EMC of Integrated Circuits : A Historical Review

E. Sicard[(1)], S. Ben Dhia[(1)], M. Ramdani[(2)], T. Hubing[(3)]
(1) INSA-Toulouse, France
(2) ESEO, Angers, France
(3) Clemson University, USA

Abstract— **This paper provides a non exhaustive review of the research work conducted in the field of integrated circuit electromagnetic compatibility over the past 40+ years.**

Keywords: History, parasitic emission, susceptibility, modeling, standards.

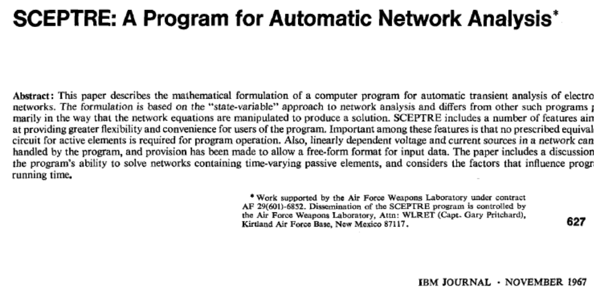
I. Introduction

Electromagnetic compatibility research focused on integrated circuits is far from being a recent topic. Early electrical simulators, ancestors of the well known SPICE simulation tools, were originally designed for simulating the susceptibility of electronic devices to radio-frequency interference. This paper is a modest attempt to review key developments that mark the history of research in integrated circuit immunity and emissions.

II. Early works in EMC of Integrated Circuits

The American military led early efforts in the field of integrated circuit EMC. As early as 1965 at the Special Weapons Center, based at Kirtland, New Mexico, they studied the effects of the electromagnetic fields trigged by nuclear explosions on electronic devices used in missile launch sites. As a result of this effort, the simulation software SPECTRE [1] was developed at IBM (Fig. 1) for simulating the effects of nuclear radiation on electronic components. With this software, it was possible to correlate simulations and experimental measurements 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.


SCEPTRE: A Program for Automatic Network Analysis*

Abstract: This paper describes the mathematical formulation of a computer program for automatic transient analysis of electronic networks. The formulation is based on the "state-variable" approach to network analysis and differs from other such programs primarily in the way that the network equations are manipulated to produce a solution. SCEPTRE includes a number of features aimed at providing greater flexibility and convenience for users of the program. Important among these features is that no prescribed equivalent circuit for active elements is required for program operation. Also, linearly dependent voltage and current sources in a network can be handled by the program, and provision has been made to allow a free-form format for input data. The paper includes a discussion of the program's ability to solve networks containing time-varying passive elements, and considers the factors that influence program running time.

* Work supported by the Air Force Weapons Laboratory under contract AF 29(601)-6852. Dissemination of the SCEPTRE program is controlled by the Air Force Weapons Laboratory, Attn: WLRET (Capt. Gary Pritchard), Kirtland Air Force Base, New Mexico 87117.

627

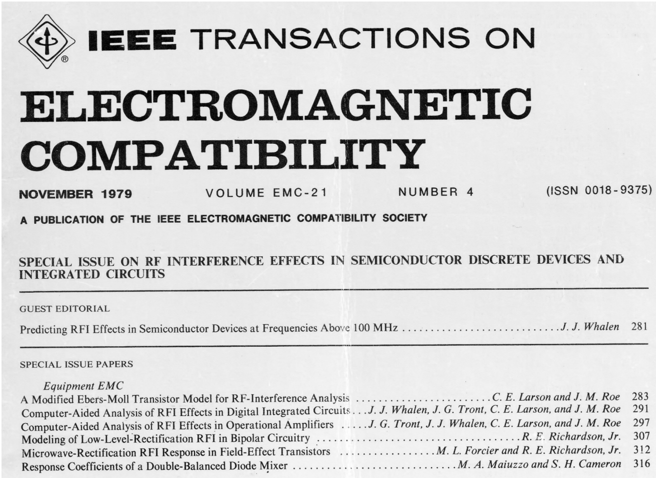
IBM JOURNAL · NOVEMBER 1967

Figure 1. The software SPECTRE was originally designed for radiation simulation on electronic devices (Sedore, 1967)

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 25mA output current capabilities, originally designed for audio applications), and was published by Wooley [2] in 1971. The author succeeded in simulating the different stages of this integrated circuit with the simulation software *CANCER,* from Berkeley University (An ancestor of the well-known analog circuit simulator SPICE).

