Common Mode Currents and Radiated Emissions from Differential Signals in Multi-Board Systems

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Outline

- Introduction and motivation
- Current modes revisited
- Simple formulas for differential to common mode conversion
  - Conductor length mismatch
  - Asymmetrical ground pin configuration
- Radiated emission from multi-board systems
  - Conductor length differences
  - Ground pin configurations
  - Board configurations
- Conclusions
Introduction

In most high-speed interfaces, differential signaling is used across multi-board systems.

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Motivation

We try to answer the following questions for the differential signal across connected PCBs:

- How to estimate differential to common mode conversion?
- What is the main contributor to the radiated emission?
- What is critical for EMI in the GHz range?
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Differential and Common Mode

Odd mode
\[ V_{odd} = \frac{1}{2} (V_1 - V_2) = (Z_{11} - Z_{12}) I_1 \]
\[ Z_{odd} = \frac{V_{odd}}{I_1} \bigg|_{V_{even}=0} = Z_{11} - Z_{12} \]

Even mode
\[ V_{even} = \frac{1}{2} (V_1 + V_2) = (Z_{11} + Z_{12}) I_1 \]
\[ Z_{even} = \frac{V_{even}}{I_1} \bigg|_{V_{odd}=0} = Z_{11} + Z_{12} \]

Differential mode impedance:
\[ Z_{diff} = 2Z_{odd} \]

Common mode impedance:
\[ Z_{comm} = \frac{Z_{even}}{2} \]

For symmetrical structure:
\[ Z_{11} = Z_{22} \]
Reality – There is no Truly Differential Signal

- Length mismatch
- Asymmetrical ground pins
- Bends
- Impedance discontinuity
- Crosstalk
- Via fields
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Length Mismatched Differential Pair

\[
\begin{bmatrix}
\hat{V}_1(l) \\
\hat{V}_2(l) \\
\hat{I}_1(l) \\
\hat{I}_2(l)
\end{bmatrix} = \Phi \cdot 
\begin{bmatrix}
\hat{V}_1(0) \\
\hat{V}_2(0) \\
\hat{I}_1(0) \\
\hat{I}_2(0)
\end{bmatrix}
\]

\[
\Phi = 
\begin{bmatrix}
\cos \beta (l + \Delta l) & k \sin \beta l \sin \beta \Delta l & -jZ_{11} \sin \beta (l + \Delta l) & -jkZ_{11} \sin \beta l \\
0 & \cos \beta l & -jZ_{11} \sin \beta l & -jZ_{22} \sin \beta l \\
-j \sin \beta (l + \Delta l) & -jk \sin \beta l \cos \beta \Delta l & \cos \beta (l + \Delta l) & -k \sin \beta l \sin \beta \Delta l \\
-jkZ_{11} \sin \beta l & -jZ_{22} \sin \beta l & 0 & \cos \beta l
\end{bmatrix}
\]

\[k\text{ is the coupling factor}\]
\[k = \frac{L_{12}}{\sqrt{L_{11}L_{22}}} = \frac{-C_{12}}{\sqrt{C_{11}C_{22}}}\]

Define a differential to common mode conversion ratio \( r \)
\[r(\hat{V}_{s1} = -\hat{V}_{s2}) = \frac{\hat{I}_{CM}(l)}{2\hat{I}_{DM}(l)}\]

For perfect termination:
\[r = \tan\left(\frac{\beta \Delta l}{2}\right) \approx \frac{\beta \Delta l}{2}, \text{ if } \beta \Delta l << 1\]
Examples of the Conversion Ratio

The major factor that influences the differential to common mode conversion is the length of the mismatch.
Mode Conversion on Asymmetrical lines

Asymmetrical diff pair
1, [L], [C], [Z]

Driver

I2(0) → I2(l)
V1(0) → V1(l)
V2(0) → V2(l)

