An Electromagnetic Emission Model for Integrated Circuits

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16 March 2001

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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

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Modeling: Requirements

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

Modeling: Different approaches

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

Modeling: Multipole Expansion I

Solution of vector wave equation in spherical coordinates:

$$\left(\Delta + \mathbf{k}^2\right)\vec{\mathbf{C}} = 0 \qquad \vec{\mathbf{C}} \in \left\{\vec{\mathbf{E}}, \vec{\mathbf{B}}, \vec{\Pi}^{e,m}\right\}$$

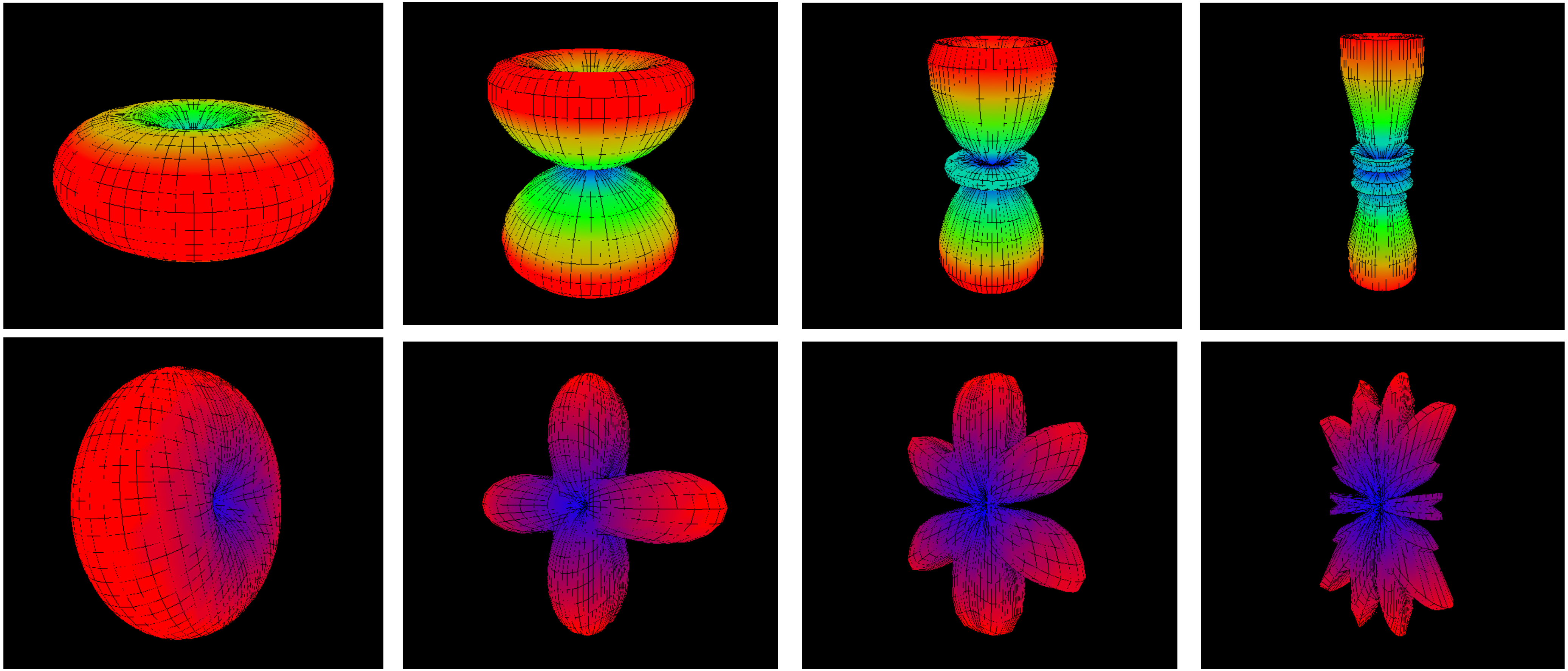
leads to field expansion in orthogonal functions:

$$\left.\begin{matrix}\vec{\Pi}_e \\ \vec{\Pi}_m\end{matrix}\right\} = \frac{\mathbf{j}}{\mathbf{k}} \sum_{n=1}^{\infty} \mathbf{r}\,\mathbf{h}_n(\mathbf{kr}) \sum_{m=0}^{n} \mathbf{P}_n^m(\cos\vartheta)\left[\left\{\begin{matrix}\mathbf{A}_{n,m} \\ \mathbf{C}_{n,m}/\mathbf{Z}_0\end{matrix}\right\}\cos(m\varphi) + \left\{\begin{matrix}\mathbf{B}_{n,m} \\ \mathbf{D}_{n,m}/\mathbf{Z}_0\end{matrix}\right\}\sin(m\varphi)\right]\cdot\vec{\mathbf{e}}_r$$

$$\vec{\mathbf{E}} = \nabla\times\nabla\times\vec{\Pi}_e - \mathbf{j}\omega\mu\nabla\times\vec{\Pi}_m \qquad \vec{\mathbf{H}} = \nabla\times\nabla\times\vec{\Pi}_m + \mathbf{j}\omega\varepsilon\nabla\times\vec{\Pi}_e$$

