BRINGING PRECISION TO MEASUREMENTS FOR MMWAVE 5G WIRELESS

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IEEE Institute of Electrical and Electronics Engineers (IEEE)

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Advancing Technology for Humanity

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

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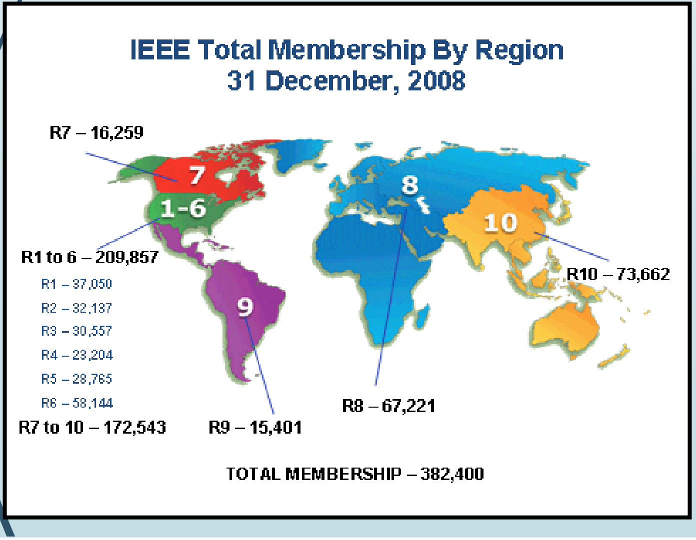
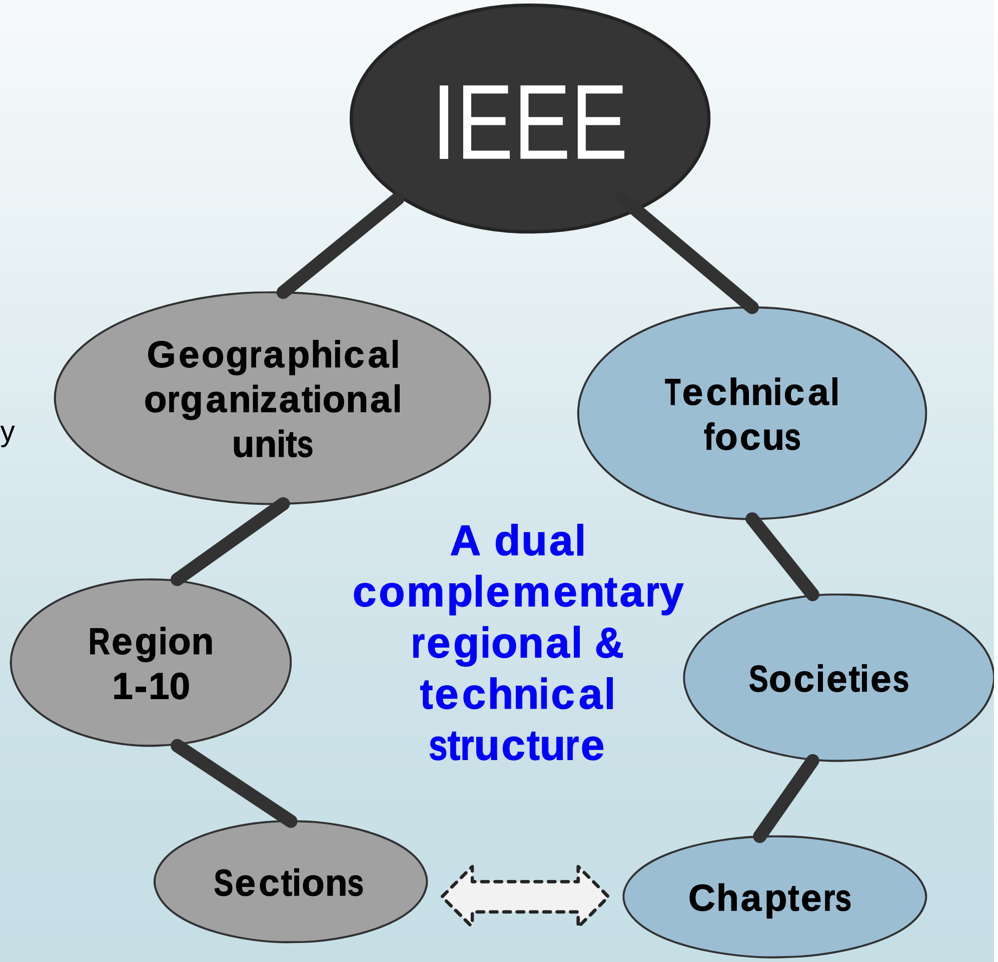
Operations center @ Piscataway, New Jersey



IEEE Total Membership By Region
31 December, 2008

TOTAL MEMBERSHIP – 382,400



IEEE

Geographical organizational units

Technical focus

Region 1-10

Societies

Sections

Chapters

A dual complementary regional & technical structure

The Founding of IEEE

1884 ········ 1912 ········ 1963 ········ Present

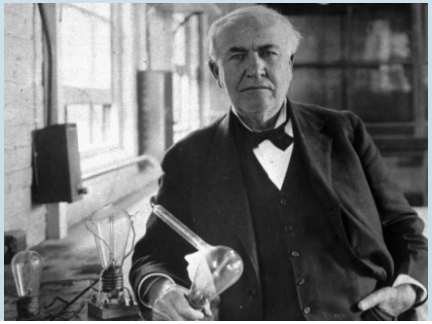
AIEE
American Institute
of Electrical Engineers

Thomas Edison,
Alexander Graham Bell,
and other notables
founded the
American Institute of Electrical Engineers.

IRE
Institute of Radio
Engineers

Pioneers of wireless
technologies
and electronics
founded the
Institute of Radio Engineers.

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 EMC Society

EMC
SOCIETY®

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

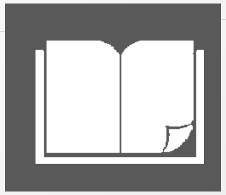
Member
Senior Member
IEEE Fellow

160
Countries

Technical Breadth

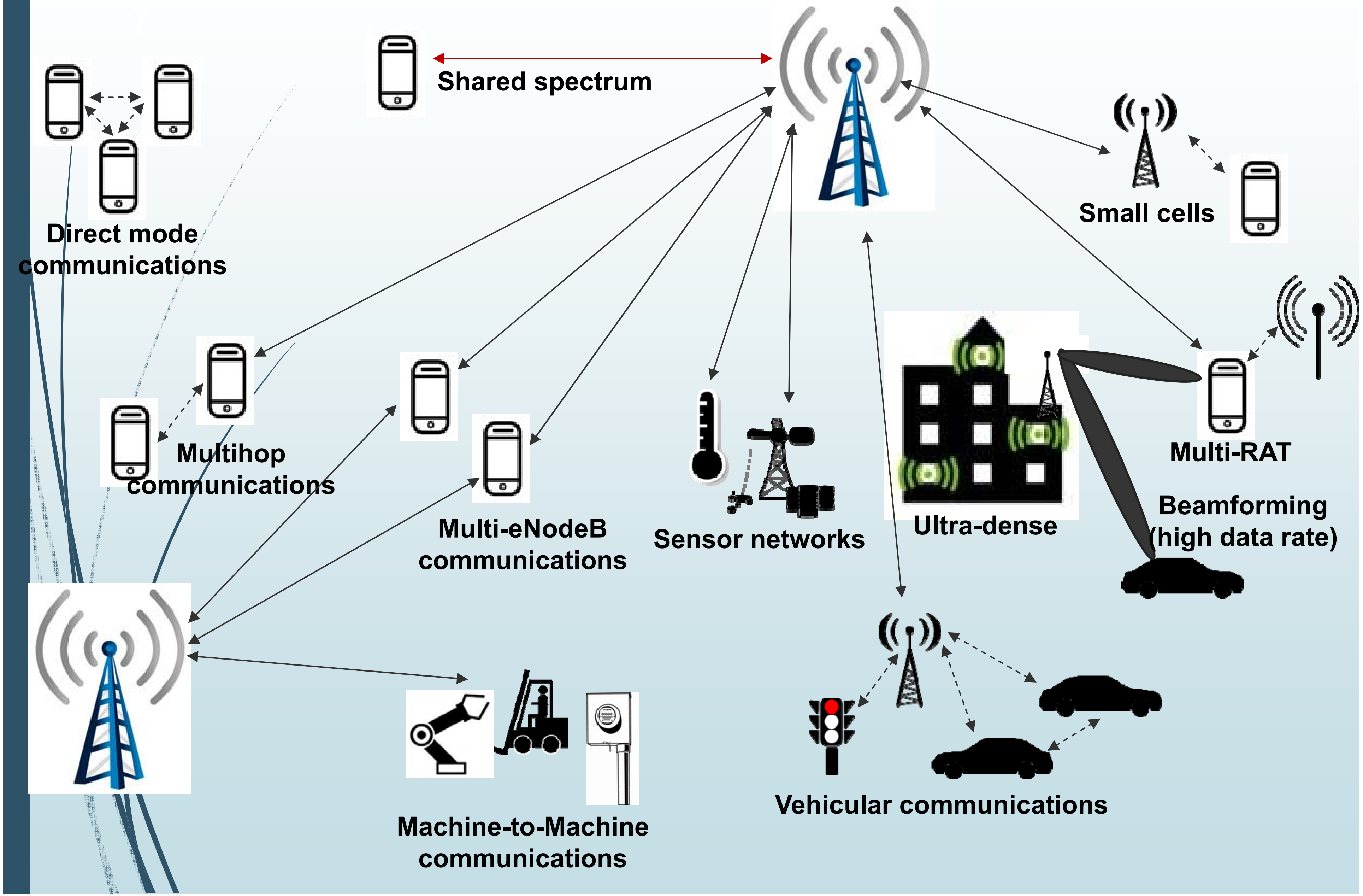
Flagship Annual Conference
IEEE International EMC Symposium

