Challenges for 5G Measurements
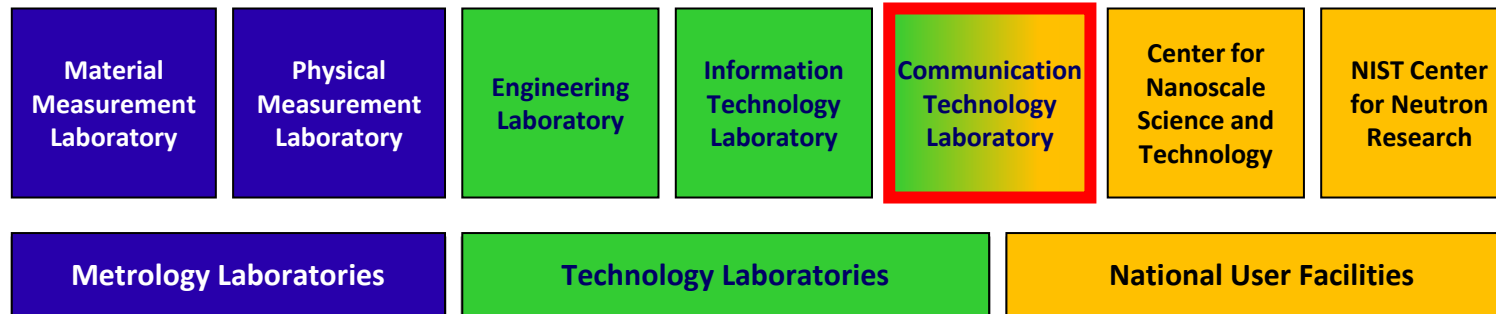
Kate A. Remley,
NIST Metrology for Wireless Systems Group
August 17, 2017

NIST and Advanced Communications

NIST Mission: To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life
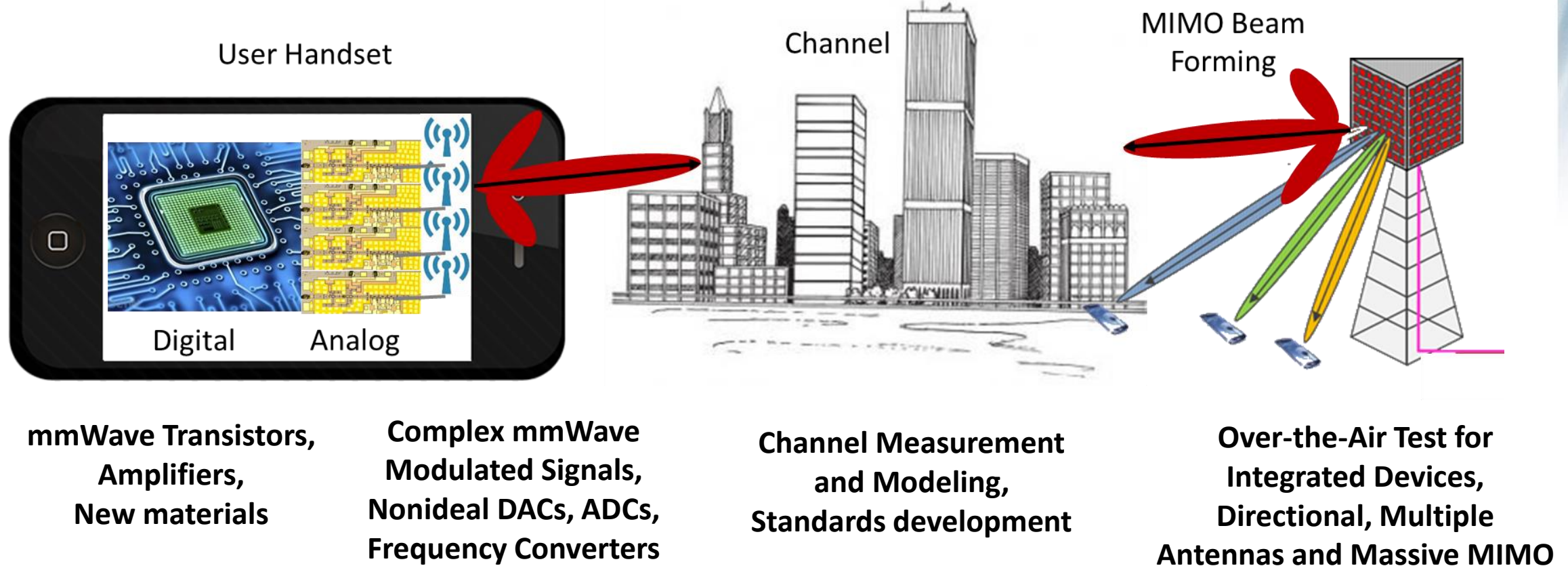
- Communications Technology Laboratory: March 2014
- Support development and deployment of advanced communications

