Modeling Electromagnetic Emission of Integrated Circuits for System Analysis

P. Kralicek*, W. John*, H. Garbe**
* Fraunhofer Institute Reliability and Microintegration Berlin/Paderborn - Germany
** University of Hannover - Germany

Abstract

In this contribution a new methodology for modeling electromagnetic emission of integrated circuits in system analysis is shown. By using a physical model based on a multipole expansion, the emitted fields can be well approximated in the space outside a component. This allows a convenient representation with a low number of model parameters which can be determined by measurement or simulation. To show the applicability, the developed models are used in a system level printed circuit board simulator. The results are compared with reference calculations.

1. Introduction

The development of modern microelectronic systems is determined by continuously rising clock-rates (internal IC clock-rates in the GHz range), increasing complexity and a high level of integration. With regard to a complete characterization of a design, special attention has to be drawn on the analysis and modeling of the electromagnetic behavior of active microelectronic components, especially integrated circuits as the major sources of RF energy.

Up to now in emission analysis on system level, integrated circuits are generally modeled by equivalent lumped sources/impedances at the end of PCB traces. Detailed analysis (typically using volume or surface discretising field solvers and an exact geometric model) is only performed when lumped parasitic elements of a package should be extracted, e.g. in [1].

Todays use of multi-layer printed circuit boards enables the designer to move the potentional radiation critical traces on the quasi-shielded inner layers and use strip-line technology (dominant TEM mode) to minimize the emission. As a result, especially at higher frequencies, the (for thermical and manufacturing reason) on the outer layers situated integrated circuits start to dominate the electromagnetic emission [2, 3]. This is particularly the case because of the exposed position and the absence of defined image current paths inside the package. Additionally from the functional point of view equal IC can create considerable different fields (see table 1), depending on the fabrication site (process parameters, shrink-level etc.) [4, 5]. All this reasons suggest an adequate consideration of EM emissions of IC is system design.

E Field ($dB\mu V/m$) at 3 m		
Frequency	Vendor A	Vendor B
30 MHz	32.8	42.8
40 MHz	27.5	33.0
50 MHz	23.0	28.0

Table 1. Electromagnetic emissions of IC with same functionality but different vendors, taken from [4]

Due to the enormous complexity of an entire system (IC and PCB) a complete analysis with numerical methods is generally impossible or only practicable for small substructures. The main purpose of this contribution is to show how suitable physically based emission macro-models of IC can be developed and used in tools for system-level analysis.

2. Theory

2.1. The Multipole Expansion

In order to model the electromagnetic field of a component a spherical wave expansion, the so called *multipole expansion*, is used. In a source free region and under the assumption of harmonic excitation the following vector differential equation can be derived form Maxwell's equations

$$\begin{aligned} \nabla \times \nabla \times \vec{E} - k^2 \vec{E} &= 0 \\ \nabla \times \nabla \times \vec{H} - k^2 \vec{H} &= 0 \end{aligned} \tag{1}$$

with the wave number $k = \omega\sqrt{\mu\varepsilon}$. Solely in carthesian coordinates the vector equation can be written as three uncoupled scalar Helmholtz equations. It can be shown [6] that a linear independent set of solutions of the vector equation can be obtained via

$$\vec{L}_n = \nabla \Phi_n \quad \vec{M}_n = \nabla \times \vec{a}\Phi_n \quad \vec{N}_n = \frac{1}{k}\nabla \times \vec{M}_n \tag{2}$$

whereas Φ_n is a solution of the homogeneous scalar Helmholtz equation

$$\Delta\Phi + k^2\Phi = 0 \tag{3}$$

and $\vec{a}$ an arbitrary constant unit vector. As the fields should be modeled in the source free region outside the IC, the $\vec{L}_n$ solutions can be left out. In [7] it is shown that the following approach for Hertz potentials

$$\vec{\Pi}^e = \frac{j}{k}\sum_n a_n^e \Phi_n \vec{r} \quad \vec{\Pi}^m = \frac{1}{Z_0}\frac{j}{k}\sum_n a_n^m \Phi_n \vec{r} \tag{4}$$

satisfies equation (1) and leads to a complete solution. For the solution of the scalar equation

$$\Phi^{e,m}(r,\vartheta,\varphi) = \sum_{l=1}^{\infty} h_l(kr) \sum_{m=0}^{l} P_l^m(cos\,\vartheta) \cdot \left(A_{l,m}^{e,m}\sin m\varphi + B_{l,m}^{e,m}\cos m\varphi\right) \tag{5}$$

can be obtained with the constraint of purely outgoing waves. Hence the radiation condition is implicitly fulfilled. With equation (4), (5) and

$$\begin{aligned} \vec{E} &= \nabla\times\nabla\times\vec{\Pi}^e - j\omega\mu\nabla\times\vec{\Pi}^m \\ \vec{H} &= \nabla\times\nabla\times\vec{\Pi}^m + j\omega\varepsilon\nabla\times\vec{\Pi}^e \end{aligned} \tag{6}$$

the desired expansions of the electromagnetic fields can be obtained. The complex constants $A_{l,m}^{e,m}$ and $B_{l,m}^{e,m}$ are called *spherical multipole moments* and, in the following, represent the model parameters.

