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Power Inverter / Motor Driver Design for Reduced Emissions

Todd Hubing

Michelin Professor of Vehicular Electronics

Clemson University

CLEMSON
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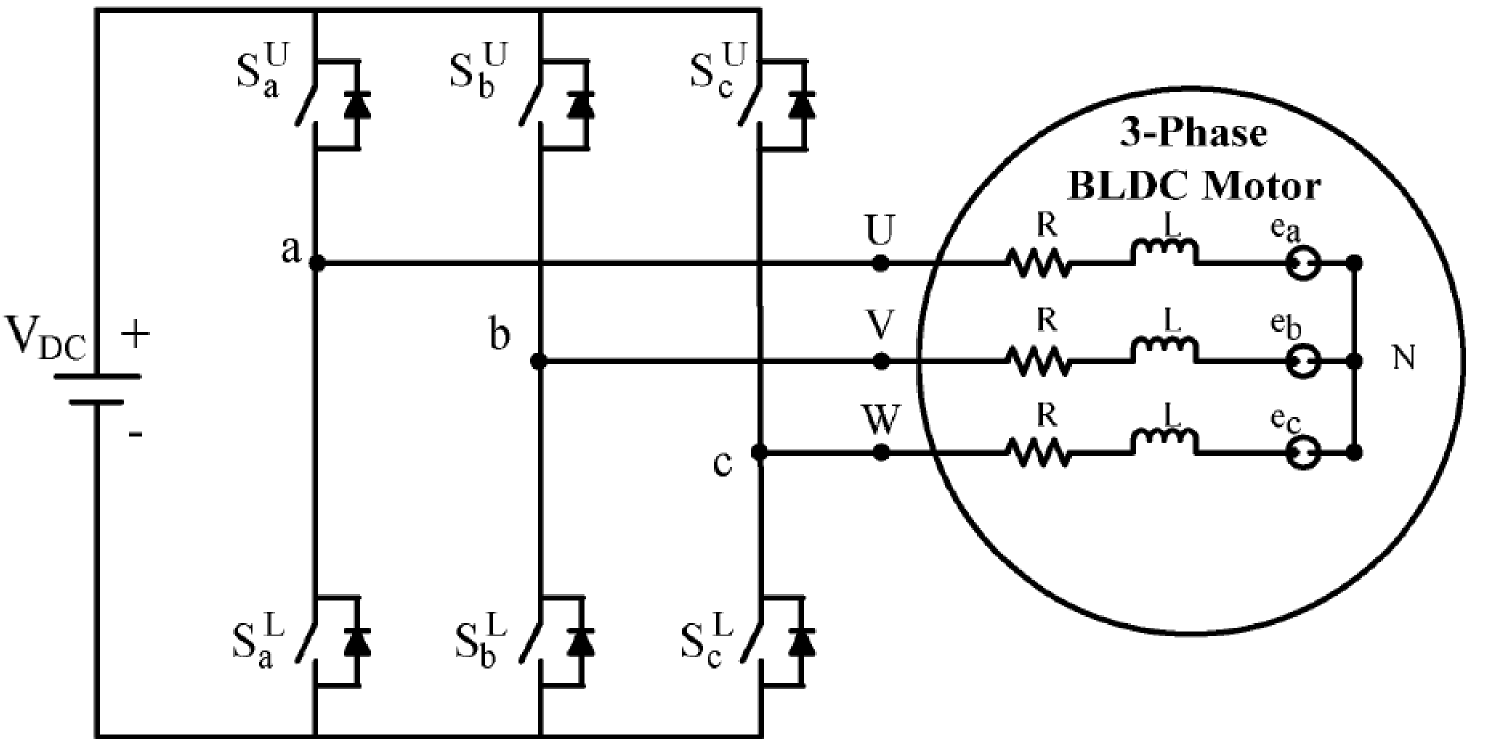
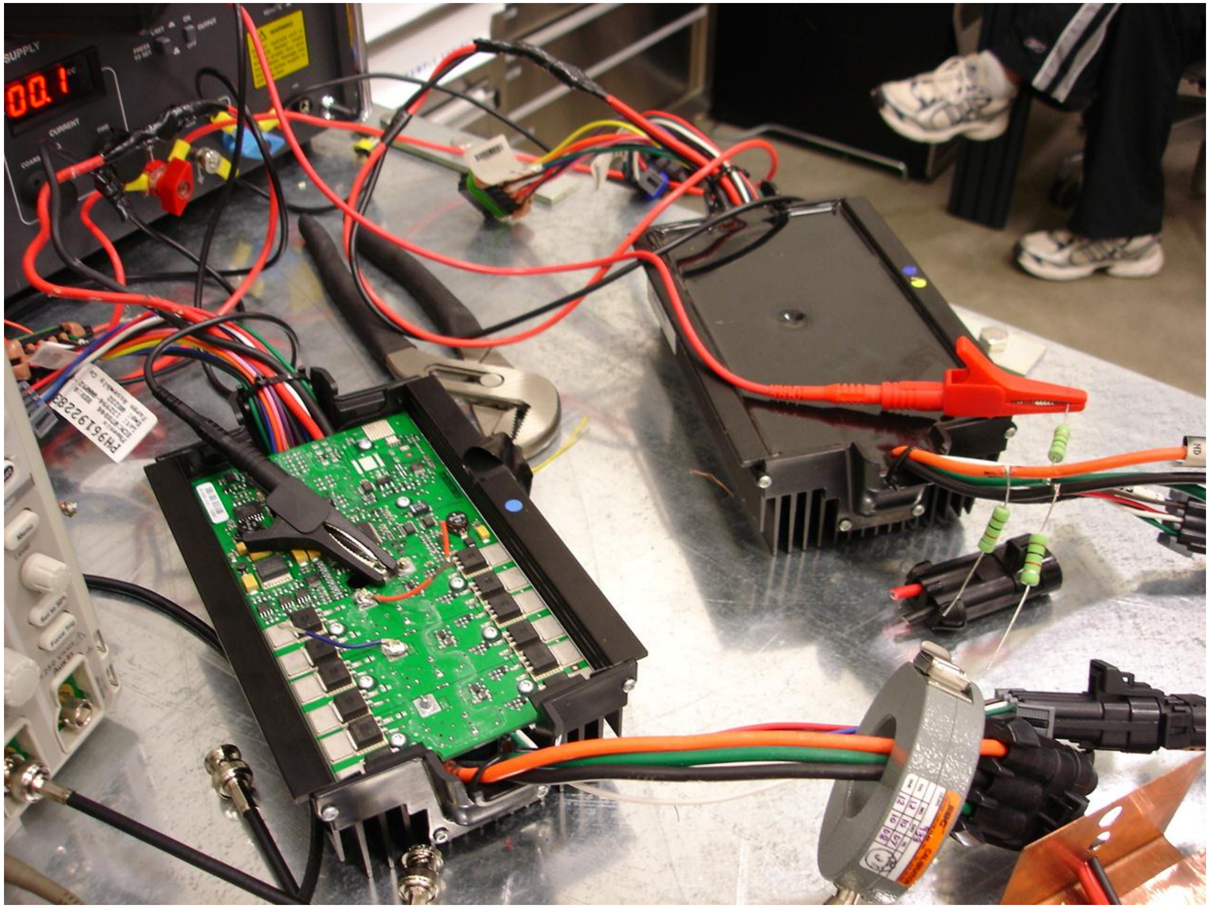
What is a Power Inverter?



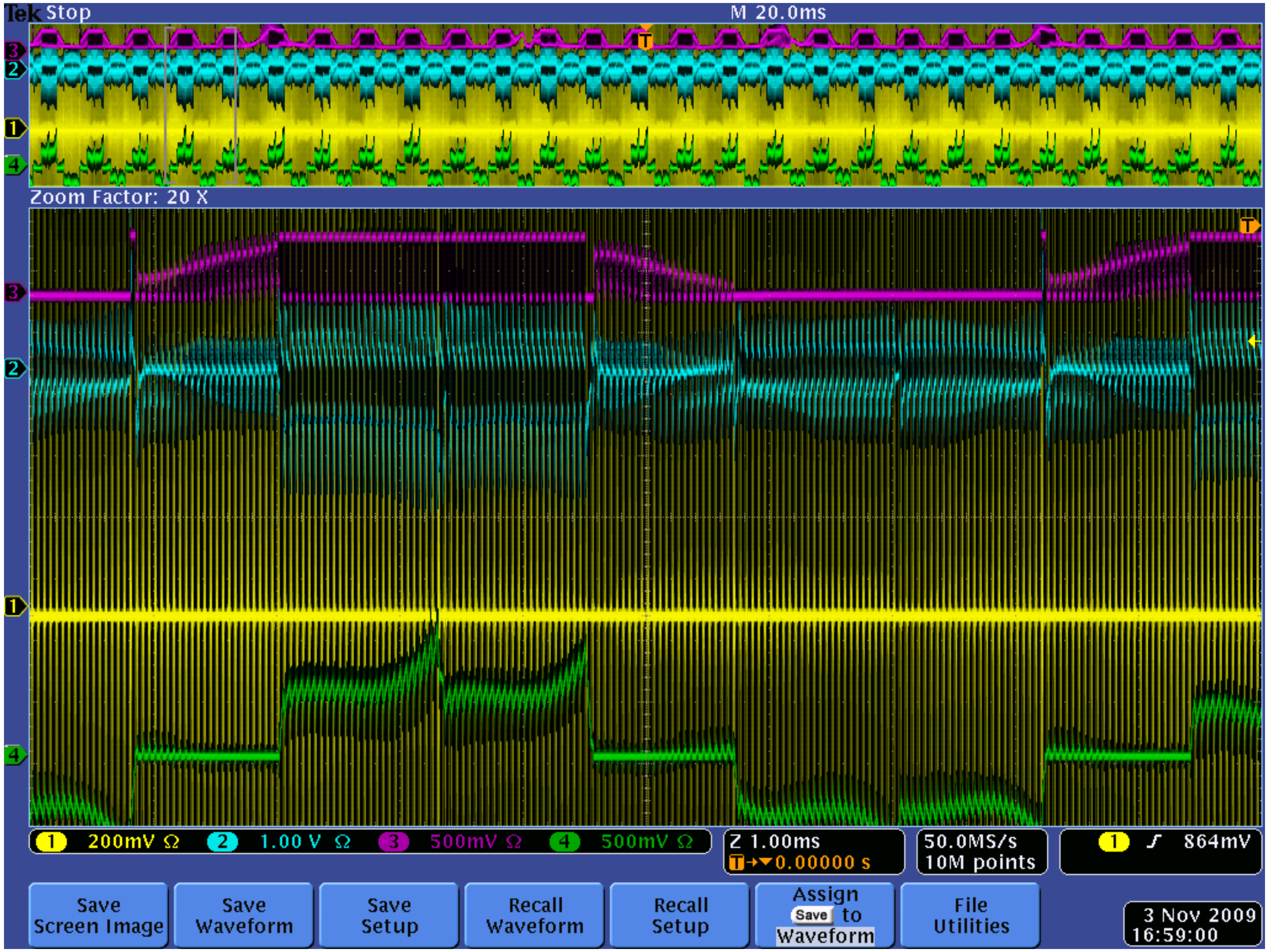
Primary Sources of EMI from Power Inverters

- Conversion of differential-mode power currents to common-mode noise currents (imbalance)
- Electric field coupling from heatsinks
- EMI from digital electronic controls

Example of a Power Inverter Layout



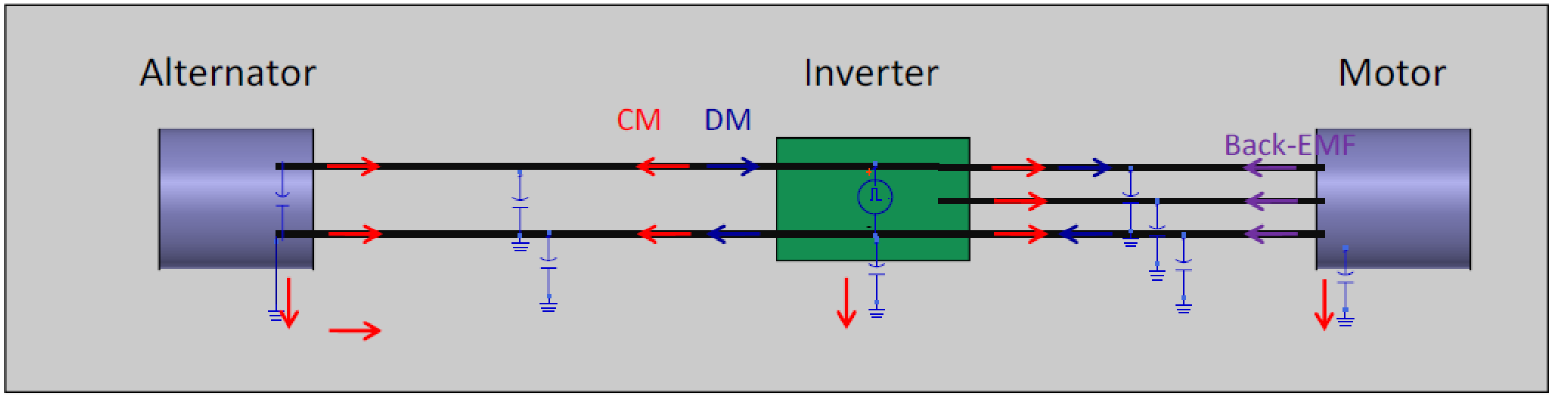
Six-Step Inversion Waveforms



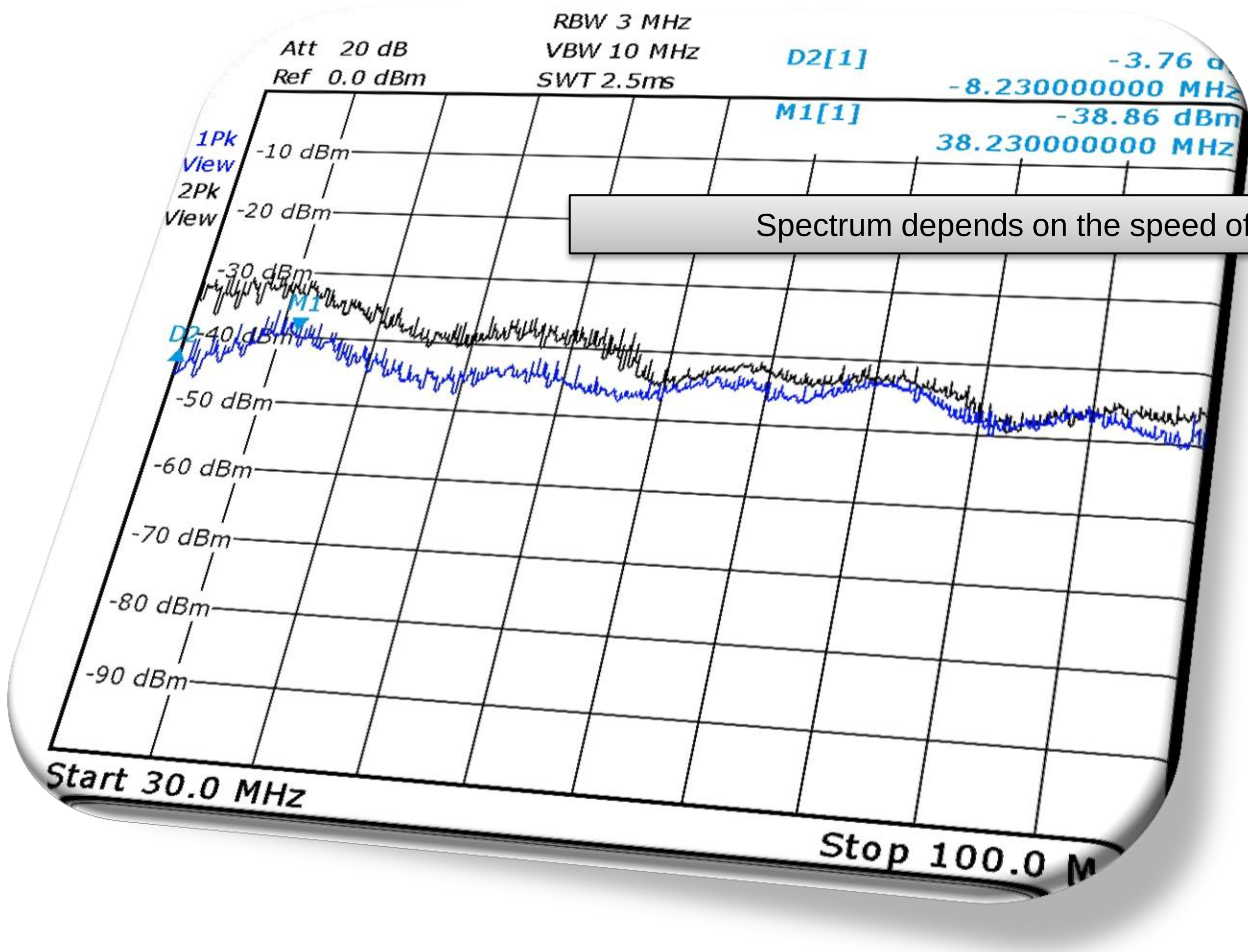
Common-Mode Currents

Phase Voltage $A_{\text{-to-circuit GND}}$ (pink), Phase Voltage $A_{\text{-to-GND}}$ (sky), Current Clamp probe voltage (yellow) and Phase Current A (Green)

Common Mode "Antenna" Currents

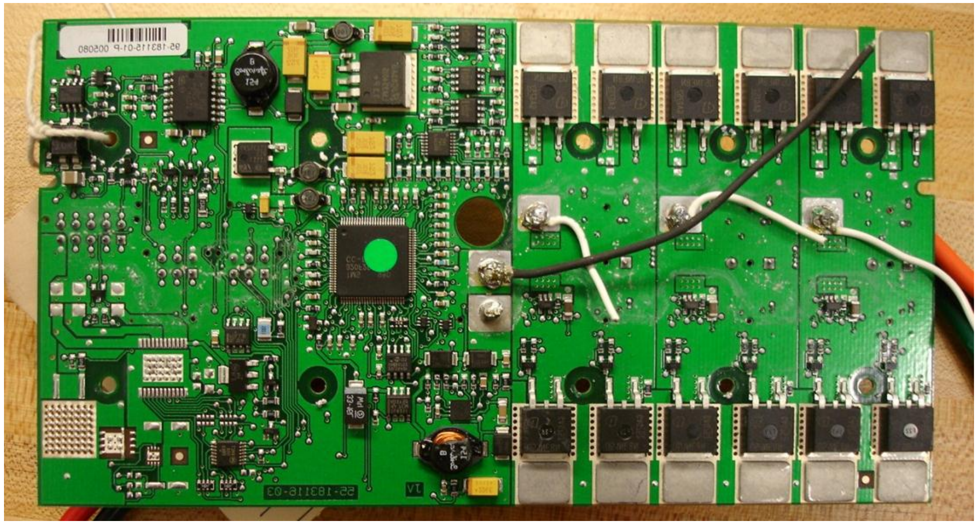


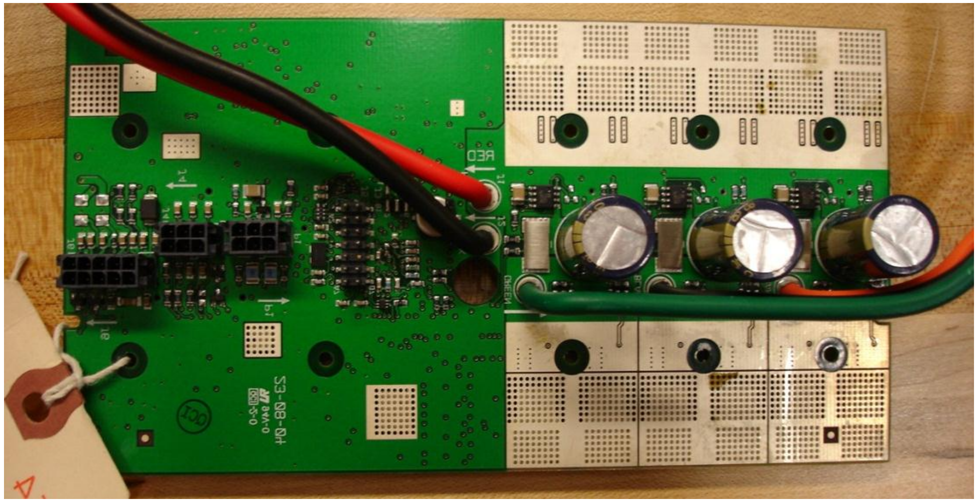
Typical CM Current (Frequency Domain)



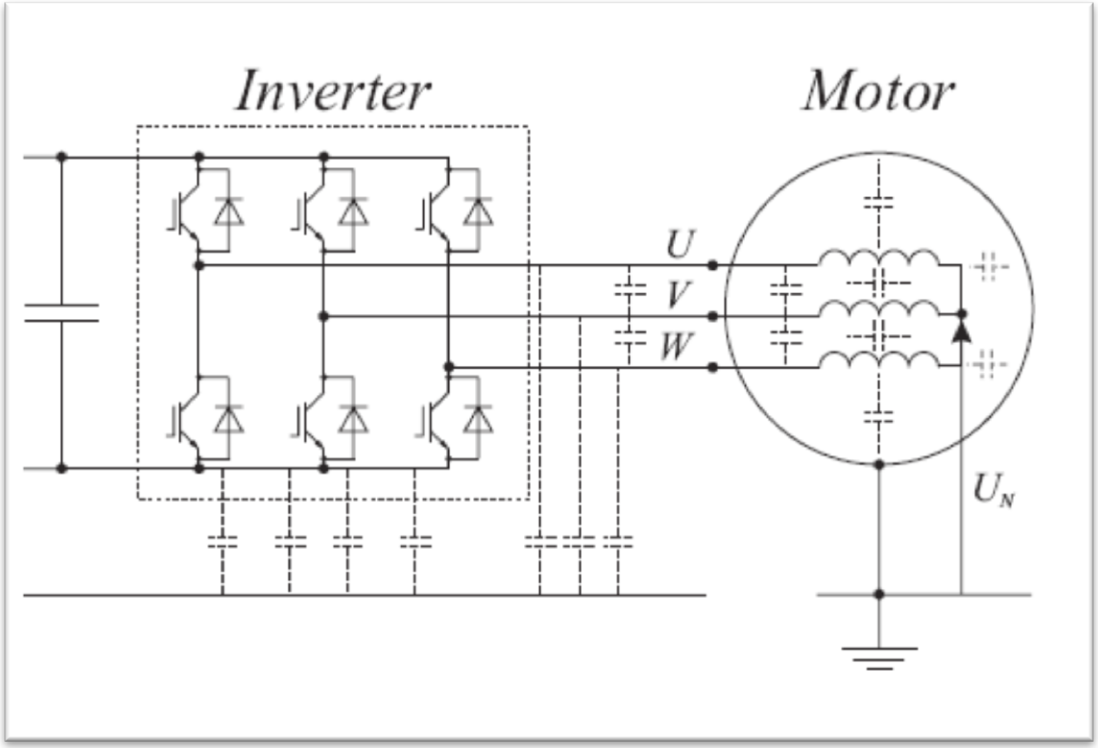
Spectrum depends on the speed of motor

Typical Layout





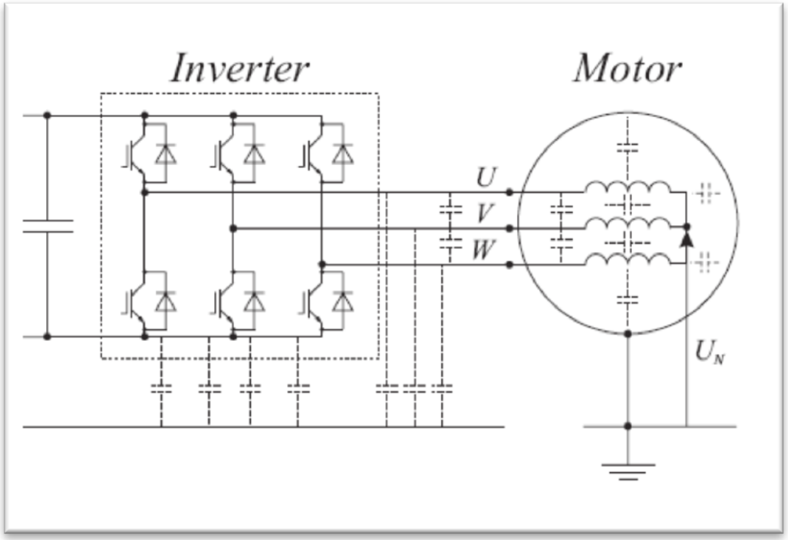
Common-Mode Current Due to Imbalance



Common-mode current from power converters and motor drivers is a common source of electromagnetic interference in automotive systems.

And yet, at their most basic level, these devices are inherently balanced.

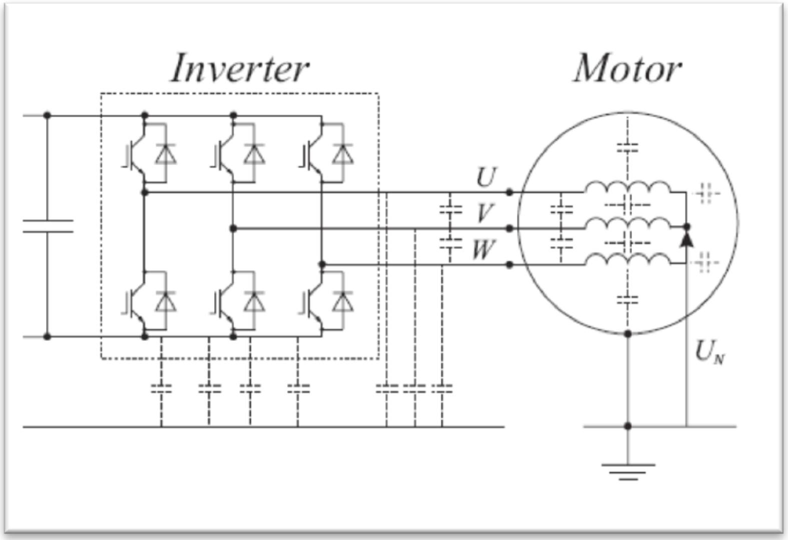
Common-Mode Current Due to Imbalance



Imbalance arises from:

- geometrical asymmetries
- unequal turn-on and turn-off times
- unbalanced PWM control
- unbalanced filtering
- switching device parasitics
- imbalances in load impedance

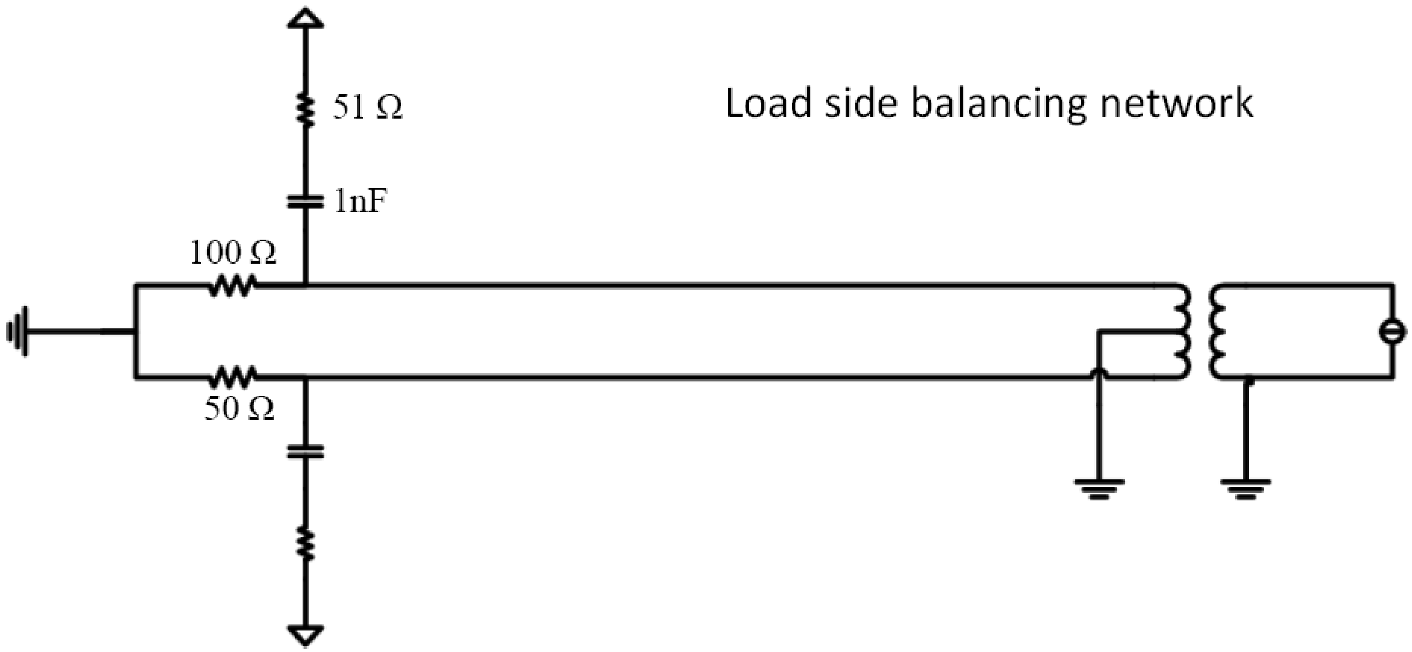
Imbalanced vs. Balanced Design



Imbalance arises from:

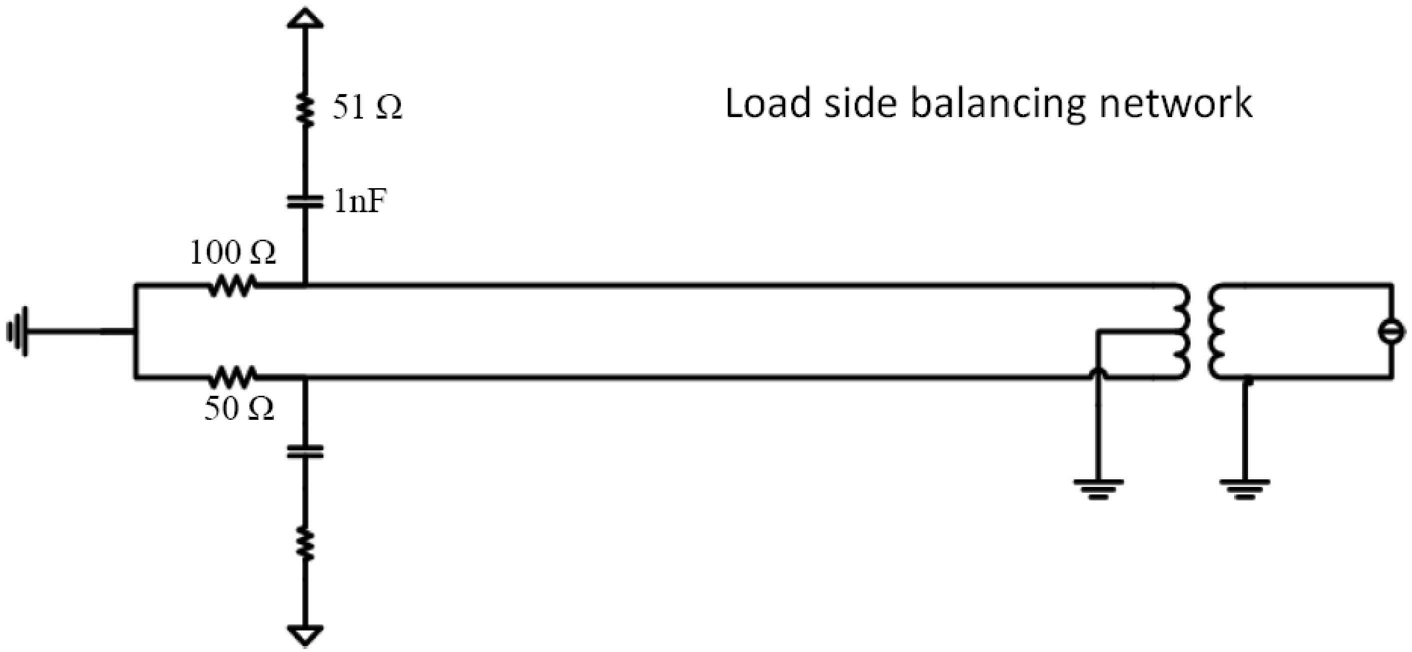
- ~~geometrical asymmetries~~ - unnecessary
- ~~unequal turn-on and turn-off times~~ – can compensate
- ~~unbalanced PWM control~~ – can use balanced method
- ~~unbalanced filtering~~ - unnecessary
- ~~switching device parasitics~~ – can compensate
- ~~imbalances in load impedance~~ – can compensate

One Approach: A Balanced Cable Interface



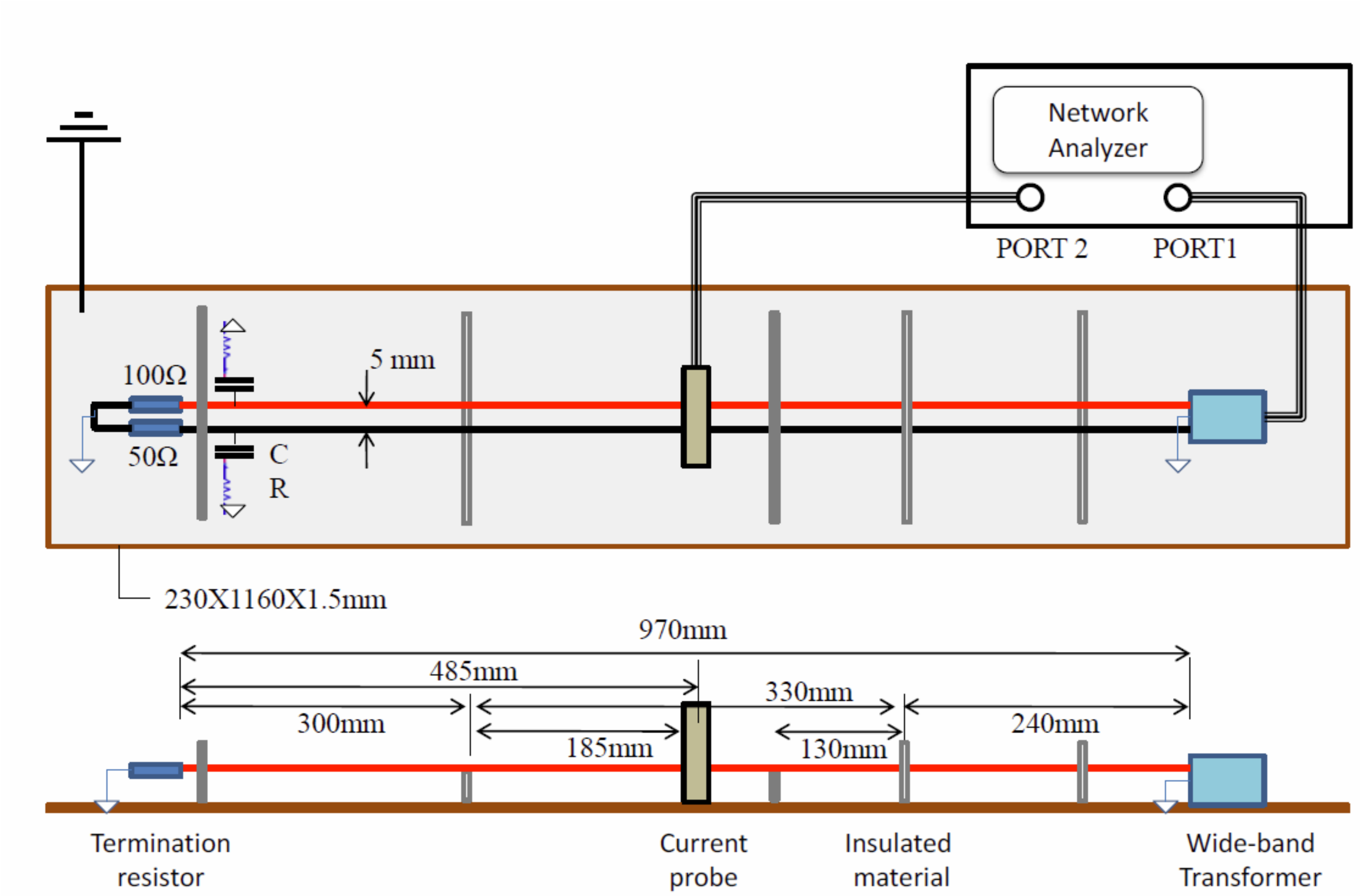
If the source and cable are balanced, but the load is imbalanced, the imbalance in the load can be "hidden" from the rest of the system with a balancing network.

A Balanced Cable Interface (Balancing Network)



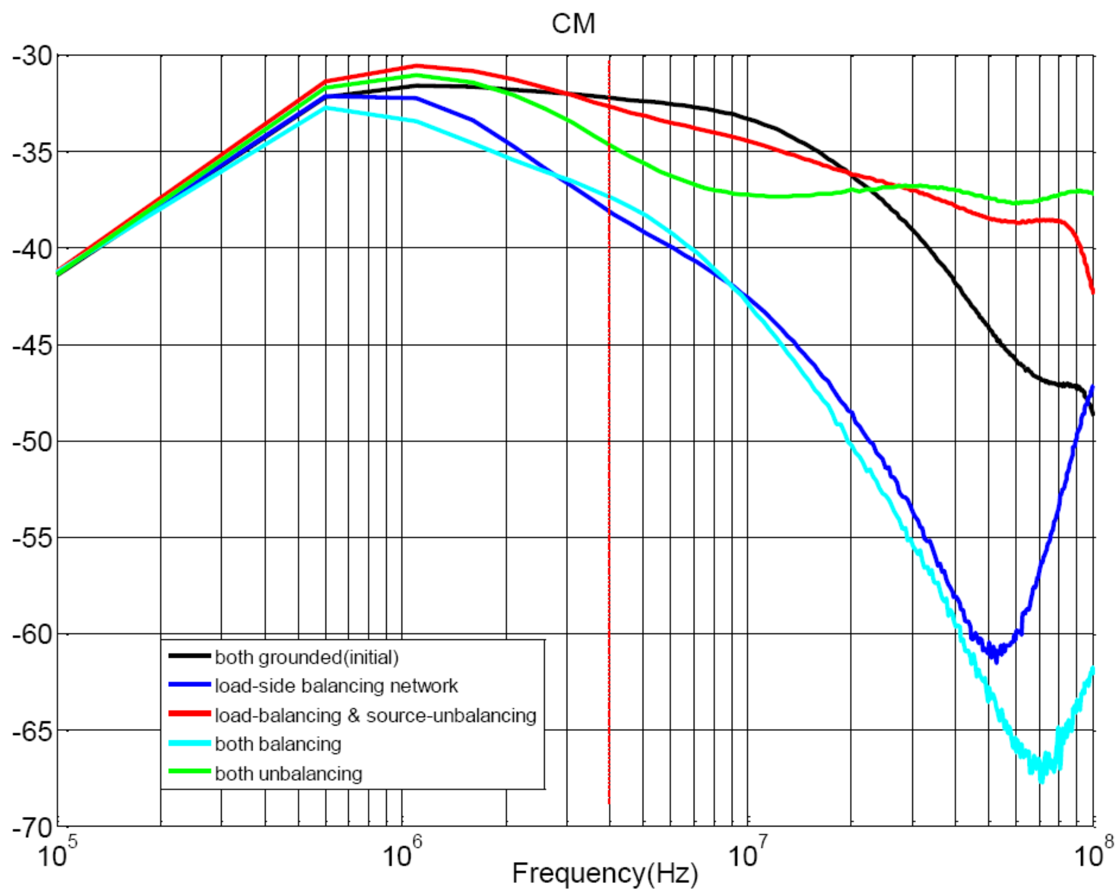
In our application (a motor driver), the source and load only need to appear balanced at radiated emission frequencies (particularly 30 – 80 MHz).

