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

Xiaomin Duan, Heinz-Dietrich Brüns, Christian Schuster

Institut für Theoretische Elektrotechnik,
Technische Universität Hamburg-Harburg (TUHH)
Hamburg, Germany

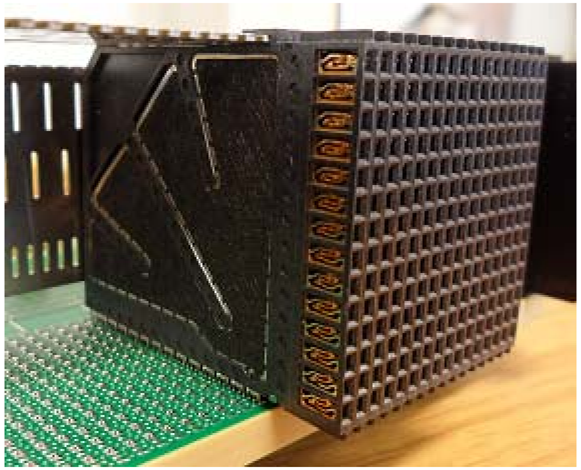
Workshop on modeling and solution for common mode noise on high-speed differential channels,

Asia-Pacific EMC Symposium, Jeju Island, Korea, May 16-19, 2011

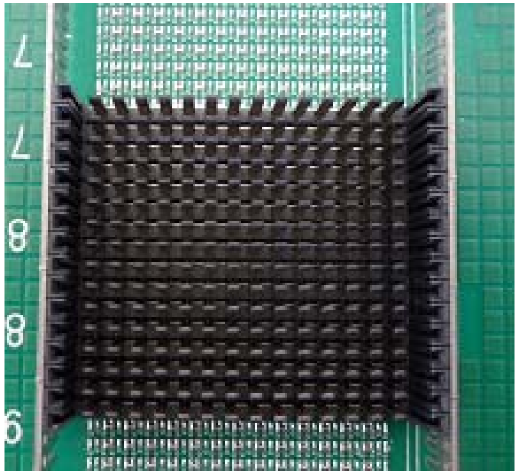
Outline

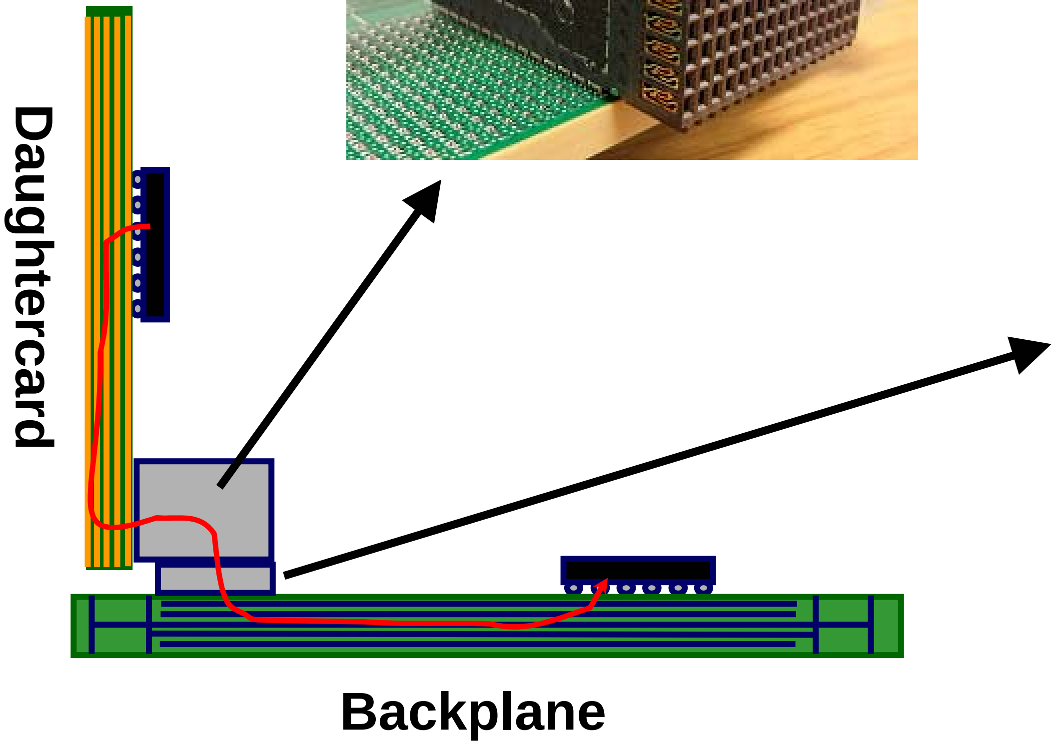
- **Introduction and motivation**
- **Current modes revisited**
- **Simple formulas for differential to common mode conversion**
  - Conductor length mismatch
  - Asymmetrical ground pin configuration
- **Radiated emission from multi-board systems**
  - Conductor length differences
  - Ground pin configurations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

Introduction



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

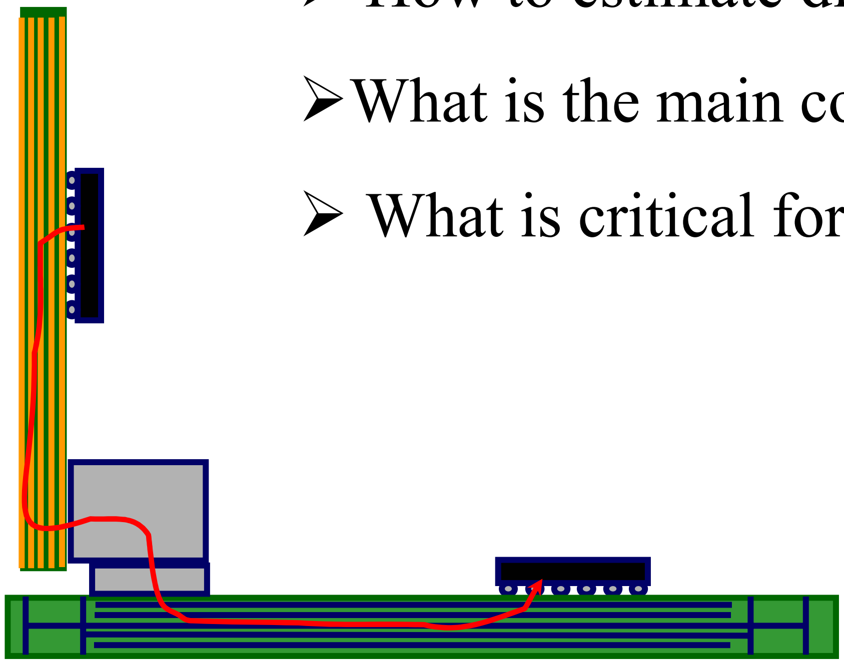




Pictures © TET, TUHH

Motivation

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

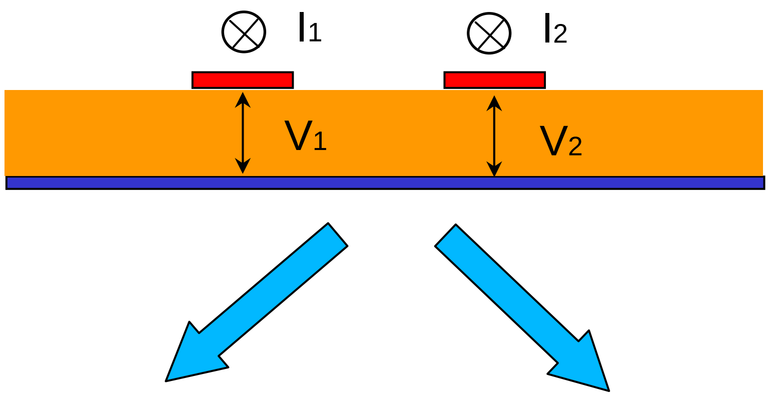


- How to estimate differential to common mode conversion?
- What is the main contributor to the radiated emission?
- What is critical for EMI in the GHz range?

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

Differential and Common Mode



$$V_1 = Z_{11}I_1 + Z_{12}I_2$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2$$

For symmetrical structure:

$$Z_{11} = Z_{22}$$

Odd mode

⊗ I_1 ⊙ $-I_1$

$$V_{odd} = \frac{1}{2}(V_1 - V_2) = (Z_{11} - Z_{12})I_1$$

$$Z_{odd} = \frac{V_{odd}}{I_1}\Big|_{V_{even}=0} = Z_{11} - Z_{12}$$

Even mode

⊗ I_1 ⊗ I_1

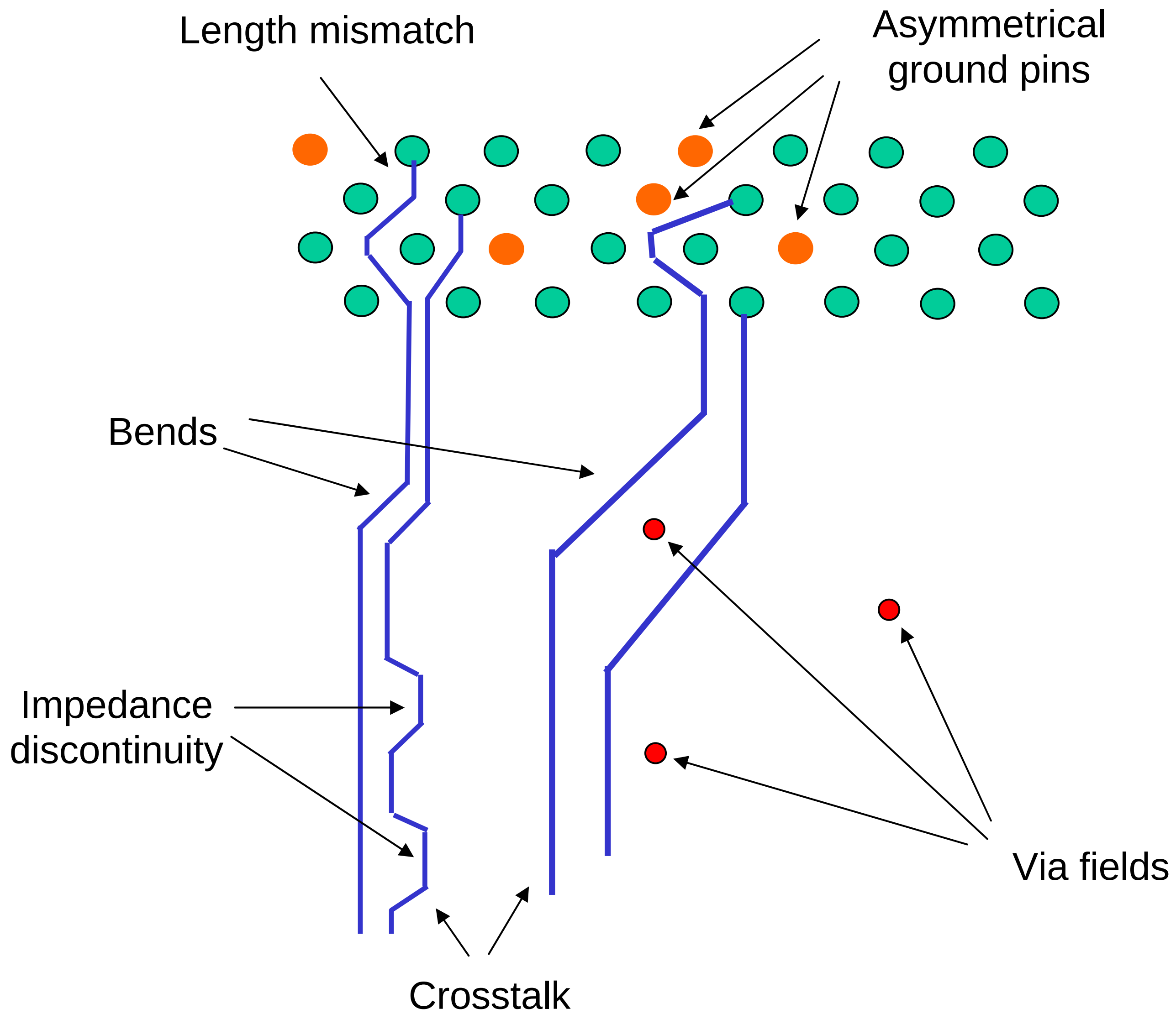
$$V_{even} = \frac{1}{2}(V_1 + V_2) = (Z_{11} + Z_{12})I_1$$

$$Z_{even} = \frac{V_{even}}{I_1}\Big|_{V_{odd}=0} = Z_{11} + Z_{12}$$

Differntial mode impedance: $Z_{diff} = 2Z_{odd}$

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

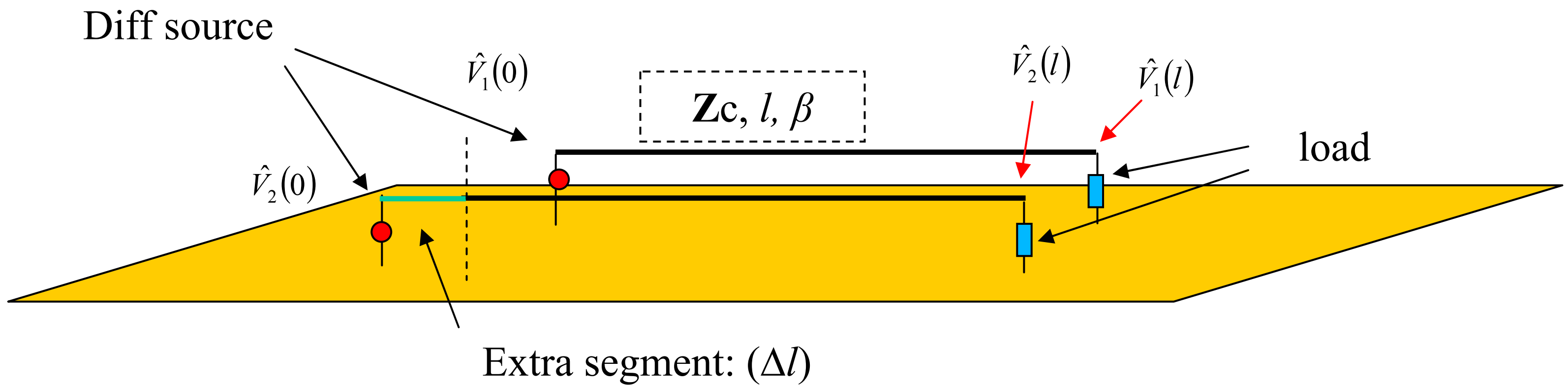
Reality – There is no Truly Differential Signal



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

Length Mismatched Differential Pair



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

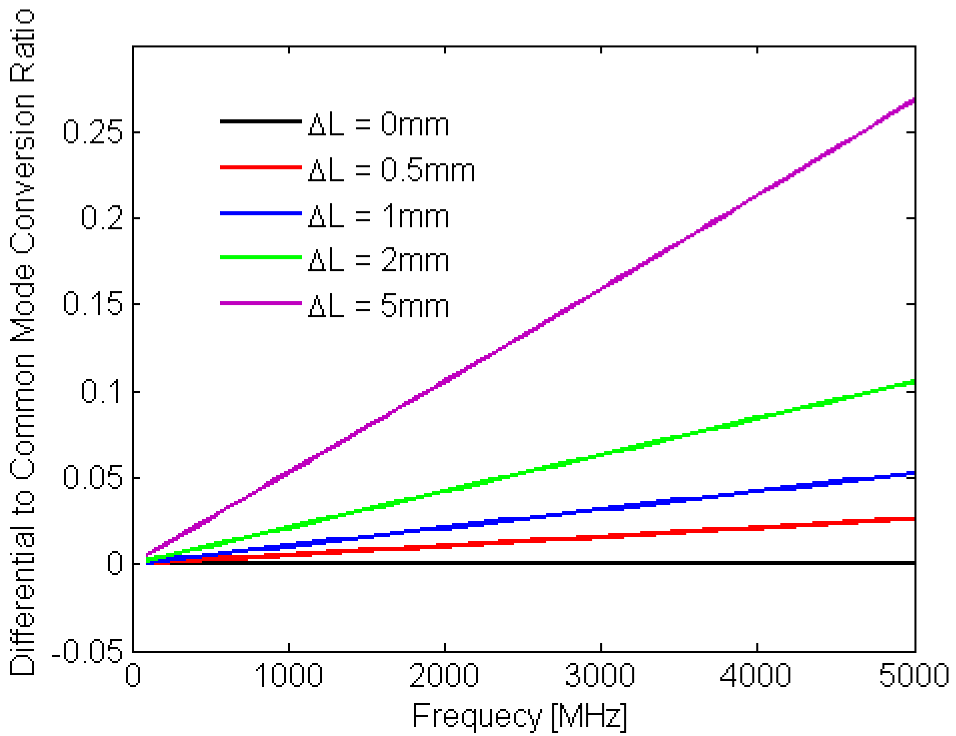
$$\boldsymbol{\Phi} = \begin{bmatrix} \cos\beta(l+\Delta l) & k\sin\beta l\sin\beta\Delta l & -jZ_{11}\sin\beta(l+\Delta l) & -jkZ_{11}\sin\beta l\cos\beta\Delta l \\ 0 & \cos\beta l & -jkZ_{11}\sin\beta l & -jZ_{22}\sin\beta l \\ -\frac{j}{Z_{11}}\sin\beta(l+\Delta l) & -\frac{jk}{Z_{11}}\sin\beta l\cos\beta\Delta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

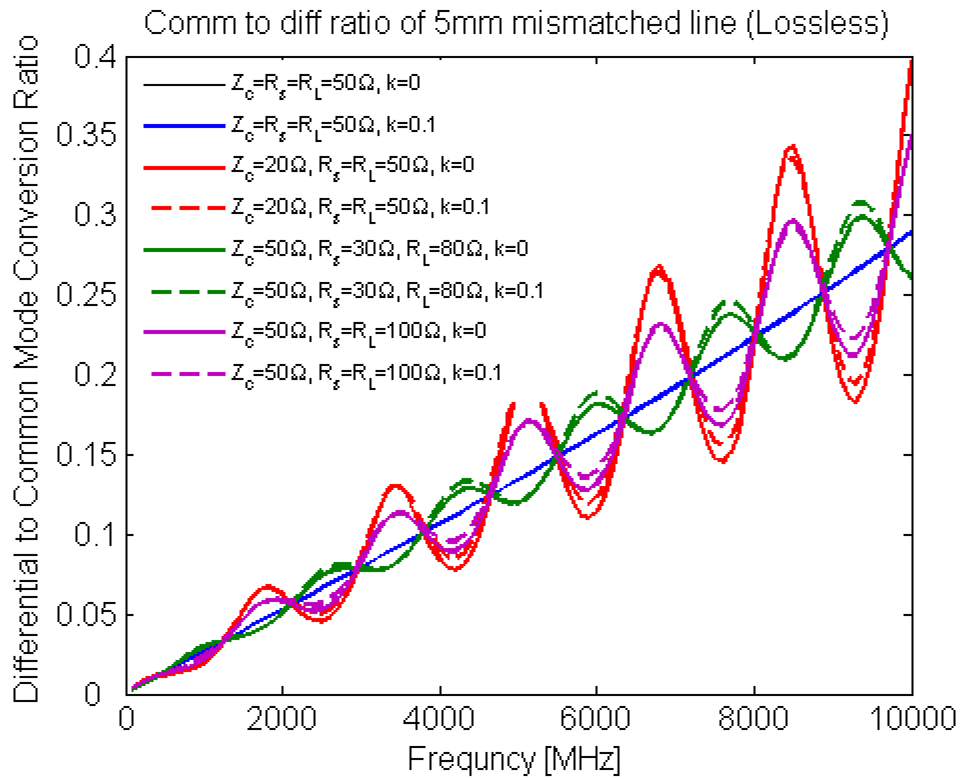
k is the coupling factor $k = \frac{L_{12}}{\sqrt{L_{11}L_{22}}} = \frac{-C_{12}}{\sqrt{C_{11}C_{22}}}$

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

For perfect termination: $\quad r = \tan\left(\frac{\beta\Delta l}{2}\right) \approx \frac{\beta\Delta l}{2}, \quad \text{if } \beta\Delta l << 1$

Examples of the Conversion Ratio

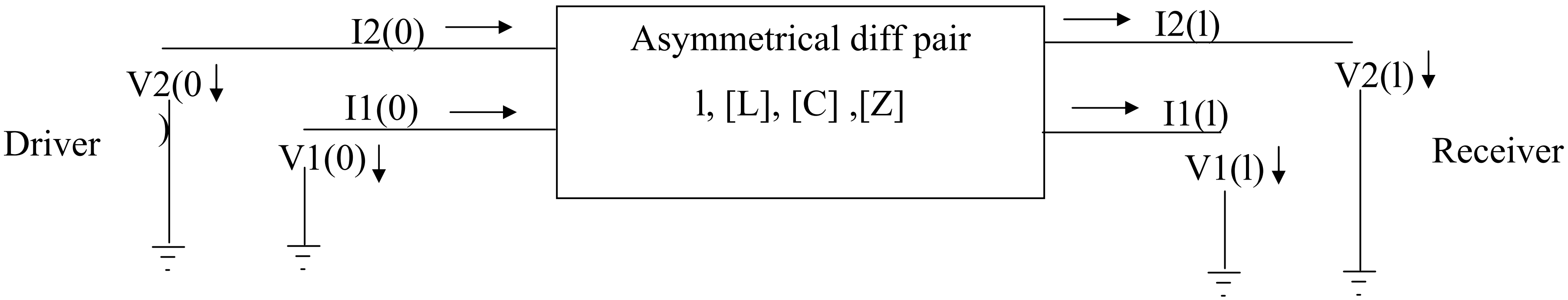




Total length of the line: 10cm

The major factor that influences the differential to common mode conversion is the length of the mismatch.