⇒ Expansion of el. and magnetic field in space outside sources

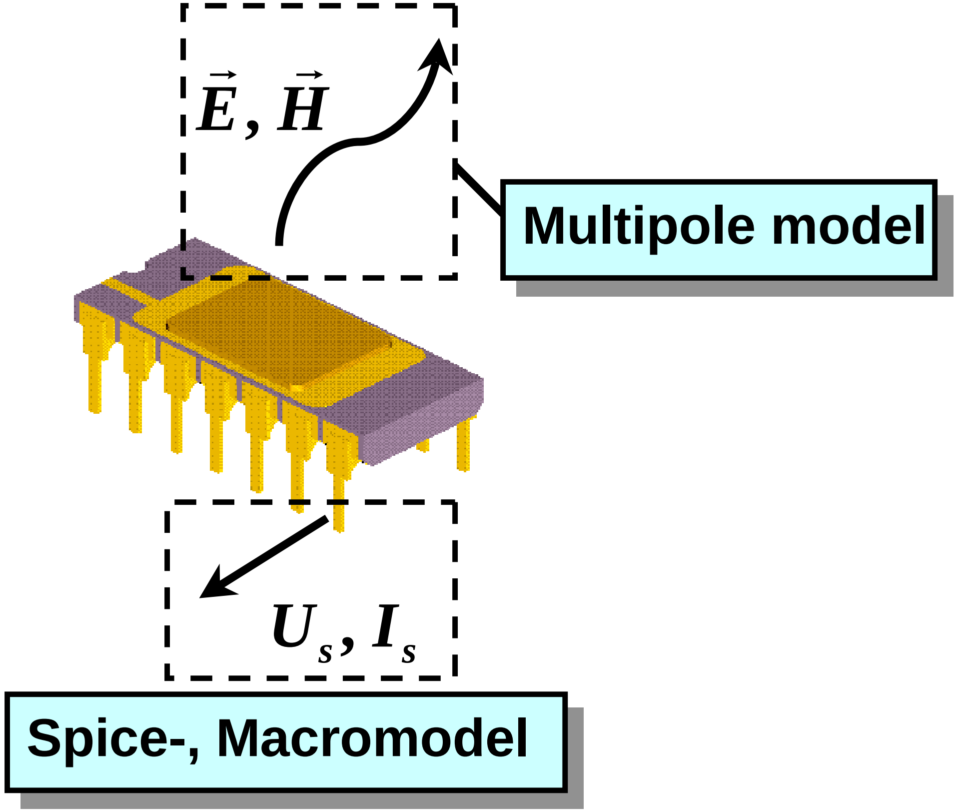
Modeling: Multipole Expansion II



Dipole | Quadrupole | Octupole | Hexapole

Proposed Model: Simple Emission Model

Simple Emission Model (SEM)



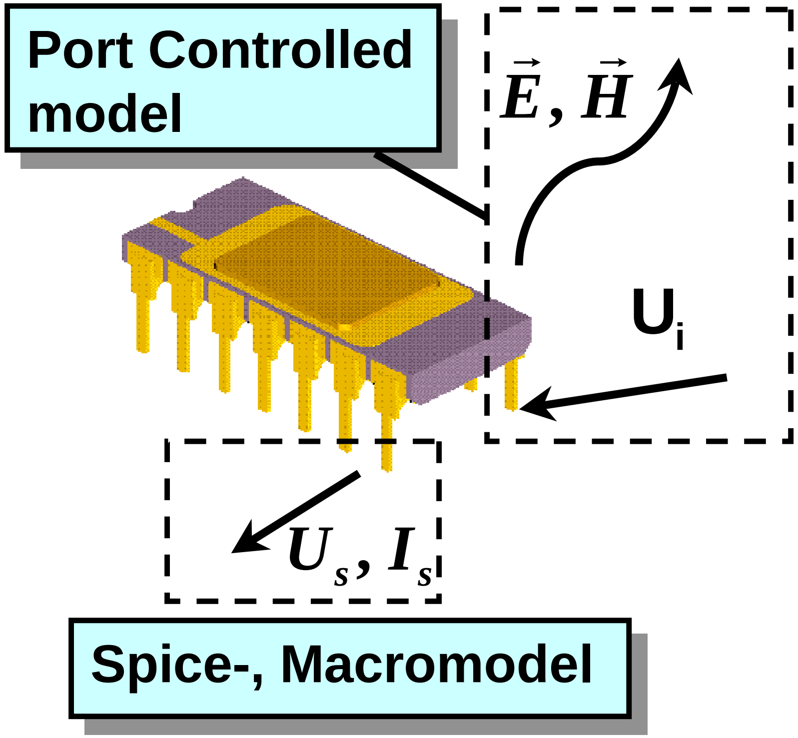
+ Valid in near- and farfield
+ physical model
+ parameter determination via measurement or simulation
- no consideration of external circuitry

Model parameters:

- Multipole coefficients
- Optionally different operation modes

Proposed Model: Controlled Emission Model

Voltage Controlled Emission Model (VCEM)



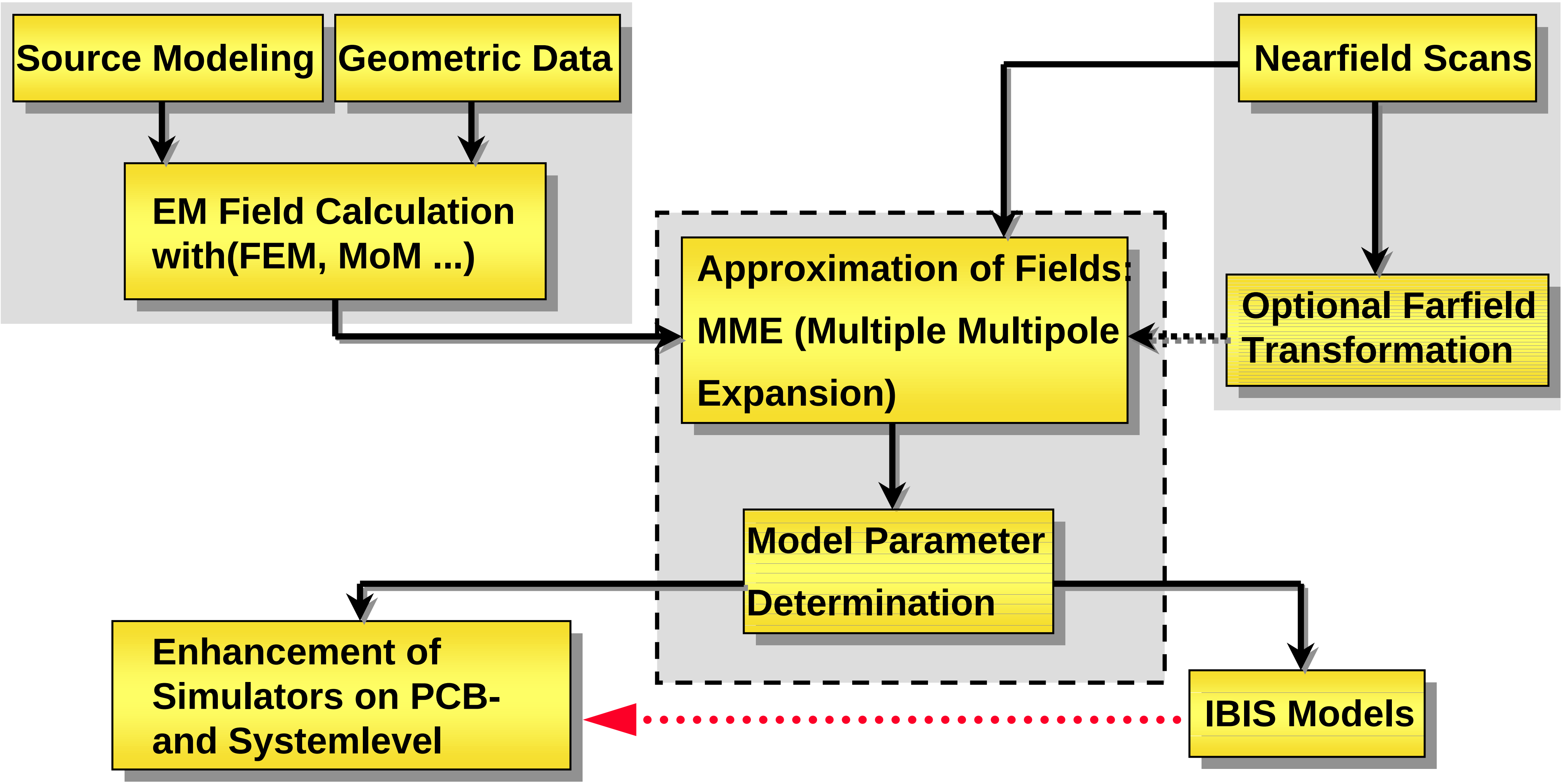
Electromagnetic equivalent model:

$$\overline{\overline{T'}} \cdot (\overline{u} - \overline{u}_0) + \overline{m}_0 = \overline{m}$$

- voltages at IC ports control modal emissions

\+ consideration of external circuitry
→ parasitics effects (unintentional signals)

Proposed Model: Modeling Workflow



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)

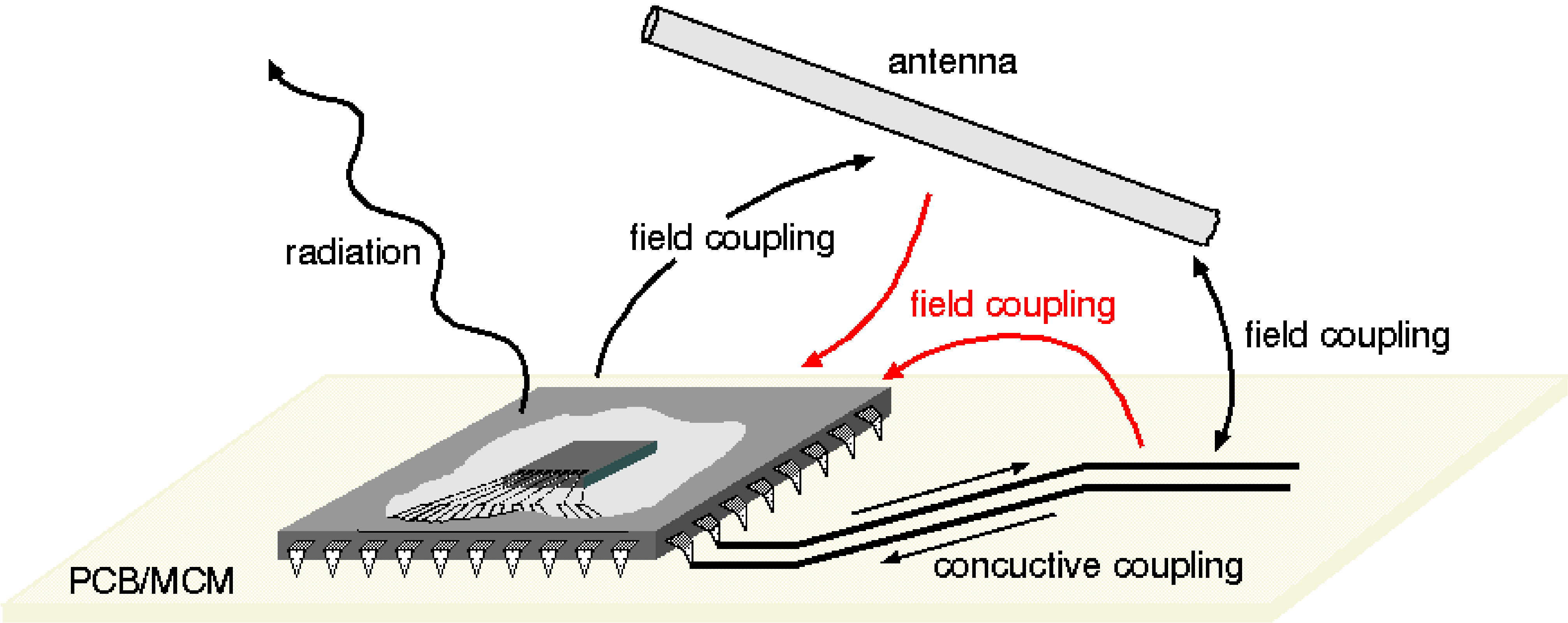
⇒ Linear system of equations to determine unknown currents:

$$\underline{\mathbf{A}} \cdot \vec{\mathbf{x}} = \vec{\mathbf{b}}$$

$$\vec{\mathbf{E}}_{\mathbf{Multipol}} \quad \oplus$$

Superposition of right side ***b*** by field contribution of multipoles

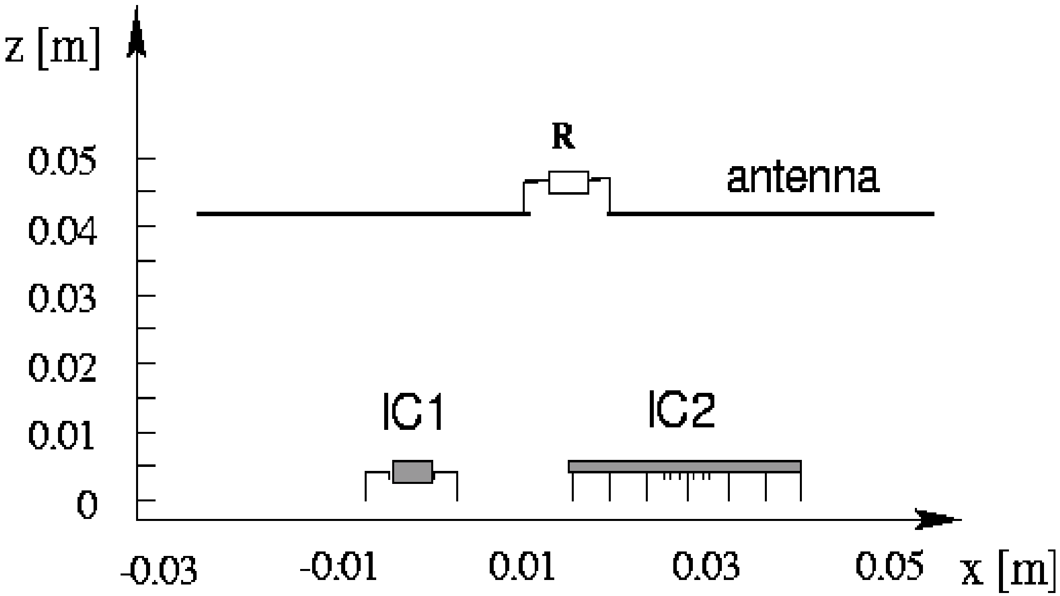
Proposed Model: Coupling mechanisms



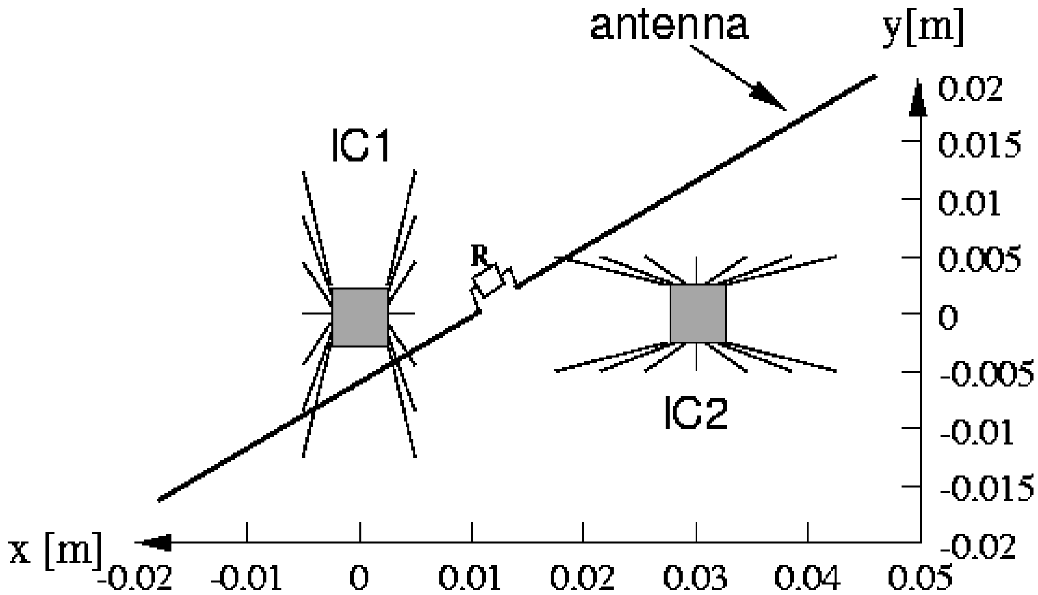
Coupling mechanisms covered by proposed models