IEEE Trans. EMC
IEEE EMC Magazine
IEEE Trans SIPI



EMC Standards

Some 5G possibilities



Shared spectrum

Direct mode communications

Small cells

Multihop communications

Multi-eNodeB communications

Sensor networks

Ultra-dense

Multi-RAT

Beamforming (high data rate)

Machine-to-Machine communications

Vehicular communications

In the U.S., 5G is moving forward

FCC's 2015 inquiry on the use of spectrum above 24 GHz

Sought comment on…

- …technologies underlying the development of mobile services using bands above 24 GHz
- …frequency bands suitable for advanced mobile services and the best ways to manage interference
- …licensing and authorization schemes for mobile operations above 24 GHz

July 2016: Nearly 11 GHz spectrum released*

- New bands centered at 28, 37, and 39 GHz for terrestrial communications
- Extended unlicensed 60 GHz band from 57 – 63 GHz up to 71 GHz
- 95 GHz band is also currently under review

*Federal Communication Commission, Report and Order FCC-16-89, July 14, 2016

NIST STAFF WORKING PART-TIME ON 5G RESEARCH: 2013

NIST Program *Traceability to Enable Multi-GigaBit-per-Second Mobile Wireless*

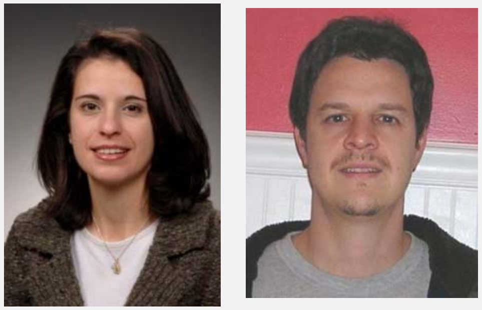
Paul
Hale

Dylan
Williams

Jeff
Jargon

High-Speed Measurements Group

Jack Wang
Statistical
Engineering Division



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Networks Division

Kate Remley
RF Fields Group

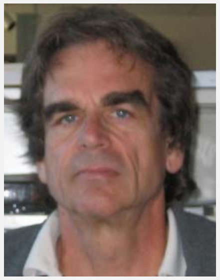
Peter Papazian
Institute for
Telecommunication Sciences

NIST STAFF WORKING FULL TIME ON 5G RESEARCH: 2017


Paul
Hale


Dylan
Williams


Jeff
Jargon


Rich
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Ari
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CTL: High-Speed Measurements Group


Jack Wang
ITL: Statistical Engineering Division


Nada Golmie and
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Kate
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Quimby


Damir
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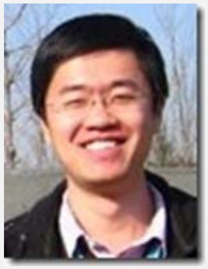
Jelena
Senic

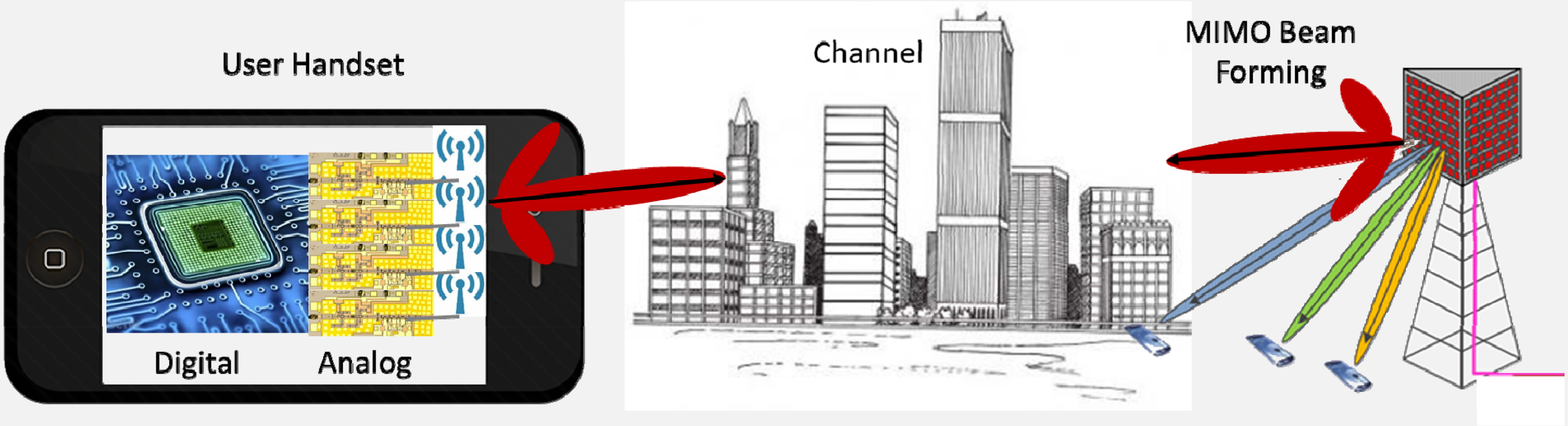

Ruoyu
Sun


Rob
Horansky


Maria Becker

CTL: Metrology for Wireless Systems Group

SO MANY SYSTEMS,
SO MUCH TO MEASURE



mmWave Transistor and Nonlinear-Device Measurements

mmWave Signal Characterization

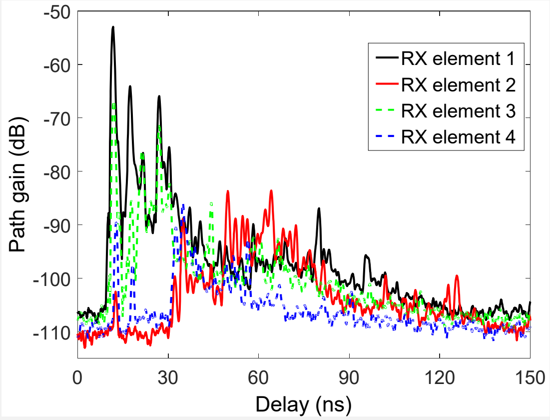
Channel Measurement and Modeling

Massive MIMO and Over-the-Air Test

CHANNEL MEASUREMENT CHALLENGES

Indoor 83 GHz channel measurements

Directional and mobile channels



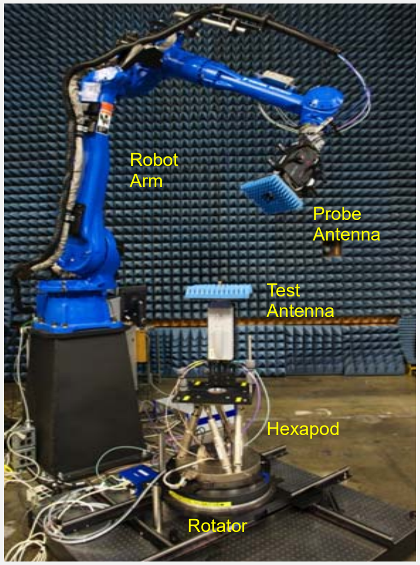
PDPs for a single location, different orientations

Channel Measurement and Modeling

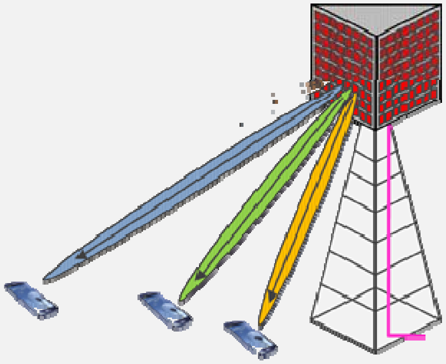
- Channel Sounding: Indoor and Outdoor
- Channel Modeling and Standards
- Effect of Uncertainty on Metrics, Models
- Angle of Departure, Angle of Arrival
- Many bands: 28, 38, 60, 72, 83 GHz, …

5G mmWave Channel Model Alliance

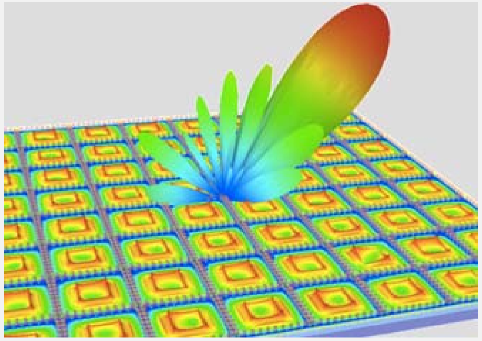
ANTENNA MEASUREMENT CHALLENGES



Antenna measurement scans



MIMO and Massive MIMO

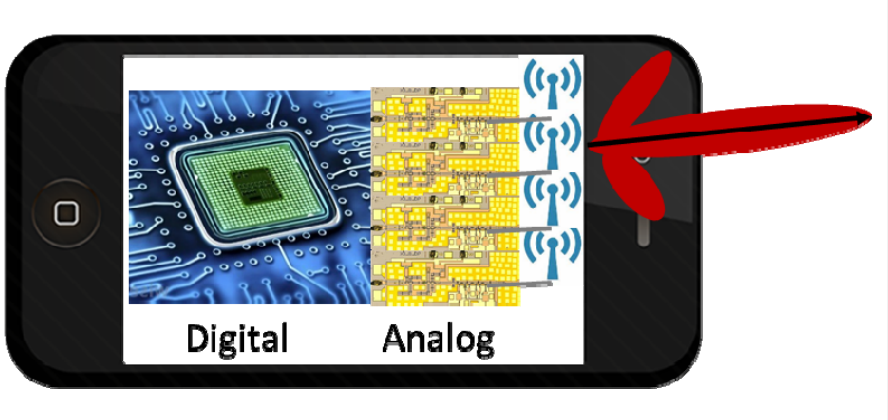


Beam Forming

Beam Forming and Multiple Antenna Systems

- Large Number of Elements/Operating States
- Antenna Element Coupling
- Wideband Antenna Calibrations
- Massive MIMO Antenna Test
- Spatial interference testing (non-ideal element leakage)
- Testing Beam-Forming Algorithms

