An Introduction to Free-Field Measurements of Wireless Devices in Reverberation Chambers

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Metrology for Wireless Systems

What is a Reverberation Chamber?

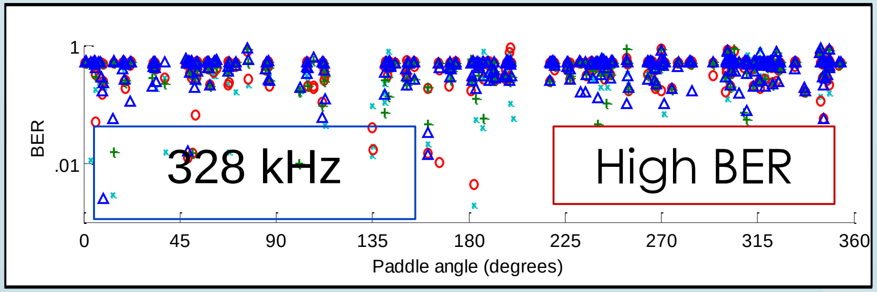
- A shielded, highly reflective free-field test chamber

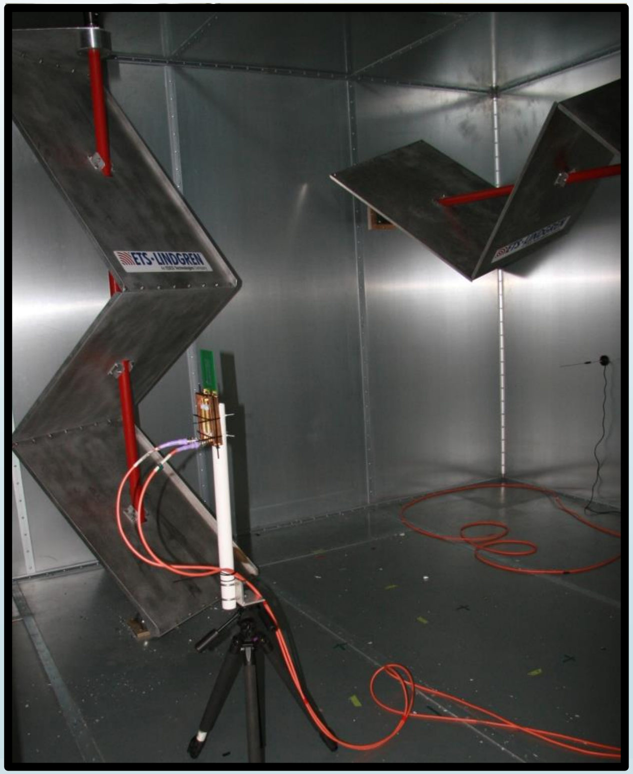
What you can do with one:

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

You can also do communication system tests

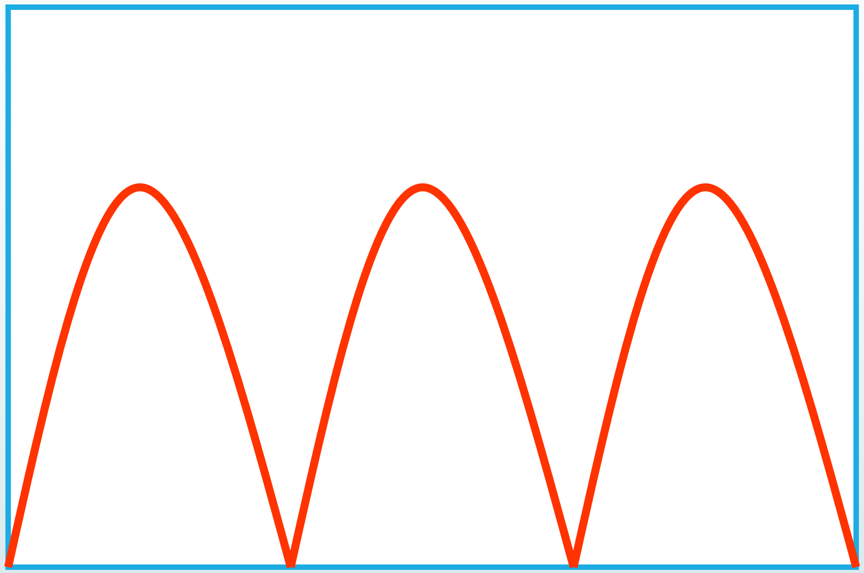
- Receiver sensitivity
- Throughput
- EVM, BER, etc.
- DUT needs realistic channel





NIST measurements of prototype 4G MIMO cellular telephone antennas

Fields in a Metal Box (A Shielded Room)*

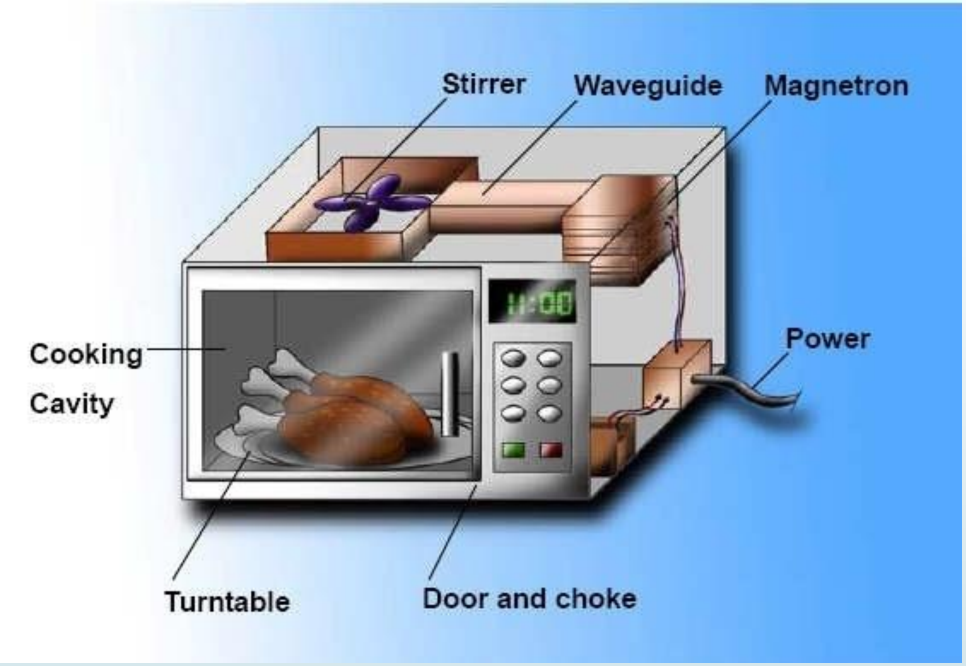


- In a metal box, the fields have well defined modal distributions.
  - Some locations have very high field values
  - Some locations have very low field values

* With thanks to Chris Holloway

Fields in a Metal Box with Large, Rotating Scatterer (Paddle)

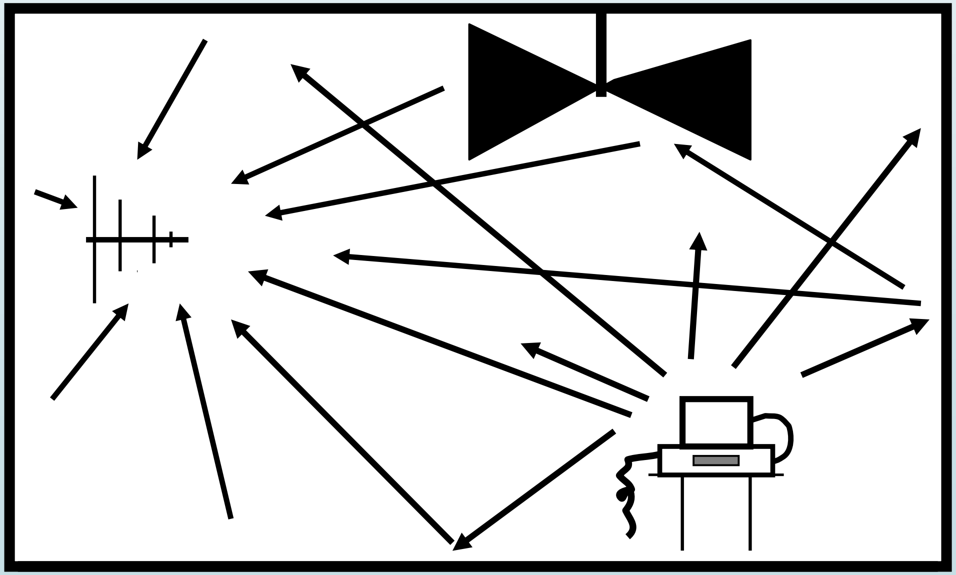
Frozen Food



- The paddle changes locations where the high and low field values occur
- After one mode-stirring sequence, all locations in the chamber will have experienced nearly the same collection of field maxima and minima

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
  - Using multiple antennas: various locations, polarizations

