RF Upset and Chaos in Circuits: Basic Investigations

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WEAPON X

Intense blasts of microwaves can black out cities and knock out computers—but leave people and buildings standing. Is this the future of warfare?

PLUS

HOLIDAY BUYING GUIDE: THE YEAR'S BEST GADGETS p. 42

HIST & TEN: HOW A.S. FOOTBALL'S YELLOW LINE GETS IN YOUR TV p. 31
OVERVIEW

HPM Effects on Electronics

Are there systematic and reproducible effects?
Can we predict effects with confidence?

Evidence of HPM Effects is spotty:

- Anecdotal stories of rf weapons and their effectiveness
- Commercial HPM devices
  - etc.

Difficulty in predicting effects given complicated coupling,
interior geometries, varying damage levels, etc.

Why confuse things further by adding chaos?

- New opportunities for circuit upset/failure
- A systematic framework in which to quantify and classify HPM effects
Overview/Motivation
“The Promise of Chaos”

• Can Chaotic oscillations be induced in electronic circuits through cleverly-selected HPM input?
• Can susceptibility to Chaos lead to degradation of system performance?
• Can Chaos lead to failure of components or circuits at extremely low HPM power levels?
• Is Chaotic instability a generic property of modern circuitry, or is it very specific to certain types of circuits and stimuli?
Chaos

Classical: Extreme sensitivity to initial conditions

\[ \dot{q}_i = \frac{\partial H}{\partial p_i} \]
\[ \dot{p}_i = -\frac{\partial H}{\partial q_i} \]

\[ H = T + V \] Hamiltonian

Best characterized as “extreme sensitivity to initial conditions”

Manifestations of classical chaos:
Chaotic oscillations, difficulty in making long-term predictions, sensitivity to noise, etc.
Time series, iterated maps, Lyapunov exponents, etc.
Extreme Sensitivity to Initial Conditions
Double Pendulum Demo

Start with similar initial conditions
The motion of the two pendula diverge

G1-60: CHAOS - TWO DOUBLE PHYSICAL PENDULA
DESCRIPTION: The two pendula are started into apparently identical oscillations, but their motion soon diverges. No matter how closely the motions of the two pendula are started, they eventually must undergo virtually total divergence. This illustrates the modern meaning of "chaos."
Chaos in Nonlinear Circuits

Many nonlinear circuits show chaos:
- Driven Resistor-Inductor-Diode series circuit
- Chua’s circuit
- Coupled nonlinear oscillators
- Circuits with saturable inductors
- Chaotic relaxation circuits
- Newcomb circuit
- Rössler circuit
- Phase-locked loops

...  
Synchronized chaotic oscillators and chaotic communication

Here we concentrate on the most common nonlinear circuit element that can give rise to chaos due to external stimulus: the p/n junction
The p/n Junction

The p/n junction is a ubiquitous feature in electronics:
Electrostatic-discharge (ESD) protection diodes
Transistors

Nonlinearities:
Voltage-dependent Capacitance
Conductance (Current-Voltage characteristic)
Reverse Recovery (delayed feedback)

HPM input can induce Chaos through several mechanisms


Electrostatic Discharge (ESD) Protection Circuits

A New Opportunity to Induce Chaos at High Frequencies in a distributed circuit

The “Achilles Heel” of modern electronics
Chaos in the Driven Diode Distributed Circuit

A simple model of p/n junctions in computers

Delay differential equations for the diode voltage

1) \[ 2V_{\text{inc}}(t) = V(t) + Z_0[gV + \frac{d}{dt}Q(V(t))]. \]

2) \[ V_{\text{ref}} = V(t) - V_{\text{inc}}(t). \]

3) \[ V_{\text{inc}}(t) = V_{\text{ref}}(t-2T) + V_g(t-T). \]

\[
\frac{d}{dt}V(t) = \frac{(1+Z_0g)}{Z_0C(V(t))}V(t) + \frac{\rho_g(1-Z_0g)}{Z_0C(V(t))}V(t-2T) + \frac{\rho_g C(V(t))}{C(V(t-2T))} \frac{d}{dt}V(t-2T) + \frac{V_g \tau_g}{Z_0C(V(t))} \cos(w(t-T)).
\]
Chaos in the Driven Diode Distributed Circuit

Simulation results

\[ V_g = .5 \text{ V} \quad \text{Period 1} \]

\[ V_g = 2.25 \text{ V} \quad \text{Period 2} \]

\[ V_g = 3.5 \text{ V} \quad \text{Period 4} \]

\[ V_g = 5.25 \text{ V} \quad \text{Chaos} \]

\[ f = 700 \text{ MHz} \]
\[ T = 87.5 \text{ ps} \]
\[ R_g = 1 \Omega \]
\[ Z_0 = 70 \Omega \]
\[ \text{PLC, } C_r = C_f/1000 \]
Chaos in the Driven Diode Distributed Circuit

Simulation results

Strobe Points (Volts)

$V_g$ (Volts)

f = 700 MHz
T = 87.5 ps
$R_g = 1 \, \Omega$
$Z_0 = 70 \, \Omega$
PLC, $C_r = C_f/1000$
Experimental Bifurcation Diagram
BAT41 Diode @ 85 MHz
T ~ 3.9 ns, Bent-Pipe

Experimental Results

Driving Power (dBm)

Peak Voltage (V)

Frequency (MHz)

Power (dBm)

Period 1
Period 2
Period 4
Period 8
Chaos
Distributed Transmission Line Diode Chaos at 785 MHz

17 dBm input

21 dBm input

NTE519
785 MHz
T ~ 3.5 ns
DC Bias=6.5 Volts
Chaos and Circuit Disruption
What can you count on?

Bottom Line on HPM-Induced circuit chaos
What can you count on? → p/n junction nonlinearity
Time scales!
Windows of opportunity – chaos is common but not present for all driving scenarios
ESD protection circuits are ubiquitous

Manipulation with “nudging” and “optimized” waveforms.

Quasiperiodic driving lowers threshold for chaotic onset
Two-tone driving lowers threshold for chaotic onset

Noise-induced Chaos:
Resonant perturbation waveform
What needs further research?

Is chaos the correct organizing principle for understanding HPM effects?

Effects of chaotic driving signals on nonlinear circuits
(challenge – circuits are inside systems with a frequency-dependent transfer function)
    Unify UMD circuit chaos and wave chaos research

Uncover the “magic bullet” driving waveform that causes maximum disruption to electronics
    Example of optimized waveform

Chaotic Driving Waveforms
    Chaotic microwave sources
Simple Chaos
1-Dimensional Iterated Maps

The Logistic Map:

\[ x_{n+1} = 4\mu x_n (1 - x_n) \]

Parameter: \( \mu \)
Initial condition: \( x_0 \)

\[ x_0 = 0.100 \]

\( \mu = 0.5 \)
\( \mu = 0.8 \)
\( \mu = 1.0 \)
Extreme Sensitivity to Initial Conditions

1-Dimensional Iterated Maps

The Logistic Map:

\[ x_{n+1} = 4\mu x_n (1 - x_n) \]

\[ \mu = 1.0 \]

Change the initial condition \((x_0)\) slightly…
Experiment on the Driven Diode Distributed Circuit

- Signal Generator
- Amplifier
- Circulator
- Directional Coupler
- Transmission Line ($Z_0$)
- 50Ω Load
- Oscilloscope
- Spectrum Analyzer
- Diode
- BAT 86
- 1N4148
- 1N5475B
- 1N5400

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