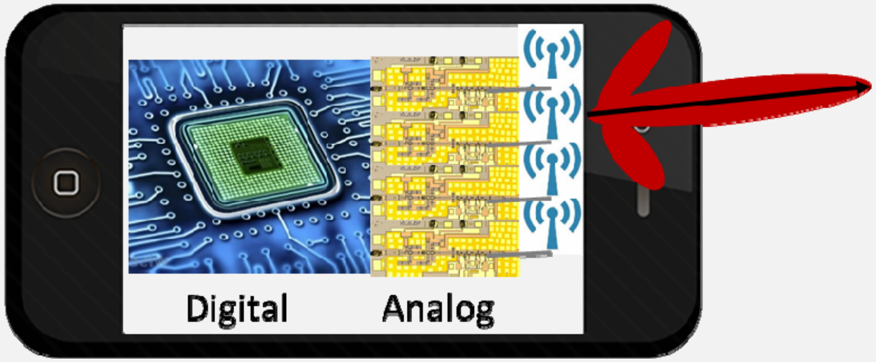
THE MEASUREMENT “ELEPHANT IN THE ROOM”

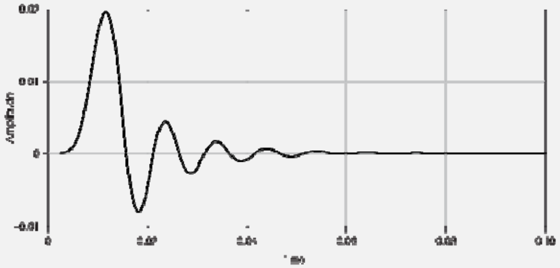


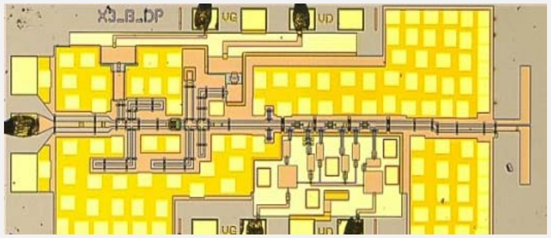
Integrated systems require On-Wafer-to-Over-the-Air Test
This complicates

- Efficiency
- Distortion
- Troubleshooting stages
- First-pass design success

SOME 5G MEASUREMENT CHALLENGES YOU MAY NOT HAVE HEARD MUCH ABOUT







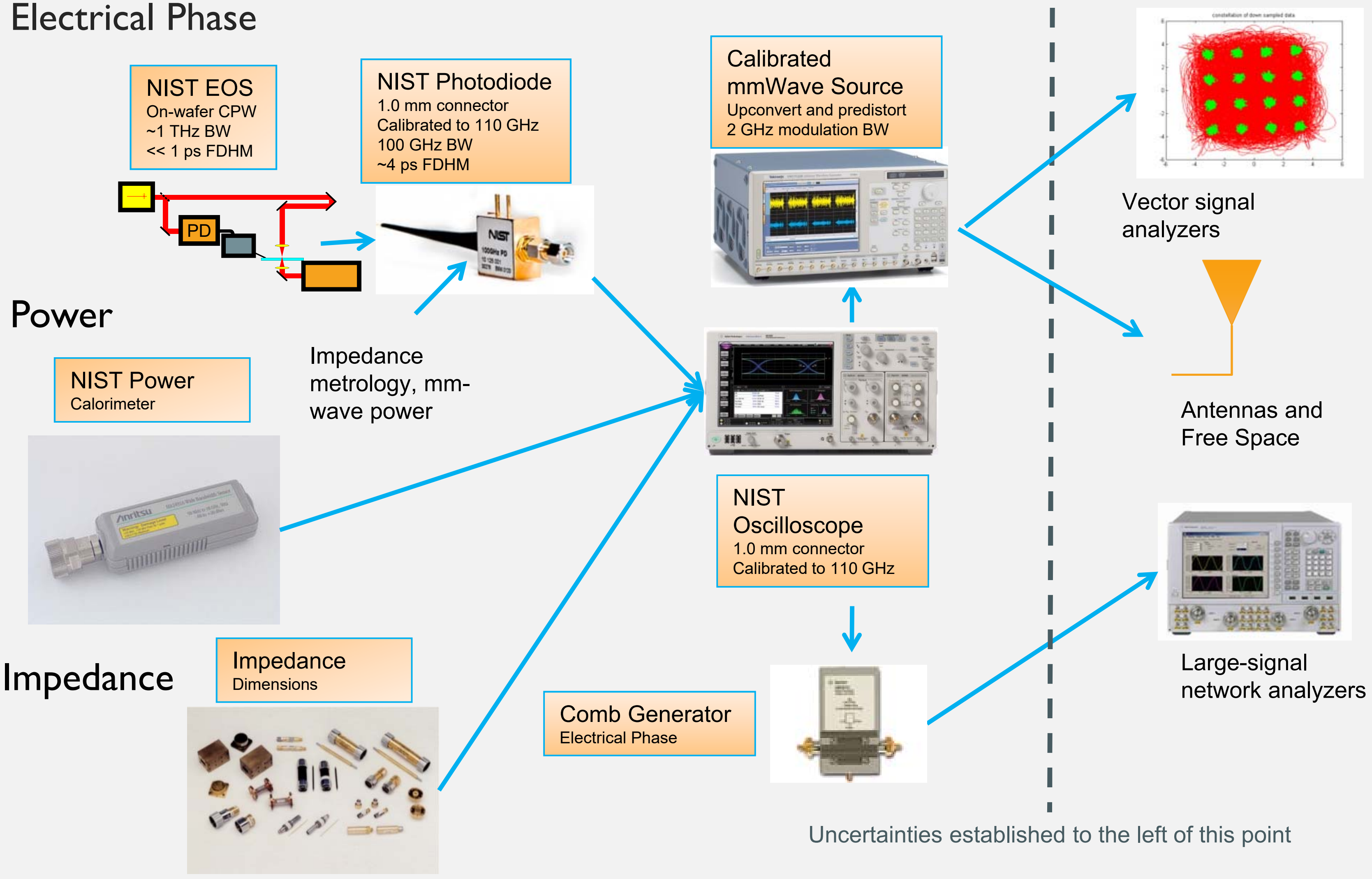
Millimeter-Wave Signal Characterization

- Waveform Traceability
- Source and Transmitter Characterization
- Impedance, Power, Noise
- Uncertainty and Demodulation Errors

Millimeter-wave Transistor and Nonlinear-Device Measurements

- mmWave Transistor Measurements and Models
- Acoustic-Wave Filters
- New Materials