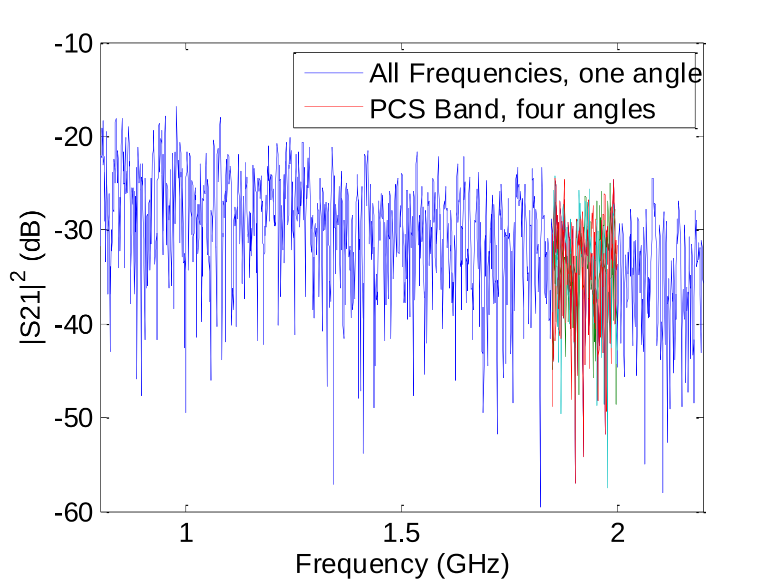


Reverberation Chambers Come in All Shapes and Sizes

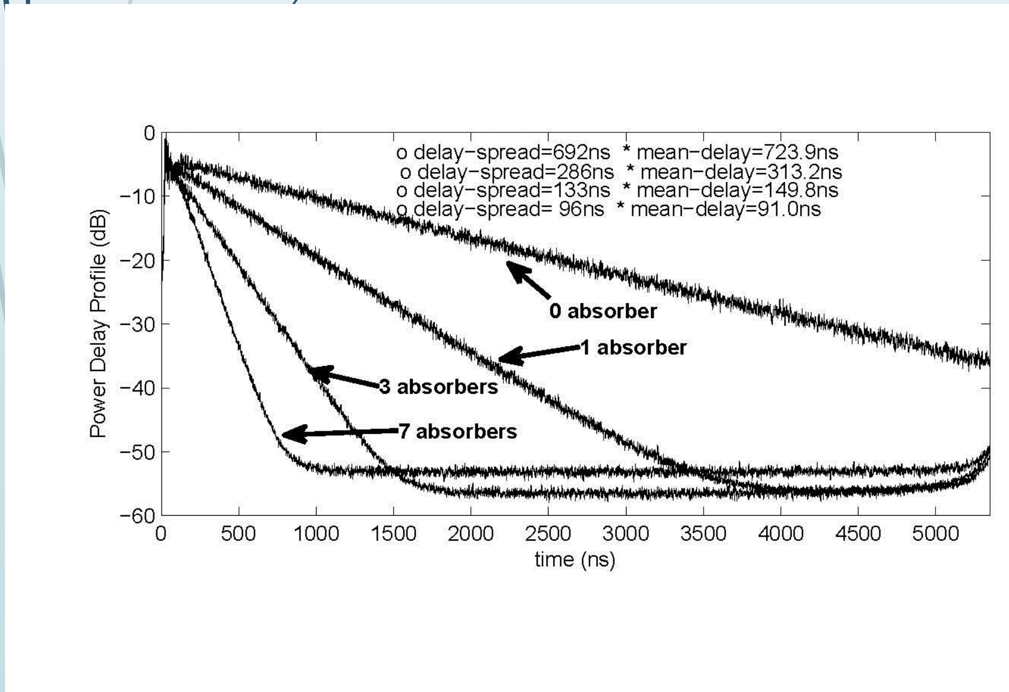
Lowest frequency of operation, uncertainties determined by chamber size, wall loss

Chamber Electrical 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

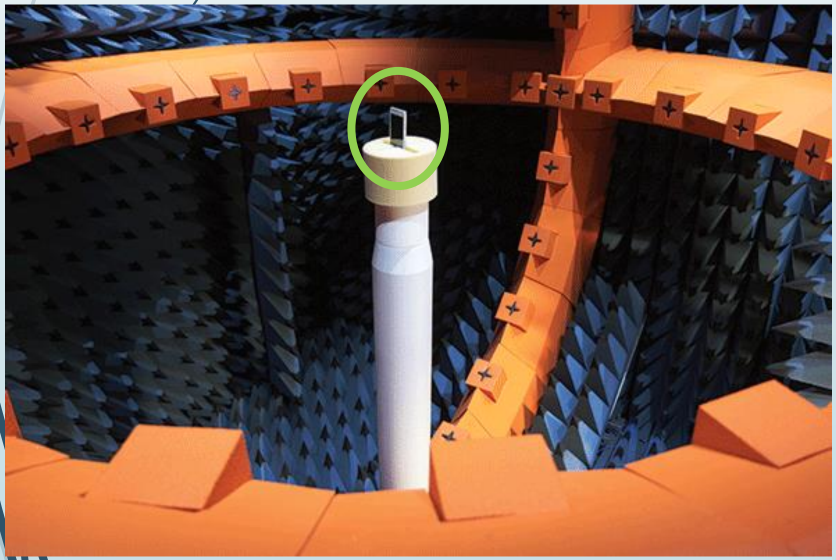
- ***Radiated Immunity***
  - components
  - large systems
- ***Radiated Emissions***
- ***Shielding***
  - cables
  - connectors
  - enclosures
- ***Antenna efficiency***
- ***Calibrate RF probes***
- ***RF/MW Spectrograph***
  - absorption properties
- ***Material heating***
- ***Biological effects***
- ***Conductivity and material properties***

Wireless Applications

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

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

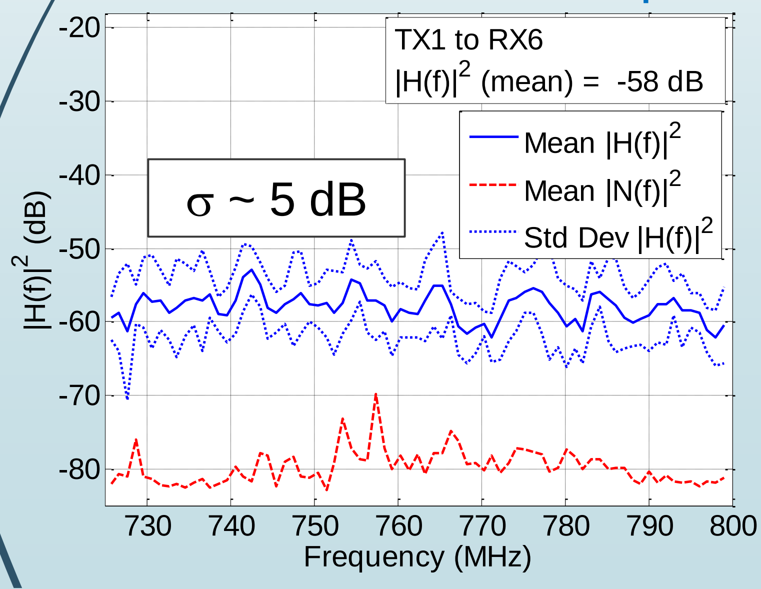


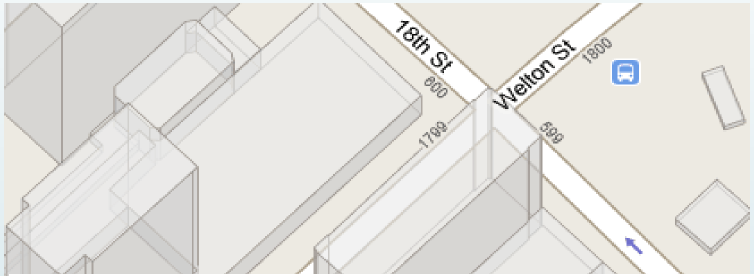
Reverberation chambers can be used as well!

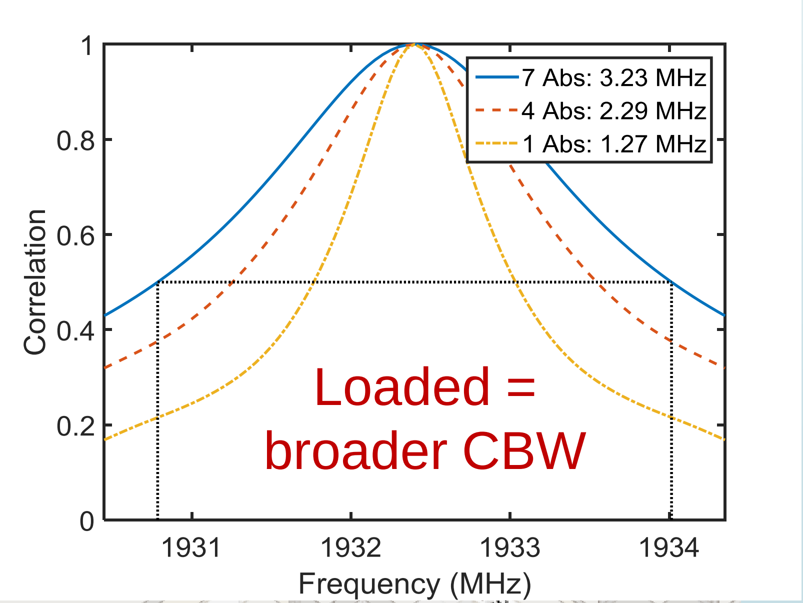
Modulated Signals in RCs:
What is different from EMC Testing?

