptable). Analog circuits are in practice more easily disturbed than their digital counterparts, since they don't have the benefit of dealing with predefined levels which ensure an innate immunity to disturbances.

The objective of the research domain presented in this book is to improve the electromagnetic immunity of considered analog integrated circuits, so that they start to fail at relevantly higher conduction levels than before.

J.-M. Redouté and M. Steyaert

Contents

Chapter 1

Introduction

Medical technicians taking a heart-attack victim to the hospital in 1992 attached her to a monitor/defibrillator. Unfortunately, the heart machine shut down every time the technicians turned on their radio transmitter to ask for advice, and as a result the woman died. Analysis showed that the monitor unit had been exposed to exceptionally high fields because the ambulance roof had been changed from metal to fibreglass and fitted with a long-range radio antenna. The reduced shielding from the vehicle combined with the strong radiated signal proved to be too much for the equipment.

—Quoted from [Arm07]

1 The pioneers of wireless communication

Since ancient times, people have been aware of the magnetic properties of the lodestone. According to Aristotle, Thales of Miletus attributed the attraction of the lodestone on iron to the fact that "it has a soul" [Ida04]. The earliest mention of the magnetic attraction of a needle appears in a Chinese work composed by Louen-heng between 20 and 100 AD, stating that "a magnetic stone attracts a needle" [Shu54]. In 1600, William Gilbert (who first used the adjective *electric* after the Greek word for amber, *electron*) published his work on magnetism and electricity ("De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure"), with which the modern history of both subjects begins [Whi60]. However, both electricity as well as magnetism were still considered to be separate entities. In 1820, the Danish scientist Hans Christian Ørsted, Professor of Natural Philosophy in Copenhagen, observed during a course of lectures on "Electricity, Galvanism and Magnetism" that a compass needle deflects from the magnetic north when the current in a nearby electric wire is switched on [Whi60]. After intensive research and diverse experiments, Ørsted, a strong believer in the unity of nature's forces, came to the conclusion that an electric current flowing through a conductor generates a magnetic

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field which is circular around the conductor and whose intensity is directly proportional to the current itself. As a consequence, he established the unique relationship existing between magnetism and electricity, and the scientific discipline of electromagnetism was born out of his findings. The four Maxwell's equations, which were presented by their author in 1864, combine the relationships between electricity and magnetism in a very concise way: these equations combine the works of Faraday, Ampère, Gauss, Thomson and others, and elegantly merge the properties of electricity to those of magnetism in a united mathematical framework [Whi60]. From then on, it was just a matter of time before electromagnetism led to wireless and wireline communication.

Radio is considered as one of the most fabulous and wonderful inventions fathered at the end of the 19th century, leaning on the magic side since the scientists, engineers, inventors and pioneers having developed it could actually not fathom exactly how it worked at that time. An interesting and very entertaining account of the history of radio communication is presented eloquently in [Wei03]. Owing to the multitude of people who contributed to a larger or lesser extent to the invention of radio wave communication, it would be very unjust to credit just one as the real inventor of the radio, although some of them (like Lee the Forest) did not hesitate to monopolize this prestigious title for themselves. The numerous experiments, developed equipment and test setups all testify to the fact that wireless communication through radio waves is a shared invention: this fact can amongst others be appreciated in [Phi80], in which an interesting summary of early radio detectors is presented. However, some important milestones in the tumultuous history of radio can objectively be distinguished.

In 1888, Heinrich Rudolf Hertz developed the first wireless receiver and transmitter in his laboratory and measured the generated electric field strength as well as its polarity: he hereby demonstrated through experimentation that electromagnetic waves exist, and that they travel a certain distance through air [Whi60]. In 1893, after successfully winning the "war of currents" by establishing the indisputable superiority of the alternating current power system over the anterior DC power system supported by Thomas Edison [1], brilliant Nikola Tesla publicly demonstrated the principles of radio waves and filed his radio patent (US645576) in 1900. One year later, in 1901, young Guglielmo Marconi combined previous knowledge and basically without inventing anything new, successfully set up the first transatlantic radio communication between Saint John's (Newfoundland) and Poldhu (Great-Britain) by transmitting the Morse code of the letter 'S' (dot-dot-dot), hereby spanning a distance of approximately 3500 km. When presented with this fact, Nikola Tesla reacted dryly

