EMI/EMC Characterization of Mixed Radio Frequency-Digital Circuits

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Understand and predict the effects of electromagnetic interference on electronic systems.

Analysis Method:
Integration of numerical EM tools with circuit tools such as ADS and HSPICE for RF/Analog/Digital Circuit Simulation.

- **Cable Bundles Subject to HPM Sources**
  - combined full wave numerical EM tools such as MLFMM MoM and Modal MoM with cable bundle tools such as CableMod and CRIPTE

- **Mixed Signal Circuits Subject to HPM Sources**
A specific problem

Inverter Subject to EMI

Inverter Subject to EMI with Different Type Modulations

Unmodulated EMI
Multi tone modulated EMI
Pulse modulated EMI

Observed Effects

EMI Effects on
• Timing Characteristics
• Logic Behaviors

Texas Instruments (TI SN74AUC1GU04) CMOS Inv
• Optimized for 1.8V operation.
• Minimum propagation delay $t_{pd}=0.6\text{ns}$ for 30pF load.
• Encrypted HSPICE Model for the inverter is used in the simulations.
• VDD=1.8V was used in our measurements.
Inverter Operating at 1.0 GHz  Unmodulated EMI at Inverter Out (Device level upset)

Input Signal @1.0GHz
Pulse width: 300ps

Our LSNA does not capture DC response; therefore, output is off and DC correction is applied for the simulations!
1. Partial Element Equivalent Circuit (PEEC) for both On & Off Board EMI

- **EM Domain**
  - EM structure

- **Circuit Domain**
  - EM structure
  - Circuits

- Both time and frequency domain analysis
- Exploit numerical advances in circuit domain
- Numerically inefficient at high frequencies

Entire EM structure is transformed into a circuit compatible form via lumped elements

2. {TDIE, FDTD, MoM} with MNA for both On & Off Board EMI

- **EM Domain**
  - EM structure

- **Circuit Domain**
  - EM structure
  - Circuits

- EM effects are fully captured
- Cannot exploit numerical advances customized for each domain
- Discretisation is dictated by the parameters in both domain

Combine EM analysis with Circuits in EM domain

3. S-Parameters

- **EM Domain**
  - EM structure

- **Circuit Domain**
  - EM structure
  - Circuits

- Freedom to choose the best solver for each domain
- Exploit numerical advances in each domain
- Suitable for optimization in both domain
- Numerically expensive for large number of ports
- Can handle only on-board EMI
Concurrent On & Off Board EMI Analysis

Conventional S-parameters

Hybrid S-parameters

External EMI Contributions
**Step 1:** Define additional port to represent external EM wave

\[
\begin{bmatrix}
 b_1^k \\
 \vdots \\
 b_N^k \\
 b_{N+1}^k
\end{bmatrix}
= \begin{bmatrix}
 S_{1,1}^k & \cdots & S_{1,N}^k \\
 \vdots & \ddots & \vdots \\
 S_{N,1}^k & \cdots & S_{N,N}^k \\
 S_{N+1,1}^k & \cdots & S_{N+1,N}^k
\end{bmatrix}
\begin{bmatrix}
 H_{1,N+1}^k \\
 \vdots \\
 H_{N,N+1}^k \\
 H_{N+1,N+1}^k
\end{bmatrix}
\begin{bmatrix}
 a_1^k \\
 \vdots \\
 a_N^k \\
 a_{N+1}^k
\end{bmatrix}
\]

**Step 2:** Solve EM structure with ports open and GPOF analysis along the transmission lines

**Step 3:** Perform open circuit analysis to obtain Hybrid S-parameters from modal voltages

**Step 4:** Solve resulting network in circuit simulator

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**Key Advantages of the Proposed Method:**
- Concurrent On & Off Board EMI Analysis
- Separate Analysis of EM Structure and Circuit Components
  (As opposed to combining whole problem into single system matrix)
  - EM structure is analyzed at best via EM Solvers
  - Electronic devices are handled most efficiently with circuit solvers
- Efficient Analysis of RF-Digital Systems via SPICE or HBM
How to compute $[HS^{EF-PCB}]$?