Example: Complex Configuration

Two IC with an antenna structure in the near-field



Side view of configuration



Top view of configuration

→ Image theory used for simplification, Simple Emission Model used

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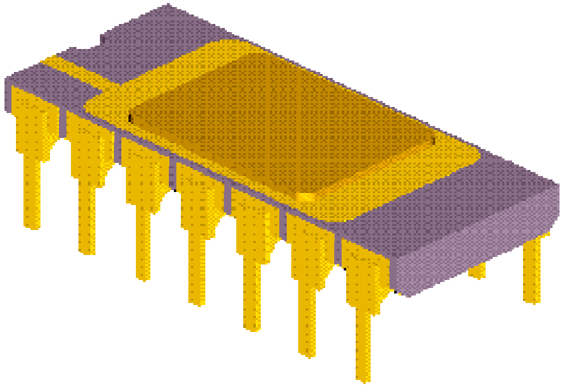
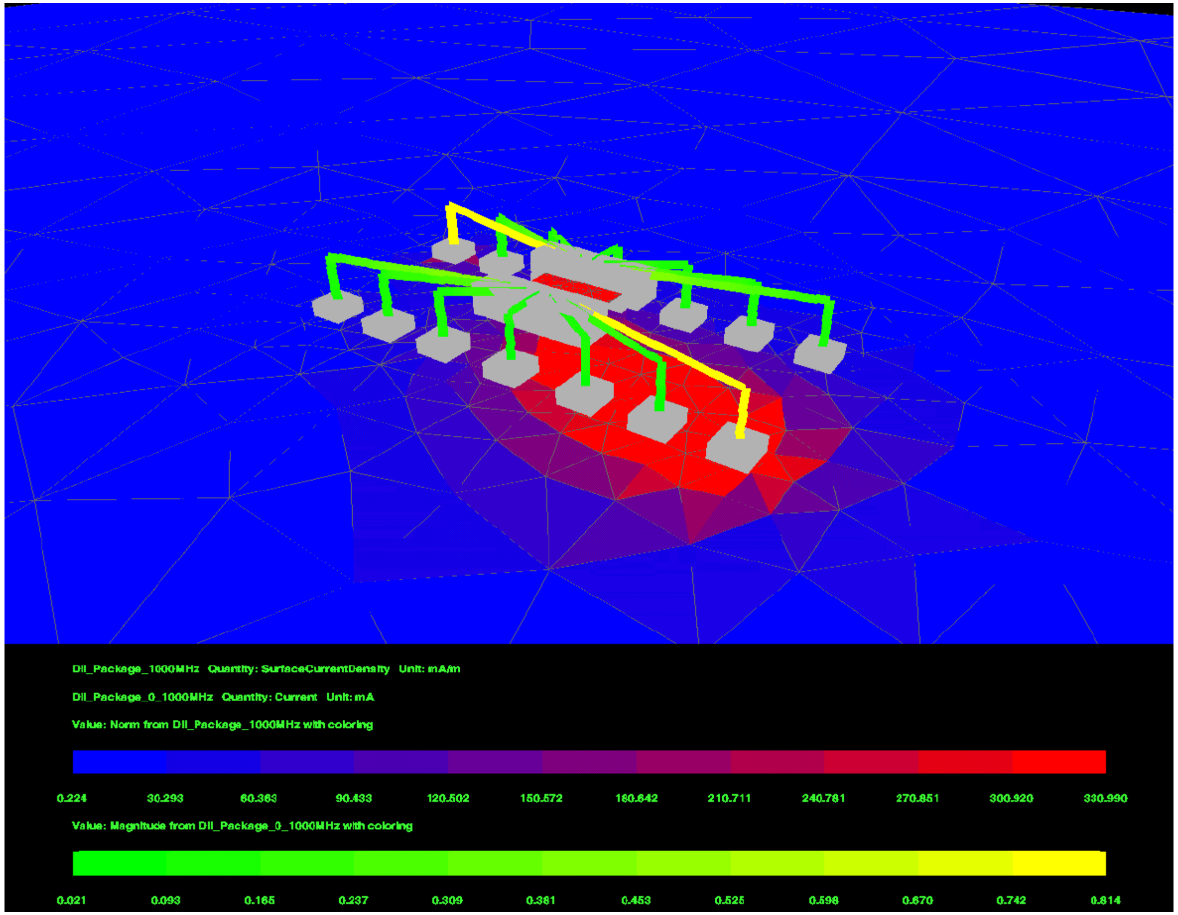
Example: Complex Configuration



