Measurement and Physics-Based Modeling of EM Radiation from Printed Circuit Board for Prediction and Suppression

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EMI Problem

- There are various radiators called EMI antenna in devices.
- EM radiation from cables attached to PCB will be the largest at resonance of EMI antenna.

➢ General methods for predicting and suppressing EM radiation over a broad band are required!
Motivation

- A prediction of the radiated emission is still quite difficult due to the incomplete knowledge of fundamental radiation mechanism.

- Investigating the basic method and consideration to establish methods predicting and suppressing EM radiation up to GHz band is essential!

- Measurement and modeling of EM noise from a PCB play an important role in the understanding of EMI problems and in establishing design techniques.

- One of the methods to analyze EMI problems with electronic devices is to identify the frequency response of common mode (imbalance) current on a PCB.
Agenda

Topic I: EM radiation from a PCB driven by a connected feed cable

- Identifying the dominant component in the total EM radiation at GHz frequency band
- Prediction of EM radiation
- Suppression of common-mode component by guard-trace

Topic II - Evaluation of imbalance component and EM radiation generated by asymmetrical differential-paired lines structure

- Imbalanced component on differential paired lines
- Correlation between imbalanced component and EM radiation
- Prediction of EM radiation
Topic I

EM radiation from a PCB driven by a connected feed cable
There are two components:

1) **Differential-Mode (DM)** is desired current for the operation

2) **Common-Mode (CM)** is not intended to present, but will be present in practical systems
Driven Mechanisms

- Mechanisms by which the DM current is converted to CM noise sources resulting in EMI have been demonstrated [*].

Two classes of coupling mechanisms;

\[ |I_{CM}| \approx \frac{\omega^2 C_{ant} L_{return} V_{DM}}{Z_l} \]

Current-driven

\[ |I_{CM}| \approx \omega C_{ant} V_{DM} \]

Voltage-driven

To propose and demonstrate equivalent circuit model for predicting and suppressing EM radiation from the PCB driven by the connected feed cable.

Equivalent circuit model:
Based on consideration of concepts of
- CM antenna impedance
- Distributed constant circuit

to the conventional mechanisms.
PCB Geometry Under Test

Top view)

- Trace \( w_t = 2.8 \) cm
- \( l_t = 50 \) cm
- \( l_c = 30 \) cm
- \( w = 10 \) cm
- FR-4 (Reverse side is ground plane)
- \( l = 150 \) cm

Side view)

- \( h = 1.53 \) cm
- Via hole

- The CM inductance: \( 0.61 \) nH/cm (3.1 nH)
Experimental Setup for CM Current

- $V_{in}$: Input of the spectrum analyzer
- $Z_T$: Transfer impedance of the current probe

$$|I_{CM}| [\text{dB} \mu \text{A}] = |V_{in}| [\text{dB} \mu \text{V}] - Z_T [\text{dB} \Omega]$$
Experimental Setup for Far-Field

**[Anechoic chamber]**

- Log-periodic antenna (300-1000MHz)
- Biconical antenna (30-300MHz)
- Double ridged waveguide horn (1-18GHz)
- Receiving antenna
- Aluminum plate
- Absorber
- PCB
- SG

Distance: $r = 3$ [m]

Output: 0dBm (107dBµV)
Method of FDTD Modeling

- **CM Current**: loop integral of the magnetic field around the cable at the current probe position
- **Total Far Electric-Field**: near to far-field transformation

Approach to Antenna Model

- The mechanism of the generation of EM noise: source-path-antenna model

\[
\text{EMI} = \text{Source} \times \text{Path} \times \text{Antenna}
\]

DM rad. \quad V_{DS} \quad \text{Loop like}

CM rad. \quad V_{DS} \quad \text{DM/CM}

DM/CM Dipole like

DM: Loop

CM: Dipole
Antenna Model

EMI at 3m = Radiation Efficiency \times Antenna Current

\[ E_{DM}(f) = \frac{\pi \mu_0 f^2}{c_0 r} 2hl_t \times \bar{I}_{DM}(f) \]

\[ E_{CM}(f) = \frac{\omega \mu_0}{4\pi r} (l + l_c) \times \bar{I}_{CM}(f) \]
Mean Current and Efficiency

