Susceptibility of Circuits and Systems to HPM Pulses

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Outline

• Review of previous results
  – RF Rectification by electrostatic discharge (ESD) protection diodes
  – Effects in logic, discrete and analog circuits

• Systems susceptibility
  – Resonant circuits within resonant cavities
  – RF fields in complicated structures
  – DC feedback controllers: An “Achilles Heel” in electronic systems

• Wideband sources
Examples of ESD protection in integrated circuits

Electrostatic discharge protection devices are integrated into nearly all chips: discrete, logic, analog, RFIC, mixed signal
Waveforms of the RF Voltage Across a Typical ESD Diode Excited with a Pulsed 850 MHz Carrier

Expanded view showing actual RF cycles.

The 20 Gs/sec sample rate was not high enough to capture the very high odd harmonics in the waveform which are necessary to reproduce clipping as the diode forward conducts.
The ESD down-converts the modulation frequencies off the microwave carrier and behaves like an RF detector.

These frequencies are likely to be within the normal operating range of the circuit.
Bandwidth limited voltage measured at the input of a CMOS circuit when excited by a microwave pulse (Frequency = 1.4 GHz)

- Good dynamic characteristics indicated by sharp rise and short delay.
- The transient response in RF detector diodes is described by the junction capacitance and a “video” resistance.
Small-signal analysis of ESD diodes as “square law” RF detectors

\[ V_d = Z_L I_d (V) = V_0 + Z_L \sum_{n=0}^{\infty} \frac{V_{rf}^{n+1}}{(n+1)!} \frac{d^n G_d}{dV^n} \]

Where:
\[ G_d = \frac{\partial I}{\partial V} \] is the diode conductance
\[ R_V = \frac{V_T}{I_S} = \frac{1}{G_d} \] is the video resistance
\[ V_T = \frac{kT}{e} \] is the thermal voltage

Basic High-Frequency Diode Parameters
Comparison of measured and simulated ESD diode response to RF Pulses
Simplified Schematic of a CMOS Circuit

LC parasitic elements form resonant circuits
Resonance at microwave frequencies in the series RLC circuit formed by the parasitic inductance and ESD junction capacitance

\[ A_V = \frac{V_d}{V_{in}} = \frac{1 + sC_j R_S}{1 + s^2 L_p C_j + sC_j R_S} \]

\[ A_V (\omega_R) = 1 - j \sqrt{\frac{L_p}{C_j (V_D)}} / R_S \]

\[ Q = \sqrt{\frac{L_p}{C_j (V_D)}} / R_S \]

Typical values:

- \( C_{j0} \approx 3 \, pF \)
- \( L_p \approx 10 \, nH \)
- \( R_V \approx 1 \, M\Omega \)
- \( R_S \approx 10 \, \Omega \)

Give:

- \( 0.5 < f_R < 3 \, GHz \)
- \( 2 < Q < 6 \)
- \( 1.5 < |A_V| < 6 \)
Impedance (small-signal) at the Input of a CMOS w/ ESD Protection at Microwave Frequencies

- When driven at resonance, the diode current and the rectified voltage increase.
Contours of measured large-signal response in advanced CMOS
This behavior has been observed and studied in a wide variety of circuits.

Discrete (JFET)  

Analog (Op Amp)
Effects in Advanced CMOS when Driven Near Resonance

- **Prompt Bit Error**
  - Graph showing voltage over time with red and blue lines labeled as Vout and Vin, respectively.

- **Oscillations**
  - Graph showing voltage over time with red and blue lines labeled as Vout and Vin, respectively.

- **Undefined Levels & Latent Latching**
  - Graph showing voltage over time with red and blue lines labeled as Vout and Vin, respectively.

- **Instability**
  - Graph showing voltage over time with red and blue lines labeled as Vout and Vin, respectively.
Distribution of parasitic resonant frequencies and quality factors in a digital communications system

View of the IC layout on the motherboard of a programmable LAN switch

Results from small-signal measurements of parasitic resonances in the IC’s of a functional set

I/O
Logic
System Controller
CPU
Memory
Overview of studies of HPM upset in electronic systems

• Systems consist of many circuits with internal resonances interconnected within cavities.