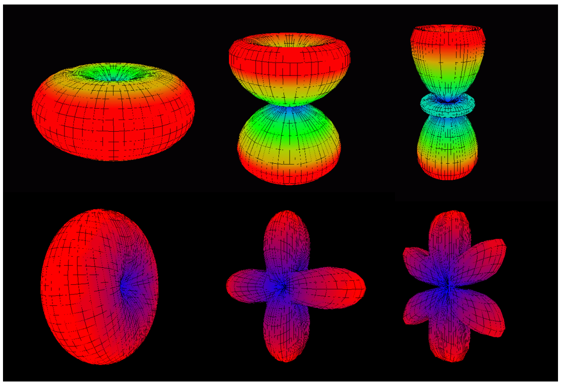

Fig. 1. Radiation pattern of the first three multipoles $l = 1..3$ with index $m = 0$ (upper row) and $m = 1$ (lower row)

In figure (1) the radiation pattern for some low order multipoles ($A_{l,m}^{e,m} = 1$) are shown. Here one of the main advantages of the multipole representation of the emission models, the spatial decomposition into different levels of detail, can be observed.

2.2. Determination of model parameters

The model parameters can be determined by different methods which are described in the following. In operator notation the task can be written as a boundary value problem

$$\mathcal{L}\hat{f} = g \text{ on } \partial D \text{ with } \hat{f} = \sum_{n=1}^{N} C_n f_n \tag{7}$$

whereas ∂D indicates the surface enclosing the volume D containing all sources. The angular multipole functions form a complete orthogonal set of functions on a unit sphere. If the function g (the field) is given on a sphere this property can used to determine all model parameters.

$$C_m = \int_{A_k} \mathcal{L}\{\tilde{f}_m\} g \, dA \text{ with } \int_{A_k} f_n \tilde{f}_m \, dA = \delta_{n,m} \tag{8}$$

It can be shown that a minimum set of data consists either of *both* radial field components or the tangential E *or* H field concerning the sphere. The procedure of orthogonal projection requires first a functional description and secondly a spherical surface which is often not useful for practical application.
Another possibility to determine the model parameters is to fullfil the fieldequations (6) at different matching points. Therefore the inner product of both sides of equation (7) with M weighting or testing functions has to be done whereas Dirac functions are used. For $N = M$ this procedure is called simple pointmatching and leads to a linear system of equations for the unknown coefficients. Furthermore it is also possible to use more matching points than model parameters $N < M$ which results in an over-determined equation system. For the pointmatching approach no restrictions exit concerning the shape of ∂D.

3. Modeling

3.1. Multipoles to model emission

In contrast to the present application of multipoles in analytical and, as basis functions [8, 9] resp. an acceleration method [10], in numerical field computing, in this paper they are used to approximate an electromagnetic field of a specific IC.
The necessary field values can be determined via numerical simulation or by measurement. For simulation a geometric model is required and equivalent excitation sources have to be modeled. This can be done, for example, for a typical application case or mode of operation. The measurement of the field is based on planar near-field scanning. To approximate the given fields a multipole is preferably situated in the center of the emission source. Then the infinite sum is

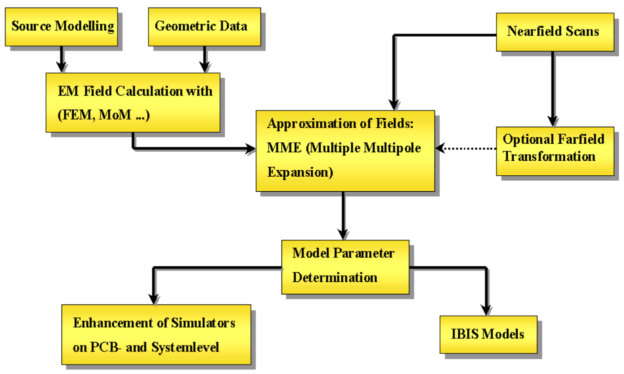

Fig. 2. Modeling workflow

cut at a specific index which determines the accuracy of the model. The index N can be determined via try and error for a given error margin or by analysis of the radial fuctions in conjunction with the size of the object r_0. If eq. (9) is less an error ε at the radius of interest r_i, set $N = n$.

$$\left| \frac{h_1(kr_0)\, h_n(kr_i)}{h_1(kr_i)\, h_n(kr_0)} \right| \leq \varepsilon \tag{9}$$

Applying the procedure described in 2.2 the unknown model parameter can be determined. Here the use of over-determined systems shows the best and most stable results. The developed emission models can on the one hand be used in system-level simulators or otherwise in extended IBIS models to describe the EMC behavior. A workflow summarizing the specific modeling steps is given in fig. (2).