- 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



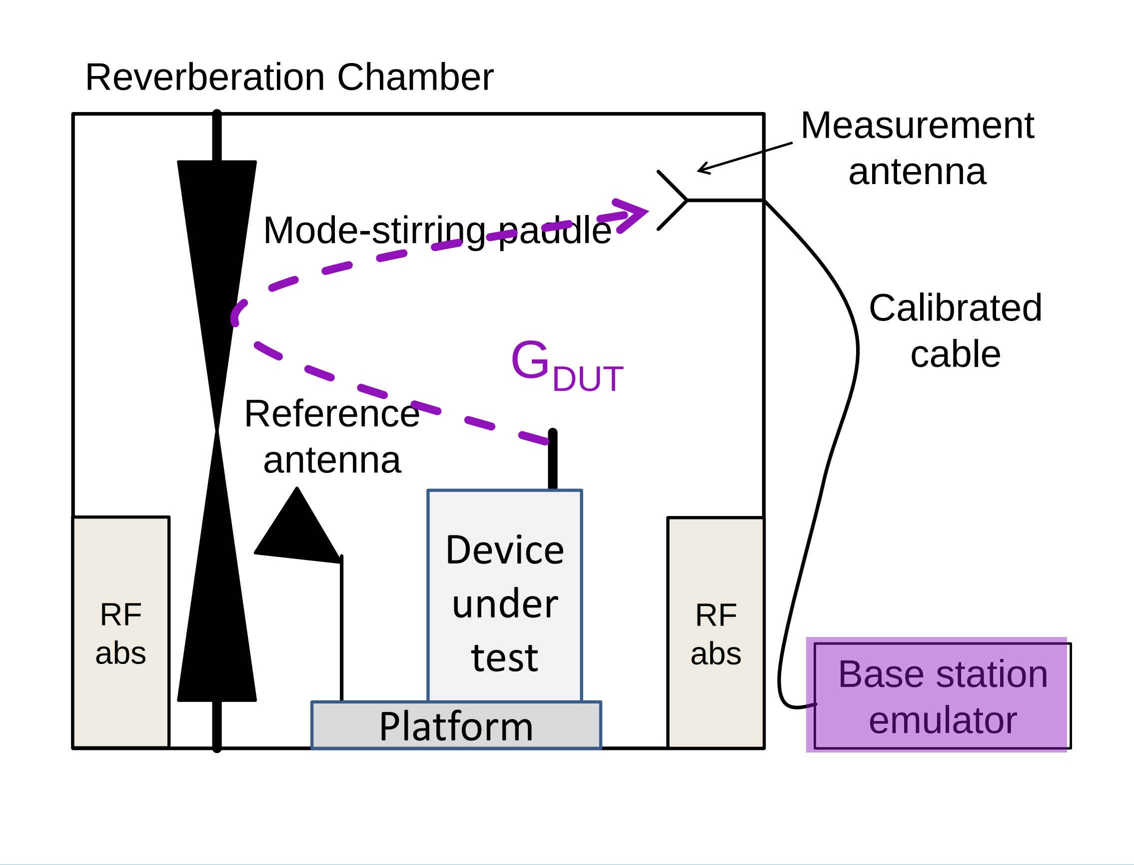




Cellular Device Testing: How is it done?

- Reference measurement provides:
  - Chamber loss: Transfer function Gref of chamber
  - Spatial uniformity of averaged fields in chamber
  - Rotating platform:

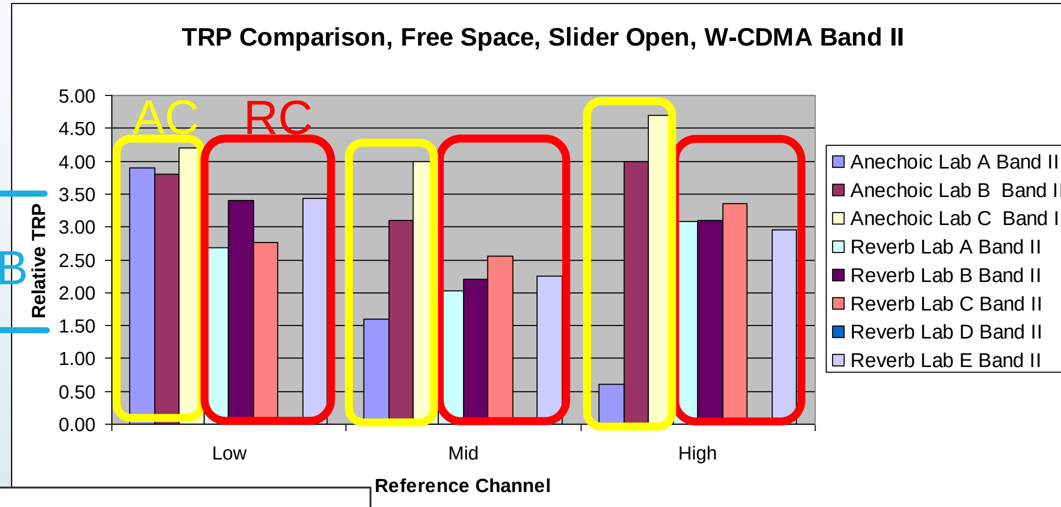
    Gref = <Gref,p>
- DUT measurement:
  - Same set-up as Ref
  - Assume $G_{DUT} = G_{ref}$



Total Radiated Power from Cell Phones

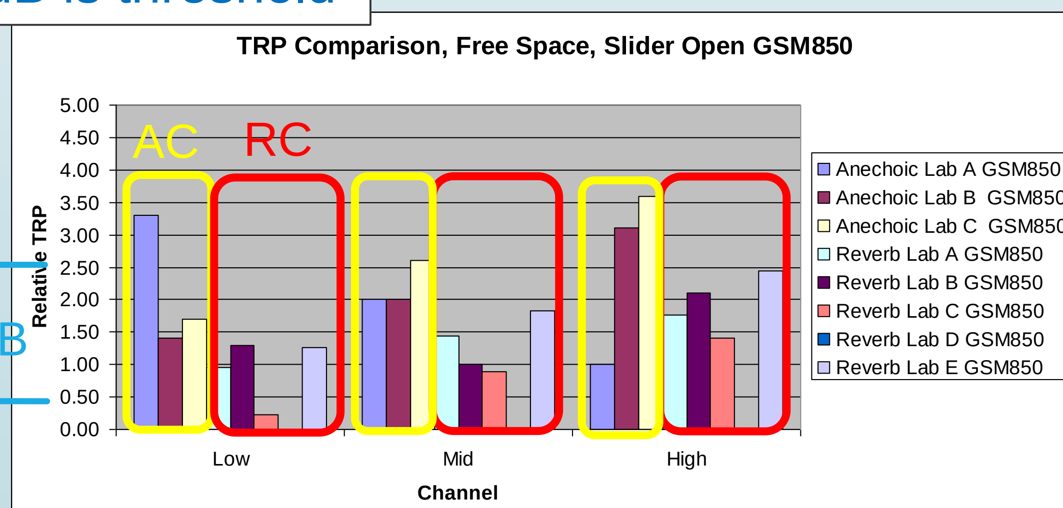
Data from CTIA working group shows good agreement between anechoic and reverberation chambers

Cell phone



2 dB

+/-2 dB is threshold



2 dB

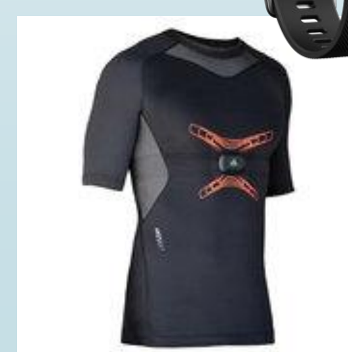
- **Cell phone testing: ca. 2010**
- **But in 2016…**

The Machine-to-Machine 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







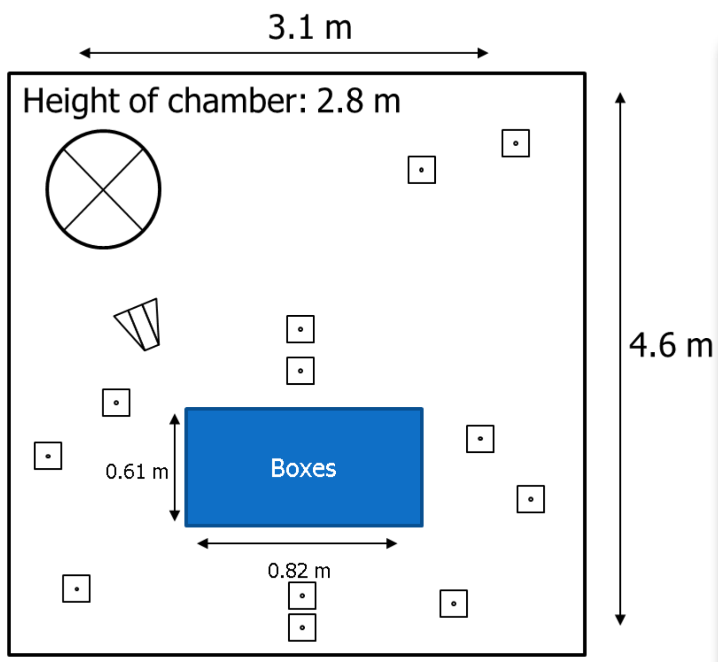
* Source Cisco

Testing Large Form-Factor Devices

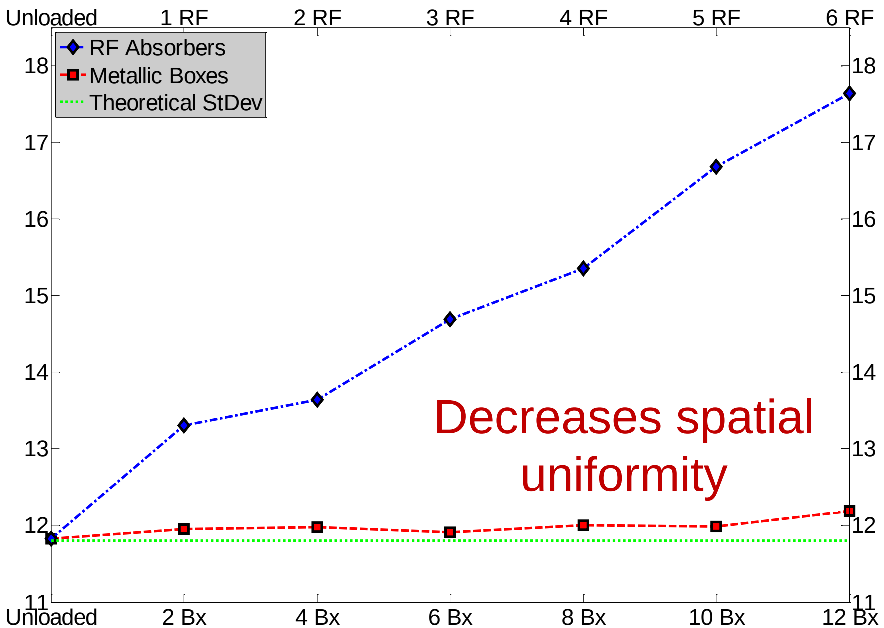
- Integrated antennas: test of entire device required
- Reverberation chamber: now only option for SISO tests
- Device placement not critical within chamber
- Relatively low cost
- OTA test issues: Large, lossy DUTs