[1] This fact accounts for the prevalence of the AC power system nowadays.

that Marconi was actually using seventeen of his patents. Suddenly, and quite against all odds, Marconi obtained the famous "four-sevens" (British patent number 7777) patent on radio in 1904, after the US patent Office mysteriously reversed its decision of granting Tesla the patent of the radio which had been filed a few years earlier. Five years later, Marconi was even awarded the Nobel prize for physics (co-shared with Karl Ferdinand Braun) in 1909. This famous British "four-sevens" patent and its equivalents in other countries, as well as the acclaimed Nobel prize, triggered a set of unrelenting and very brutal patent legal disputes between Marconi and Tesla, often leading to arbitrary rulings which varied between the full nullification to the full acceptance of Marconi's radio patent. In 1943, a few months after Tesla's death, this legal onslaught was resolved in the United States when the US Supreme Court upheld Tesla's original radio patent (US645576), confirming the importance of prior research which had been conducted by Nikola Tesla, Oliver Lodge, John Stone Stone and others. However, this decision which finally recognized and credited the genius of Nikola Tesla was not fully guided by pure altruism: since the Marconi Company was suing the United States Government for the use of its patents during the first World War, the Court simply avoided this action by restoring the priority of Tesla's patent over Marconi.

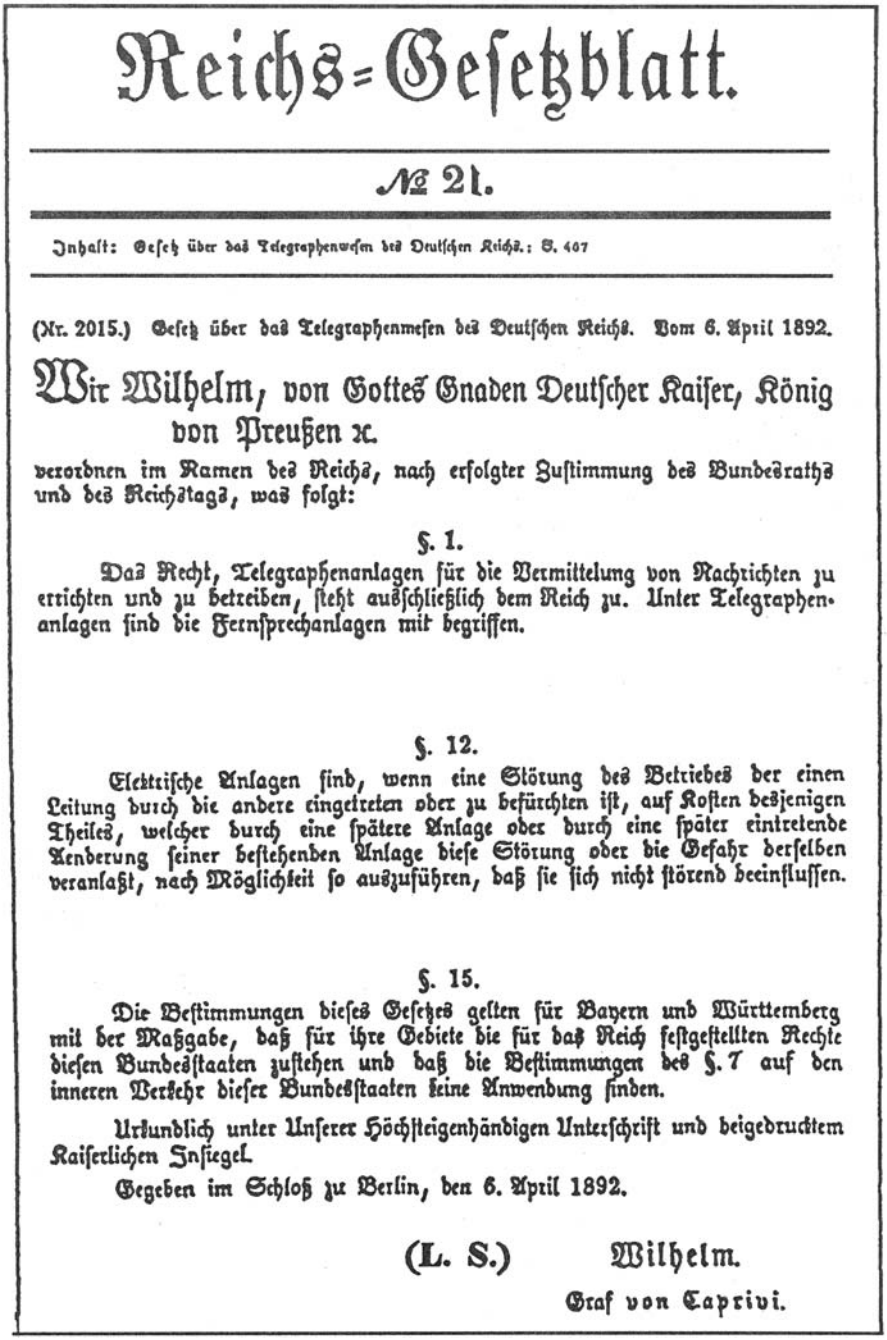
Since these early radio days, the quantity of wireless communication devices has been continuingly increasing, and the amount of electromagnetic compatibility (EMC) problems between communication appliances coexisting in the same environment have been increasing simultaneously. It would be incorrect, however, to attribute the origin of electromagnetic compatibility issues solely to the presence of wireless communication systems.