Mode Conversion on Asymmetrical lines



$$\begin{bmatrix} \hat{V}_{DM}(l) \\ \hat{V}_{CM}(l) \\ \hat{I}_{DM}(l) \\ \hat{I}_{CM}(l) \end{bmatrix} = \mathbf{\Phi_m} \cdot \begin{bmatrix} \hat{V}_{DM}(0) \\ \hat{V}_{CM}(0) \\ \hat{I}_{DM}(0) \\ \hat{I}_{CM}(0) \end{bmatrix}$$

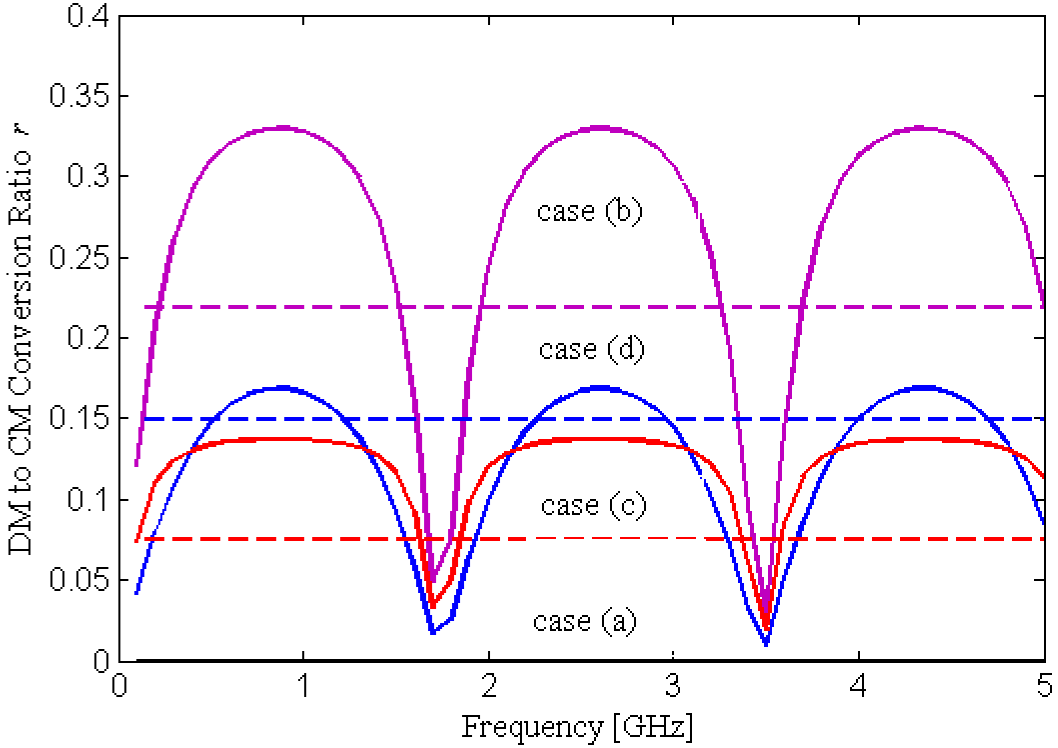
$$\mathbf{\Phi_m} = \begin{bmatrix} \cos\beta l \cdot \mathbf{1_2} & -j\sin\beta l \cdot \mathbf{Z_M} \\ -j\sin\beta l \cdot \mathbf{Z_M}^{-1} & \cos\beta l \cdot \mathbf{1_2} \end{bmatrix}$$

$$\mathbf{Z_M} = \mathbf{T_v} \mathbf{Z}_C \mathbf{T_i}^{-1} = \begin{bmatrix} Z_{11} + Z_{22} - 2Z_{12} & \dfrac{Z_{11} - Z_{22}}{2} \\ \dfrac{Z_{11} - Z_{22}}{2} & \dfrac{Z_{11} + Z_{22} + 2Z_{12}}{4} \end{bmatrix}$$

$$\begin{bmatrix} \hat{V}_{DM}^{+} \\ \hat{V}_{CM}^{+} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & -1 \\ 1/2 & 1/2 \end{bmatrix}}_{\mathbf{T_v}} \begin{bmatrix} \hat{V}_1^{+} \\ \hat{V}_1^{+} \end{bmatrix} \qquad \begin{bmatrix} \hat{I}_{DM}^{+} \\ \hat{I}_{CM}^{+} \end{bmatrix} = \underbrace{\begin{bmatrix} 1/2 & -1/2 \\ 1 & 1 \end{bmatrix}}_{\mathbf{T_i}} \begin{bmatrix} \hat{I}_1^{+} \\ \hat{I}_2^{+} \end{bmatrix} \qquad \begin{bmatrix} \hat{V}_{DM}^{+} \\ \hat{V}_{CM}^{+} \end{bmatrix} = \mathbf{Z_M} \cdot \begin{bmatrix} \hat{I}_{DM}^{+} \\ \hat{I}_{CM}^{+} \end{bmatrix}$$

Examples of the Conversion Ratio

For perfect termination: $r = \dfrac{Z_{11} - Z_{22}}{Z_{11} + Z_{22} + 2Z_{12}}$



Solid lines: each line terminated with 50Ω

Dashed lines: perfect termination

Case (a) $[Z] = \begin{bmatrix} 62 & 8 \\ 8 & 62 \end{bmatrix} \Omega$

$r = 0$

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

$r = 0.149$

Outline

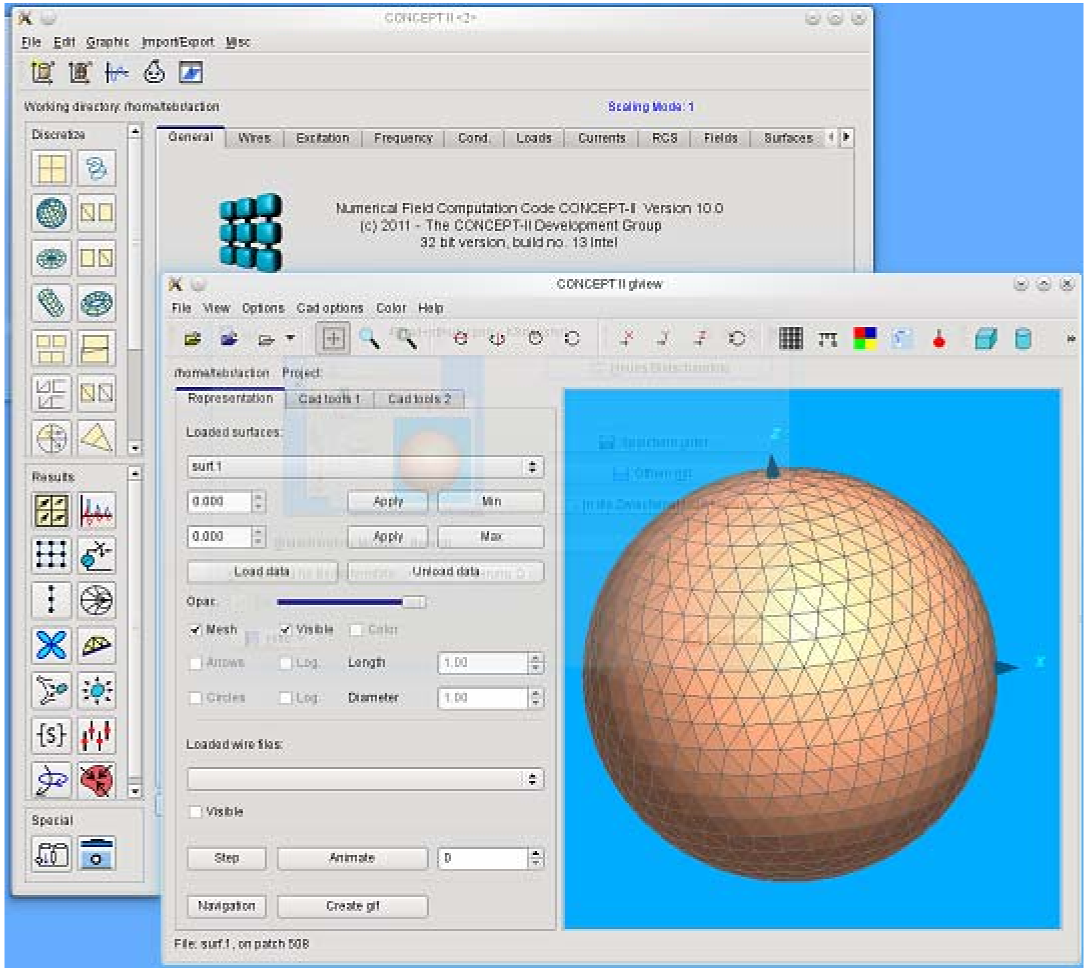
- **Introduction and motivation**
- **Current modes revisited**
- **Simple formulas for differential to common mode conversion**
  - Conductor length mismatch
  - Asymmetrical ground pin configuration
- **Radiated emission from multi-board systems**
  - Conductor length differences
  - Ground pin configurations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