Loading Decreases Spatial Uniformity

Loading helps with demodulation
but introduces other “nonideal” effects



- “Boxes” = Metallic
- “Absorbers” = RF Absorber

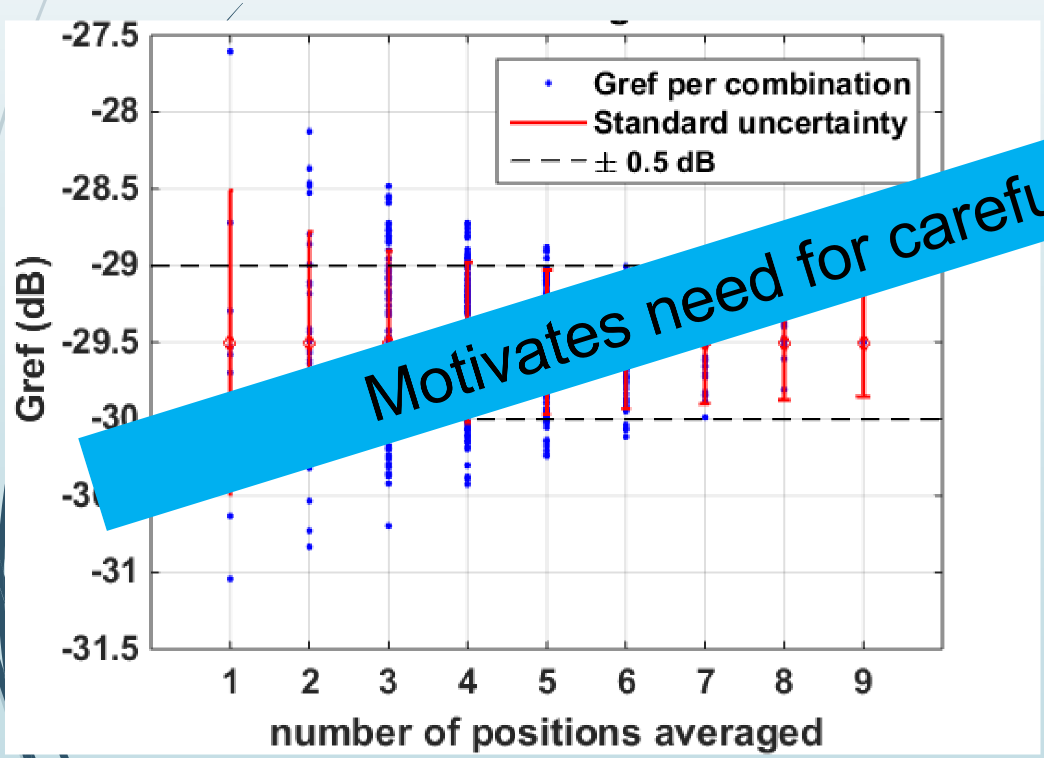


σ increases with loading (in percent)

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

- Spatial lack of uniformity a necessity:
  - unstirred energy
  - correlated samples: paddle position, location, frequency
- Industry uses position, polarization, source stirring to improve estimate of DUT performance



Motivates need for careful set-up

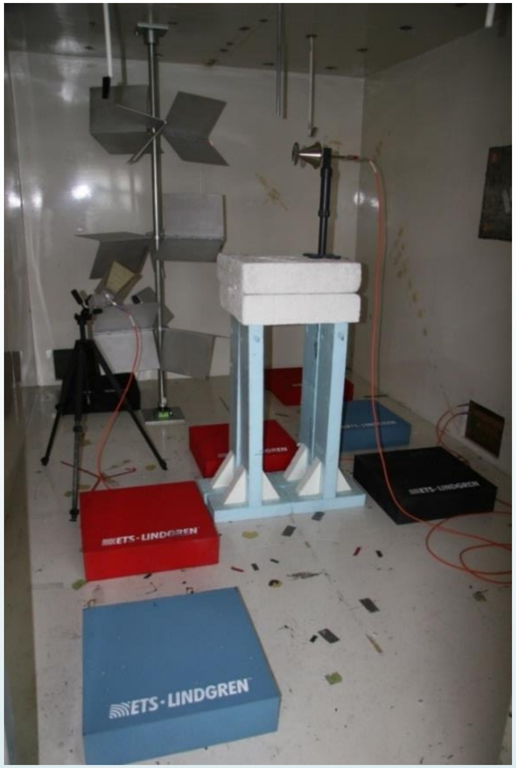
- Chamber reference for PCS channel 9262 (1.850-1.854 GHz)
- VNA : 9 spatially uncorrelated positions
- Combinations of all sets of data

Set-up: Absorber Placement

- Standing on floor
- Lying on floor
- Stacked

Considerations:

- Exposed absorber surface area
- Exposed metal surfaces
- Proximity to antennas



Comparable Loading, Different Uncertainty

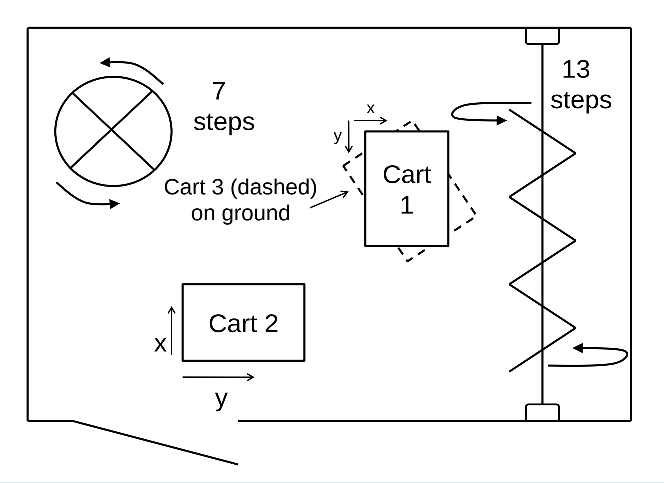
PCS band measurement (~1950 MHz)

- 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

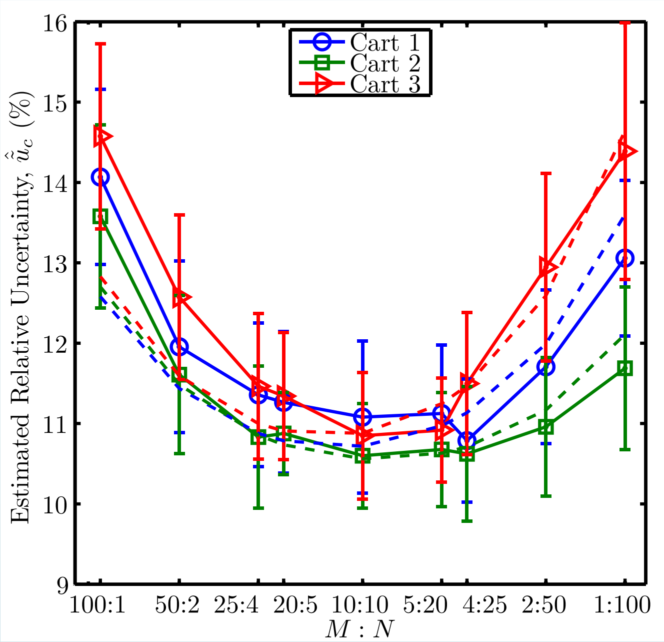
	Distributed on Floor: Standing	Stacked	Distributed on Floor: Lying
CBW (MHz)	3.13	3.32	3.48
No. abs	3	7	4
G_{ref} (dB)	-29.46	-29.69	-29.78
$\sigma_{G_{\text{ref}}}$ (dB)	0.15	0.30	0.35

Set-up: Stirring Sequence is Important

- Stirring mechanisms influence results differently
- Each chamber will have a different “mix” of optimal stirring



Measure effects of paddle angle and antenna position at three locations in a loaded chamber



Measured and modeled uncertainty at the three locations

K.A Remley, R.J Pirkl, H.A Shah, and C.-M. Wang, "Uncertainty from choice of mode-stirring technique in reverberation-chamber measurements," *IEEE Trans. Electromagnetic Compat.*, vol. 55, no.6, pp. 1022-1030, Dec. 2013.