Material Measurement Laboratory	Physical Measurement Laboratory	Engineering Laboratory	Information Technology Laboratory	Communication Technology Laboratory	Center for Nanoscale Science and Technology	NIST Center for Neutron Research

Metrology Laboratories	Technology Laboratories	National User Facilities

Targeted research: test and measurement of new communication technologies

- o Calibrations and traceability for wireless instrumentation
- o Validation of test-protocols, models, and simulation tools
- o New test methods for spectrum sharing, 5G and other national priorities

# 5G and Beyond: So Many Systems, So Much To Measure

User Handset

Channel

MIMO Beam Forming

Digital   Analog

mmWave Transistors, Amplifiers, New materials

Complex mmWave Modulated Signals, Nonideal DACs, ADCs, Frequency Converters

Channel Measurement and Modeling, Standards development

Over-the-Air Test for Integrated Devices, Directional, Multiple Antennas and Massive MIMO
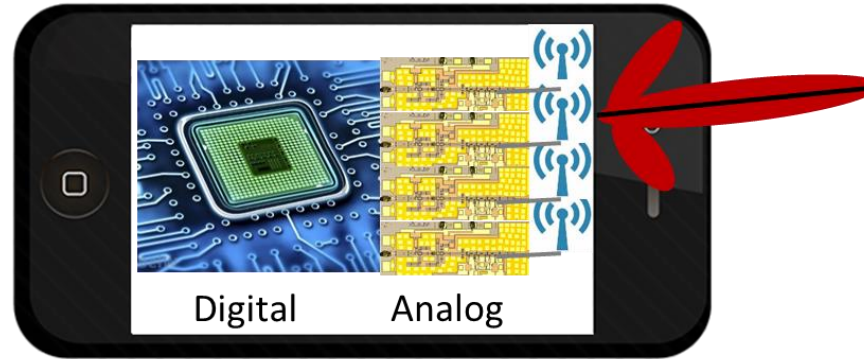
Measurement challenges for an industry in its infancy

Device-Level Measurements

Errors reduce device efficiency, first-pass design success
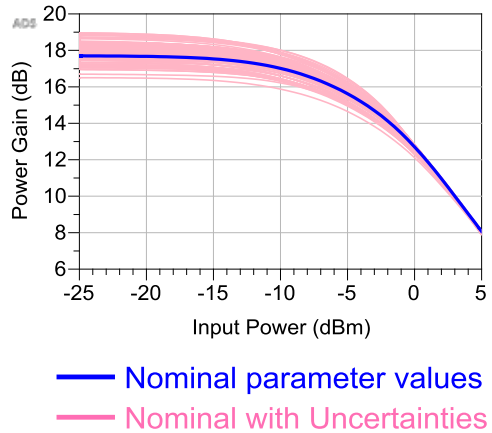
Power sweep at 94 GHz
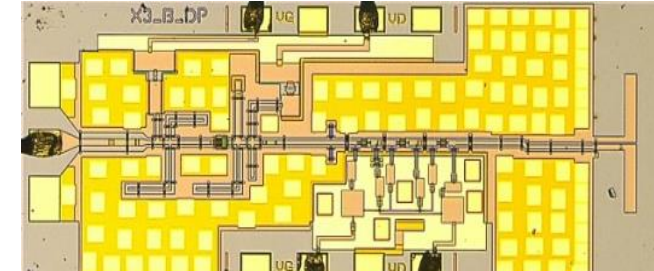
Plated on-wafer calibration structures reduce coupling