MILLIMETER-WAVE SIGNAL TRACEABILITY PATH



Electrical Phase

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

Calibrated mmWave Source
Upconvert and predistort
2 GHz modulation BW

Vector signal analyzers

Power

NIST Power
Calorimeter

Impedance metrology, mm-wave power

Antennas and Free Space

NIST Oscilloscope
1.0 mm connector
Calibrated to 110 GHz

Large-signal network analyzers

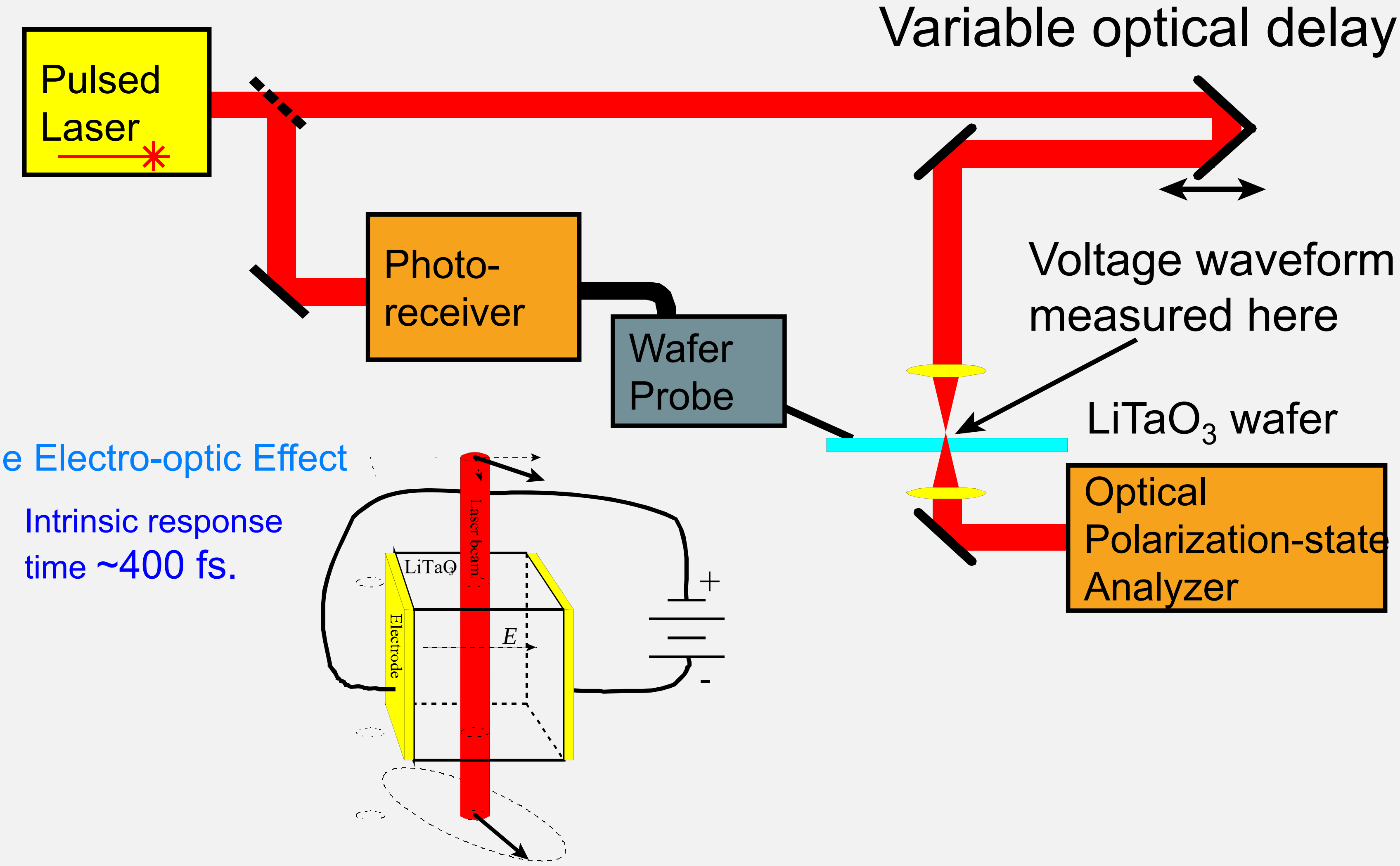
Impedance

Impedance
Dimensions

Comb Generator
Electrical Phase

Uncertainties established to the left of this point

NIST ELECTROOPTIC SAMPLING SYSTEM



Pulsed Laser

Variable optical delay

Photo-receiver

Wafer Probe

Voltage waveform measured here

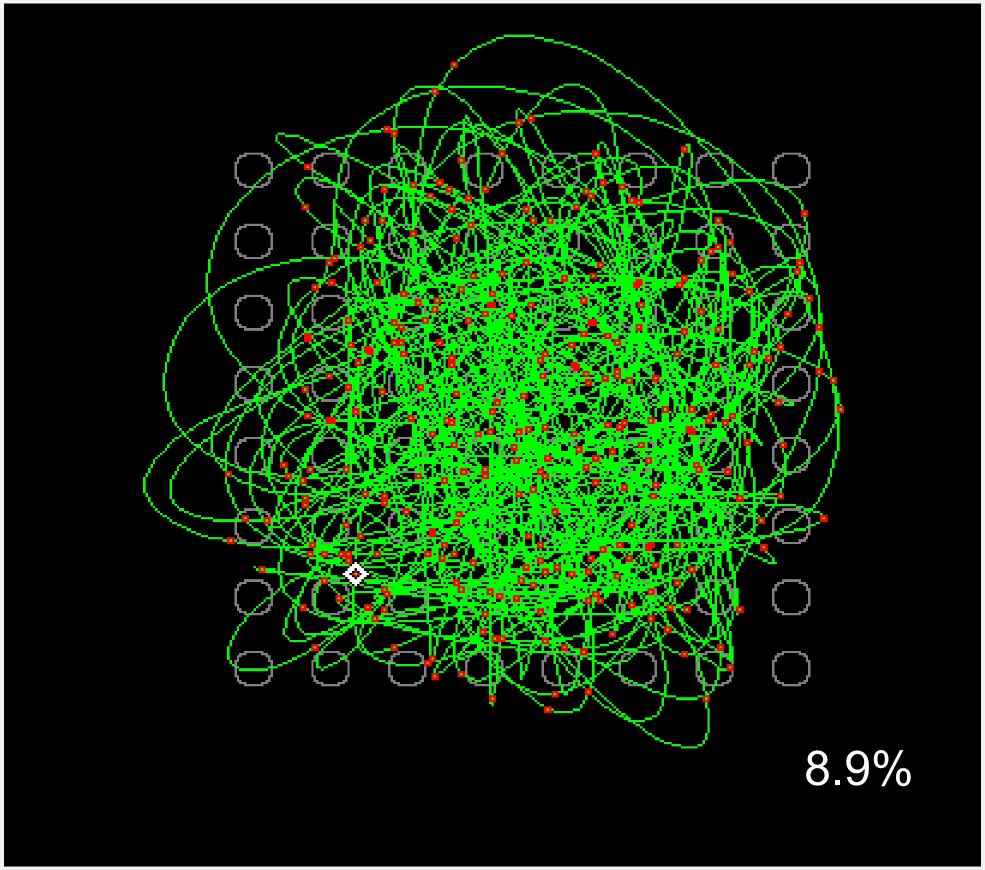
$LiTaO_3$ wafer

Optical Polarization-state Analyzer

The Electro-optic Effect

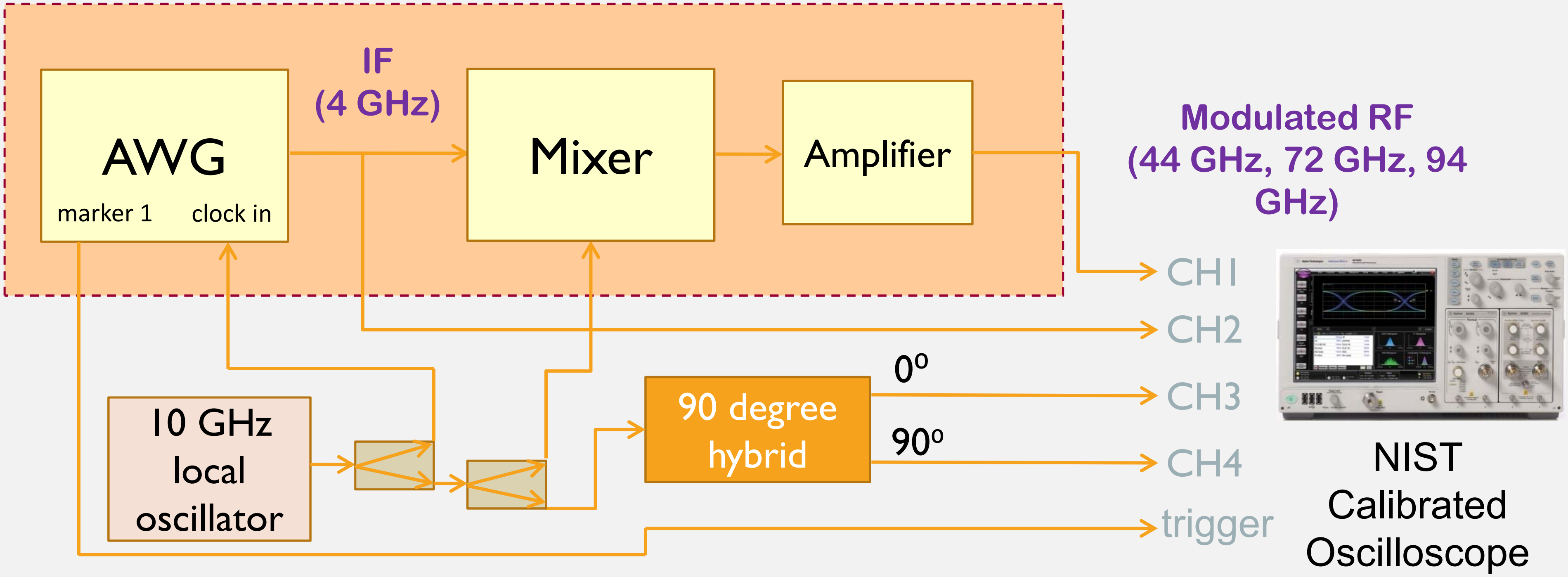
Intrinsic response time ~400 fs.