• What parts of the system are most likely to be upset once RF penetrates the enclosure?
Characteristics of electronic systems

• Most electronic systems contain modular components that are packaged according to standardized form factors (4U, 19” bays, ATX, etc.)

• Does this present any universal conditions or likely avenues for HPM attack?

• The enclosures are clearly natural microwave resonators.
Results of S-parameter measurements in an operating LAN switch

- Port #1 is a dipole launching antenna and port #2 is connected to the main +12 VDC power bus on the motherboard

- Strong resonances are observed across L-band (~1-2 GHz)
Simulation of resonances in LAN switch using HFSS eigenmode solver

- Power cable is modeled as a copper half-cylinder with its edges in contact with the board and a lossy block.
- Typically, all power lines originate at DC filter capacitors which are lossy at microwave frequencies.
Plots of RF Field Intensity and Surface Current Density for Various TEM Eigenmodes on the Board

- $f = 1.284 \, \text{GHz}$
- $f = 1.502 \, \text{GHz}$
- $f = 1.591 \, \text{GHz}$
- $f = 1.654 \, \text{GHz}$
Plots of RF Field Intensity and Surface Current Density for Various TE Eigenmodes on the Board

f = 1.117 GHz

f = 1.353 GHz

f = 1.678 GHz

f = 1.768 GHz
Studies of Pulsed RF Upset in a Programmable LAN Switch

- RF was injected into Port #1 while the +12 VDC power bus was monitored at Port #2 in an operating LAN switch.
- For each frequency step from 1.0 to 3.0 GHz, the RF amplitude was increased until the system was upset.
- At upset, the deviation in DC voltage and the RF amplitudes were recorded.

LAN switch upset testing
At upset, the RF caused the switching power supply to either completely shut down or output the incorrect voltage for times that were 100 – 1000 times the RF pulse width.

This forced the microcontroller to completely reboot the system.
Schematic of a typical switching power supply

Rectified RF voltage at the feedback pin fools the comparator into detecting an over-voltage condition. It then sends a shutdown signal to the power controller via an opto-isolator.

The power controller feedback is designed to shutdown the system (~30 sec) even if the “fault” is momentary (microseconds).
As IC technology has advanced, operating voltages have dramatically decreased and power regulation has become a critical issue creating a serious HPM vulnerability.
Schematic of Chaotic Oscillator Circuit

IREAP

Hughes 8537H TWTA
Variable Atten.
Delay Line

30 dB

20 dB

Bias Tee

20 dB

Spectrum Analyzer

RF Detector

Scope

DUT = ALVC

Vbias

Vout

Attenuator
TWT Output Amplitude vs. Time

The graph shows the TWT output amplitude over time, with the y-axis representing amplitude in det and the x-axis representing time in microseconds. The graph exhibits a fluctuating pattern with peaks and troughs, indicating the amplitude variations over the specified time period.
Time-averaged Spectrum of Wideband Oscillations in TWT
Sequence of Attractor Maps of TWT Amplitude as Feedback Gain is Increased

0.2 dB

0.5 dB

0.7 dB

2.0 dB
Response of Advanced Low-Voltage CMOS to wideband RF source (RF amplitude = 450 mV)
Conclusions

- RF rectification by ESD protection diodes and parasitic resonances have been identified as major susceptibility issues.
- The RF characteristics of these devices can be accurately described using lumped-element circuit models with simple high-frequency diode parameters.
- Upset can be easily predicted in terms of the high-frequency transfer characteristics of the circuit and the RF voltage, frequency and modulation at the circuit terminals.
- In systems, the problem requires an EM or RCM treatment.
- Power controllers with feedback have been identified as a major and universal problem.
- An informed basis for developing effects sources:
  - L-band
  - Wideband or chaotic modulation
  - 10-100 MW Power levels