2 Evolution of awareness of electromagnetic compatibility

In 1892, an edict issued by the German parliament and signed by Wilhelm II, Kaiser of Germany and King of Prussia [2], indicated that in the event electromagnetic disturbances perturb the correct operation of telegraph cables or telegraph equipment, the owner(s) of the appliance(s) that is (are) responsible of causing the disturbances should solve the problem and indemnify the owner(s) of the telegraph cables and telegraph equipment whom he has disturbed (Fig. 1.1). This edict is an important milestone in the history of EMC in the sense that it was the first known regulation to be adopted which attempted to make electrical appliances compatible with each other.

The first EMC problem between two different appliances that has been the subject of intensive studies and scientific investigations, is the radio receiver which is fitted in a car. The primary cause for this generated interference is the

[2] *Gesetz über das Telegraphenwesen des Deutschen Reichs, Reichsgesetzblatt S. 467.*



Reichs-Gesetzblatt.

№ 21.

Inhalt: Gesetz über das Telegraphenwesen des Deutschen Reichs. S. 407

(Nr. 2015.) Gesetz über das Telegraphenwesen des Deutschen Reichs. Vom 6. April 1892.

Wir Wilhelm, von Gottes Gnaden Deutscher Kaiser, König von Preußen rc.

verordnen im Namen des Reichs, nach erfolgter Zustimmung des Bundesraths und des Reichstags, was folgt:

§. 1.

Das Recht, Telegraphenanlagen für die Vermittelung von Nachrichten zu errichten und zu betreiben, steht ausschließlich dem Reich zu. Unter Telegraphenanlagen sind die Fernsprechanlagen mit begriffen.

§. 12.

Elektrische Anlagen sind, wenn eine Störung des Betriebes der einen Leitung durch die andere eingetreten oder zu befürchten ist, auf Kosten desjenigen Theiles, welcher durch eine spätere Anlage oder durch eine später eintretende Aenderung seiner bestehenden Anlage diese Störung oder die Gefahr derselben veranlaßt, nach Möglichkeit so auszuführen, daß sie sich nicht störend beeinflussen.

§. 15.

Die Bestimmungen dieses Gesetzes gelten für Bayern und Württemberg mit der Maßgabe, daß für ihre Gebiete die für das Reich festgestellten Rechte diesen Bundesstaaten zustehen und daß die Bestimmungen des §. 7 auf den inneren Verkehr dieser Bundesstaaten keine Anwendung finden.