Test Set-up


Network
Analyzer
PORT 2
PORT1
100Ω
50Ω
5 mm
C
R
230X1160X1.5mm
970mm
485mm
330mm
300mm
240mm
185mm
130mm
Termination
resistor
Current
probe
Insulated
material
Wide-band
Transformer

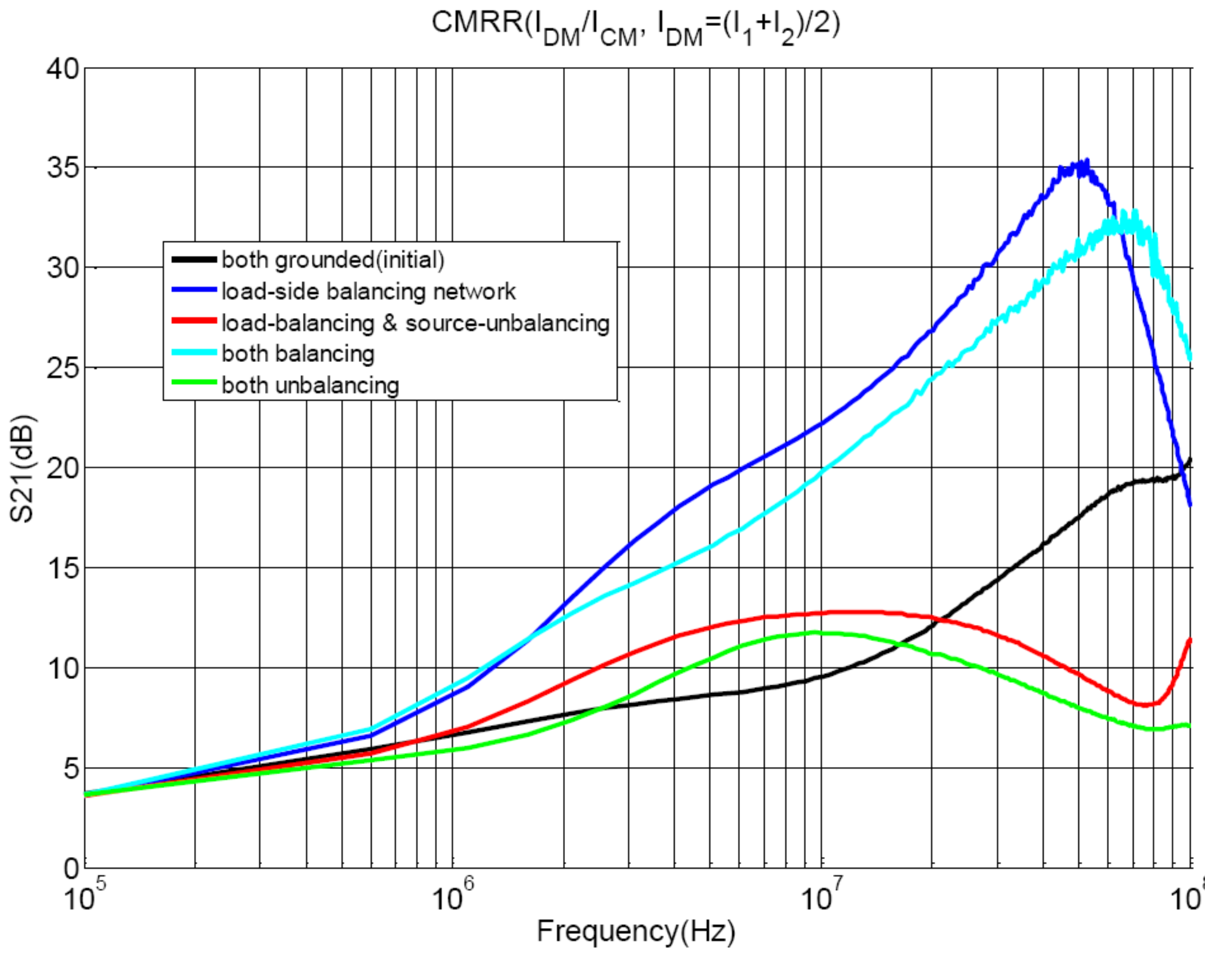
A Balanced Cable Interface (Balancing Network)

Measured common-mode current with and without the balancing network

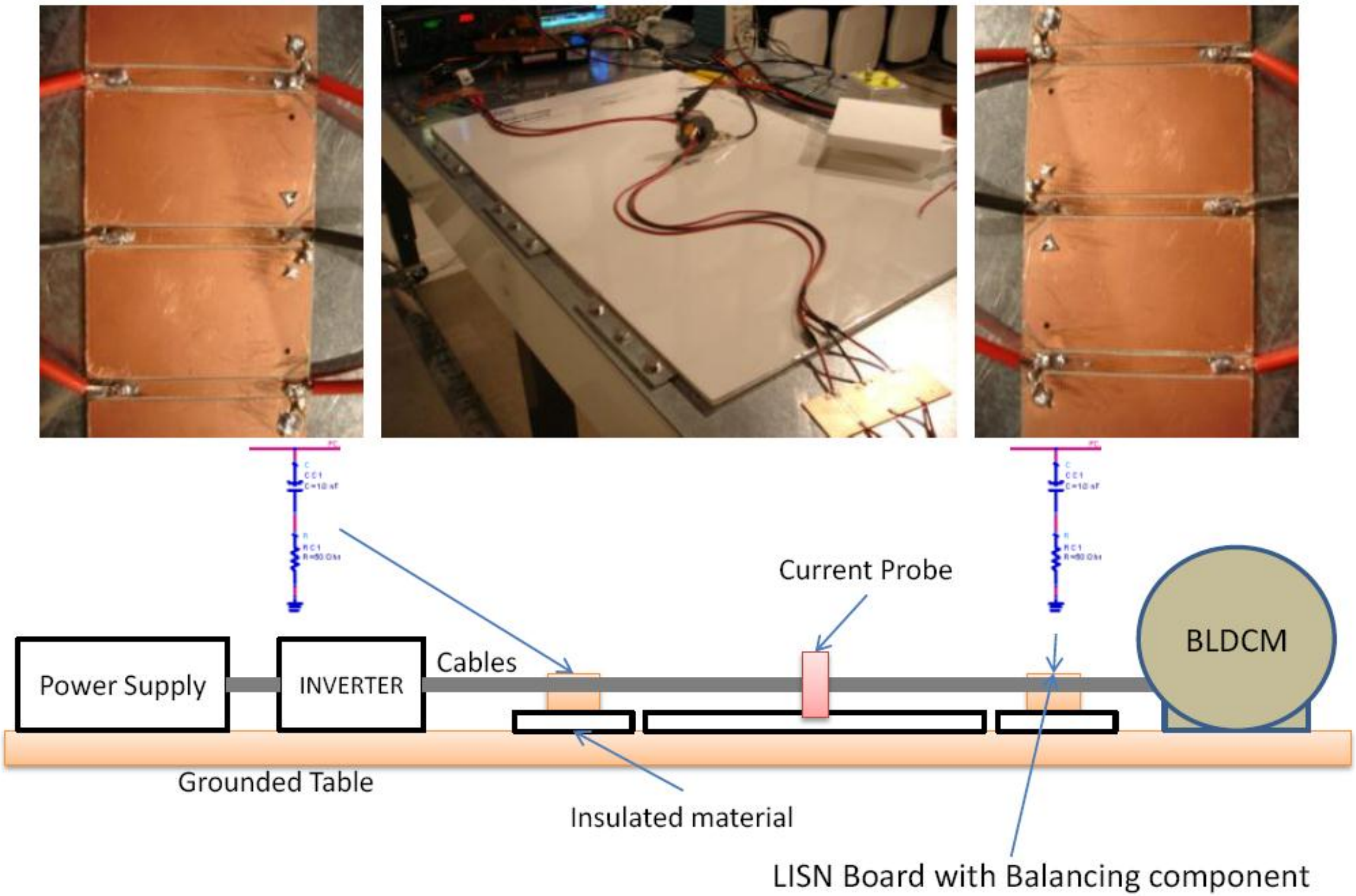


A Balanced Cable Interface (Balancing Network)

Measured common-mode rejection ratio with and without the balancing network

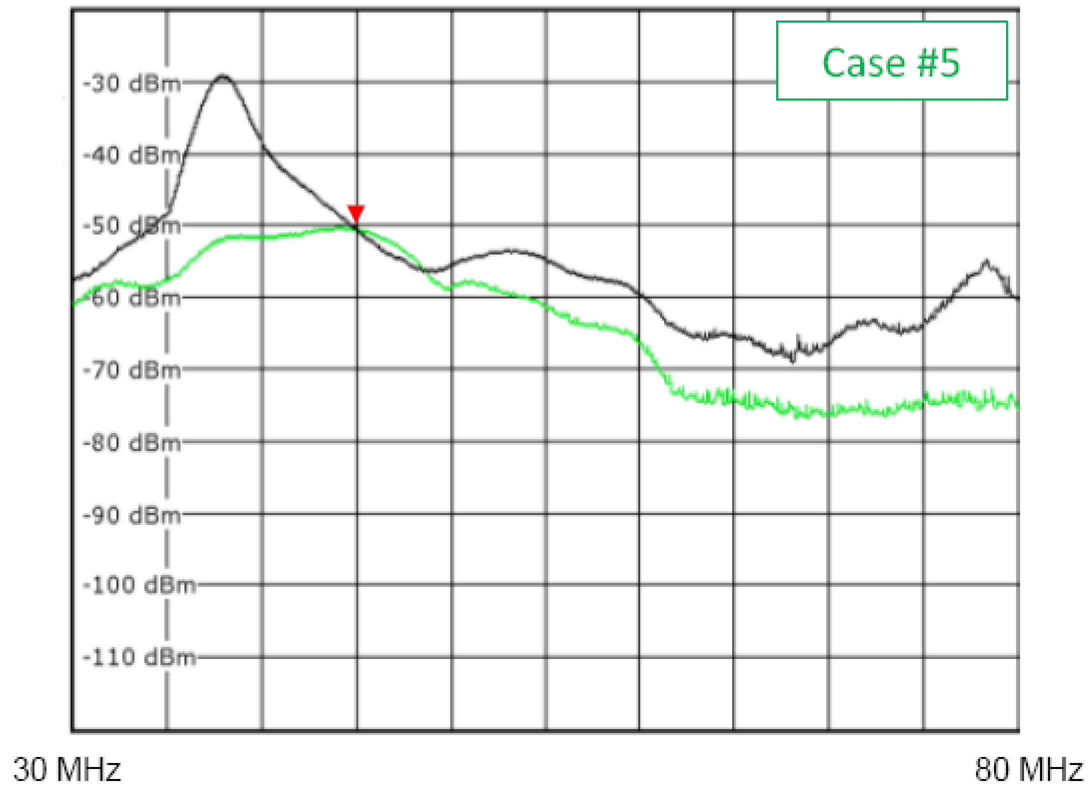


Evaluation of balancing network on motor driver



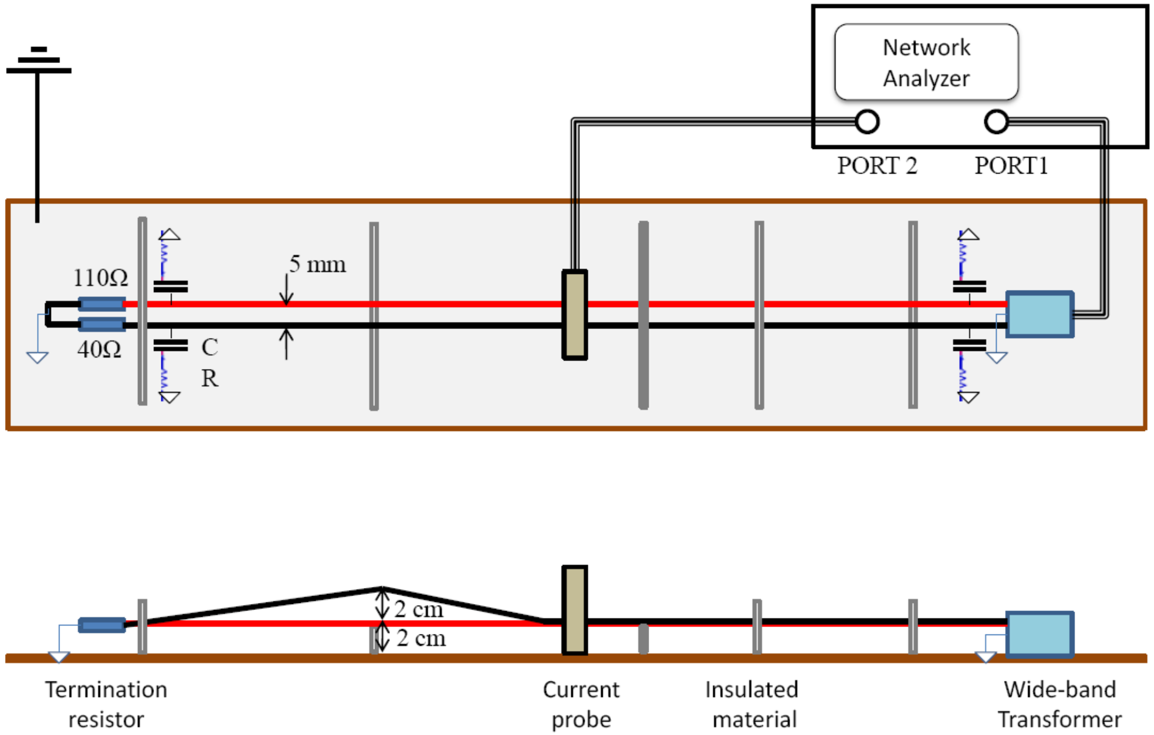
Evaluation of balancing network on motor driver

Measured common-mode current with (green) and without (black) the balancing network

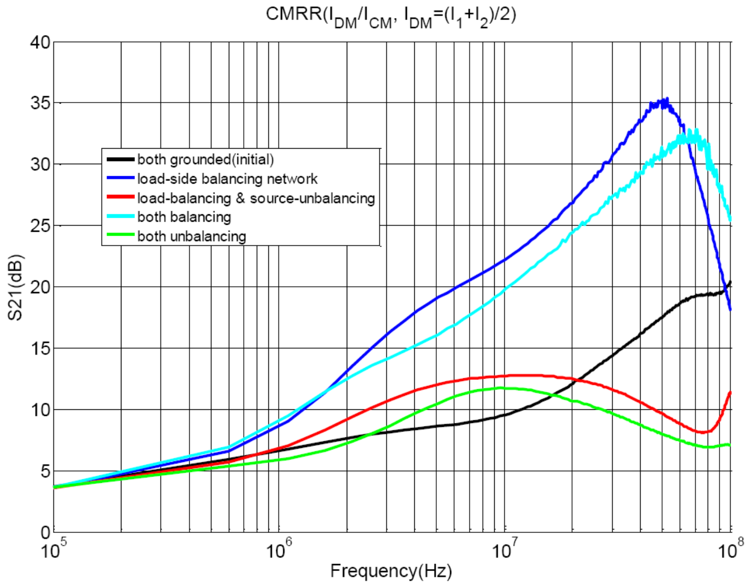


Evaluation of balancing network on motor driver

How balanced do the cables need to be?

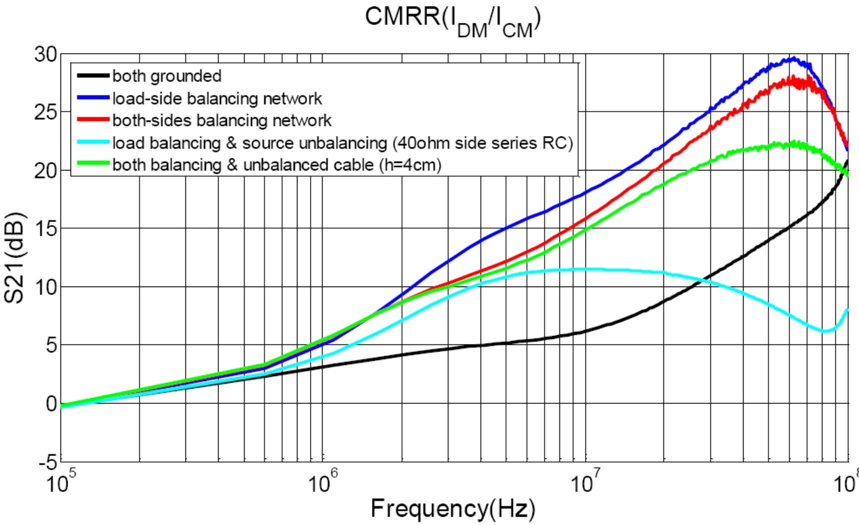


Evaluation of balancing network on motor driver

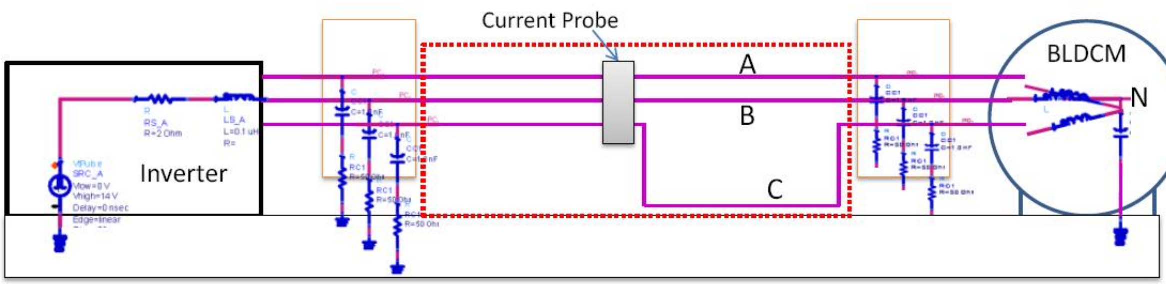


Well balanced cables

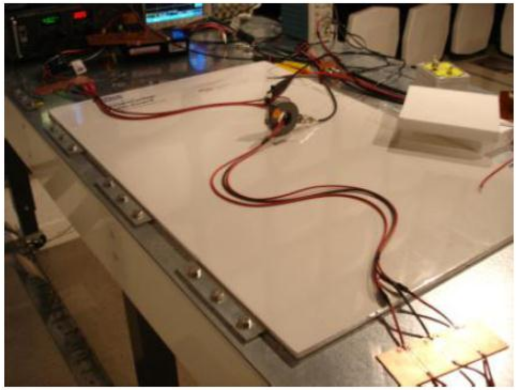
Poorly balanced cables



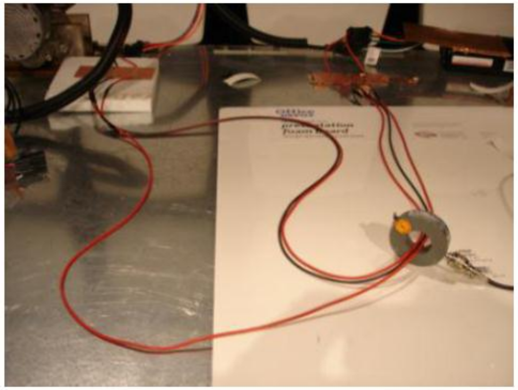
Evaluation of balancing network on motor driver



Balanced cables

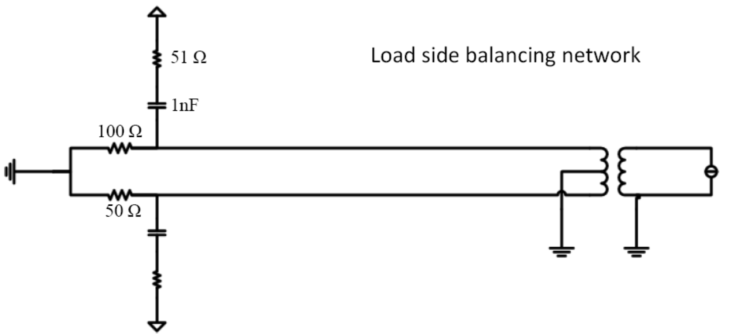


Unbalanced cables



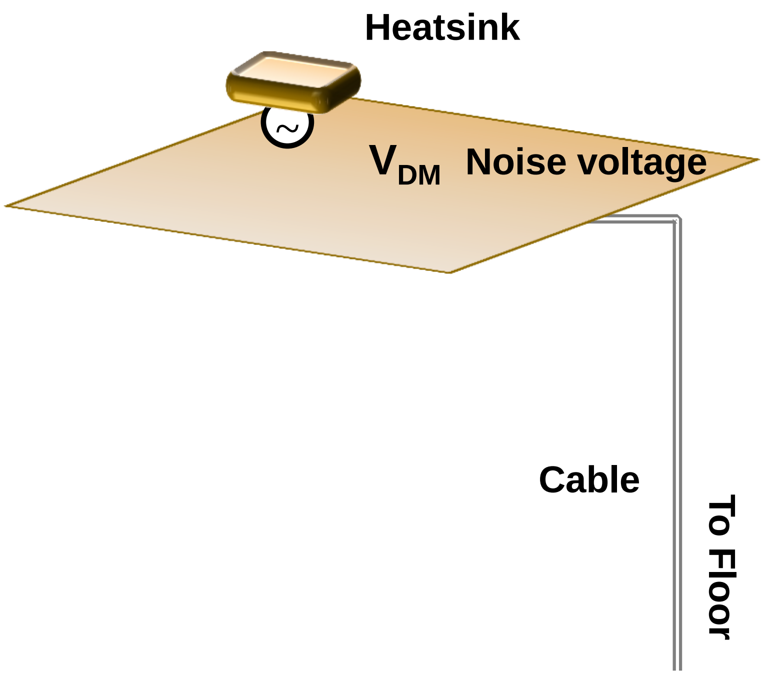
How balanced do the cables need to be?

Summary



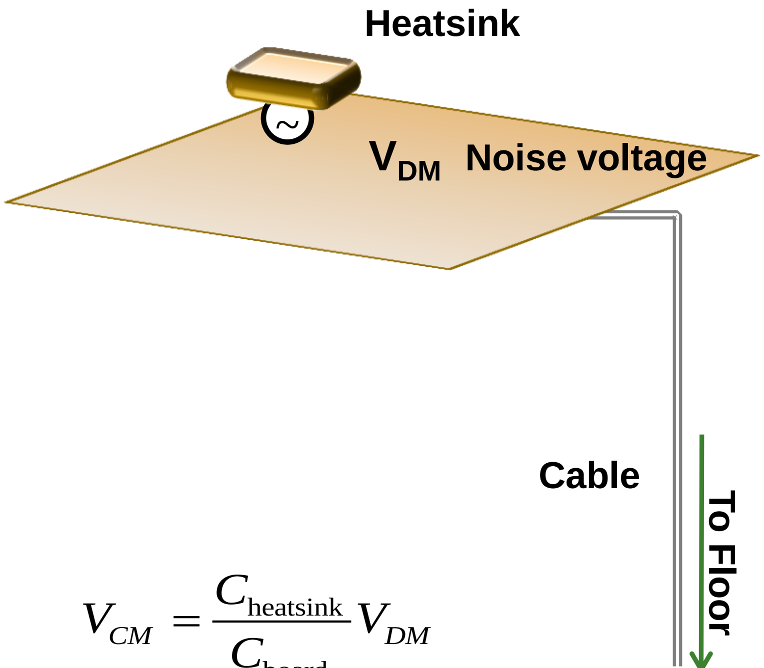
- A balancing network can significantly reduce the common-mode currents on a balanced cable connected to an unbalanced load and/or source.
- These networks are relatively inexpensive to implement and can be more effective than common-mode chokes or ferrites.
- Although they are similar to standard filters, they are different in function and design. They reduce common-mode currents much more than differential-mode currents.

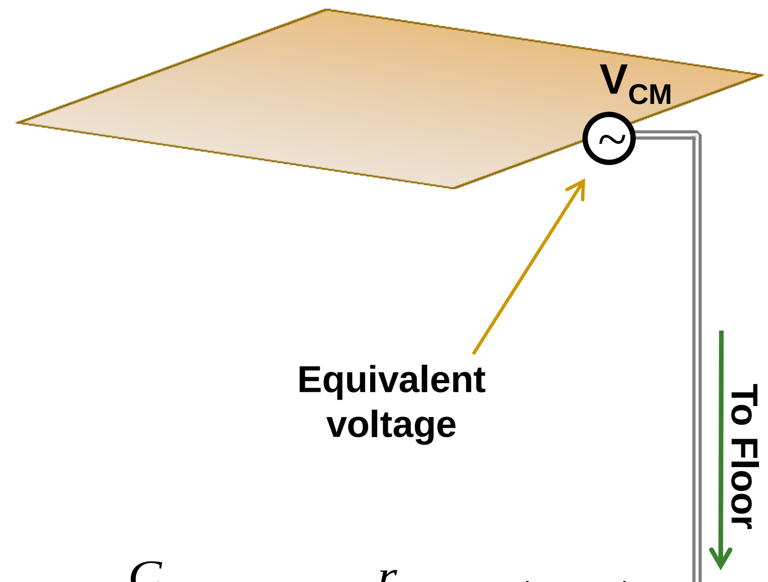
CM Current Due to Coupling from Heatsinks



Electric field coupling from heatsinks creates common-mode current on attached cables

Maximum Radiated Emissions Calculation





$$V_{CM} = \frac{C_{\text{heatsink}}}{C_{\text{board}}} V_{DM}$$

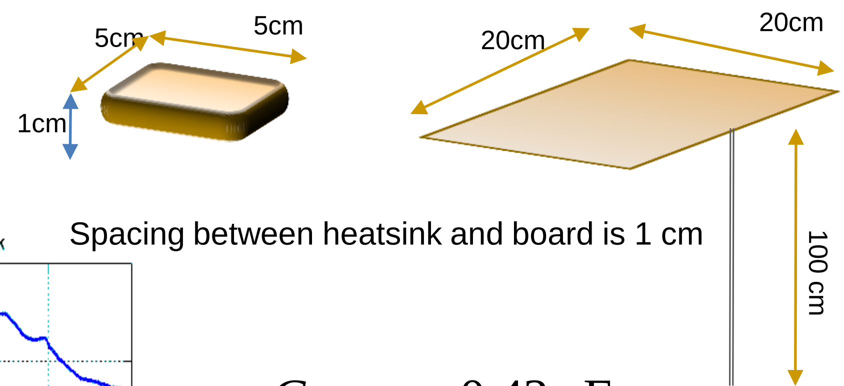
$$V_{DM} = 0.2234 \frac{C_{\text{board}}}{C_{\text{heatsink}}} \times \frac{r}{F_{\text{board}} F_{\text{cable}}} \times \left| E_{\max} \right|$$

References

[1] H. Shim and T. Hubing, “Model for Estimating Radiated Emissions from a Printed Circuit Board with Attached Cables Driven by Voltage-Driven Sources,” IEEE Transactions on Electromagnetic Compatibility, vol. 47, no. 4, Nov. 2005, pp. 899-907.

[2] Shaowei Deng, Todd Hubing, and Daryl Beetner, "Estimating Maximum Radiated Emissions From Printed Circuit Boards With an Attached Cable,“ IEEE Trans. on Electromagnetic Compatibility, vol. 50, no. 1, Feb. 2008, pp. 215-218.

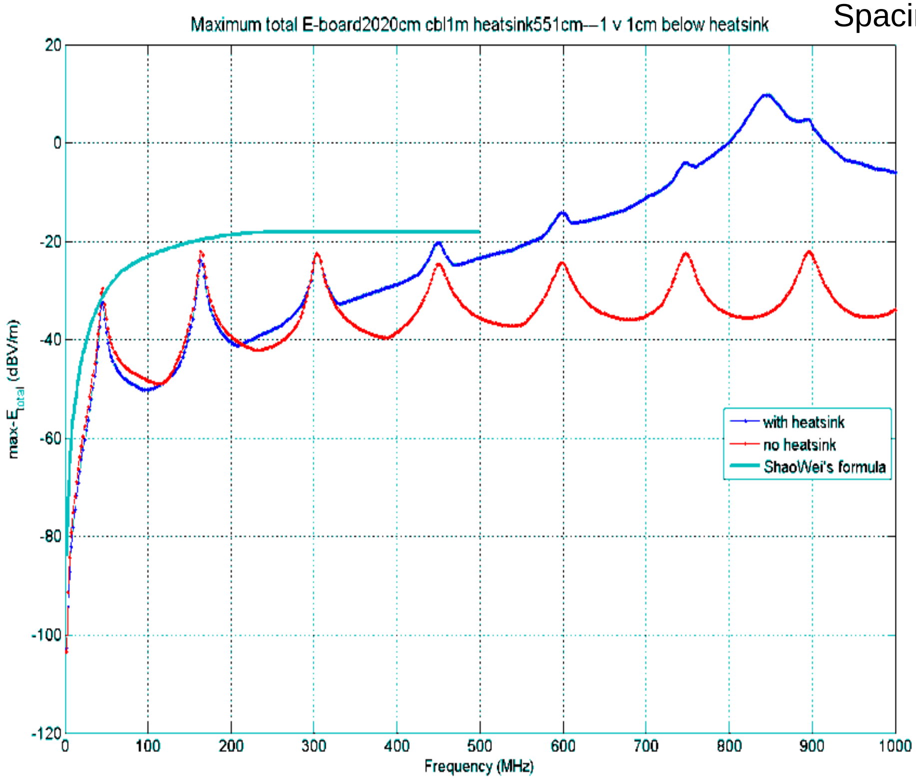
Maximum Radiated Emissions Calculation



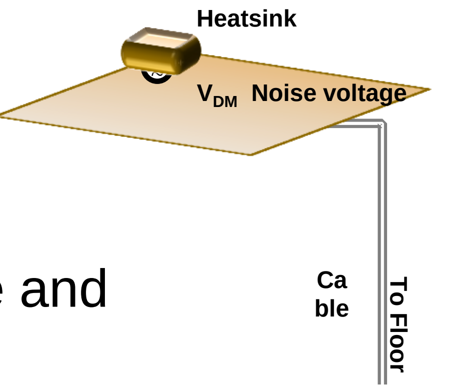
Spacing between heatsink and board is 1 cm

$$C_{\text{heatsink}} = 0.43\ \text{pF}$$

$$C_{\text{board}} = 5.14\ \text{pF}$$



Summary



- Heatsink coupling is proportional to heatsink size and voltage of heatsink relative to reference ground.
- CM current is split among various cables (i.e. more cables doesn’t result in more CM current).

Design Recommendations

- Pay close attention to all sources of imbalance.
- Put a chassis ground on board and incorporate a balancing network for medium to high power inverters.
- Keep voltage on heatsinks low relative to reference ground.
- Apply standard (good) EMC board design and layout practices for digital controls.
  (discussed in next presentation)

Grounding & Shielding in Mixed Signal PCBs

Todd H. Hubing

Clemson Vehicular Electronics Laboratory

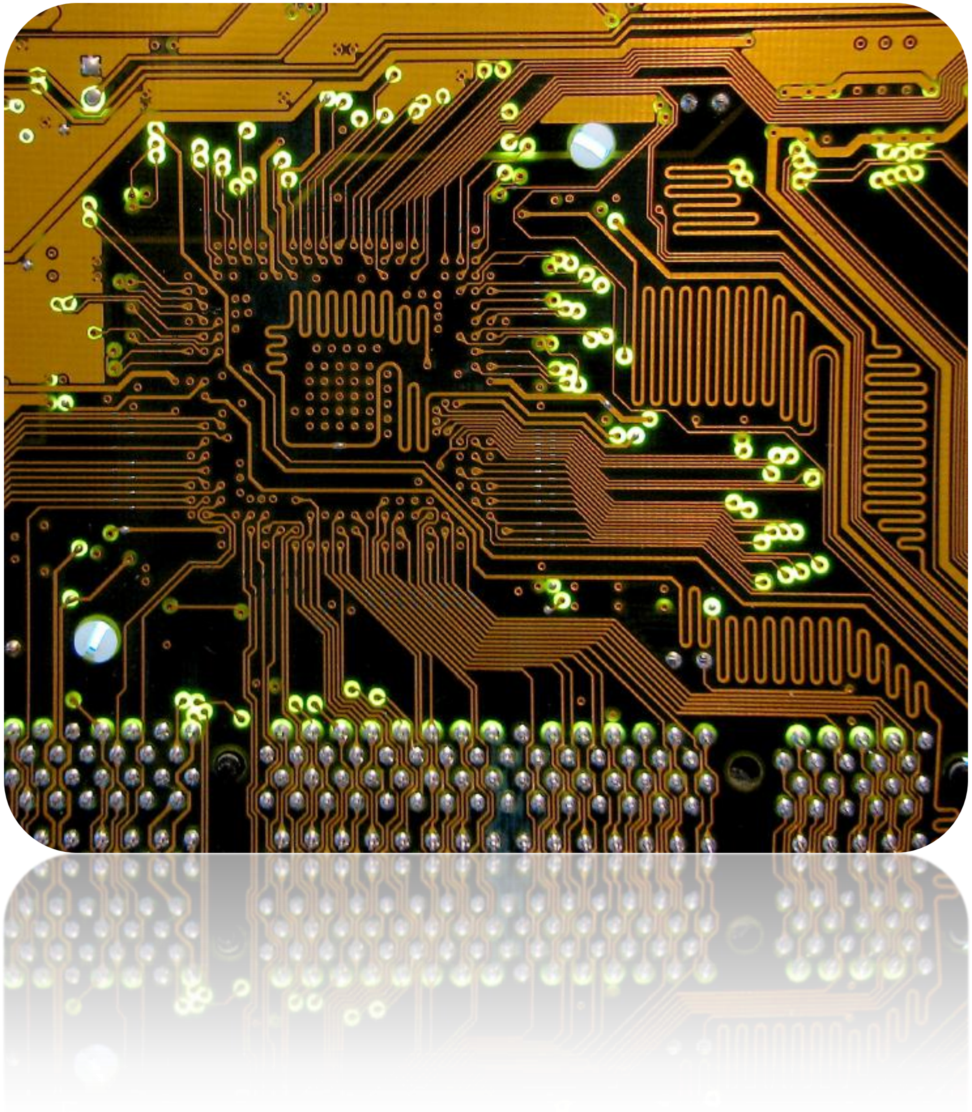
Clemson University

CLEMSON
UNIVERSITY

Recommendations

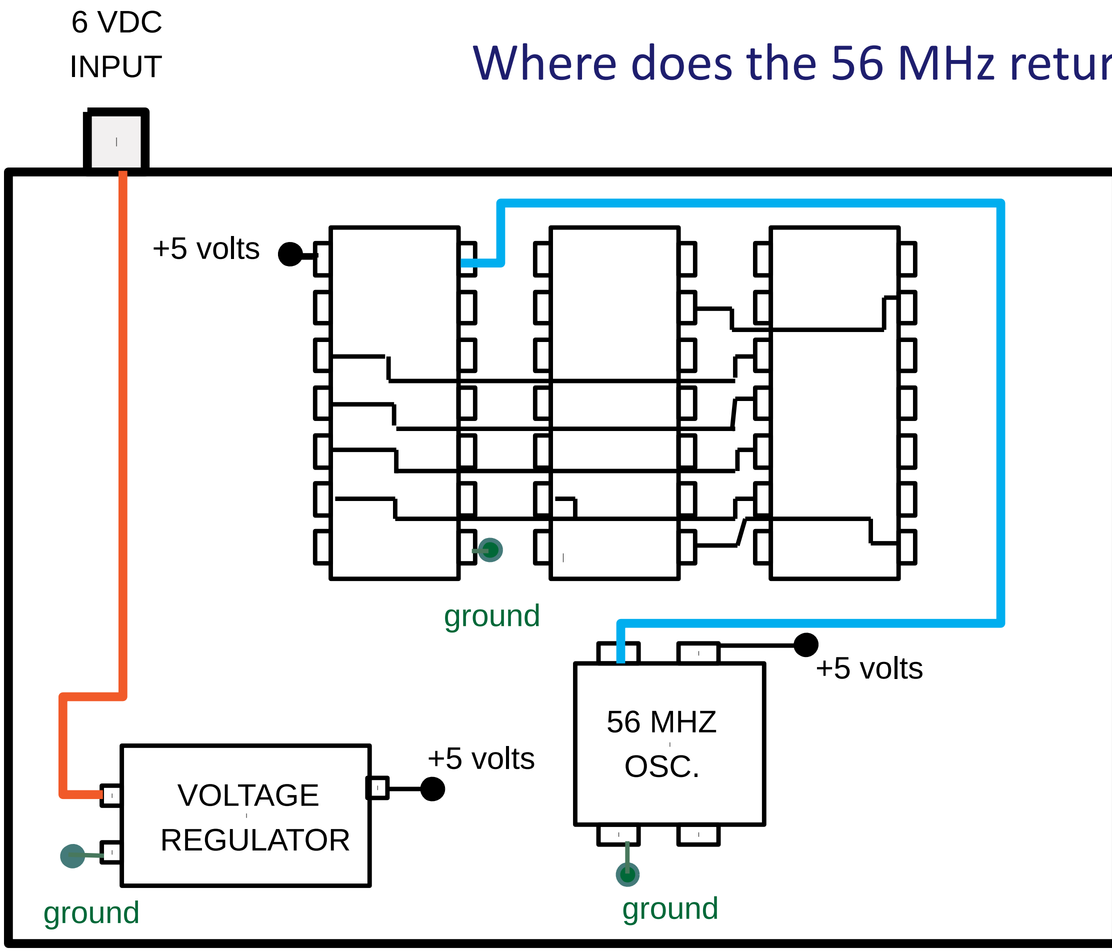
- Don’t rely on EMC Design Guidelines
- Be familiar with currents and current paths
- Learn to recognize good EMI sources
- Learn to recognize good antennas
- Be aware of fundamental EMI radiation mechanisms

Signal Routing and Termination



Identify Current Paths

Where does the 56 MHz return current flow?



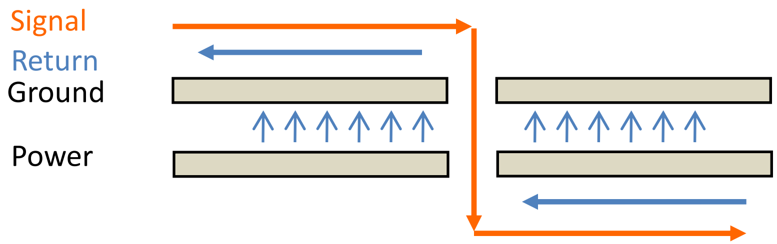
Identify Current Paths

Current takes the path of least impedance!

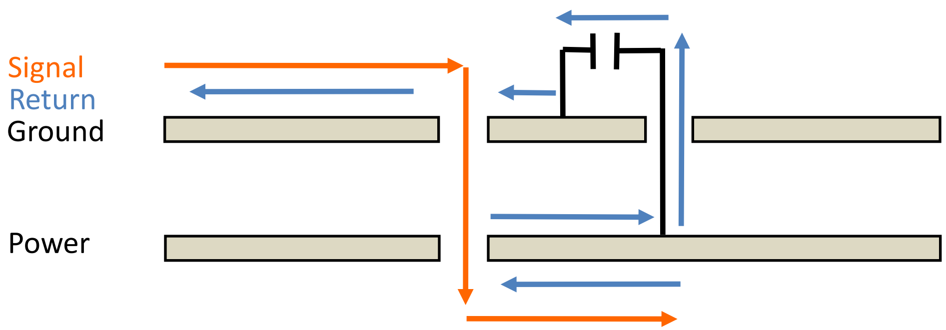
> 100 kHz this is generally the path of least inductance

< 10 kHz this is generally the path(s) of least resistance

Current Paths in traces that pass between plane pairs

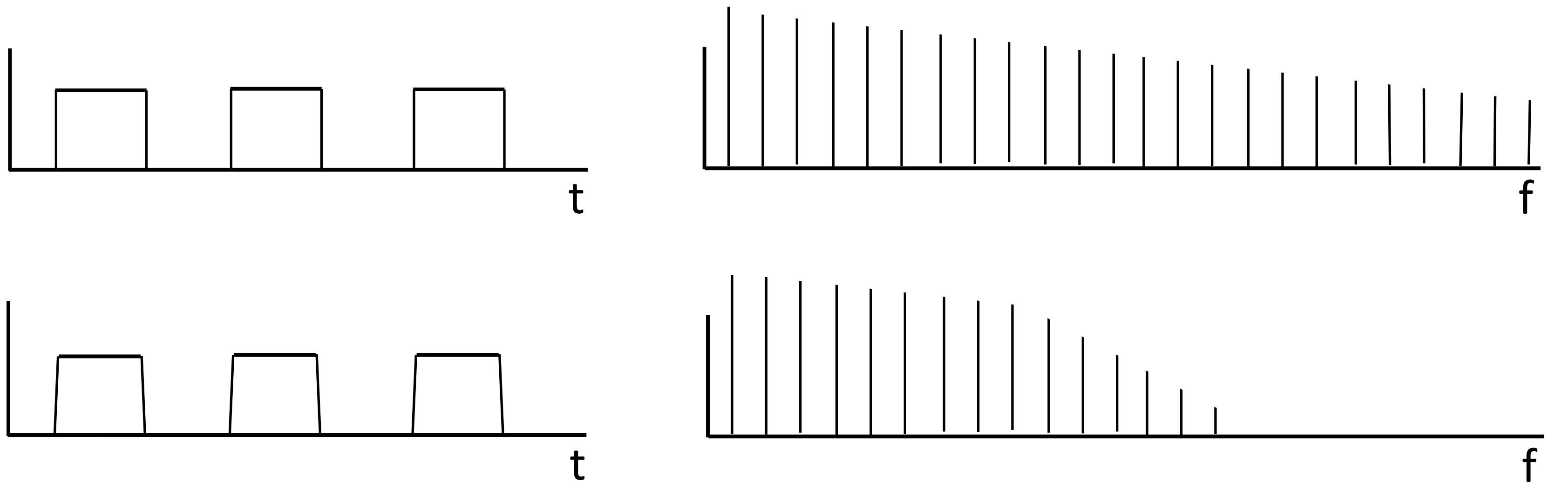


Closely Spaced Planes
(e.g. < 10 mils or 0.25 mm)



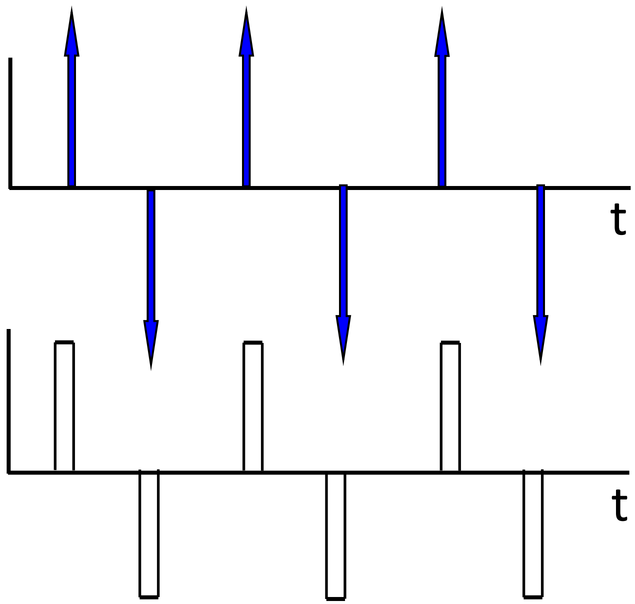
Widely Spaced Planes

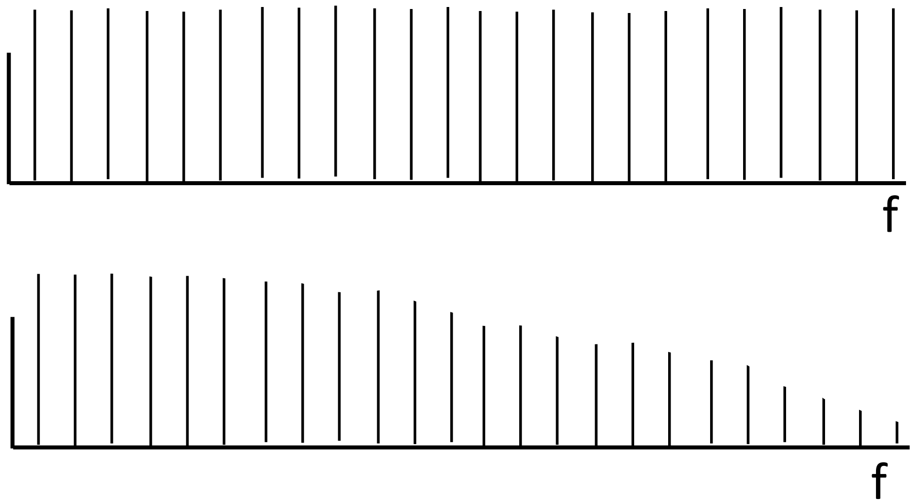
Signal Voltage



Control transition times of digital signals!

Signal Current





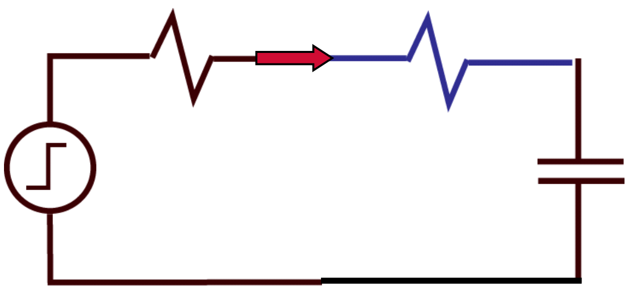
Control transition times of digital signals!

Can use a series resistor or ferrite when load is capacitive.

Use appropriate logic for fast signals with matched loads.

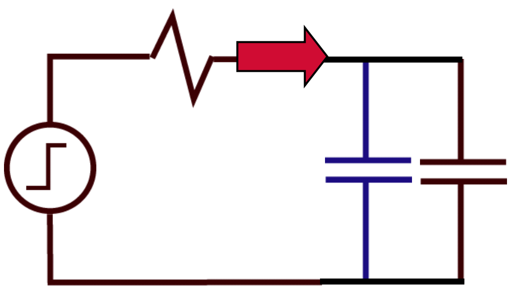
Signal Termination

Reducing risetime with a series resistor



Good idea

Reducing risetime with a parallel capacitor

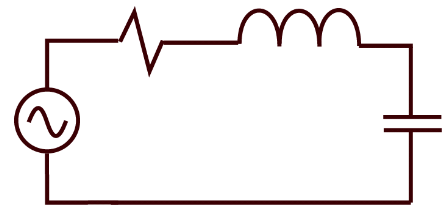


Bad idea

Signal Termination

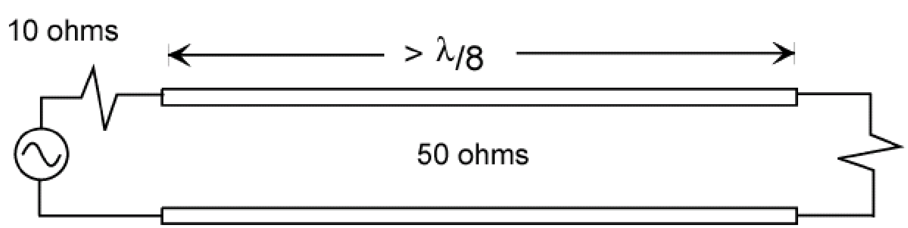
Eliminating ringing with a series resistor

- Electrically small circuits
- Generally caused by too much inductance

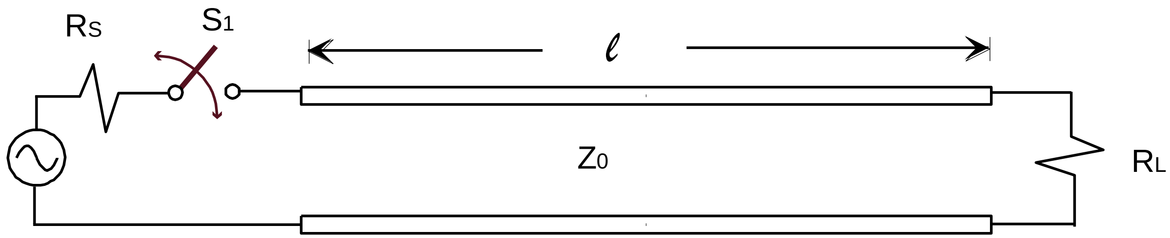


Eliminating ringing due to mismatched transmission lines

- Electrically long circuits (length > risetime * velocity)
- Must match characteristic impedance at load or source end



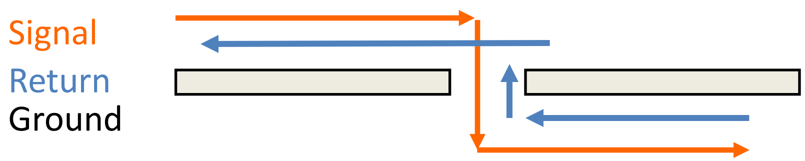
When is a trace or cable a transmission line?



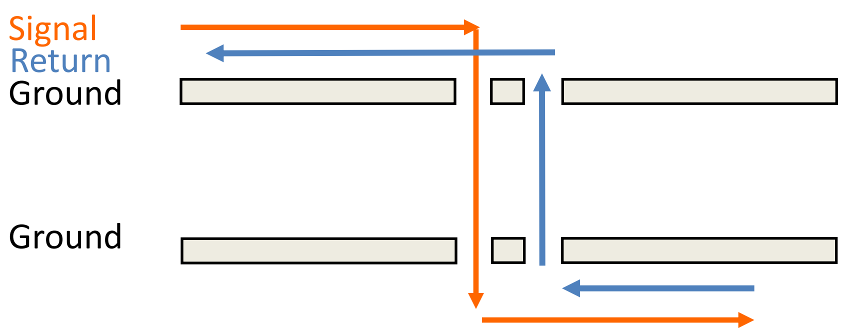
- Steady state solution is always the wire-pair solution
- If we don't care about how we get to the steady state, then we don't need to worry about transmission line solutions.
- In many applications, we don't care!

