PCB Radiation Mechanisms: Using Component-Level Measurements to Determine System-Level Radiated Emissions

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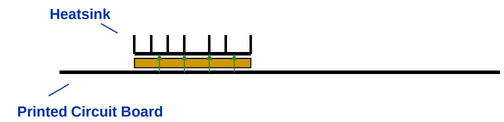
Radiation Directly from PCB Structures

Signal or component voltage appears between two good antenna parts.

Example:



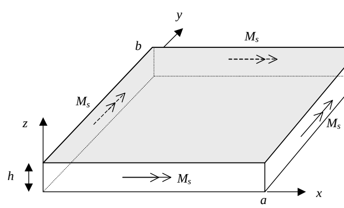
$V_s = 1\,volt\ @\,1\,GHz$

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

More than 50 dB above the FCC Class B limit!

Power Bus Radiation

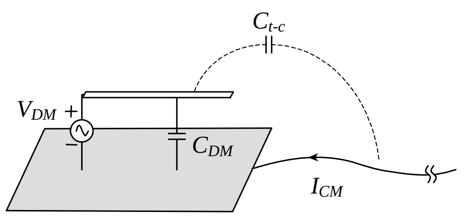
$$Q(f) = \left(\frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_{comp}} \right)^{-1}$$



$$|E| = \frac{120 I_i}{\varepsilon_r \min(a,b)} \cdot \frac{h}{r} \cdot Q(f)$$

H. Shim and T. Hubing, "Estimating radiated emissions from the power planes in a populated printed circuit board," *IEEE Trans. on Electromagnetic Compatibility*, vol. 48, no. 1, Feb. 2006.

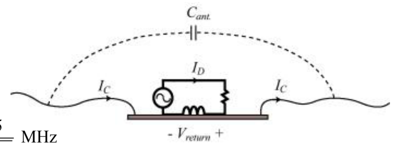
Electric Field Coupling



$$E = \frac{2V_{DM}}{r} \frac{C_{t-c}}{C_{board}} \sqrt{30/R_{rad}}$$

H. Shim and T. Hubing, "Model for estimating radiated emissions from a printed circuit board with attached cables driven by voltage-driven sources," *IEEE Trans. on Electromagnetic Compatibility*, vol. 47, no. 4, Nov. 2005.

Magnetic Field Coupling



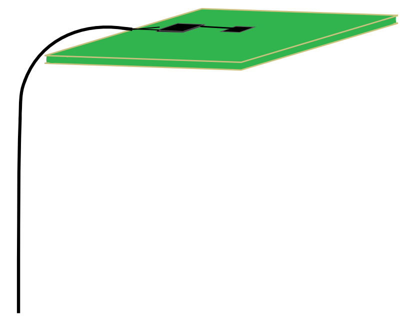
$$V_{ret,i} = \begin{cases} \omega L_{p,i} I_{DM,i}, & f \le \frac{75}{a\sqrt{\varepsilon_r}} \text{ MHz} \\ \frac{4.71\times 10^8 \times L_{p,i} I_{DM,i}}{a\sqrt{\varepsilon_r}}, & f \ge \frac{75}{a\sqrt{\varepsilon_r}} \text{ MHz} \end{cases}$$

$$\left|E_{\text{cable-to-board}}\right| \simeq 0.365 \times \frac{100 \times V_{ret}}{\sqrt{100^2 + \frac{1}{(\omega C_B)^2}}}$$

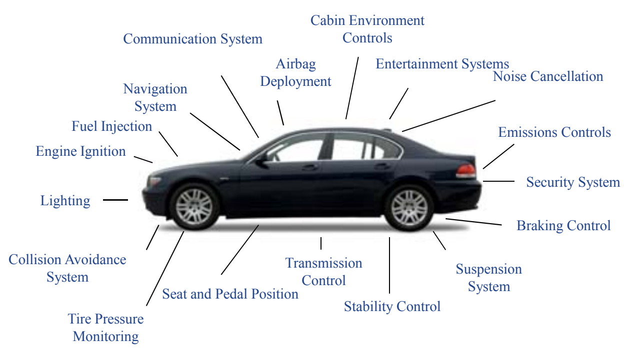
D. M. Hockanson et. al., "Quantifying EMI resulting from finite-impedance reference planes," *IEEE Trans. on EMC*, vol. 39, no. 4, Nov. 1997, pp. 286-297.

H. Shim et. al., "Expert system algorithms for identifying radiated emission problems in printed circuit boards," *Proc. of the 2004 IEEE International Symposium on EMC*, Santa Clara, CA, USA, Aug. 2004, pp. 57-62.