Receiver

I1(0) → I1(l)

\[
\begin{bmatrix}
\hat{V}_{DM}(l)
\
\hat{V}_{CM}(l)
\
\hat{i}_{DM}(l)
\
\hat{i}_{CM}(l)
\end{bmatrix} = \Phi_m \cdot \begin{bmatrix}
\hat{V}_{DM}(0)
\
\hat{V}_{CM}(0)
\
\hat{i}_{DM}(0)
\
\hat{i}_{CM}(0)
\end{bmatrix}
\]

\[
\Phi_m = \begin{bmatrix}
\cos \beta l \cdot 1_2 & -j \sin \beta l \cdot Z_{M}^{-1} \\
-j \sin \beta l \cdot Z_{M} & \cos \beta l \cdot 1_2
\end{bmatrix}
\]

\[
Z_{M} = T_v Z_c T_i^{-1} = \begin{bmatrix}
Z_{11} + Z_{22} - 2Z_{12} & Z_{11} - Z_{22} \\
\frac{Z_{11} - Z_{22}}{2} & \frac{Z_{11} + Z_{22} + 2Z_{12}}{4}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{V}_{DM}^+ \\
\hat{V}_{CM}^+
\end{bmatrix} = \frac{1}{4} \begin{bmatrix}
1 & -1
\end{bmatrix} \begin{bmatrix}
\hat{V}_1^+
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{i}_{DM}^+ \\
\hat{i}_{CM}^+
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & -1
\end{bmatrix} \begin{bmatrix}
\hat{i}_1^+
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{V}_{DM}^+ \\
\hat{V}_{CM}^+
\end{bmatrix} = \begin{bmatrix}
\hat{V}_1^+ \\
\hat{V}_1^+
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{i}_{DM}^+ \\
\hat{i}_{CM}^+
\end{bmatrix} = \begin{bmatrix}
\hat{i}_1^+ \\
\hat{i}_2^+
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{V}_{DM}^+ \\
\hat{V}_{CM}^+
\end{bmatrix} = Z_{M} \cdot \begin{bmatrix}
\hat{i}_{DM}^+ \\
\hat{i}_{CM}^+
\end{bmatrix}
\]
Examples of the Conversion Ratio

For perfect termination:

\[ r = \frac{Z_{11} - Z_{22}}{Z_{11} + Z_{22} + 2Z_{12}} \]

Solid lines: each line terminated with 50Ω
Dashed lines: perfect termination

Case (a) \[ [Z] = \begin{bmatrix} 62 & 8 \\ 8 & 62 \end{bmatrix} \text{Ω} \]
\[ r = 0 \]

Case (b) \[ [Z] = \begin{bmatrix} 239.9 & 42.4 \\ 42.4 & 68.3 \end{bmatrix} \text{Ω} \]
\[ r = 0.218 \]

Case (c) \[ [Z] = \begin{bmatrix} 279.8 & 115.8 \\ 115.8 & 176.1 \end{bmatrix} \text{Ω} \]
\[ r = 0.075 \]

Case (d) \[ [Z] = \begin{bmatrix} 62.9 & 18.3 \\ 18.3 & 132.1 \end{bmatrix} \text{Ω} \]
\[ r = 0.149 \]
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CONCEPT-II Introduction

COde for the Numerical Computation of Electromagnetic Processes for Thin Wire and Thin Shell Structures

Developed at the Institute of Electromagnetic Theory

Computation of radiation and scattering problems in the frequency domain
CONCEPT-II Features

- Based on the Method of moments for both EFIE and MFIE
- Suitable for structures with wires, metallic surface and dielectric bodies.
- Solvers:
  - Parallelized LU decomposition
  - MLFMA and parallelized FMM
  - ACA/SVD solver for single core
- Hybrid and combination with other methods
  - Shielding effectiveness (hybrid technique with analytical solution)
  - Physical Optics
  - MTL and network solver (Qt-mtl)
- Capabilities and outputs:
  - Various excitation possible
  - Surface current distribution
  - Field plots in 1D, 2D, and 3D
  - System responses in frequency and time domain
  - SAR
CONCEPT-II Simulation Examples