M = antenna positions
N = paddle angles

Set-up: Antenna Placement is Important

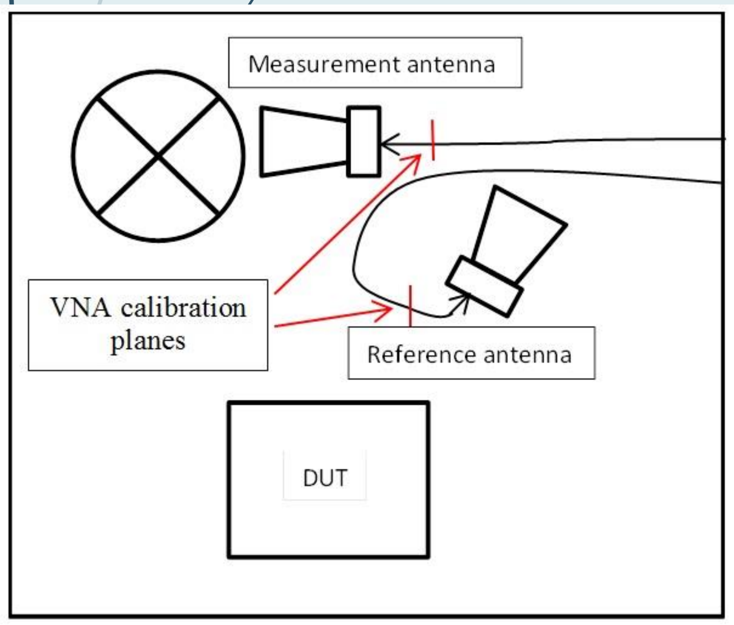
Unstirred energy: increased K factor, reduced spatial uniformity

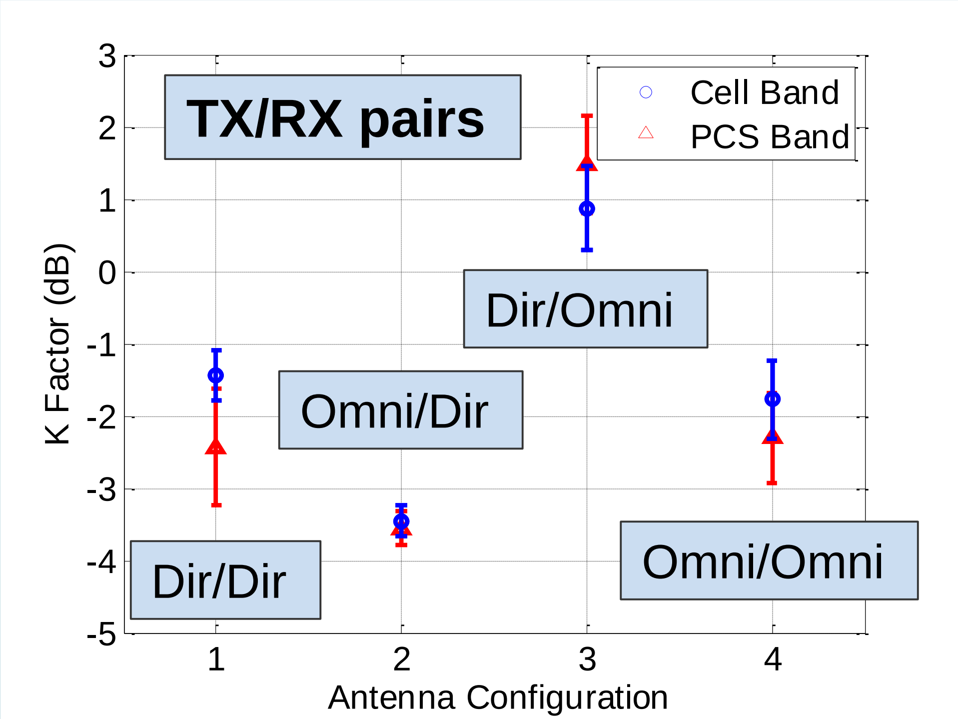
Antenna placement guidelines:

- Orient away from each other
- Cross polarize
- Aim toward stirrers

DUT: Unknown pattern?

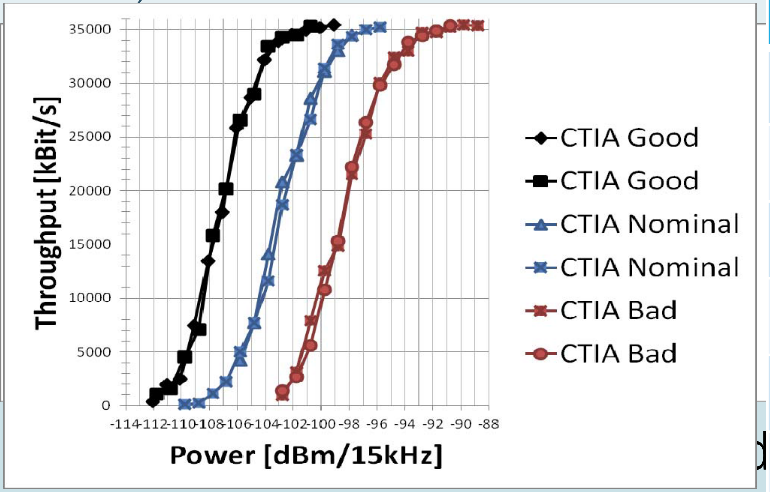
Relationship between antennas and absorber is also important





Good Set-up = Good Results

- Must account for
  - placement and amount of RF absorber
  - number, type, and correlation of mode-stirring samples
  - antenna type and placement
- Good comparison between chambers: throughput vs. input power



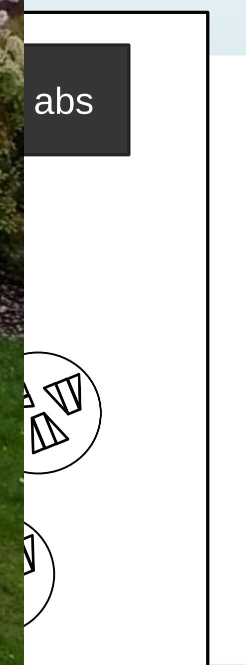
Lab	Good	Nominal	Bad
AC1	-100.50	-99.00	-94.20
AC2	-102.80	-100.00	-94.20
RC1	-103.58	-100.29	-93.40
RC2	-101.46	-98.22	-92.12
RC3	-101.93	-98.66	-90.91
Spread+/-	1.54	1.04	1.65

From MOSG131207

Results show good repeatability and comparison with anechoic methods

TRP for Large M2M Device

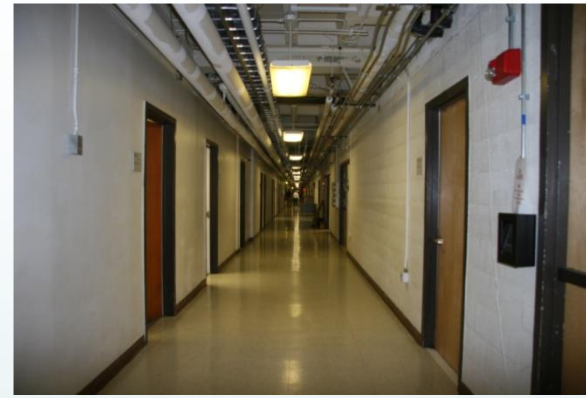
- Wireless, solar-powered trash compactor
- … MHz)
- … MHz)