**Current**

\[ I_{CM} \ll I_{DM} \]
**CM**: GND & Cable
**DM**: 
\[(1+2n)\lambda_g/2 \rightarrow \text{Res.} \]
\[n\lambda_g \rightarrow \text{Ant. Res.} \]

**Efficiency**

\[ |E_{CM}/I_{CM}| \propto f \]
\[ |E_{DM}/I_{DM}| \propto f^2 \]

- Diff. @ 100MHz = 50 dB
- @ 10GHz = 10dB
Frequency Response of Far-Field

MHz band: \( I_{CM} < I_{DM} \) but \( E/I_{CM} >> E/I_{DM} \) ➔ CM dominant!

Above 4GHz \( I_{CM} < I_{DM} \) but \( E/I_{CM} = E/I_{DM} \) ➔ DM dominant!
Equivalent Circuit Model

- Concepts of CM antenna impedance and distributed constant circuit are included in the current and voltage-driven mechanisms.

- $Z_{ant}$: antenna impedance (capacitive at lower frequencies)

![Equivalent Circuit Model Diagram](image)

How do we quantify $Z_{ant\ CD}$, $Z_{ant\ VD}$?
CM EMI Antenna Model

Two CM EMI antenna models have been proposed to explain the frequency response of CM current[*].

- CM EMI antenna 1: ground plane
  → correspond to antenna impedance $Z_{ant \ CD}$

- CM EMI antenna 2: trace on the ground plane
  → correspond to antenna impedance $Z_{ant \ VD}$

Frequency Response of CM Antenna Impedance

Input impedance $|Z_{ant}| [\Omega]$

- $|Z_{ant \: CD}| \propto \frac{1}{f}$
- $|Z_{ant \: VD}| \propto \frac{1}{f}$

Frequency [Hz]

- Experiment
- FDTD

$10^{7}$ $10^{8}$ $10^{9}$
Method for Predicting CM Current (1)

Assumption
- Characteristic impedance $Z_0$ of the trace is matched to the source impedance $R_S = 50\Omega$.
- Transmission line is lossless.

The DM current $I_{DM}(x)$ on the signal trace:

$$I_{DM}(x) = I(0)\left(1 - \Gamma e^{-j2\beta(l_{t} - x)}\right)e^{-j\beta x}$$

$$I(0) = \frac{V_S}{R_S + Z_0} = \frac{V_S}{2}$$

$$\Gamma = \frac{Z_l - Z_0}{Z_l + Z_0}$$
Method for Predicting CM Current (2)

- Since the $I_{CM}$ is orders of magnitude much smaller than $I_{DM}$, return current on the ground plane is almost the same as $I_{DM}$.
- Voltage drop $V_{CM}$ in the inductance $L_{CM}$:
  \[
  V_{CM} = \int_{0}^{l_t} j\omega L_{CM} I_{DM}(x)dx
  \]
- The CM current $I_{CM_{CD}}$ due to the current-driven mechanism
  \[
  I_{CM_{CD}} = \frac{V_{CM}}{Z_{ant_{CD}}} \approx -\omega^2 C_{ant_{CD}} L_{CM} \int_{0}^{l_t} I_{DM}(x)dx \quad f < f_{r1}
  \]
Method for Predicting CM Current (3)

- CM current $I_{CMVD}$ due to the voltage-driven mechanism

$$I_{CMVD} = \frac{V_l}{Z_{antVD}} \approx j\omega C_{antVD} \left. V_l \right|_{f < f_{r1}}$$

where,

$$V_l = (1 + \Gamma)V_{DM} = (1 + \Gamma)\frac{V_S}{2}$$
Net CM current on the PCB is expressed as vectorial sum

\[ \vec{I}_{CM} = \vec{I}_{CM_{CD}} + \vec{I}_{CM_{VD}} \]
Frequency Response of CM Current ($Z_l=0\Omega$ case)

