Measurements of Wireless Devices in Reverberation Chambers

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Mission: Advance technological innovation and excellence for the benefit of humanity
The Founding of IEEE

- 1884: Thomas Edison, Alexander Graham Bell, and other notables founded the American Institute of Electrical Engineers (AIEE).
- 1912: Pioneers of wireless technologies and electronics founded the Institute of Radio Engineers (IRE).
- 1963: AIEE and IRE merged to become the Institute of Electrical and Electronics Engineers, or IEEE.
IEEE Today at a Glance

**Our Global Reach**

- 421,000+ Members
  - Member
  - Senior Member
  - IEEE Fellow
- 39 Technical Societies
- 160 Countries

**Our Technical Breadth**

- 1,600 Annual Conferences
- 3,900,000+ Technical Documents
- 170+ Top-cited Periodicals
IEEE Electromagnetic Compatibility Society: the world's largest organization dedicated to the development and distribution of information, tools, and techniques for reducing electromagnetic interference.

The society's field of interest: standards, measurement techniques and test procedures, instrumentation, equipment and systems characteristics, interference control techniques and components, education, computational analysis, and spectrum management, along with scientific, technical, industrial, professional and other activities that contribute to this field.

Founded in 1957
Professional Group on Radio Frequency Interference (PGRFI)
Institute of Radio Engineers (IRE)
IEEE EMC Society

Global Reach

60th anniversary (2017)
~4,000 Members
160 Countries

Technical Breadth

Flagship Annual Conference
IEEE International
EMC Symposium

IEEE Trans. EMC
IEEE EMC Magazine
IEEE Trans SIPI

EMC Standards
NIST, Wireless, and 5G

Communications Technology Laboratory (March 2014)
Targeted research: test and measurement of new communication technologies
- Calibrations and traceability for wireless instrumentation
- Refinement and validation of test protocols, models, and simulation tools
- New test methods for spectrum sharing, 5G, and other national priorities
Metrology for Wireless Systems Group

- Test methods and uncertainties for modulated-signal measurements
- Support for standards development
  - Standards and certification groups (CTIA, IEEE, ANSI, ...)
  - Data for standards development (smart manufacturing initiative, NFPA, ...)

OTA Test in reverberation chambers involves all except calibration services
What is a Reverberation Chamber?

- A shielded, highly reflective radiated-signal test chamber

What you can do with one:

- Create known fields (EMC/susceptibility)
- Radiated emissions and power (CW and modulated-signal)
- Antenna parameters ($\Gamma$, efficiency, etc.)

You can also do communication system tests

- Receiver sensitivity
- Throughput
- EVM, BER, etc.
- DUT needs realistic channel

NIST measurements of prototype 4G MIMO cellular telephone antennas
Fields in a Metal Box (Cavity)*

- In a metal box, the fields have well defined modal distributions.
  - Some locations have very high field values
  - Some locations have very low field values

* With thanks to Chris Holloway
Fields in a Metal Box with Large, Rotating Scatterer (Paddle)

- The paddle changes internal field distributions (modes) where the high and low field values occur.
- Ideally, after one mode-stirring sequence, all locations in the chamber will have experienced nearly the same collection of field maxima and minima.

Frozen Food
A “Statistical” Test Chamber

- Quantities measured in the reverberation chamber are averaged over a *mode-stirring sequence*
- Randomize fields with
  - Mode-stirring paddles
  - Changing physical position or moving walls
  - Using multiple antennas with various locations, polarizations, etc.
Reverberation ChambersCome in All Shapes and Sizes

Lowest frequency of operation, uncertainties determined by chamber size, wall loss

Reverberation Chamber with Moving Walls

NASA: Glenn Research Center (Sandusky, OH)
Reverberation Chamber Characteristics

Constructive and destructive interference for each mode-stirring sample

- Frequency domain ($|S_{21}|^2$): Reflections create multipath

- Time domain (power delay profile): Decay time of reflections depends on chamber reflectivity
Original Applications

- **Radiated immunity:**
  - high field strength
    - components
    - large systems
- **Radiated emissions**
- **Shielding**
  - cables
  - connectors
  - enclosures