Transistor and Nonlinear-Device Measurements
- mmWave large-signal transistor and amplifier measurements and models
- Nonlinearity, imbalance, quantization noise of DACs, ADCs
- On-wafer calibrations and coupling
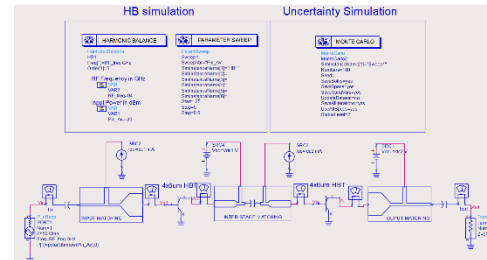
NIST Device Measurements for mmWave Applications

- Small-Signal Device Calibrations and Measurements to 1 THz
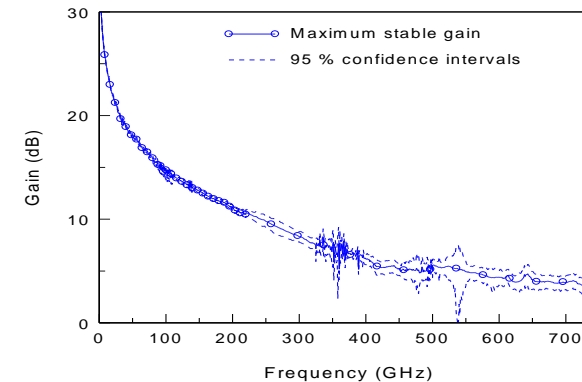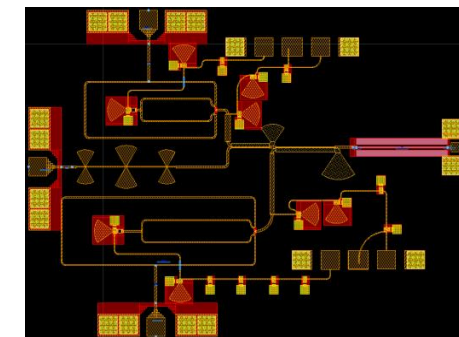

750 GHz transistor measurements with uncertainties
(DARPA THz Electronics Program)

- mmWave Large-Signal Measurements and Models with Uncertainties
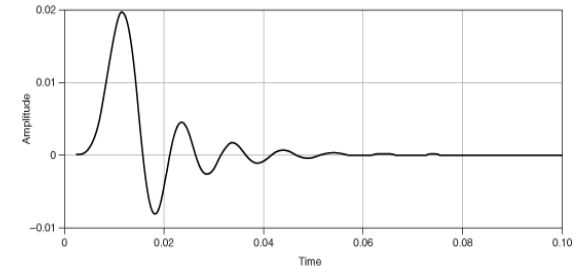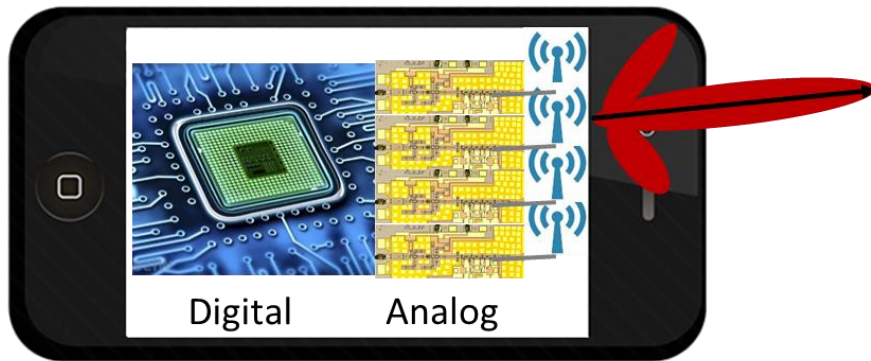