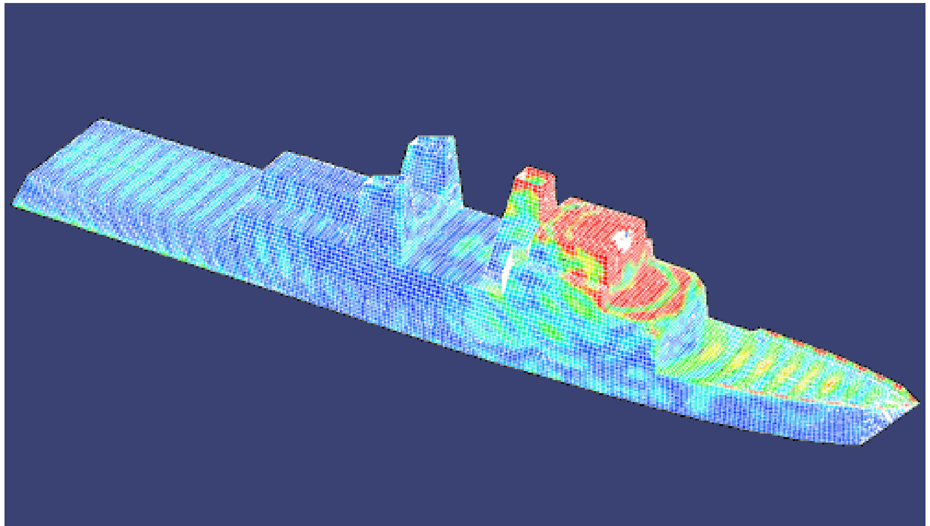
CONCEPT-II Introduction

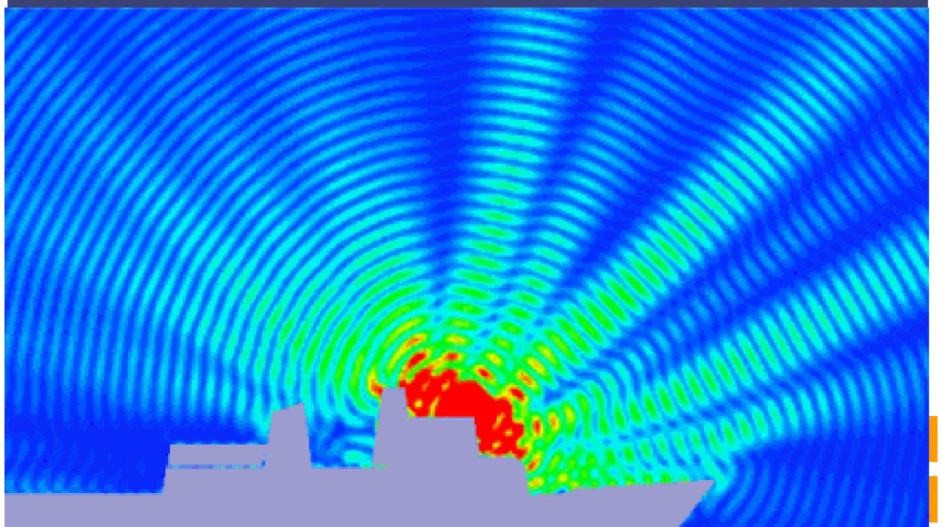
COde for the **N**umerical **C**omputation of **E**lectromagnetic **P**rocesses for **T**hin Wire and Thin Shell Structures

Developed at the Institute of Electromagnetic Theory

Computation of radiation and scattering problems in the frequency domain



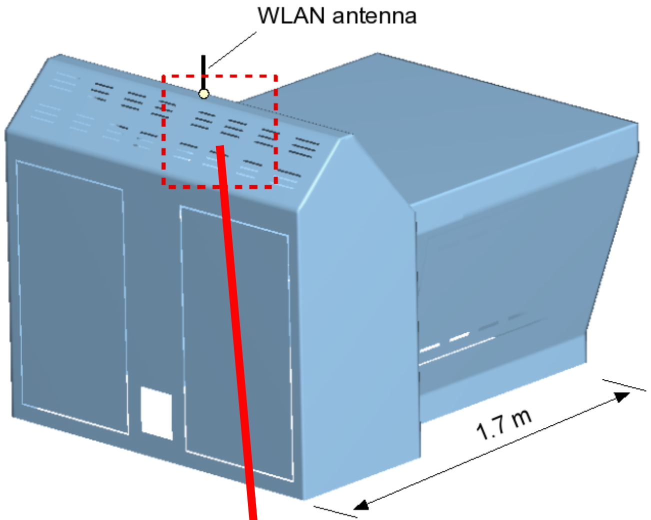


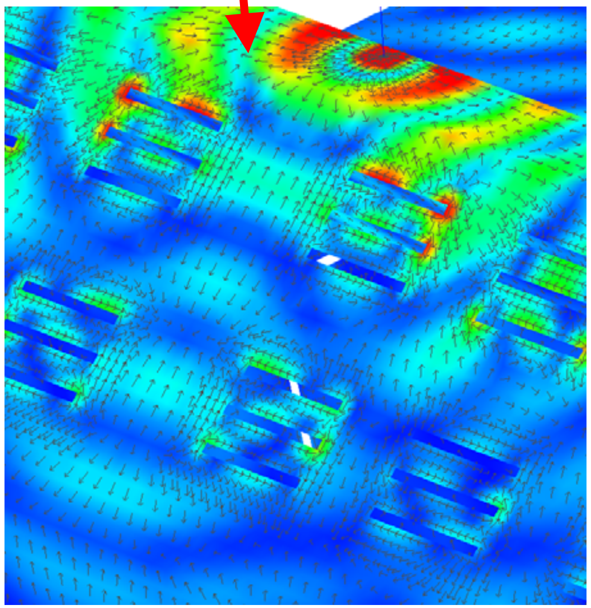


CONCEPT-II Features

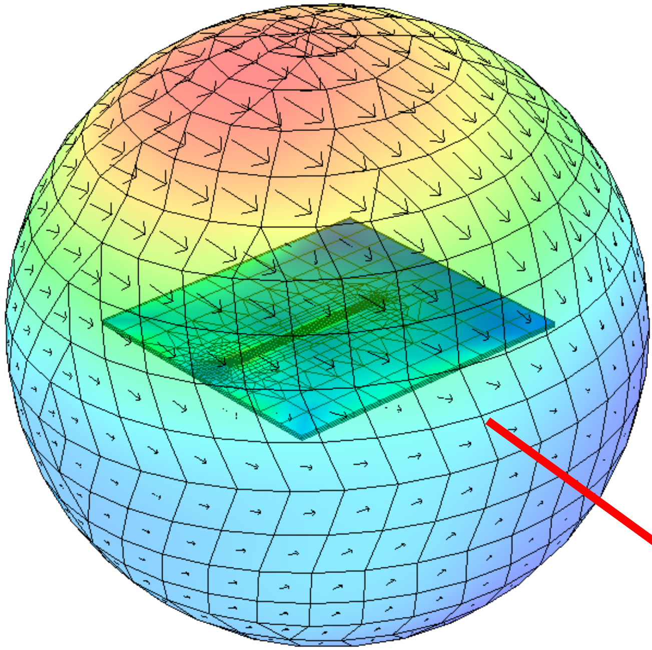
- Based on the Method of moments for both EFIE and MFIE
- Suitable for structures with wires, metallic surface and dielectric bodies.
- Solvers:
  - Parallelized LU decomposition
  - MLFMA and parallelized FMM
  - ACA/SVD solver for single core
- Hybrid and combination with other methods
  - Shielding 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

