International Journal of Microelectronics and Digital Integrated Circuits
Vol. 1: Issue 1
www.journalspub.com

Electromagnetic Compatibility of Integrated Circuits

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Abstract
This is a review on assumption of a range of historical work conducted in the area of electromagnetic compatibility of the integrated systems and circuits.

Keywords: *Interference, emissions, circuits, electro-magnetic fields*

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INTRODUCTION

Electromagnetic compatibility researches are focused on integrated circuits which are far from a recent topic nowadays. Early electrical simulators were designed for simulating the susceptibility of electronic devices and radio-frequency interference. These key developments mark the history of research in integrated circuits.

EARLY WORKS IN EMC OF INTEGRATED CIRCUITS

In the year 1965, at the Special Weapons Center, in Mexico, study of the effects of the electromagnetic fields trigged by nuclear explosions on electronic devices used in missile launch sites. As a result, the simulation software was been developed for simulating the effects of nuclear radiation on electronic components. With this software, the correlation was possible between the simulations and experimental measurements were obtained on an electromagnetic impulse test-bench.

At the electronic equipment level, techniques were developed to protect radio, television and radar transmitters. Several military standards were published in the United States to define the interference levels that equipment should withstand and specifying measurement methods for electromagnetic interference characterization.

One of the earliest academic publications, on the simulation of integrated circuits concerned the 741 integrated operational amplifier (a versatile linear amplifier including around 100 bipolar and passive devices, with 25 mA output current capabilities, originally designed for audio applications), and was published by Wooley[1] in 1971. The author succeeded in simulating the different stages of this integrated circuit with the simulation software *CANCER*, from Berkeley University).

Whalen[2] was another pioneer in the field of integrated circuit EMC. In 1975, he published studies on the radio-frequency pulse susceptibility of discrete transistors. The *IEEE Transactions on Electromagnetic Compatibility* invited 'Prof. Whalen' to edit a special issue devoted to the effects of radio frequency interference on integrated circuits. In his editorial, Whalen justified the need for the special issue in terms of the rising risk of interference from electromagnetic sources in the Very High Frequency bands. The special issue dealt specifically with the effects of interference on semiconductor devices and the modeling of these effects by means of dedicated simulation tools. The need to modify available device models to account for the unusual conditions of radio-frequency interference was expressed by C. E. Larson, proposed a modification of the bipolar transistor model[3].

The first susceptibility analysis of MOS components was published in 1980 and involved memory circuits. Roach characterized the sensitivity of 1-kbyte NMOS memories. Some years later, a study was published by Tront concerning the behavior of the 8085 processor in the presence of 100 and 220 MHz radio-frequency interference. Using the simulation software SPICE, he reproduced some of the phenomena observed during measurements.

Watchdog circuits were added to microprocessors[4] for structural integrity checking. Watchdog circuits were found to be of great importance for processor recovery and safe reset after undergoing electromagnetic interference.

RESEARCH IN EMC FOR ICS BETWEEN

Bakoglu (1990)[5] compiled a remarkable synopsis of the parasitic effects in integrated circuits, packaging and printed circuit boards. He described different problems linked to transient current consumption at active edges of the clock and detailed the basic mechanisms for integrated circuit resonance. Package models were provided for Dual- In-Line (DIL), Quad-flat-pack (QFP) and Pin-Grid-Array (PGA) families. Also in 1990, Kenneally presented measurement results for simple integrated circuits in CMOS and TTL technologies as shown in Figure 1. He noticed that the sensitivity decreased as the radio-frequency interference increased, from 1 to 200 MHz[6].

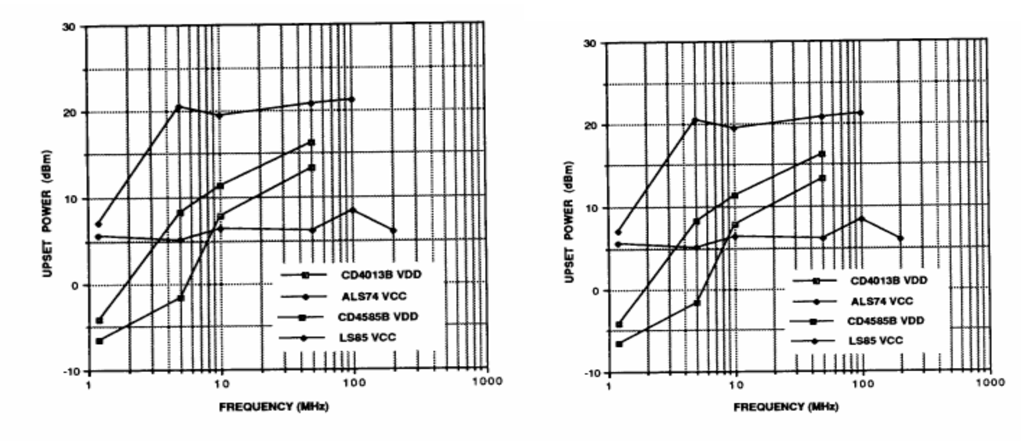

Fig. 1: *Susceptibility Thresholds Vary Depending on the Technology.*

Significant differences were exhibited depending on the fabrication technology. CMOS circuits tended to be less robust than TTL circuits from 1 to 10 MHz. A student at the University of Toronto, Laurin (1991)[7] published a study of the effects of radio frequency perturbations on the oscillator circuits used in a Motorola 6809 processor. When placing an electric current loop close to the oscillator, he observed clock jitter, function losses in the microprocessor and data losses on the serial data bus.