NIST PRECISION MMWAVE SOURCE



Without calibration: high error vector magnitude (EVM)

PRECISION MMWAVE SOURCE



IF
(4 GHz)

AWG
marker 1
clock in

Mixer

Amplifier

Modulated RF (44 GHz, 72 GHz, 94 GHz)

10 GHz local oscillator

90 degree hybrid

0°

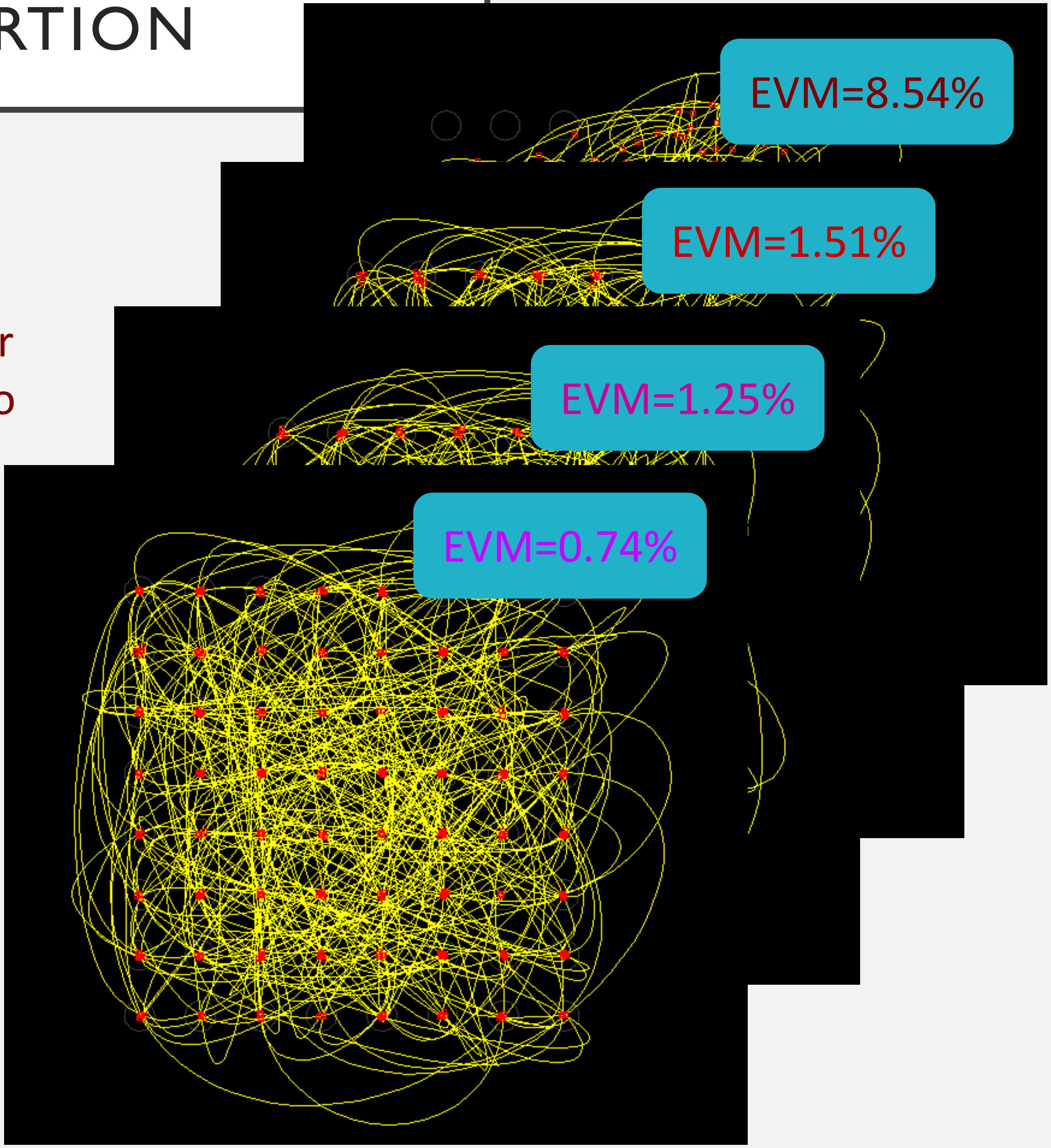
90°

CH1
CH2
CH3
CH4
trigger

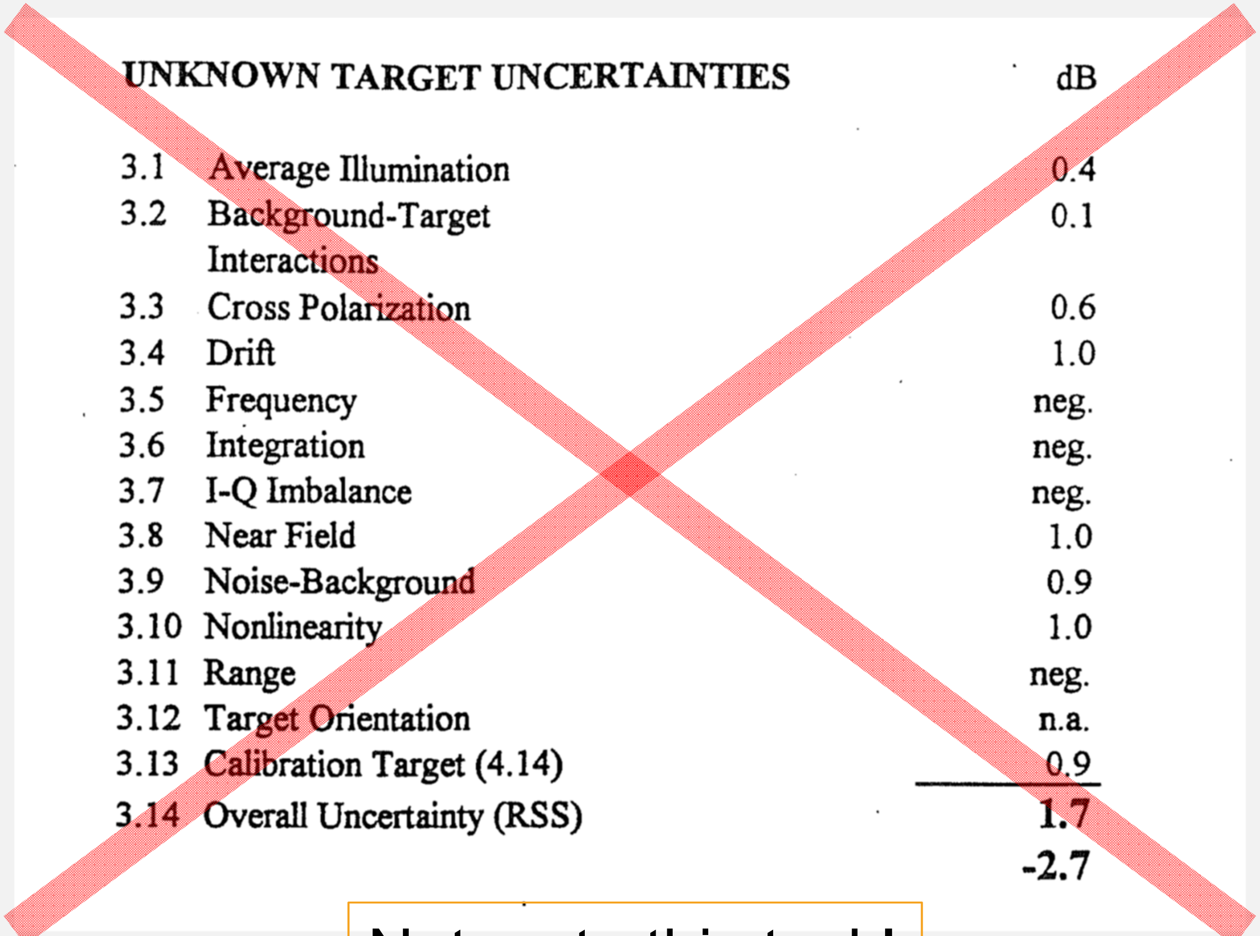
NIST Calibrated Oscilloscope

ITERATIVE PRE-DISTORTION

- Measure waveform, correct for oscilloscope errors, compare to ideal
- First pre-distortion iteration
- Second pre-distortion for nonlinear effects
- Final result after mismatch correction



STANDARD UNCERTAINTY ANALYSIS

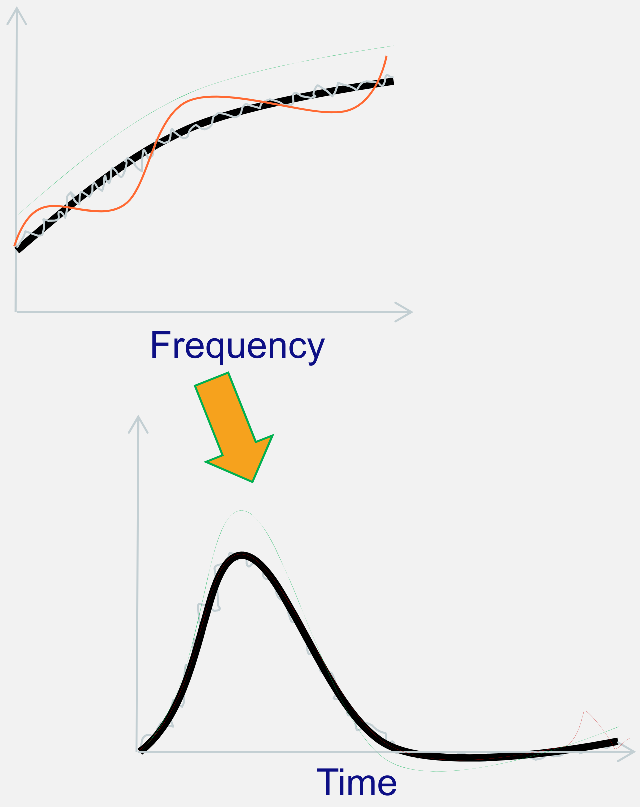


UNKNOWN TARGET UNCERTAINTIES		dB
3.1	Average Illumination	0.4
3.2	Background-Target Interactions	0.1
3.3	Cross Polarization	0.6
3.4	Drift	1.0
3.5	Frequency	neg.
3.6	Integration	neg.
3.7	I-Q Imbalance	neg.
3.8	Near Field	1.0
3.9	Noise-Background	0.9
3.10	Nonlinearity	1.0
3.11	Range	neg.
3.12	Target Orientation	n.a.
3.13	Calibration Target (4.14)	0.9
3.14	Overall Uncertainty (RSS)	**1.7** **-2.7**

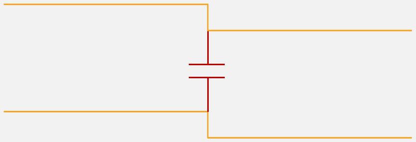
Not up to this task!