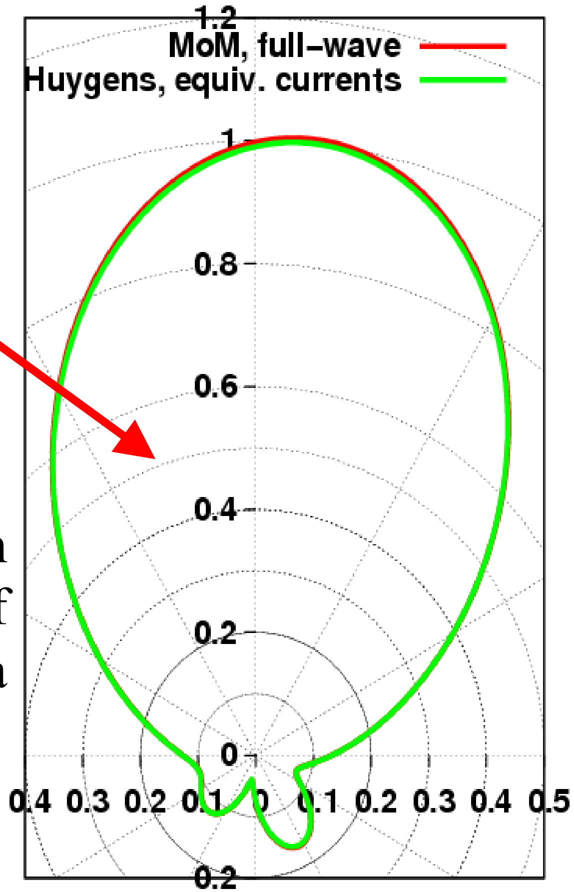
CONCEPT-II Simulation Examples





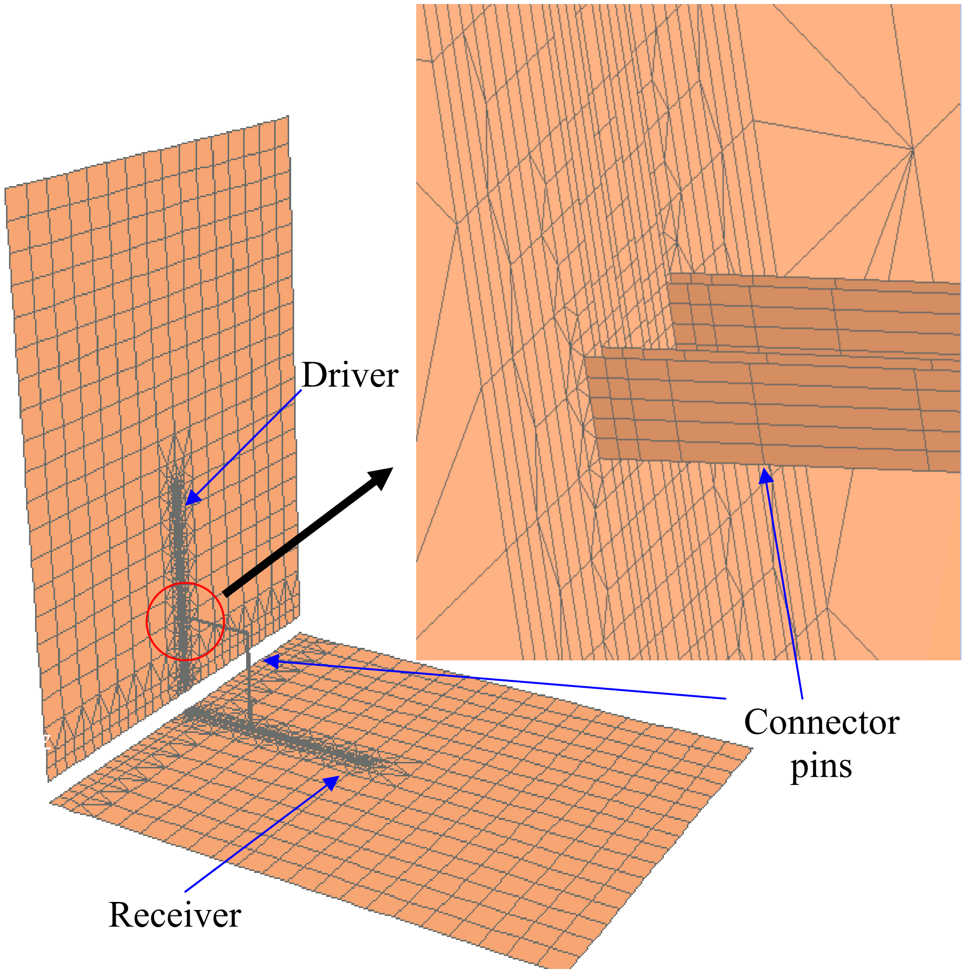
Current distribution around WLAN antenna





Radiation Diagram of Patch Antenna

Full-Wave Simulation with Concept-II



-- About 18k unknowns, 5G memory

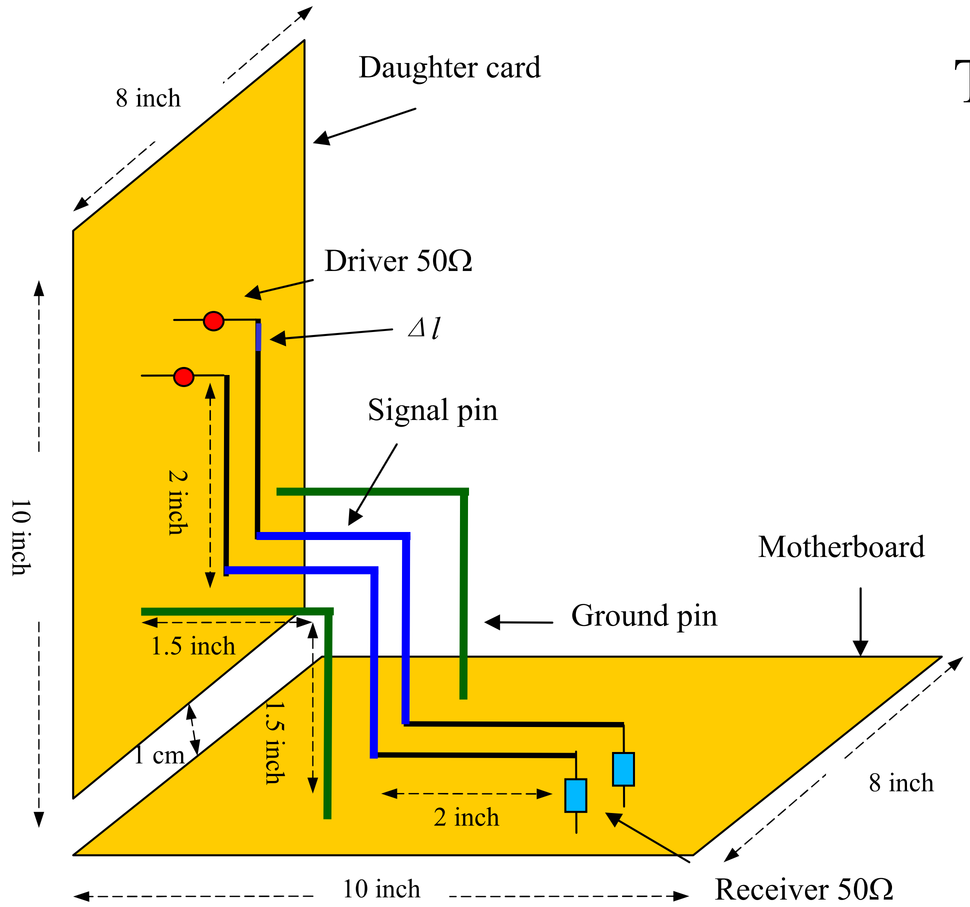
-- Parallel solver with 2.8G CPU 1.6G memory at each node

-- Solving time per frequency

Number of nodes	Setup time	Solve time	Total time
4	32min	20min	52min
6	22min	14min	36min
8	17min	11min	28min