When Routing Controlled Impedance Traces

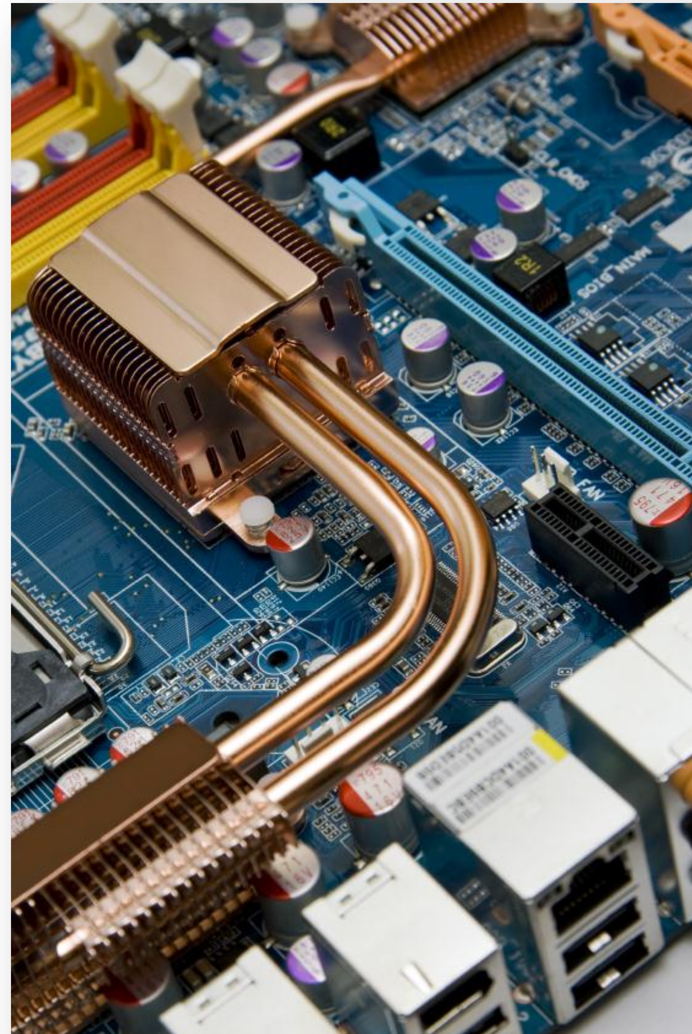
- When routing a trace between layers, route on either side of the same return plane.



- When routing a trace between 2 different planes, use a transfer via near the signal via.

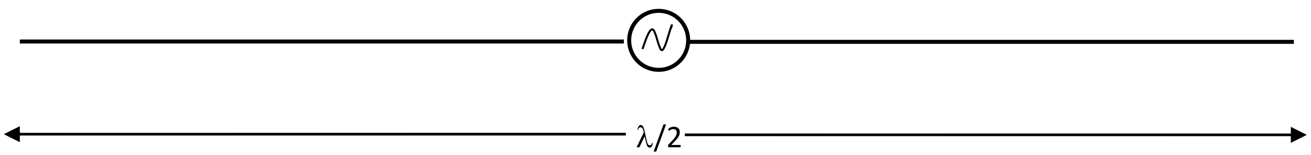


Identifying the Unintentional Antennas on a Circuit Board



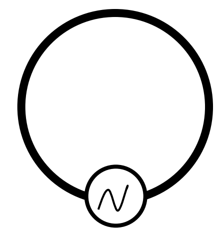
Identifying Antennas

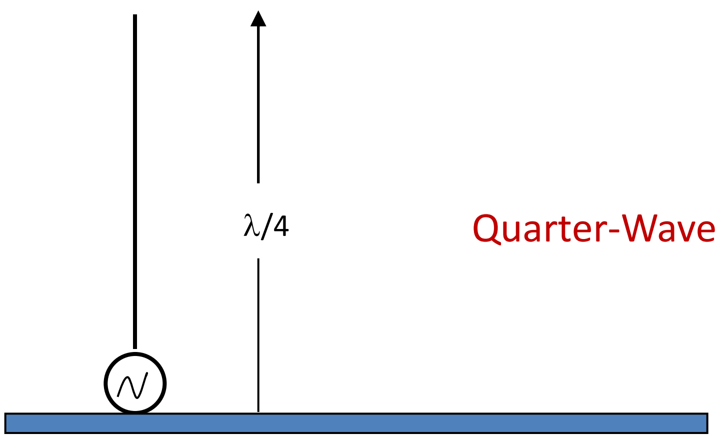
What makes an efficient antenna?



Half-Wave Dipole ↑

Electrically Small Loop ↓





Quarter-Wave Monopole ↑

- **Size**
- **Two Halves**

Identifying Antennas

Good Antenna Parts		Poor Antenna Parts	
<100 MHz	>100 MHz	<100 MHz	>100 MHz
Cables	Heatsinks	Microstrip or stripline traces	Microstrip or stripline traces
	Power planes		
	Tall components	Anything that is not big	
	Seams in shielding enclosures		

Free-space wavelength at 100 MHz is 3 meters

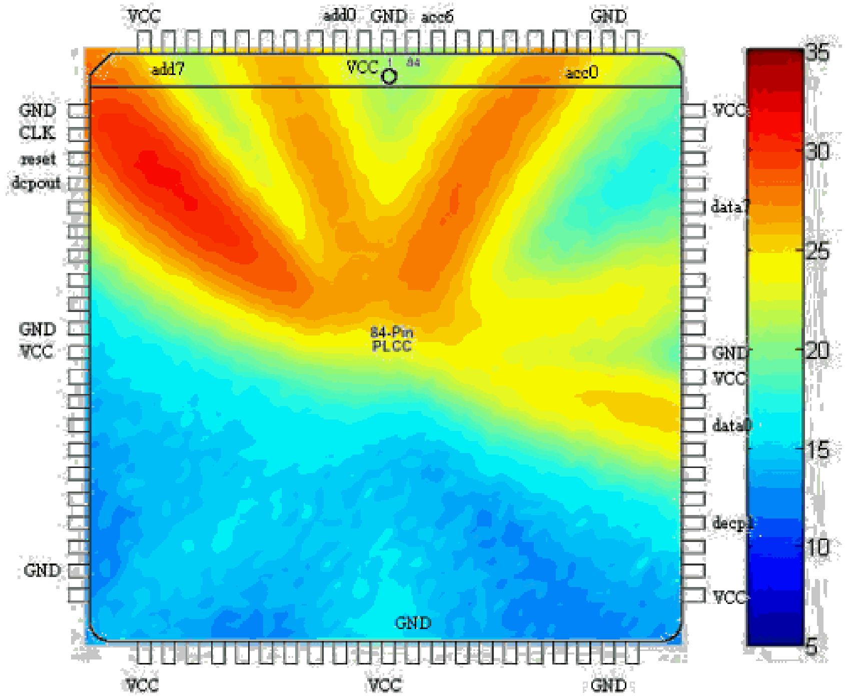
Noise Sources and Coupling Mechanisms

Identifying Sources (Diagnostics)

Clocks	Narrow band, consistent
Digital Data	Not as narrow as clocks, but clock frequency is usually identifiable.
Analog signals	Bandwidth determined by signal source, consistent
Power supply switching	Appears broadband, but harmonics of switching frequency can be identified, consistent
Arcing	Broadband, intermittent
Parasitic oscillations	Narrowband, possibly intermittent

Identifying Sources

Noise on the low-speed I/O



For some ICs, significant high-frequency currents appear on low-speed I/O including outputs that never change state during normal operation!

Recognizing Coupling Mechanisms

Noise can be coupled from a source to an antenna by one or more of three different coupling mechanisms:

Conducted

Electric field coupled

Magnetic field coupled

For printed circuit board analysis and design, it is convenient to express these coupling mechanisms in terms of voltage and current.

Recognizing Coupling Mechanisms

Voltage Driven

Signal or component voltage appears between two good antenna parts.

Example:

$$V_s = 1 volt @ 500 MHz$$

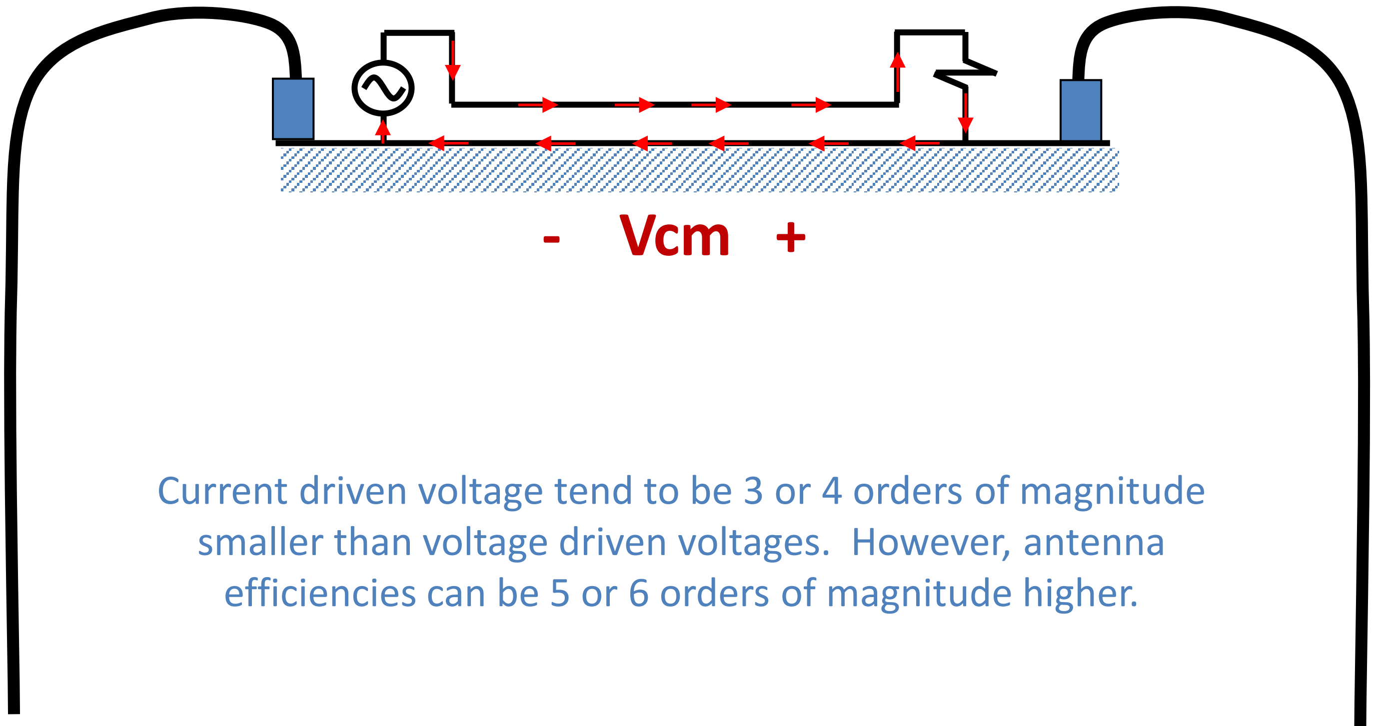
$$E_{rad} \approx 360 mV / m @ 3 meters$$

More than 60 dB above the FCC Class B limit!

Recognizing Coupling Mechanisms

Current Driven

Signal current loop induces a voltage between two good antenna parts.

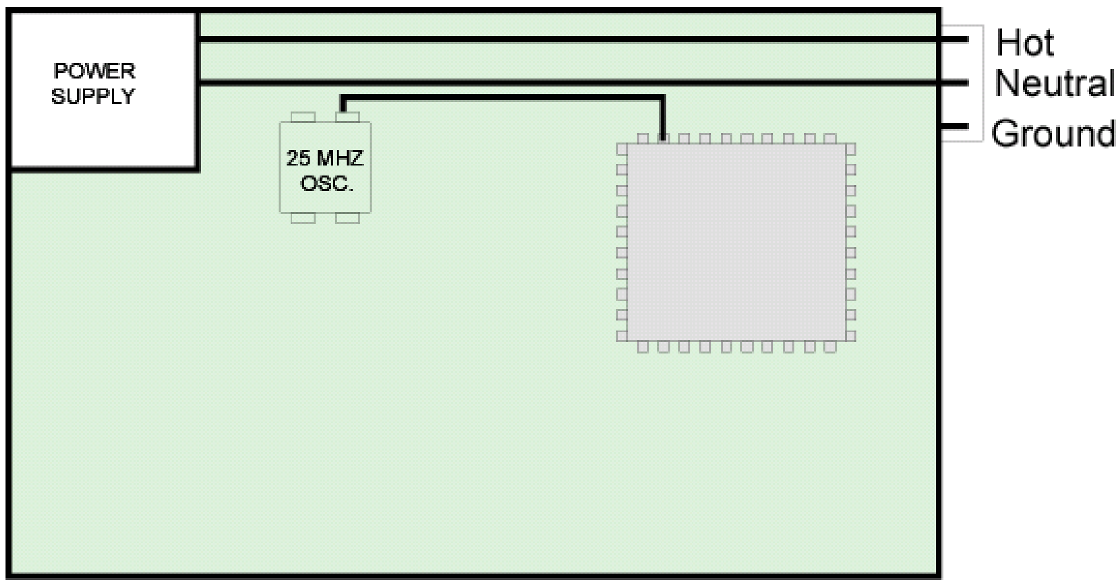


Current driven voltage tend to be 3 or 4 orders of magnitude smaller than voltage driven voltages. However, antenna efficiencies can be 5 or 6 orders of magnitude higher.

Recognizing Coupling Mechanisms

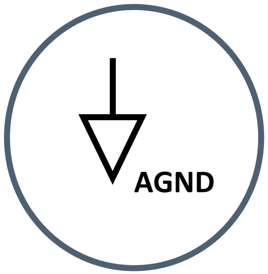
Direct coupling to I/O

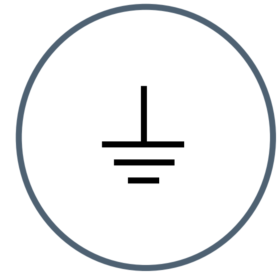
Signals coupled to I/O lines carry HF power off the board.



Grounding
for Mixed Signal PCBs

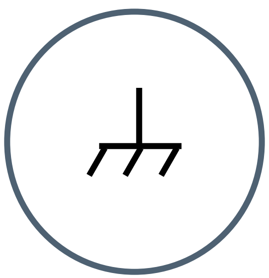
Ground vs. Signal Return

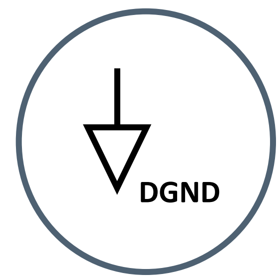




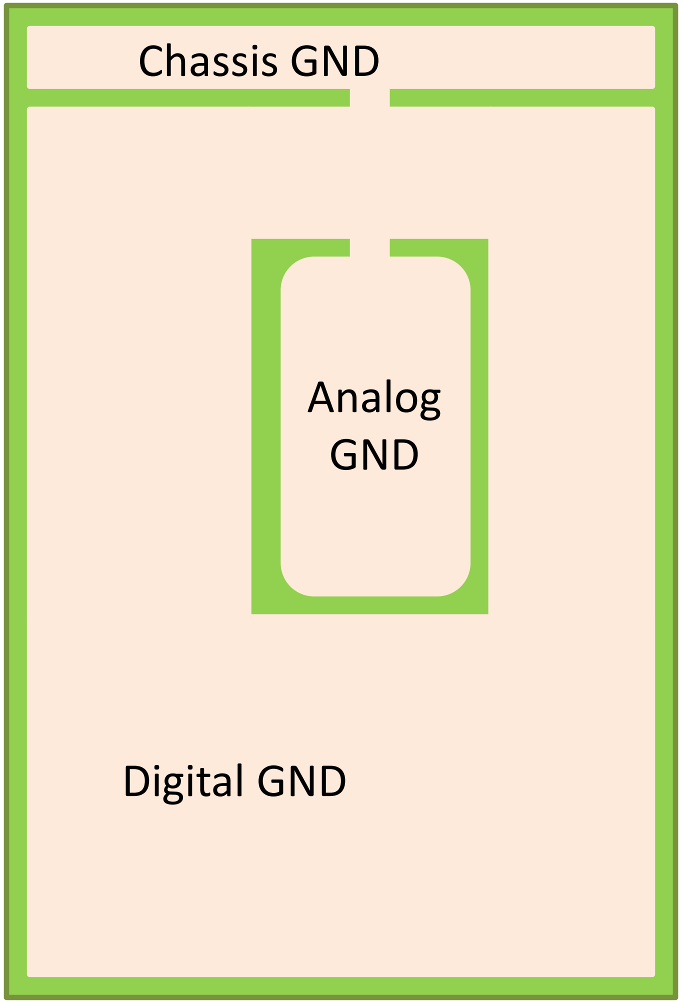
"Whenever I see more than one of these symbols on the schematic, I know there is [EMC] work for us here."

T. Van Doren



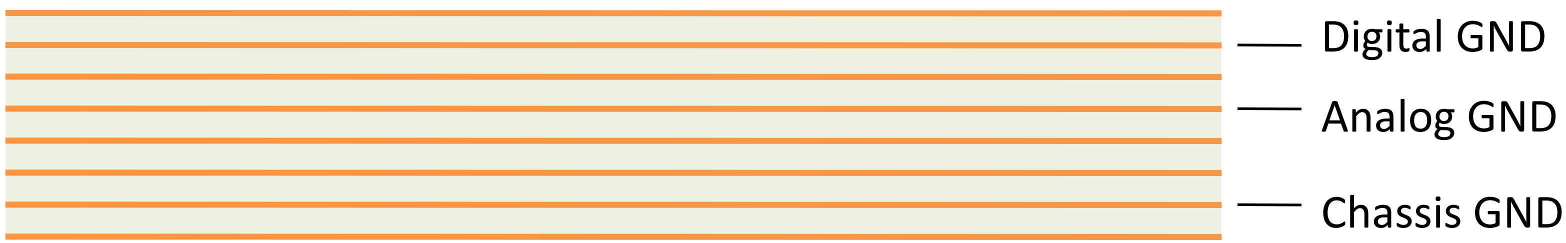


Lateral Isolation



- Rarely appropriate
- Often the source of significant problems

Vertical Isolation



- Only one plane usually needs to be full size.
- One or zero vias should connect planes with different labels.

Key Questions

- Why do I need more than one ground?
- Where does each ground need to be?
- How do I connect the grounds?

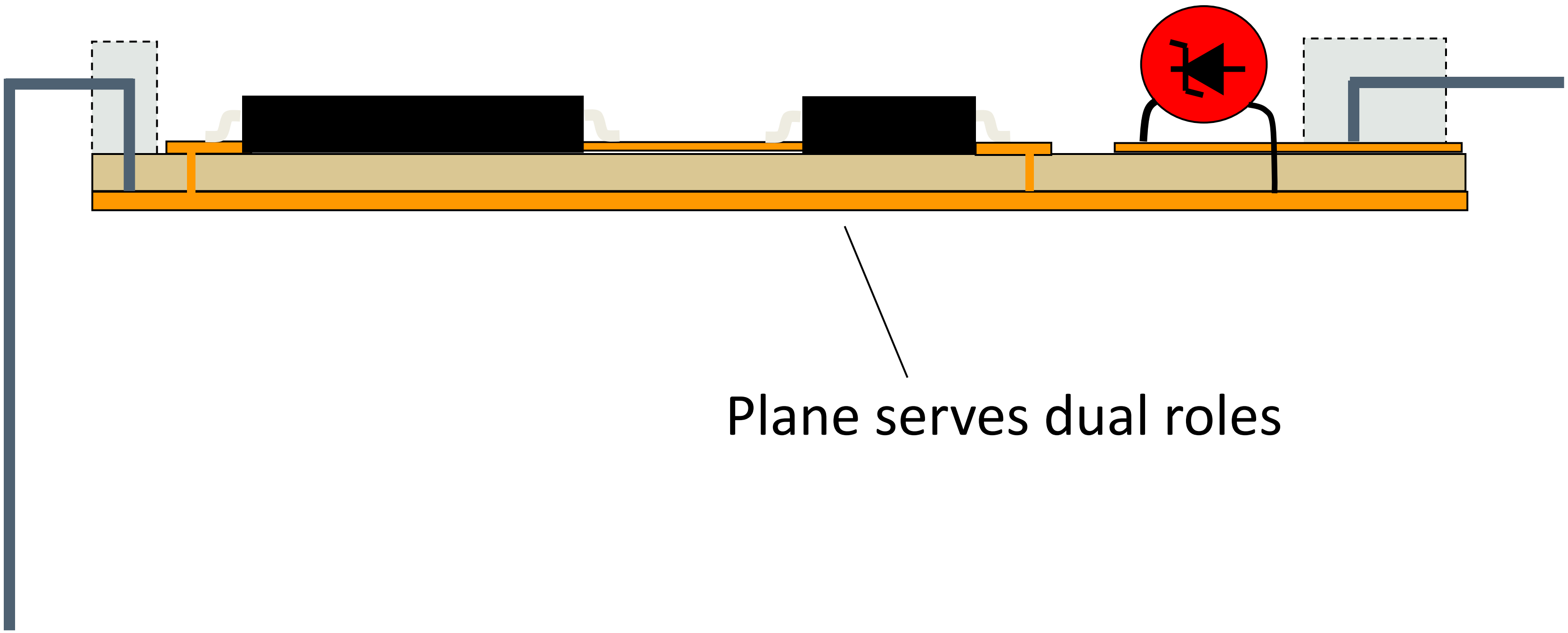
Ground vs. Signal Return

The purpose of a system ground is to provide a reference voltage and/or a safe path for fault currents.

Signal currents flowing on a “ground” conductor can prevent a ground conductor from serving its intended purpose.

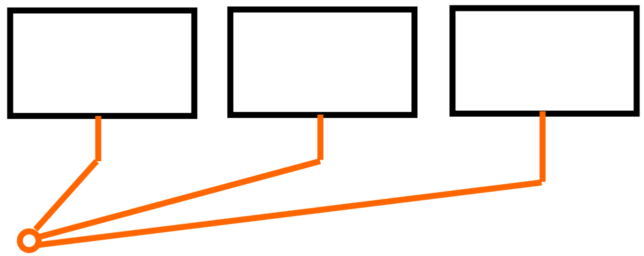
Don’t confuse ground conductors with signal return conductors. Rules for the routing of “ground” may conflict with the rules for routing signal or power returns.

Ground vs. Signal Return

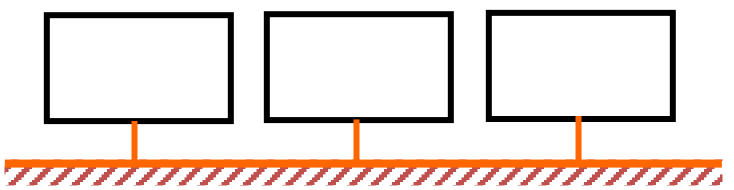


Plane serves dual roles

Confusing Concept



Single-Point Ground



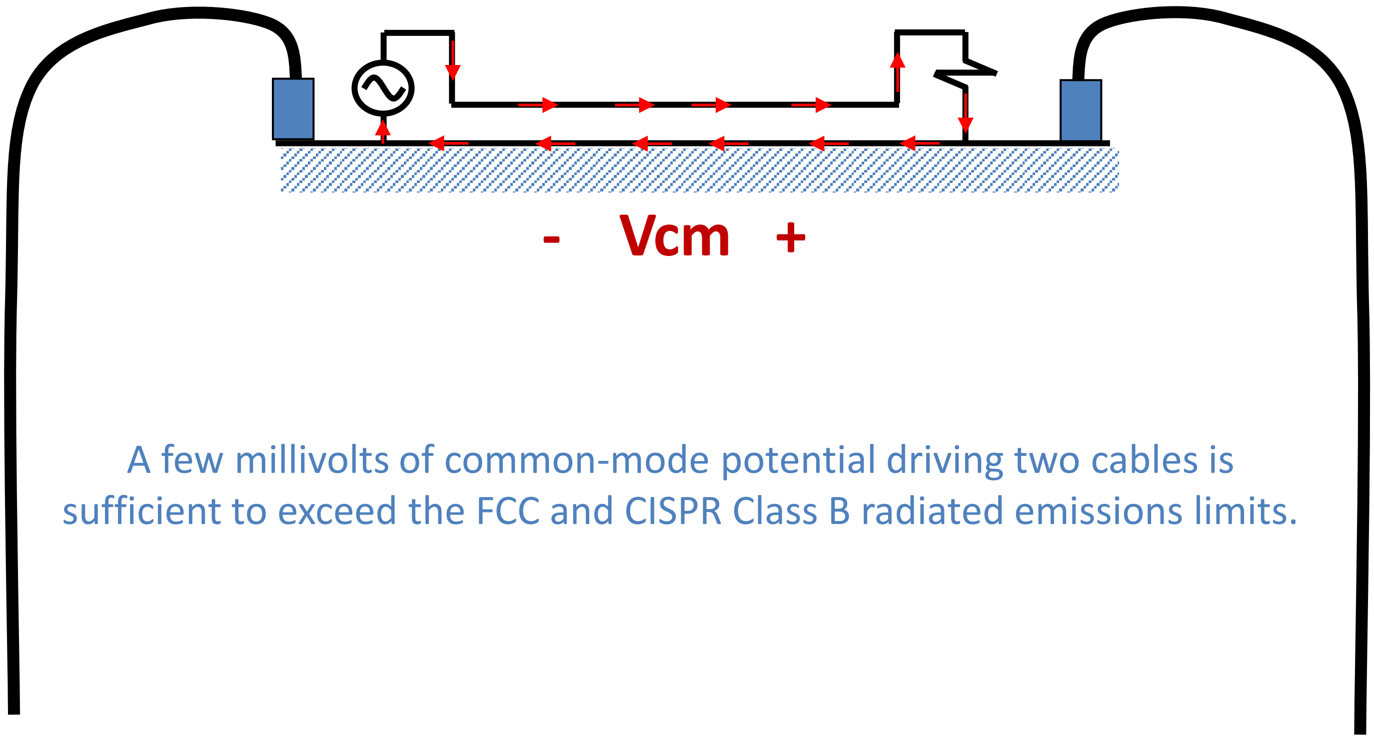
Multi-Point Ground

These are grounding strategies, not signal return strategies!

Important Concept

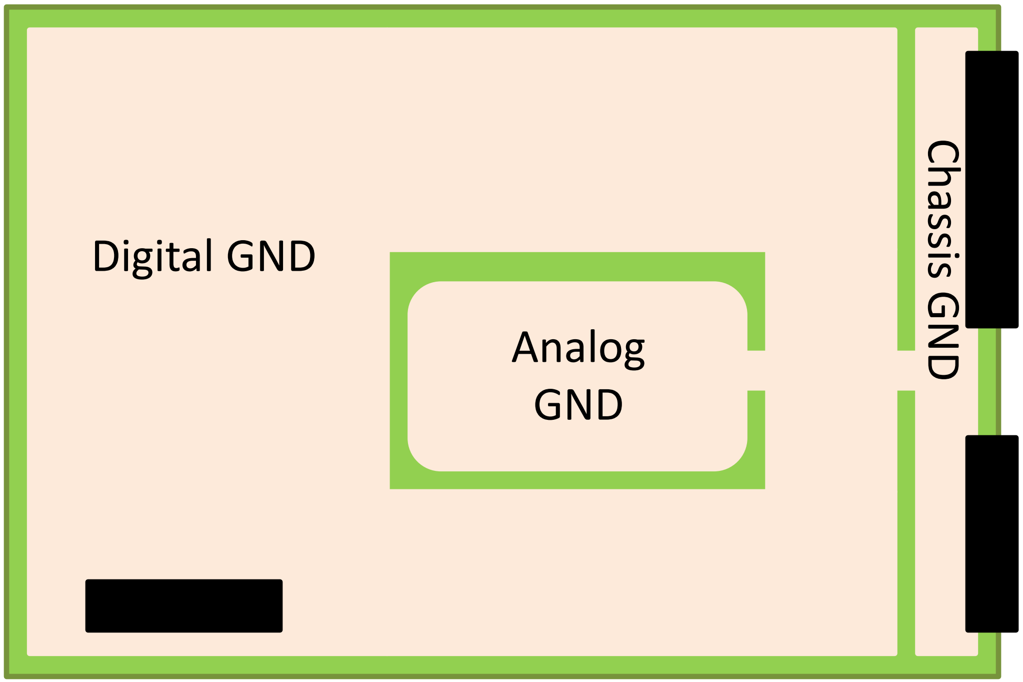
Current Driven Radiation Mechanism

Signal current loop induces a voltage between two good antenna parts.



A few millivolts of common-mode potential driving two cables is sufficient to exceed the FCC and CISPR Class B radiated emissions limits.

How Much Isolation Can We Tolerate?



Ground vs. Signal Return

Circuit boards should have 1 high-frequency ground!

Why?

Conductors referenced to different grounds can be good antennas.

Signals referenced to two different grounds will be noisy (i.e. include the noise voltage between the two grounds).

Layouts with more than one ground are more difficult, require more space and present more opportunities for critical mistakes.

Excuses for employing more than one ground are generally based on inaccurate or out-dated information.

Ground vs. Signal Return

If grounds are divided, it is generally to control the flow of low-frequency (<100 kHz) currents.

For example,

Isolating battery negative (i.e. chassis ground) from digital ground

Isolating digital ground from analog ground in audio circuits.

This can be necessary at times to prevent common impedance coupling between circuits with low-frequency high-current signals and other sensitive electronic circuits.

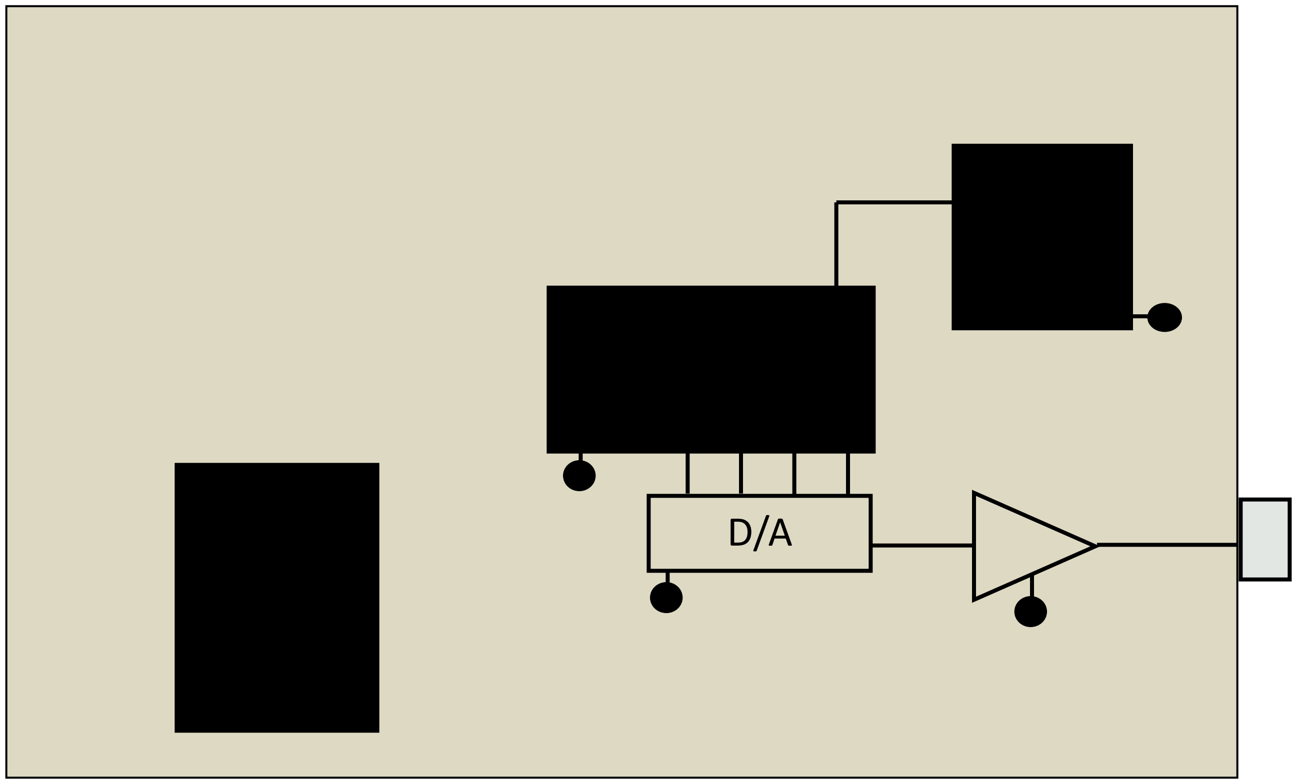
HOWEVER, it is still necessary to ensure that there is only

1 (ONE)

high-frequency ground.

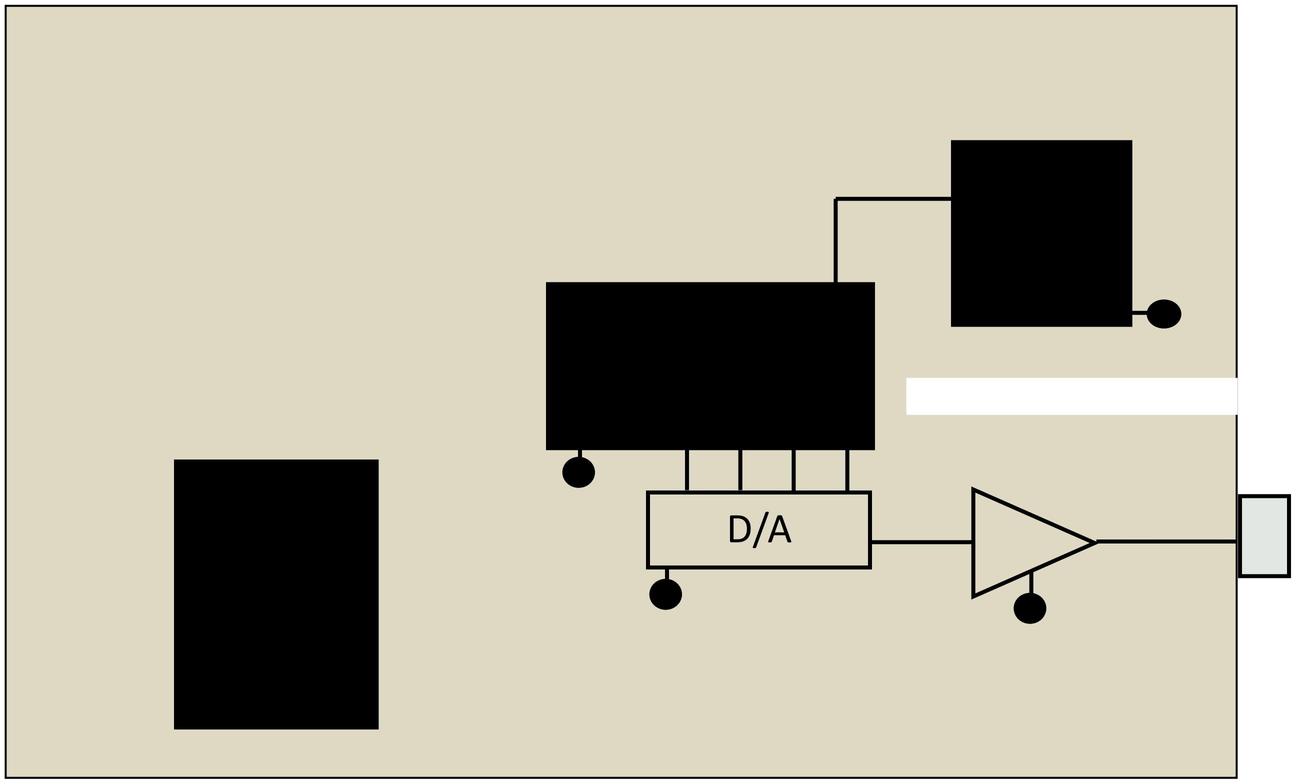
Ground vs. Signal Return

Exercise: Trace the path of the digital and analog return currents.



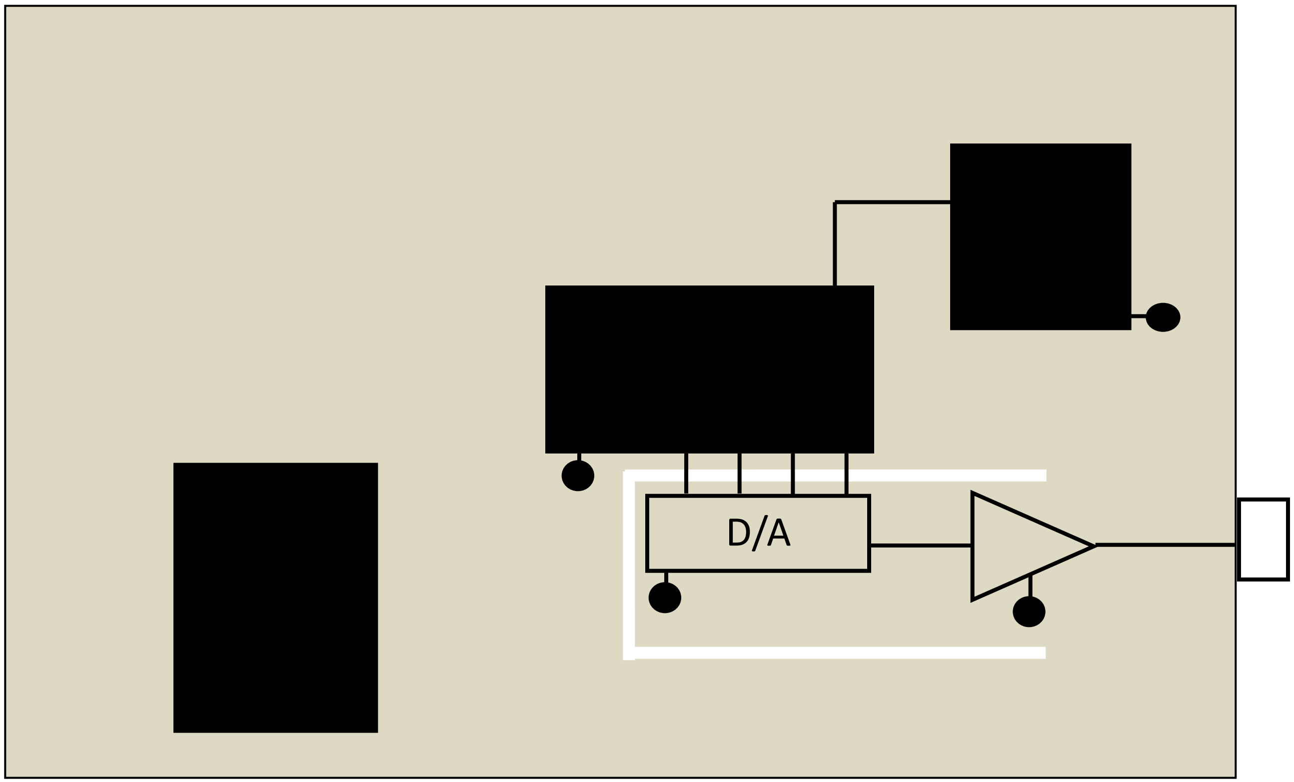
Ground vs. Signal Return

Exercise: Trace the path of the digital and analog return currents.



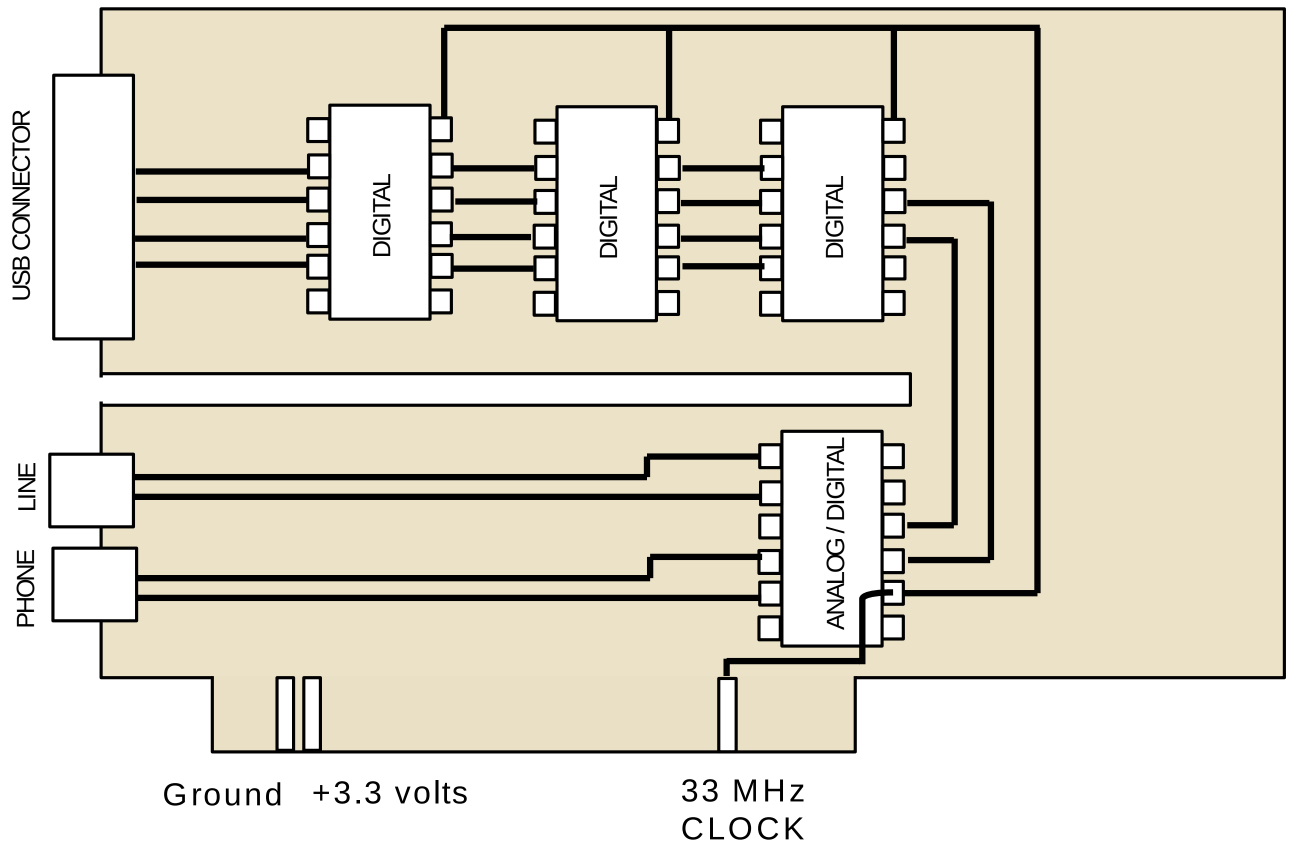
Ground vs. Signal Return

Exercise: Trace the path of the digital and analog return currents.



Ground vs. Signal Return

Design Exercise: What is wrong with this design and how would you improve it?



Ground vs. Signal Return

You don’t need to gap a plane to control the flow of high frequency (>1MHz) currents. If you provide a low-inductance path for these currents to take, they will confine themselves to this path very well.

Ground vs. Signal Return

Rules for gapping a ground plane:

1. Don't do it!
2. If you must do it, never ever allow a trace or another plane to cross over the gap.
3. If you must do it, never ever place a gap between two connectors.
4. Remember that the conductors on either side of the gap are at different potentials.
5. See Rule #1!

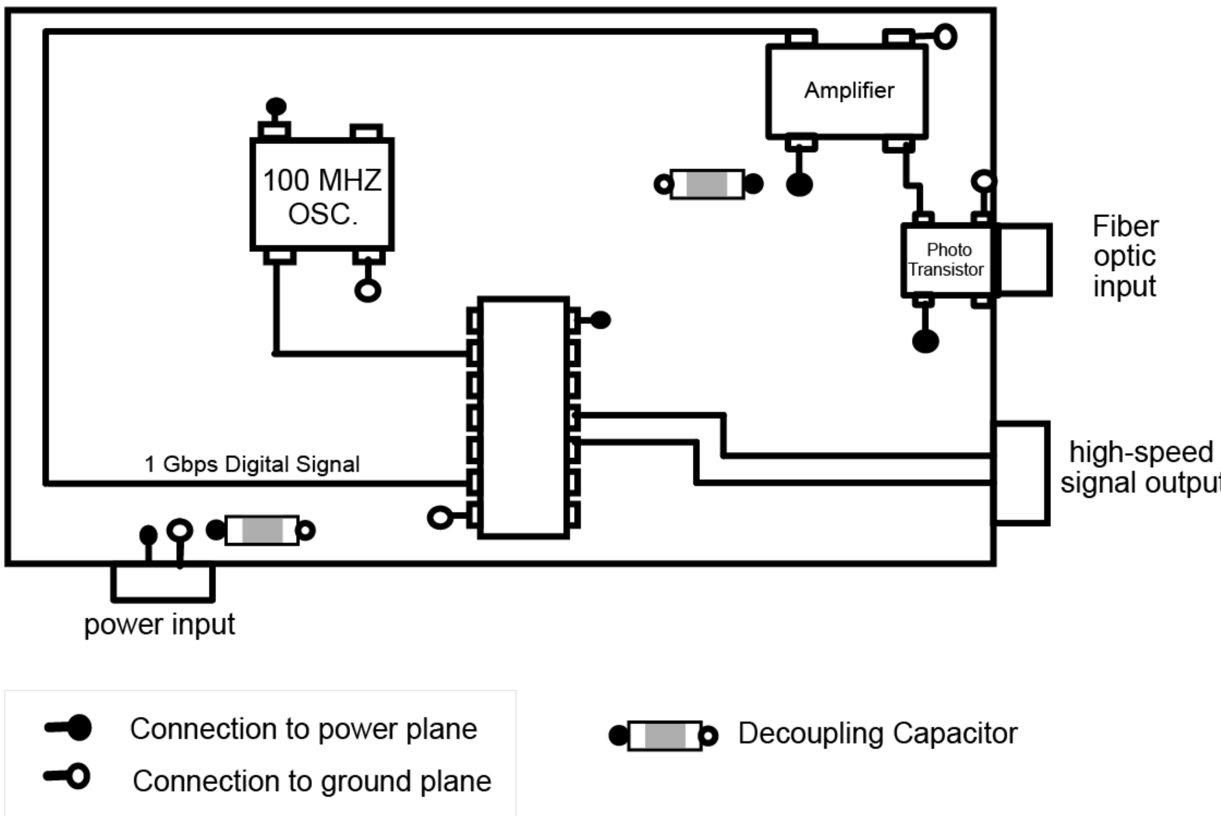
Mixed-Signal Designs

If you have analog and digital returns that must be isolated (to prevent common-impedance coupling):

- Route the returns on separate conductors
- Provide a DC connection at the one point (or in the one area) where the reference potential must be the same.
- This must include every place where a trace crosses the boundary between the analog and digital regions.