Also in relation with microprocessors, Tang (1993)[8] showed that electromagnetic interference could cause non- fatal failures that resulted in counting inaccuracies in microprocessors. He performed conducted and radiated susceptibility measurements, and could demonstrate a specific byte-swap problem on the most significant byte of a counter, leading to severe counting errors. Solutions based on software modifications and PCB layout improvements were proposed. The author pointed out that low-speed systems were as vulnerable to EMI as high-speed systems.

EMC books published in the early 90s focused mainly on printed-circuit-board EMC. Most of these books gave only a little insight regarding the specific problems of integrated circuits. In chapter 3 of his book "*Principles and applications of EMC*", Weston (1991) compared the switching characteristics of various families of integrated circuits, as well as their impact on radiated and conducted emissions[9].

A study was published by Graffi (1991)[10] describing the behavior of 741 operational amplifiers (the same type of device than the one analyzed by Wooley[1] in 1971) when a 200 kHz - 50 MHz interference signal was superimposed on normal signals. He obtained good correlation between experimental measurements and simulations using a simplified macro-model that accelerated the computation by a factor of up to 50.

Synchronous switching noise is one of the most significant chip-level concerns for EMC and signal integrity engineers. One of the earliest publications on this topic was a paper by (Downing, 1993)[11] on the characterization of decoupling capacitance effects including on-chip decoupling and decoupling close to the integrated circuit.

SUSCEPTIBILITY OF INTEGRATED CIRCUITS

The effects of electromagnetic wave coupling to PCB traces and the consequences of this coupling on simple circuits were analyzed by Laurin (1995)[12]. With field strengths as high as 200 V/m, no disturbance was observed on the component. Adding a metal wire that was a half- wavelength long at the interference frequency allowed fields as low as 2 V/m to cause severe malfunctions due to erroneous switching. The authors differentiated between a *static regime* and *transient regime*. In the static regime, only perturbations with high energy affected logic levels. In the transient regime, even weak perturbations could affect switching delays and circuit thresholds.

Chappel (1997)[12,13] discussed the possibility of *hardening* integrated circuits to electromagnetic interference by specific design techniques that raised the immunity level of ICs from a low 1.5 V to more than 5 V, in the frequency range 1 to 10 MHz. Several other circuits have also been proposed that exhibit a high immunity to RFI including Schmidt triggers, low-voltage differential swing circuits and delay–insensitive structures.

While the demand for mobile communications was exploding, the behavior of integrated circuits in the presence of GHz-range interference was not extensively studied.

In 2000, an updated version of the *Integrated Circuit Electromagnetic Immunity Handbook* published by NASA gave valuable information on the immunity levels of simple integrated circuits up to 10 GHz. Chapter 4 presented measurement results concerning simple components along with a very interesting comparison to similar measurements performed in the early 80s. The frequency range was 10 MHz to 10 GHz. From the results shown in Figure 5, the immunity level of recent components has proven to be higher those 70s versions. This could be explained by input/output protection improvements.

Through experience gained on a variety of microprocessors and microcontrollers, some engineers started developing strategies for hardening microprocessor-based systems.

Coulson (1997)[13] identified the vulnerable points and then proposed specific circuits such as supply supervisors or watch-dogs and also some software-based techniques such as memory integrity checking, token passing, and redundancy coding.

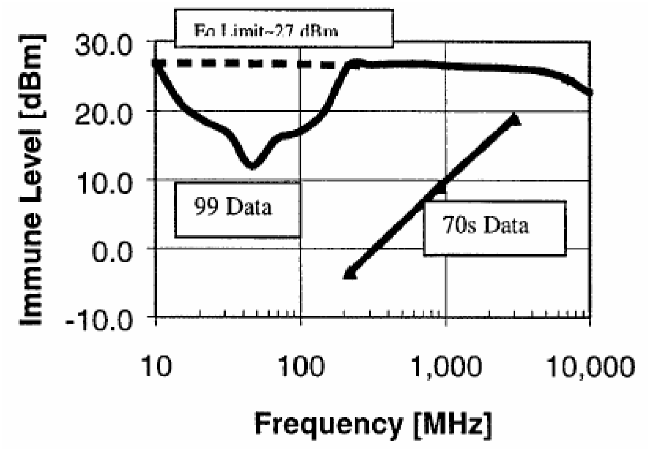

Fig. 2: *Immunity of the NAND 74LS00.*

PARASITIC EMISSION OF INTEGRATED CIRCUITS

Hardin and His colleagues at Lexmark Corporation were among the first to propose the idea of reducing peak emissions in the harmonics of the clock frequency by fluctuating the clock period in a controlled manner (Hardin, 1994)[14–16]. This idea is illustrated in Figures 2, 3. Goodman (1995) published results of a comparison between measurements and simulations of signal propagation in Pin- Grid Arrays (PGAs). He demonstrated various deleterious effects on signal transmission depending on the geometry of the package pins.