Urkundlich unter Unserer Höchsteigenhändigen Unterschrift und beigedrucktem Kaiserlichen Insiegel.

Gegeben im Schloß zu Berlin, den 6. April 1892.

(L. S.) Wilhelm.

Graf von Caprivi.

Figure 1.1. Excerpt of the edict issued by the German parliament, regulating electromagnetic disturbances in the telegraph system.

motor noise, which is picked up and conducted over long power lines and into sensitive equipment [Arc04]. While the US military encountered interference problems prior to World War I when trying to equip a car with a radio, little is known about the first efforts to minimize or at least find ways to counter or shield this interference. After the First World War, the radio technology which was used and perfected during the conflict, blossomed into civilian broadcasting. As more and more radio transmitters were built, it became necessary to assign different frequencies to various types of radio uses on an international basis in order to avoid interference. Aside from the harmonics generated by neighboring radio transmitters, radio receivers were in turn susceptible to adjacent channel interferences as well as to the unsuppressed impulsive noise generated by electric motors and ignition systems [Mar88]. The radio receiver which fitted into a car was consequently very susceptible to these disturbances, and it is therefore no wonder that its EMC performance has been observed and studied intensively from then on. The first IRE paper written on this subject stems from 1932, and describes the "electrical interference in motor car receivers" [Cur32] [3].

The awareness of EMC kept growing throughout the second World War, where new systems like radar emerged, and on-board radio communication became more prevalent in cars, aircraft and ships. The metal superstructure of aircraft provided excellent (yet unpredictable) energy transfer paths between various systems, and the armament and fuel tanks were consequently susceptible to ignition by sparks caused by large radio frequency fields. Additionally, intermodulation products originating from radio transmitters caused by the nonlinear electrical properties of metal joints corroded by seawater, disrupted various radio receivers on ships [Mar88]. Opposed to this, radio and radar jamming which are a form of intentional electromagnetic interference, were extensively developed and used during the second World War as well, e.g. to perturb the reception of the BBC throughout Nazi occupied Europe and to disturb the radio communication of enemy planes [Alb81].

3 Electromagnetic compatibility of integrated circuits

During the post-war period and through the 1960s, EMC was primarily a concern for the military, for example to control and regulate radar emissions which could (and in some cases did) cause inadvertent weapons releases by interfering with electronic fire mechanisms. Mankind will probably never know for sure how close such EMC incompatibilities have brought it to the brink of World War III, although its potentially disastrous effects can be duly appreci-

[3] The IRE, "Institute of Radio Engineers", merged in 1963 with the AIEE, the "American Institute of Electrical Engineers", to the present day "Institute of Electrical and Electronics Engineers", better known as IEEE.

ated in [Arm07] by means of real-life events [4]. The first research on the effect of electromagnetic interferences on integrated circuits (IC's) started in 1965 at the Special Weapons Center, based at Kirtland, New Mexico, USA. It is not surprising that 3 years after the Cuban missile crisis and in the middle of the cold war, the first EMC studies related to IC's investigated the effects of electromagnetic fields triggered by nuclear explosions, on electronic devices used in missile launch sites [Sic07a]. The electromagnetic pulse (better known as EMP) radiates from a nuclear detonation, and has an immense field strength. A nuclear detonation at an altitude in excess of 40 km, may disrupt and irrevocably damage electric and electronic systems up to 5000 km from the site of detonation [Kei87].

The military dominion in EMC related matters changed radically after the massive home computer proliferation starting from the 1970s. Indeed, interference problems from computing devices became a significant problem to radio and television broadcasting. In order to limit and control these interferences, various national instances as the FCC in the USA (Federal Communications Commission), or the CISPR (Comité International Spécial des Perturbations Radioélectriques) of the IEC (International Electrotechnical Commission) in Europe, started to compile a set of rules to regulate the amount of emissions, and how the measurements of these electromagnetic emissions were to be performed. In 1979, a complete issue of the *IEEE Transactions on Electromagnetic Compatibility* (vol. 21, no. 4) was devoted to electromagnetic interference problems in integrated circuits. Amongst others, this issue contained a paper describing a methodology to simulate radio frequency interferences (RFI) effects in the 741 operational amplifier designed with bipolar transistors, using computer aided simulations and macromodels [Tro79].