Terminate each port on PCB open circuit and compute induced voltage at the ports.

$$\begin{align*}
\begin{bmatrix}
V_1 \\
\vdots \\
V_N
\end{bmatrix} &=
\begin{bmatrix}
Z_{1,1} & \cdots & Z_{1,N} \\
\vdots & \ddots & \vdots \\
Z_{N,1} & \cdots & Z_{N,N}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_N
\end{bmatrix}
+ \begin{bmatrix}
I_1 \\
\vdots \\
I_N
\end{bmatrix} =
\begin{bmatrix}
V_1 \\
\vdots \\
V_N
\end{bmatrix}
$$

$$\sqrt{Z_{ref}} [a+b] = \sqrt{Z_{ref}} \begin{bmatrix}
1 \\
\vdots \\
1
\end{bmatrix} + \sqrt{V_{oc}}$$

where $[HZ]a_{N+1} = V_{oc}$

$$\bar{b} = \left( \sqrt{Z_{ref}} + \sqrt{Z_{ref}} \right)^{-1} \left( \sqrt{Z_{ref}} - \sqrt{Z_{ref}} \right) a + \left( \sqrt{Z_{ref}} + \sqrt{Z_{ref}} \right)^{-1} V_{oc}$$

Set $a_{N+1} = \frac{|E_0|}{\sqrt{Z_{ref} N+1}}$, $[HS^{EF-PCB}] = \sqrt{Z_{ref} N+1} \left/ E_0 \right| \left( \sqrt{Z_{ref}} + \sqrt{Z_{ref}} \right)^{-1} V_{oc}$

Relation between $\overline{Z}$, $\overline{S}$ or $a, b$.
A Pair of Transmission Lines subject to External EMI

$E = (\hat{x}1000 + \hat{y}500 + \hat{z}1500)e^{-jkx}$

$k = k_0 \frac{\hat{x} + \hat{y} \cdot \hat{z}}{\sqrt{3}}$

$F = 2 \text{ GHz}$

$\text{radius} = 0.125 \text{mm}$

$I = 10 \text{ mA}$

$h = 2 \text{ mm}$

$L = 250 \text{ mm}$

$Z_L = 100 \Omega$

Port 1 = 250$\Omega$ and Port 2 = 800$\Omega$

$V_{\text{enforced}}$

$V_{\text{scat1}} = (0.57 + j0.04)e^{-j24.69y} + (-0.37 - j1.29)e^{+j42.76y} + (-0.74 - j0.61)e^{-j42.03y}$

$V_{\text{scat2}} = (0.56 + j0.05)e^{-j24.46y} + (-0.77 - j1.29)e^{+j42.77y} + (-0.16 - j0.37)e^{-j41.84y}$

Extracted Propagation Constants via Generalized Pencil of Functions (GPOF)

<table>
<thead>
<tr>
<th></th>
<th>$k_{\text{enforced}}$</th>
<th>$k_{\text{modal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>24.18</td>
<td>41.88</td>
</tr>
<tr>
<td>GPOF</td>
<td>24.69</td>
<td>42.7</td>
</tr>
</tbody>
</table>
Results

Constant Forced Voltage Sources

EMI Port
Intentional EMI on RF Power Amplifier, and impact on Digital Modulation Schemes

Designed by ElectroScience Lab EMI/EMC team in conjunction with Non-linear RF Lab

Optimized for best performance in GSM and W-CDMA Band

Free Scale MRF281S Class AB RF Power Amplifier
Measurement and Post-Processing Setup

-Device Level Upset-

VECTOR SIGNAL GENERATOR

Agilent ESG 4438C

Anritsu MG3692A CW Generator

EMI is injected into gate of PA

Extraction of Gain

Post-Processing in MATLAB

EMI Measurement and Post-Processing Setup

Multi-tone data

LSNA
Effects of Intentional EMI on Performance of Power Amplifier

Intentional EMI leads to significant degradation on gain of PA, partially due to that:

- Power is distributed over intermodulation products.
- Device heats up very quickly.

**Nonlinear region**

- \( f_0 @ 0.94 \text{ GHz (GSM Band)} \)
- EMI @ .95GHz Single Tone
- \( P_{1dB} = 35 \text{ dBm} \)
Degradation of Gain due to high power EMI

-ADS Simulations-

EMI at 0.949GHz
EMI Power=15dBm

Harmonic Balance Parameters:
Order=4

Without EMI
Gain decreased since power is distributed over intermodulation products

Gain decreased by 3 dB
Higher power at adjacent modes
EMI on Digital Modulation Schemes

Why digital modulation?
- More Information Capacity
- Higher Data Security
- Better Quality

