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

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Power Bus Radiation

\[ Q(f) = \left( \frac{1}{Q_a} + \frac{1}{Q_b} + \frac{1}{Q_{comp}} \right)^{-1} \]

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


Radiation Directly from PCB Structures

Signal or component voltage appears between two good antenna parts.

Example:

Heatsink
Printed Circuit Board

\[ V_r = 1 \text{ volt} @ 1 \text{ GHz} \]

\[ E_{rad} = 360 \text{ mV } / \text{ m} @ 3 \text{ meters} \]

More than 50 dB above the FCC Class B limit!

Electric Field Coupling

\[ E = \frac{2V_{DM}}{r} \cdot \frac{C_{tot}}{C_{board}} \times \sqrt{\frac{30}{R_{rad}}} \]

Magnetic Field Coupling

\[ V_{\text{cable-to-board}} = \begin{cases} \frac{a_k f_d I_{\text{diss}}}{\mu_0} & \text{if } f \leq \frac{75}{2a_k^2 \mu_0} \text{ MHz} \\ 4.7 \times 10^7 \times a_k^2 I_{\text{diss}} & \text{if } f \geq \frac{75}{2a_k^2 \mu_0} \text{ MHz} \end{cases} \]

\[ E_{\text{cable-to-board}} = 0.365 \times \frac{100 \times V_{\text{cable-to-board}}}{\sqrt{100^2 + \left(\omega C_k \right)^2}} \]


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Differential to Common Mode Conversion

Automobiles are Complex Electronic Systems

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

Measurements must be:

- Meaningful
- Repeatable
- Targeted

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

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

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

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

- The A-B output indicates the amount of magnetic field coupling.
- The A+B output indicates the amount of electric field coupling.

Voltage-Driven Radiation Mechanism

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

Correlating $C_{\text{trace}}$ to $C_{\text{TEM}}$

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

Hybrid TEM Cell Electric Field Coupling

Electric Moment

\[ V_{EC} |ωC_{TEM} \approx \frac{|V_{measured}|}{25} \]

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).

\[ V_{CM} = \frac{4}{π} \cdot \frac{V_{cm}}{2} \cdot (W + H) \]

**Hybrid TEM Cell Magnetic Field Coupling**

![Diagram of Magnetic Field Coupling](image)

Magnetic Moment

\[ |V_{measured}| = |I_\text{IEC}| \omega M_{\text{TEM}} \]

**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 Thévenin Equivalent source for each terminal pair, including power pins.
- $R_{\text{min}}$ is the ratio of $V_{\text{open}}$ to $I_{\text{short, max}}$.
- Reactive elements are not necessary.
- Only “logical” ports need to be characterized.

**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 component’s 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.

**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.*

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

*Yes!*

**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.*