3.2. Integration in High-Level simulators

In the following the integration of the developed emission models into a system-level tool is exemplarily shown for the PCB simulator COMORAN [11].

In general, emission analysis on PCB level only takes the conducting traces on the PCB itself into account. Components and integrated circuits are replaced by equivalent lumped circuits, which cannot *directly* contribute to the electromagnetic emission of the system.

The simulator COMORAN is based on the solution of the electromagnetic field integral equation (EFIE) in frequency domain by the method of moments (MoM). Therewith the field problem can be reduced to the solution of a linear system of equations of the form:

$$\underline{\mathbf{Z}}\, \underline{I} = \underline{U} \tag{10}$$

Here $\underline{\mathbf{Z}}$ represents the impedacematrix, $\underline{I}$ the vector with the unknown currents and $\underline{U}$ the so called excitation vector. By superimposing the multipole fields to the excitation vector the coupling between the models and the simulator is achieved. The main advantage of this approach is that the number of unknowns (the factor which determines the simulation time and memory) stays constant. Thus it is possible to calculate the current distribution and the emitted fields considering the electromagetic emission of IC.

4. Results

4.1. Example of an emission model

To validate the presented approach a simplyfied model of a DIP-Package with 14 pins is analyzed. Figure (3) shows the used geometric model and the resulting current distribution at $f = 2\,GHz$. For calculation a discrete voltage source has

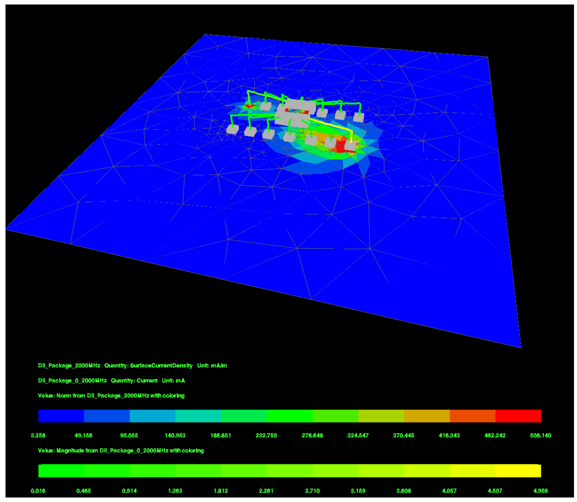

Fig. 3. 14 pin DIP package with current distribution at f=2 GHz

been connected to pin 1. To determine the multipole parameters the field has been calculated on a surface surrounding the object. Figure (4) shows the model parameters, respectively the magnitudes of the electric and magnetic multipole moments. As also higher order moments exist it can be con-

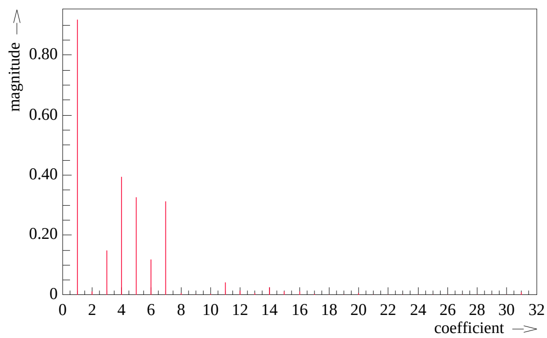

Fig. 4. Magnitude of the multipole moments (electrical and magnetical) at f=2 GHz

cluded that a simple dipole based modeling approach would not lead to sufficient accuracy. Another model parameter is the expansion degree, respectively the degree of detail. To analyze its influence, the field has been approximated for various expansion degrees. Figure (5) shows the total relative error of the electrical field components in dependence of the expansion degree. It can be concluded that, in this

