An Electromagnetic Emission Model for Integrated Circuits

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Overview

• Motivation/Introduction
• General Modeling
• Proposed Emission Model
• Modeling example
• Summary
Motivation: Problems and their solutions

**System/PCB analysis:**

- IC typically modeled by equivalent circuits → no direct contributions to emitted field
- Not sufficient for today’s high clock rates and complex packaging
- Complete analysis of IC/package and PCB/system not possible:
  - high complexity
  - scale level differences

⇒ only practicable for small substructures

Development of macro-models representing essential properties
Requirements for an emission model:

- Good approximation of emitted fields (near- and far field)
- Low number of model parameters
- Parameter determination via measurement and simulation
- Simple integration into existing commercial tools for system/PCB analysis
- Considering different operation modes and connected circuitry
Some possibilities of modeling EM-fields:

- Equivalence principle (known field values around IC)
- Superposition of plane waves (plane-wave spectrum)
- Equivalent radiating structures:
  - simple antennas: dipoles, loops (constant current distribution)
  - patch antennas
  - antennas with non-constant current distribution
- Multipole Expansion of electromagnetic field
Solution of vector wave equation in spherical coordinates:

\[
\left( \Delta + k^2 \right) \vec{C} = 0 \quad \vec{C} \in \{ \vec{E}, \vec{B}, \vec{\Pi}^{e,m} \}
\]

leads to field expansion in orthogonal functions:

\[
\begin{aligned}
\vec{\Pi}_e &= \frac{j}{k} \sum_{n=1}^{\infty} r h_n(kr) \sum_{m=0}^{n} P_n^m(\cos \vartheta) \left[ \begin{array}{c}
A_{n,m} \\
C_{n,m} / Z_0
\end{array} \right] \cos(m\varphi) + \left[ \begin{array}{c}
B_{n,m} \\
D_{n,m} / Z_0
\end{array} \right] \sin(m\varphi) \cdot \vec{e}_r \\
\vec{\Pi}_m &= r \sum_{n=0}^{\infty} P_n^m(\cos \vartheta) \left[ \begin{array}{c}
A_{n,m} \\
C_{n,m} / Z_0
\end{array} \right] \cos(m\varphi) + \left[ \begin{array}{c}
B_{n,m} \\
D_{n,m} / Z_0
\end{array} \right] \sin(m\varphi) \cdot \vec{e}_r
\end{aligned}
\]

\[
\vec{E} = \nabla \times \nabla \times \vec{\Pi}_e - j \omega \mu \nabla \times \vec{\Pi}_m \quad \vec{H} = \nabla \times \nabla \times \vec{\Pi}_m + j \omega \varepsilon \nabla \times \vec{\Pi}_e
\]

⇒ Expansion of el. and magnetic field in space outside sources
Modeling: Multipole Expansion II

- Dipole
- Quadrupole
- Octupole
- Hexapole
Simple Emission Model (SEM)

- Valid in near- and farfield
- Physical model
- Parameter determination via measurement or simulation
- No consideration of external circuitry

**Model parameters:**
- Multipole coefficients
- Optionally different operation modes

**Multipole model**

**Spice-, Macromodel**
Proposed Model: Controlled Emission Model

Voltage Controlled Emission Model (VCEM)

Electromagnetic equivalent model:

$$\overline{T^t} \cdot (\overline{u} - \overline{u}_0) + \overline{m}_0 = \overline{m}$$

- voltages at IC ports control modal emissions

+ consideration of external circuitry
  → parasitics effects (unintentional signals)
Proposed Model: Modeling Workflow

Source Modeling → Geometric Data → EM Field Calculation with (FEM, MoM ...)

Approximation of Fields:
- MME (Multiple Multipole Expansion)

Model Parameter Determination → Enhancement of Simulators on PCB- and Systemlevel → IBIS Models

Nearfield Scans → Optional Farfield Transformation
Proposed Model: **Integration into High-Level Tools**

- Use of models with weak coupling in fieldsolver COMORAN
- Calculation of current and radiated fields considering the IC emissions
- Only minimal increase in calculation time (MoM matrix dim. constant)

⇒ Linear system of equations to determine unknown currents:

\[
\mathbf{A} \cdot \mathbf{x} = \mathbf{b}
\]

Superposition of right side \( \mathbf{b} \) by field contribution of multipoles
Proposed Model: **Coupling mechanisms**

**Coupling mechanisms covered by proposed models**
Example: Complex Configuration

Two IC with an antenna structure in the near-field

→ Image theory used for simplification, Simple Emission Model used
Example: Complex Configuration

→ “Simple” geometric package model used to allow full-wave reference calculation of complete configuration

Current distribution at f=2GHz
Example: **Excitation**

Excitation signal

Respective spectrum (up to 3GHz)
Example: Nearfield-Effects

Time domain voltage at antenna resistor

Mag. Of current on antenna at f = 2 GHz

red = Model; blue = reference
Radial part of Poynting vector at $f = 3$ GHz in plane $x = \text{const.}$

Spectrum of $x$-component of electrical field 3m above

red = Model; blue = reference
Example: Comparison to Dipole Model

E-field 3m above structure; red: $E_x$, blue $E_y$, purple $E_z$; pure electric dipole model (left) and multipole model (right)
Example: **Computational Effort**

**Computational resources:**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Calculation time</th>
<th>Memory used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>297:43 min</td>
<td>95 MB</td>
</tr>
<tr>
<td>Model creation</td>
<td>48:12 min</td>
<td>21 MB</td>
</tr>
<tr>
<td>Model use</td>
<td>0:21 min</td>
<td>0.2 MB</td>
</tr>
</tbody>
</table>

- Efficient consideration of electromagnetic IC emission
- Enable fast analysis of different configurations → design optimizations
Summary

- High complexity of IC → expensive modeling necessary
  ⇒ no integration in system design possible

- Use of Multipole expansion as macro-model
  ⇒ low number of necessary parameters

- Simple integration in PCB- and system-level tools

- Good agreement with full-wave reference calculations

- Substantial gain of computational- and memory resources