Differential to Common Mode Conversion

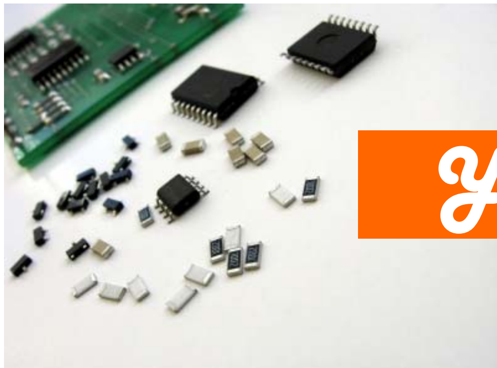


Automobiles are Complex Electronic Systems



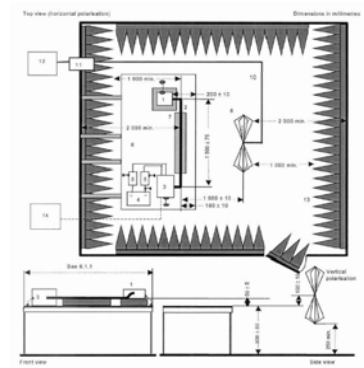
Can we predict system-level performance from component-level information?

Can we predict system-level performance from component-level information?



Yes!

CISPR-25 Component-Level EMC



CISPR-25 Measurements do not provide appropriate information for system-level simulation!

We need to characterize automotive components the way we characterize circuit board components!

Old Approach: Put the components in a “typical” system and measurement the system performance.

Better Approach: Fully characterize the components themselves, then model system behavior.

Case in Point: 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
  $1\Omega/150\Omega$ direct coupling
- IEC 61967-5 Measurement of electromagnetic emissions
  workbench Faraday cage method
- IEC 61967-6 Measurement of electromagnetic emissions
  magnetic probe method

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.

Integrated Circuit EMC Measurement Methods

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

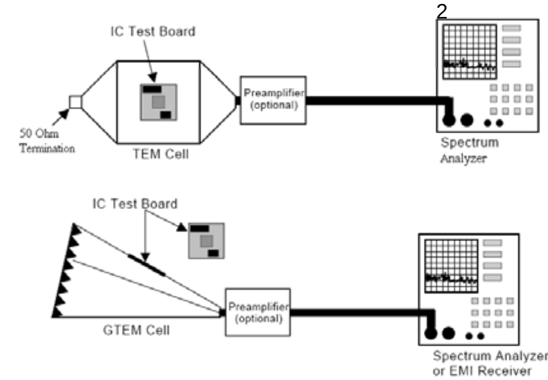
Integrated Circuit EMC Measurement Methods

Measurements must be:

- Meaningful
- Repeatable
- Targeted

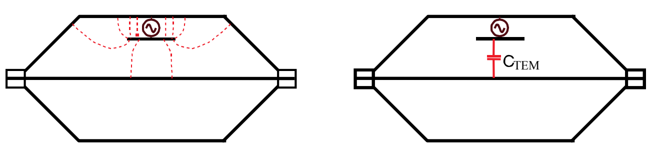
Integrated Circuit EMC Measurement Methods

Standards SAE J1752/3 and IEC 61967-2



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

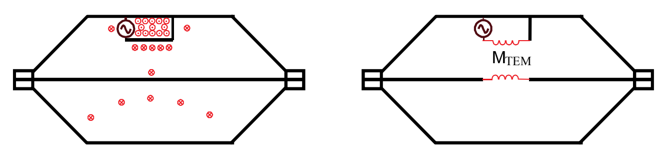
Electric field coupling can be represented with a mutual capacitance, $C_{TEM.}$ The voltage coupled to either end of the TEM cell will be identical.



(a) (b)

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

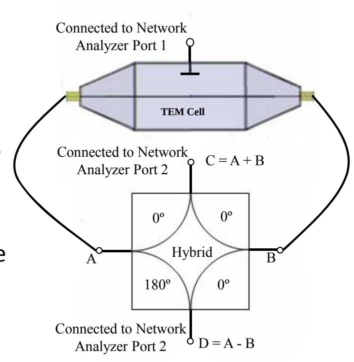
Magnetic field coupling can be represented with a mutual inductance, $M_{TEM.}$ Voltage appears across both terminations with opposite phase.



