EMI Driven by Signal Integrity

Fundamentals of Coupled SI/PI/EMI
Part 2

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SI + PI = EMI

**Trend:** Cost / Performance targets drive the integration of IC’s, SoCs, and SiPs onto low cost printed circuit boards.

Chip/Packet/Board Co-design is required

**Signal Integrity**

**EMC/EMI**

**Power Integrity**
Where is the problem? Intentional Signals

- Focus on Clock and High Speed Signals
  - Stripline not necessarily better than Microstrip
  - Examine Clock Harmonics – filter if necessary

- Differential signaling is a standard to improve signal-to-noise ratios, however, its use always leads to Common mode noise
  - Common Mode Conversion
    \[
    SCD11 = 0.5 \times (S(1,1) - S(1,3) + S(3,1) - S(3,3))
    \]
    \[
    SCD21 = 0.5 \times (S(2,1) - S(2,3) + S(4,1) - S(4,3))
    \]
Where is the problem? Unintentional Signaling

- Common mode will always exist
  - Common Mode noise is the main contributor to EMI

- How? Through Crosstalk
  - Beware the low speed nets; use post-layout analysis to scan for unintended coupling
  - Coupling may be direct, through intermediate metal or even from plane cavities

This presentation focuses on crosstalk, the primary SI contributor to EMI radiation
Crosstalk
Definition and Sources

• Signal integrity examines the quality of transmitted waveforms through a physical interconnect; Traces, connectors, vias, etc

• Crosstalk is the coupling of energy from one current carrying conductor to another. It occurs when the electromagnetic fields from one conductor interferes with another conductor, thus changing its desired characteristics

• There are 2 main components to Crosstalk:
  – Mutual Inductance and Mutual Capacitance
How to calculate crosstalk
Mutual Inductance

- Mutual Inductance induces current from an aggressor line onto a victim line by the magnetic field.
  - The noise voltage that is injected onto the victim line can be calculated by 2 methods

  **Method #1**
  Analytical Calculation

  \[ V_{\text{noise},Lm} = Lm \frac{di}{dt} \]

  **Method #2**
  Field Solution

\[ \vec{a}_y \left( \frac{\partial E_x}{\partial z} = -\mu \frac{\partial H_y}{\partial t} \right) \]
How to calculate crosstalk
Mutual Capacitance

– Mutual Capacitance is the coupling between 2 conductors via the electric field.
  • The induced noise that shows up on the victim net can be calculated by 2 methods

Method #1
Analytical Calculation

Method #2
Field Solution

\[ I_{\text{noise}, \text{Cm}} = C_{\text{m}} \frac{dv}{dt} \]
Near and Far End Crosstalk

- The magnitude of the Mutual Capacitive and Inductive Coupling will determine the amount of current induced on the victim net. The summation of these currents determine near and far end crosstalk.

\[ I_{\text{near}} = I_{CM} + I_{LM} \]

\[ I_{\text{far}} = I_{CM} - I_{LM} \]
Back of the envelope calculations can be used as a quick check:

**Terminated Victim**

**Driven Line**

**Un-driven Line “victim”**

**Near End**

**Far End**

Terminated Victim

\[
A = \frac{V_{input}}{4} \left[ \frac{L_M}{L} + \frac{C_M}{C} \right]
\]

\[
TD = X\sqrt{LC}
\]

\[
B = -\frac{V_{input} \cdot X}{2T_r} \left[ \frac{L_M}{L} - \frac{C_M}{C} \right]
\]

\[
Z_o = \sqrt{\frac{L}{C}}
\]

Near-End Crosstalk \([NEXT]\) = \(\frac{V_b}{V_a}\)

Crosstalk Coefficient \([kb]\) = \(\frac{V_b}{V_a}\)
### Analytical Crosstalk Calculation Example

**Trace Dimensions**
- Trace Width: 13mil
- Height: 10mil
- Trace Separation: 7mil
- Thickness: 2mil
- Dk: 3.55

**Calculation Details**

- **Z_{o} = \sqrt{\frac{L}{C}} = \sqrt{\frac{8.55\text{nH}}{2.26\text{pF}}} = 61.5\text{ohm}**

- **A = \frac{V_{\text{input}}}{4} \left[ \frac{L_{M}}{L} + \frac{C_{M}}{C} \right] = \frac{500\text{mV}}{4} \left[ \frac{2.39\text{nH}}{8.55\text{nH}} + \frac{0.389\text{pF}}{2.26\text{pF}} \right] = 56\text{mV}**

- **TD = X\sqrt{\text{LC}} = \text{1in}\sqrt{8.55\text{nH} \times 2.26\text{pF}} = 0.139\text{ns}**

- **B = -\frac{V_{\text{input}}X\sqrt{\text{LC}}}{2T_{r}} \left[ \frac{L_{M}}{L} - \frac{C_{M}}{C} \right] = -\frac{500\text{mV} \times \text{1in}\sqrt{8.55\text{nH} \times 2.26\text{pF}}}{2 \times 100\text{ps}} \left[ \frac{2.39\text{nH}}{8.55\text{nH}} - \frac{0.389\text{pF}}{2.26\text{pF}} \right] = -37\text{mV}**

**Additional Parameters**
- **V_{\text{source}}**: 1V
- **V_{\text{input}}**: 500mV
- **Trace Length**: 1in
- **Source Impedance**: 50ohms
- **Termination Impedance**: 61.5ohms
- **Risetime**: 100ps
- **Delay Time**: 200ps