$\Delta f = 100\text{MHz}$, $f_{min} = 100\text{MHz}$, $f_{max} = 5\text{GHz}$

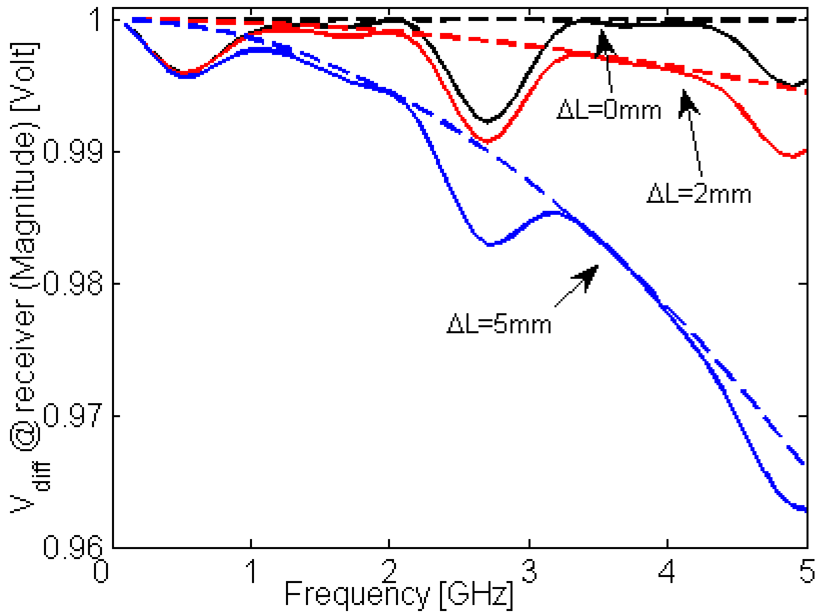
Simulation Configurations

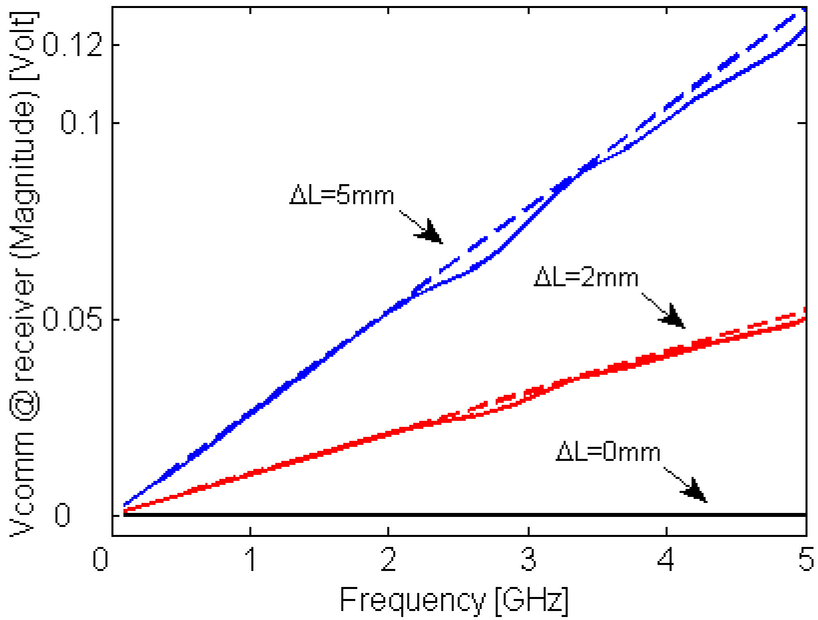


The following variations are analyzed

- Δl
- Ground pin configurations
- Board sizes and positions

Differential vs. Common Mode Voltage



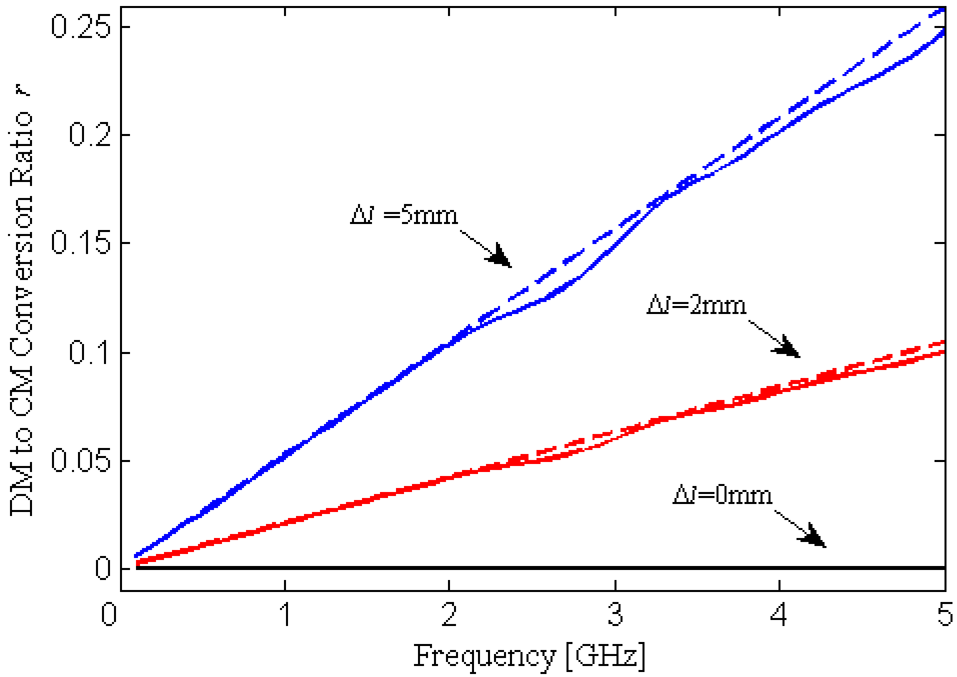


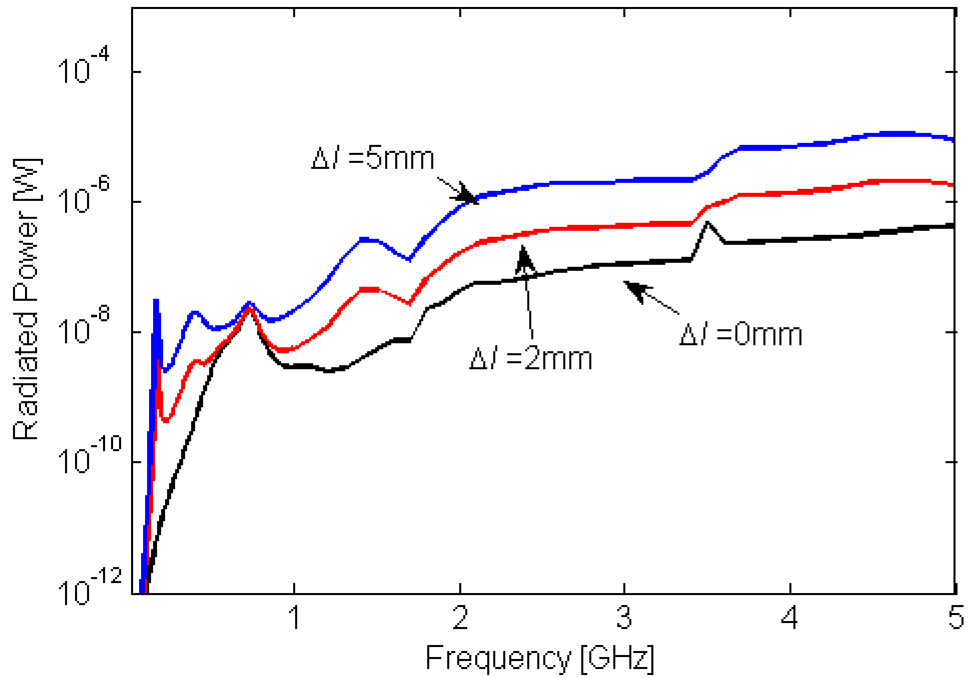
For the conductor length mismatched case:

Differential signal decreases quadratically with frequency

Common mode signal increases linearly with frequency

Radiated Power





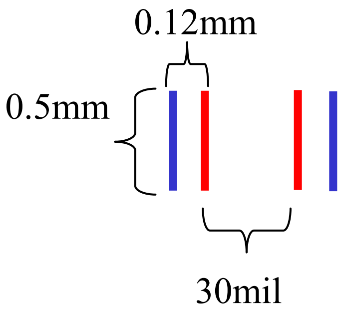
Radiation increases proportionally to the conductor length mismatch

Radiated power: $P_{rad} = \oiint_A \vec{S} \cdot d\vec{A}$

Ground Pin Assignment

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

Case (a)

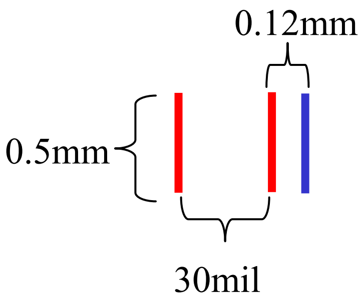


$$[Z]=\begin{bmatrix}62 & 8\\ 8 & 62\end{bmatrix}\Omega$$

$Z_{diff}=108\Omega \quad Z_{comm}=35\Omega$

$r=0$

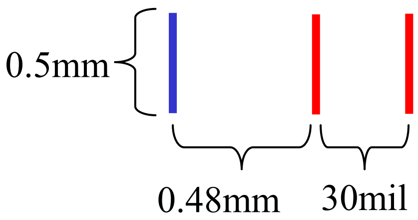
Case (b)



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

$r=0.218$

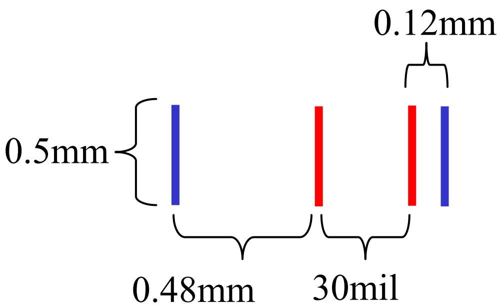
Case (c)



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

$r=0.075$

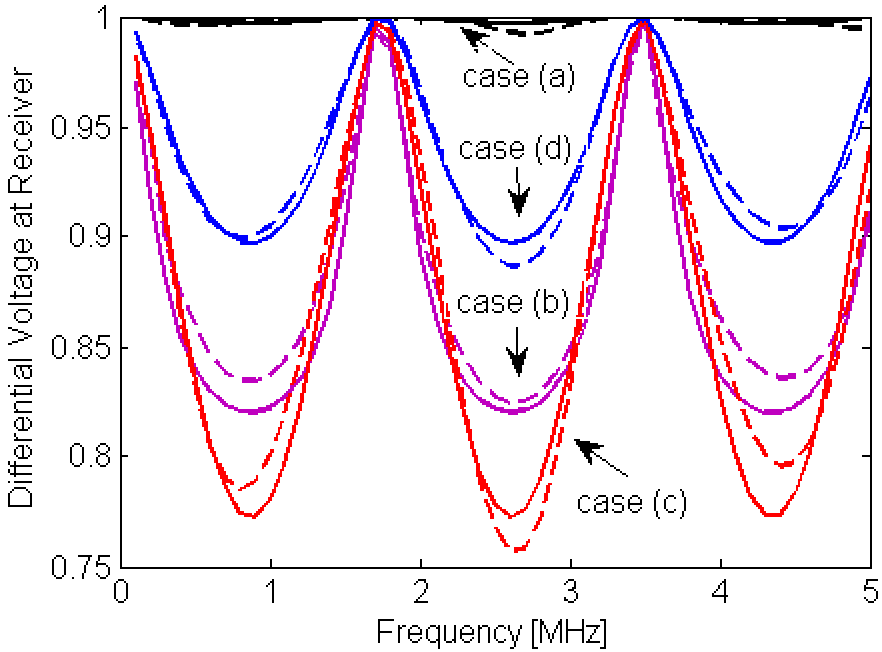
Case (d)