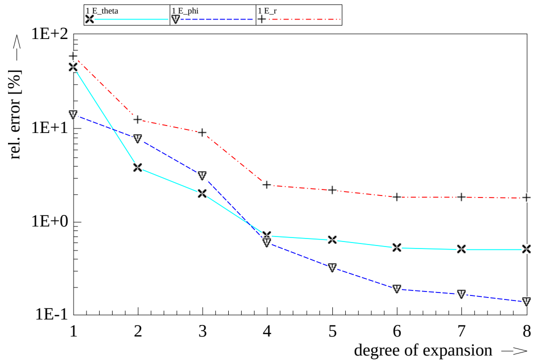

Fig. 5. Relative total approximation error of the electric field components in dependence of the expansion degree N

case, a degree of four or five is sufficient to create a good approximation. From equation (9) follows with $r_0 = 2cm$ and $r_i = 5cm$ that $N = 4$ for $\varepsilon = 5\%$ at $2GHz$.

4.2. A complex configuration

In order to validate the multipole models and to show the benefit in calculation time and system resources a complex configuration has been analysed. The structure consists of two 14 pin IC and a dipole antenna above. The IC are excited by a periodic trapezoidal signal at pin one. For the calculation 24 harmonics are taken into account (up to $3\,GHz$).

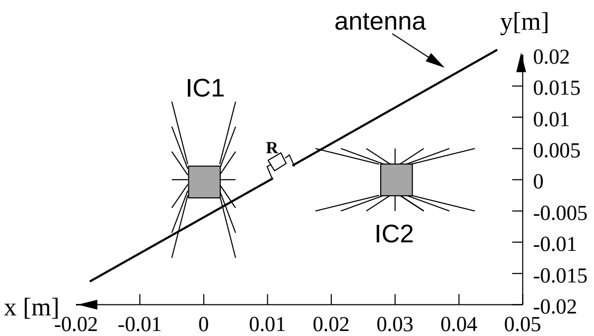

Fig. 6. Complex configuration, top view

Figure (6) and (7) show the geometric dimensions of the test configuration. In the calculation with the enhanced (see sec. 3.2) simulator COMORAN, the two IC are replaced by equivalent multipole models with the result that only the antenna structure has to be discretisized and calculated.

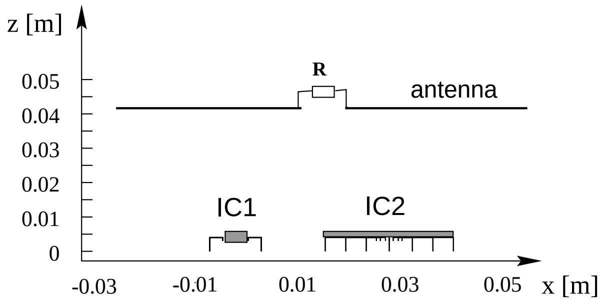

Fig. 7. Complex configuration, side view

To account for the infinite ground plane image theory has been used. As reference, geometric models of all, the two IC and the antenna, have been calculated.

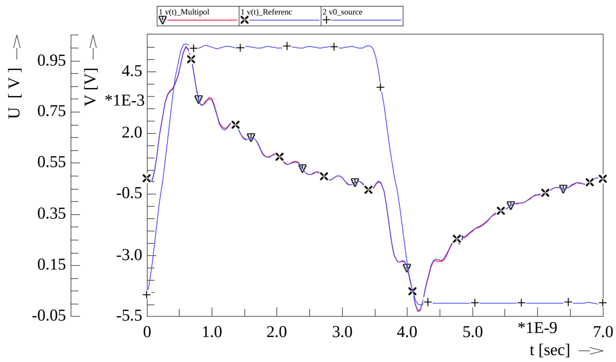

Fig. 8. Time domain voltages; ∇ = antenna resistor multipole model; $\times$ = antenna resistor reference calculation; $+$ = excitation signal

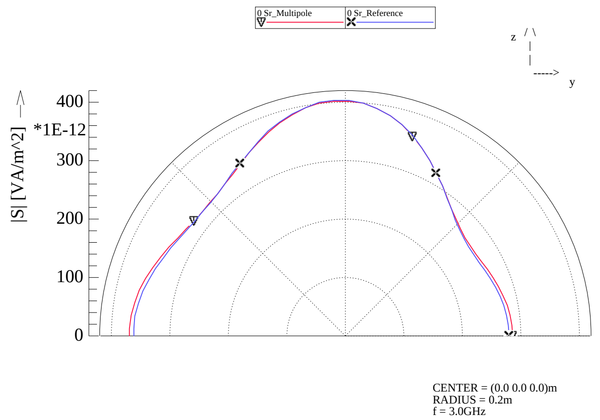

Fig. 9. Poynting vector at $r = 0.2\,m$ and x=const. at $3\,GHz$; ∇ = multipole model, $\times$ = reference calculation

Figure (8) shows a comparison of the time domain voltage signals at the antenna resistor ($R = 20\,k\Omega$) and the excitation signal of the IC. Both signals show a very good agreement. In addition figure (9) shows the comparison of the radial part of the Poynting vectors. The fields have been calculated in a distance of $r = 20cm$ of IC1 at $3\,GHz$ in the plane x=const. Again the multipole models show an excellent agreement to the reference calculation. Above results suggests, that the simplifications made due to modeling with multipoles (neglection of field coupling antenna→IC1/IC2 and IC1↔IC2) have no effect on the results.