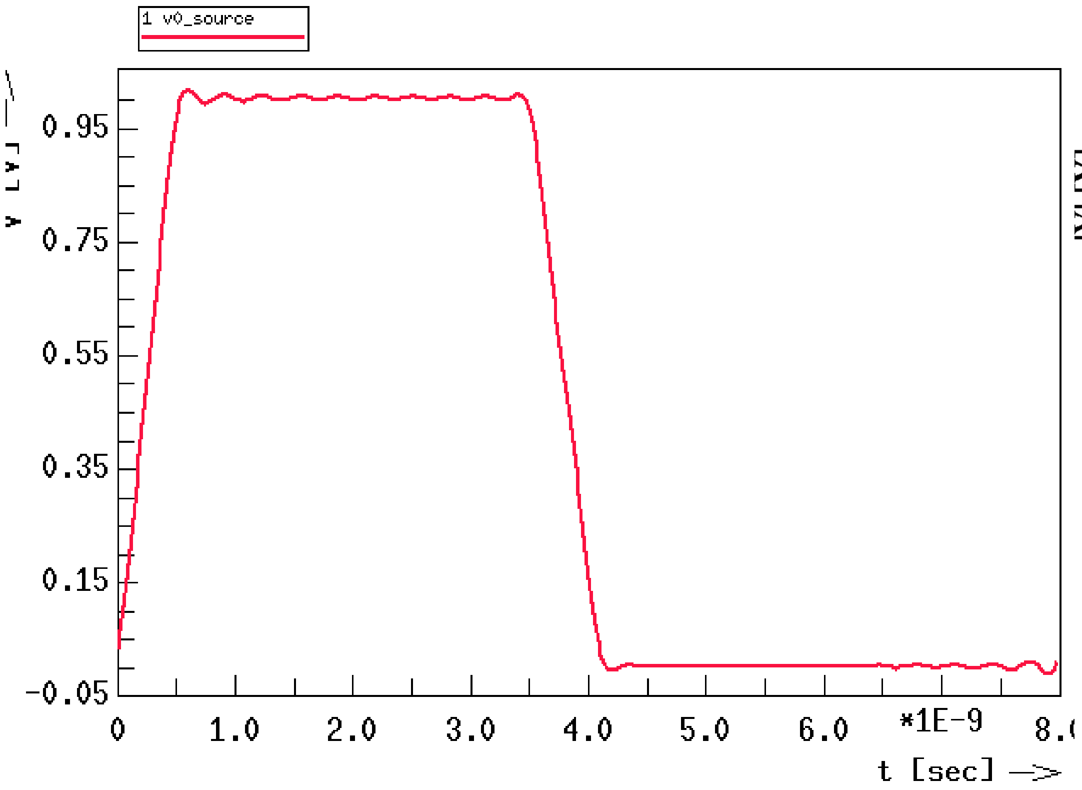
IC/package



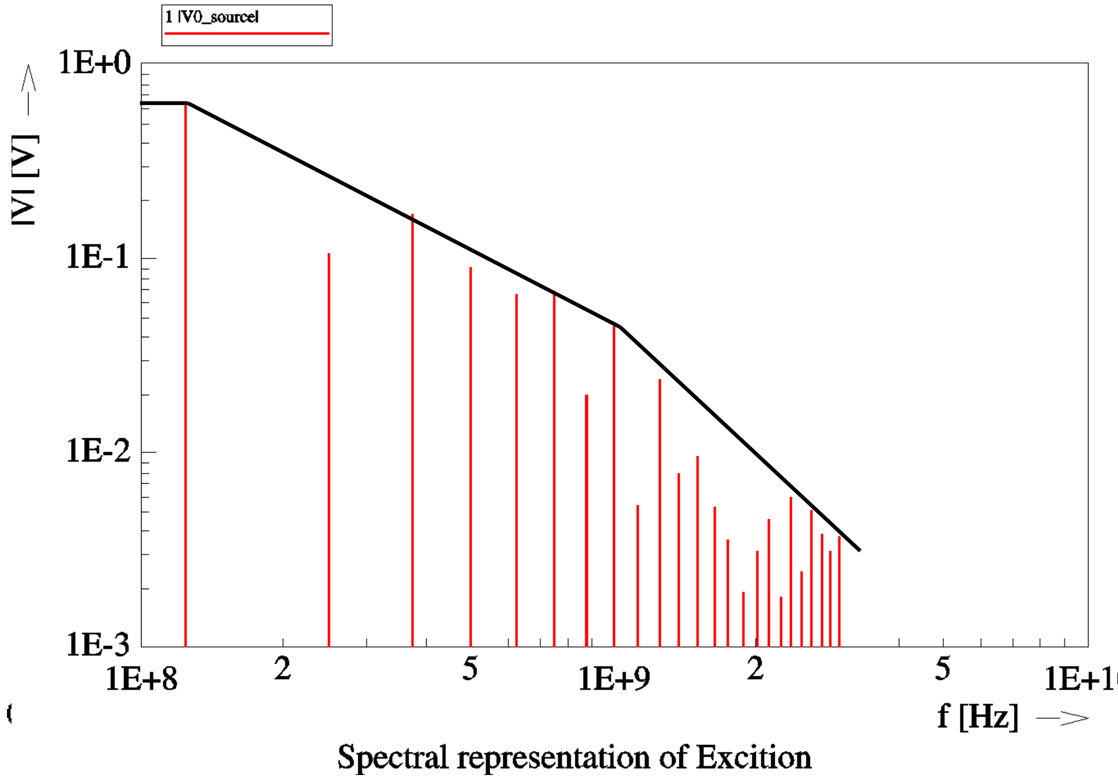
Current distribution at f=2GHz

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

Example: Excitation