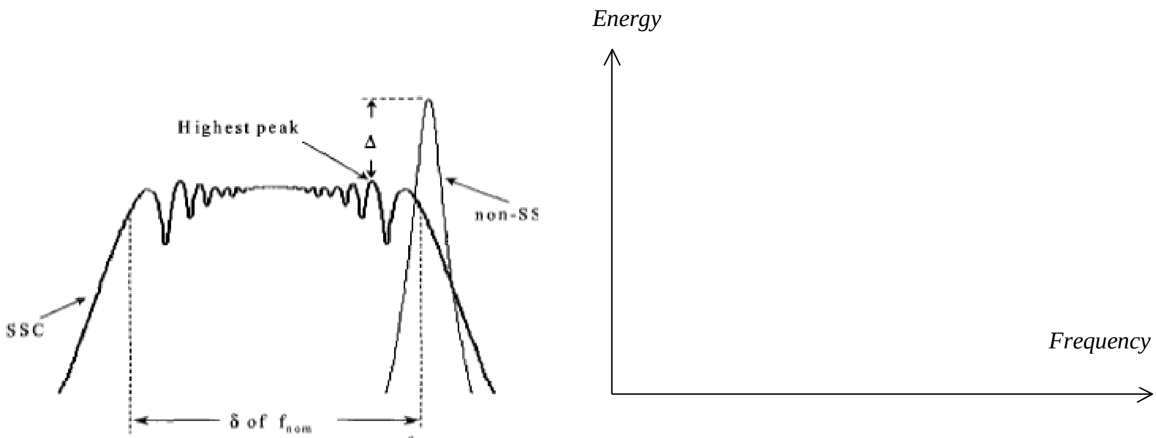

Fig. 3: *The Spread-Spectrum Technique Helps to Reduce Radiated Emission.*

While using discrete RLC components to model package leads, bonding and integrated input/output structures, he used transmission lines for the printed circuit board tracks to validate his models up to 4 GHz. Constant increases in integrated circuit complexity require packages with higher pin density and broader bandwidth. (McCredie, 1996) successfully modeled the switching noise of an ASIC mounted on a compact BGA with around 1000 I/O pins using distributed current sources, on-chip and on-package decoupling capacitance models as well as serial connection inductances.

In the United States, the Society for Automotive Engineering (SAE) proposed a measurement method for quantifying the radiated emissions from integrated circuits using a TEM cell. Comparative studies were published by Slattery (1997)[16] regarding 8 and 16 bit microcontrollers that characterized the impact of IC technology, packaging and temperature on the spectrum.

Robinson (1998)[17] compared the radiated emissions produced by different families of logic circuits. An antenna was mounted 3 meters away from a test board on an open-field test site. Results were obtained for simple circuits such as inverters and NAND gates from various logic families. Significant behavioral differences were observed, as illustrated in Figure 4.

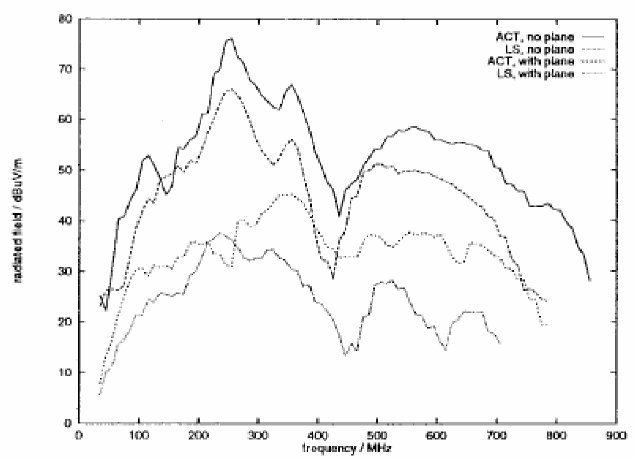

Fig. 4: *Far-field Emission (50 MHz-900 MHz) Produced by Simple ICs for Varying Technologies (Robinson, 1998).*

CONCLUSION

Researchers are been pursuing the development of measurement methods, prediction tools and design techniques for improving the Electromagnetic compatibility of integrated circuits. This is expected to be continued to become an active area of study in the future, as ICs are turning larger, denser and are operated at higher speeds and lower supply of energy in the form of voltages.

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