- **Antenna efficiency**
- **Calibrate RF probes**
- **RF/MW Spectrograph**
  - absorption properties
- **Material heating**
- **Biological effects**
- **Conductivity and material properties**
Wireless Applications

- **Multipath environments**
  - Rayleigh, Rician multipath channels: with/without channel emulators
  - Time response: power delay profile, delay spread

- **Biological effects of modulated-signal exposure**

- **Gain from multiple antenna systems**
  - TX or RX diversity
  - MIMO

- **Standardized over-the-air test methods**
  - Radiated power of mobile wireless devices
  - Receiver sensitivity
  - Large-form-factor and body-worn devices (with phantoms)
  - Public-safety emergency equipment
Emulating Multipath Environments

NIST channel measurements: Standards development for electronic safety equipment such as firefighter beacons
Channel Measurements: Denver High Rise

- Transmitting antenna
- Tripods 62 inches
- VNA Port 1 Port 4
- Optical Fiber
- Receiving antenna
- Fiber Optic Receiver
- Fiber Optic Transmitter
- 160 cm
- Ground Plane
- 200 m Optical Fiber
- VNA measurement test locations are in pink
Replicate Environment in Reverberation Chamber

- Add RF absorbing material to "tune" the decay time of the chamber
- Distributed multipath (reflections) matched by chamber’s decay profile

Time response of channel replicated in chamber

Reverberation chamber with absorbing material
Emulating Other Reflective Environments

- Oil Refinery
Emulating Other Reflective Environments

- Automobile Factories

![Automobile Factories Image]

- Automobile Factories Image 2

- Automobile Factories Image 3
Urban Canyon Multipath Effects

- Measurements made in Denver urban canyon 2009
- Channel characterization: LOS and NLOS

Line of Sight (LOS)  Non Line of Sight (NLOS)
Replicating Clustered Multipath in Reverberation Chamber

Clusters of exponentially distributed signals received off of buildings

- Blue: Mean of 27 NLOS measurements
- Red: RC + channel emulator
- Dashed: Exponential model
“Channel Models” used for standardized over-the-air (OTA) tests

- Outdoor-to-indoor channel model for 700 MHz
  - 8 environments, hundreds of measurements
- Included in proposed 3GPP reverberation-chamber-based test methods

![Excess tap delay vs. Relative power](image)

- 700 MHz, measured
- 4900 MHz, measured
- 700 MHz, fit
- 4900 MHz, fit

RMS DS: 80 ns
@ 700 MHz

Reverberation chamber can easily replicate diffuse multipath

<table>
<thead>
<tr>
<th>Excess tap delay [ns]</th>
<th>Relative power [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>40</td>
<td>-1.7</td>
</tr>
<tr>
<td>120</td>
<td>-5.2</td>
</tr>
<tr>
<td>180</td>
<td>-7.8</td>
</tr>
<tr>
<td>210</td>
<td>-9.1</td>
</tr>
<tr>
<td>260</td>
<td>-11.3</td>
</tr>
<tr>
<td>350</td>
<td>-15.2</td>
</tr>
</tbody>
</table>

Discrete version of the “NIST Model” for anechoic-chamber measurements

Cellular Wireless: Over-the-Air Tests Required

- Network providers assess performance of every wireless device model on their network:
  - Total Radiated Power (TRP)
  - Total Isotropic Sensitivity (TIS)
- OTA testing traditionally done in anechoic chambers

Reverberation chambers can be used as well!
Modulated Signals in RCs: What is different from EMC Testing?

- Receiver needs a realistic “frequency flat” channel
- Loading required: Add RF absorber to chamber
- Coherence bandwidth should match DUT design
- Spatial uniformity decreases
- Position stirring required

Real Channel: Slow Variations with Frequency

| TX1 to RX6 | \( |H(f)|^2 \text{ (mean)} = -58 \text{ dB} \) | \( \sigma \sim 5 \text{ dB} \) |

**Graphs:****

- **Mean \(|H(f)|^2\)
- **Mean \(|N(f)|^2\)
- **Std Dev \(|H(f)|^2\)

- **Correlation**

- **Loaded = broader coherence bandwidth**
Cellular Device Testing: How is it done?