Harmonic Balance linked to Uncertainty simulations

- Electro-Optic-Sampling-Based mmWave Large-Signal Network Analyzer

Load-pull and electro-optic sampling circuitry

Modulated-Signal Characterization

Errors increase EVM of generated and received signals
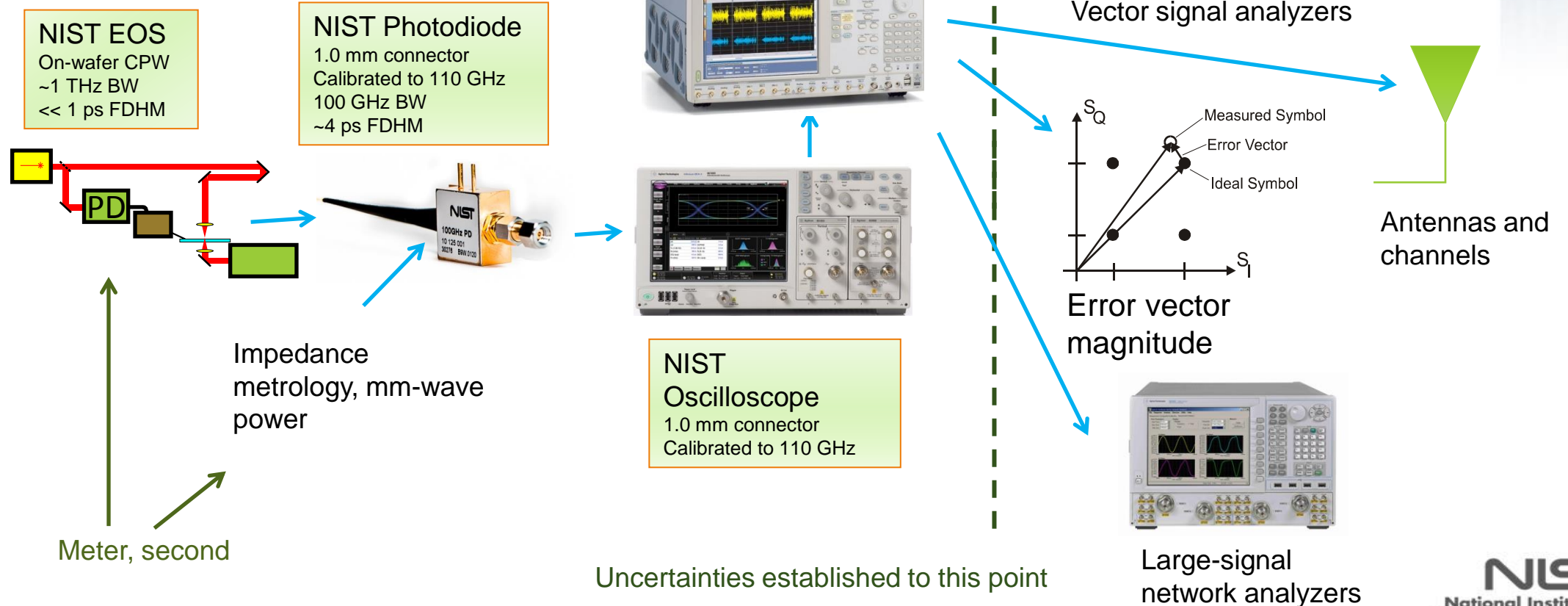
Digital   Analog

Millimeter-Wave Signal Characterization

- Effects of nonideal frequency converters and signal converters (DACs and ADCs)
- Source and transmitter characterization (with nonlinearities)
- Impedance, power, noise
- Uncertainty and demodulation errors

Millimeter-Wave Signal Characterization

The NIST Traceability Path for

Modulated Signals

Calibrated mmWave Source
Upconvert and predistort
2 GHz modulation BW

NIST EOS
On-wafer CPW
~1 THz BW
<< 1 ps FDHM

NIST Photodiode
1.0 mm connector
Calibrated to 110 GHz
100 GHz BW
~4 ps FDHM

NIST Oscilloscope
1.0 mm connector
Calibrated to 110 GHz

Impedance metrology, mm-wave power

Meter, second

Vector signal analyzers

S_Q

Measured Symbol
Error Vector
Ideal Symbol

S_I

Error vector magnitude

Antennas and channels

Large-signal network analyzers

Uncertainties established to this point

CTL Communications Technology Laboratory

NIST National Institute of Standards and Technology U.S. Department of Commerce

Millimeter-Wave Signal Characterization

The NIST Microwave Uncertainty Framework:
Tracking uncertainties and their correlations

VNA measurements and uncertainties for various calibrations within the Uncertainty Framework

Traceability and Uncertainty in EVM

Distribution of EVM and uncertainty for a 44 GHz, 64 QAM signal (DARPA ELASTx)