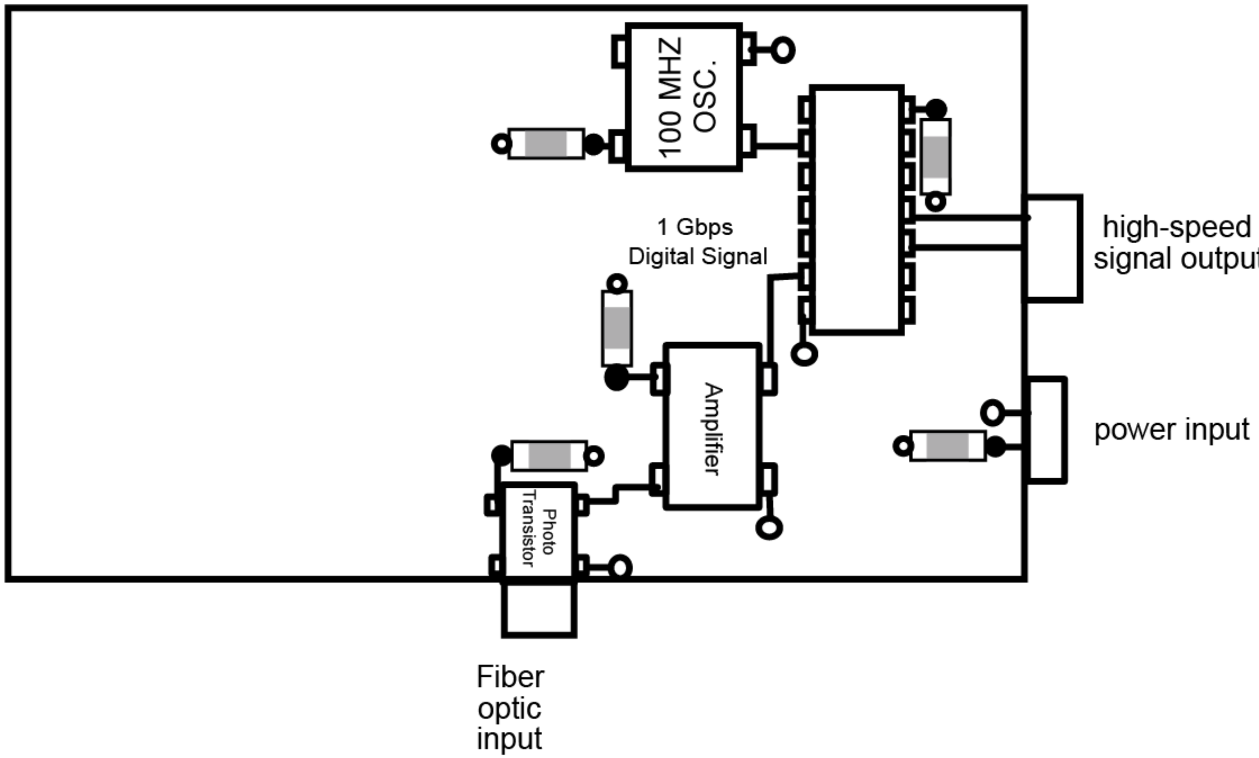
Mixed-Signal Designs

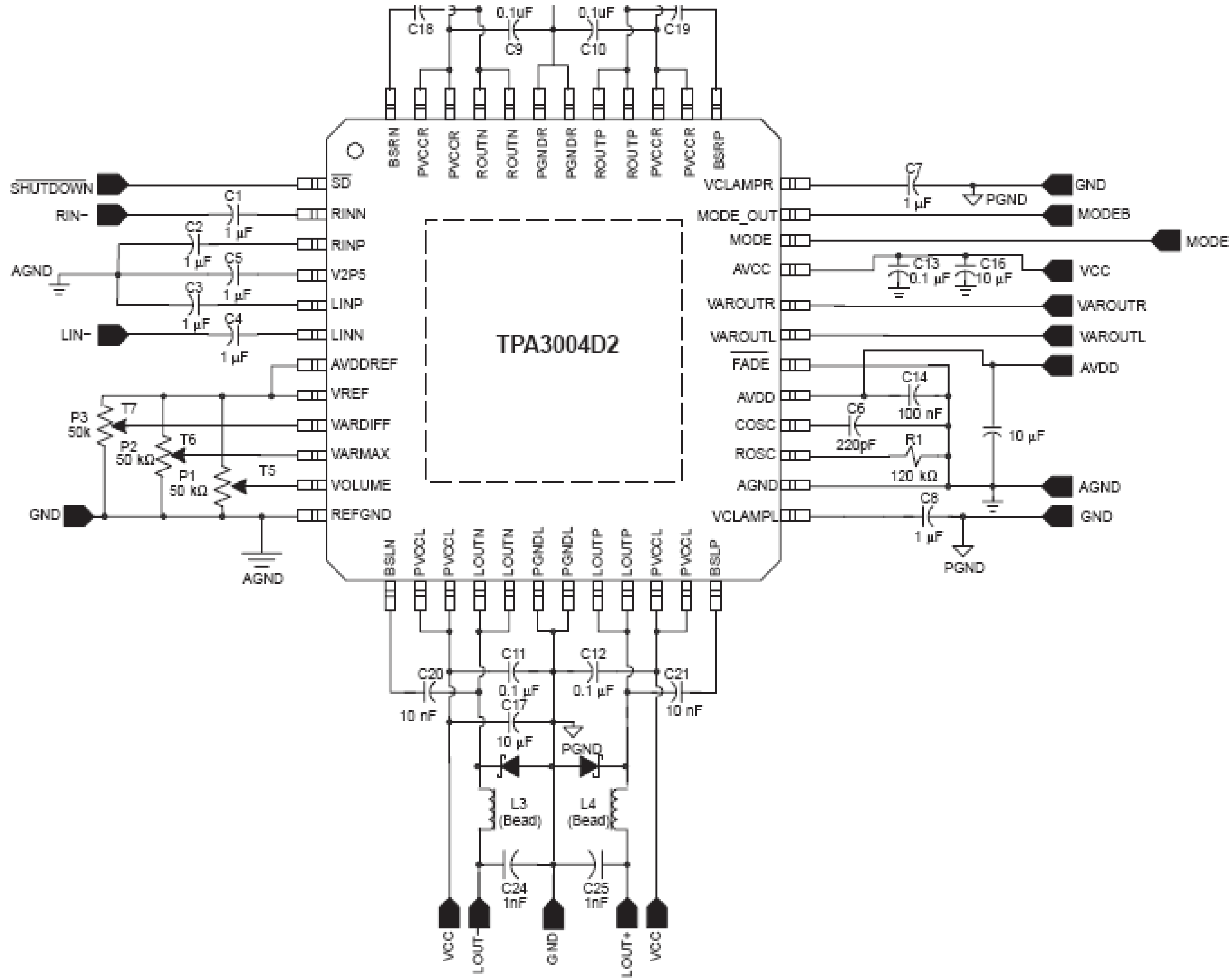
Example: How would you modify this design?



Mixed-Signal Designs

Example: A much better design

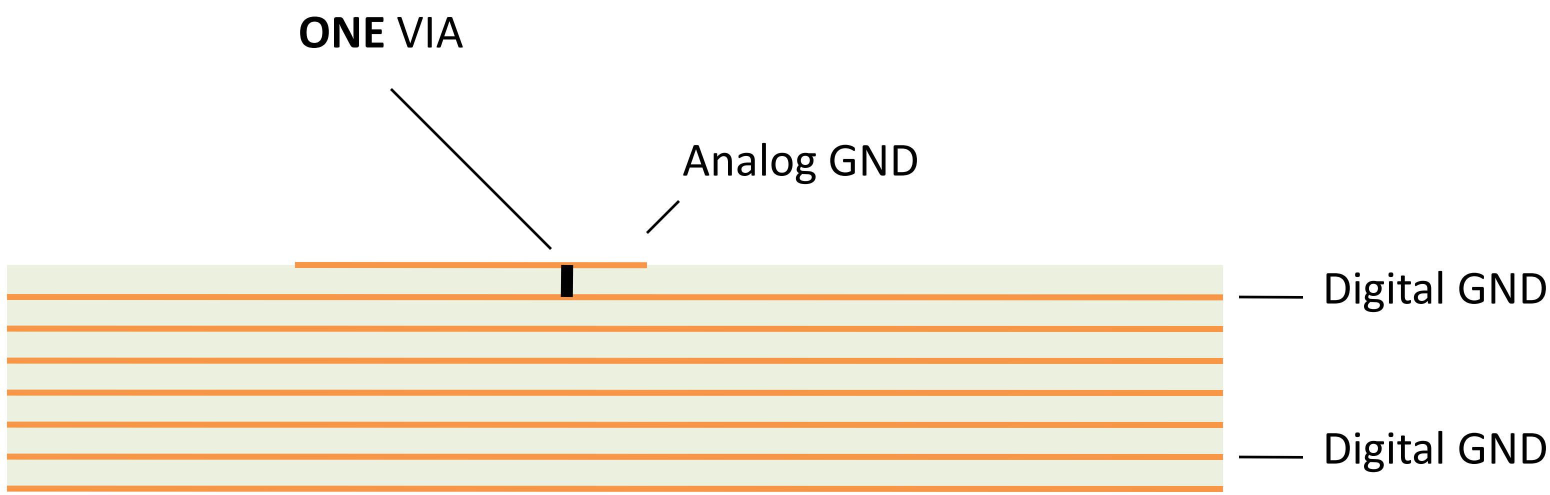




†Schottky diodes only needed for short circuit protection when $V_{CC} > 15$ V. See SHORT CIRCUIT PROTECTION section in Application Information.

Figure 35. Stereo Class-D With Single-Ended Inputs

Sensitive A/D Isolation



If you think you need two vias, then you shouldn't be isolating the analog and digital grounds.

Provide a good HF chassis ground at connector

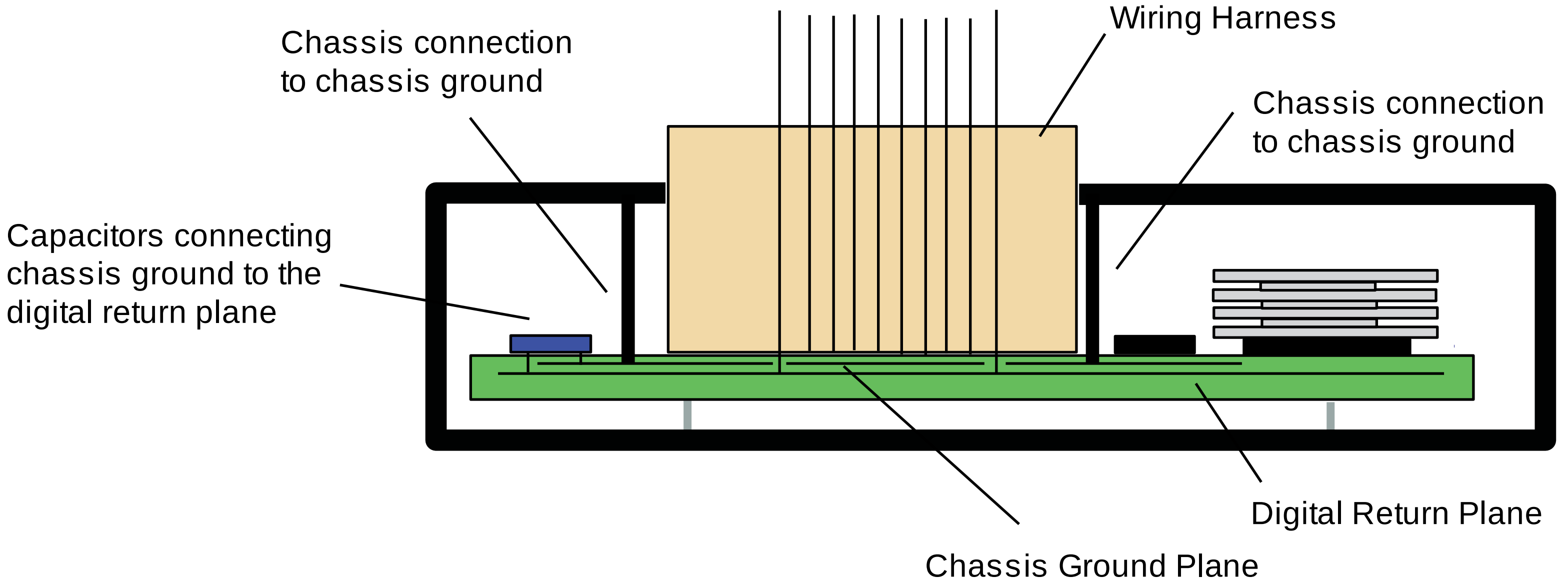
Cables and enclosures are both good antenna parts. If they are not held to the same potential, they are likely to create a radiation problem.

Exceptions:

- When there is no chassis ground
- When there are no connectors with cables

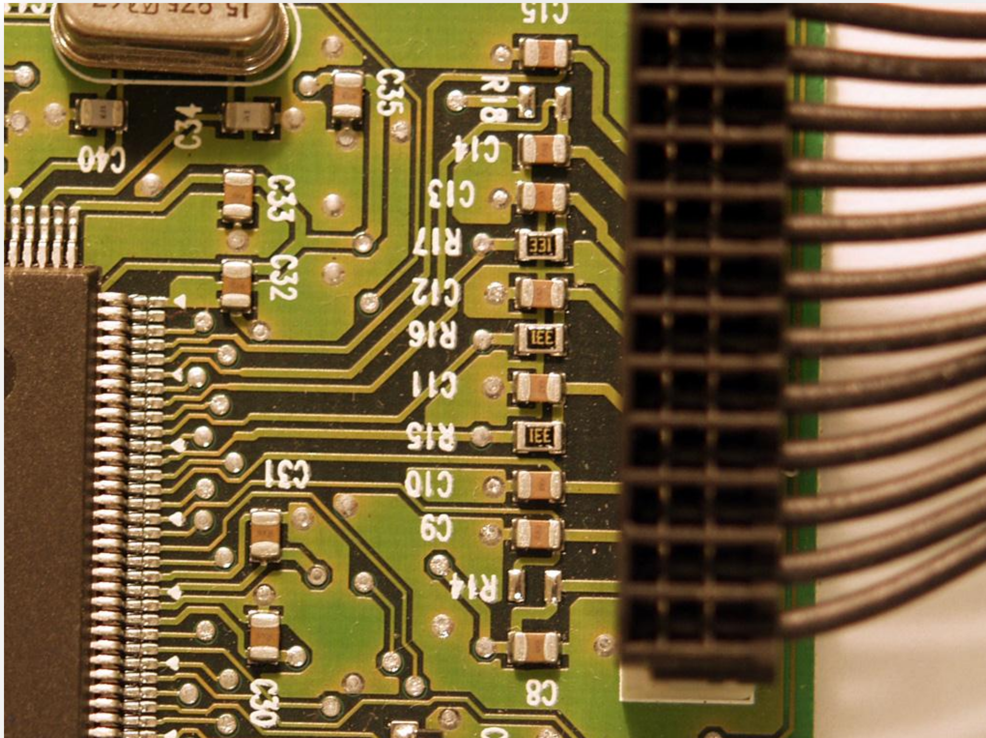
Note: Sometimes low-frequency isolation between chassis and digital ground is necessary control the flow of low-frequency currents. However, even in these situations it is usually important to provide a good high-frequency connection.

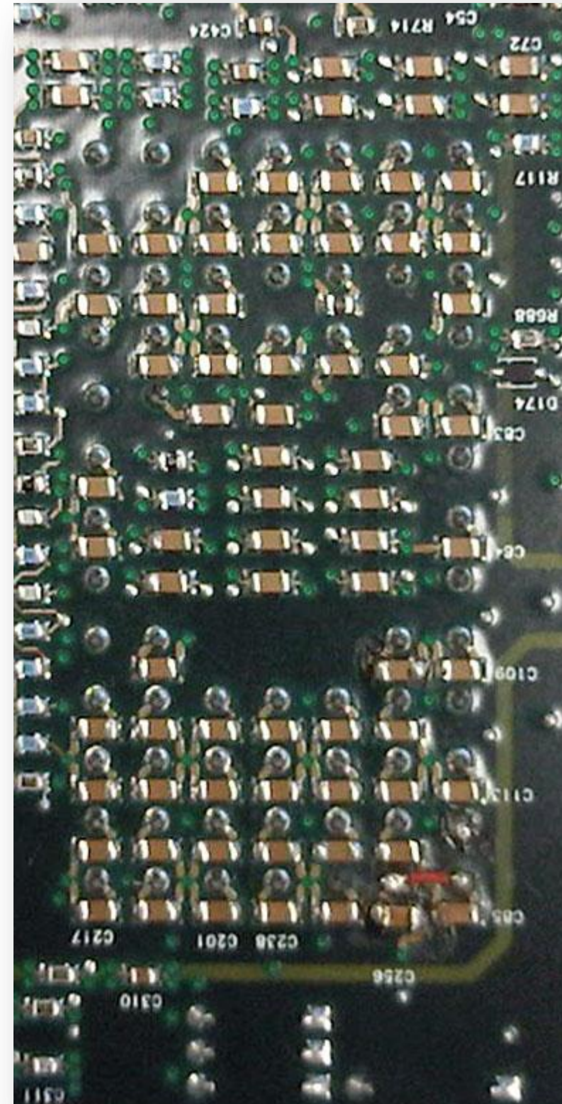
Isolating Chassis and Digital Grounds



Capacitors from I/O to Chassis

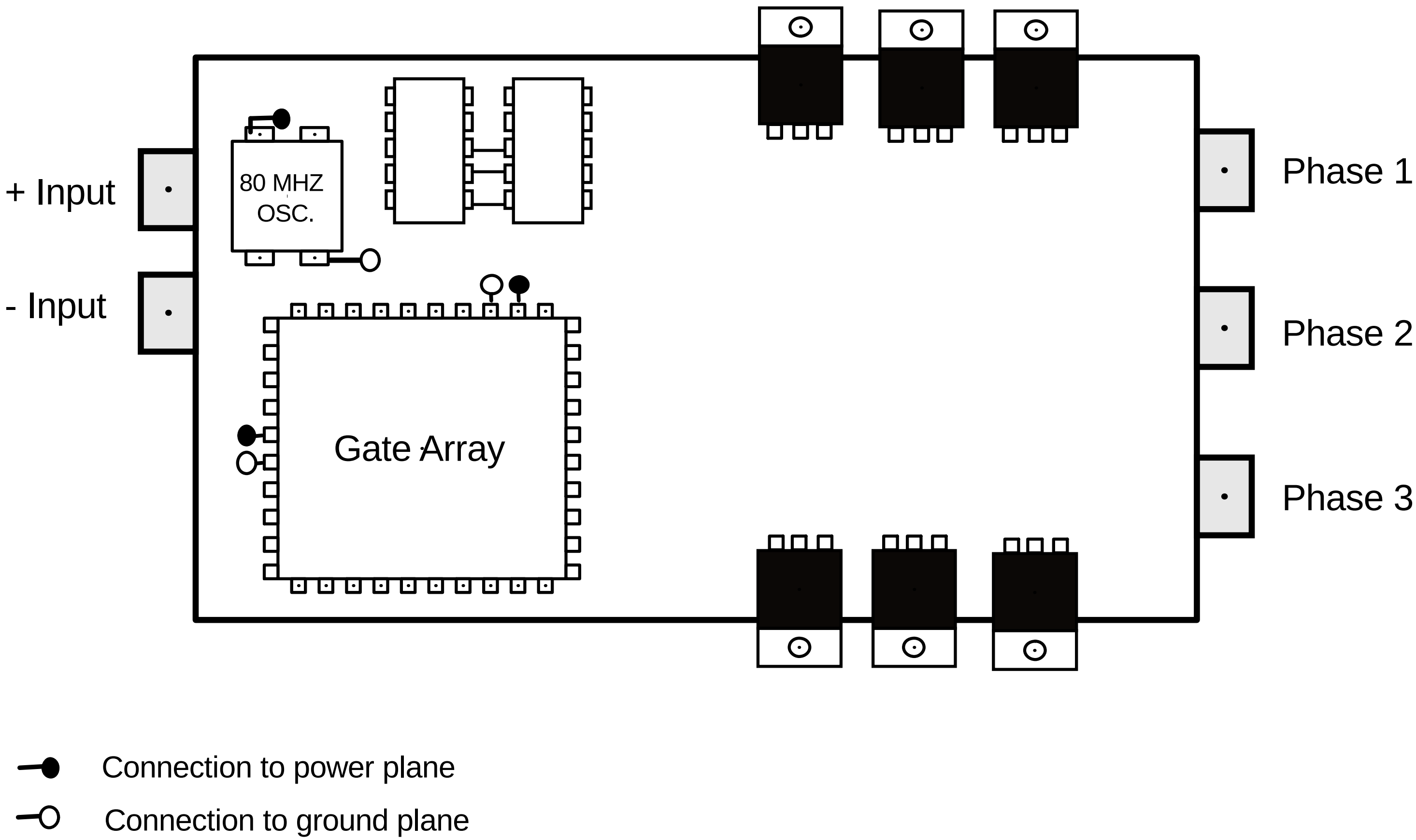
Caps with traces



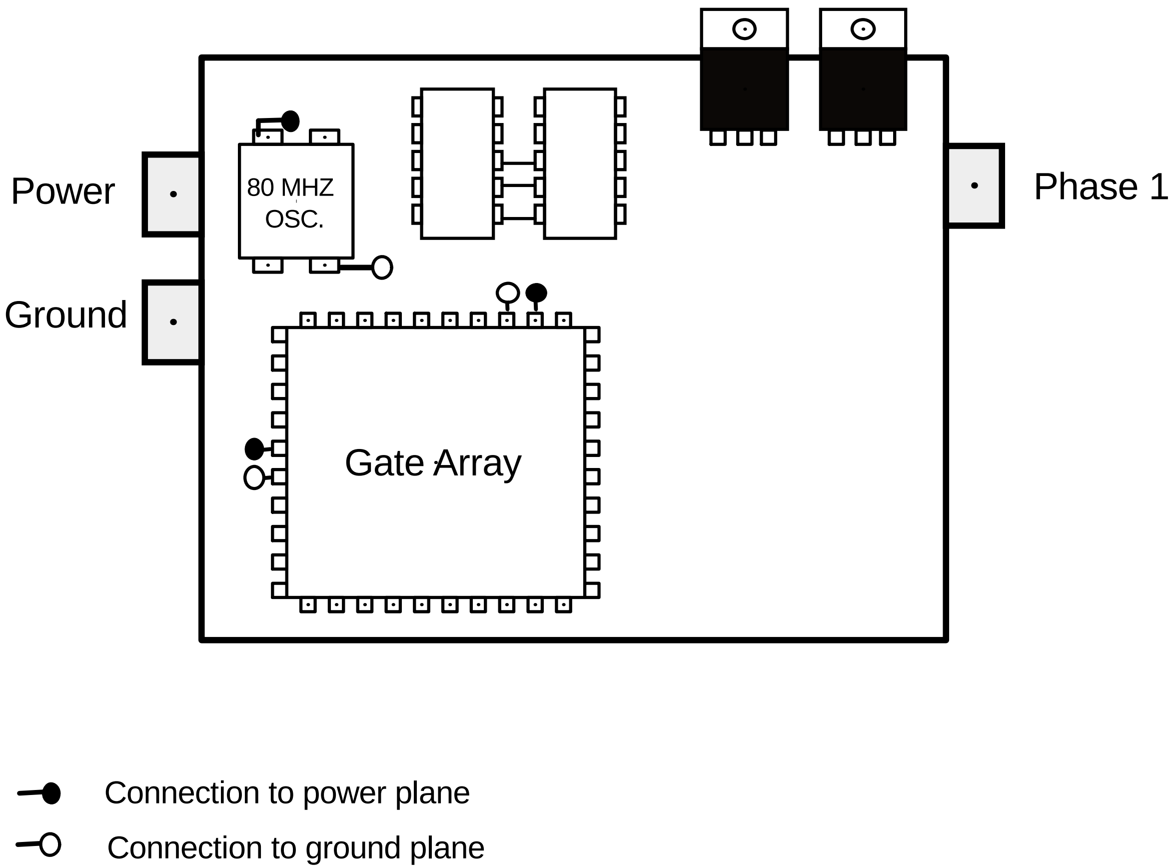


Better implementation

Design Example



Design Example



Key Points

- Identify your HF ground and be sure it is the only ground that is large or connected to anything large!

- Don’t call anything other current carrying nets “ground”. For example, refer to a current carrying analog reference net as “analog return”.

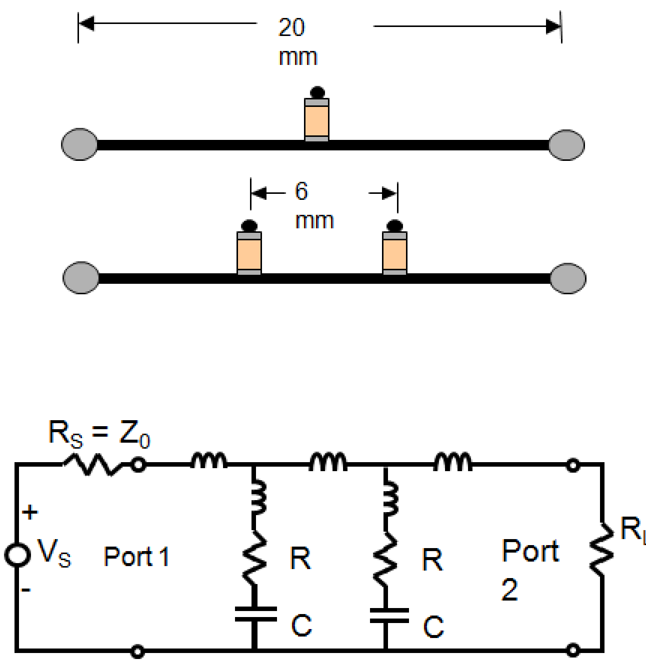
- Be aware of where your HF and LF currents are flowing!

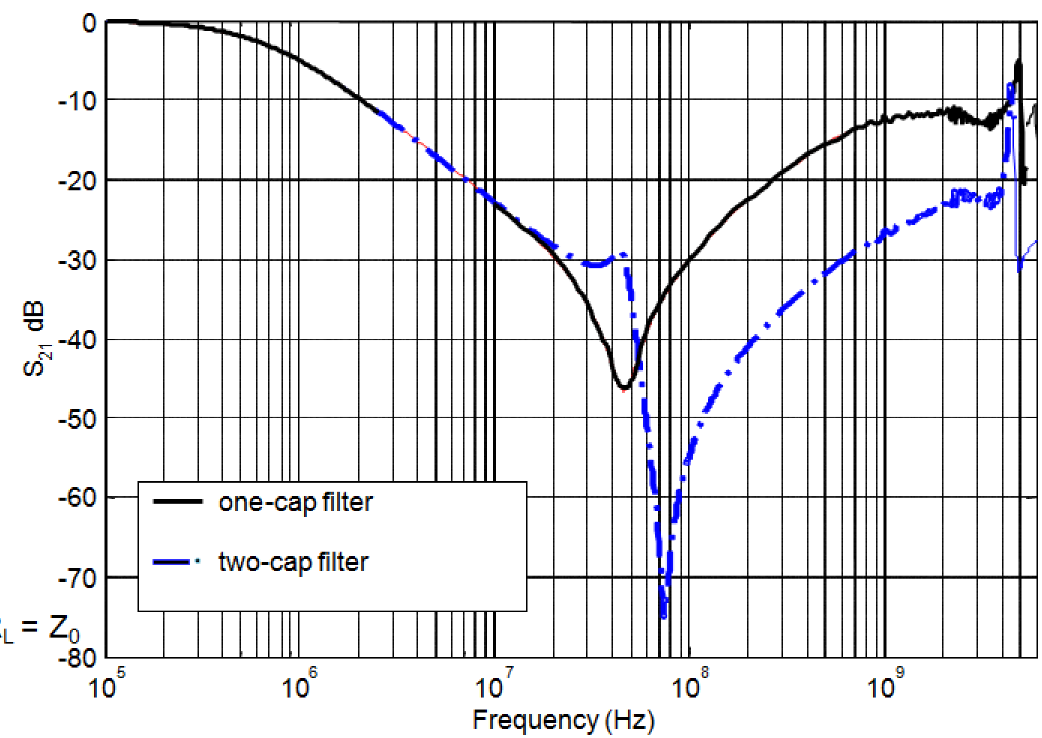
- Isolate returns only when necessary to control the flow of low frequency currents.

- If you isolate two large conductors at low frequencies, be sure they are well connected at high frequencies.

Filtering

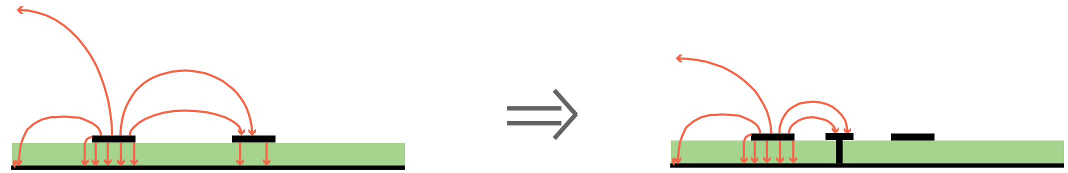
Two capacitors more than twice as good as one.



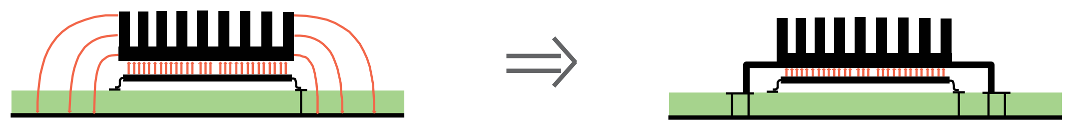


Shielding

Electric Field Shielding



(a.)



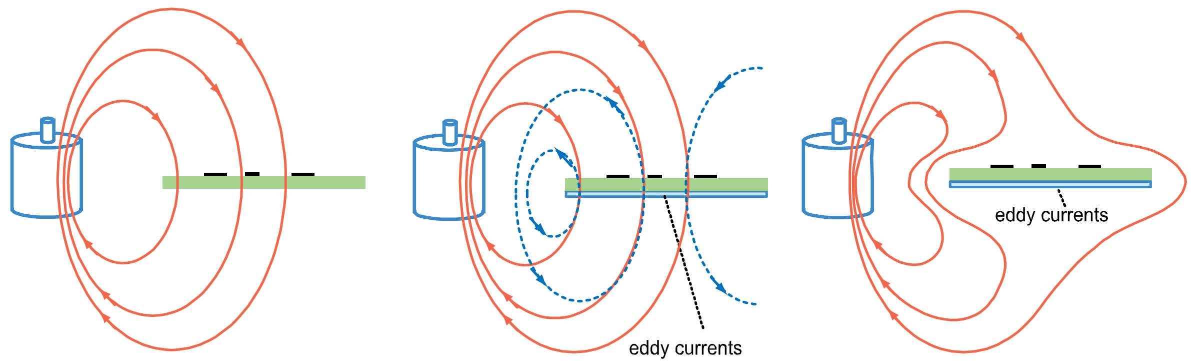
(b.)

(c.)

Shielding

Magnetic Field Shielding

(at high frequencies)

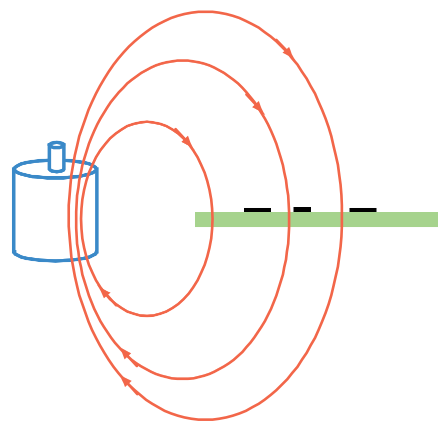


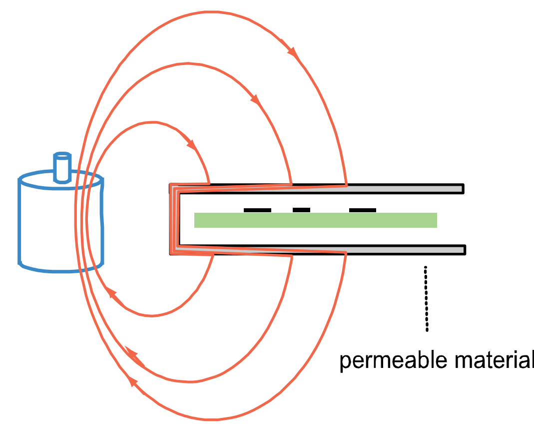
(a.) (b.) (c.)

Shielding

Magnetic Field Shielding

(at low frequencies)


(a.)



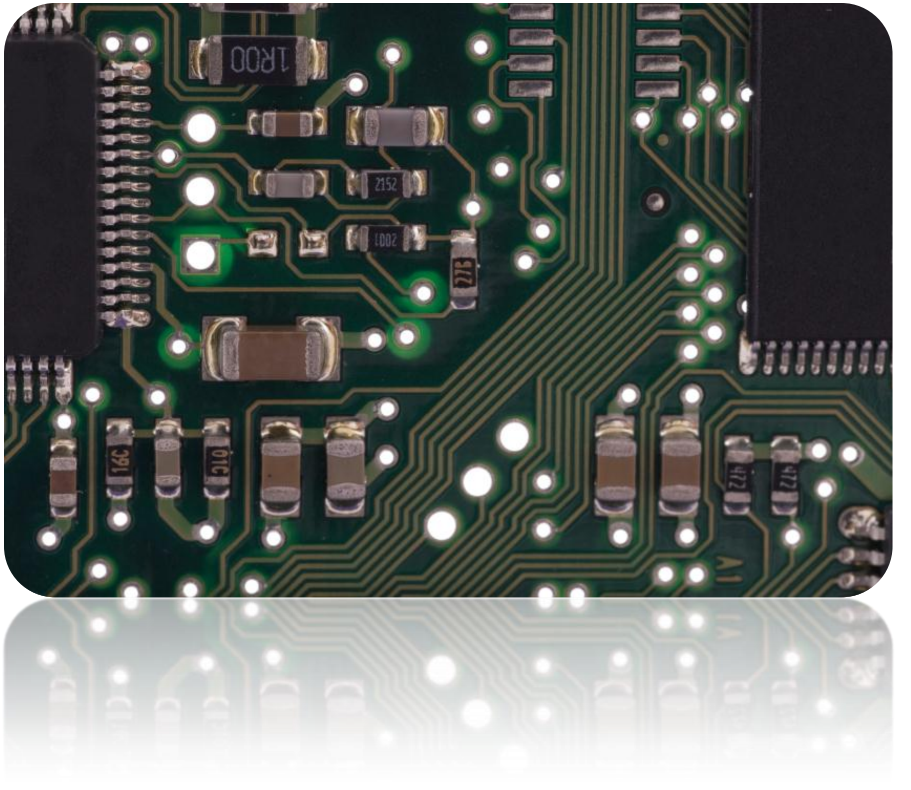
(b.)

Shielding

Enclosure

Shielding

DC Power Distribution and Decoupling



Power Bus Decoupling Strategy

With closely spaced (<.25 mm) planes

- **size bulk decoupling to meet board requirements**
- **size local decoupling to meet board requirements**
- **mount local decoupling in most convenient locations**
- **don't put traces on capacitor pads**
- **too much capacitance is ok**
- **too much inductance is not ok**

References:

T. H. Hubing, J. L. Drewniak, T. P. Van Doren, and D. Hockanson, "Power Bus Decoupling on Multilayer Printed Circuit Boards," *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-37, no. 2, May 1995, pp. 155-166.

T. Zeeff and T. Hubing, "Reducing power bus impedance at resonance with lossy components," IEEE Transactions on Advanced Packaging, vol. 25, no. 2, May 2002, pp. 307-310.

M. Xu, T. Hubing, J. Chen, T. Van Doren, J. Drewniak and R. DuBroff, "Power bus decoupling with embedded capacitance in printed circuit board design," IEEE Transactions on Electromagnetic Compatibility, vol. 45, no. 1, Feb. 2003, pp. 22-30.

Power Bus Decoupling Strategy

With widely spaced (>.5 mm) planes

- **size bulk decoupling to meet board requirements**
- **size local decoupling to meet device requirements**
- **mount local decoupling near pin connected to furthest plane**
- **don’t put traces on capacitor pads**
- **too much capacitance is ok**
- **too much inductance is not ok**

References:

J. Chen, M. Xu, T. Hubing, J. Drewniak, T. Van Doren, and R. DuBroff, “Experimental evaluation of power bus decoupling on a 4-layer printed circuit board,” *Proc. of the 2000 IEEE International Symposium on Electromagnetic Compatibility*, Washington D.C., August 2000, pp. 335-338.

T. H. Hubing, T. P. Van Doren, F. Sha, J. L. Drewniak, and M. Wilhelm, “An Experimental Investigation of 4-Layer Printed Circuit Board Decoupling,” *Proceedings of the 1995 IEEE International Symposium on Electromagnetic Compatibility,* Atlanta, GA, August 1995, pp. 308-312.

J. Fan, J. Drewniak, J. Knighten, N. Smith, A. Orlandi, T. Van Doren, T. Hubing and R. DuBroff, “Quantifying SMT Decoupling Capacitor Placement in DC Power-Bus Design for Multilayer PCBs,” IEEE Transactions on Electromagnetic Compatibility, vol. EMC-43, no. 4, Nov. 2001, pp. 588-599.

Power Bus Decoupling Strategy

With no power plane

- **layout low-inductance power distribution**
- **size bulk decoupling to meet board requirements**
- **size local decoupling to meet device requirements**
- **two caps can be much better than one**
- **avoid resonances by minimizing L**

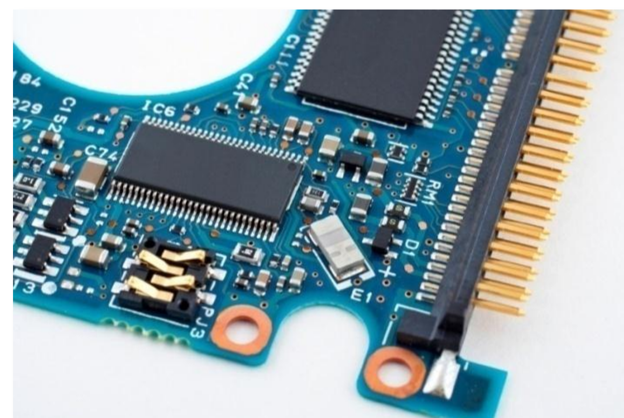
References:

T. Hubing, “Printed Circuit Board Power Bus Decoupling,” *LG Journal of Production Engineering*, vol. 3, no. 12, December 2000, pp. 17-20. (Korean language publication) .

T. Zeeff, T. Hubing, T. Van Doren and D. Pommerenke, “Analysis of simple two-capacitor low-pass filters,” IEEE Transactions on Electromagnetic Compatibility, vol. 45, no. 4, Nov. 2003, pp. 595-601.

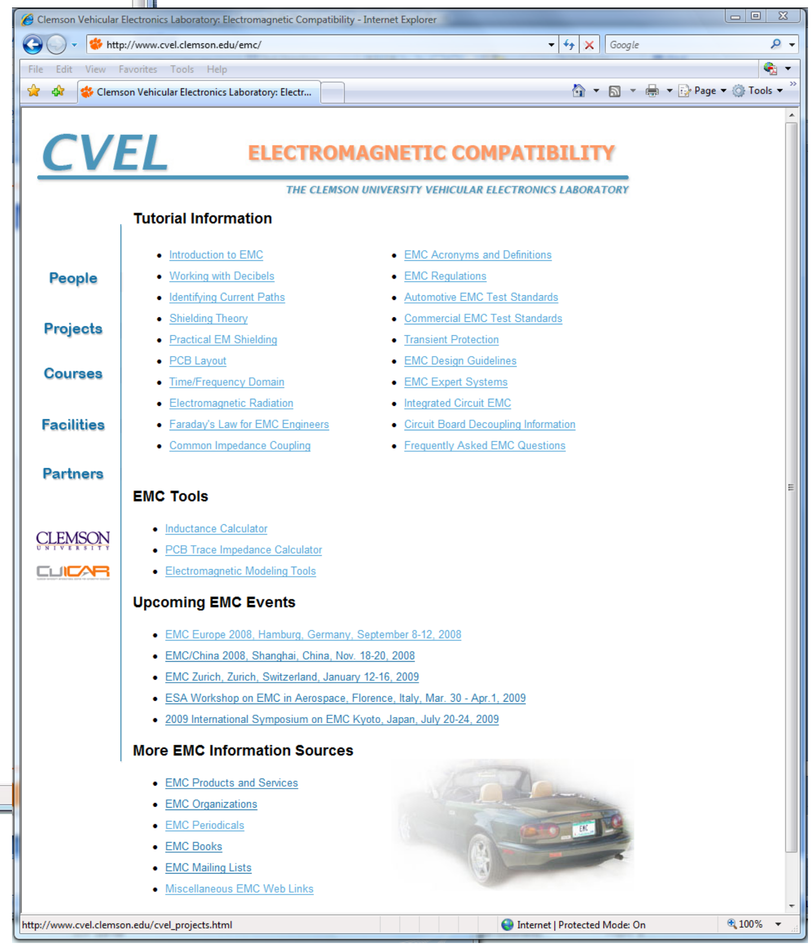
Design Summary

- Early EMC design is important
- Don’t rely on design guidelines!
- Pay attention to current paths!
- Pay attention to transition times!
- Recognize antennas!
- Recognize sources!
- Don’t gap digital ground planes!