- $I_{CM}$ (Experiment)
- $I_{CM}$ (FDTD)
- $I_{CM}$ (Prediction)
- $I_{CM\ CD}$ (Prediction)
- $I_{CM\ VD}$ (Prediction)

There is no $I_{CM\ VD}$ → $I_{CM}=I_{CM\ CD}$

Slope of 40dB/decade
Frequency Response of CM Current \( (Z_l=51\Omega \text{ case}) \)

\[ I_{CM} = I_{CM} VD \quad (f<200\text{MHz}) \]

\[ I_{CM} = I_{CM} CD \quad (f>200\text{MHz}) \]

- **\( I_{CM} \)** (Experiment)
- **\( I_{CM} \)** (FDTD)
- **\( I_{CM} \)** (Prediction)
- **\( I_{CM} CD \)** (Prediction)
- **\( I_{CM} VD \)** (Prediction)
Relationship Between $I_{CM}$ at 10MHz and $Z_l$

FDTD and predicted results are in good agreement within 1dB

$Z_l$ is larger
Relationship Between Slope of the Frequency Response of CM Current and Terminating Resistor

- 12 dB/oct. (40 dB/dec.): current-driven
- 6 dB/oct. (20 dB/dec.): voltage-driven

Slope of the increment 10-20MHz of results

Proposed model can predict and explain frequency response!
Prediction of Total EM Radiation up to 18GHz

- $E_x (r=3\text{m})$

$$E_{DM}(f) = \frac{\pi \mu_0 f^2}{c_0 r} 2hl_t \bar{I}_{DM}(f)$$

$$E_{CM}(f) = \frac{\omega \mu_0}{4\pi r} (l + l_c) \bar{I}_{CM}(f)$$

- $I_{DM}$: Transmission Line Model
- $I_{CM}$: Proposed equivalent circuit model!
Consequently, it is possible to predict outline of the frequency response of undesired EM radiation from the PCB driven by the connected feed cable up to 18GHz.
As example of application of equivalent circuit model to EMC design, effect of width of the ground plane in the short case is discussed.
Effect of Width of the Ground Plane on CM Current

$L_{CM}$ and $C_{ant\ CD}$

- $L_{CM}$ is inversely proportional to $w$
- As the $w$ becomes wider, $C_{ant\ CD}$ increases.

The relationship is not proportional simply, because antenna is comprised of ground plane and cable.
Effect of Width of the Ground Plane on CM Current

Example: When $w$ expands from 10mm to 100mm

$C_{ant\ CD}$ increases 3 times (9.5dB)

$L_{CM}$ decreases to 1/10 (-20dB)

$\Rightarrow$ Consequently, suppression effectiveness = 10.5dB
Example: When $w$ expands from 10mm to 100mm

- Calculated using proposed equivalent circuit model and FDTD modeling are in good agreement.
- Proposed model could be useful for EMC design.
Suppression of CM by Guard-Band

- In order to suppress the ground-inductance, the guard-band (guard-trace) structure is proposed.

**Top view**

- SMA connector
- Trace $w_t$ and Termination Resistor
- 0.085-in semi-rigid coaxial cable
- FR-4 (Reverse side is ground plane)
- $l=30$ and $l=150$

**Front view**

- Center Trace
- $w_t, w_{GB} = 2.0$
- via hole
- (distance between trace and GB: 0.5)

1.53
Typical Structure for Comparison

- The $w_t$ was designed so that characteristic impedance $Z_0$ of the trace was set at $50\Omega$. 
S-MSL-GB can suppress CM current, without resonance.
Guard-Band is effective in suppressing EM radiation!
Identification of Dominant Radiation

- DM component should be taken into account in predicting EM radiation at GHz frequencies

Equivalent Circuit Model

- The proposed model can
  - predict a frequency response of CM current with an accuracy suitable for engineering applications
  - explain frequency response of CM, and also identify the dominant coupling-path.