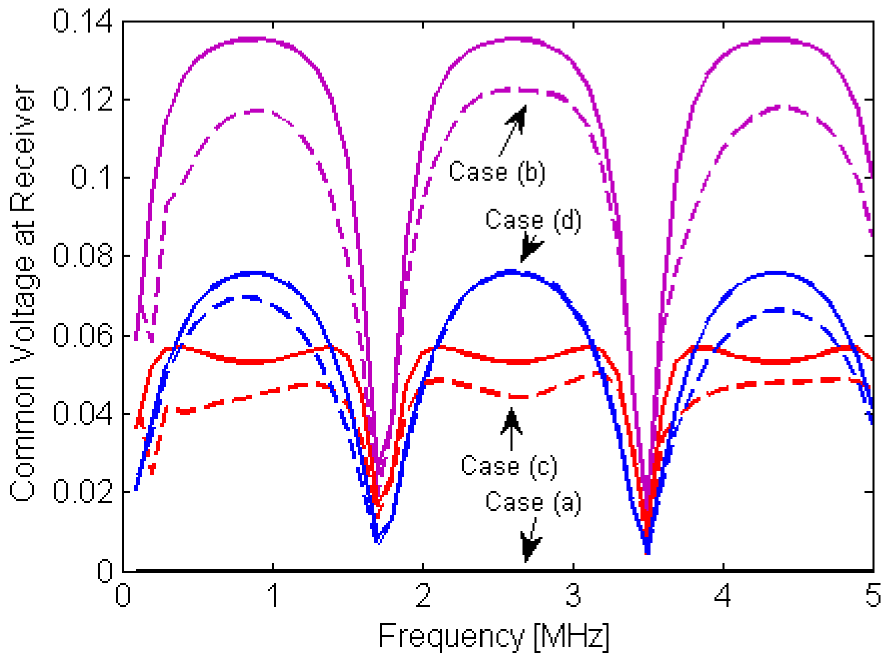


$$[Z]=\begin{bmatrix}62.9 & 18.3\\ 18.3 & 132.1\end{bmatrix}\Omega$$

$r=0.149$

Differential Signal at the Receiver End

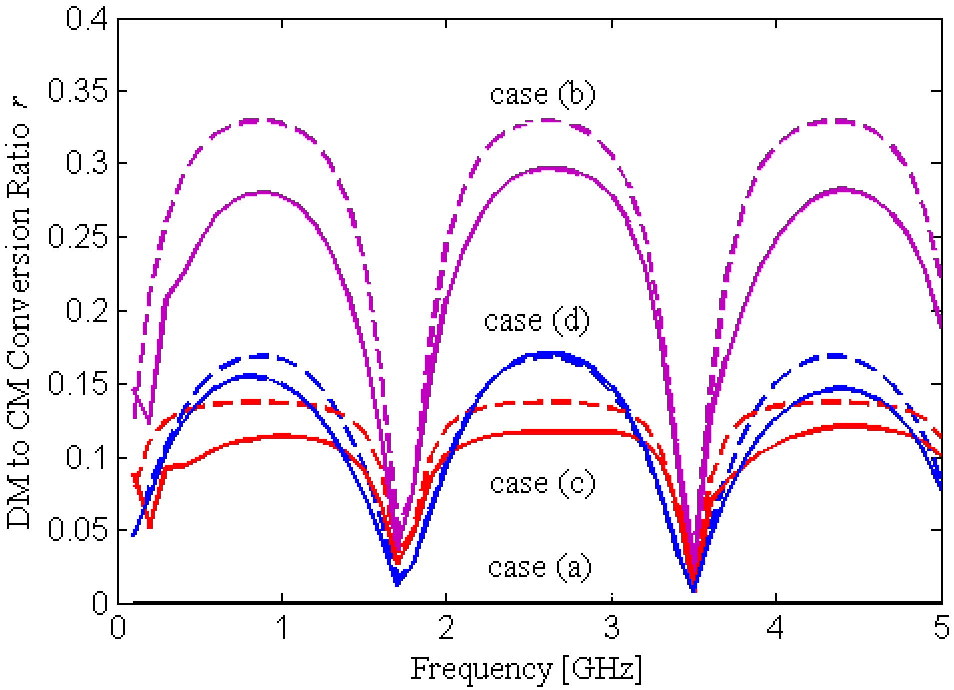


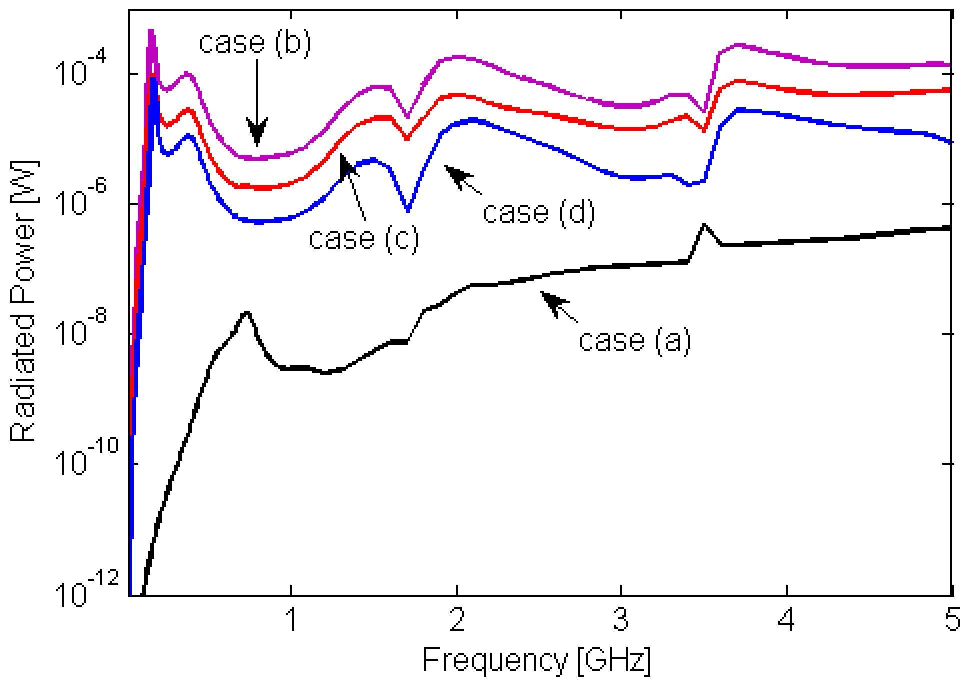


Differential mode signal in this case is mainly affected by the termination condition. Here, case (c) is the worst case

Common mode signal is mainly determined by the symmetry of the configuration. Here, case (b) is the worst case

Radiated Power

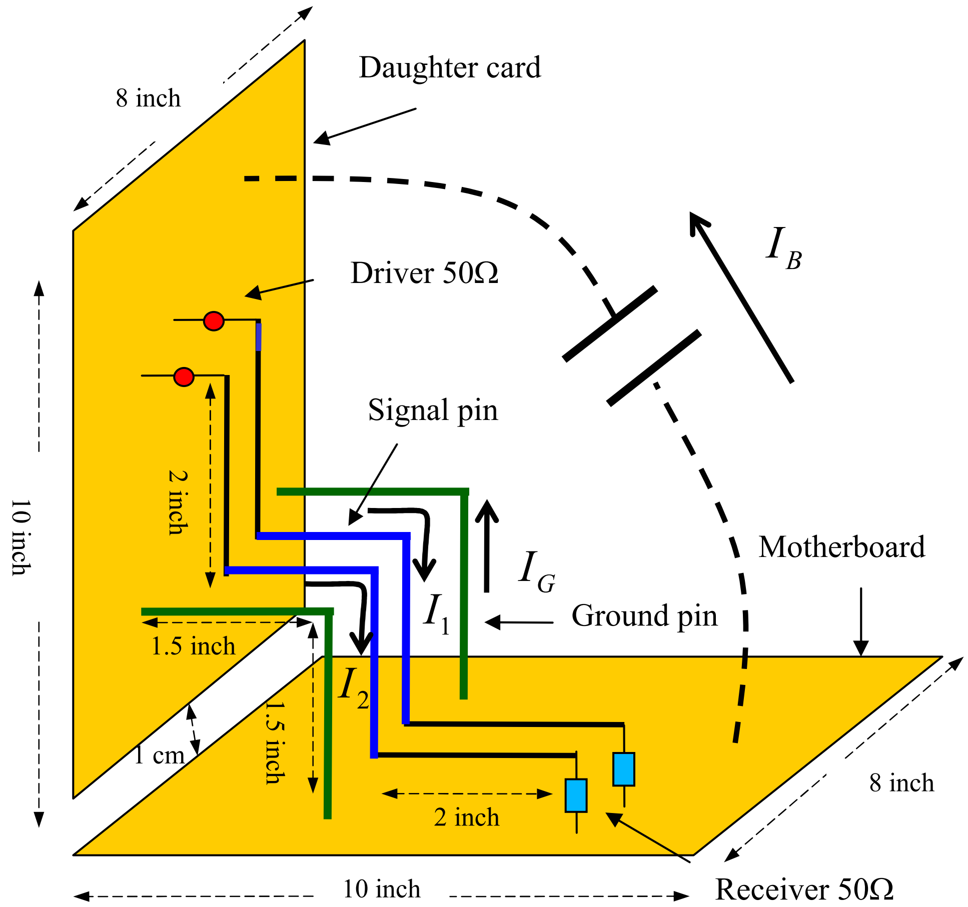


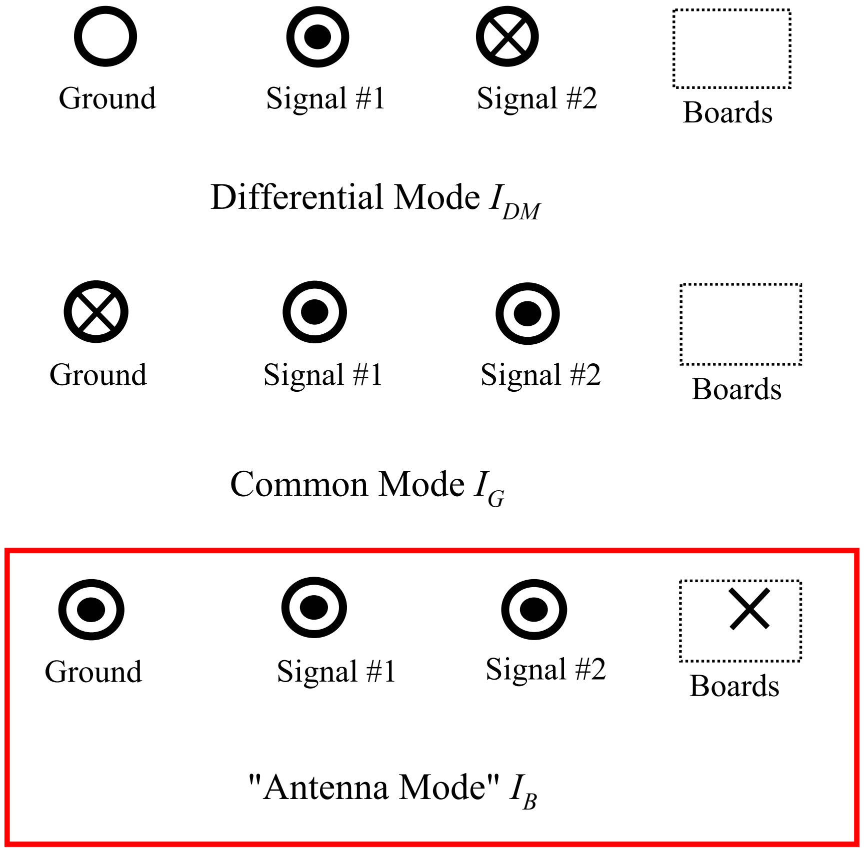


Although case (c) has a lower conversion ratio than case (d), the radiation is higher.

Differential to common mode conversion is not the sole cause of emission in this case, ground pin configuration play a critical role here.