Digital Modulation

Constant Envelope
- BPSK
- QPSK
- MSK
  - In-band EMI Interference
  - Out-of-band EMI Interference

Non-constant Envelope
- QAM16
  - In-band EMI Interference
  - Out-of-band EMI Interference

What are the observables?
- How much power (in-band/out-of-band) is needed to fail a typical communication system
- Which modulation scheme is more susceptible to EMI
- What modulation features play critical role in system level upset
- Effects of Intentional EMI imposed onto devices on performance of communication system
Measurement and Post-Processing Setup
-System Level Upset-

VECTOR SIGNAL GENERATOR

Agilent ESG 4438C
Anritsu MG3692A CW Generator

EMI is injected into gate of PA

Demodulation
Constellation
EVM analysis

Post-Processing in MATLAB

LSNA
Error Vector Magnitude (EVM)

EVM is a figure of merit for transmit modulation
3GPP standard in assessing the quality of signal transmitted
It possesses direct relation with BER and SNR
Quadrature Phase Shift Keying (QPSK)

Performance: 2 bits/second/Hertz

Applications

- Digital Video Broadcasting-Satellite (DVB-S)
- Code Division Multiple Access (CDMA)
- Wireless Local Loop

QPSK: Constellation Diagram
QPSK: Performance of PA in NonLinear Region (No EMI)

64 bit random data sequence is input to the system

**Polar Transition Diagram**

Input @ 22dBm

Intermodulation products due to high nonlinearity

Output

**Constellation Diagram**

Input @ 22dBm

Output Nonlinear Region (No EMI)

\[ f_0 = 940\text{MHz} \]

\[ f_0 = 940\text{MHz} \]
QPSK: Out-of-Band EMI (18 dBm : 0.63V)

64 bit random data sequence is input to the system

Intermodulation products

Device is forced to nonlinear region but very minimal effect on the performance
BPSK: Performance of PA in Linear Region (No EMI)

64 bit random data sequence is input to the system

I/Q at the output

**Input @ 9dBm**

\[ f_0 = 940 \text{MHz} \]

**Output**

\[ f_0 = 940 \text{MHz} \]
BPSK: Out-of-Band EMI (18 dBm: 0.63V)

64 bit random data sequence is input to the system

Input @ 2dBm

EMI @ 18dBm

20MHz $f_{EMI} = 1885MHz$

$f_0 = 940MHz$

Output

Intermodulation products

Device is forced into nonlinear region by intentional EMI but strong effect on system performance
Electronic systems employing constant amplitude modulation schemes are less susceptible to intentional EMI than those employing varying modulation envelopes.

In-band interference plays the most critical role in failing communication systems.
EMI/EMC Analysis In Presence of Complex Enclosures

Tools/Methods

Large Surrounding Structures
1. Modal MoM (Green’s Functions)
2. EMCAR (MLFMM)

Interconnecting Cables
TICE (Telegrapher’s Iterative Coupling Equations)

Printed Circuit Boards (PCBs)
a) Hybrid S Parameters
b) PEEC

Proposed Hybrid Solution

Step 1: Scattering from Surrounding Structures
Scattered Field \( E_{inc}(r) \) at locations of PCB Interconnects and Cables enclosed within Empty Enclosure

Step 2: EMI/EMC Analysis of Cables
a) Terminate Cables connecting to PCB by Thevenin’s Equivalent
b) TICE for Induced Current and Voltages on Cables

Step 3: Scattered Fields from Cables

Step 4: Induced Current on PCB Interconnects
a) Direct Coupling: PEEC with Incident Field as Voltage Sources
b) Indirect Coupling: Induced Current on Cables conductively flowing into PCB traces

Experiment/Validation
Cascaded Cavity Structure with Penetrating Wires, Cables, Analog/Digital PCBs and Enclosed Cavities
a) Compact Range/ Open Air Measurements
b) Shielding Effectiveness Study for 1-3 GHz
c) Induced Voltages at loads
d) Coupling Between Penetrating and Shielded Cables
Compact Range Measurements

Empty Cavity

Electric Field at center of cavity

Cavity with Penetrating Wires

Electric Field Inside Cavity
The system level analysis will study two factors:
- Effects of HPM pulse duration and repetition rate
- Best direction and polarization to fail the device

IC Design of D-latch and Timer using MOSIS 0.5μ and 1.5μ technology line. UMD will perform device level upset while OSU will study system level upset in complex platforms.