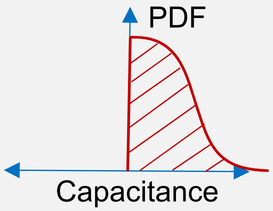
UNCERTAINTY PROPAGATION

Correlated Uncertainty



Nonlinear Processes and Algorithms

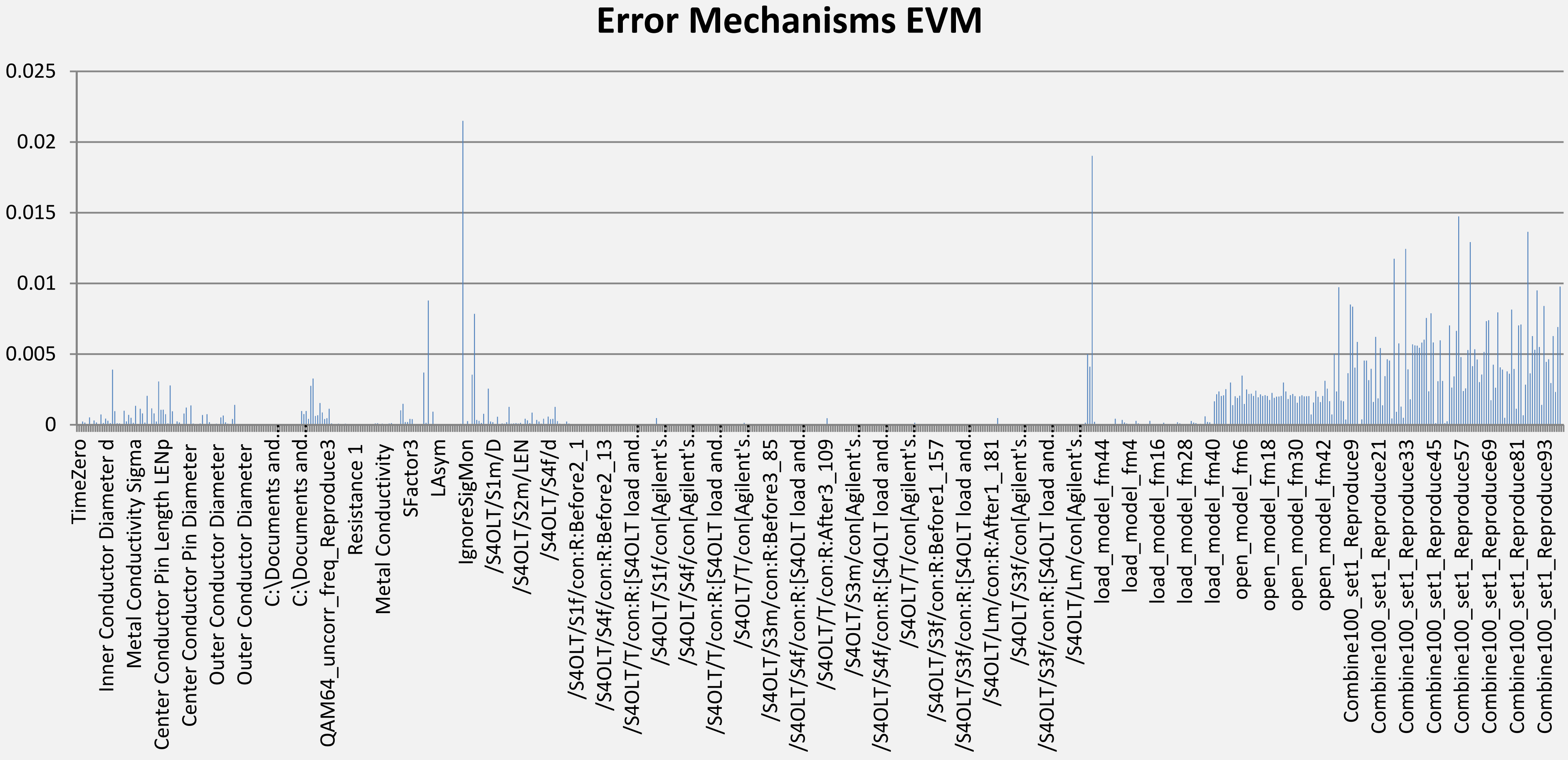




Must capture and accommodate:

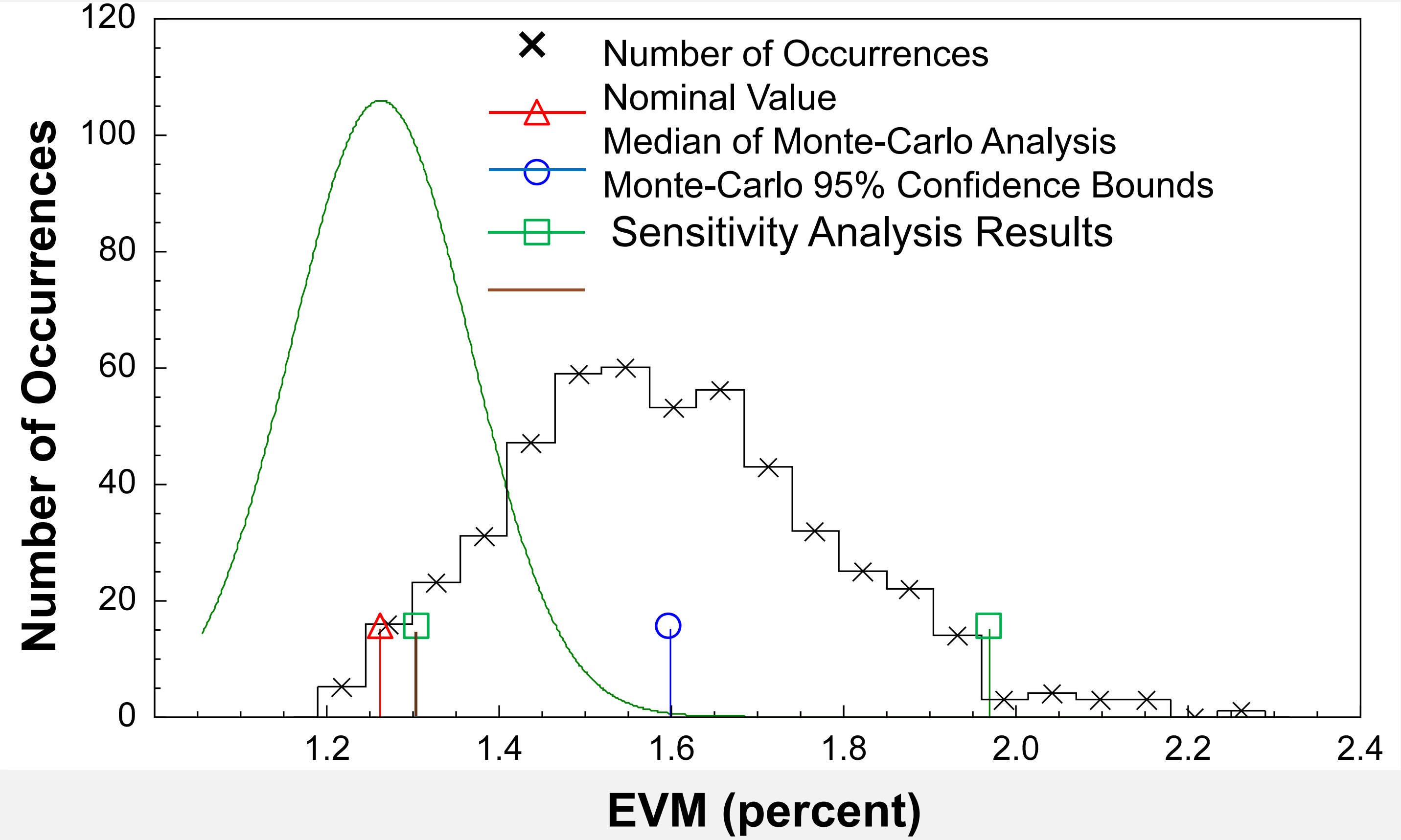
1. Correlations within data (*e.g.* frequency, time)
2. Correlations between data (*e.g.* artifact reuse)
3. Probability distribution functions
4. Propagatable intermediate results

NIST MICROWAVE UNCERTAINTY FRAMEWORK



There were 693 error mechanisms for this EVM measurement, and we can easily see which ones dominate (e.g., repeatability)