For More Information

http://www.cvel.clemson.edu/



Component-Level Characterization for System-Level Emissions Simulations

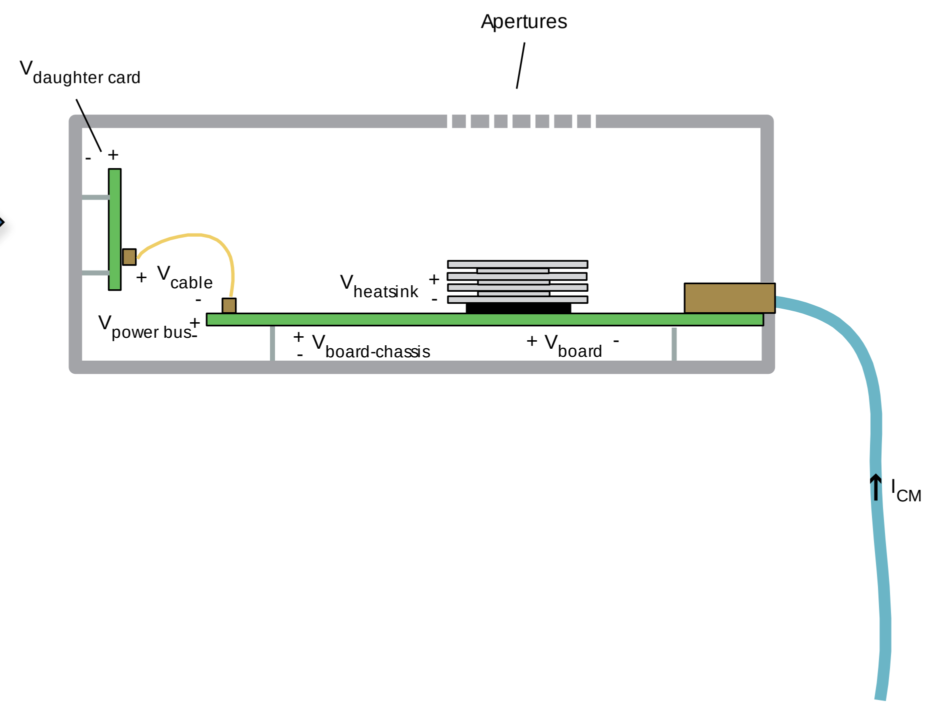
Todd Hubing

Michelin Professor of Vehicular Electronics
Clemson University

CLEMSON
UNIVERSITY

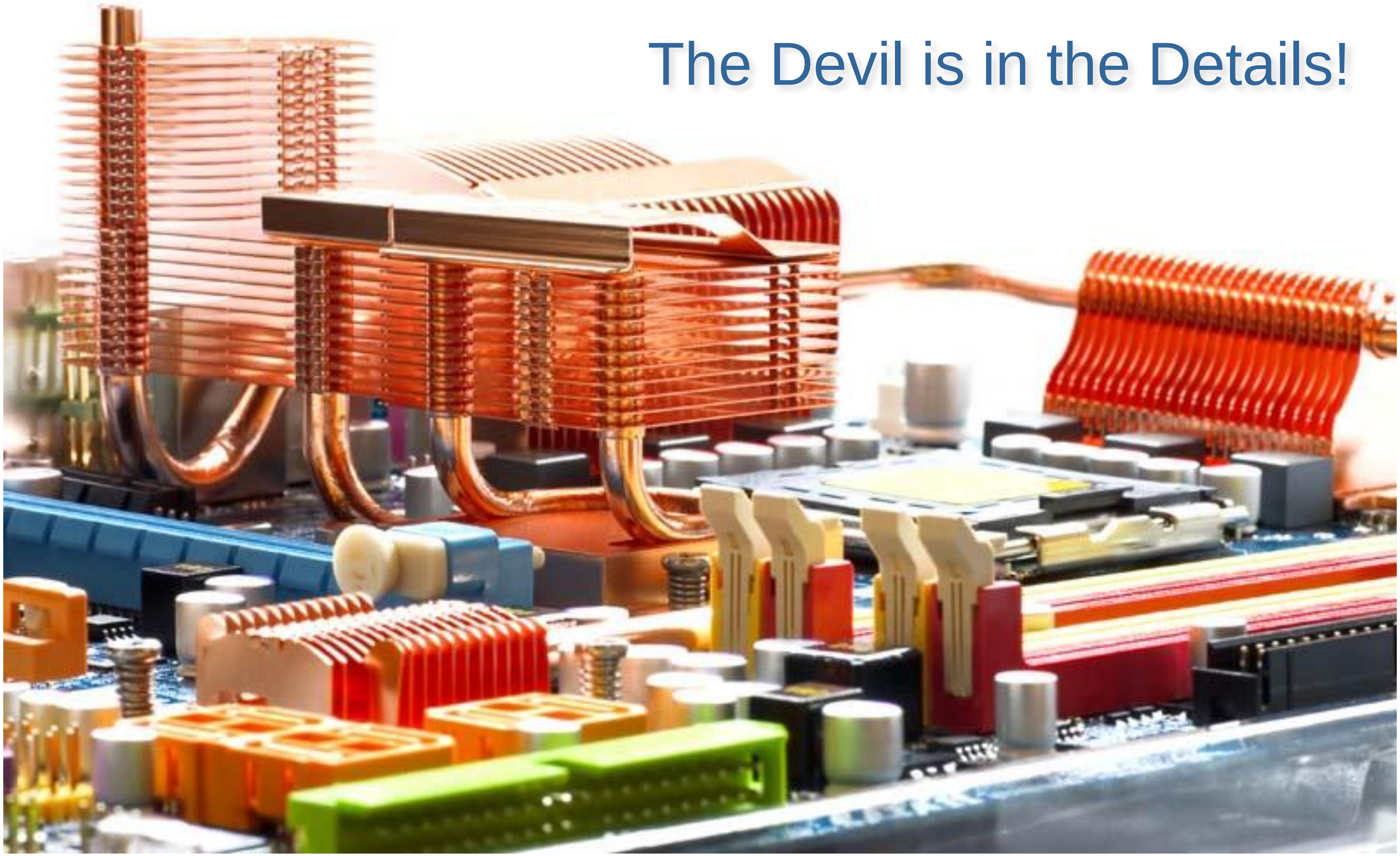
Full-Wave EM Modeling of Real Systems

Requires a little intelligent simplification!



Full-Wave EM Modeling of Real Systems

The Devil is in the Details!



Integrated Circuit EMC Measurement Methods

- IEC 61967-1 General conditions and definitions
- IEC 61967-2 Measurement of radiated emissions TEM cell method
- IEC 61967-3 Measurement of radiated emissions surface scan method
- IEC 61967-4 Measurement of electromagnetic emissions 1Ω/150Ω direct coupling
- IEC 61967-5 Measurement of electromagnetic emissions workbench Faraday cage method
- IEC 61967-6 Measurement of electromagnetic emissions magnetic probe method

Integrated Circuit EMC Measurement Methods

- IEC 61967-1 General conditions and definitions
- IEC 61967-2 Measurement of ~~radiated~~ emissions TEM cell method
  field-coupled
- IEC 61967-3 Measurement of ~~radiated emissions~~ surface scan method
  near fields
- IEC 61967-4 Measurement of ~~electromagnetic~~ emissions 1Ω/150Ω direct coupling
  conducted
- IEC 61967-5 Measurement of ~~electromagnetic emissions~~ workbench Faraday cage method
  who knows what
- IEC 61967-6 Measurement of ~~electromagnetic emissions~~ magnetic probe method
  who knows what

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Integrated Circuit EMC Measurement Methods

Component measurements should characterize the source in order to build models that can be used at the system level.

Otherwise, they are not particularly useful for system-level modeling!

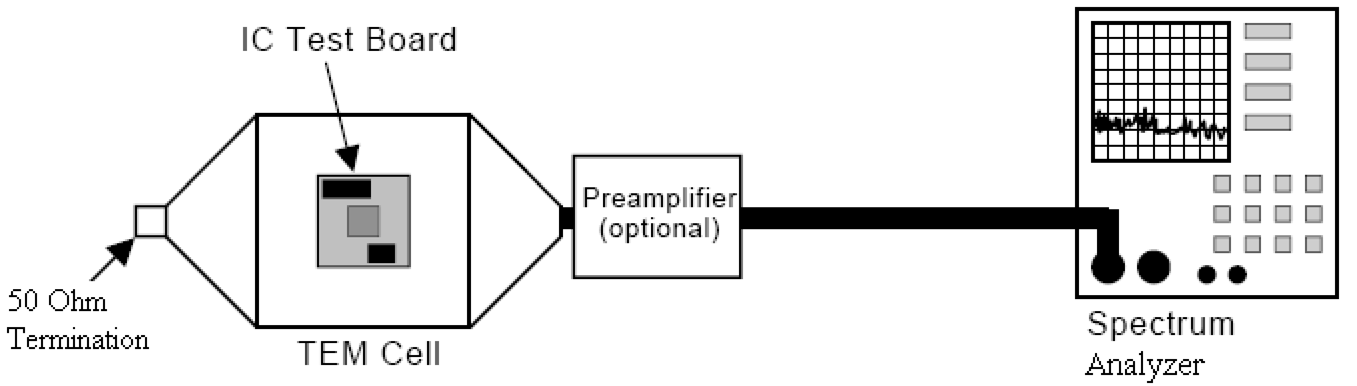
Integrated Circuit EMC Measurement Methods

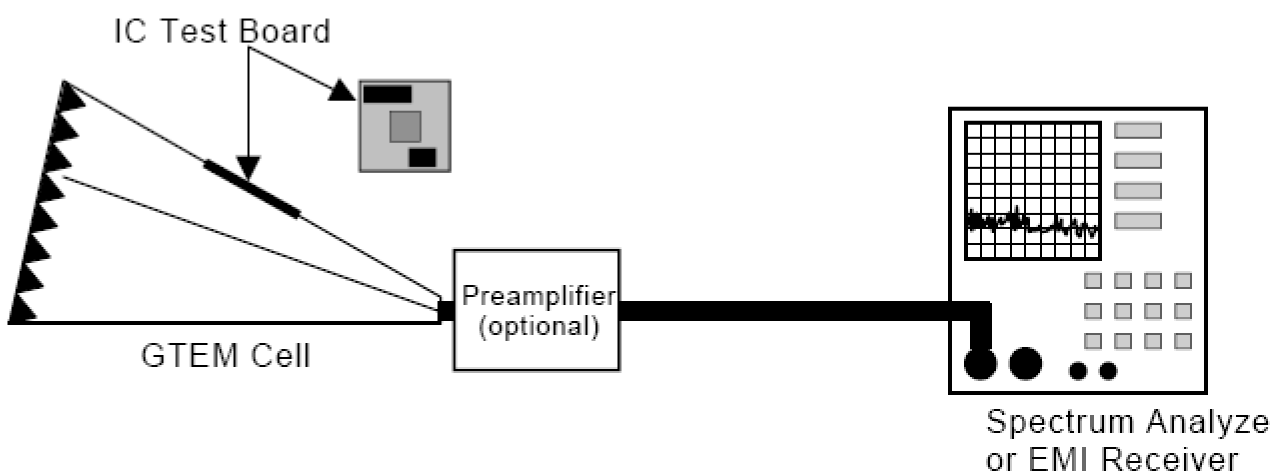
Measurements must be:

- Meaningful
- Repeatable
- Targeted

Integrated Circuit EMC Measurement Methods

Standards SAE J1752/3 and IEC 61967-2





Energy must be coupled from an IC before it can be radiated

- Integrated circuits (ICs) are generally the ultimate source of unintentional electromagnetic emissions from electronic devices and systems.
- However, ICs are too small to radiate significantly themselves.
- In order to radiate fields strong enough to cause an interference problem, energy must be coupled from the IC package to larger structures that act as antennas such as circuit board planes, heatsinks or cables.

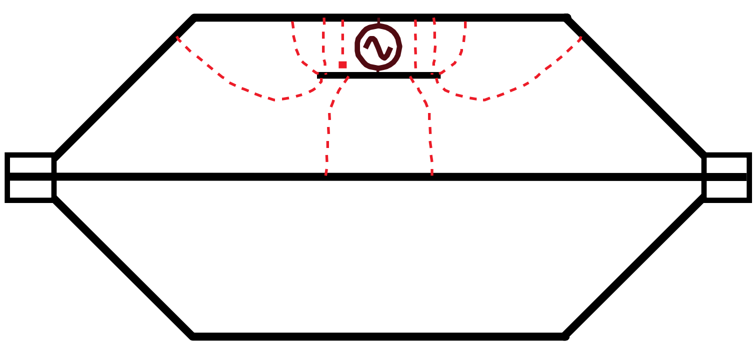
Energy must be coupled from an IC before it can be radiated

There are only three ways that energy can be coupled from an IC to surrounding structures:

- Conducted on two or more pins;
- Electric field coupled;
- Magnetic field coupled.

Electric Field Coupling to the Septum of a Mini-TEM Cell

Electric field coupling can be represented with a mutual capacitance, C_{TEM}. The voltage coupled to either end of the TEM cell will be identical.



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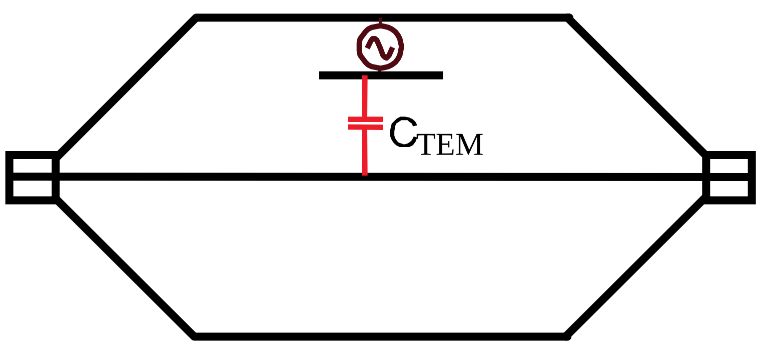
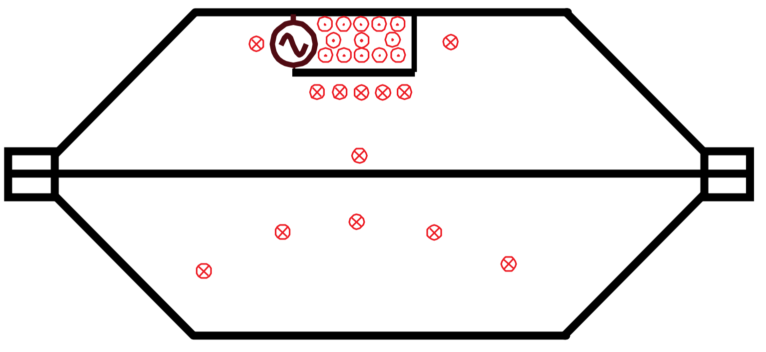


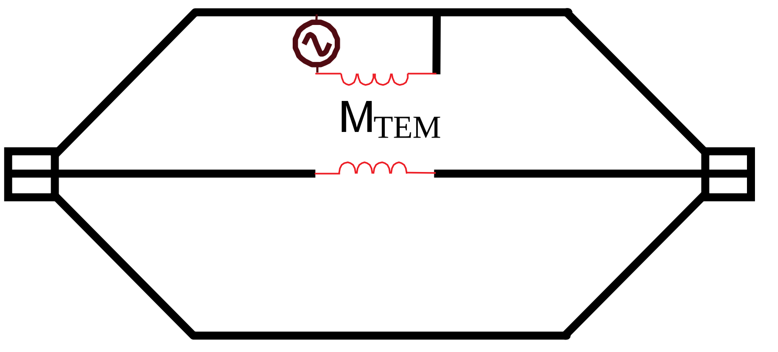
(b)

Magnetic Field Coupling to the Septum of a Mini-TEM Cell

Magnetic field coupling can be represented with a mutual inductance, M_{TEM}. Voltage appears across both terminations with opposite phase.



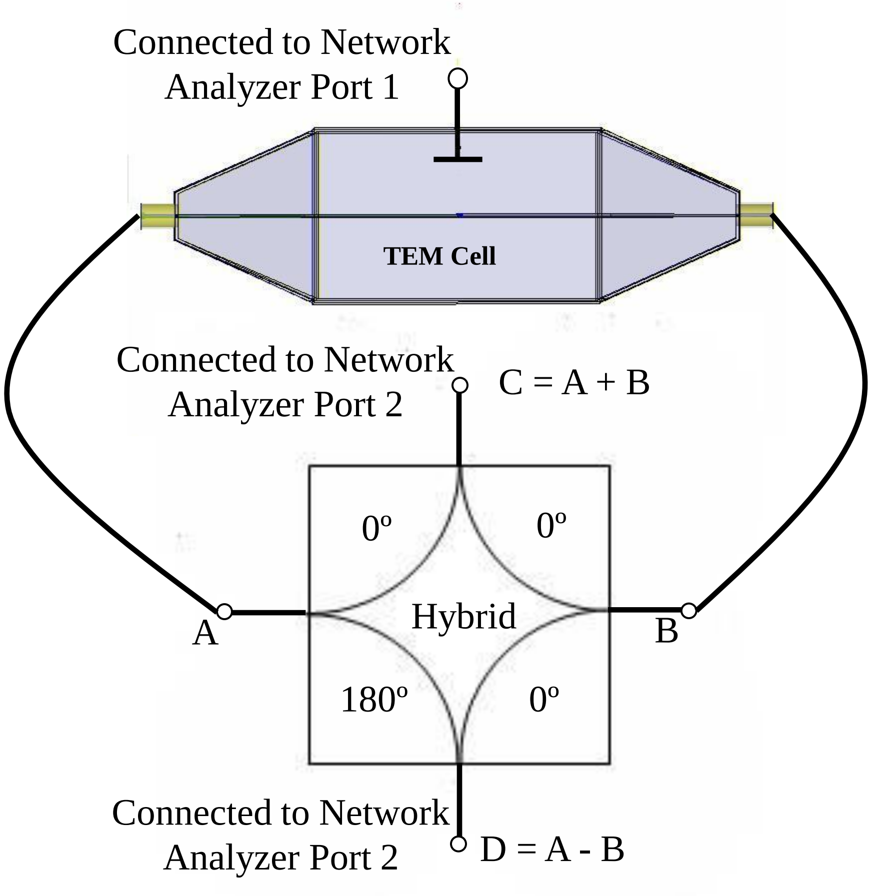
(a)



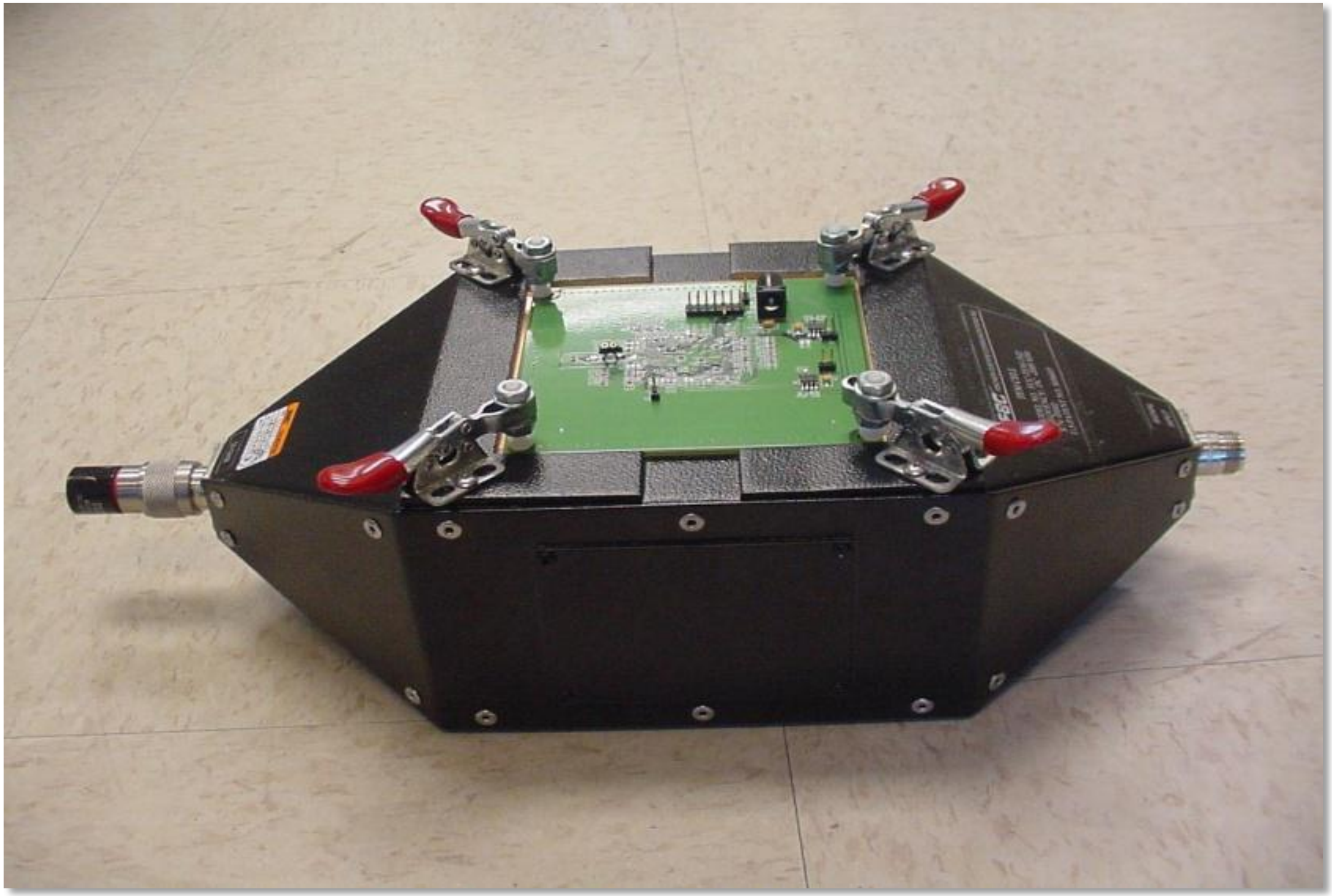
(b)

Separating Coupling Mechanisms using a Hybrid Coupler

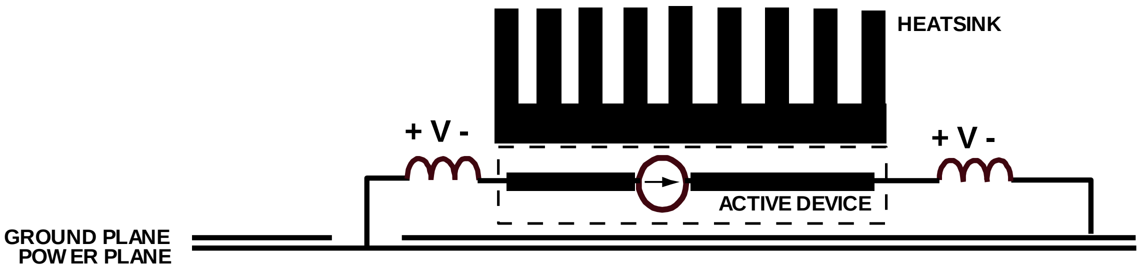
- A hybrid can be used to differentiate electric and magnetic field coupling.
- The A-B output indicates the amount of magnetic field coupling.
- The A+B output indicates the amount of electric field coupling.



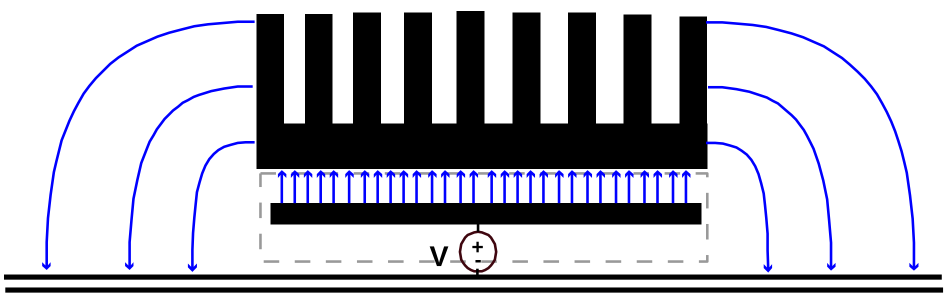
Mini-TEM Cell



Electric Field Coupling



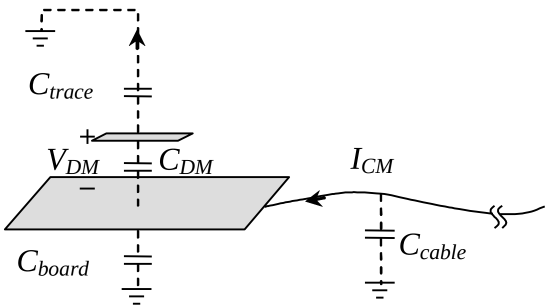
(a.)

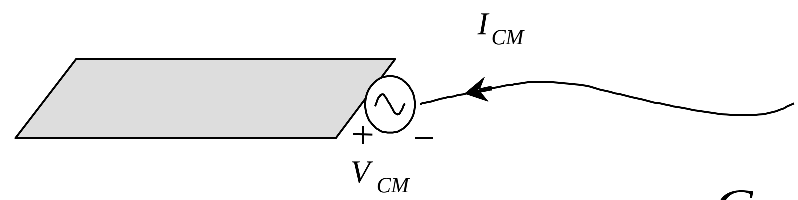


(b.)

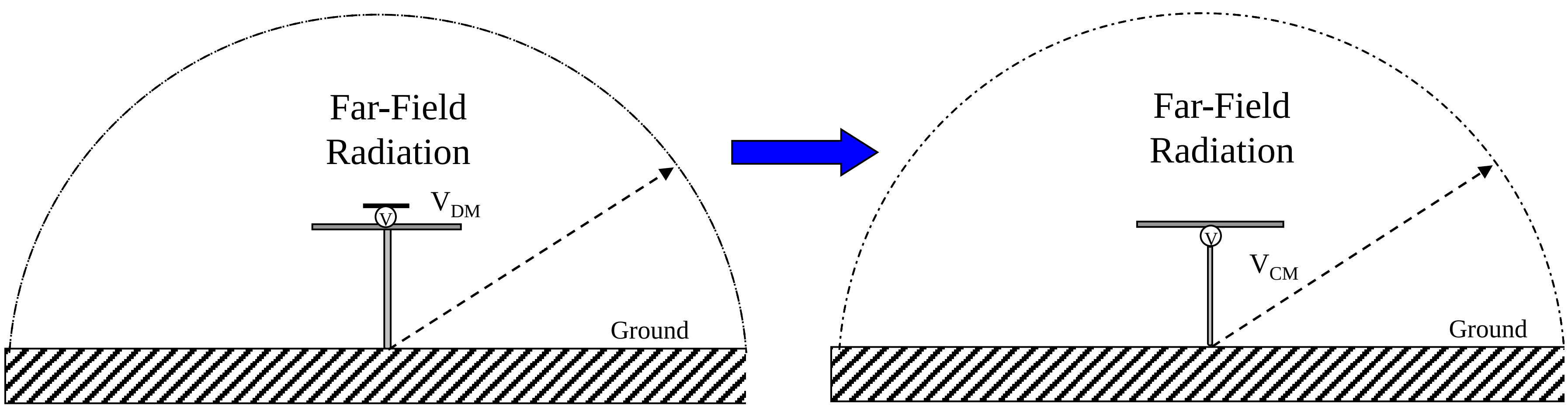
Voltage-Driven Radiation Mechanism

If we know C_{trace} and V_{DM}, we can calculate maximum possible radiated emissions due to electric field coupling!



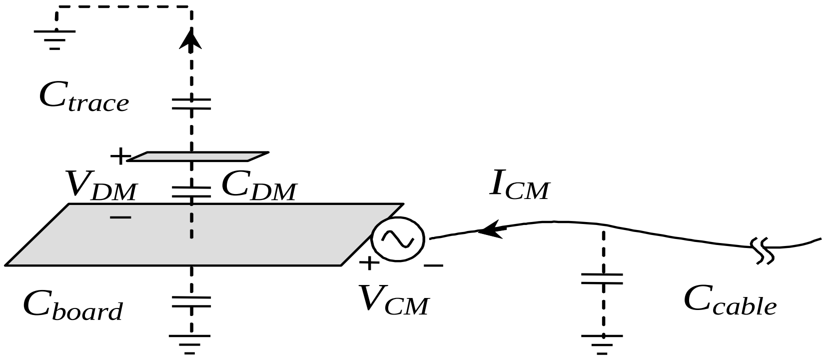


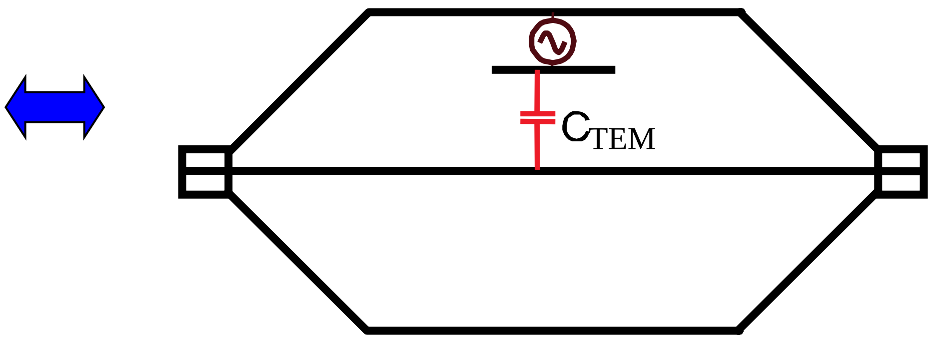
$$V_{CM} \approx \frac{C_{trace}}{C_{board}} V_{DM}$$



Correlating C_{trace} to C_{TEM}

A TEM cell measurement gives us the product of C_{trace} and V_{DM}, which is sufficient to calculate maximum possible radiated emissions due to electric field coupling!

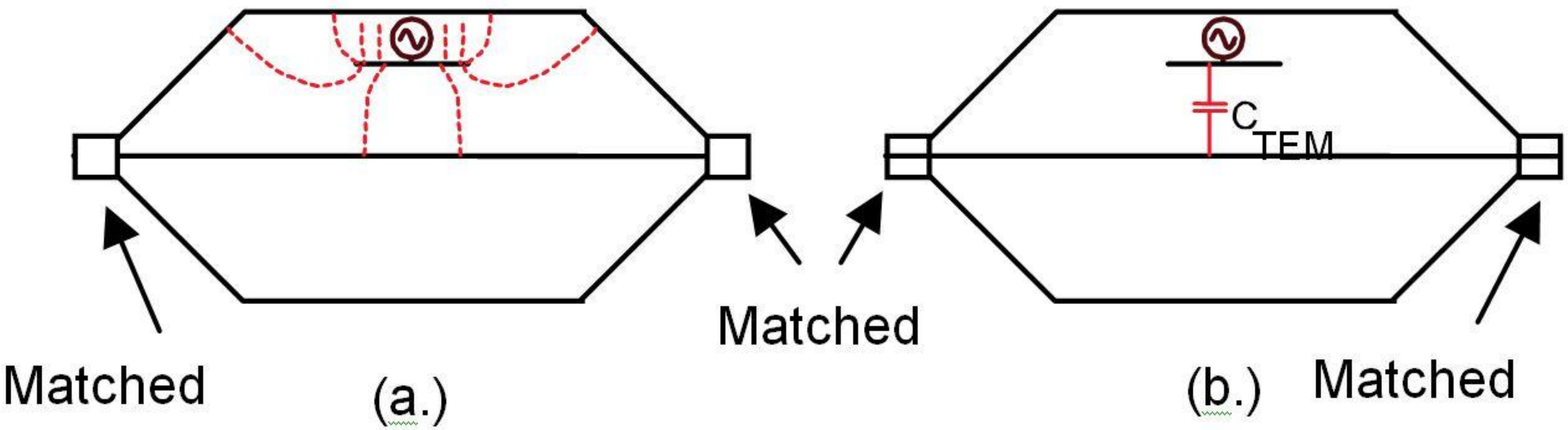




$$C_{trace} \approx C_{TEM} / 2.1$$

S. Deng, et. al., "Characterizing the Electric-Field Coupling from IC-Heatsink Structures to External Cables using TEM-Cell Measurements," *IEEE Trans. on Electromagnetic Compatibility*, vol. 49, no. 4, Nov. 2007, pp. 785-791.

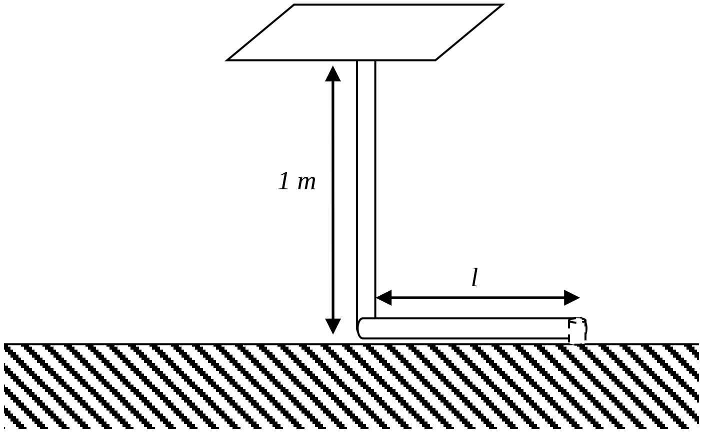
Hybrid TEM Cell Electric Field Coupling

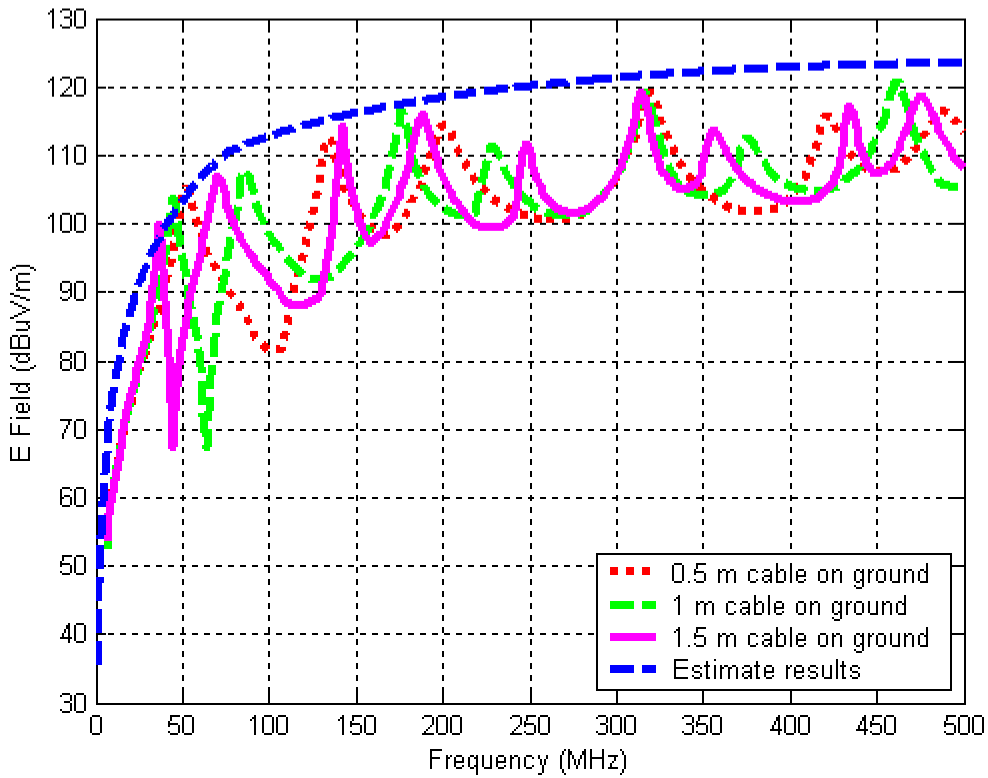


Electric Moment

$$\left|V_{IC}\right|\omega C_{TEM} \approx \frac{\left|V_{measured}\right|}{25}$$

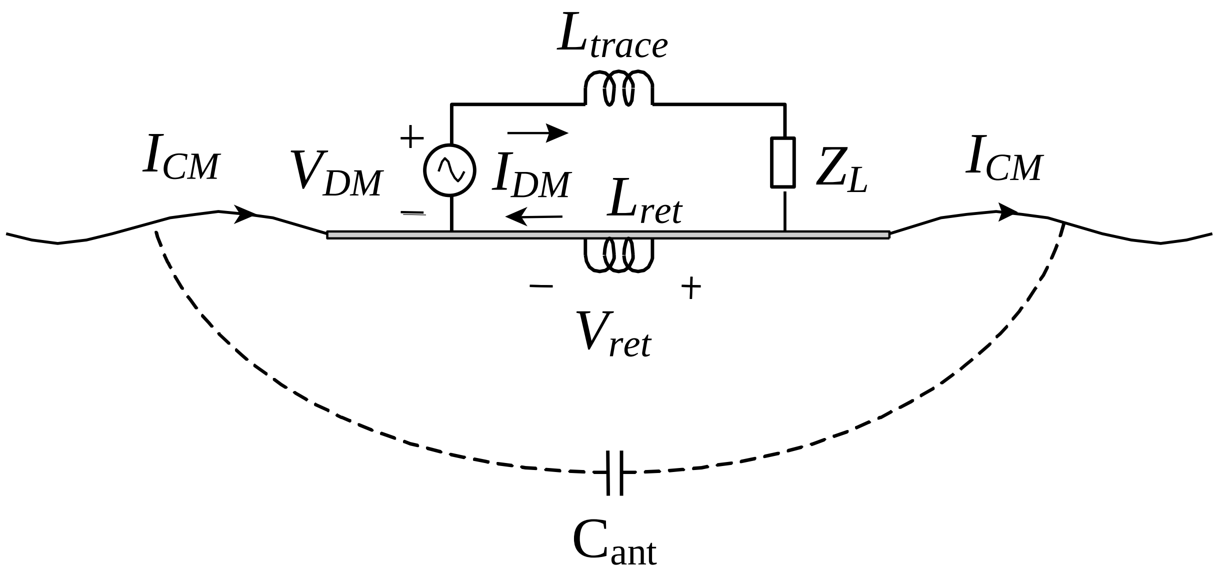
Calculation of Emissions Based on a TEM Cell Measurement





Magnetic Field Emissions

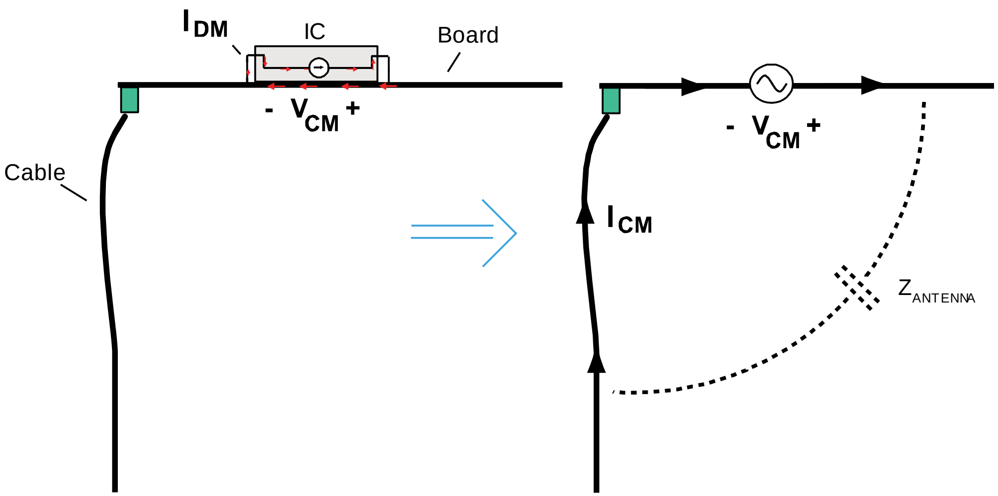
Current-Driven Common-Mode (Magnetic-Field) Coupling



Source can be fully characterized by the current I_{DM} and the mutual inductance (source loop to antenna loop).

Magnetic Field Emissions

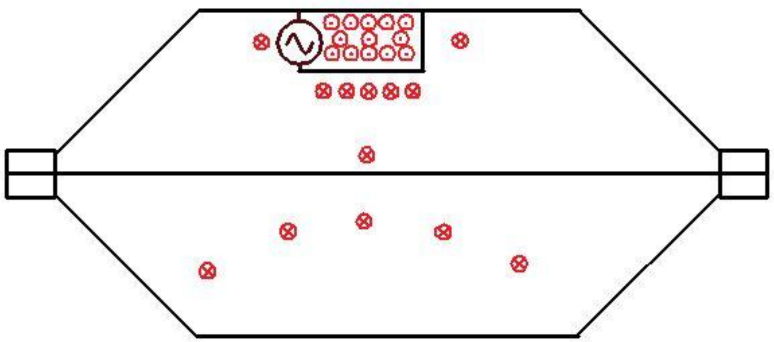
A TEM cell measurement gives us the value of V_{CM}, which is sufficient to calculate maximum possible radiated emissions due to magnetic field coupling!



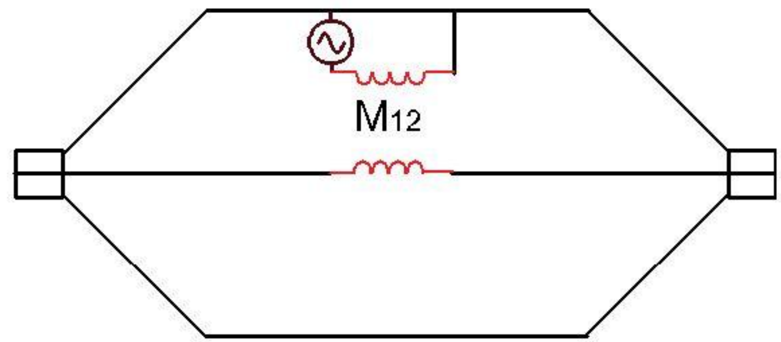
$$V_{CM} = \frac{4}{\pi^2 \cdot w} \cdot V_{TEM} \cdot 2 \cdot (W + H)$$

S. Deng, et. al., "Using TEM Cell Measurements to Estimate the Maximum Radiation from PCBs with Attached Cables due to Magnetic Field Coupling," *IEEE Transactions on Electromagnetic Compatibility*, May 2008.

Hybrid TEM Cell Magnetic Field Coupling



(a.)



(b.)

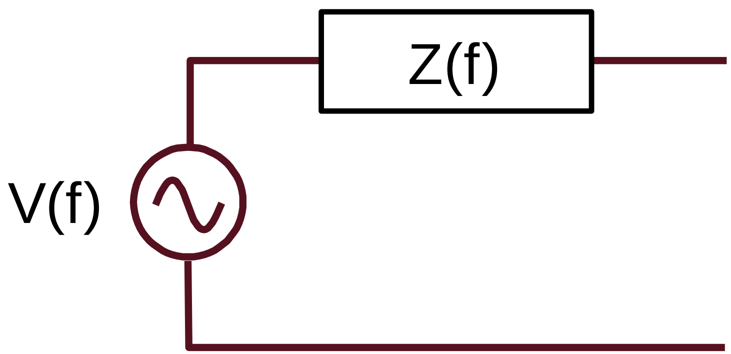
Magnetic Moment

$$\left|V_{measured}\right| = \left|I_{IC}\right| \omega M_{TEM}$$

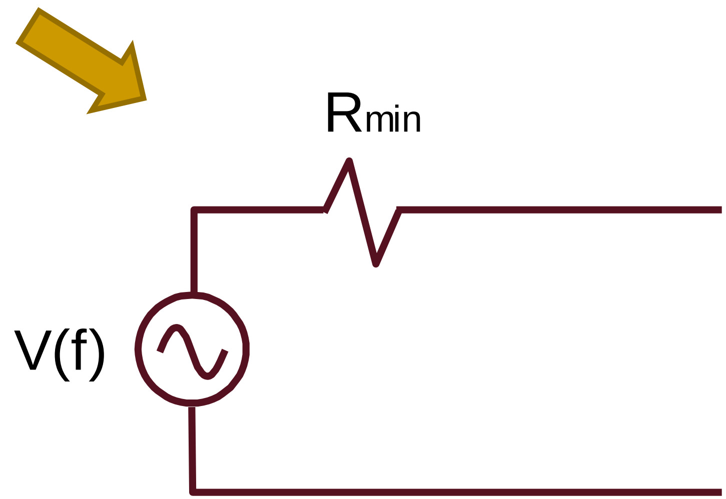
Using Mini-TEM Cell Measurement Results

- By connecting both outputs of the TEM cell to a hybrid, it is possible to separate the electric field coupling from the magnetic field coupling.
- Magnetic-Field coupling is fully characterized by the source current and mutual inductance to the radiating structure. These are both determined by the TEM cell measurement.
- Electric-Field coupling is fully characterized by the source voltage and the capacitance of the device being driven to infinity. These can both be determined by the TEM cell measurement.
- Therefore, a TEM cell measurement can be used to extract the parameters required to predict maximum radiated emissions due to coupling from an electrically small source.

Conducted Coupling

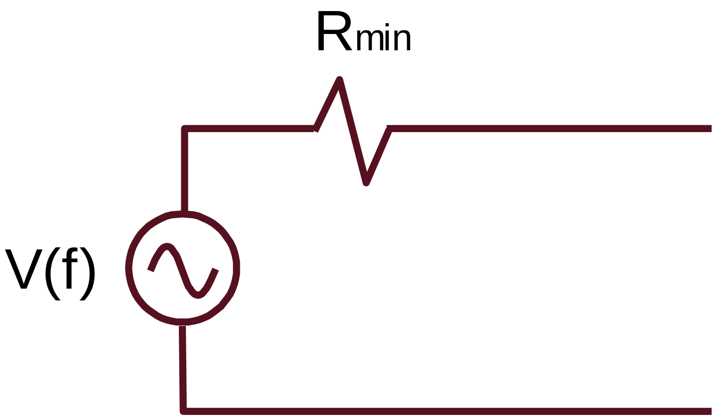


- Need a Thevenin Equivalent source for each terminal pair, including power pins.



- R_{min} is ratio of V_{open} to I_{short_max}
- Reactive elements are not necessary
- Only "logical" ports need to be characterized.