EMC problems and consecutive emission and immunity requirements persisted throughout the 1980s, and became even more stringent in the 1990s, owing to the growing use of electronic equipment and the ever increasing integration of different systems in the same product as well as in the same environment, invariably linking the EMC problem to the coexistence issue between circuits and systems. When different circuits and systems are densely integrated in the same appliance, the parasitic electromagnetic coupling between these circuits sharing the same printed circuit board (PCB), power supply and ground lines, is indeed a critical design parameter that can no longer be safely excluded from a product design flow. As an example, Bluetooth, GSM and WiFi services have to coexist and operate simultaneously within the close con-

[4] [Arm07] enumerates and describes the first 500 'banana skins' that have been published to date in *The EMC Journal*, published by Nutwood UK. These banana skins offer an account of real life EMC experiences, and were compiled from research reports, official documents and personal anecdotes, and vary from amusing to highly tragic situations.

finement of a modern mobile phone. Furthermore, the use of higher frequencies all contribute to an increased high frequency interference. All this means that the EMC history is repeating itself since small PCB tracks and wires pick up the disturbing signals just as easy as long power supply lines which picked up the motor noise and injected this into sensitive electronic appliances ... more than half a century ago. Currently, the victims of these electromagnetic disturbances are the integrated circuits which nowadays heavily populate and form the beating heart of almost any given electronic appliance.

According to [Deu03a], what is required to design EMC robust IC's, is amongst others: a better knowledge of how fast switching transients generate and affect electromagnetic emission, better package simulation models, better tools for simulating the EMC management on-chip, reduction of signal integrity, higher IC immunity to EMI, better control over radiated emissions, better packages with smaller parasitic elements, a controlled slew rate to reduce the di/dt noise and last but not least more design engineers who understand the generation of IC's emissions and how to improve their immunity. As advocated wisely in [Deu03a], if all these points are followed, we can expect to keep up with Moore's Law for a long time, where EMC is concerned.

4 Scope of this book

The scope of this book is to describe the design of analog integrated circuits which achieve a higher degree of immunity against electromagnetic interference (EMI). This is in itself a very vast subject, and many research is still required in this domain, since any circuit can (and will) exhibit EMC related problems, as long as the injected EMC level is sufficiently important. The performed research has been concentrated on performing a generalized study on how IC's are affected by EMI, and what steps based on circuit modifications can be taken in order to resolve appearing EMC problems. This does of course not mean that a sloppy and an EMC-unaware PCB layout is either acceptable or justified. On the contrary, this research is meant to be an addition in increasing the global immunity of a whole system, starting from the cabling and the wire harness, to the PCB, using proper shielding where necessary and finally by improving the immunity of IC's which are connected and interconnected to this PCB in question. This work describes the studies that have been pursued, and the results that have been obtained in this matter. To this end, this book is organized as follows:

- **Chapter 1** introduces EMC from a historical perspective, and describes the scope of this work.
- **Chapter 2** starts by explaining and defining common EMC related terms. Following this, the gap which seemingly exists between electromagnetism and EMC at integrated circuit level is bridged by explaining how electro-

magnetic waves interfere and tie-in with an arbitrary IC. Unfortunately, many EMC related reference material still contains whiffs from the past, when EMC specialists used a set of rules known to themselves and which were largely based on experience and rule of thumb guidelines to solve particular EMC issues. It is the purpose of this chapter to demystify these definitions, and to illustrate briefly where these general design guidelines come from and how they should be interpreted. Finally, the standardized electromagnetic immunity measurement methods at IC level are summarized and explained.

- **Chapter 3** covers some general aspects concerning the effect of EMI in IC's. As will be shown, these appearing EMC effects can be categorized in two classes, namely a parasitic coupling, and a parasitic mixing with in particular a self-mixing resulting in a DC component, which may lead to a shift in the DC operating point (DC shift). These principles are demonstrated and derived using four design cases. The concept of DC shift is derived and illustrated in the first three case studies, discussing respectively a NMOS diode connected transistor, a source follower and a CMOS current mirror. A basic electrostatic discharge (ESD) protective structure is described in the fourth case study in order to highlight which kind of EMC interferences can be expected in them.