EVM measurement errors from Framework

Estimating Uncertainty in EVM:
IEEE Working Group P1765

NIST-led IEEE Best Practice Guide

Channel-Measurement Challenges

Errors distort channel response: path loss, timing, and angle

Indoor 83 GHz channel measurements

Channel
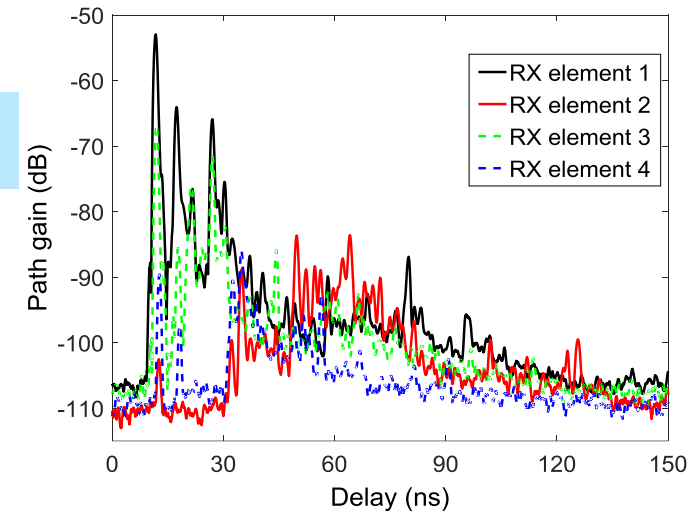
PDPs for a single location,
different angles of arrival

Non-line-of-sight, high-multipath
indoor environments
(NOAA server room)

Channel Measurement and Modeling
- Need for mmWave data: Indoor and Outdoor
- Need for Channel Modeling and Standards
- Measurement Uncertainty on Metrics, Models
- Angle of Departure, Angle of Arrival
- Many bands: 28, 38, 60, 72, 83 GHz, …

NIST Channel Measurement and Modeling

- NIST mmWave Channel Sounders: 28 GHz, 60 GHz, 83 GHz

- mmWave 5G Channel Model Alliance
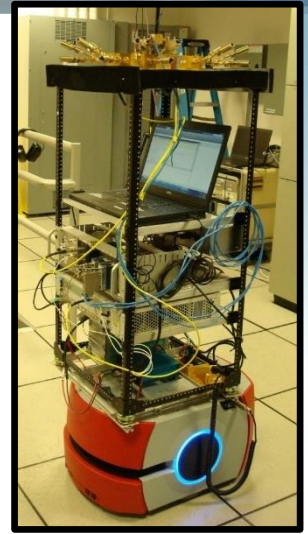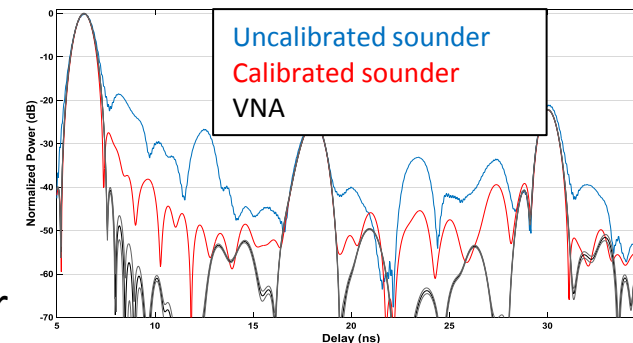 - NIST-led consortium
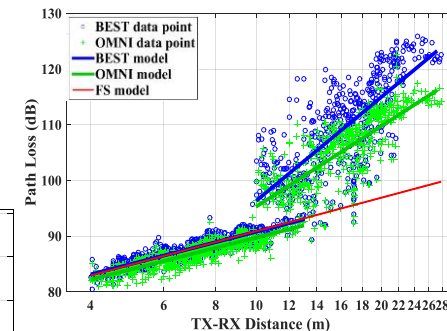 - Over 130 members