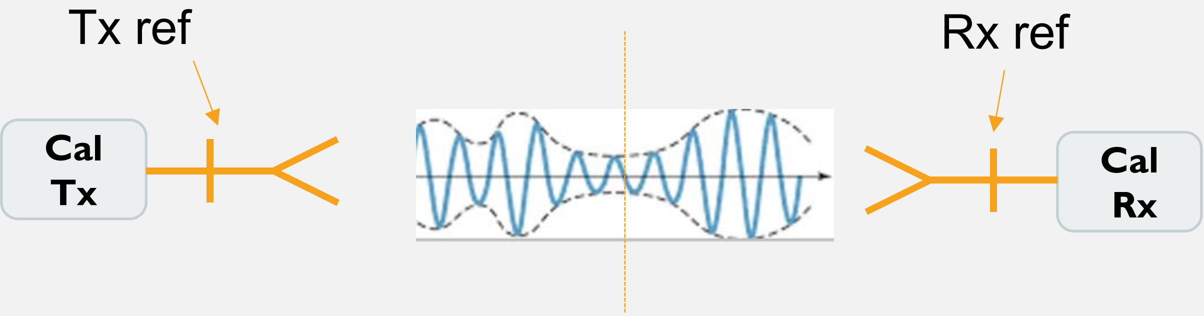
UNCERTAINTIES IN METRICS WITH THE MICROWAVE UNCERTAINTY FRAMEWORK



Distribution of EVM and uncertainty
for a 44 GHz, 64 QAM signal

IN PROCESS: FREE-FIELD MODULATED SIGNALS

- Excite antenna with characterized source
- Scattering matrix of antenna
  - Gain extrapolation measurements: three antenna method
  - Fit complex S parameters
  - Propagate uncertainties
- On- and off-axis EVM



LARGE-SIGNAL NETWORK ANALYSIS

“Standard” vector network analyzer

- S-parameter calibration
- Power calibration
- Phase calibration

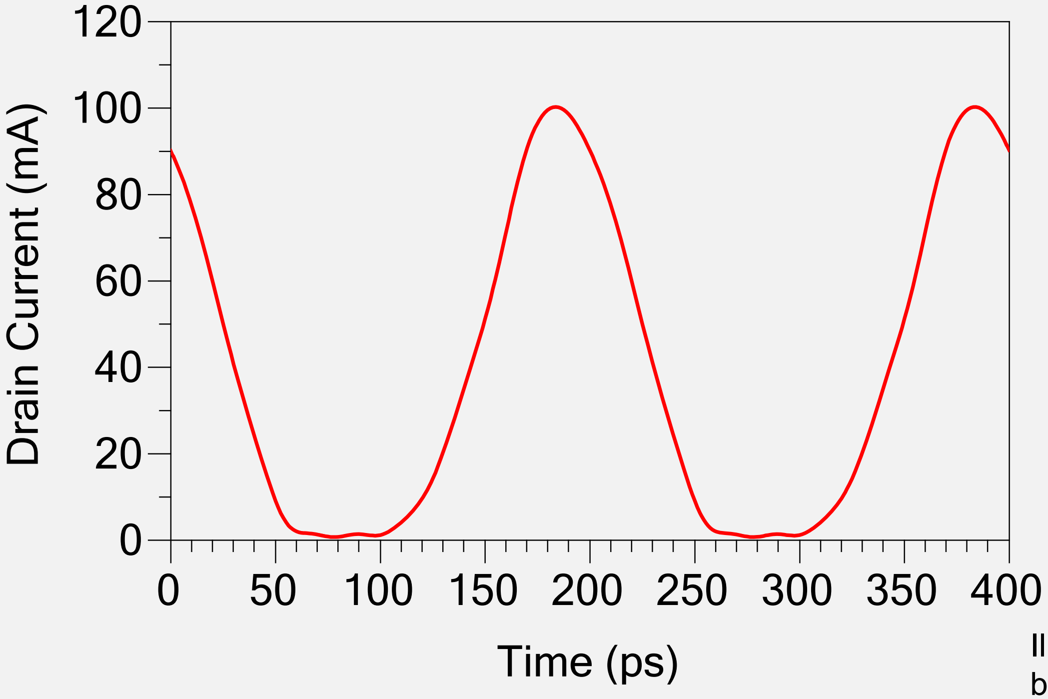
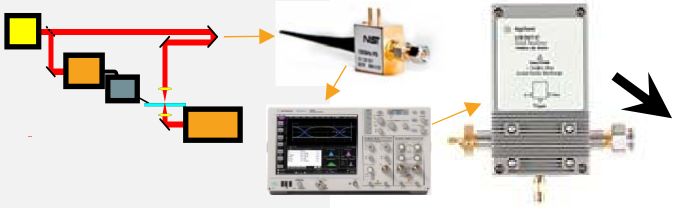


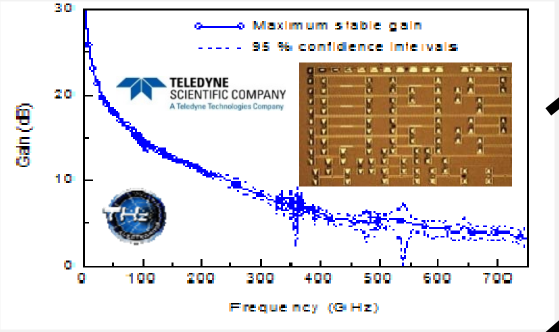
Illustration of certain products does not imply endorsement by NIST. Other products may work as well or better.

GETTING TO THE APPLICATION WITH THE MICROWAVE UNCERTAINTY FRAMEWORK

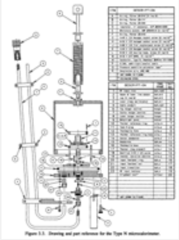
Electrical Phase



Impedance/S-Parameters



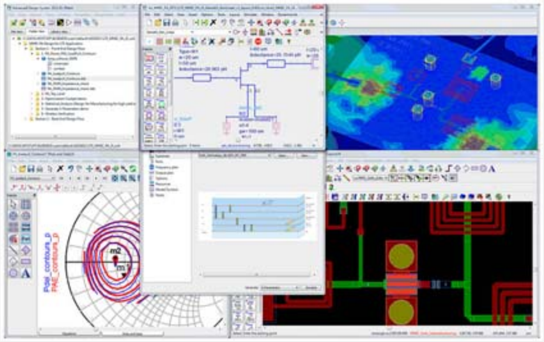
Power



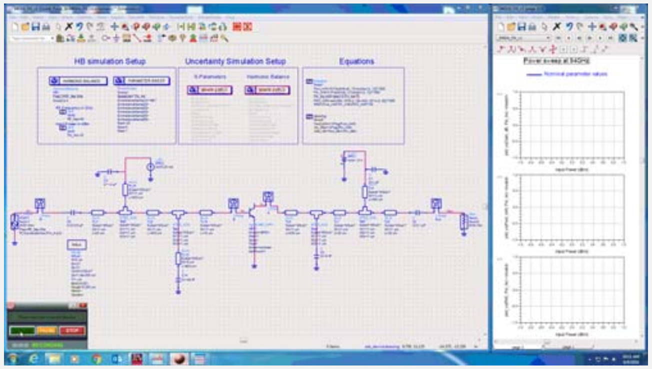
Large-Signal Measurements

The process does not end here!