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**Inspiring Engineering**

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Field Solution Crosstalk Example

Same example using Method #2 – Field solutions

**m2(A) = 57.4mV**
**m1 (B) = -37.2mV**
**m4-m3 (TD) = 0.1359ns**
Parameterization Captures Trends
Impact of Length and Spacing

Trace Length = 1, 2, 3, … 10 in

As Length increases, $I_{far}$ accumulates

Trace Spacing = 7, 12, 17, 22, 27 mil

As Trace Spacing increases, $I_{near}$ decreases

As Trace Spacing increases, $I_{far}$ decreases
Parameterization Captures Trends

<table>
<thead>
<tr>
<th>Crosstalk</th>
<th>Increase</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cm</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Lm</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Trace Spacing</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>GND Plane Distance</td>
<td>↓ NE ↑ FE</td>
<td>↑ NE ↓ FE</td>
</tr>
<tr>
<td>Dk</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Trace Width</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Under-etching</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Good Coupling, when Xtalk is desired
Differential Signaling

• Why Differential Signaling?
  – When lines are tightly coupled, noise affects both lines. Thus at the receiver, the difference between the two lines remains constant
  – Stray transient noise on the two conductors will self-cancel, which leads to a reduction of noise from the power supply
  – Because differential signaling creates a known return path, signal quality will significantly improve in the presence of non-ideal ground return paths, or other discontinuities such as connectors, wirebonds, vias, etc..
Good Coupling  
Differential Signaling

Back of the envelope calculations of Differential and Common Mode Impedance can be used as a quick check

\[ L_{odd} = L_{11} - L_{12} \]
\[ C_{odd} = C_{11} + C_{12} \]
\[ Z_{odd} = \sqrt{\frac{L_{odd}}{C_{odd}}} = \sqrt{\frac{L_{11} - L_{12}}{C_{11} + C_{12}}} \]
\[ Z_{differential} = 2 \times Z_{odd} \]

\[ L_{even} = L_{11} + L_{12} \]
\[ C_{even} = C_{11} - C_{12} \]
\[ Z_{even} = \sqrt{\frac{L_{even}}{C_{even}}} = \sqrt{\frac{L_{11} + L_{12}}{C_{11} - C_{12}}} \]
\[ Z_{common} = (\frac{1}{2}) \times Z_{even} \]
3D Crosstalk Needs Field Solution

2.2 inch total length of trace.
88 mil via transition

Peak Near-End Crosstalk: 25mV
Peak Far-End Crosstalk: -21.8mV
Bad Coupling Via Transition

Peak Near-End Crosstalk: 13.1mV
Peak Far-End Crosstalk: -14mV

Total length of parallel via routing is 4% of the total length. Yet the Near-End Crosstalk only reduces by 48%. The Far-End Crosstalk only reduces by 36%.
Bad Coupling Via Transition

Added Ground Vias

Peak Near-End Crosstalk: 10.3mV
Peak Far-End Crosstalk: -10.9mV

Near-End Probe
Far-End Probe

Total length of parallel via routing is 4% of the total length. Yet the Near-End Crosstalk only reduces by 24%. The Far-End Crosstalk only reduces by 8%.
Package and Board Models

Case #1

- Package has been merged onto board
- Coupling between the bondwires, leadframe, and board are simulated
Apache’s Chip Power Model

CPM

I/O Interface

Slwave Full-Wave Package/PCB Model

Chip Power Model

VDD

VSS

VDDQ

Input Buffer

Level Shifter

Buffer

Package

PCB

SIG
Drive VDDs with CPM
Capture coupled high-frequency noise
Run Near/Far-Field Simulations using transient results
Time and Frequency Domain Results

Transient Power Noise

3m Far Fields
Near Fields at 1GHz

Baseline

1.27 V w/ Decap

1.1 V
Driver settings

Spectre Driver Model (Nexxim)

PKG/PCB Models (SIwave)

(HFSS) Antenna Model
Solving the Field Solution Using Time Domain Information

FFT of Transient Data

Near/Far Fields Computed in SIwave and HFSS

Time
Frequency
Radiation
Agreement captured in simulation

10 M Measurement

ONLY PCB Spectrum

SIwave
Excessive Common Mode coming from Driver

Glitch seen in falling waveform; this will create Common Mode Noise

Original Driver

Ideal Driver

Transient Waveform

Common Mode Spectrum
Intentional Signaling contributing to EMI

Original Driver

Ideal Driver

Even Harmonics are now absent but EMI is still high

Problem is not just common mode

Inspiring Engineering
Adding a filter to reduce problematic higher harmonics

Pi Filter added to driver output to squelch higher harmonics of 13.56 MHz clock

Component values optimized in Designer
Reduced Common Mode after filtering

Ideal Driver

Filtered Driver

Transient Waveform

Common Mode Spectrum

Signal integrity still OK but high frequency spectrum is reduced.
EMI from Intentional and Unintentional Signaling suppressed

Original Driver

Filtered Driver

EMI is now sufficiently suppressed
Conclusions

• Crosstalk is major concern for SI
  – Need to examine all relevant coupling: vias, traces, etc.
  – Simulation can help determine acceptable levels of coupling

• Target impedance helps ensure good PI
  – Target impedance is defined in Frequency domain
  – Need to verify ripple in time domain

• EMC is comprised of good PI and SI
  – Poor plane design can spread common mode noise
  – Unintentional coupling is a big source of radiated emissions