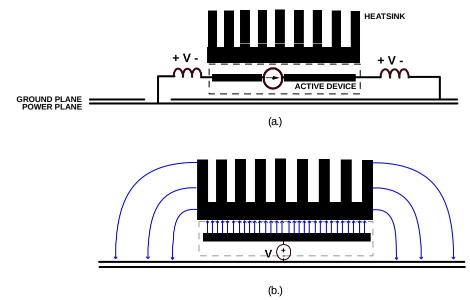
(a) (b)

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.

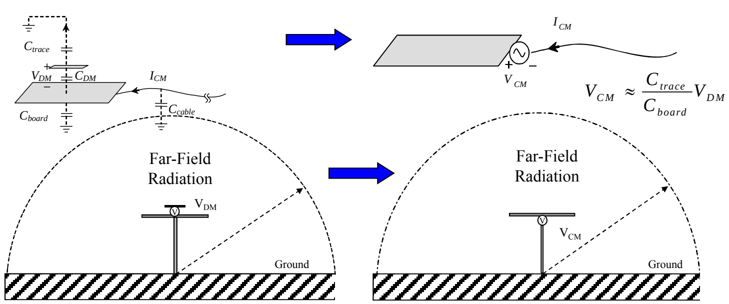


Electric Field Coupling



Voltage-Driven Radiation Mechanism

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

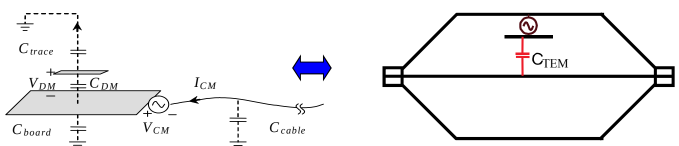


$$V_{CM} \approx \frac{C_{trace}}{C_{board}} V_{DM}$$

Correlating C_{trace} to C_{TEM}

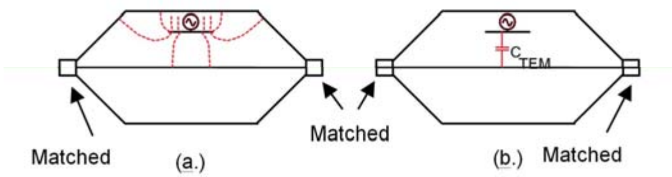
A TEM cell measurement gives us the product of C_{trace} and V_{DM}, which is sufficient to calculate maximum possible radiated emissions due to electric field coupling!

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



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.

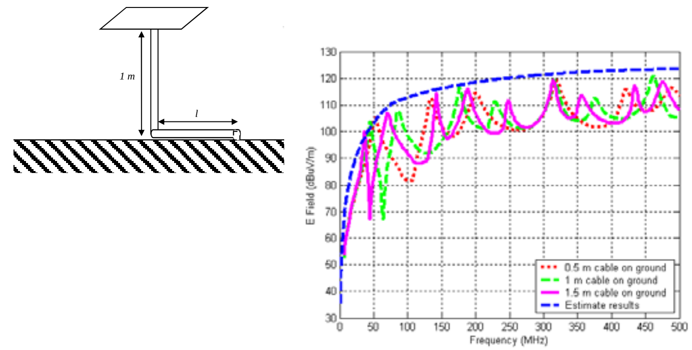
Hybrid TEM Cell Electric Field Coupling



Electric Moment

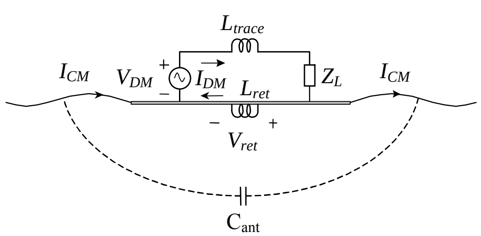
$$|V_{IC}|\omega C_{TEM} \approx \frac{|V_{measured}|}{25}$$

Calculation of Emissions Based on TEM Cell Measurement



Magnetic Field Emissions

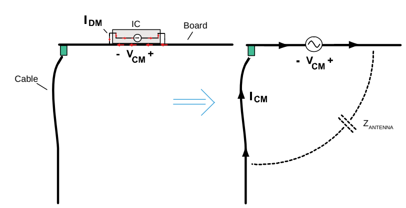
Current-Driven Common-Mode (Magnetic-Field) Coupling



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

Magnetic Field Emissions

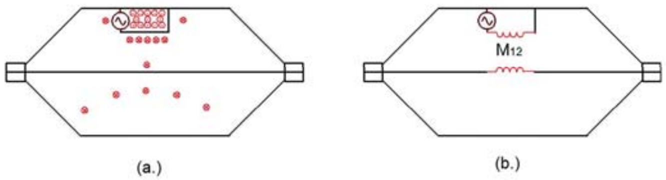
A TEM cell measurement gives us the value of V_{CM}, which is sufficient to calculate maximum possible radiated emissions due to magnetic field coupling!