Current distribution around WLAN antenna

Radiation Diagram of Patch Antenna
Full-Wave Simulation with Concept-II

-- About 18k unknowns, 5G memory
-- Parallel solver with 2.8G CPU 1.6G memory at each node
-- Solving time per frequency

<table>
<thead>
<tr>
<th>Number of nodes</th>
<th>Setup time</th>
<th>Solve time</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>32min</td>
<td>20min</td>
<td>52min</td>
</tr>
<tr>
<td>6</td>
<td>22min</td>
<td>14min</td>
<td>36min</td>
</tr>
<tr>
<td>8</td>
<td>17min</td>
<td>11min</td>
<td>28min</td>
</tr>
</tbody>
</table>

$\Delta f = 100$MHz, $f_{\text{min}} = 100$MHz, $f_{\text{max}} = 5$GHz
The following variations are analyzed:

- $\Delta l$
- Ground pin configurations
- Board sizes and positions
Differential vs. Common Mode Voltage

For the conductor length mismatched case:
Differential signal decreases quadratically with frequency
Common mode signal increases linearly with frequency
Radiated Power

Radiation increases proportionally to the conductor length mismatch

\[ P_{\text{rad}} = \iint_{A} \vec{S} \cdot d\vec{A} \]
Ground Pin Assignment

The impedances are calculated using 2D MoM tool qt-mtl

Case (a)

\[ [Z] = \begin{bmatrix} 62 & 8 \\ 8 & 62 \end{bmatrix} \Omega \]

\[ Z_{\text{diff}} = 108 \Omega \quad Z_{\text{comm}} = 35 \Omega \]

\[ r = 0 \]

Case (b)

\[ [Z] = \begin{bmatrix} 239.9 & 42.4 \\ 42.4 & 68.3 \end{bmatrix} \Omega \]

\[ r = 0.218 \]

Case (c)

\[ [Z] = \begin{bmatrix} 279.8 & 115.8 \\ 115.8 & 176.1 \end{bmatrix} \Omega \]

\[ r = 0.075 \]

Case (d)

\[ [Z] = \begin{bmatrix} 62.9 & 18.3 \\ 18.3 & 132.1 \end{bmatrix} \Omega \]

\[ r = 0.149 \]
Differential mode signal in this case is mainly affected by the termination condition. Here, case (c) is the worst case.

Common mode signal is mainly determined by the symmetry of the configuration. Here, case (b) is the worst case.
Although case (c) has a lower conversion ratio than case (d), the radiation is higher. Differential to common mode conversion is not the sole cause of emission in this case, ground pin configuration play a critical role here.
Introduction of an Antenna Mode

\[ I_{DM} = \frac{1}{2}(I_1 - I_2) \quad I_{CM} = I_1 + I_2 = I_G + I_B \]
Experiment of Changing Board Configuration

 Radiation in the GHz range changes little for different board separations and board positions.
The board configuration has a great impact on radiation in the MHz range.

However, pin assignment has a bigger influence on radiation in the GHz range than board configuration.
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Conclusions

- On single boards simple formulas can be derived to quantify the differential to common mode conversion on coupled transmission lines:
  - It is proportional to the length of the conductor mismatch,
  - It is proportional to the degree of asymmetry of pin assignment.

- On multi-board systems more common mode current does not necessarily lead to higher radiation.

- Increased radiation from multi-board systems can be attributed to an "antenna mode" current which radiates orders of magnitudes more than the usual common mode current.

- Board configuration has little effect on radiated emission in the GHz range but the connector pin assignment strongly influence the EMI behavior of the connected PCBs.

- Symmetry of connector pin configurations is important to mitigate radiated emission.
Reference