As an Associate Professor at the State University of New York in Buffalo, USA, James J. Whalen, was another pioneer in the field of integrated circuit EMC. In 1975, he published studies on the radio-frequency pulse susceptibility of discrete transistors [3]. The *IEEE Transactions on Electromagnetic Compatibility* (Fig. 2) invited Prof. Whalen to edit a special issue devoted to the effects of radio frequency interference on integrated circuits [4]. 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, who proposed a modification of the bipolar transistor model.

1-4244-1350-8/07/$25.00 ©2007 IEEE



IEEE TRANSACTIONS ON

ELECTROMAGNETIC COMPATIBILITY

NOVEMBER 1979 VOLUME EMC-21 NUMBER 4 (ISSN 0018-9375)

A PUBLICATION OF THE IEEE ELECTROMAGNETIC COMPATIBILITY SOCIETY

SPECIAL ISSUE ON RF INTERFERENCE EFFECTS IN SEMICONDUCTOR DISCRETE DEVICES AND INTEGRATED CIRCUITS

GUEST EDITORIAL

Predicting RFI Effects in Semiconductor Devices at Frequencies Above 100 MHz ... *J. J. Whalen* 281

SPECIAL ISSUE PAPERS

Equipment EMC

A Modified Ebers-Moll Transistor Model for RF-Interference Analysis ... *C. E. Larson and J. M. Roe* 283

Computer-Aided Analysis of RFI Effects in Digital Integrated Circuits ... *J. J. Whalen, J. G. Tront, C. E. Larson, and J. M. Roe* 291

Computer-Aided Analysis of RFI Effects in Operational Amplifiers ... *J. G. Tront, J. J. Whalen, C. E. Larson, and J. M. Roe* 297

Modeling of Low-Level-Rectification RFI in Bipolar Circuitry ... *R. E. Richardson, Jr.* 307

Microwave-Rectification RFI Response in Field-Effect Transistors ... *M. L. Forcier and R. E. Richardson, Jr.* 312

Response Coefficients of a Double-Balanced Diode Mixer ... *M. A. Maiuzzo and S. H. Cameron* 316

Figure 2 . A special issue on radio-frequency interferences in integrated circuits (IEEE Trans. EMC, 1979)

The first susceptibility analysis of MOS components was published in 1980 and involved memory circuits. J.N. Roach [5] characterized the sensitivity of 1-kbyte NMOS memories. Some years later, a study was published by Tront [6] 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 (Fig. 3).

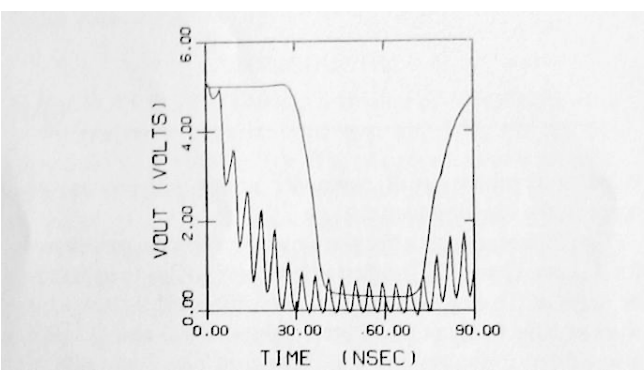


Fig. 3. V_{OUT} versus time for $V_M = 20$ V and $f = 220$ MHz. A plot of the unperturbed V_{OUT} is superimposed on the curve.

Figure 3. Unperturbed and perturbed signals simulated by (Tront, 1985).

Watchdog circuits were added to microprocessors (Lu, 1982 [7]) for structural integrity checking. Watchdog circuits were found to be of great importance for processor recovery and safe reset after undergoing electromagnetic interference.

III. RESEARCH IN EMC FOR ICS BETWEEN 1990 AND 1995

Bakoglu (1990) [8] 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 [9] presented measurement results for simple integrated circuits in CMOS and TTL technologies. He noticed that the sensitivity decreased as the radio-frequency interference increased, from 1 to 200 MHz.

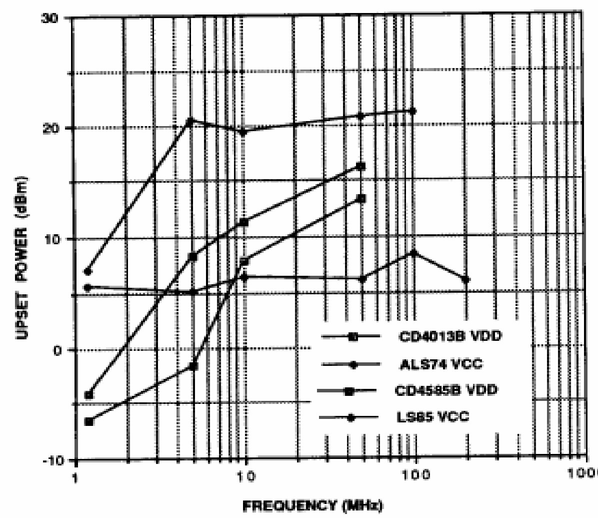


Figure 4 Susceptibility thresholds vary depending on the technology (Kenneally, 1990)

Significant differences were exhibited depending on the fabrication technology. CMOS circuits tended to be less robust than TTL circuits from 1 to 10 MHz (Fig. 4). As a Ph.D. student at the University of Toronto, Laurin (1991) [10] 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) [11] 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 [12].