- Reference measurement provides:
  - Chamber loss: Transfer function of chamber
  - Spatial uniformity of averaged fields in chamber
  - Rotating platform: \[ G_{\text{ref}} = \langle G_{\text{ref}}, p \rangle \]

- DUT measurement:
  - Same set-up as Ref
  - Assume \( G_{\text{DUT}} = G_{\text{ref}} \)
Total Radiated Power from Cell Phones

Data from CTIA working group shows good agreement between anechoic and reverberation chambers

- Cell phone testing: ca. 2010
- But in 2017…
The Machine-to-Machine (M2M) Revolution

- By 2019: 11.5 billion mobile devices (world population 7.6 B)*
- M2M/IoT growing faster than smart phones
  - 2014: 495 million
  - 2019: 3 billion

* Source Cisco
M2M and the Internet of Things (IoT)

- Large, cellular enabled devices:
- Low-cost, rough duty, solar-powered, becoming ubiquitous

Illustration of name brands does not imply endorsement by NIST: other products may work as well or better.
Testing Large Form-Factor Devices

- Integrated antennas: test of entire device required
- Reverberation chamber: currently only option for single-antenna devices
- Device placement not critical within chamber
- Relatively low cost
- OTA test issues: Large devices, loaded chamber
Loading Provides Improved Channel

Loading helps with demodulation:
Test DUT response to stimulus, NOT to chamber
But it introduces other “nonideal” effects

S. van de Beek et al., Characterizing large-form-factor devices in a reverberation chamber, EMC Europe 2013.
Loading and Position Stirring go Hand in Hand

- Industry uses position, polarization and source stirring to reduce K factor, improve estimate of DUT performance
- Non-negligible K factor a necessity:
  - unстirred energy
  - correlated samples: paddle angle, spatial, frequency

Measured estimate of chamber’s power transfer function (Gref) improves with position stirring
Set-up: Absorber Placement

• Standing on floor
• Lying on floor
• Stacked

Considerations:
• Exposed absorber surface area
• Exposed metal surfaces
• Absorber location
Comparable Loading, Different Uncertainty

PCS band measurement (~1950 MHz)

- Load chamber for approximately the same CBW
- Chamber loss approximately the same as well
- $\sigma_{G_{\text{ref}}}$ is higher when absorbers lie on floor
  - Less exposed metal surface
  - Higher proximity effect

<table>
<thead>
<tr>
<th></th>
<th>Distributed on Floor: Standing</th>
<th>Stacked</th>
<th>Distributed on Floor: Lying</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBW (MHz)</td>
<td>3.13</td>
<td>3.32</td>
<td>3.48</td>
</tr>
<tr>
<td>No. abs</td>
<td>3</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>$G_{\text{ref}}$ (dB)</td>
<td>-29.46</td>
<td>-29.69</td>
<td>-29.78</td>
</tr>
<tr>
<td>$\sigma_{G_{\text{ref}}}$ (dB)</td>
<td>0.15</td>
<td>0.30</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Total Isotropy Sensitivity (TIS): Wireless Router

- Absorbers stacked
- Reference and DUT measurements:
  - 9 different locations, heights
- TIS underestimated with insufficient loading
TRP for Large M2M Device

- Wireless, solar-powered trash compactor
- TRP measured for W-CDMA signal (BW = 3.84 MHz)
- Loading: stacked absorbers
- Coherence bandwidth: Verified >3.84 MHz (4.42 MHz)
- Antenna proximity effect: No effect at 1 λ (at $f_c$)
- Reference: Nine locations, DUT one location

Agreement with anechoic chamber:
- 0.2 dB, PCS band (1.850 GHz to 1.995 GHz)
- 1.95 dB, Cell band (800 MHz to 900 MHz)

Currently, the only accepted test method for large devices involves reverberation chambers
Summary: Cellular Device Testing in Reverberation Chambers

OTA Tests Require Loading:
- Provide realistic channel for receiver
- Increase unstirred energy
- Reduce spatial uniformity

Configure Chamber with Care:
- Placement of absorbers, antennas affects accuracy
- Validation of set-up required
- RC OTA tests compare well to other methods

The Future Will Bring:
- OTA for multiple antenna systems
- mmWave testing for 5G
Watch this space for more information on over-the-air testing with reverberation chambers