- Channel Sounder Verification

16 RX antennas on mobile positioner

Clustered multipath components

NIST channel sounder verification artifact
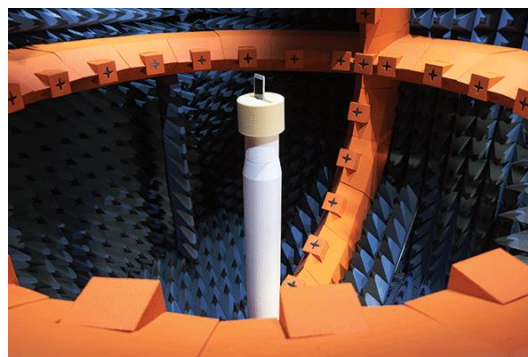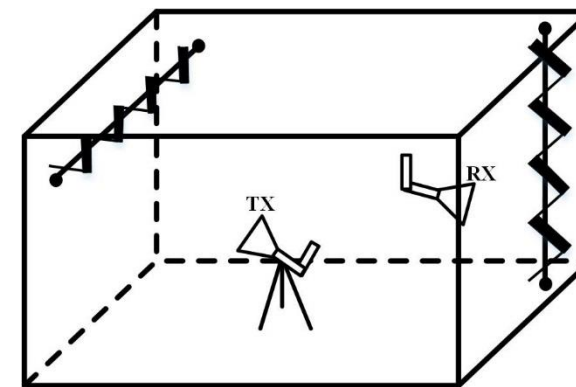
New mmWave path-loss models

Over-the-Air Measurements for Integrated Devices

Errors in power, sensitivity, and throughput: exceed limits, reduce comparability

Cellular OTA test of multiple antenna system in anechoic chamber

OTA test at mmWave in reverberation chamber

Machine-to-Machine and Internet of Things: Ubiquitous wireless

OTA Test and DUT Verification
- Integrated antennas: on-wafer-to-OTA test planes
- Calibrated Free-Field modulated signals for verifying e.g., two-stage measurements
- Anechoic-Chamber Methods
- Reverberation-Chamber Methods
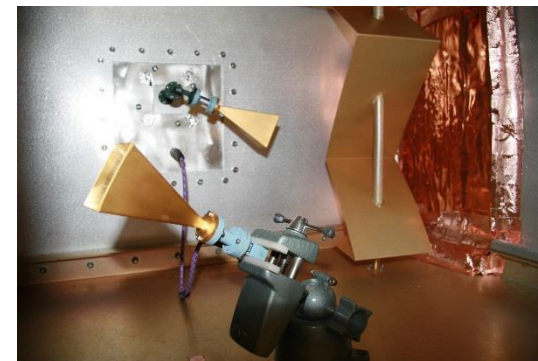
Over-the-Air Test for Future Cellular

- Traceability for Free-Field Modulated Signals

Reference modulated-signal field in space (resolve OTA test differences, test off-axis EVM, etc.)
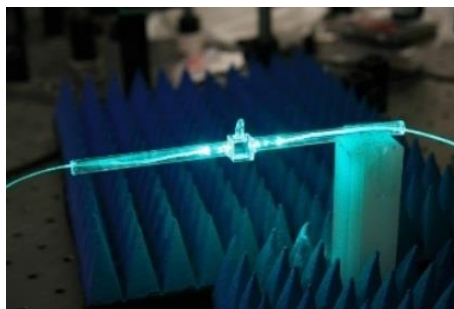

Known Field

Tx ref   Rx ref

Cal Tx   Cal Rx
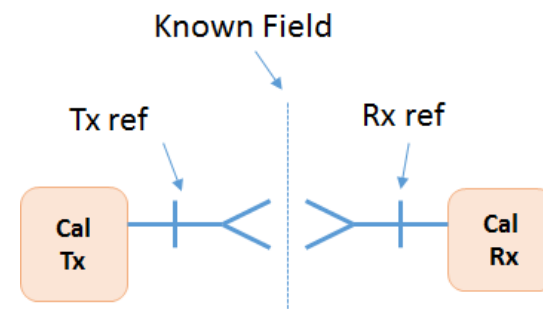
- Reverberation Chamber OTA Measurements

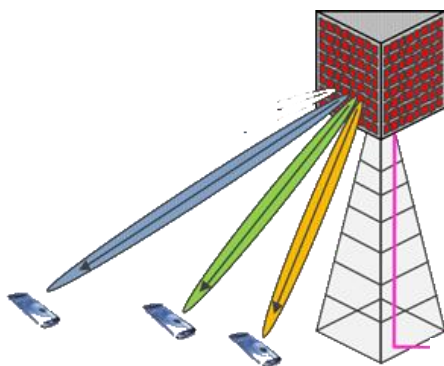LSNA techniques and directional testbed

- Calibrations for E-field Metrology
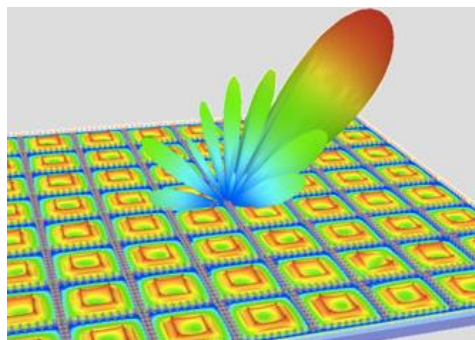
NIST quantum field probe