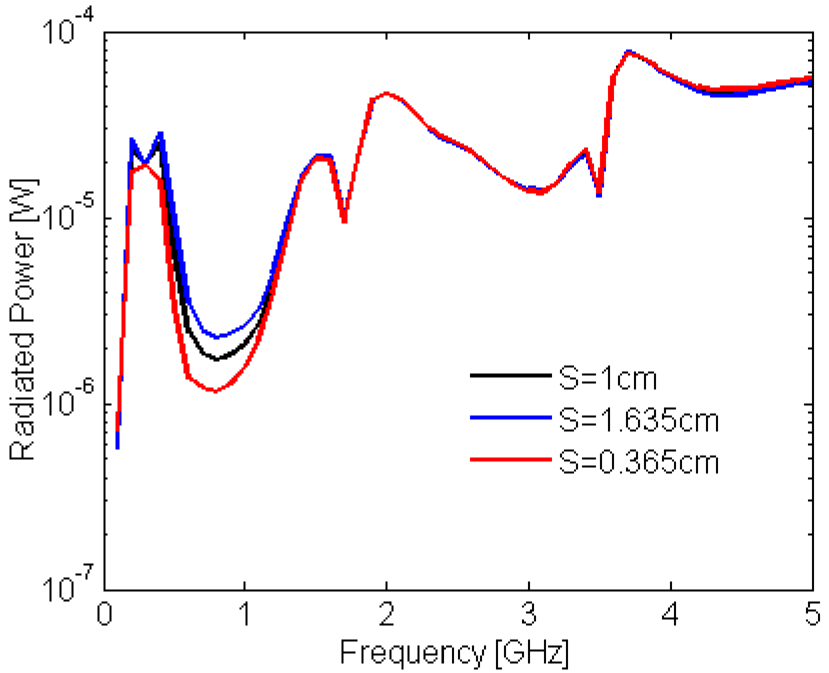
Introduction of an Antenna Mode

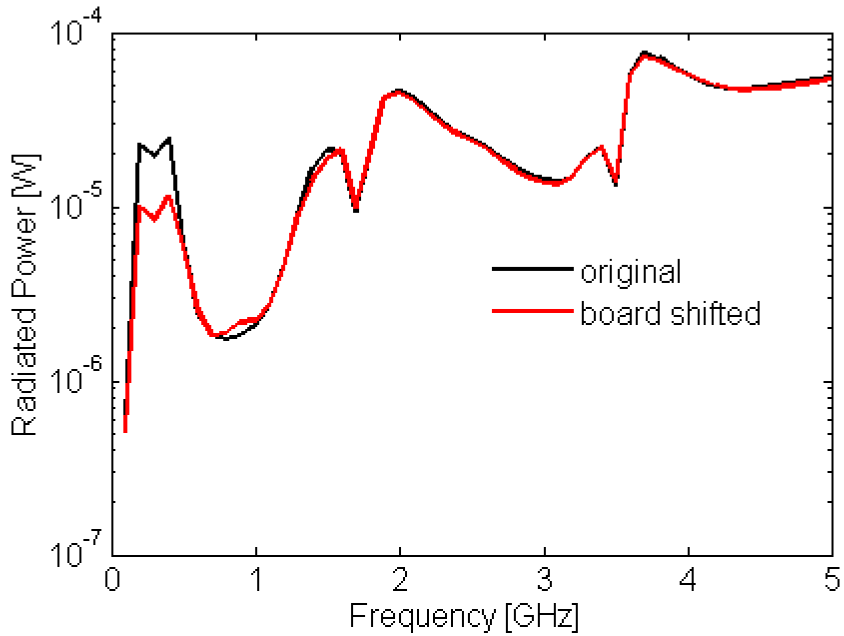


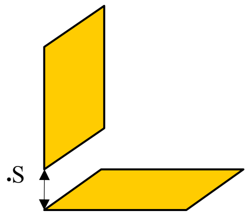


$$I_{DM} = \frac{1}{2}(I_1 - I_2) \qquad I_{CM} = I_1 + I_2 = I_G + I_B$$

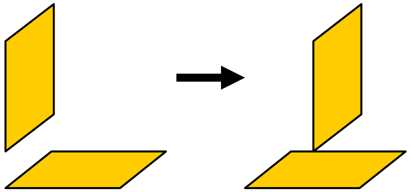
Experiment of Changing Board Configuration



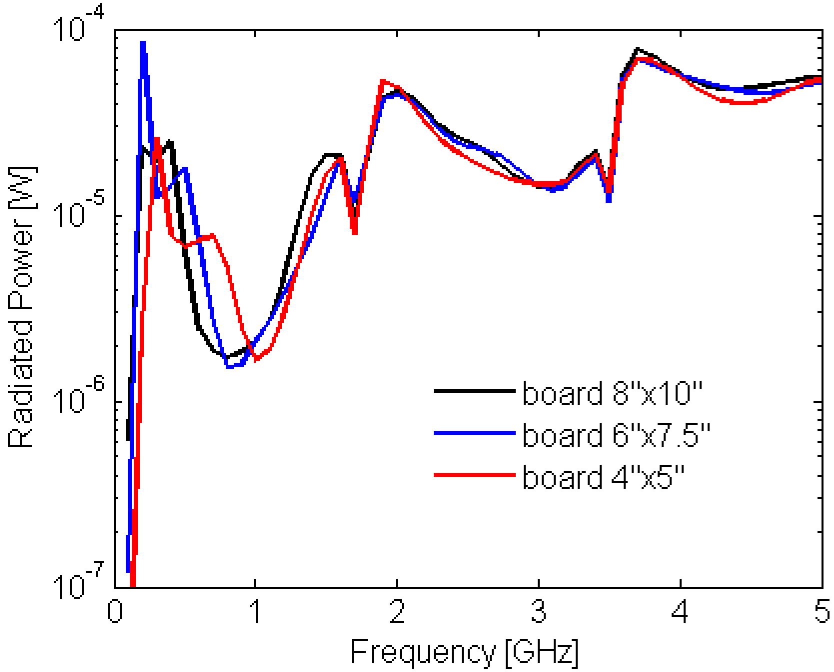


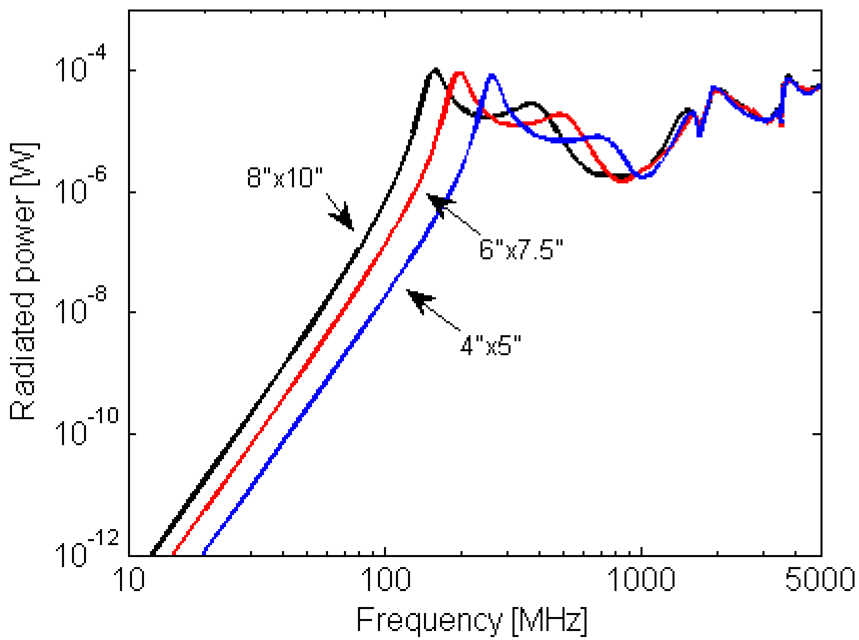


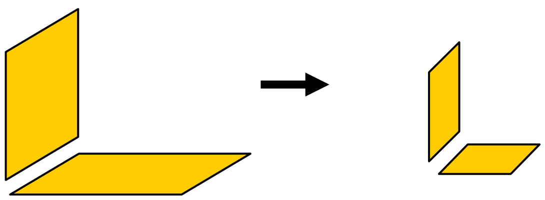
Radiation in the GHz range changes little for different board separations and board positions



Experiment of Changing Board Configuration







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.

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**

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

[1] X. Duan, B. Archambeault, H.-D. Brüns, and C. Schuster, "EM emissions of differential signals across connected printed circuit boards in the GHz range," *IEEE Int. Symp. EMC*, Austin, TX, 2009

[2] D. M. Hockanson, J. L. Drewniak, T. H. Hubing, T. P. Van Doren, F. Sha and M. J. Wilhelm, "Investigation of fundamental EMI source mechanisms driving common-mode radiation from printed circuit boards with attached cables," *IEEE Trans. Electromagn. Compat.,* Vol. 38, no.4, pp. 557–565, 1996

[3] M. Mondal, B. Mutnury, P. Patel, S. Connor, B. Archambeault, and M. Cases, "Electrical Analysis of Multi-board PCB Systems with Differential Signaling Considering Non-ideal Common Ground Connection," EPEP, pp.37 - 40, 2007

[4] M. Leone and V. Navratil, "On the electromagnetic radiation of Printed-Circuit-Board interconnections," *IEEE Trans. Electromagn. Comp.*, Vol. 47, No. 2, pp.219-226, May 2005

[5] X. Ye, J. Nadolny, J. L. Drewniak, T. H. Hubing, T. P. Van Doren and D. E. DuBroff, "EMI associated with inter-board connection for module-on-backplane and stacked-card configurations," *IEEE Trans.. Electromagn. Compat.*, Vol. 2, pp:797–802, Aug. 1999

[6] D. M. Hockanson, X. Ye, J. L. Drewniak, T. H. Hubing, T. P. Van Doren and R. F. DuBoff, "FDTD and experimental investigation of EMI from stacked-card PCB configurations," *IEEE Trans. Electromagn. Compat.,* Vol. 43, pp. 1–10, Feb. 2001

[7] X, Ye, J. L. Drewniak, J. Nadolny and D. M. Hockanson, "High-performance inter-PCB Connectors: Analysis of EMI Characteristics," *IEEE Trans. Electromagn. Compat.,* Vol. 44, pp. 165–174, Feb. 2002

[8] K, Li, M. Ali, S. Y. Poh, M. Tsuk, R. T. Shin and J. A. Kong, "FD-TD analysis of electromagnetic radiation from Modules-on-backplane Configurations," *IEEE Trans. Electromagn. Compat.*, Vol. 37, No. 3, pp.326-332, Aug. 1995

[9] D. E. Bockelman, W. R. Eisenstadt, "Combined differential and common-mode scattering parameters: theory and simulation," *IEEE Trans. Microwave Theory and Techniques*, Vol. MTT-43, pp. 1530–1539, July 1995

[10] Y. Kayano, M. Tanaka, J. L. Drewniak and H. Inoue, "Common-mode current due to a trace near a PCB edge and its suppression by a guard band," *IEEE Trans. Electromagn. Compat.*, Vol. 46, No. 1, pp. 46 - 53, Feb. 2004

[11] C. L. Holloway and E. F. Kuester, "Net and partial inductance of a microstrip ground plane," *IEEE Trans. Electromagn. Compat.*, Vol. 40, No. 1, Feb. 1998

[12] C. R. Paul, *Analysis of Multiconductor Transmission Lines*, Wiley, New York, 1994

[13] CONCEPT-II home page. [Online]. Available: http://www.tet.tu-harburg.de/en_EN/en_concept.php

[14] C. R. Paul, "A comparison of the contributions of common-mode and differential-mode currents in radiated emissions," *IEEE Trans. Electromagn. Compat.*, Vol. 31, No. 2, pp. 189–193, May 1989

[15] C. R. Paul, *Introduction to electromagnetic compatability*, Wiley, New York, 1992