OTA Tests to Model Multipath Environment

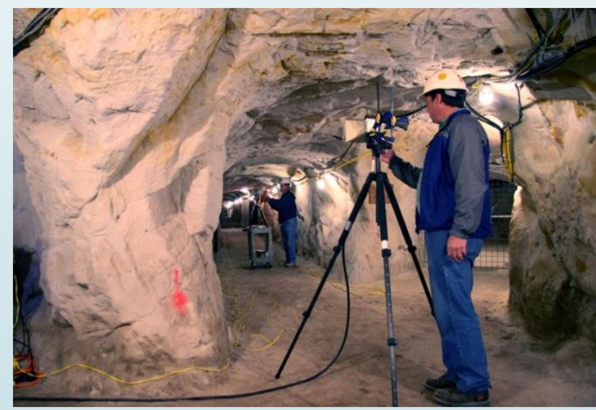
Apartment Building

Oil Refinery



Office Corridor

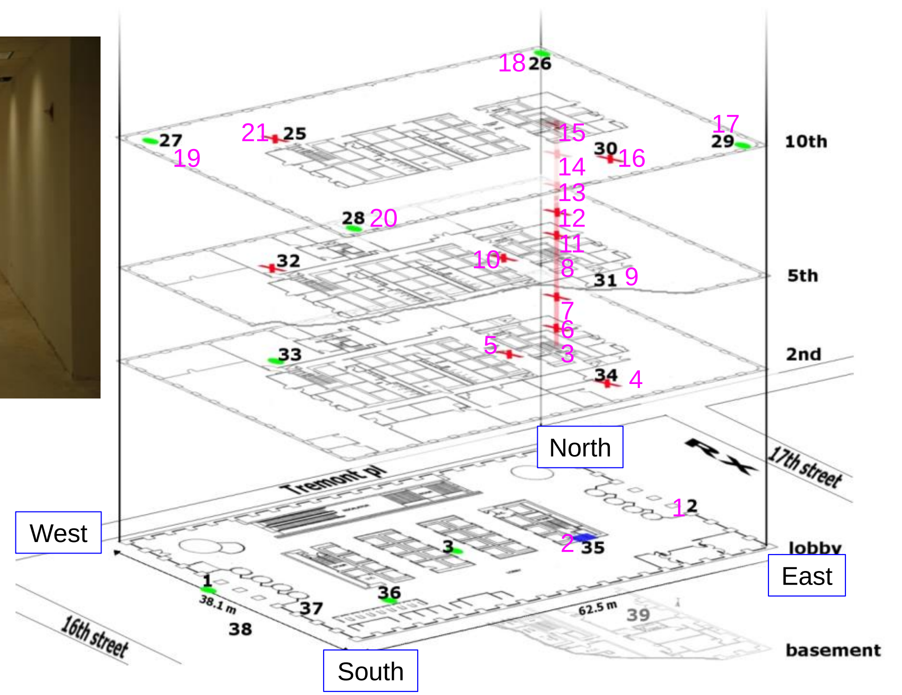
Automobile Plants



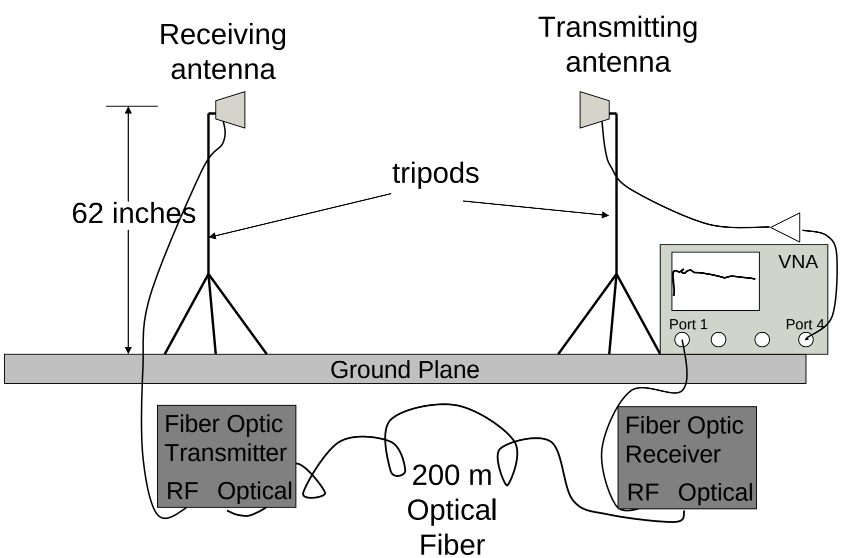
Subterranean Tunnels

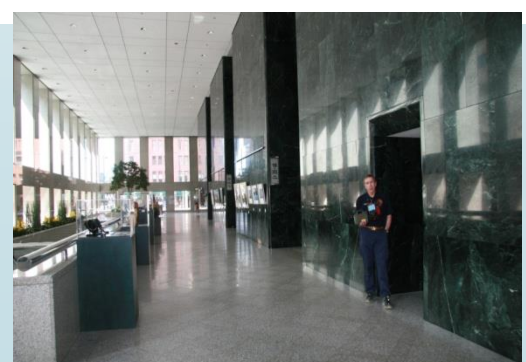
NIST channel measurements: Standards development for electronic safety equipment such as firefighter beacons

Channel Measurements: Denver High Rise



VNA measurement test locations are in pink



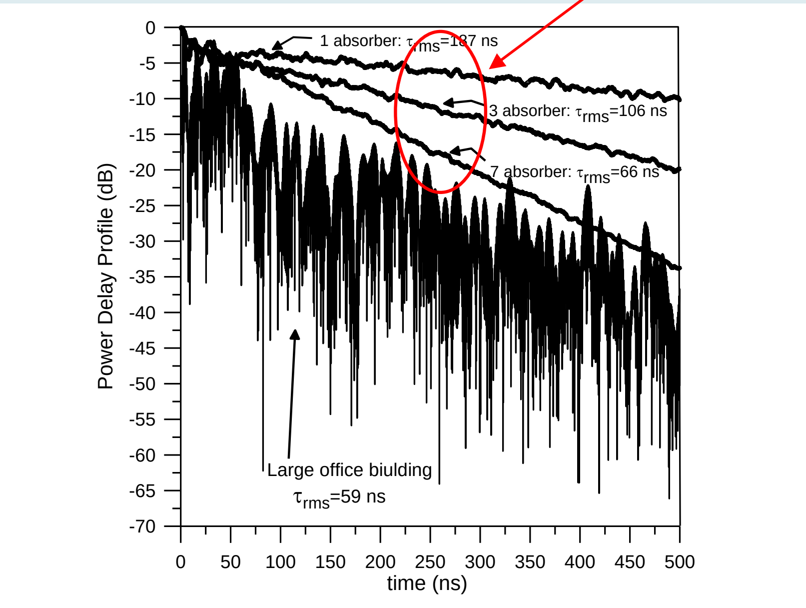


Replicate Environment in Reverberation Chamber

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

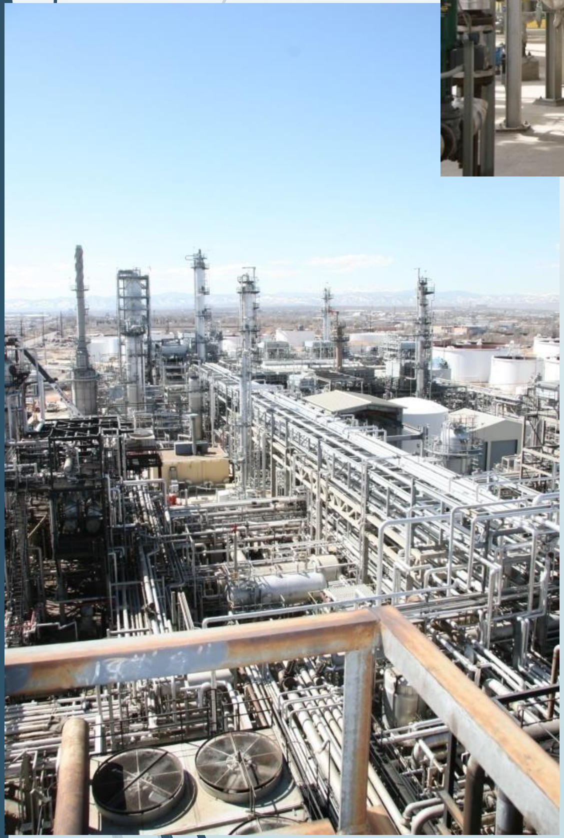
Reverberation chamber with absorbing material

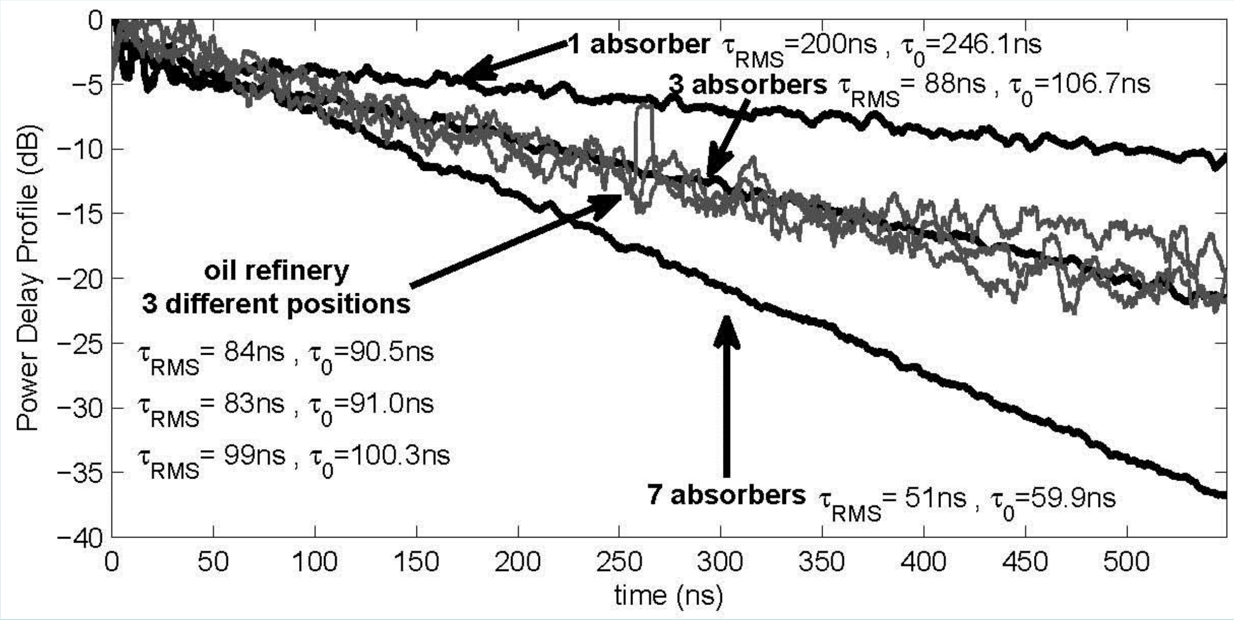
Time response of channel replicated in chamber