Excitation signal



Respective spectrum (up to 3GHZ)

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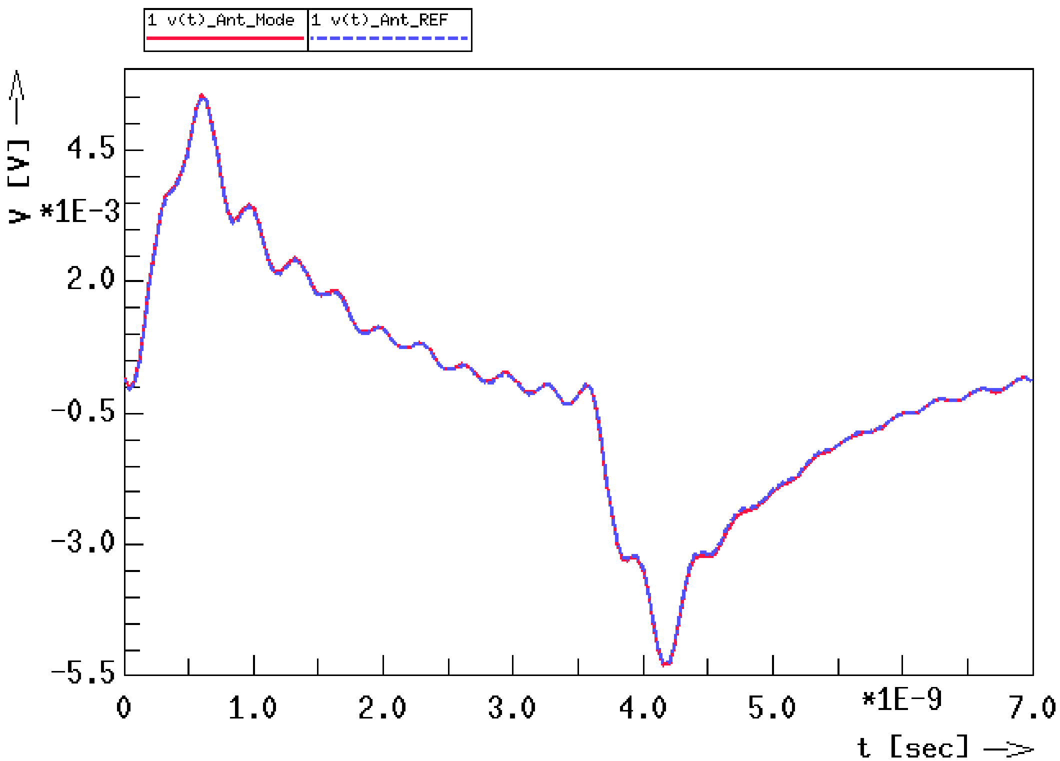
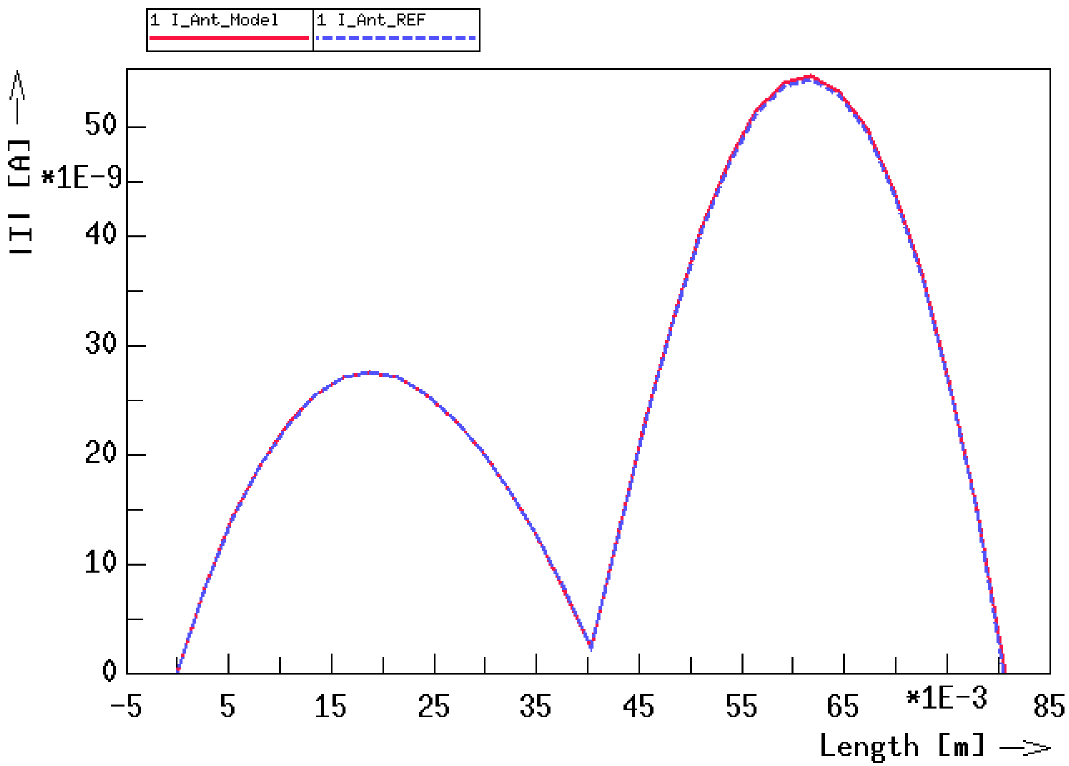
Example: Nearfield-Effects