A study was published by Graffi (1991) [13] describing the behavior of 741 operational amplifiers (the same type of device than the one analyzed by Wooley [2] 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) [14] on the characterization of decoupling capacitance effects including on-chip decoupling and decoupling close to the integrated circuit.

IV. SUSCEPTIBILITY OF INTEGRATED CIRCUITS (STARTING 1995)

The effects of electromagnetic wave coupling to PCB traces and the consequences of this coupling on simple circuits were analyzed by Laurin (1995) [15]. 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) [16] 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 [16]. 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 Fig. 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) [17] 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.

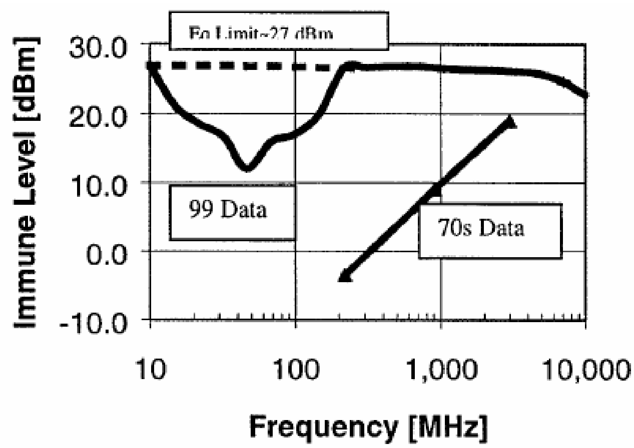


Figure 5.: Immunity of the NAND 74LS00.

V. 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) [18]. This idea is illustrated in Fig. 6. Goodman (1995) [19] 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.

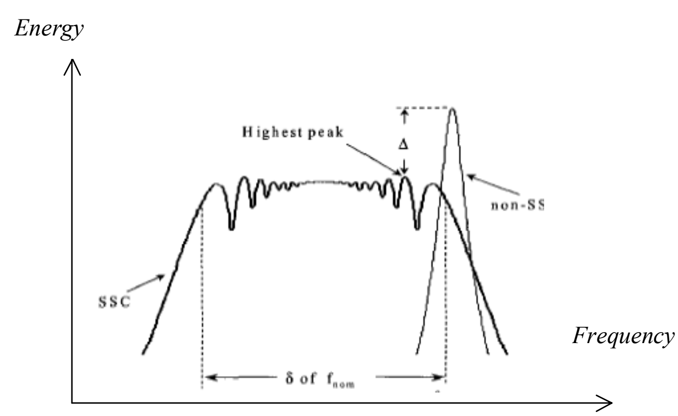


Figure 6. The spread-spectrum technique helps to reduce radiated emission (Hardin, 1994)

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) [20] 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) [21] regarding 8 and 16 bit microcontrollers that characterized the impact of IC technology, packaging and temperature on the spectrum.

Robinson (1998) [22] 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 Fig. 7.

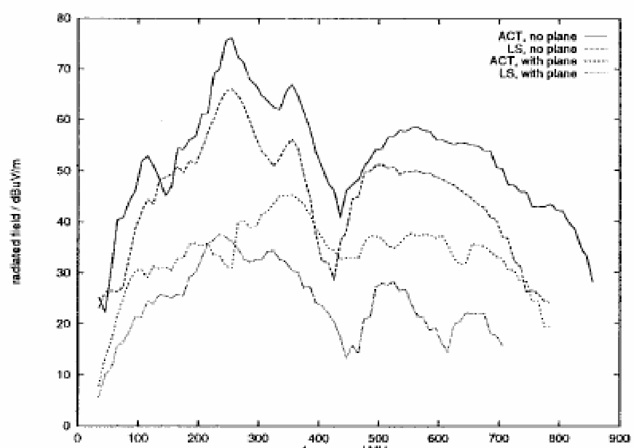


Figure 7. Far-field emission (50 MHz-900 MHz) produced by simple ICs for varying technologies (Robinson, 1998)

VI. Conclusion

For more than 40 years, researchers have been pursuing the development of measurement methods, prediction tools and design techniques for improving the EMC performance of integrated circuits. We expect this to continue to be an active field of study in the future, as ICs become larger, denser and operate at higher clock speeds and lower supply voltages.