Emulating Other Reflective Environments

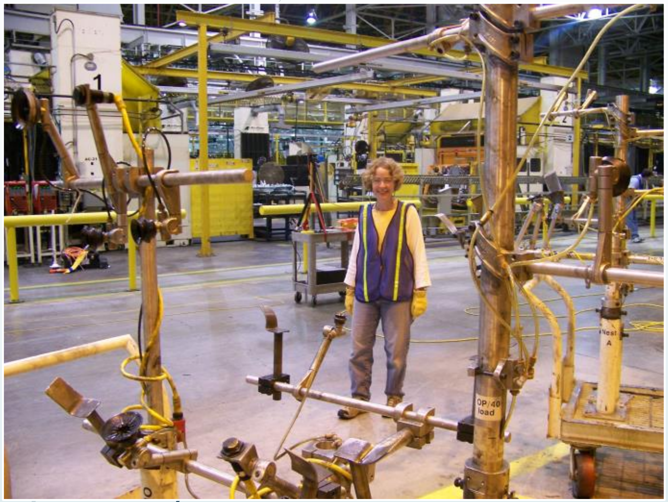
- Oil Refinery

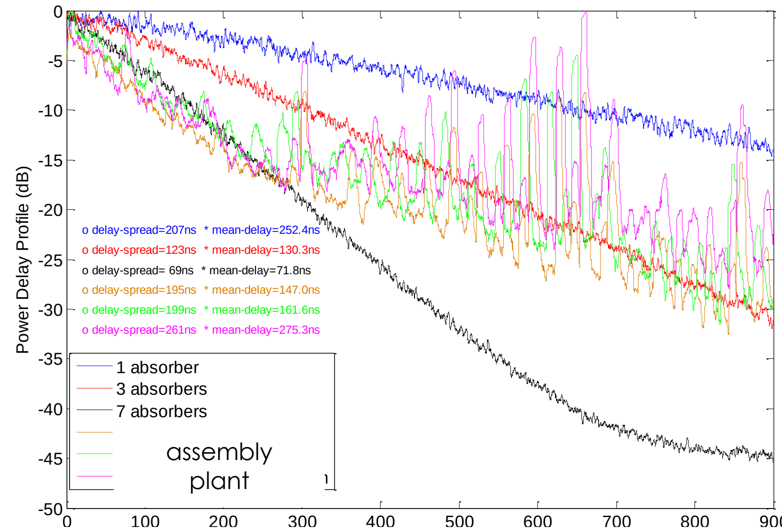


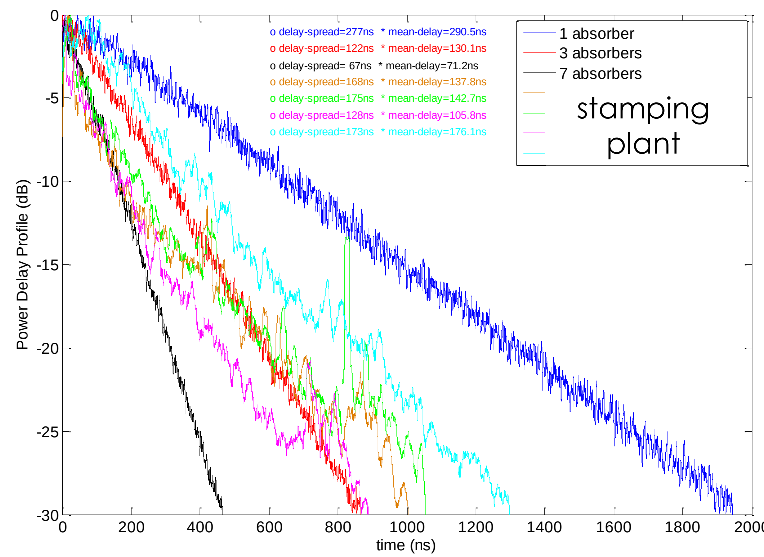


Emulating Other Reflective Environments

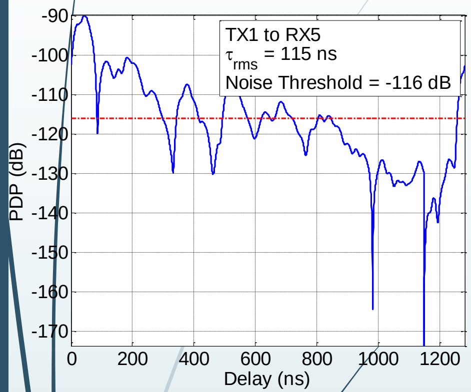
- Automobile Factories



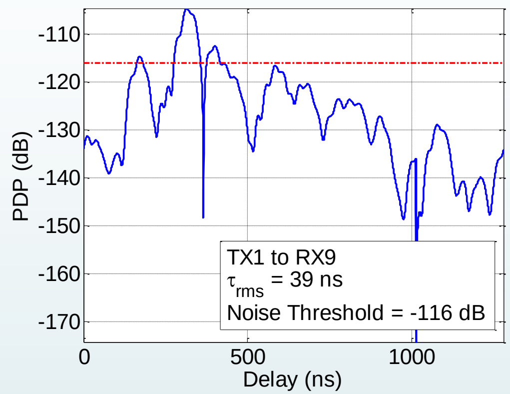




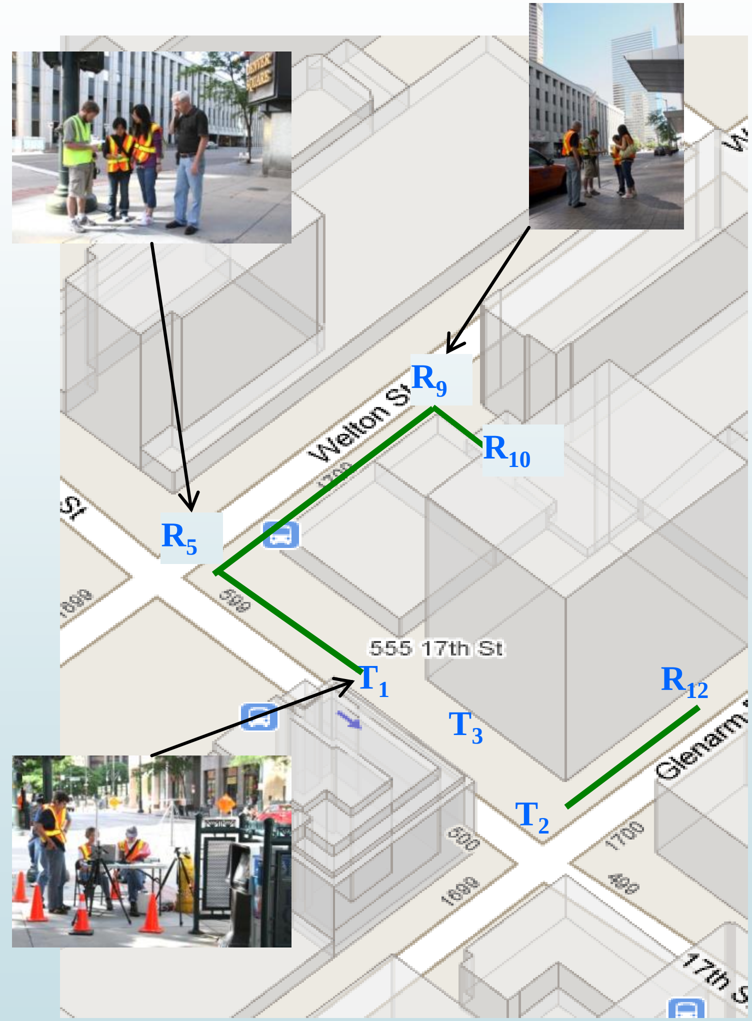
Urban Canyon Multipath Effects



Line of Sight

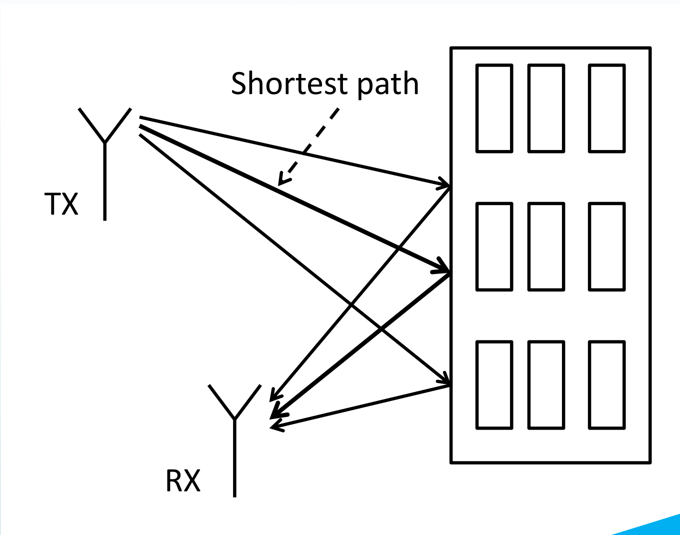


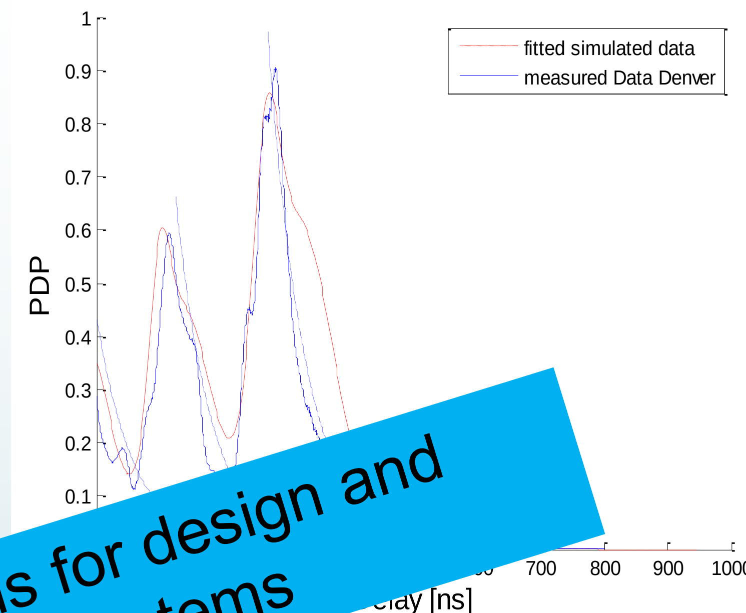
Non Line of Sight



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

Replicating Clustered Multipath in Reverberation Chamber

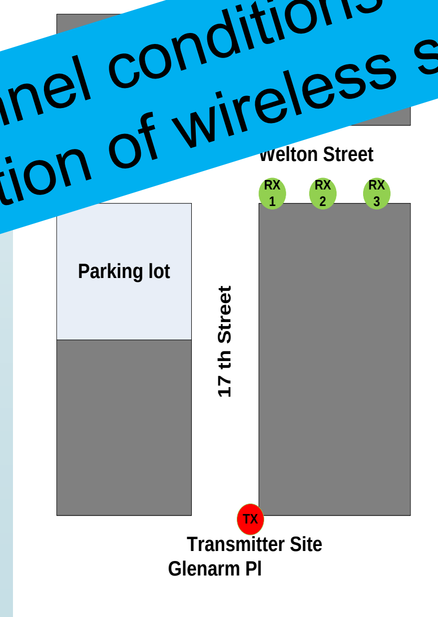




Replicate channel conditions for design and verification of wireless systems

Clus…

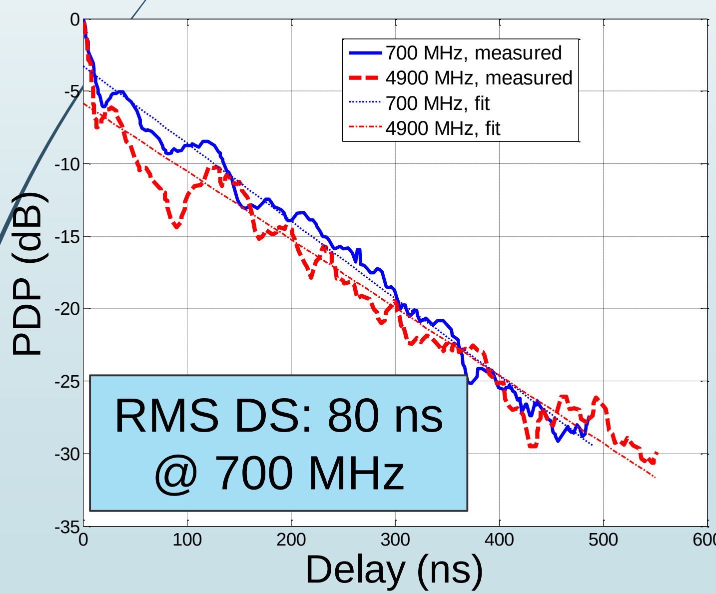
d…ed signals received off of buildings



- Blue: Mean of 27 NLOS measurements
- Red: RC + channel emulator
- Dashed: Exponential model