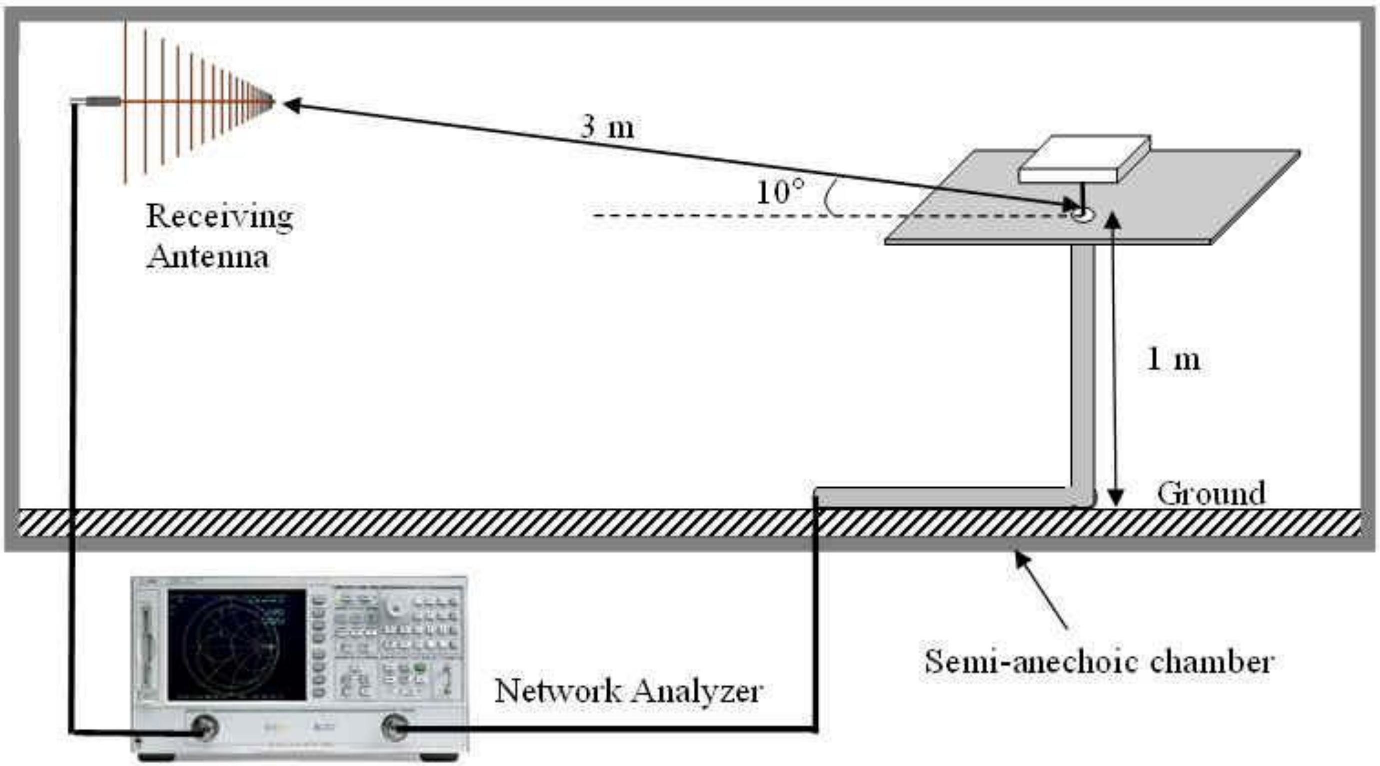
Conducted Coupling



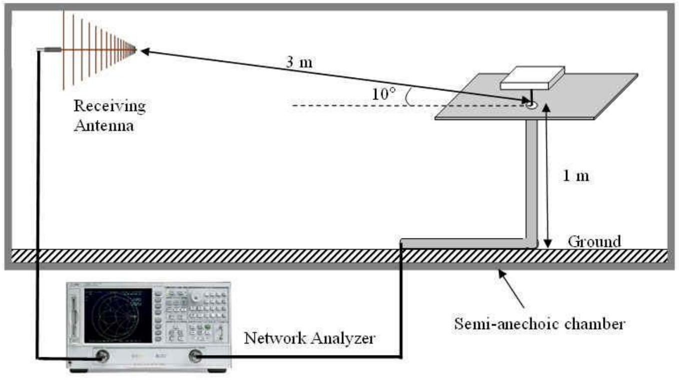
Existing methods for measuring conducted emissions are limited by parasitics, however it is often possible to make meaningful measurements up to GHz frequencies.

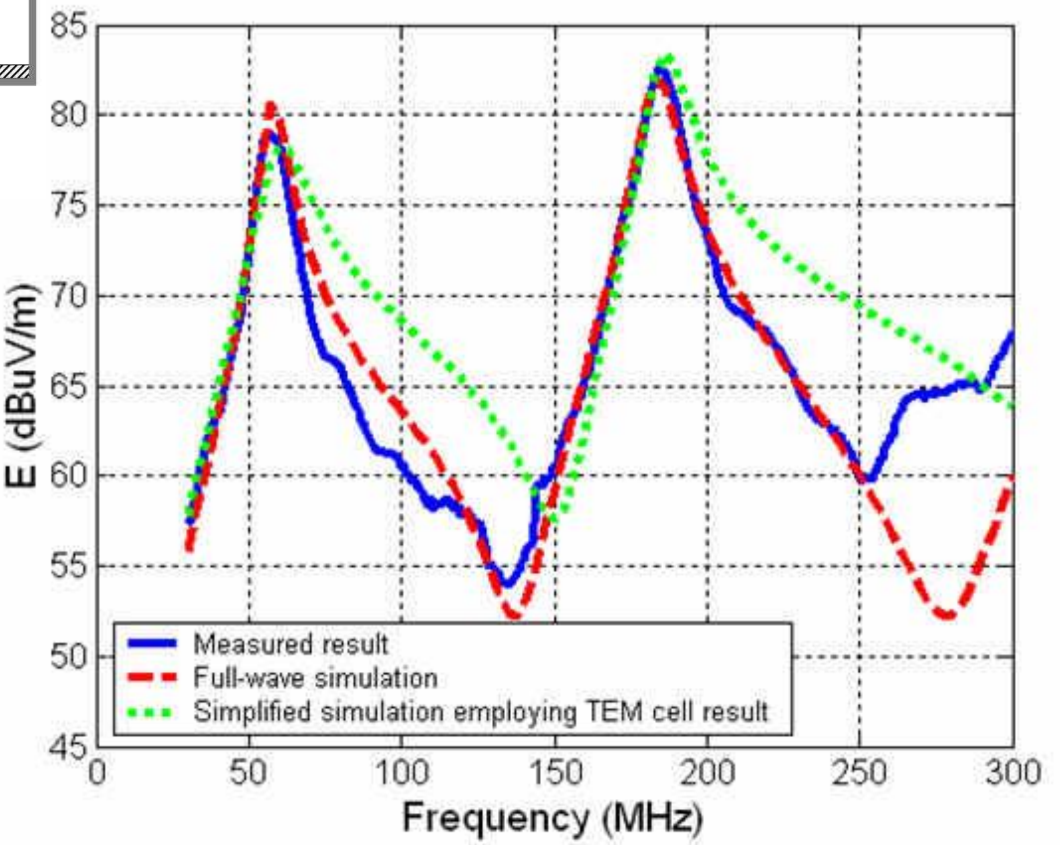
- V_{open} is approximately equal to the voltage measured across a 150 Ω load if connection parasitics are controlled.
- I_{short_max} is approximately equal to the current delivered to a 1 Ω load if connection parasitics are controlled.
- Internal capacitances can be modeled explicitly if known or implicitly included in the value of V(f)

Measurement Test Set-Up

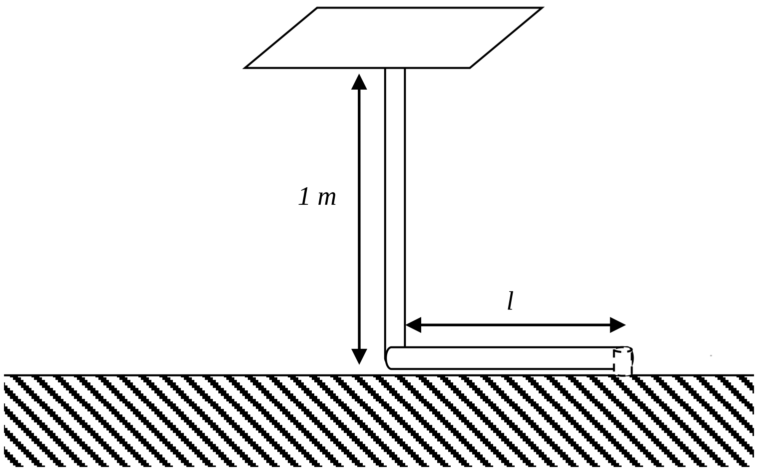


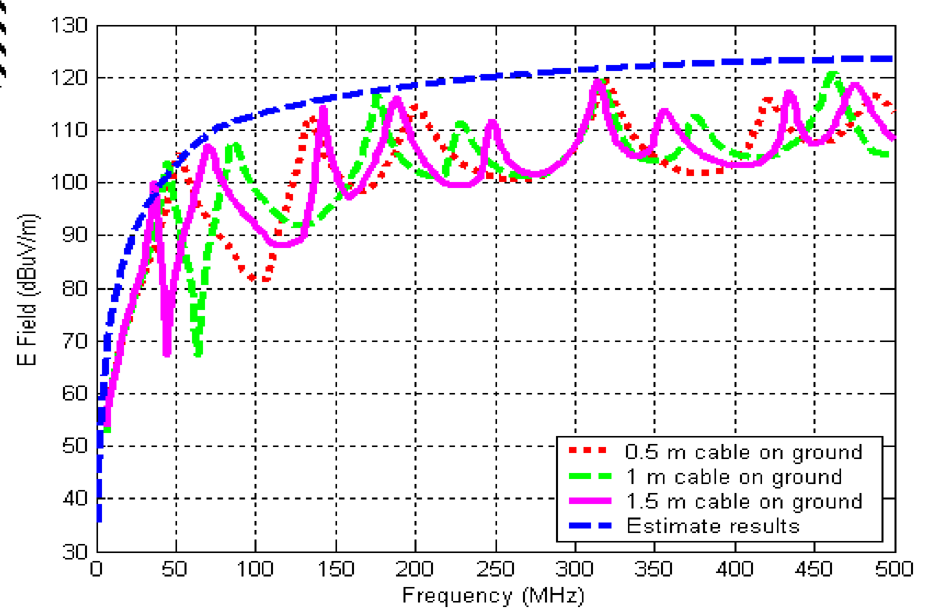
Model vs. Measurement





Maximum Emissions Estimate





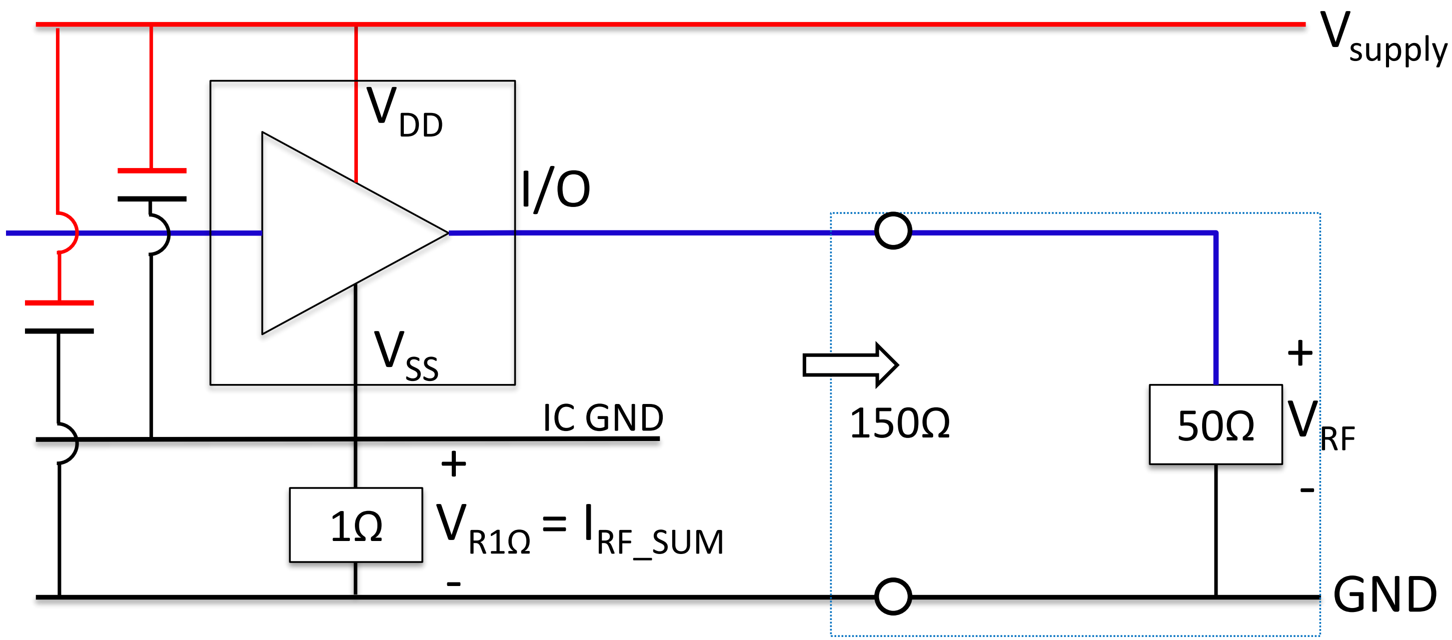
Conducted Coupling Source Model

ICEM

LECCS

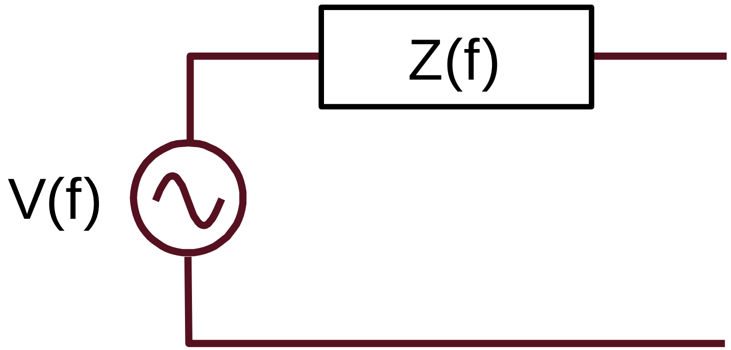
Black Box Model

IEC 61967-4 Test Configuration

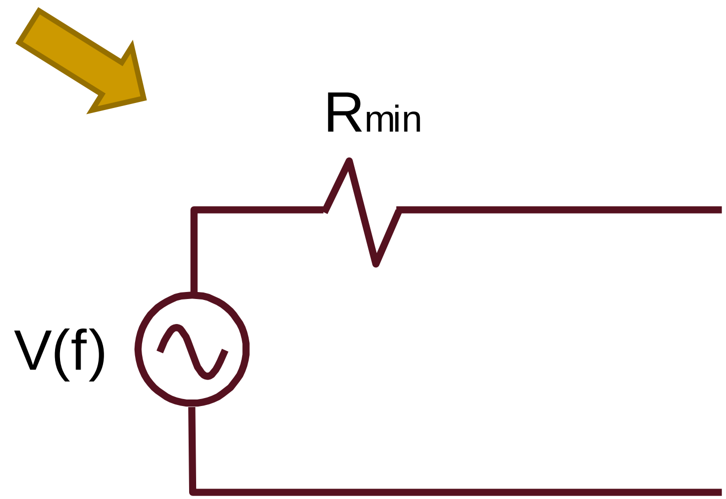


helpful for selecting an IC, but the procedure has significant limitations and does not fully characterize the IC output drivers.

Conducted Coupling

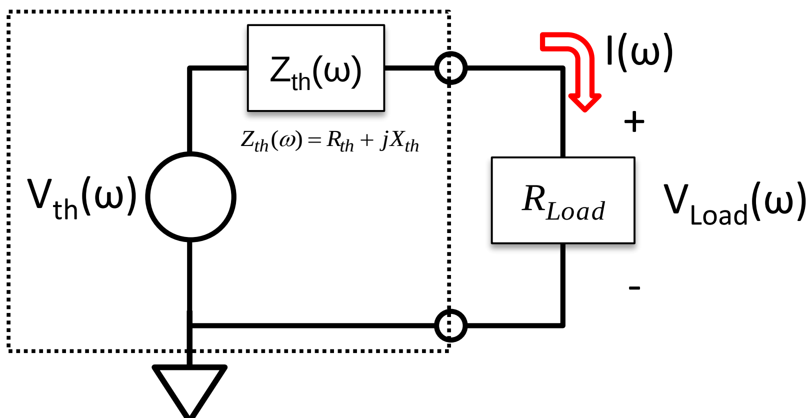


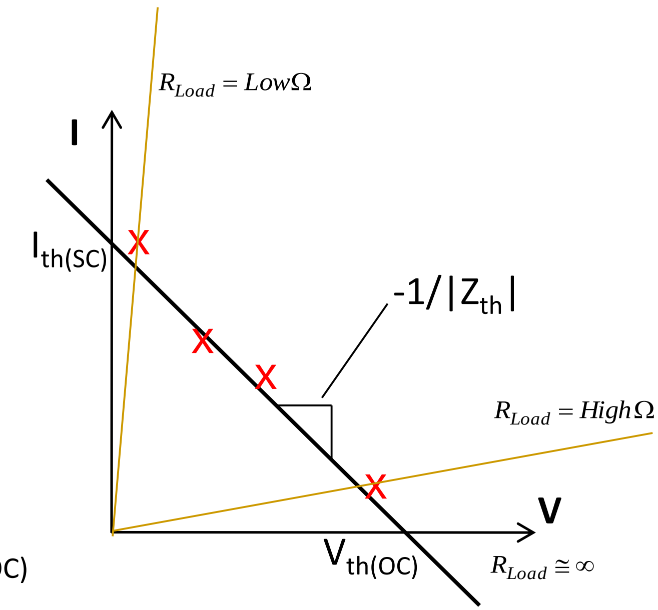
- Need a Thevenin Equivalent source for each terminal pair, including power pins.



- R_{min} is ratio of V_{open} to I_{short_max}
- Only "logical" ports need to be characterized.
- Existing test procedure cannot be used to determine value of R_{min}

Thevenin Equivalent Circuit and V-I Curve

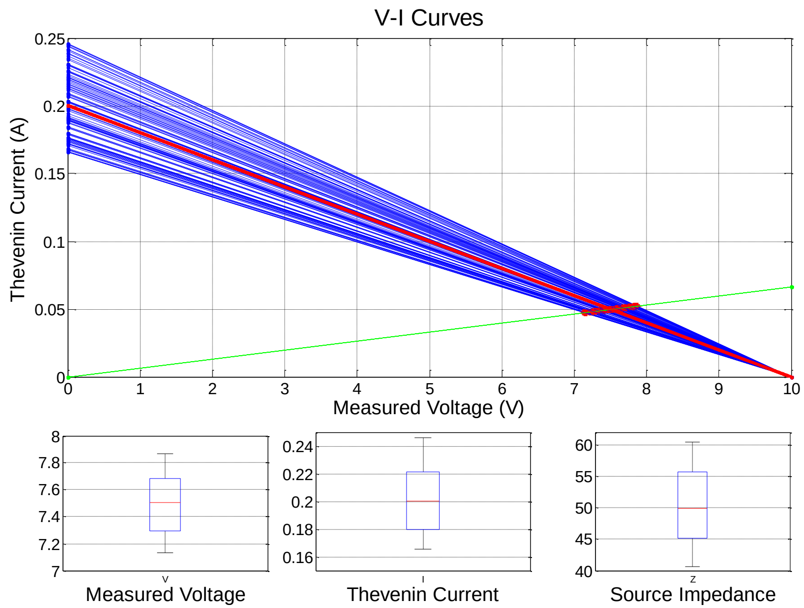




$R_{load} = \infty \rightarrow V_{th(OC)}$

$R_{load} = 0 \rightarrow I_{th(SC)}$

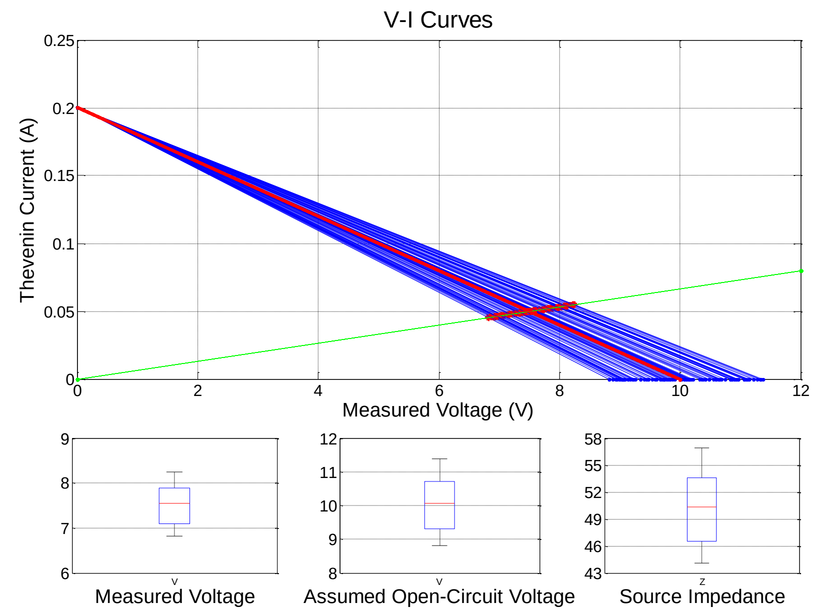
Limitation Of IEC 61967-4



Known source

V_{oc}: 10V, R_{th}: 50Ω

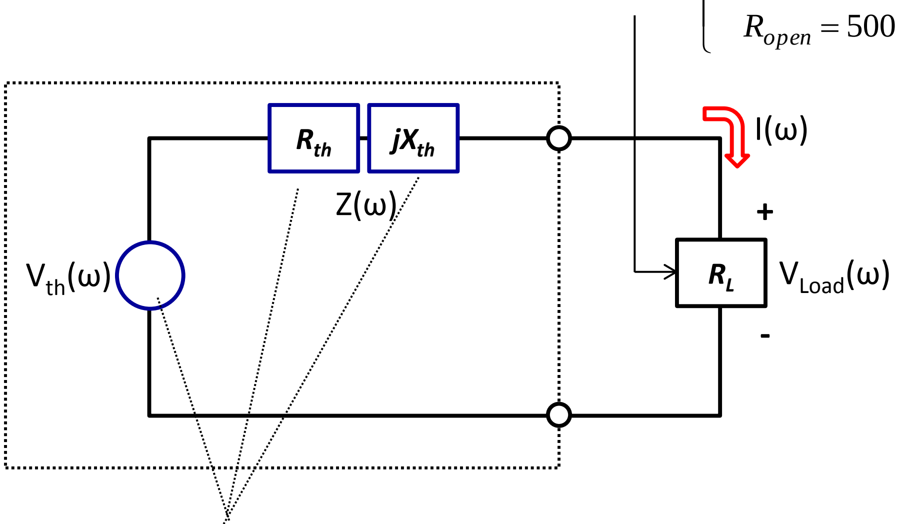
- Sensitive to Measurement error
  - Sensitive to the assumed V_{oc}
    - Sensitive to the ωL ,$|Z_{th}|$



Conducted Coupling

There are **3** unknowns:
V(f), R(f) and |X(f)|
requiring **3** measurements to characterize the source.

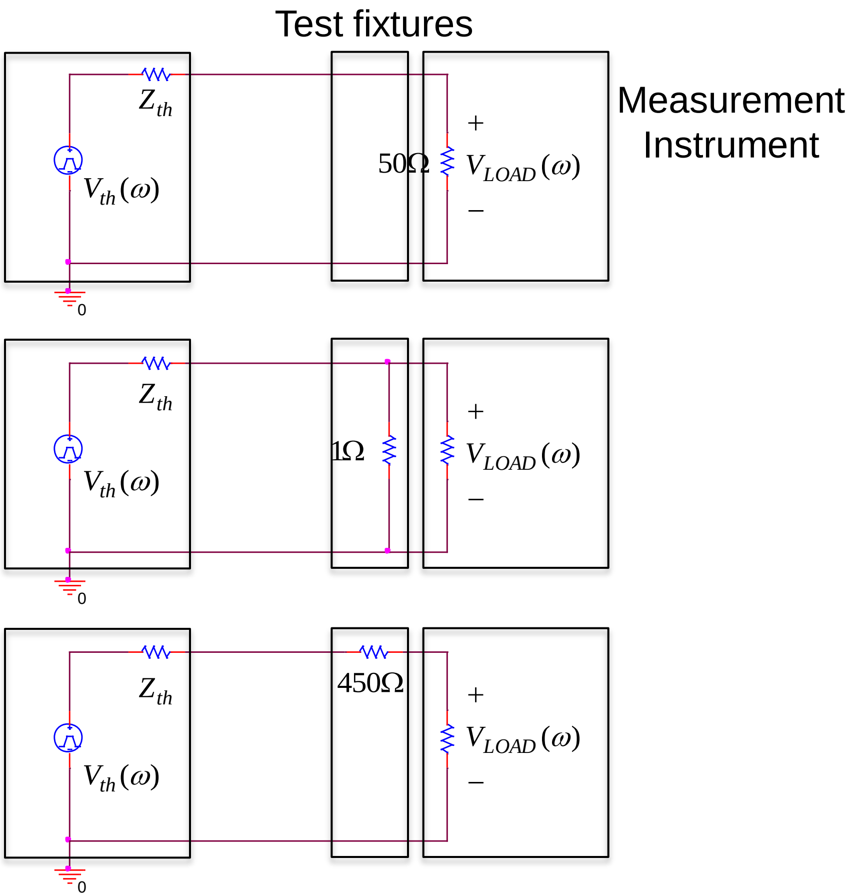
$$R_L = \begin{cases} 50\ \Omega \\ R_{short} = 1\ \Omega \,||\, 50\ \Omega \\ R_{open} = 500\ \Omega \end{cases}$$



3 source parameters

- V_{open} is approximately equal to the voltage measured across a 500-Ω load if connection parasitics are controlled.
- I_{short_max} is approximately equal to the current delivered to a 1-Ω load if connection parasitics are controlled.
- Additional measurement across a 50-Ω load gives us the 3 data points required to characterize the source.

Three load conditions for characterizing conducted EMI sources



$$\left|V_{50\Omega\_Load}\right| = \left|V_{th}\right| \left|\frac{50\Omega}{50\Omega + Z_{th}}\right|$$

$$\left|V_{short\_Load}\right| = \left|V_{th}\right| \left|\frac{R_{short}}{R_{short} + Z_{th}}\right|$$

$$\left|V_{open\_Load}\right| = \left|V_{th}\right| \left|\frac{R_{open}}{R_{open} + Z_{th}}\right|$$

$$Z_{th} = R_{th} + jX_{th}$$

$$R_{short} = 1\Omega \,||\, 50\Omega, \; R_{open} = 500\Omega$$

Conducted EMI Measurement Conclusions

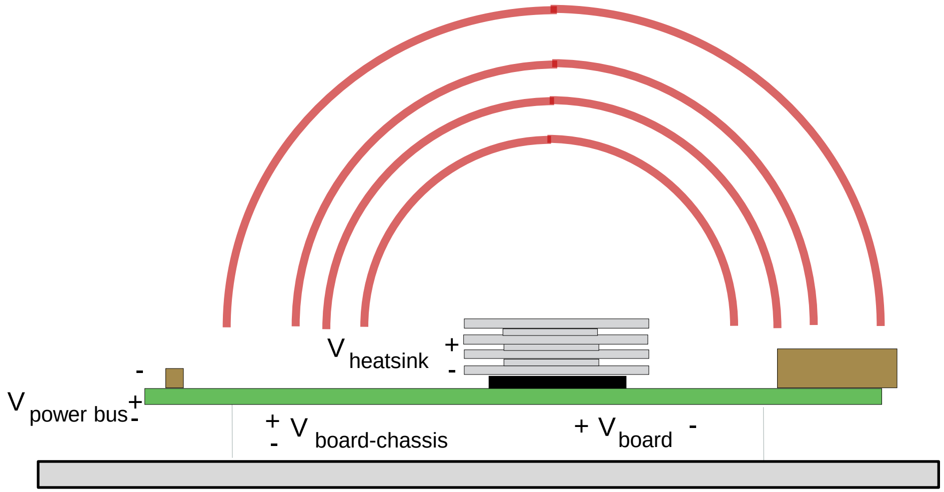
- Open and short circuit measurements are usually best approximated by 1-ohm and 500-ohm measurements on real devices

- Small measurement errors can result in large model errors.

- A 1/50/500 ohm measurement reduces the susceptibility of the test the measurement errors.

- Reactive source impedances require multiple complex loads to characterize accurately.

Direct Radiation from Component



At GHz frequencies, ICs with large heatsinks can radiate directly

These measurements can be made by mounting the board on the floor of a semi-anechoic chamber.

Summary

- Measurements of an integrated circuit in a hybrid TEM cell configuration can be used to obtain values for the “electric moment” and “magnetic moment” associated with an IC as it is configured on a given circuit board.

- Direct radiation can be measured in a semi-anechoic chamber, but component should be mounted in the floor to eliminate unwanted reflections and prevent currents on cables and other objects from contributing to the measurement.

- A 1/50/500 ohm conducted emissions measurement (as opposed to the current 1/150 ohm measurement) is capable of determining the value of Rmin, which is critical for system-level modeling.

Summary

- ICs with smaller moments are less likely to couple to other parts of a system resulting in unintentional radiated emissions.

- Electric and magnetic moments can be used in full-wave electromagnetic models of a system, replacing complex IC-package geometries with simple equivalent sources.

- A similar procedure involving a hybrid TEM cell could be used to determine these “moments” for larger structures (e.g. automotive components) at lower frequencies.

How EMC Engineers Use Electromagnetic Modeling Tools

Todd H. Hubing

Clemson Vehicular Electronics Laboratory

Clemson University

Modeling Software

Fastcap EMA3D Fasthenry NEC

GEMACS SuperNEC FEKO Quickfield

SUPERFISH VISULA FLO/EMC

MaxSIM-F Accufield EMC Workbench

Microwave Explorer MagNet EMIT Fastlap

Maxwell 3D COMPLIANCE EMAP

XFDTD Flux3D MSC EMAS

COMORAN ContecRADIA QUIET

APOGEE EM IE3D MiniNEC HFSS

The HYPE

[redacted]

Comprehensive EM Solutions
field computations involving objects of arbitrary shape

You are here: Home → Applications → EMC analysis

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[redacted]

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EMC analysis

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POST RESPONSE | RETURN TO INDEX | READ PREV MSG | READ NEXT MSG

Fluent Releases New [redacted] Software for Rapid Electromagnetic Compatibility and Interference (EMC/EMI) Designs

Posted By: Fluent <Send Email>
Date: Wed, 19 Oct 2005, 7:47 a.m.

[redacted] enable Thermal-EM Co-simulation

October 18, 2005, Austin, TX, USA

Fluent Inc., the worldwide leader in computational fluid dynamics (CFD), announces the immediate release of [redacted] 0, a three dimensional time-domain full-wave electro package. Along with the industry-leading thermal design software [redacted] wave enables thermal and electromagnetic compatibility and interference (EMC/EMI) co-simulat designers of high-performance electronics systems to dramatically reduce the time required for EMC/EMI design and verification by simulating electronic products in a virtual en

Complete Technology for 3D Electromagnetic Simulation

Choose Complete Technology for your electromagnetic simulation needs. Profit from our broad range of solver technology in an intuitive interface.

Find the solution best fitted for your problem in your market area:

Microwave & RF
Passive microwave & RF component design...

Signal Integrity / EDA
Signal Integrity is an ever increasing concern...

EMC / EMI
Electromagnetic Compatibility and Electromagnetic Interference...

Charged Particle Dynamics
Dynamics of free moving charged particles in electromagnetic fields...

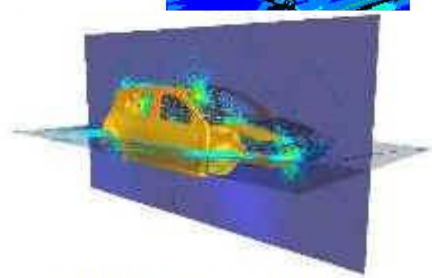
Low Frequency
Structures which are very small in comparison to a wavelength...

FEKO can compute electric and magnetic shielding factors for metallic or dielectric enclosures of arbitrary shape with arbitrary openings cut into them. Shielding effectiveness is typically tested for two scenarios:

available from the manufacturer.)

Software reduces physical testing in automotive EMC.

April 6, 2004 - [redacted] is computational electromagnetic simulation software for analyzing compatibility and interference problems. It includes [redacted], for induced phenomena on cable networks, and [redacted], for low-frequency analysis. Features include capabilities for antenna radiation simulation, modeling for on-board antennas and cable networks, and simulation of 3D radiated fields and induced effects on vehicle cable networks.



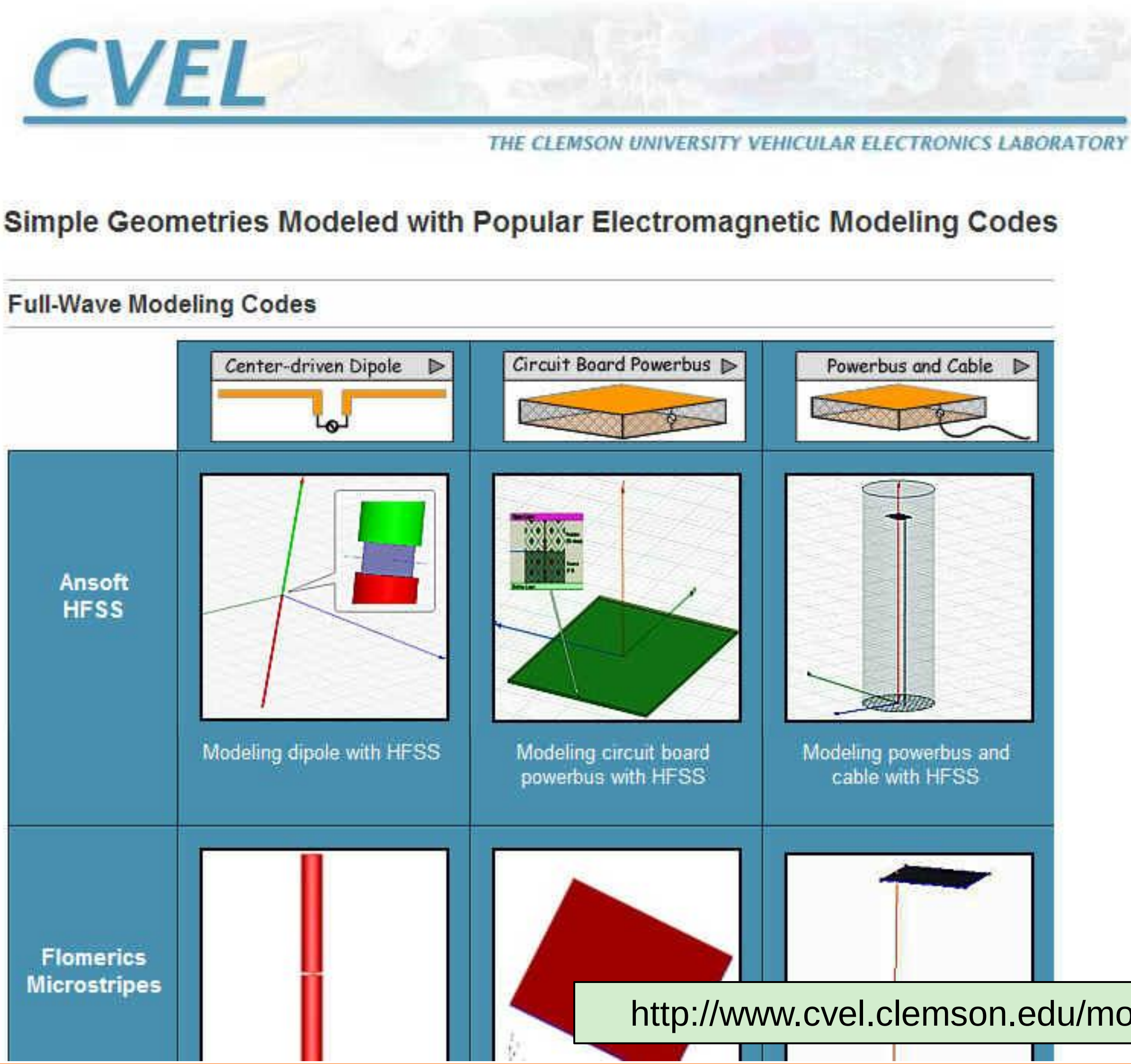
Software reduces physical testing in automotive EMC.

diagrams.

Examples:
- Differential Via Pair
- Multipin Connector
- SI Design from Allegro

EMC/EMI
Electromagnetic radiation from electronic components and radiation into housing can be studied with Microwave Studio. Field monitors are used to determine the EMC spectrum at the standard 3 and 10 meters distances. Linear or circularly polarized plane waves can be used to illuminate a housing to study EMI effects.

The REALITY



- Even simple geometries are difficult to model using most commercial tools.
- Software attempts to model configurations that it can't model.
- Geometries analyzed are not always the what the user is led to believe.
- Users must understand EM theory.
- Users must be familiar with the limitations of the particular technique.
- Users must be familiar with the peculiarities of the software and its user interface.

http://www.cvel.clemson.edu/modeling/software/

EMC Analysis Software

- Analytical Modeling Software

  specific geometries, closed-form equations
  limited scope, maximum convenience

- Numerical Modeling Software

  solves Maxwell's equations, accurate solutions to well-defined problems
  limited scope, requires expert user

- Design Rule Checkers

  review designs for rule violations that may result in problems
  very limited scope, maximum convenience

- Expert System / Maximum Emissions Calculators

  review designs for specific problem sources
  identify areas requiring a more careful evaluation
  estimate maximum possible emissions

EM Modeling Software

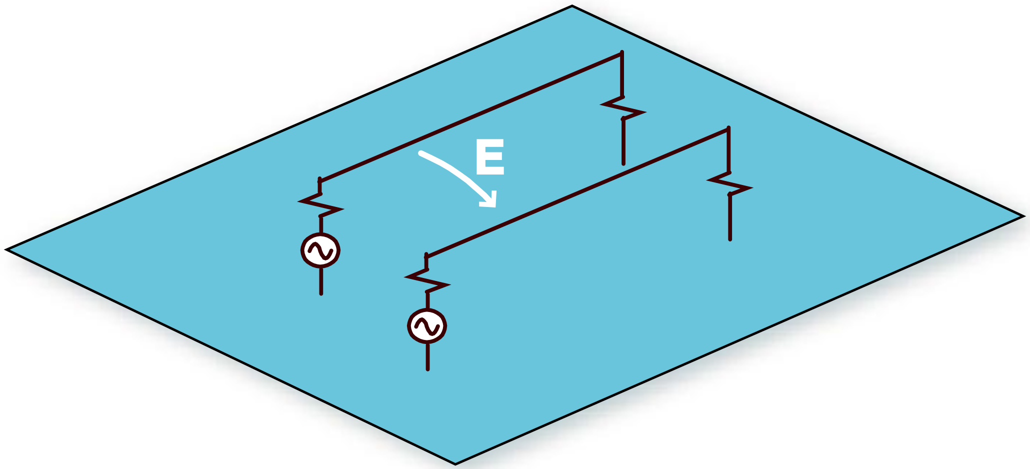
- Circuit and Transmission Line Solvers
- 2D and 3D Static Field Solvers
- 2D and "2.5 D" HF Field Solvers
- 3D HF (Full-Wave) Field Solvers

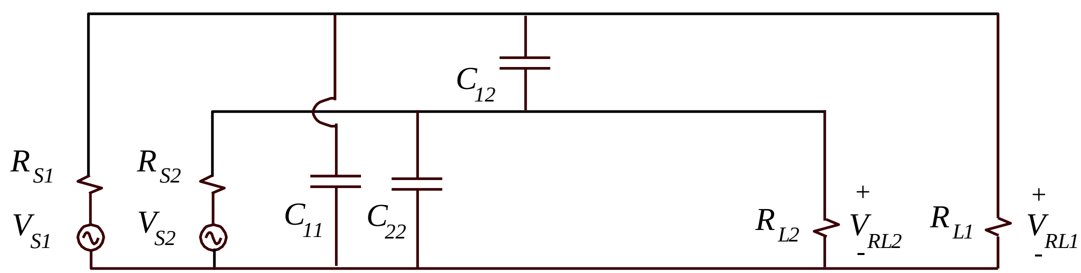
Circuit Solvers

Every EMC Engineer should have access to a basic SPICE-like circuit solver.

- Help's engineers to intuitively understand how intentional and unintentional currents propagate.
- For lumped-element modeling of signal paths and coupling paths.
- For time-domain modeling of RLC equivalent circuits.
- For modeling non-linear behavior of components and circuits.

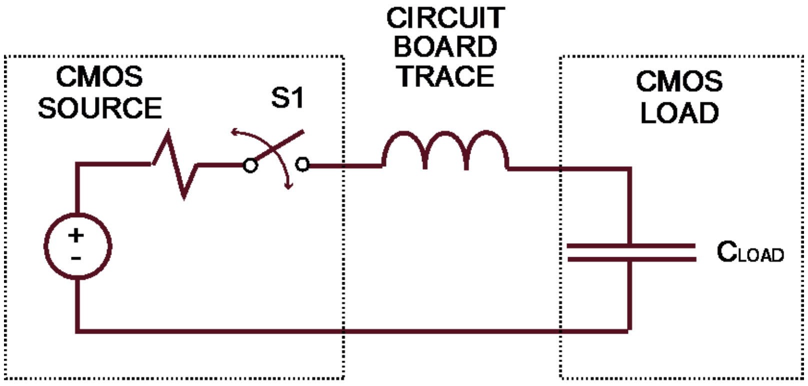
Lumped-Element Modeling

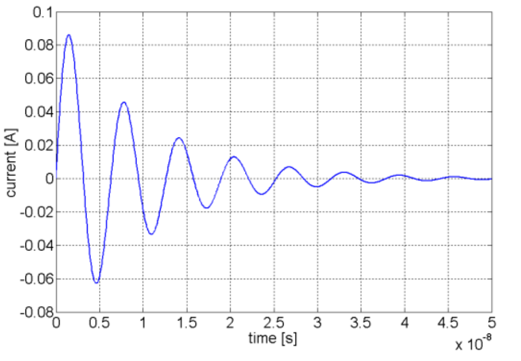




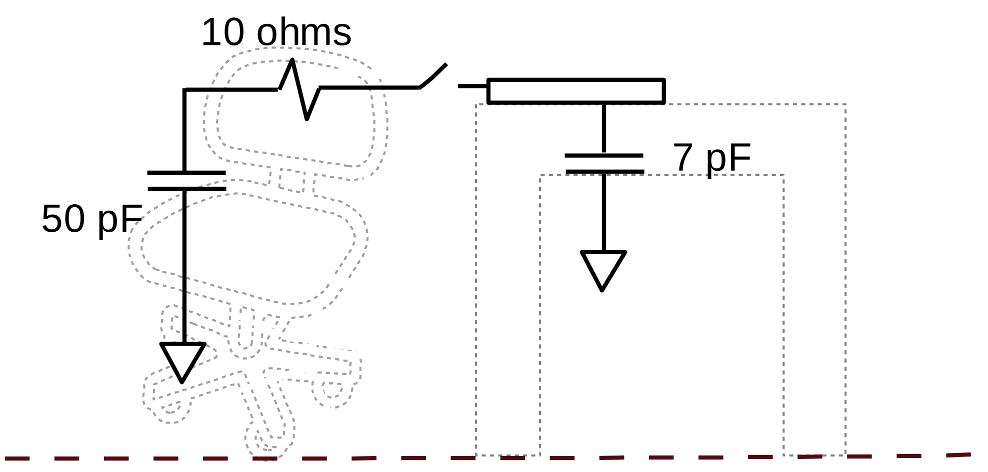
Modeling Time-Domain RLC Circuits

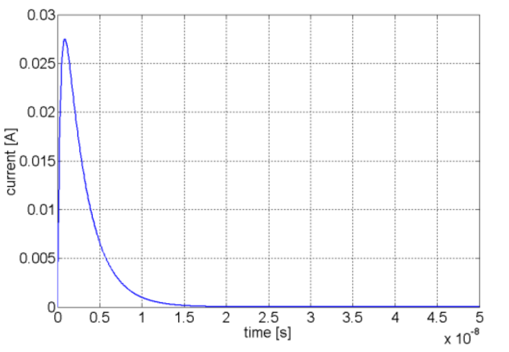
Circuit Board Nets



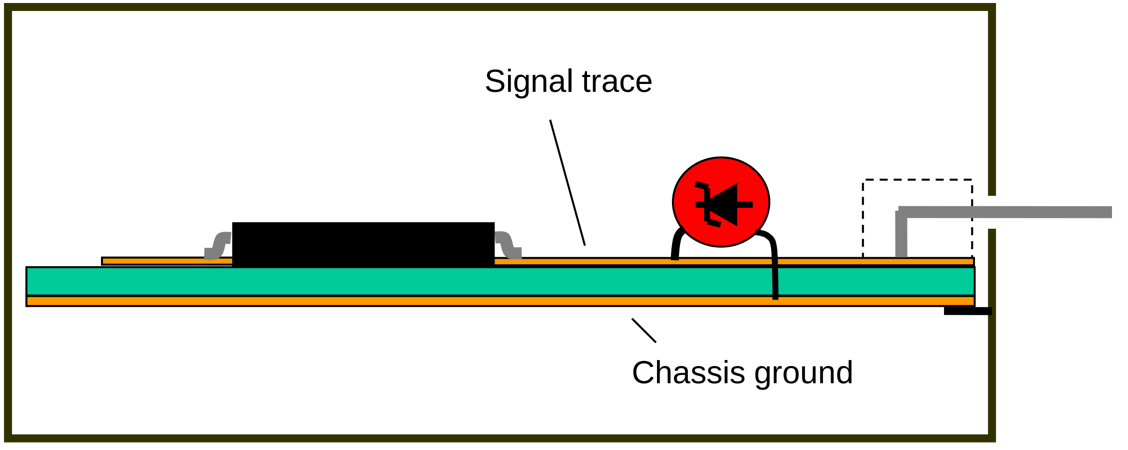


Electrostatic Discharge Events



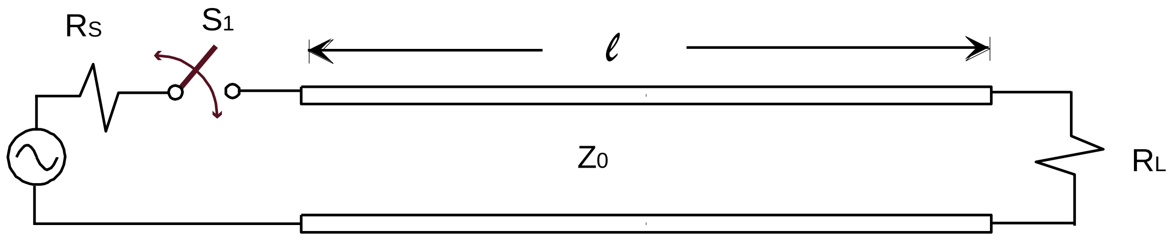


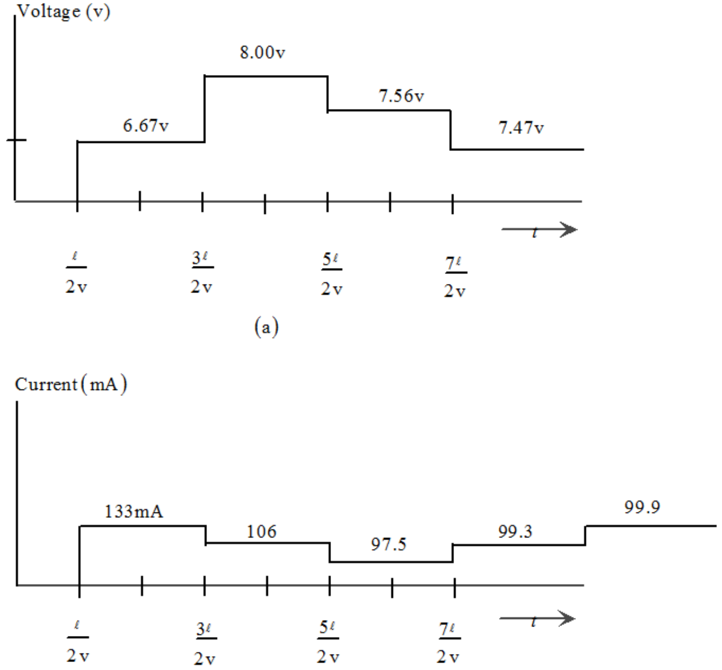
Modeling Non-Linear Behavior

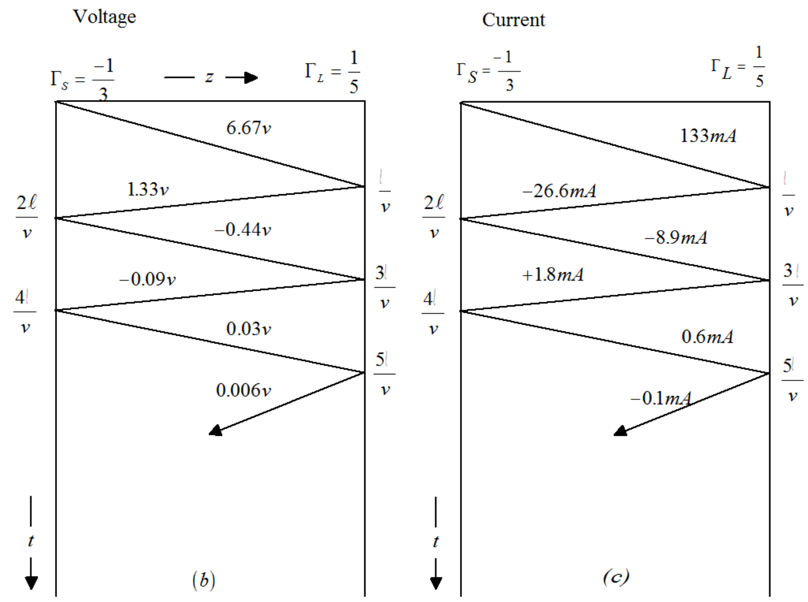


- Transient protection
- Ferrites near saturation
- IC inputs near saturation

Transmission Line Modeling





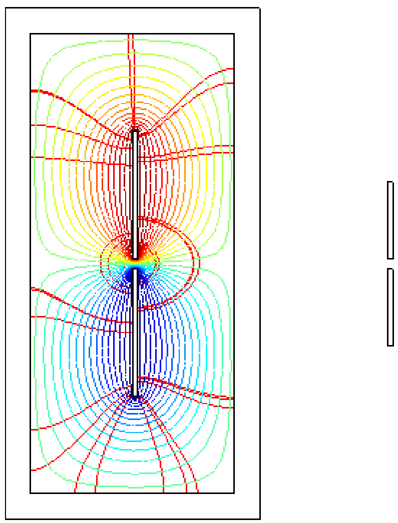


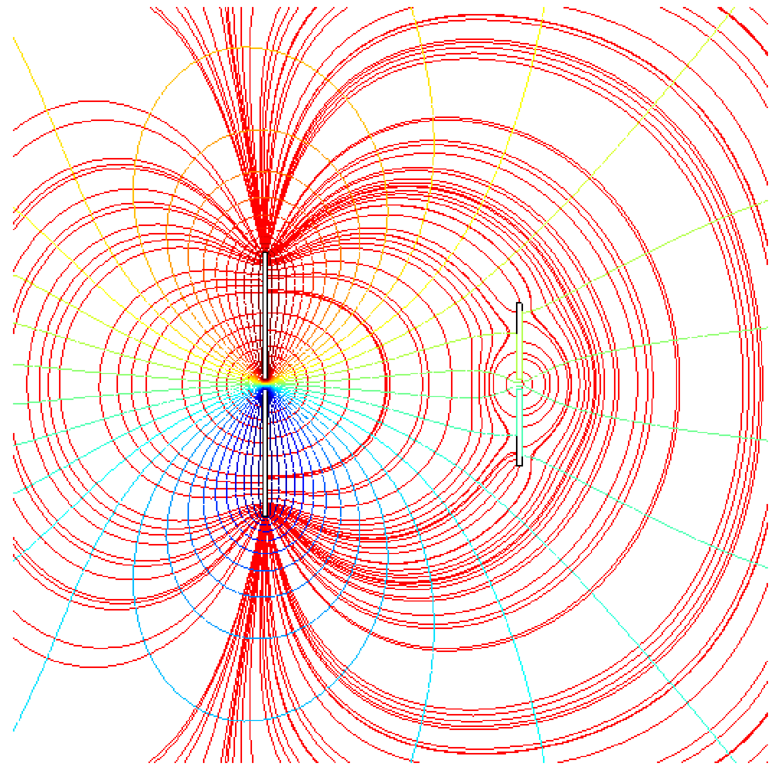
Static Electric-Field Solvers

A 2D or 3D static field solver is often the most useful computer modeling tool in an EMC Engineer's tool kit.