- It was demonstrated that outline of the frequency response of EM radiation can be predicted up to 18GHz.
Topics II
Evaluation of imbalance component and EM radiation generated by asymmetrical differential-paired lines structure
Differential Signaling

- **Differential signaling (DS) techniques**: digital electronics devices (SCSI bus, Ethernet)
- One of the popular signaling schemes: **low-voltage differential signaling (LVDS)**
Serious Problem of Differential-Signaling

Asymmetrical waveform:

- **asymmetrical structure**
- change of DM impedance of differential pair line
- unbalance of driver output
- Deteriorate signal integrity
- Intensify EMI

![Diagram showing asymmetrical structure and skew](Image)

[Ground](Image)

Paired line

[Symmetric](Image)

[Asymmetric](Image)

Meander delay line

[National Semiconductor]
Designers in design stage want to know
“Does the asymmetrical waveform affect SI/EMI?”

- Full-wave analysis for simple model is available.
- The design guideline for prediction and suppression of EM radiation from practical PCBs driven by LVDS have not yet been completely established due to the difficulty of complex geometries.
Identifying the dominant radiation factor of the EM radiation from differential pairs structure is indispensable to establish technique of high-speed digital circuit.

To identify and quantify the correlation between imbalance component on differential paired-line and EM radiation from an asymmetrical differential paired line driven by LVDS, for the establishment of the design guideline.
Approach

Physical quantities:

- **Imbalanced Component on Differential Paired Lines**
  - Evaluation of effect on SI issues
  - Time-Domain Voltage Waveform
  - Evaluation of conversion from DM to CM
  - Mixed Mode $S$ Parameter
  - Evaluation of propagation-mode
  - Near Magnetic Field

- **Radiated Emission**
PCB Geometries

PCB1 (Symmetric)

PCB2 (Different length)

PCB3 (Symmetric with bend)

PCB4 (Equi-distance routing)
Equi-Distance Routing

PCB5: equi-distance routing (n=1)

PCB5: equi-distance routing (n=2)

PCB5: equi-distance routing (n=3)
Calculated Voltage Waveform (2.5GHz)

PCB1

PCB2

PCB5(n=1)

Normalized Voltage

Normalized Voltage

Normalized Voltage

396 ps

210 ps

374 ps
Frequency Response of $|S_{dd21}|$

- $|S_{dd21}|$ in the PCB2 case is deteriorated!
Frequency Response of $|S_{cd21}|$

- **equi-distance routing**
- **different length**
- $n=1$
- $n=2$
- $n=3$

- **balanced**

- **Experiment**
- **FDTD**
Experimental Setup for Near-Magnetic Field

**Measured Frequency**

- **25 MHz**: Fundamental frequency of the crystal oscillator
- **1.0 or 1.85GHz**: the frequency, larger $S_{cd21}$ is observed.
Magnetic Field Destitution at 25MHz

PCB1

PCB2

PCB3

PCB4
Magnetic Field Distribution at 1.85GHz

Magnetic-coupling (Common, even-mode)
Magnetic Field Distribution at 1GHz

PCB5 ($n=1$)

PCB5 ($n=2$)

PCB5 ($n=3$)
Experimental Setup for Far-Field

- **Horizontal component:**
  \[ E_\phi \text{ at } (\phi, \theta) = (90, 90), \ E_x \]

- **Vertical component:**
  \[ E_\theta \text{ at } (\phi, \theta) = (90, 90), \ E_z \]
The radiations in the “PCB5” cases are relatively large compared with the radiation in the “PCB1”.
Discussions on the Correlation

- Although equi-distance routing is suitable for improvement of SI issues, it is not effective in suppressing the EMI.

- Only the measurement of $S_{cd21}$ is insufficient for predicting the EM radiation.