Measurement of Beamforming and Multiple Antennas

Errors in directionality: critical for

MIMO and Spatial Diversity

Beam Forming

New Applications in Challenging Environments (e.g., Factories)

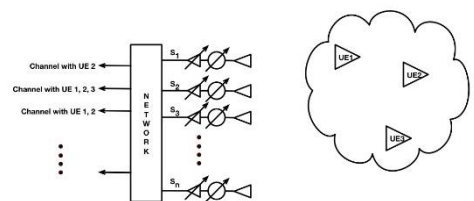**Beam Forming and Multiple Antenna Systems**
- Testing Beam-Forming Algorithms
- Large Number of Elements/Operating States
- Antenna Element Coupling
- Wideband Antenna Calibrations
- Massive MIMO Antenna Test
- Spatial interference testing (leakage due to non-ideal antennas)

NIST Work in Multiple Antenna and Massive MIMO

- Robotic Methods for Antenna Positioning and Traceability

CROMMA facility:
25 µm alignment

Robot Arm

Probe Antenna

Test Antenna

Hexapod

Rotator

- Digital Beamforming Hardware Testbed

Channel with UE 2
Channel with UE 1, 2, 3
Channel with UE 1, 2

S_1
S_2
S_3

NETWORK

S_n

UE1
UE2
UE3

Coherent TX/RX testbed
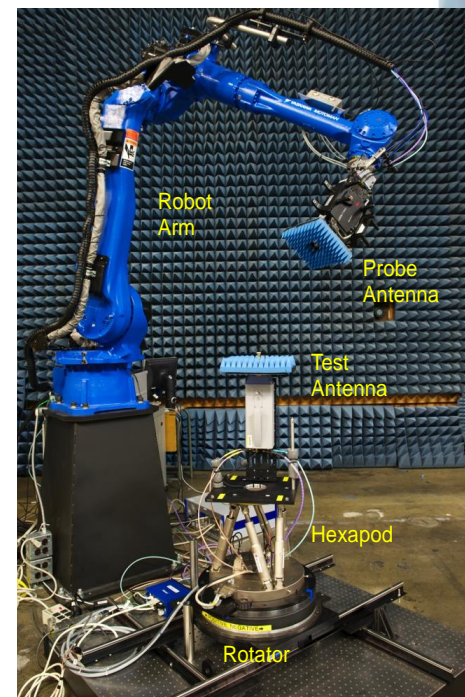
- Antenna Element Coupling using Large-Signal Measurements

Some Measurement Questions for Discussion

- **Devices and Materials:**
  - What are prospects for large-signal network analysis at mmWave frequencies?
  - What are issues tuning mmWave harmonics?
  - What is the role of materials measurements in future wireless?

- **Signal characterization:**
  - How to handle issues with cascading nonideal, distortion-inducing instruments (similar to Additive EVM)?
  - What is the role of traceability in waveform measurements?
  - Off-axis EVM: free-field sources with spatial distortion as well as electronic distortion

- **Channel measurements:**
  - Why is it more important to decouple the antenna from the channel measurement?
  - Will nonideal channel-sounder hardware be more important at mmWave frequencies?

- **OTA Test, Antennas and Massive MIMO:**
  - How does one generate and utilize a known test field for multiple-element antenna arrays?
  - What is the role of statistics in testing arrays that operate in more states than you can count?
  - What are issues with distributed array timing and synchronization?

- **The Elephant in the Room:**
  - How to merge on-wafer and OTA test to verify performance?

Watch this space for updates to metrology issues

- Transistors and nonlinear device characterization

- Modulated-signal field traceability and off-axis EVM

- Channel measurement and modeling

- Multiple-antenna metrology for wideband signals

- Extending metrology for fundamental parameters to communications applications:
  - Power
  - S parameters
  - Noise