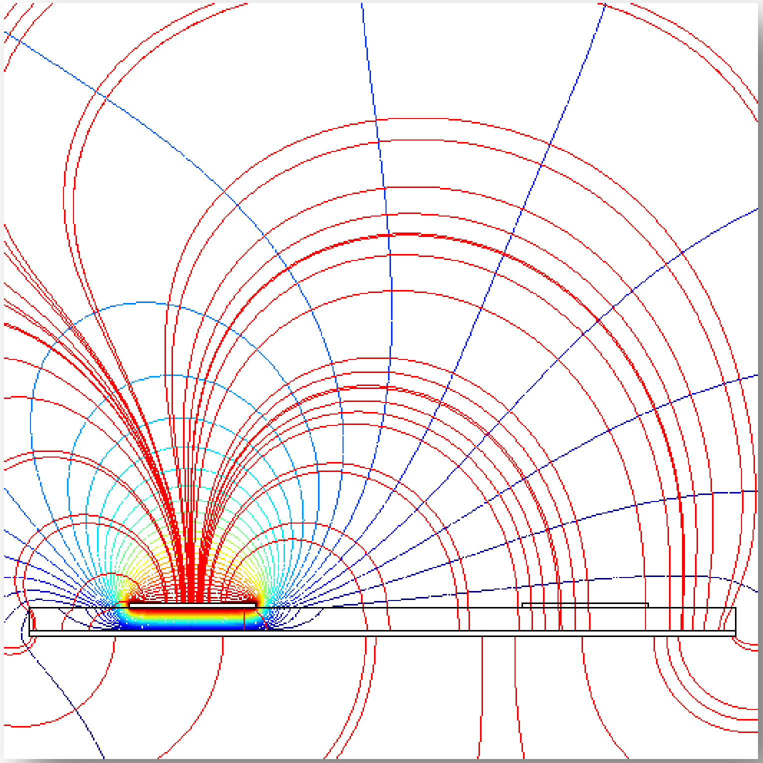
- Help's engineers to visualize electric fields
  - This is an essential skill for EMC engineers and HF board designers.
- Calculating "balance factor"
- Evaluating effectiveness of electric-field shields
- Estimating mutual capacitance of structures

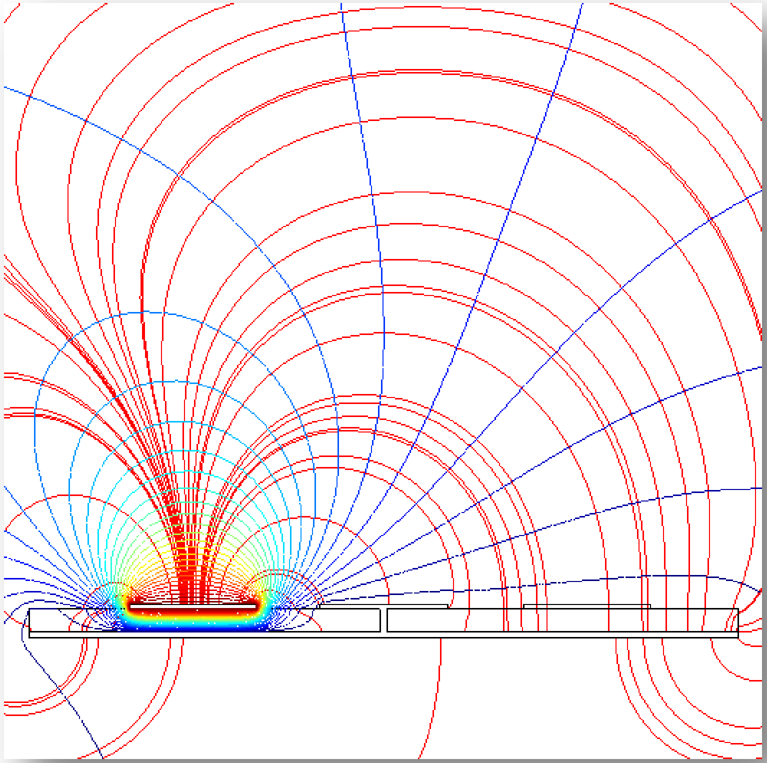
Electric Field Coupling/Shielding



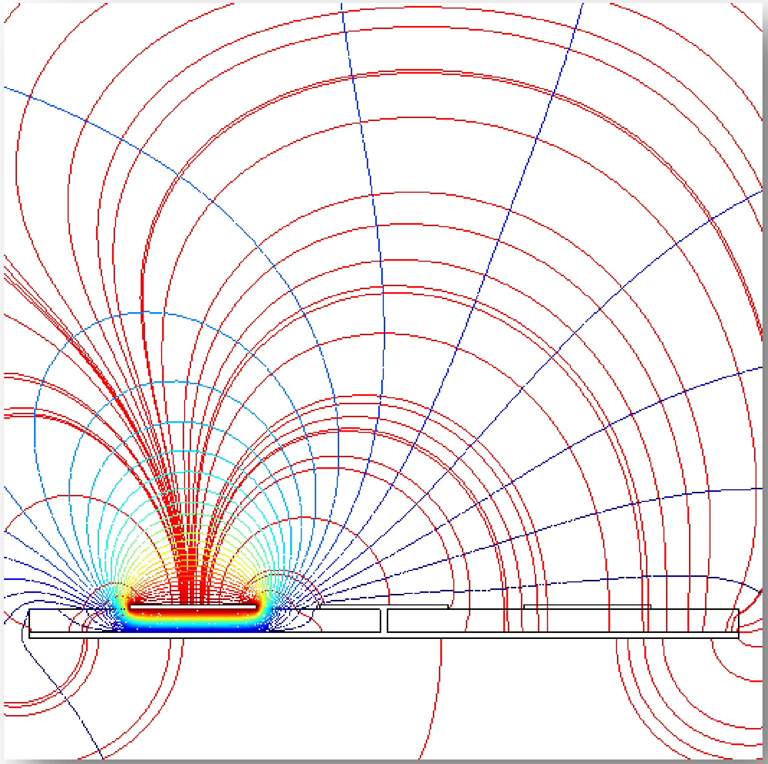


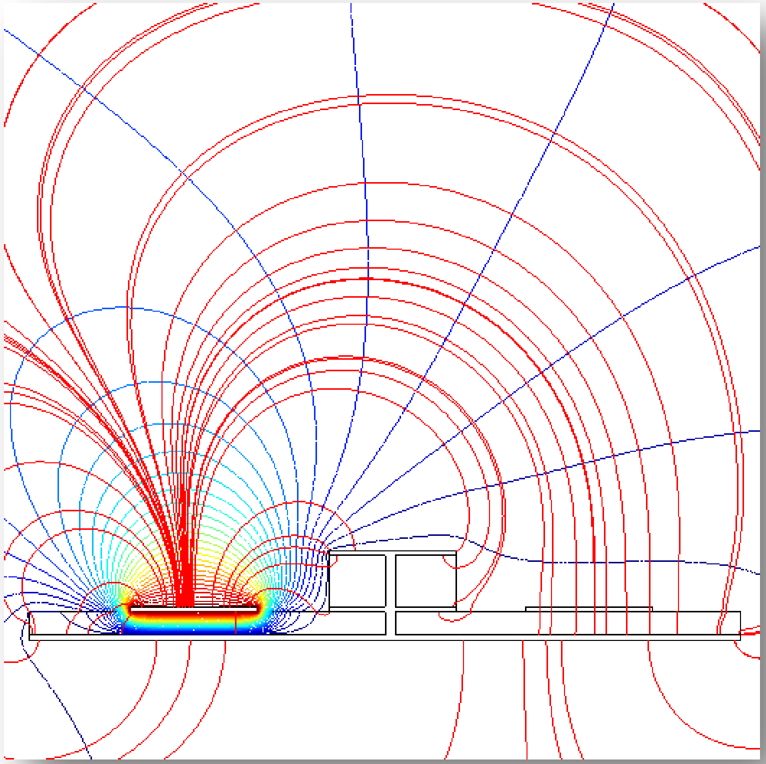
Guard Trace Effect



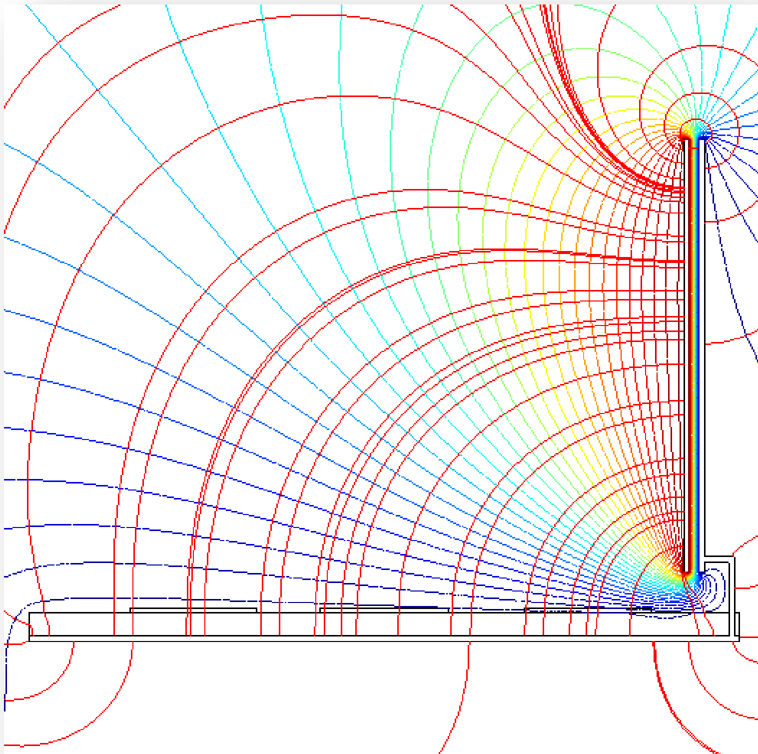


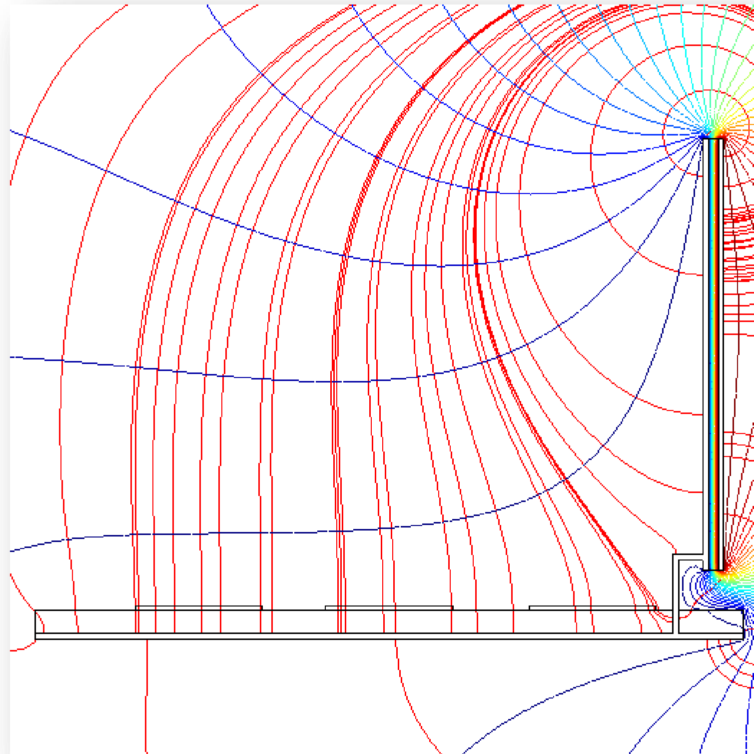
Guard Trace vs. Guard Stack



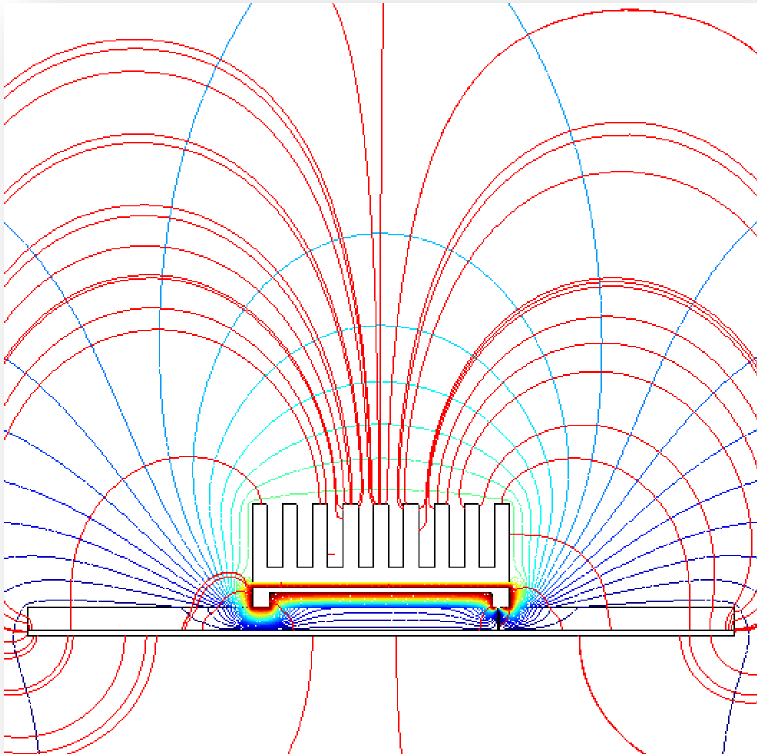


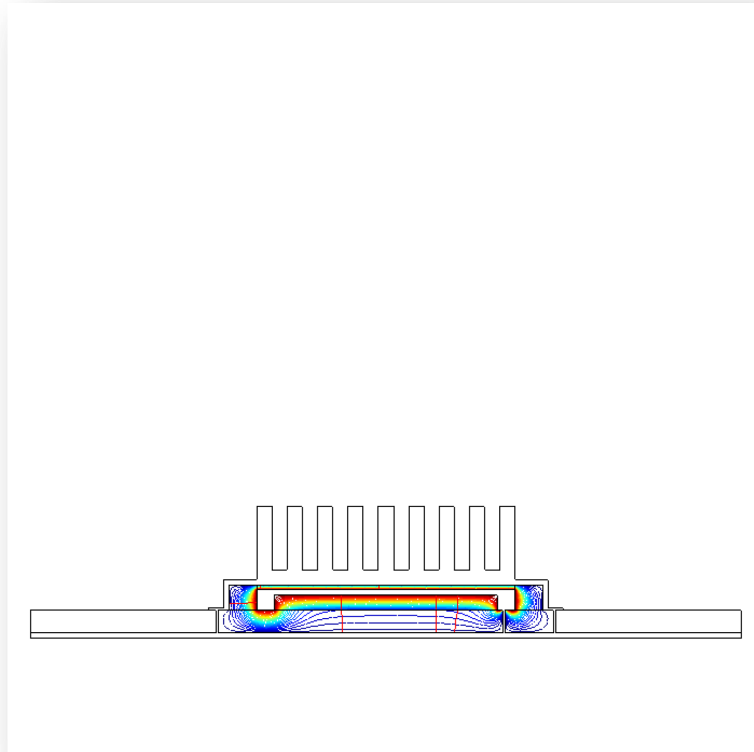
Orientation of Daughter Card



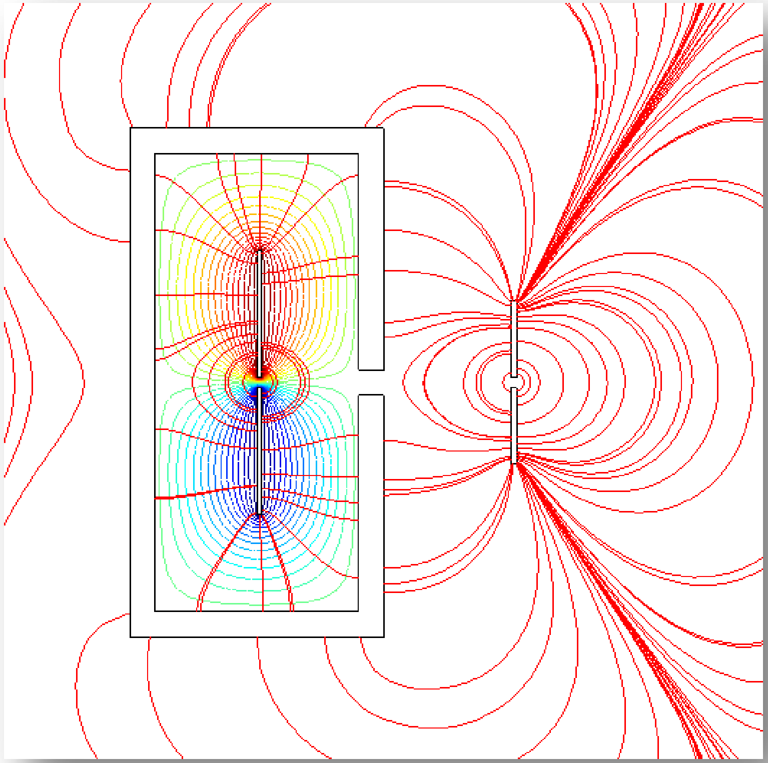


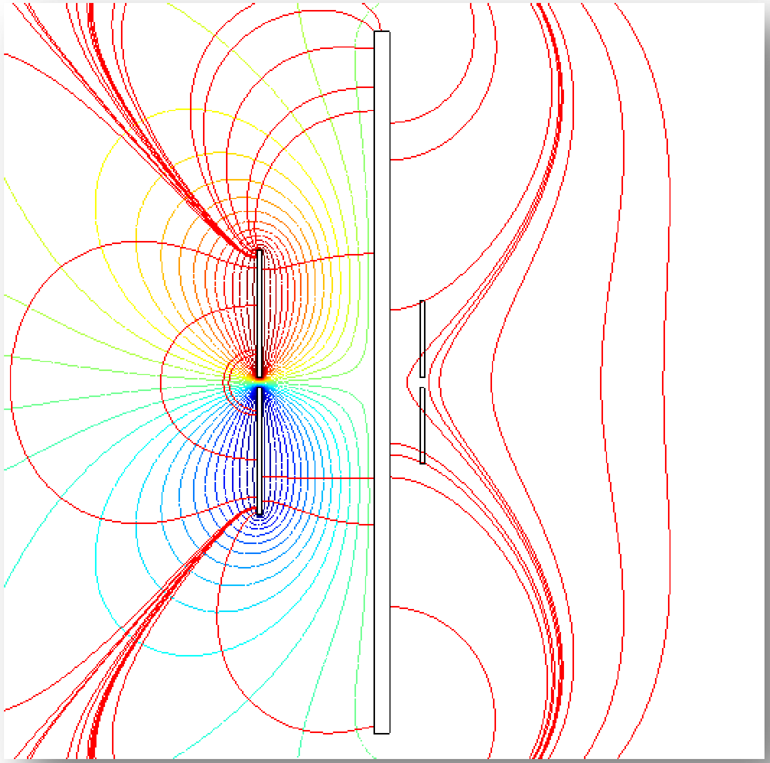
Grounding of Heatsink



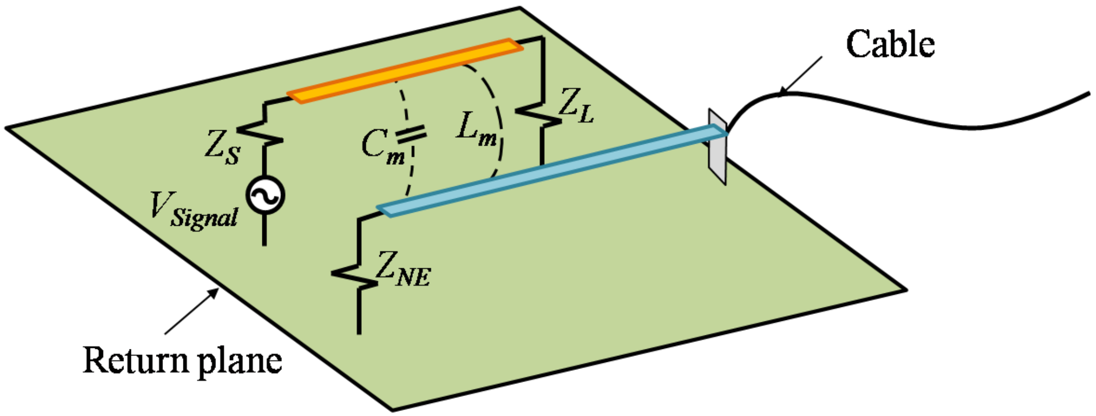


Effectiveness of Electric Field Shields

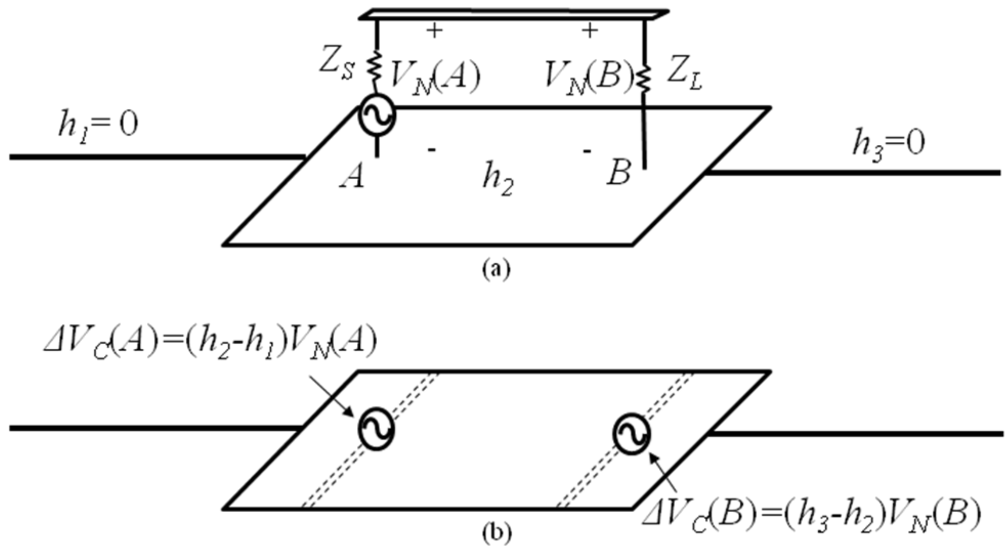




Calculating Mutual Capacitance



Calculating Imbalance Factor



$$\Delta V_C(A) = (h_2 - h_1)V_N(A)$$

$$\Delta V_C(B) = (h_3 - h_2)V_N(B)$$

T. Watanabe, O. Wada, T. Miyashita, and R. Koga, "Common-Mode-Current Generation Caused by Difference of Unbalance of Transmission Lines on a Printed Circuit Board with Narrow Ground Pattern," IEICE Trans. Commun. vol. E83-B, no. 3, Mar. 2000.

Calculating Imbalance Factor

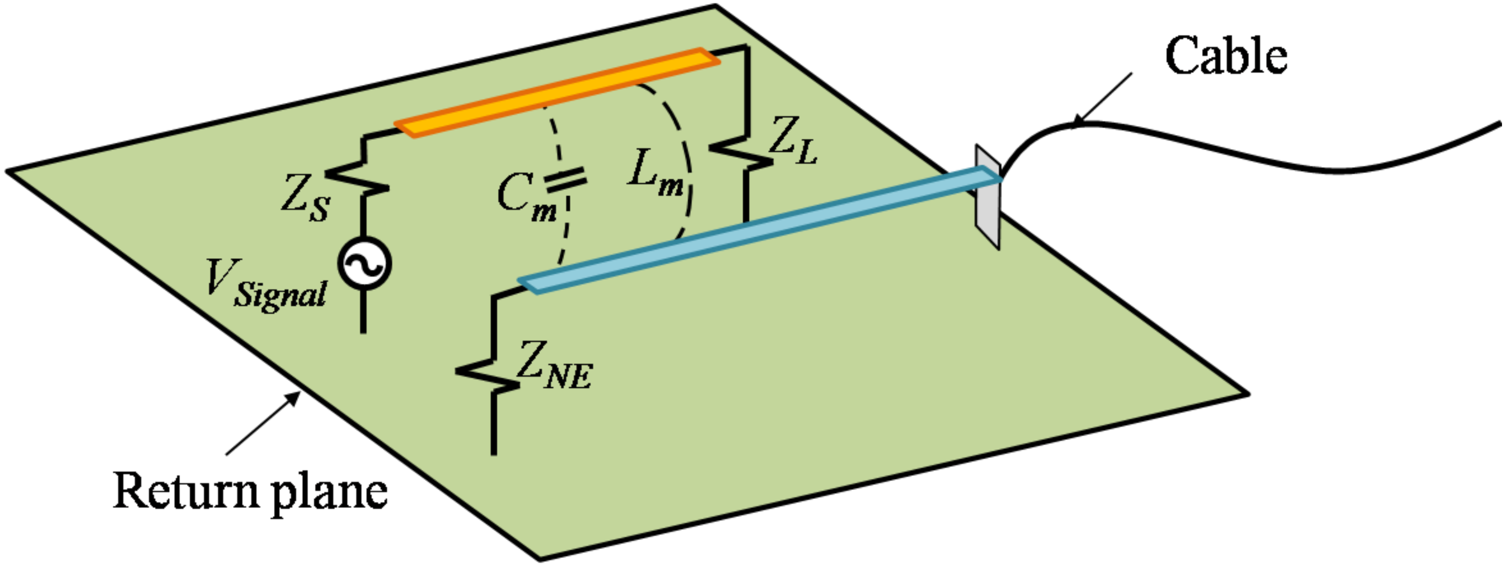
For microstrip trace structures, the imbalance parameter is given by,

$$h = \frac{C_{trace}}{C_{trace} + C_{board}}$$

where C_{trace} and C_{board} are the stray capacitances per unit length of the signal trace and the ground plane, respectively.

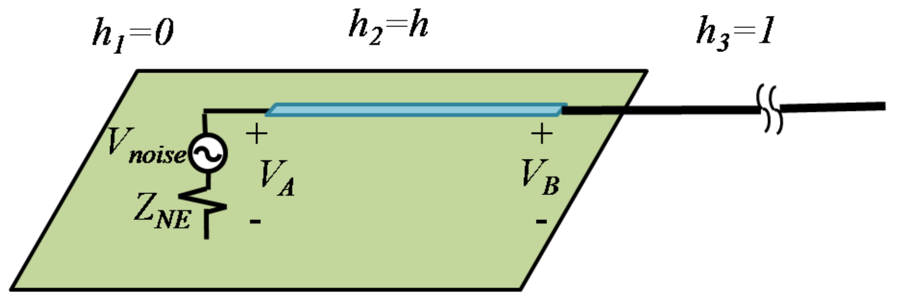
T. Watanabe, H. Fujihara, O. Wada, Y. Toyota, R. Koga, and Y. Kami, “A prediction method of common-mode excitation on a printed circuit board having a signal trace near the ground edge,” *IEICE Trans. Commun*. vol. E87-B, no. 8, Aug. 2004.

Example: Using balance factor to calculate emissions

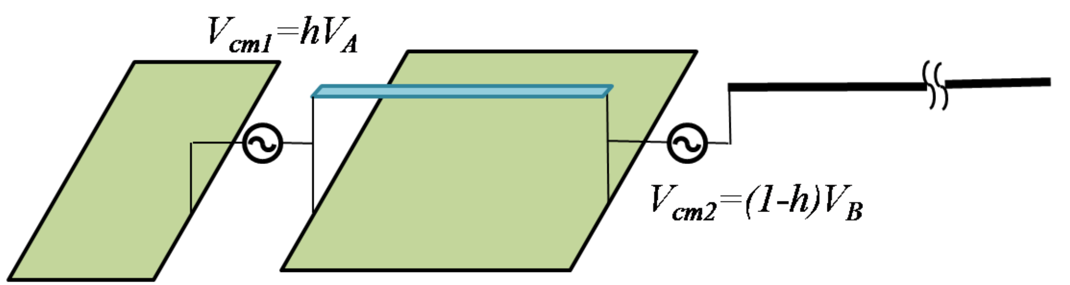


Unintended coupling to an I/O line.

Example: Using balance factor to calculate emissions



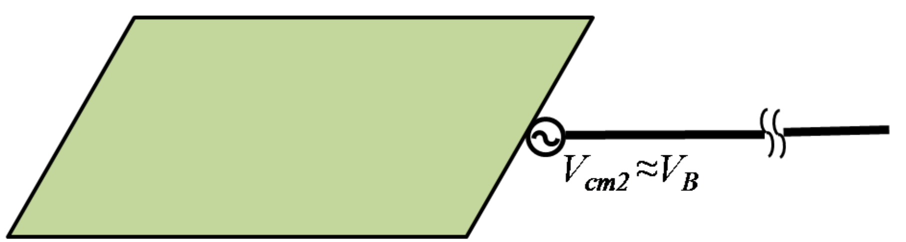
(a)



(b)

$$V_{CM1} = hV_A$$

$$V_{CM2} = (1-h)V_B$$

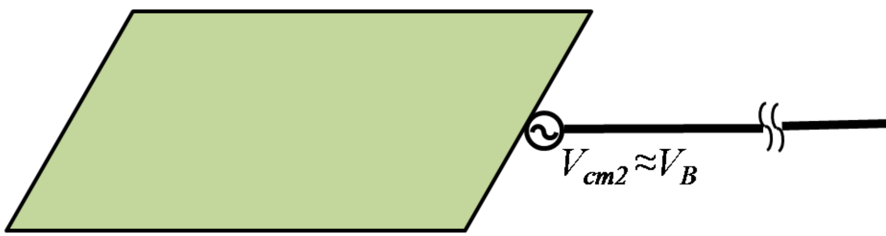


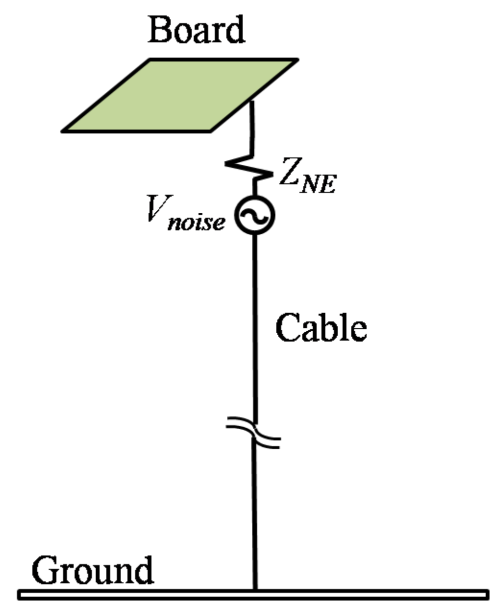
(c)

$$V_{CM1} \approx 0$$

$$V_{CM2} \approx V_B$$

Example: Using balance factor to calculate emissions





$$V_B = \left| \frac{Z_{FE}}{Z_{NE} + Z_{FE}} \right| V_{noise}$$

Equivalent antenna model.

2-D and "2.5-D" High-Frequency Field Solvers

High-Frequency field solvers are generally not capable of modeling static fields, but 2-D and 2.5-D tools have several advantages when compared to 3D Full-Wave field solvers.

Generally, they …

- Are **much** more efficient (i.e. faster and/or model more detail)
- Have a more intuitive user interface
- Less prone to numerical errors

2-D and "2.5-D" High-Frequency Field Solvers

Examples of 2-D and 2.5-D HF field solvers:

- 2D tools for modeling axi-symmetric 3D configurations
- 2D tools for modeling PCB cross-sections
- 2.5-D tools for modeling PCB traces in layered media

3-D High-Frequency (Full Wave) Field Solvers

3-D full wave modeling codes are useful for:

- Learning about EM wave propagation
- Understanding how different structures can act as antennas
- Modeling the behavior of circuit components and packages
- Developing and validating other types of models
- Validating measurements of well defined source configurations

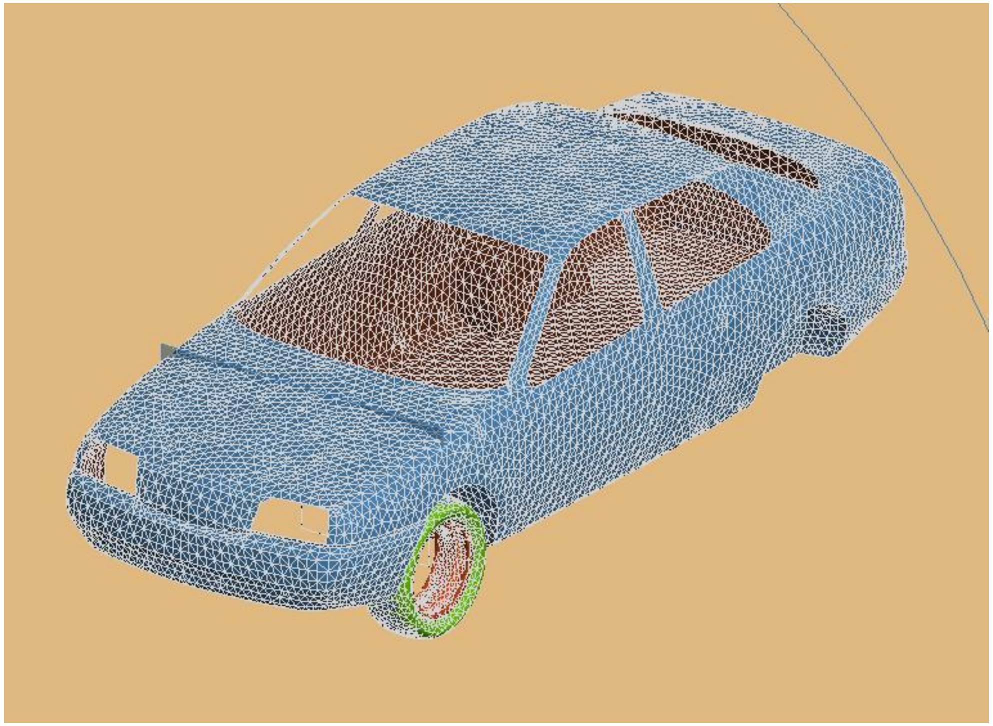
3-D High-Frequency (Full Wave) Field Solvers

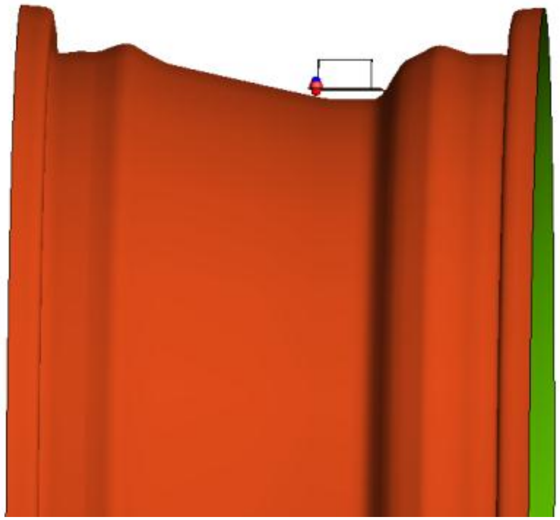
3-D full wave modeling codes are NOT useful for:

- Evaluating existing product designs
- Predicting EMC problems
- Troubleshooting EMC problems
- Validating EMI measurements of electronic devices

3-D High-Frequency (Full Wave) Field Solvers

Understanding how different structures can act as antennas

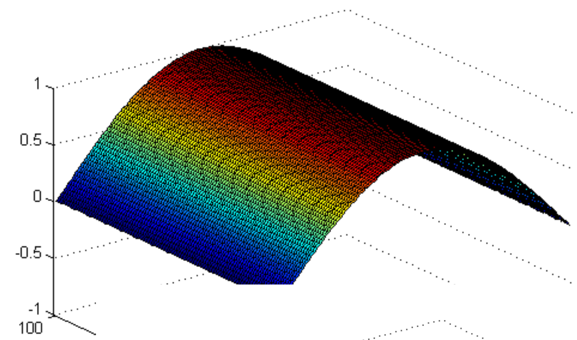


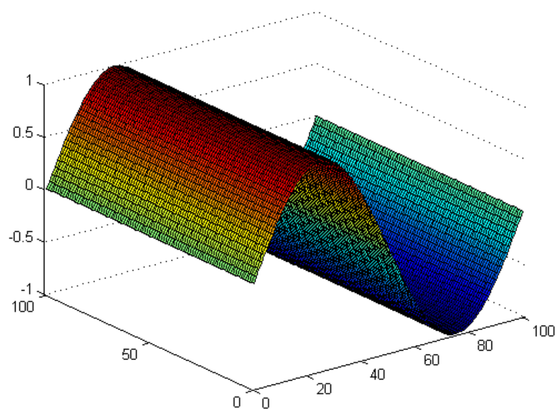


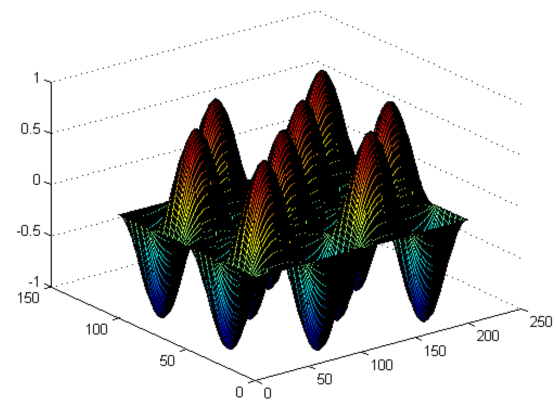
CLEMSON UNIVERSITY INTERNATIONAL CENTER FOR AUTOMOTIVE RESEARCH

3-D High-Frequency (Full Wave) Field Solvers

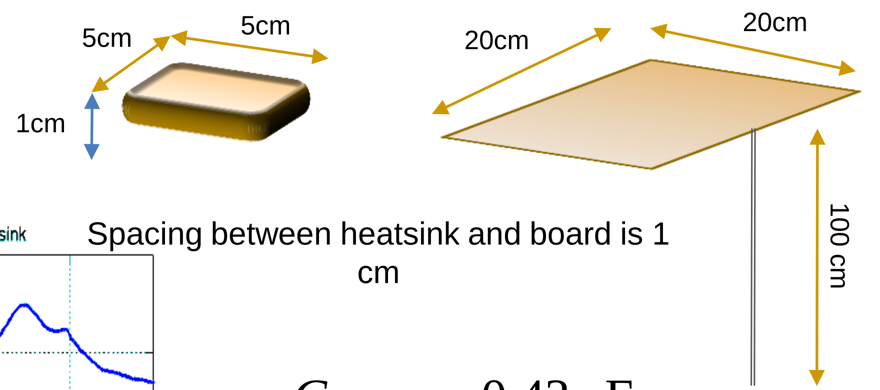
Finding resonant frequencies of structures



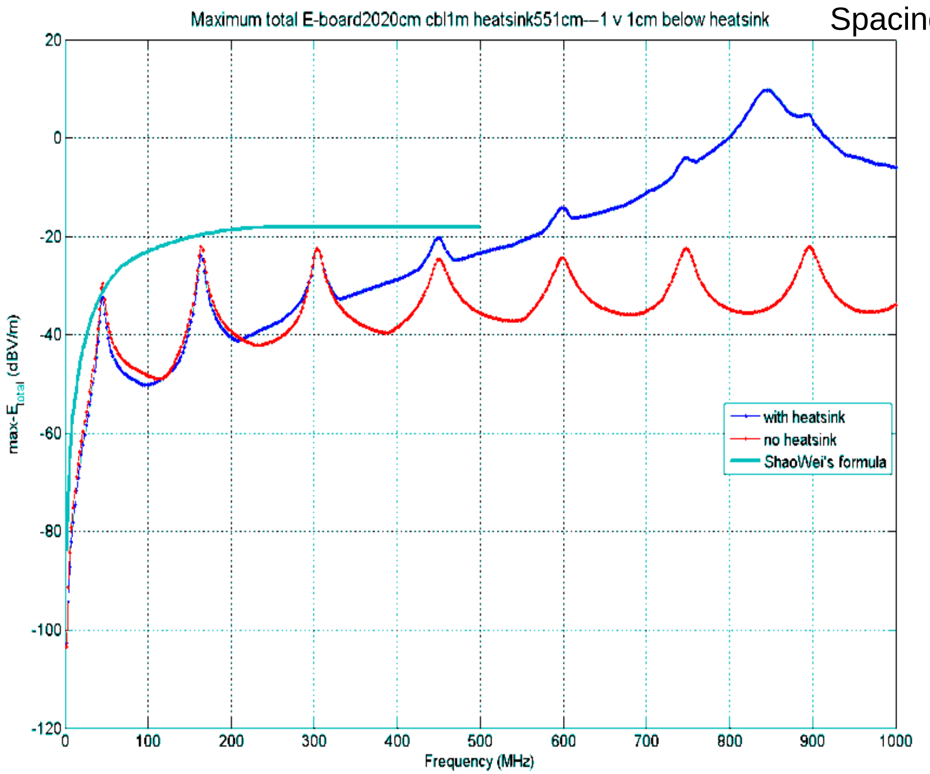




Validating Maximum Radiated Emissions Calculations



Spacing between heatsink and board is 1 cm



$$C_{\text{heatsink}} = 0.43\ \text{pF}$$

$$C_{\text{board}} = 5.14\ \text{pF}$$

Low-Cost CEM Tools

Free Software:

- FEMM
- Ansoft Maxwell SV
- EMAP
- Students' QuickField
- Antenna Model
- LC
- MEEP
- OpenFMM
- pdnMesh
- Radia
- ToyFDTD
- Scatlab

$2k - $10k:

- EZ-EMC
- EZNEC Pro
- GEMACS
- Tricomp-Estat
- Trace Analyzer

CEM Tools (more than $10k)

- AMDS
- All IES codes (Ampere …)
- Analyst
- ApsimFDTD-SPICE
- AXIEM
- CableMod/PCBMod
- Compliance
- Comsol Multiphysics
- CRIPTE
- CST Microwave Studio
- EMA3D
- EMC Studio
- EMDS
- Maxwell
- MFlex
- emGine Environment
- EMPIRE Xccel
- Fidelity
- FEKO
- GEMS
- HFSS
- HFWorks
- IE3D
- JCMSuite
- OptEM Cable Designer
- OptEM Inspector
- Magnet
- Microwave Office
- Momentum
- PAM-CEM
- Q3D Extractor
- SEMCAD X
- Sonnet
- WIPL-D Pro
- Xenos
- XFDTD
- XGtd

Key Point

Computer models often yield incorrect results because:

- Software was not capable of analyzing the input configuration
- Software defaults were inappropriate for the problem
- The input was not exactly what the user thought
- Results were misinterpreted by the user

Summary

- Numerical EM modeling tools require the user to be familiar with EM theory, the limitations of the techniques being applied, and the limitations of the particular software implementation.

