A FULLY 3-D BIE EVALUATION OF THE RESISTANCE AND INDUCTANCE OF ON-BOARD AND ON-CHIP INTERCONNECTS

Martijn Huynen, Daniël De Zutter, Dries Vande Ginste
OUTLINE

• Motivation
• Proposed technique
• Examples
• Conclusions
OUTLINE

• Motivation
• Proposed technique
• Examples
• Conclusions
MOTIVATION

Smaller & faster electronics

Increasing complexity, functionality, signal integrity, power constraints, …

New solutions such as 3-D ICs
MOTIVATION

Many challenges

Heat distribution

Signal integrity (crosstalk, dispersion, distortion, …)

Rigorous modeling increasingly essential!
PROBLEM STATEMENT

- Finite conductivity, skin effect, proximity effect
  → difficult to model broadband
- Solved in 2-D [1, 2] using a Dirichlet-to-Neumann operator
- Open question in 3-D
- Recently proposed for 3-D cylinders and cuboids [3, 4]

OUTLINE

• Motivation
• Proposed technique
• Examples
• Conclusions
PROPOSED TECHNIQUE

Field equivalence principle

Original situation

Equivalent situation
PROPOSED TECHNIQUE

Electric field integral equation

\[ \mathbf{e}_0 - \mathbf{e}_i = -j\omega \mathbf{a} - \nabla \phi \]

Test and basis functions

\[ \begin{cases} \mathbf{j}_s \\ \mathbf{e}_0 \end{cases} = \sum_m \begin{cases} I_m \\ E_{0,m} \end{cases} \]
PROPOSED TECHNIQUE

\[ e_0 - e_i = -j\omega a - \nabla \phi \]

Discretization

\[
\overline{G}E_0
\]

\[
\overline{G}_{m,n} = \int_{S} \cdot \ dS
\]
**PROPOSED TECHNIQUE**

Discretization

$$\mathcal{G} \mathbf{E}_0 - \mathbf{V}_i$$

$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega \mathbf{a} - \nabla \phi$$

$$(\mathbf{V}_i)_m = \int_{S_m} \mathbf{e}_i \cdot \mathbf{dS}$$
PROPOSED TECHNIQUE

\[ e_0 - e_i = -j \omega a - \nabla \phi \]

Discretization

\[ \overline{G} E_0 - V_i = -j \omega \overline{L} I \]

\[ L_{m,n} = \mu_0 \int \int G(r, r') \, \text{d}S \]
PROPOSED TECHNIQUE

\[ e_0 - e_i = -j\omega a - \nabla \phi \]

Discretization

\[ \overline{G}E_0 - V_i = -j\omega \overline{L}I + V^+ - V^- \]

Via partial integration:

\[ V_m^\pm = \int_{R_m^\pm} \frac{\phi}{A_m^\pm} dS \]

Average potential on each rectangle \( R_m^\pm \)
PROPOSED TECHNIQUE

\[ \bar{G}E_0 - V_i = -j\omega \bar{L}I + V^+ - V^- \]

Circuit interpretation

Still 2 sets of unknowns:

- \( I \)
- \( E_0 \)
PROPOSED TECHNIQUE

3-D Dirichlet-to-Neumann operator $\mathcal{D}_k$: [3, 4]

Differential surface admittance operator

$$ u_n \times h_1 = \mathcal{D}_k e_1^t $$

$$ \Rightarrow j_s = \mathcal{V} e_0^t = (\mathcal{D}_k - \mathcal{D}_{k_0}) e_0^t $$


[4] M. Huynen, D. De Zutter and D. Vande Ginste, accepted at IEEE MWCL
PROPOSED TECHNIQUE

\[ \mathbf{j}_s = \mathcal{V} \mathbf{e}_0^t = (\mathcal{D}_k - \mathcal{D}_{k_0}) \mathbf{e}_0^t \]

\[ \mathbf{j}_s = \eta \sum_{l} \left[ \frac{|k_l|^2}{(k_l^2 - k^2) (k_l^2 - k_0^2)} N_l^2 \int_S (\mathbf{u}_n \times \mathbf{e}_0) \cdot \mathbf{h}_l^* \, dS \right] (\mathbf{u}_n \times \mathbf{h}_l) \]