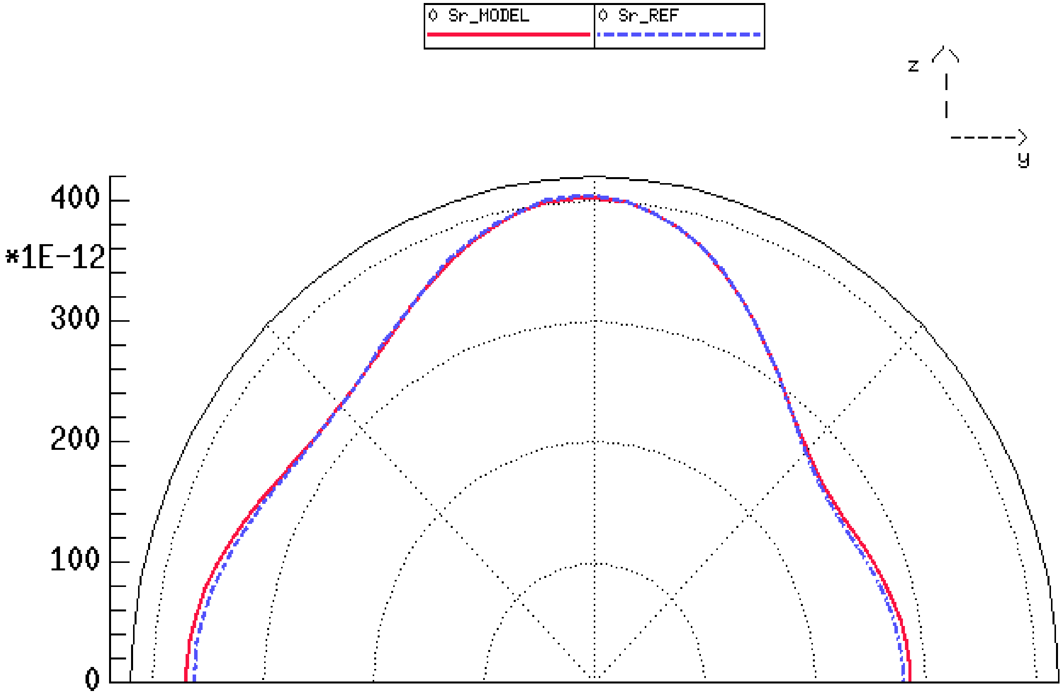
Time domain voltage at antenna resistor

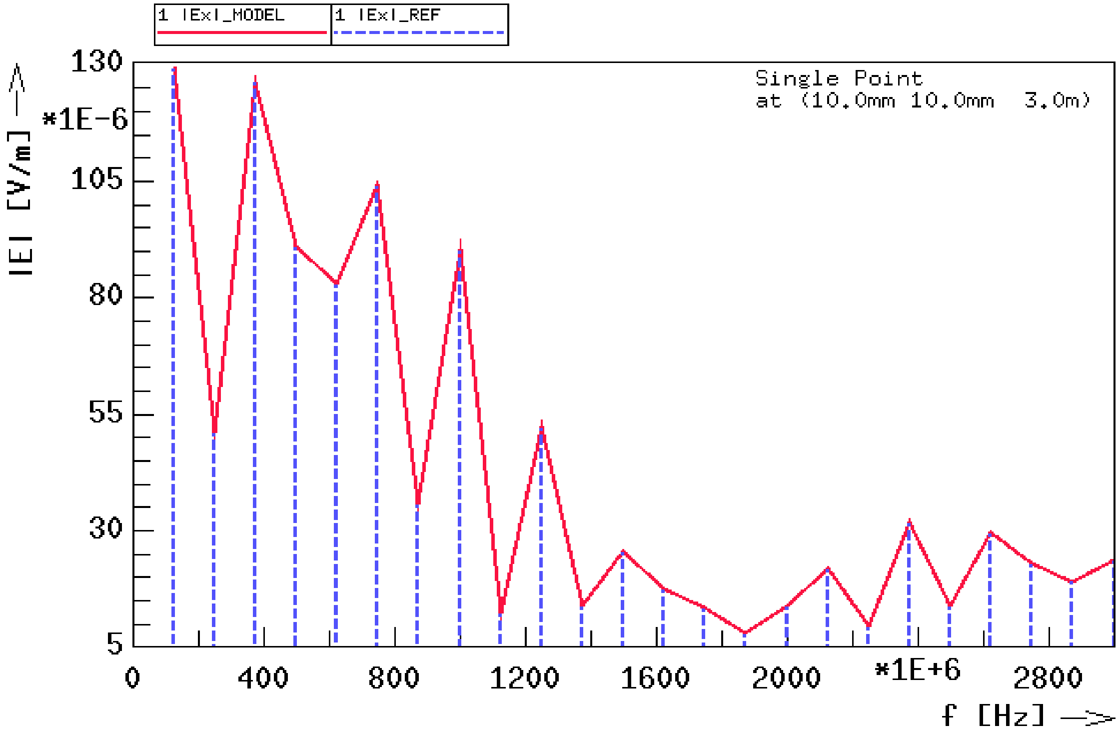


Mag. Of current on antenna at f = 2 GHz

red = Model; blue = reference

Example: Farfield-Effects



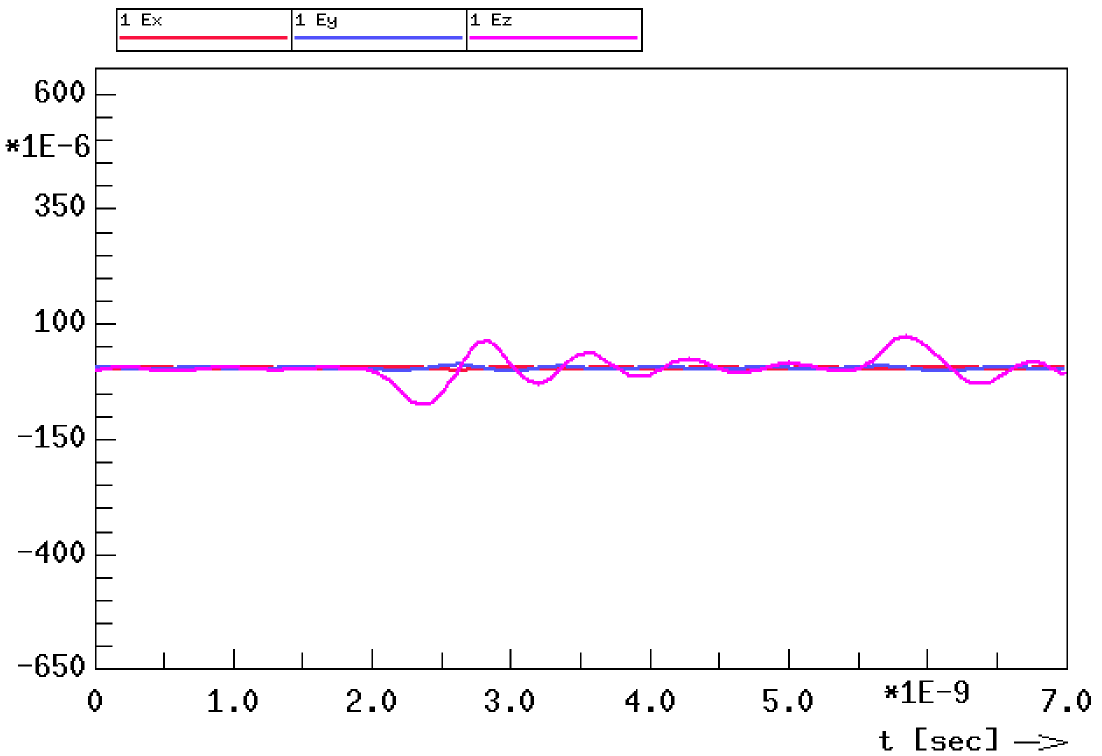


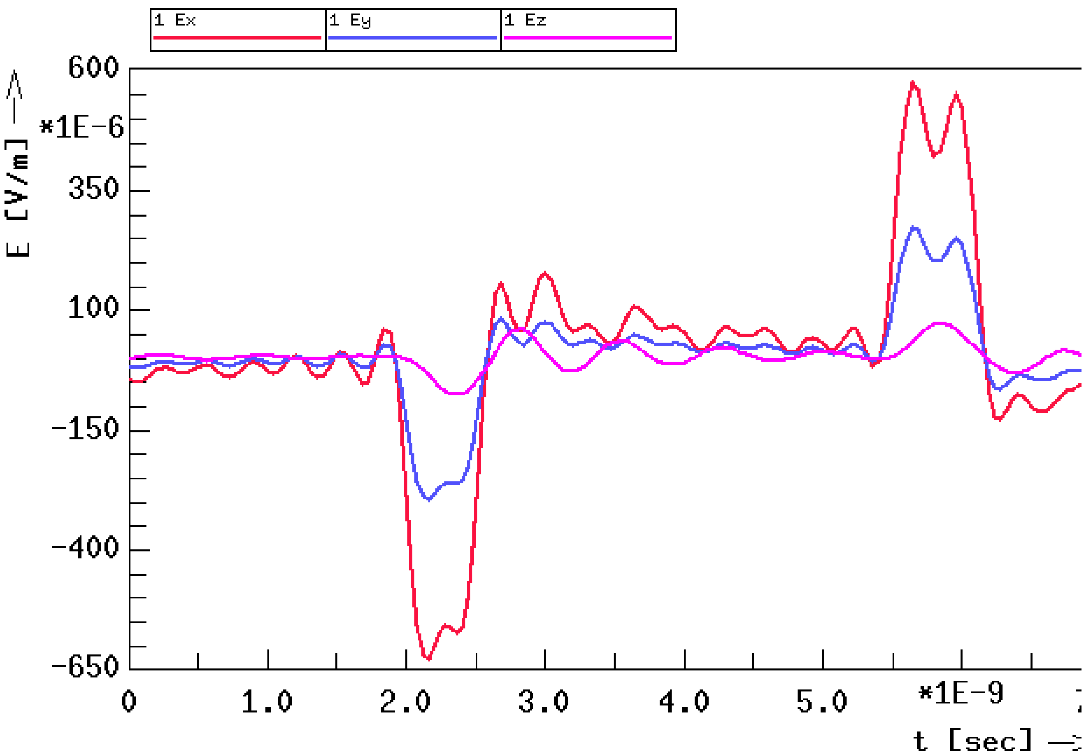
Radial part of Poynting vector at f = 3 GHz in plane x=const.

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:

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

- Efficient consideration of electromagnetic IC emission
- Enable fast analysis of different configurations
  $\rightarrow$ design optimizations

Summary

- High complexity of IC $\rightarrow$ expensive modeling necessary
  $\Rightarrow$ *no integration in system design possible*
- Use of Multipole expansion as macro-model
  $\Rightarrow$ *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

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