- Numerical EM modeling tools should only be trusted when the solutions can be confirmed by other methods.

- Numerical EM modeling tools are NOT particularly useful for the design and troubleshooting of digital electronics products.

Design Rule Checkers

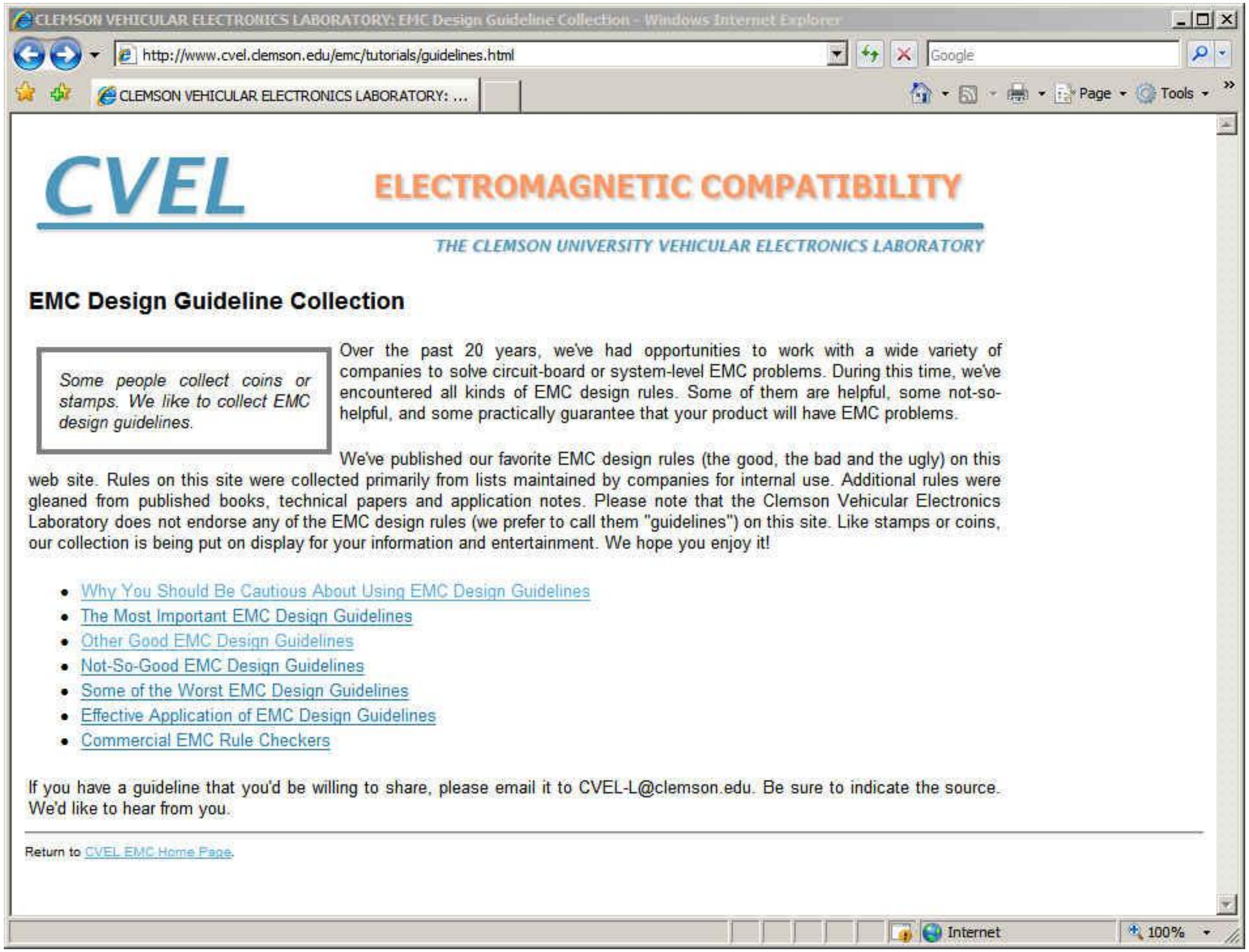
Scan a board layout looking for design rule violations.

Advantages – Easier to understand what the software is doing
Easier to use.

Disadvantages – Design rules don't apply in all situations
Higher board cost to meet unnecessary design rules
Will not detect problems that don't violate a pre-defined rule

EMC Design Guideline Collection

http://www.cvel.clemson.edu/emc/


CLEMSON VEHICULAR ELECTRONICS LABORATORY: EMC Design Guideline Collection - Windows Internet Explorer

http://www.cvel.clemson.edu/emc/tutorials/guidelines.html

CVEL ELECTROMAGNETIC COMPATIBILITY

THE CLEMSON UNIVERSITY VEHICULAR ELECTRONICS LABORATORY

EMC Design Guideline Collection

Some people collect coins or stamps. We like to collect EMC design guidelines.

Over the past 20 years, we've had opportunities to work with a wide variety of companies to solve circuit-board or system-level EMC problems. During this time, we've encountered all kinds of EMC design rules. Some of them are helpful, some not-so-helpful, and some practically guarantee that your product will have EMC problems.

We've published our favorite EMC design rules (the good, the bad and the ugly) on this web site. Rules on this site were collected primarily from lists maintained by companies for internal use. Additional rules were gleaned from published books, technical papers and application notes. Please note that the Clemson Vehicular Electronics Laboratory does not endorse any of the EMC design rules (we prefer to call them "guidelines") on this site. Like stamps or coins, our collection is being put on display for your information and entertainment. We hope you enjoy it!

- Why You Should Be Cautious About Using EMC Design Guidelines
- The Most Important EMC Design Guidelines
- Other Good EMC Design Guidelines
- Not-So-Good EMC Design Guidelines
- Some of the Worst EMC Design Guidelines
- Effective Application of EMC Design Guidelines
- Commercial EMC Rule Checkers

If you have a guideline that you'd be willing to share, please email it to CVEL-L@clemson.edu. Be sure to indicate the source. We'd like to hear from you.

Return to CVEL EMC Home Page.

What is a PCB EMC Expert System?

EMC Expert System software should work with automated printed circuit board layout tools to:

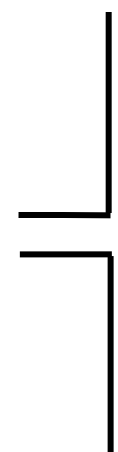
- review and analyze printed circuit board designs;
- point out problems with the layout;
- estimate levels of radiated EMI;
- anticipate ESD and radiated susceptibility problems; and
- provide circuit and board layout design advice.

Using the same general approach that human experts would use.

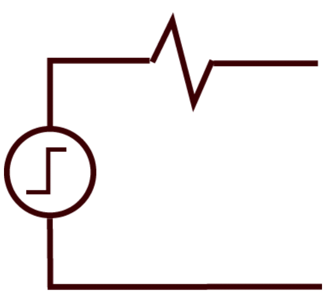
EMI Estimation Algorithms

- Identify Sources
- Identify Antennas
- Evaluate Radiation Mechanisms

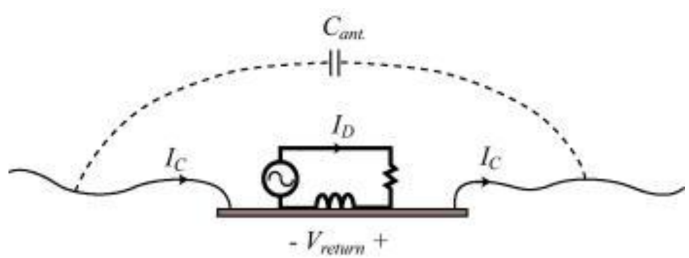
Antenna Model



Source Model



Coupling Path Model



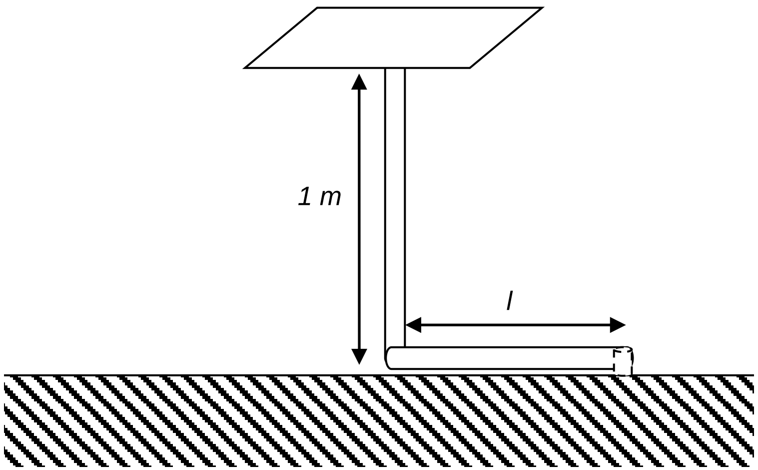
Radiation Mechanisms

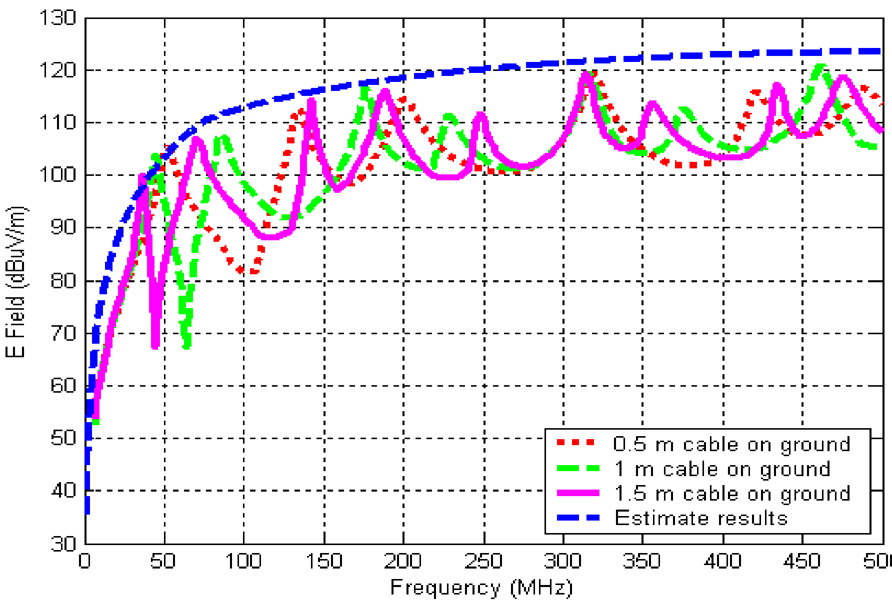
- Differential-Mode Radiation
  - from electrically small structures
  - from resonant structures
- Coupling to I/O Radiation
  - crosstalk on circuit board
  - near-field coupling to connector
- Voltage-Driven Common-Mode Radiation
  - from cables (coupled from traces or heatsinks)
  - from shielded enclosures
- Current-Driven Common-Mode Radiation
  - from cables
  - from shielded enclosures
- Power Bus Radiation
  - directly from power bus
  - coupled to shielded enclosure

Expert System Algorithms are constantly asking the question,

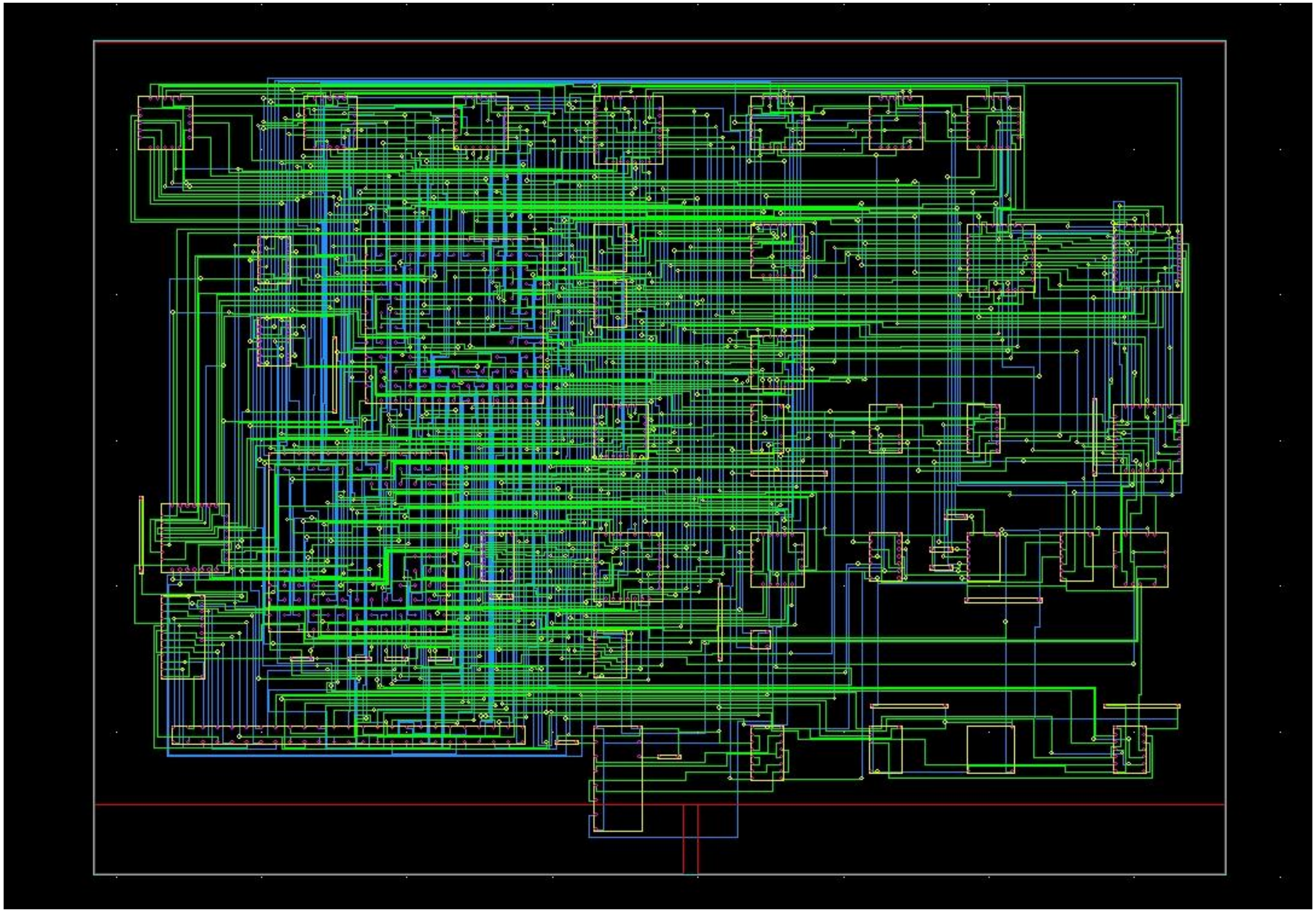
What is the worst that could happen?

Effect of Extended Cable on Ground





Algorithms Locate Hard-to-Find Problems



Algorithms Locate Hard-to-Find Problems

Type of Problem Identified

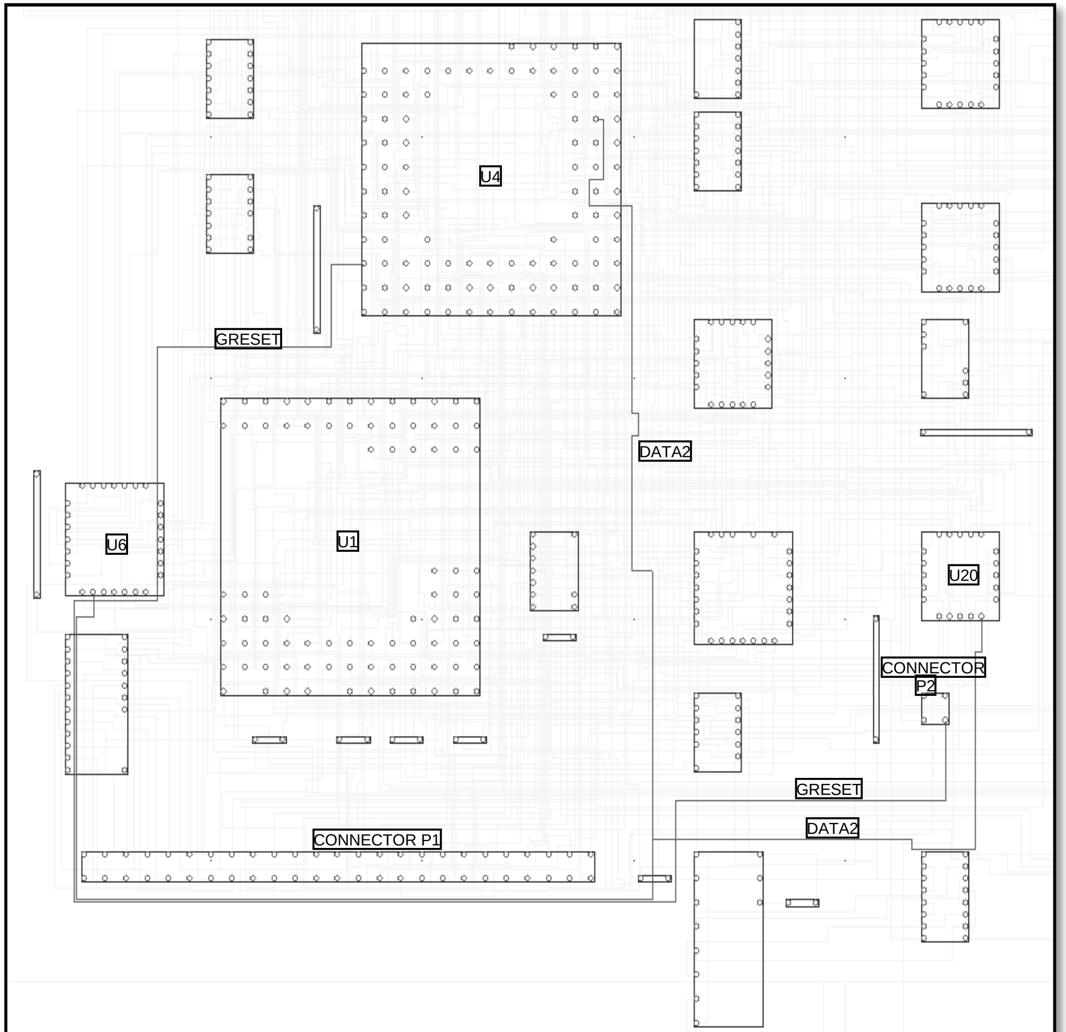
Problem	Advice
UMR Signal Net Analysis - This net is coupled to I/O Net GRESET.	Re-Route this net or I/O Net GRESET

DRC	Net	Summary	Total_E/Frequency	DM_E/Frequency	ICM_E/Frequency	VCM_E/Frequency	Antennas
All	All	All	All	All	All	All	All
UMR Signal Net Analysis	DATA2	Edge Rate Too Fast	28.0 450.0	24.0 710.0	19.0 595.0	27.0 130.0	C--B
UMR Signal Net Analysis	DATA2	Coupled to I/O Net	28.0 450.0	24.0 710.0	19.0 595.0	27.0 130.0	C--B
UMR Signal Net Analysis	DATA2	Voltage driven common mode	28.0 450.0	24.0 710.0	19.0 595.0	27.0 130.0	C--B

Location of Problem

Magnitude and Frequency of Problem

Algorithms Locate Hard-to-Find Problems



View of left half of board showing the problem nets.

Algorithms Locate Hard-to-Find Problems

Type of Problem Identified

Problem: UMR Signal Net Analysis - The ground noise voltage drives Connector P2 against Connector P1.

Advice: Locate Connector P2 and Connector P1 closer to each other

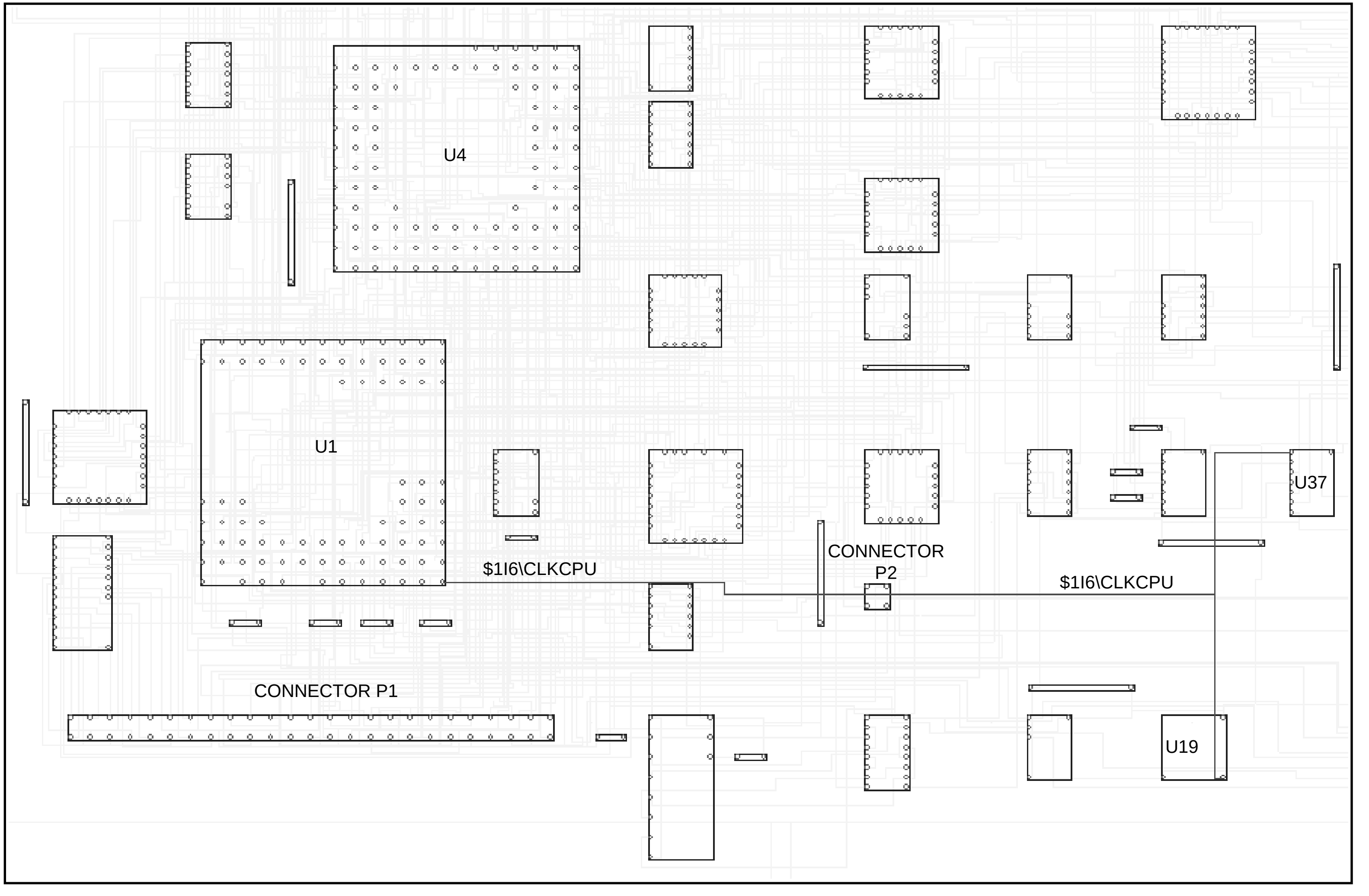
DRC	Net	Summary	TotaL_E/Frequency	DM_E/Frequency	ICM_E/Frequency	VCM_E/Frequency	Antennas
All	All	All	All	All	All	All	All
UMR Signal Net Analysis	$1I6\CLKCPU	Current driven common mode	52.0 650.0	50.0 750.0	49.0 450.0	-99.0 50.0	C--C
UMR Signal Net Analysis	$1I6\CLKCPU	Edge Rate Too Fast	52.0 650.0	50.0 750.0	49.0 450.0	-99.0 50.0	C--C
UMR Signal Net Analysis	$1I6\CLKCPU	Too Much Surface Route	52.0 650.0	50.0 750.0	49.0 450.0	-99.0 50.0	C--C

Location of Problem

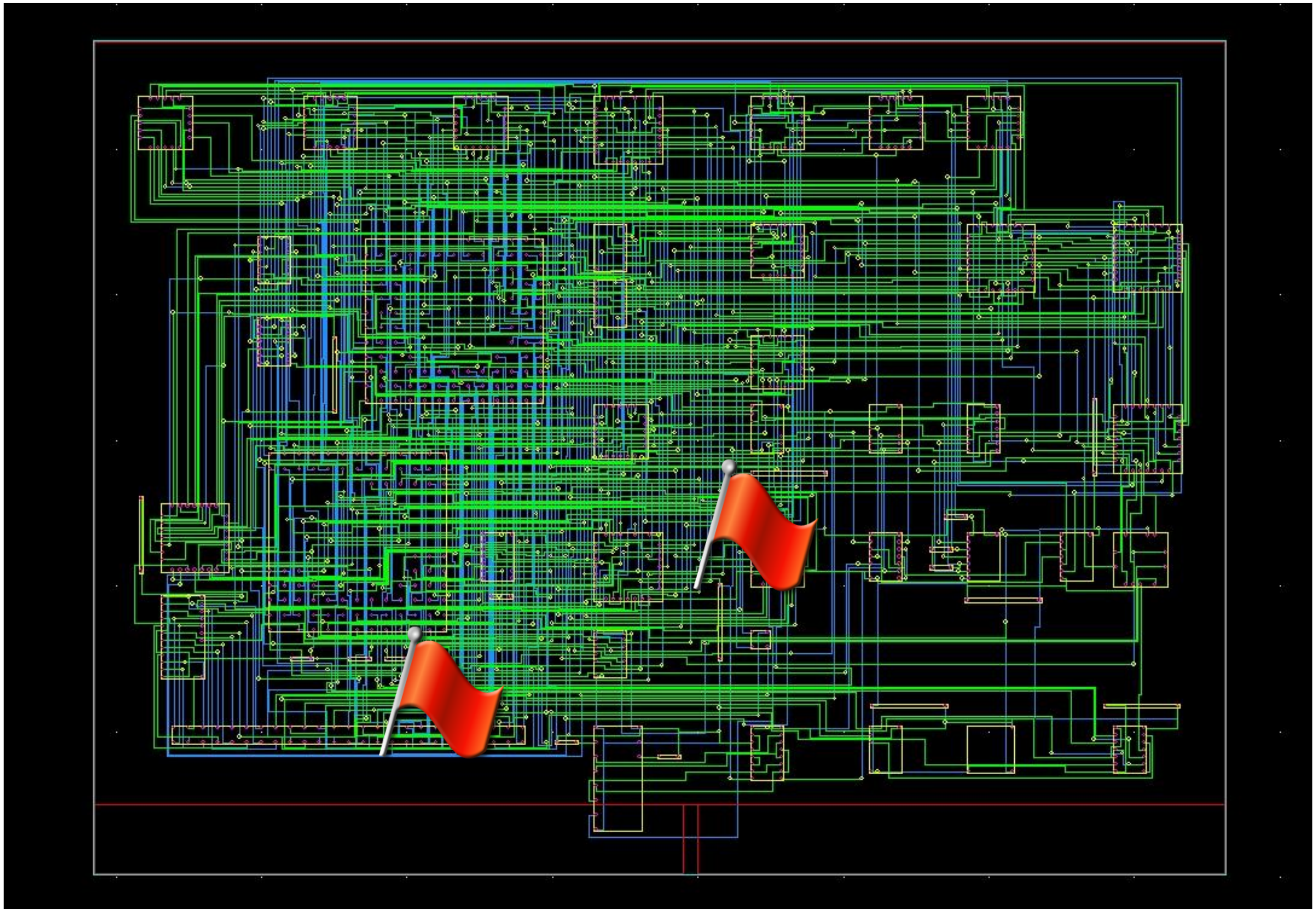
Magnitude and Frequency of Problem

Algorithms Locate Hard-to-Find Problems

Current-Driven Common-Mode Problem.



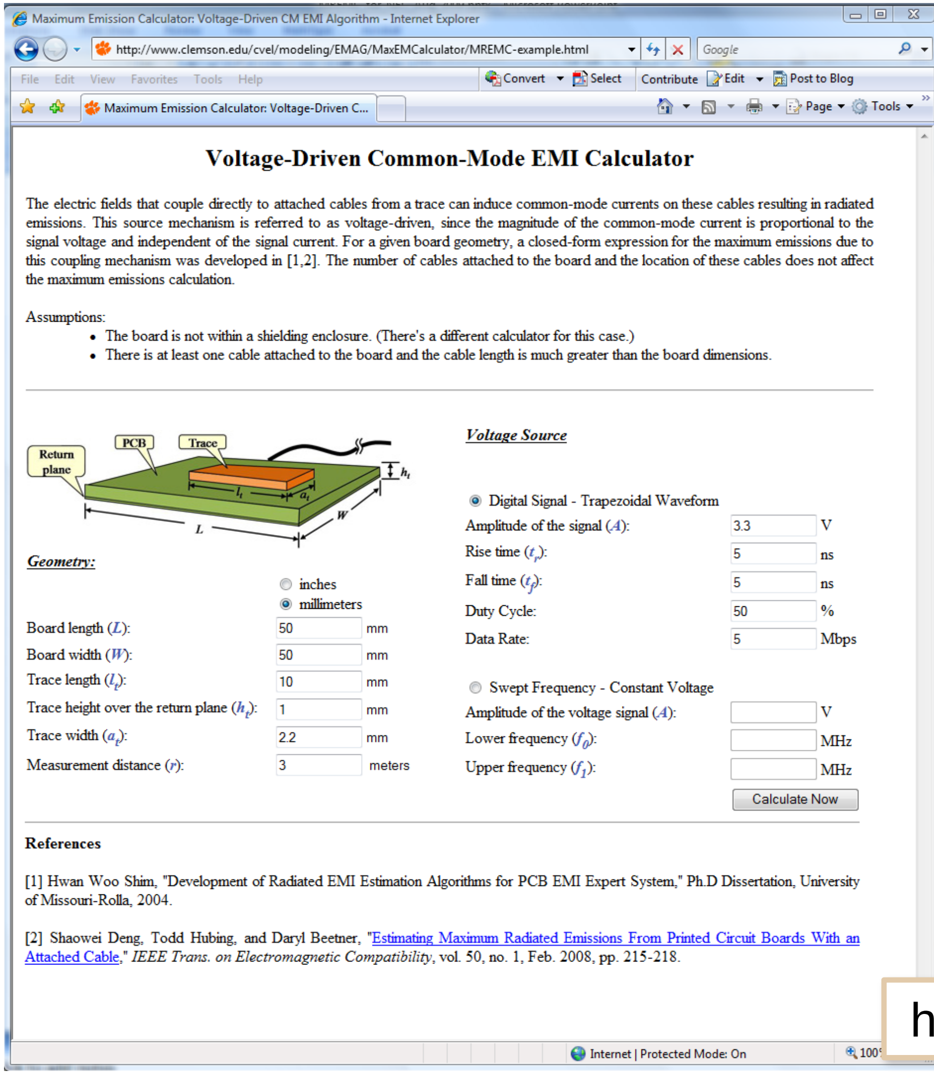
Algorithms Locate Hard-to-Find Problems



Maximum Radiated EMissions Calculator

MR EMC

Maximum Radiated Emissions Calculator



Maximum Emission Calculator: Voltage-Driven CM EMI Algorithm - Internet Explorer

http://www.clemson.edu/cvel/modeling/EMAG/MaxEMCalculator/MREMC-example.html

Voltage-Driven Common-Mode EMI Calculator

The electric fields that couple directly to attached cables from a trace can induce common-mode currents on these cables resulting in radiated emissions. This source mechanism is referred to as voltage-driven, since the magnitude of the common-mode current is proportional to the signal voltage and independent of the signal current. For a given board geometry, a closed-form expression for the maximum emissions due to this coupling mechanism was developed in [1,2]. The number of cables attached to the board and the location of these cables does not affect the maximum emissions calculation.

Assumptions:

- The board is not within a shielding enclosure. (There's a different calculator for this case.)
- There is at least one cable attached to the board and the cable length is much greater than the board dimensions.

Geometry:

- inches
- millimeters

Board length (L):	50	mm
Board width (W):	50	mm
Trace length (l_t):	10	mm
Trace height over the return plane (h_t):	1	mm
Trace width (a_t):	2.2	mm
Measurement distance (r):	3	meters

Voltage Source

Digital Signal - Trapezoidal Waveform

Amplitude of the signal (A):	3.3	V
Rise time (t_r):	5	ns
Fall time (t_f):	5	ns
Duty Cycle:	50	%
Data Rate:	5	Mbps

Swept Frequency - Constant Voltage

Amplitude of the voltage signal (A):		V
Lower frequency (f_0):		MHz
Upper frequency (f_1):		MHz

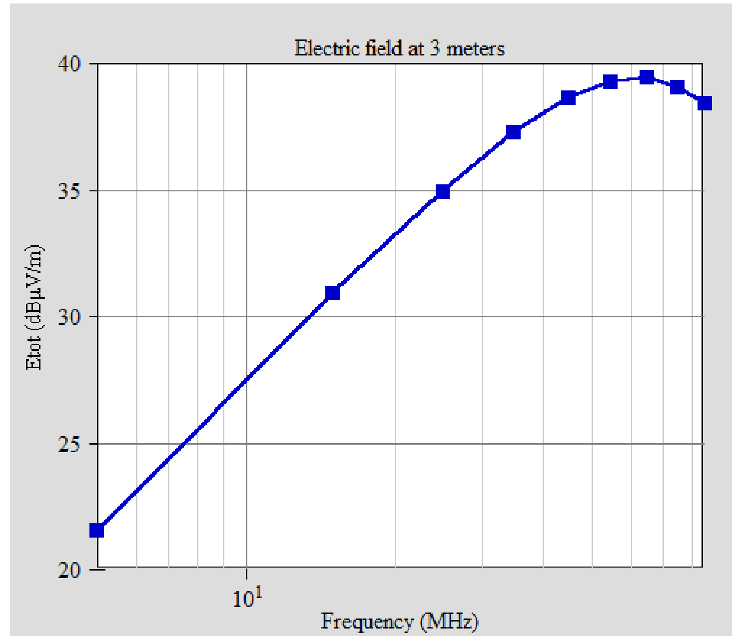
Calculate Now

References

[1] Hwan Woo Shim, "Development of Radiated EMI Estimation Algorithms for PCB EMI Expert System," Ph.D Dissertation, University of Missouri-Rolla, 2004.

[2] Shaowei Deng, Todd Hubing, and Daryl Beetner, "Estimating Maximum Radiated Emissions From Printed Circuit Boards With an Attached Cable," *IEEE Trans. on Electromagnetic Compatibility*, vol. 50, no. 1, Feb. 2008, pp. 215-218.

Internet | Protected Mode: On



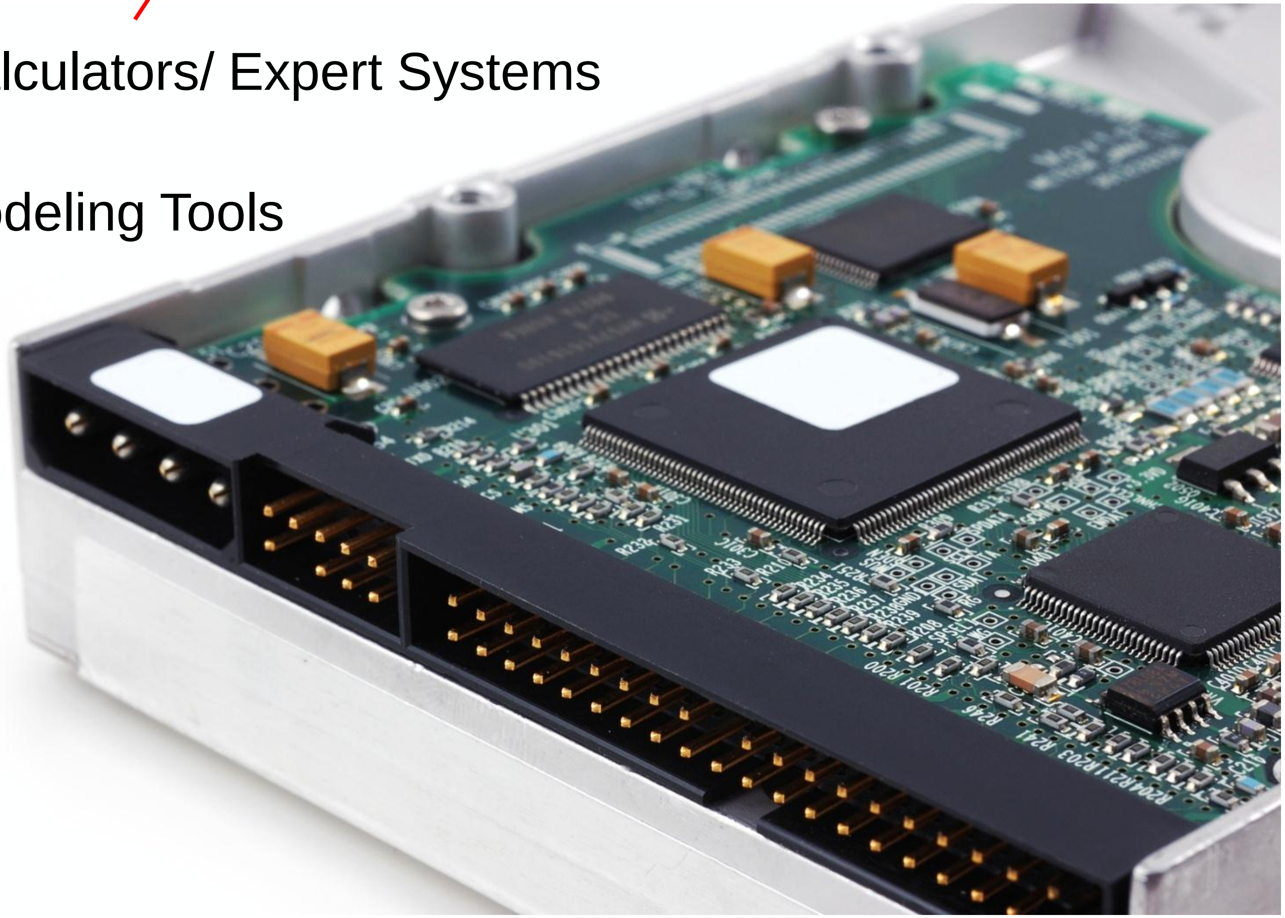
http://www.clemson.edu/cvel/modeling

Computer Modeling Tools for EMC Engineers

- Rule Checkers
- Emissions Calculators/ Expert Systems
- Numerical Modeling Tools

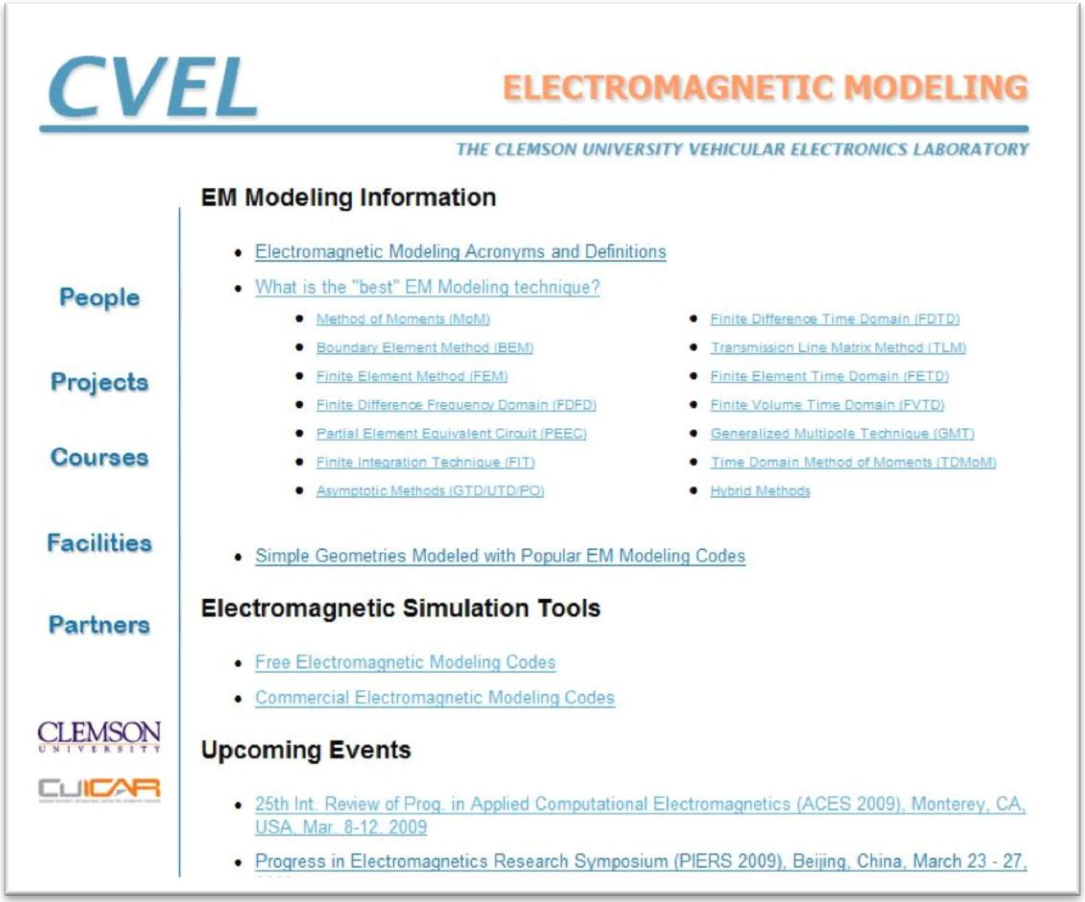
For analyzing existing system designs.

For understanding basic field behavior in well defined situations.



For More Information:

http://www.cvel.clemson.edu/modeling



- List of “free” EM modeling codes.
- List of commercial EM modeling codes.
- Info on EM modeling techniques.
- Info on EM modeling software.
- Prototype MR EMC calculator.