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

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

Hybrid TEM Cell Magnetic Field Coupling



Magnetic Moment

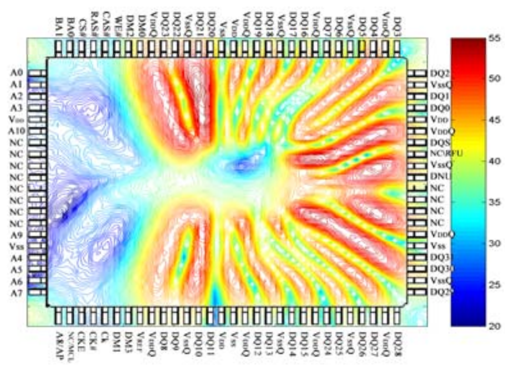
$$\left|V_{measured}\right| = \left|I_{IC}\right| \omega M_{TEM}$$

Using TEM Cell Measurement Results

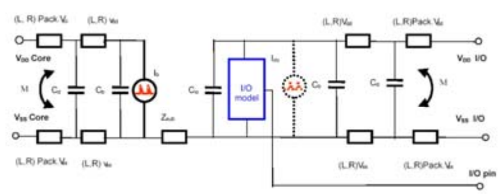
- By connecting both outputs of the TEM cell to a hybrid, it is possible to separate the electric field coupling from the magnetic field coupling.
- Magnetic-Field coupling is fully characterized by the source current and mutual inductance to the radiating structure. These are both determined by the 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

Near magnetic field measurements are the best way to map high-frequency currents; but not the best way to quantify them.

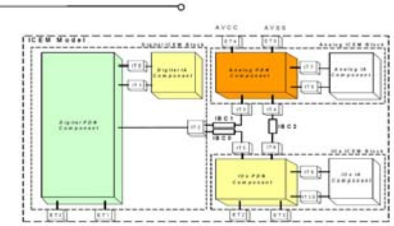


ICEM Models

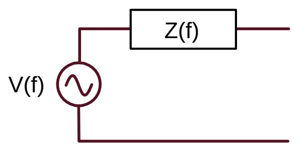


ICEM is a potentially powerful tool for modeling the EMC of ICs in systems.

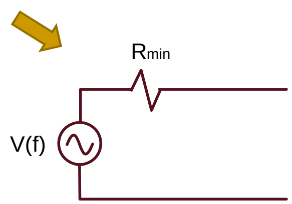
We'd like to have a simple measurement procedure that would give us ICEM models, the ICEM models are too complex for EMC approval testing of ICs.



Conducted Coupling

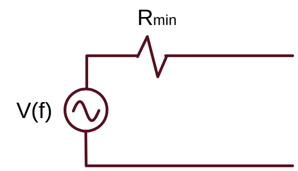


- Need a Thevenin Equivalent source for each terminal pair, including power pins.



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

Radiated Emissions

- Radiated emissions can't be measured in a TEM cell!
- Radiated emissions can't be measured by an antenna located in the near field of the source.
- We don't want to know the radiated emissions from a "typical" system, just the emissions directly from the component.
- Recommendation: Place the component on a raised metal floor in a semi-anechoic environment and put all supporting equipment below the floor (or outside the chamber).

Automotive System Solution

- Automotive components are often the source of radiated energy, but usually not the "antenna" below several hundred MHz.
- Automotive components usually couple to the structures that serve as antennas by way of conducted, electric-field, or magnetic-field coupling.
- The electric and magnetic field coupling from a component can often be quantified by measurements using a TEM Cell and a hybrid coupler.
- These measurement results can be expressed as electric or magnetic moments that describe a components ability to couple to nearby objects.

Automotive System Solution

- Radiated emissions can be quantified with a radiated field measurement of the component (must be in the true far field).
- Conducted emissions can be quantified by high-impedance voltage and low-impedance current measurements at the harness interface.

Can we predict system-level performance from component-level information?

Yes!

Conclusion

Existing EMC test standards can help to identify potential problems with a component before it is installed in a system; but they are not very helpful for predicting system-level behavior.

Conclusion

New EMC test procedures employing hybrid TEM cells, high-impedance voltage and low-impedance current measurements, and true radiated emissions measurements will quantify the important parameters of interest providing component-level information that can be used to predict system-level performance.