\( \sigma_0 - \sigma + j \omega (\epsilon_0 - \epsilon) \)

Wavenumber of \( \mathbf{h}_l \)

Magnetic eigenfunctions of \( \mathcal{V} \)

Normalization of \( \mathbf{h}_l \)
PROPOSED TECHNIQUE

\[ j_s = \mathcal{Y} e_t^0 = (\mathcal{D}_k - \mathcal{D}_{k_0}) e_t^0 \]

Discretization

\[ E_0 = \begin{pmatrix} \bar{Y}^{-1} & \bar{G} \end{pmatrix} I \]
PROPOSED TECHNIQUE

\[
\left( \overline{G \overline{Y}}^{-1} \overline{G} \right) \mathbf{I} - \mathbf{V}_i = -j\omega \overline{L} \mathbf{I} + \mathbf{V}^+ - \mathbf{V}^-
\]

Circuit interpretation

Only 1 set of unknowns left:

- \( \mathbf{I} \)
OUTLINE

• Motivation
• Proposed technique
• Examples
• Conclusions
EXAMPLE: PARALLEL CONDUCTORS

Normalized resistance = total resistance (3-D) / length

![Graph showing the relation between Pouillet DC resistance and frequency for different s values and l values.](image)
EXAMPLE: PARALLEL CONDUCTORS

Normalized inductance

EXAMPLE: RIGHT-ANGLED CORNER

right-angled corner

\[ a = 2 \text{ mm} \]

\[ L \]

\[ 2 \text{ mm} \]

\[ D \]

cuboid

\[ D \]

\[ a = 2 \text{ mm} \]

\[ L \]

\[ 2 \text{ mm} \]
EXAMPLE: RIGHT-ANGLED CORNER

right-angled corner

\[ a = 2 \text{ mm} \]

2 mm

\[ L \]

\[ D \]
Resistance

\[ \frac{L}{a} = 1, \quad \frac{D}{a} = 1 \]
\[ \frac{L}{a} = 2.5, \quad \frac{D}{a} = 0.5 \]

Proximity effect \( \rightarrow \) crossover

Finite difference method (FDM) \( \rightarrow \) DC value
EXAMPLE: RECTANGULAR LOOP
EXAMPLE: RECTANGULAR LOOP

Resistance

Confirmation of rigorous modeling of 3-D effects

Inductance

Faulty meshing → unphysical kink

EXAMPLE: RECTANGULAR LOOP

Resistance

![Graph showing the relationship between frequency and resistance for different loop lengths. The graph indicates that smaller loop sizes result in stronger proximity effects.](image)
EXAMPLE: RECTANGULAR LOOP

Inductance

![Graph showing inductance vs frequency for different loop lengths.]

- $l = 10 \, \mu m$
- $l = 15 \, \mu m$
- $l = 20 \, \mu m$
- $l = 25 \, \mu m$
- $l = 30 \, \mu m$
OUTLINE

• Motivation
• Proposed technique
• Examples
• Conclusions
CONCLUSIONS

Novel 3-D interconnect modeling tool
- Based on BIE (without volume meshing)
- Fully 3-D differential surface admittance operator

⇒ Rigorous approach for skin effect, proximity effect, etc. in 3-D interconnects

Validation and applications
- Application to PCB and IC interconnect structures
- Accurate modeling of corners
- Broadband extraction of R- and L-parameters
- Thoroughly compared to industry standards
FURTHER READING

2-D:


3-D:

M. Huynen, D. De Zutter and D. Vande Ginste, “Boundary integral equation study of the influence of finite conductivity on antenna radiation using a 3-D differential surface admittance operator”, ACES Symposium - Italy (March 2017)

M. Huynen, D. De Zutter and D. Vande Ginste, “Rigorous full-wave resistance and inductance computation of 3-D interconnects”, accepted at IEEE MWCL
Martijn Huynen
PhD student
ELECTROMAGNETICS GROUP

E  Martijn.Huynen@ugent.be
T  +32 9 331 48 81

www.ugent.be
www.imec.be

Universiteit Gent
@ugent
Ghent University