VII. References

[1] Sedore, S R., 1967a, Automated digital computer program for determining responses of electronic circuits to transient nuclear radiation (SCEPTRE), AFWL TR 66-126, *Air Force Weapons Laboratory.*

[2] Wooley, B.A., Pederson, D.O., 1971, A computer-aided evaluation of the 741 amplifier, *IEEE Journal of Solid-State Circuits*, **6**(6): 357–366

[3] Whalen, J., 1975, The RF Pulse Susceptibility of UHF Transistors, *IEEE Transaction on Electromagnetic Compatibility*, **17**: 220-225.

[4] Whalen, J., 1979, Predicting RFI Effects in Semiconductor Devices at Frequencies Above 100MHz, *IEEE Transaction on Electromagnetic Compatibility*, **21**: 281-282

[5] Roach, J. N., 1981, The susceptibility of 1 K NMOS memory to conducted electromagnetic interference, *IEEE International Electromagnetic Compatibility Symposium*, Boulder, CO, pp. 85–90.

[6] Tront, J. G., 1985, Predicting RFI upset of MOSFET digital IC's, *IEEE Transaction on Electromagnetic Compatibility*, **27**: 64–69

[7] Lu, D. J, 1982, Watchdog Processor and Structural Integrity Checking, *IEEE Transactions on Computers*, **31**(7): 681-685

[8] Bakoglu, H., 1990, *Circuit, Interconnections And Packaging For VLSI*, MA: Addison-Wesley, ISBN 0-201-06008-6

[9] Kenneally, D.J., Wilson, D.D., Epshtein, S., 1990, RF upset susceptibilities of CMOS and low power Schottky 4-bit magnitude comparators, *IEEE International Symposium on Electromagnetic Compatibility*, pp. 671–67

[10] Laurin, J.-J., Zaky, S.G., Balmain, K.G., 1991, EMI-induced failures in crystal oscillators, *IEEE Transactions on Electromagnetic Compatibility*, **33**(4): 334–342

[11] Tang, H.K., 1993, EMI-induced failure in microprocessor-based counting, *Microprocessors and Microsystems*, **17**(4): 248-252

[12] Weston, D. A., Dekker, M., 1991, Electromagnetic Compatibility: Principles and Applications

[13] Graffi, S., Masetti, G., Golzio, D., 1991, New macromodels and measurements for the analysis of EMI effects in 741 op-amp circuits, *IEEE Transactions on Electromagnetic Compatibility*, **33**(1): 25–34.

[14] Downing, R., Gebler, P., Katopis, G., 1993, Decoupling capacitor effects on switching noise, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, **16**(5): 484–489.

[15] Laurin, J.-J., Zaky, S.G., Balmain, K.G., 1995, On the prediction of digital circuit susceptibility to radiated EMI, *IEEE Transactions on Electromagnetic Compatibility*, **37**(4):528–535.

[16] Sketoe, J.G., 2000, Integrated Circuit Electromagnetic Immunity Handbook, NASA/CR-2000-210017, *NASA Marshall Space Flight Center, AL 35812*, pp. 64, http://see.msfc.nasa.gov.

[17] Coulson DR, 1997, EMC-Hardening Microprocessor-based Systems, *IEE Colloquium on Achieving Electromagnetic Compatibility*, UK.

[18] Hardin, K.B., Fessler, J.T., Bush, D.R., 1994, Spread spectrum clock generation for the reduction of radiated emissions, *IEEE International Symposium on EMC*, pp. 227–231

[19] Goodman, T.W., Fujita, H., Murakami, Y., Murphy, A.T., 1995, High speed electrical characterization and simulation of a pin grid array package, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, **18**(1): 163-167

[20] McCredie, B.D., Becker, W.D., 1996, Modeling, measurement, and simulation of simultaneous switching noise, Part B: Advanced Packaging, *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, **19**(3): 461–472

[21] Slattery, K., Muccioli, J.P., North, T., 1997,. Characterization of the RF emissions from a family of microprocessors using a 1GHz TEM cell, *IEEE EMC symposium*, Austin

[22] Robinson, M.P., Benson, T.M., Christopoulos, C., Dawson, J.F., Ganley, M.D., Marvin, A.C., Porter, S.J.,. Thomas, D.W.P., and Turner, J.D., 1998, Effect of logic family on radiated emissions from digital circuits, *IEEE Transactions on Electromagnetic Compatibility*, **40**(3): 288-293