Channel Models Used for Standardized OTA tests

- Outdoor-to-indoor channel model for 700 MHz
  - 8 environments, hundreds of measurements
- "NIST Model" included in 3GPP reverberation-chamber-based test methods



Reverberation chamber can easily replicate diffuse multipath

Excess tap delay [ns]	Relative power [dB]
0	0.0
40	-1.7
120	-5.2
180	-7.8
210	-9.1
260	-11.3
350	-15.2

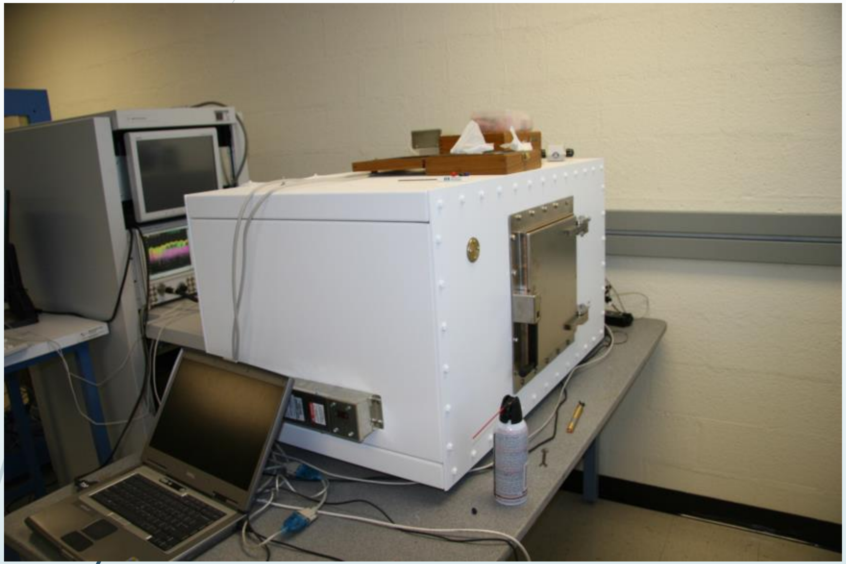
Discrete version of the "NIST Model" for anechoic-chamber measurements

D.W. Matolak, K.A. Remley, C.L. Holloway, and C. Gentile, "Outdoor-to-Indoor Channel Dispersion and Power-Delay Profile Models for the 700 MHz and 4.9 GHz Bands," *IEEE Antennas and Wireless Propagat. Lett.*, vol. 15, 2016, pp. 441-443.

Millimeter-Wave Wireless for "5G"

5G Wireless Concepts:

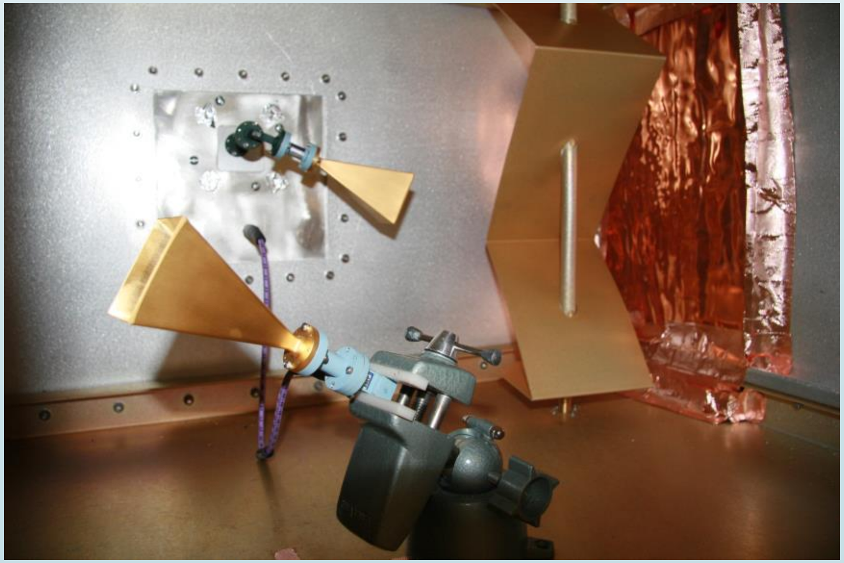
- Massive MIMO
- Tiered spectrum (licensed and unlicensed)
- Millimeter-wave frequencies



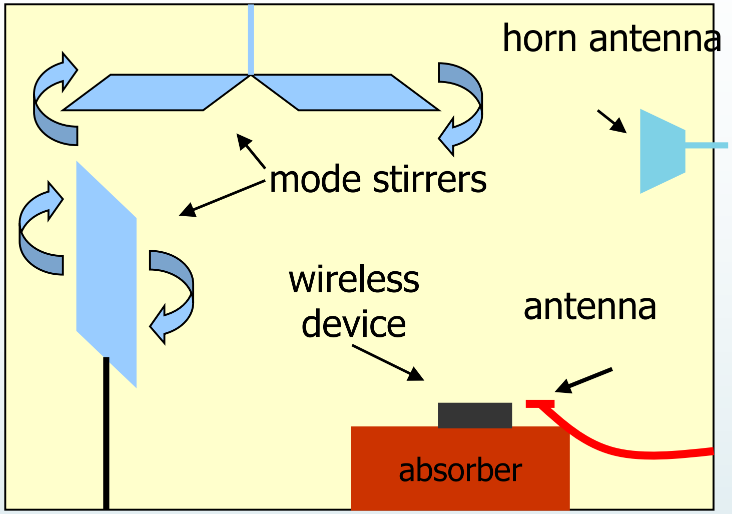
Low Uncertainty Required:

- High carrier frequencies
- High modulation bandwidths

Stay tuned …



Reverberation Chambers for Wireless Test



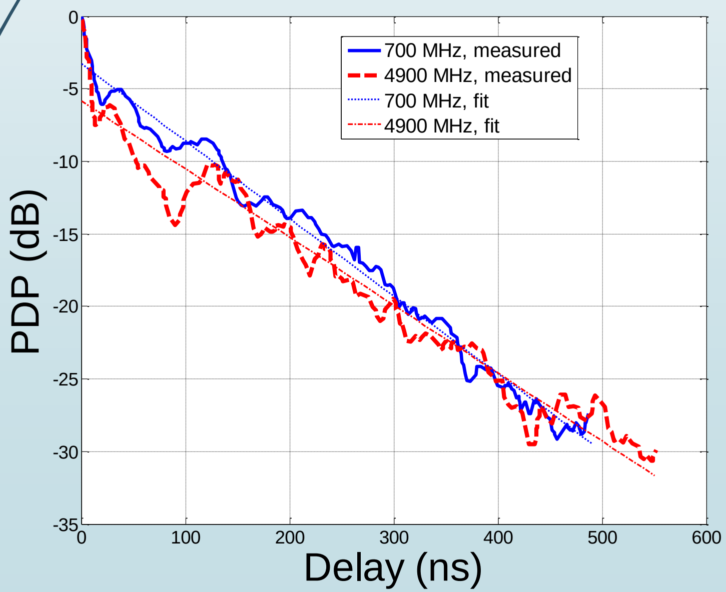
Some issues:

- Angle-of-arrival information lacking
  - Advanced transmission, multiple antenna systems
  - Test methods (CTIA, 3GPP groups)
- Instantaneous channel can be problematic for receiver (even if mean characteristics are OK)
- Field non-uniformity increases with loading and loading is often required for receiver tests
- Testing devices with repeaters is difficult

Reverberation Chambers for Wireless Test

Some benefits:

- Capable of simulating key characteristics of many multipath environments for the testing of wireless devices
- For OTA test reverberation chambers are:
  - Accurate – uncertainties on par with anechoic methods
  - Able to provide realistic distributed power delay profile
  - Suitable for testing diversity and MIMO gain (due to multipath)
  - Cost effective
  - Space efficient



The “NIST Model” for building penetration: 8 environments
RMS DS: 80 ns @ 700 MHz

Excess tap delay [ns]	Relative power [dB]
0	0.0
40	-1.7
120	-5.2
180	-7.8
210	-9.1
260	-11.3
350	-15.2

D.W. Matolak, K.A. Remley, C.L. Holloway, and C. Gentile, “Outdoor-to-Indoor Channel Dispersion and Power-Delay Profile Models for the 700 MHz and 4.9 GHz Bands,” *IEEE Antennas and Wireless Propagat. Lett*., vol. 15, 2016, pp. 441-443.

Watch this space for more information on over-the-air testing with reverberation chambers

CTL Communications Technology Laboratory

NIST National Institute of Standards and Technology