Chaos and High Power RF Effects: Statistical Analysis of Induced Voltages

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Goal

To develop a quantitative statistical understanding of induced voltage and current distributions in circuits inside complicated enclosures, based upon minimal information about the system.
Coupling of external radiation to computer chips is a complex process:
- Apertures
- Resonant cavities
- Transmission Lines
- Circuit Elements

System Size > Wavelength

We want to understand the scattering properties of this system including the effects of coupling

- Statistical Distribution using Wave Chaos
Why Quantum / Wave Chaos?

Difficulty in making predictions of electromagnetic field structure in complicated enclosures

Predictions can depend sensitively on details

The “soda can problem”

Related work: (Field distributions in reverberation chambers, etc.)
and others…
The Difficulty in Making Predictions…

- The EM Response of Complicated Enclosures is Very Sensitive to details (boundary conditions, cable locations, etc.) ⇒ Analytic Solutions are Impractical

- Solution: Statistical Description using Wave Chaos !!
2 Dimensional Quarter Bow Tie Wave Chaotic cavity
- Classical ray trajectories are chaotic - short wavelength - Quantum Chaos
- 1-port, 2-port S and Z measurements in the 3-18 GHz range
- Ensemble average through 100 locations and orientations of the perturbations
- Perturbers are of size $\sim \lambda$ or bigger
Uncover simple statistical properties of:

- Eigen-frequencies,
- Eigen-functions, 
- Scattering matrix, 
- Impedance matrix, 
- Admittance matrix, etc.

Many of these simple statistical properties are described by Random Matrix Theory.

D. H. Wu and S. M. Anlage, 
Practical Implications for Real Life Problems
Bare Minimum Specifications for Induced-Voltage Statistics

What are the bare minimum specifications to accurately predict voltage Statistics?

**Minimum Information:**
- Frequency, Volume and Losses
- Radiation impedance of the ports

Determine the “Key Parameter” \( \frac{k^2}{\Delta k_n^2 \cdot Q} \)

Determines the shape and scales of cavity Z and S PDFs.
Algorithm for Predicting Component Induced-Voltage Distributions:

\[ Z = j \text{Im}[Z_{rad}] + z \cdot \text{Re}[Z_{rad}] \]

- Losses
- Frequency
- Volume
- Radiation Impedance \( Z_{rad} \)
- Cavity Impedance \( Z \)
- Specific Input Waveform
- Mode of HPM Attack

Probability Density Function of Voltages on all components inside enclosure
Prescription to Engineer Cavities with Desired Electromagnetic Properties:
Simple 1-Port Example

Numerically Generated (z)
Depends only upon $\frac{k^2}{\Delta k_n} \cdot Q$

$Z_{cav} = jX_{rad} + z \cdot R_{rad}$

$Z_{rad} = R_{rad} + jX_{rad}$

- Freq: 6 to 9.6 GHz
- Antenna Dia (2a) = 1.27mm

$S = |S| e^{j\phi_s}$

$P\{|S|^2\}$

$P\{\phi_s\}$
Application of RCM to a Real Problem
Induced Voltage PDFs in a Computer Enclosure and Room

Port 1: 1 W @ 5.3 GHz
Q = 5
Port 1: Bare Wire

Port 2: Bare Wire

Laptop Dim: 0.24m x 0.27m x 0.04m

Port 1: Hertzian Dipole

Port 2: PCB track

Room Dim: 12’ x 10’ x 8’

Q = 100
Port 1: 1 W @ 1 GHz

|V_2| (Volts)

PDF (|V_2|)

0.0 0.5 1.0
0.00 0.25 0.50

|V_2| (Volts)

PDF (|V_2|)
Variance of Voltage and Current Distributions on the Target

Given the variance of $S_{11}$ and $S_{22}$, we can predict the variance of the induced voltage and current distributions in the target.

\[ Var(S_{12}) \approx \frac{1}{2} \sqrt{Var(S_{11})Var(S_{22})} \] (ONERA)

Or even better:

\[ Var(Z_{12}) = \frac{1}{2} \sqrt{Var(Z_{11})Var(Z_{22})} \] (Maryland)
Operational Statements:

Measure $\text{Var}(Z_{11})$ of the target to quantify its degree of susceptibility to HPM attack.

Minimizing $\text{Var}(Z_{11})$ of the target is a strategy for minimizing damage from HPM attack.
Cavity Impedance and Field PDF Engineering

RCM Results

\[ Z_{\text{cavity}} = R_{\text{cavity}} + i X_{\text{cavity}} \]

- **(high loss)**
- **(intermediate loss)**
- **(low loss)**

**R\text{Rad}** sets the scale for **R\text{cavity}**
Low-loss case: **R\text{cavity} < R\text{Rad}**
Lossy case: \( \Rightarrow \) Gaussian distribution, width \( \sim \sqrt{Q} \)

**X\text{Rad}** sets the scale for **X\text{cavity}**
Low-loss case: broad tails, width \( \sim R\text{Rad} \)
Lossy case: narrow distribution, width \( \sim \sqrt{Q} \)
Conclusions

Deterministic measurements (or calculation/simulation) of the radiation impedance remove the effects of coupling to recover universal statistical electromagnetic properties.

Experimental tests of many basic 1 port and 2-port predictions have confirmed that the approach is correct.

Frequency, Volume Losses

\[ \frac{k^2}{\Delta k_n^2 Q} \]

Determine the Z, S PDFs

Radiation impedance of the ports

Proposed a universal relation for impedance variances in 2-port systems

Clear strategies to engineer the PDFs to suit one’s purpose

Our Vision for the Future…

• Random Coupling Model shows very promising signs... But still in its infancy.

• Experimentally Validate RCM in realistic 3D environments:
  • GENEC device
  • Mode-Stirred Chambers at ONERA
  • Realistic antenna configurations (apertures, bundle of cables, etc.)
  • Non-Reciprocal Media as a way to mitigate EM “Hot Spots” –Darmstadt-Germany

• Transfer the Model and it’s predictive capabilities to the END User:
  • Document the strengths and weaknesses of the model
  • Demonstrate it’s utility (User’s Guide)
  • Educate the User in the strategy and execution of predictions

• Extend RCM to Pulsed Time-Domain Measurements:
  • Compelling Theoretical Work initiated – Hart, Antonsen, Ott

• Connect RCM to the EM Topology Approach:
  • Quantum graphs and chaos on networks
• For really complex systems, a small change in frequency, orientation of EM features can result in vastly different internal field configurations.

• Need for a Statistical Approach

Some Other Future Plans

Consider the effects of objects inside the enclosure

Scars
Refraction and “Freak Waves”

\[
\text{Very large amplitude waves}
\]

SCARS \ (Heller, 1984)

Concentrations of wave density along unstable periodic orbits.

Quantum counterpart to classical phase space density is not uniform on the energy surface.

Study of mixed dynamics (Chaotic and regular)
What can be done with Time-Reversed Electromagnetics?
Combine with Chaos to do new things
Deliver a localized “Electromagnetic Punch”

**Receive mode**
- Put a source emitting a pulse or a known signal at the location of interest
- Reflecting boundaries (ray-chaotic environment)
- No effect / damage at locations nearby!

**Transmit mode**
- Time-reverse, amplify and broadcast the coda
- \( E(ri, t) \)
- \( E(ri, T-t) \)