4.3. Calculation times

One of the main advantages of the use of multipole models is the enormous reduction of calculation time and computational resources. In table (2) the calculation times for the different simulations are given. The first number indicates the calculation time for the reference configuration, the second for the model creation process (which has to be performed only one time) and the last for the reduced configuration (model use) where the IC are replaced by the multipole models.

Simulation	Calculation time	Memory used
Reference	297:43 min	95 MB
Model creation	48:12 min	21 MB
Model use	0:21 min	0.2 MB

Table 2. Calculation times for reference, model creation and model-use simulation

All calculation have been carried out on a Sun UltraSparc 10 computer with 360 MHz and 768 MB of physical RAM.

5. Conclusion

The high complexity of modern integrated circuits and package techniques requires an extensive and detailed modeling (e.g. Method of Moments, Finite Elements etc.) of all structure elements. As a result the consideration of electromagnetic emission of IC in system-level analysis has practically been impossible so far. In this contribution it has been shown, that these emissions can be represented by a physical model based on a multipole expansion. Using this macro-representation of the generated electromagnetic fields the number of necessary parameters can be drastically reduced. To show the applicability of the new approach the PCB simulator COMORAN has been enhanced to use the developed models. Comparing the results of a complex configuration very good agreement of the multipole approach with reference calculations has been shown. Additionally the high efficiency of this approach concerning computation time and memory consumption has been described. As the parameterization of the model is performed using just field values, also a detailed IC model together with an appropriate simulation method (e.g. FEM, FDTD) or meassurememts results could be used to create the emission model.

References

[1] R. W. Jackson. Microwave-Circuit Modeling of High Lead-Count Plastic Packages. In *IEEE Transactions on Microwave Theory and Techniques, Vol.45, No.10*, October 1997.

[2] S.Criel, F.Bonjean, R.De Smedt, J.De Moerloose, L. Martens, F. Olyslader, D. De Zutter. Accurate Characterization of Some Radiative EMC Phenomena at Chip Level, Using Dedicated EMC-testchips. In *IEEE EMC Symposium, Aug. 24-28*, Denver CO (USA), 1998.

[3] R.De Smedt, S.Criel, F.Bonjean, G.Spildooren. Checking Radiation Effects of Components with EMC Test Chips. In *CEM COMPO 99 Seminars*, Toulouse, France, 1999.

[4] M. Mardiguian. *Controlling Radiated Emissions by Design*. Van Nostrand Reinhold, New York, 1992.

[5] J.P. Muccioli, T.M. North, K.P. Slattery. Characteristics of RF Emissions from a family of Microprozessors using a 1GHz TEM Cell. In *IEEE International Symposium on EMC*, Austin, 1997.

[6] J. A. Stratton. *Electromagnetic Theory*. McGraw-Hill Book Company, 1941.

[7] K. Simonyi. *Theoretische Elektrotechnik*. VEB Deutscher Verlag der Wissenschaften, 1979.

[8] C. Hafner. *The Generalized Multipole Technique for Computational Electromagnetics*. Artech House Inc., Boston, 1990.

[9] G. Klaus. *3-D Streufeldberechnungen mit Hilfe der MMP-Methode*. PhD thesis, Eidgenoessische Technische Hochschule Zuerich, 1985.

[10] N. Engheta, W.D. Murphy, V.Rokhlin, M.S. Vassiliou. The Fast Multipole Method (FMM) for Electromagnetic Scattering Problems. In *IEEE Transactions on Antennas and Propagation*, pages Vol.40, NO.6 pp.634–641, 1992.

[11] S. Öing; W. John; M. Künne. Radiation and Irradiation Effects on Printed Circuit Boards Calculated with an Extended EMC–Workbench. In *Proceedings of the '1994 International Symposium on Electromagnetic Compatibility'*, pages 48–51, Sendai, Japan, 1994.

Acknowledgments

This work is supported by German ministry of education and research under grant 01 M 3034 H and Alcatel Bell EMC Research Antwerpen (Belgium). The responsibility for this publication is held by the authors only.