- This is significant problem of design of a meander delay line for high-speed clock distribution.
Reason why equi-distance can’t suppress EMI

- **Even-mode propagation due to asymmetric**
  - Significant radiation due to CM

- **Wide separation of the paired line**
  - Deterioration of cancellation effect of EMI

- **Routed in the PCB edge**
  - CM current increases
Physics-Based Modeling

In order to identify and quantify frequency response of the EM radiation from an asymmetrical differential-paired lines on an infinite ground plane, the physics-based-model is proposed.

The radiated emission can be obtained by integrating the current-distribution over the surface of the radiator.

Proposed model:

1. An equivalent circuit model to calculate the current-distribution on the differential-paired lines
2. A radiation model to calculate the far-electric field
The structures are divided into plural regions.

Two kinds of cross-sectional schemes:

- **Coupled microstrip**
  - \[ L_m \Delta l \]
  - \[ L_{s1} \Delta l \]
  - \[ L_{s2} \Delta l \]
  - \[ C_m \Delta l \]
  - \[ C_{s1} \Delta l \]
  - \[ C_{s2} \Delta l \]

- **Microstrip**
  - \[ L_s \Delta l \]
  - \[ C_s \Delta l \]

The behavior of the entire geometry is obtained by connecting all regions together.
The discrepancies above 5GHz

⇒ due to a dielectric loss of FR-4 material.

✓ The envelopes of the frequency responses are predicted with accuracy suitable for engineering applications.
The dominant factor of the imbalance component: phase-difference of propagation signal between the differential-paired lines generated by the EM coupling in bend region.
The proposed model reveals the contributions of each region for identification and quantification.
Predicted Emission – PCB2

Dominant radiation factor
Up to 1GHz: region 2c (factor 1: even-mode propagation)
Above 2GHz: region 2b (factor 2: wide-separation)

⇒ The dominant radiation factor can be identified!
Predicted Emission – PCB5 \((n=1)\)

**Dominant radiation factor**

Up to 1GHz: region 5n1c (factor 1: even-mode propagation)

Above 2GHz: region 5n1b and 5n1d (factor 2: wide-separation)
Discussions on Equi-Distance Routing

- Once the phase-difference of propagation signal between the differential-paired lines arises, a cancellation treatment of DS for EM radiation at observation point will be deteriorated dramatically. Hence EM radiation increases.

- A meander delay line for improvement of skew should be located near the point where the skew is originated!

⇒ The length of the region c should be shorter.
Normalized radiation vs Spaceing $S_c$.

\[
\alpha = \frac{E_{DS}}{E_{\text{single-end}}}
\]

\begin{itemize}
  \item \(\phi = 0^\circ \) (\(I_2 = I_1\), even-mode)
  \item \(\phi = 90^\circ \) (\(I_2 = 0\))
  \item \(\phi = 135^\circ \) (\(I_2 = -0.707I_1\))
  \item \(\phi = 150^\circ \) (\(I_2 = -0.866I_1\))
  \item \(\phi = 170^\circ \) (\(I_2 = -0.985I_1\))
\end{itemize}

\(\phi = 180^\circ \) (\(I_2 = -I_1\), ideally differential-signaling)

\(\Phi \in \{0^\circ, 90^\circ, 135^\circ, 150^\circ, 170^\circ\}\)

\textbf{Factor 1: +30dB}

\textbf{Factor 2: +20dB}

\textbf{@1GHz}

\(\checkmark\) The impact of the factor(1) is larger than impact of the factor (2).
Summary of Topic II

- Although equi-distance routing is suitable for improvement of SI issues, it is not effective in suppressing the EMI.
- Only the measurement of $S_{cd21}$ is insufficient for predicting the EM radiation.
- Physics-based model is proposed and its validity is demonstrated.

Identifying the dominant radiation-mechanisms facilitates the mitigation of EMI problem in PCBs.

- This study has successfully established a basic method to effectively predict EM radiation from practical differential-paired lines.
Further Studies

- Studies of engineering implications
- Development of easier interpretations for coupling and CM generation-mechanisms.
- Development of design guideline