- **Chapter 4** discusses the effect of EMI on analog output stages. Many different output stages can be distinguished, and for this reason this chapter starts with an elementary generalization, where outputs are classified according to whether the output is driven by a transistor source, whether by a transistor drain. This basic differentiation helps to understand and solve appearing EMI problems in analog output stages from a conceptual point of view. The theoretical deductions are further elaborated and applied in two case studies, namely in an EMI resisting DC current regulator which is resistively trimmed, and in a local interconnect network (LIN) driver, which must present a high degree of electromagnetic immunity at its output. Both structures exhibit a high susceptibility to EMI in their original form, which is analyzed mathematically using the observations made in the first part of this chapter. Proposed solutions circumvent the appearing EMC problems by modifying the circuit topologies. Measurements of respective test-IC's illustrating their improved EMI performance are presented, and corroborate the general theoretical framework as well as the individual concepts behind both circuits.

- **Chapter 5** reports the effect of EMI on analog input stages. Two distinct input circuits are distinguished in this chapter. Firstly, the electromagnetic susceptibility of operational amplifiers is studied when EMI is injected into their input terminals. Existing differential pair circuits increasing the immunity to electromagnetic interference are repertoried and compared in terms of EMI induced offset suppression, current consumption and noise performance. Finally, a source-buffered differential pair structure exhibiting a high resistance to EMI is introduced. The measurements of a test-IC are described in detail, and are shown to correlate with the analytical developments. Secondly, the input stage of an instrumentation amplifier which has to resist a very high interfering common-mode voltage at its inputs is studied. As illustrated, existing input structures are very susceptible to mismatch, which translates a portion of the common-mode EMI into a detrimental differential-mode EMI component. A new input structure using current modulation is introduced and described. Simulations illustrate the superior performance and the smaller dependence on matching of the proposed input structure compared to classic structures.

- **Chapter 6** considers the effect of EMI which is conveyed through the power supply lines into linear voltage regulators. The latter are extensively used in order to regulate internal supply voltages and must, consequently, present a high degree of immunity against EMI which is injected into the external power supply terminals. First of all, the effect of EMI injected in a Kuijk-type bandgap voltage reference is studied analytically. It is illustrated how EMI couples from the supply to the reference node, and this analysis is used in order to design two EMI resisting Kuijk-type bandgap references. The measurements of a test IC comparing the original Kuijk bandgap structure to the EMI resisting ones are presented and compared to the mathematical analysis. In the second part of this chapter, the EMI susceptibility of LDO voltage regulators is studied from a conceptual point of view. It is illustrated with simulations how, applying the same design rules derived while improving the EMI resistance of a Kuijk bandgap in the first part of this chapter, the theoretical EMI immunity of LDO voltage regulators can be increased.

- Finally, the most important conclusions of this work are summarized in **Chapter 7**, and future possible research paths based on this work are briefly enumerated.

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.

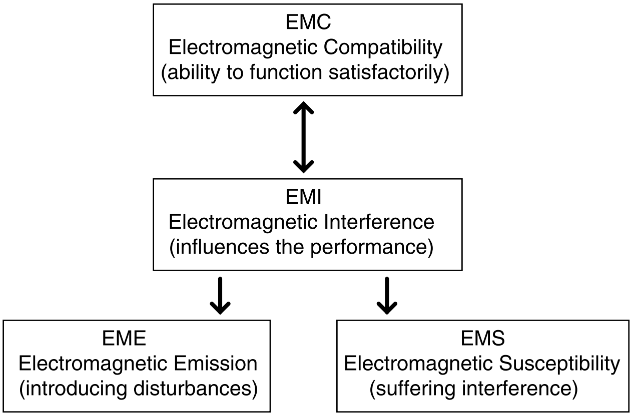

Figure 2.1. The used EMC terms in this work and their interrelationships, as represented in [Goe01].

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:

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