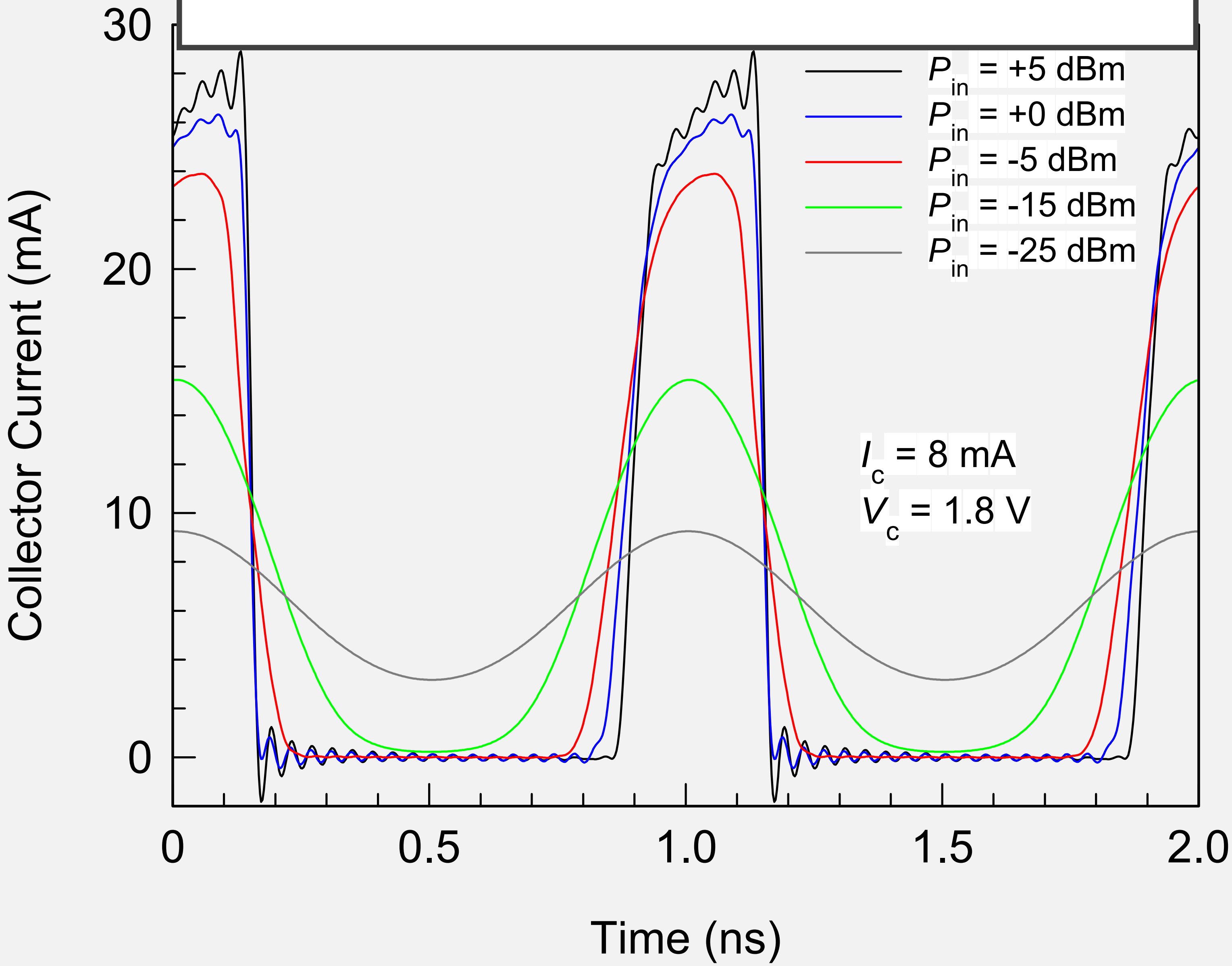
Model Extraction



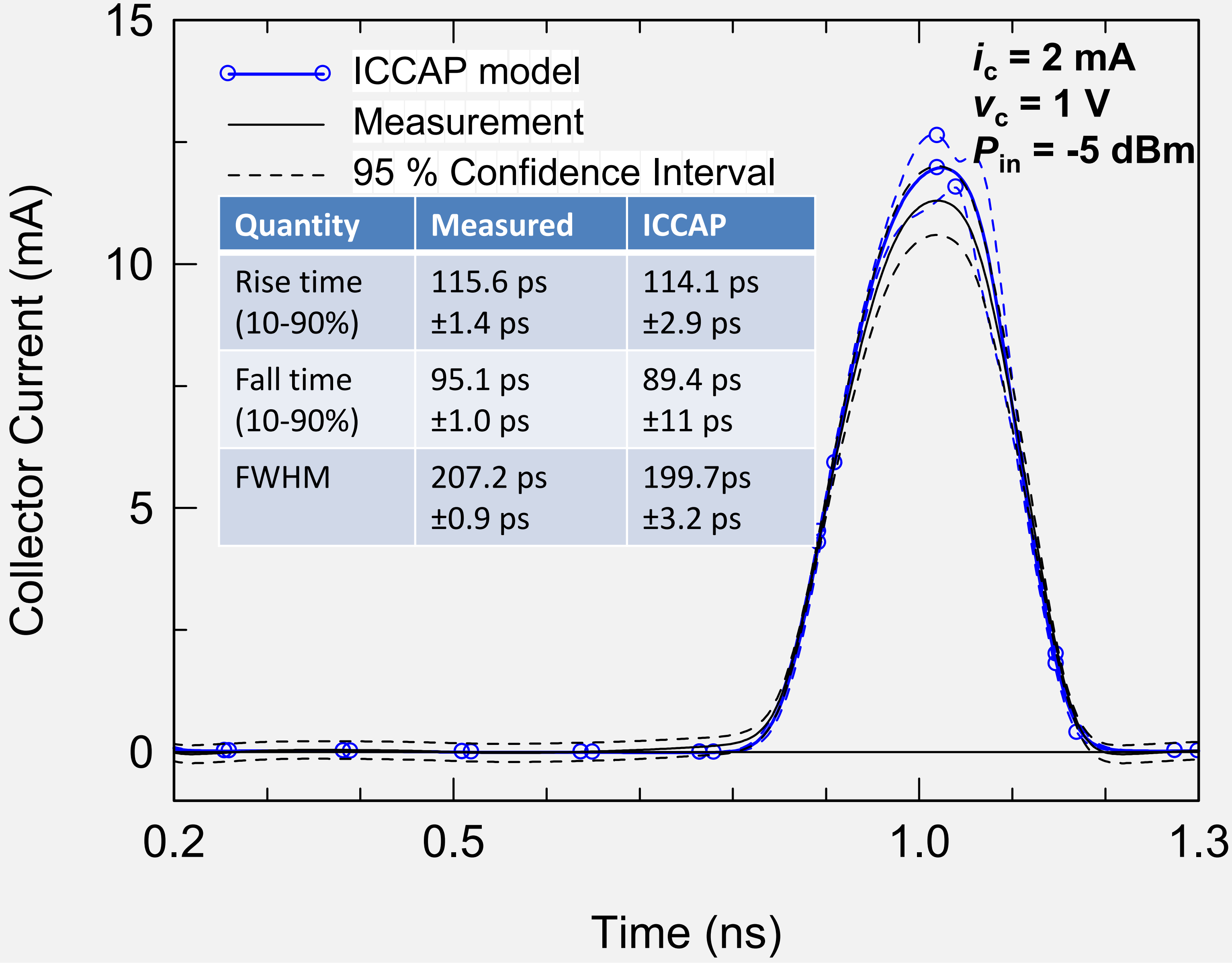
Circuit Design



ON-WAFER DEVICE MEASUREMENT: INCREASING DRIVE LEVEL

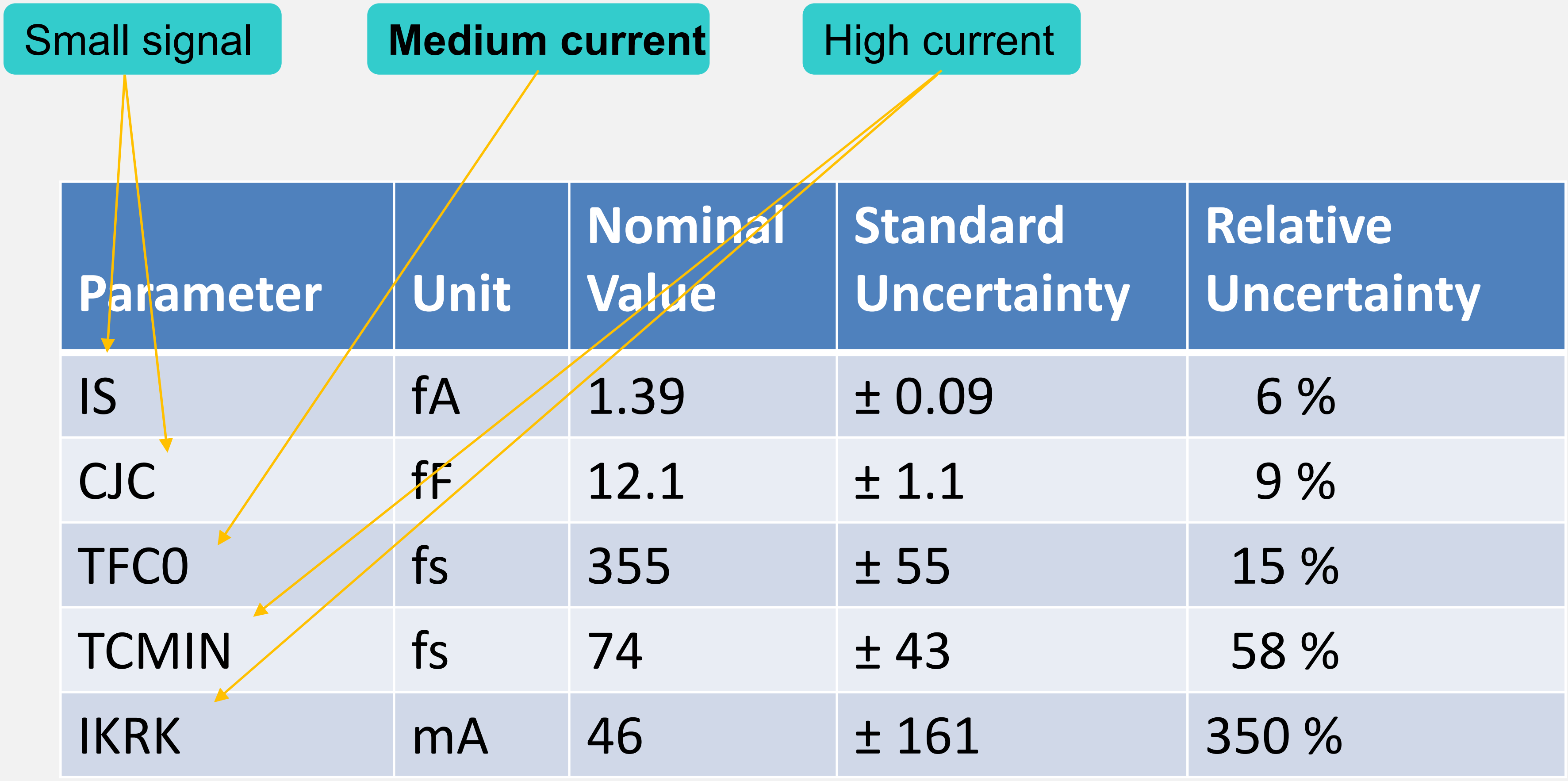


ICCAP MODEL – MEDIUM DRIVE



Quantity	Measured	ICCAP
Rise time (10-90%)	115.6 ps ±1.4 ps	114.1 ps ±2.9 ps
Fall time (10-90%)	95.1 ps ±1.0 ps	89.4 ps ±11 ps
FWHM	207.2 ps ±0.9 ps	199.7ps ±3.2 ps

EXTRACTING MODEL PARAMETERS



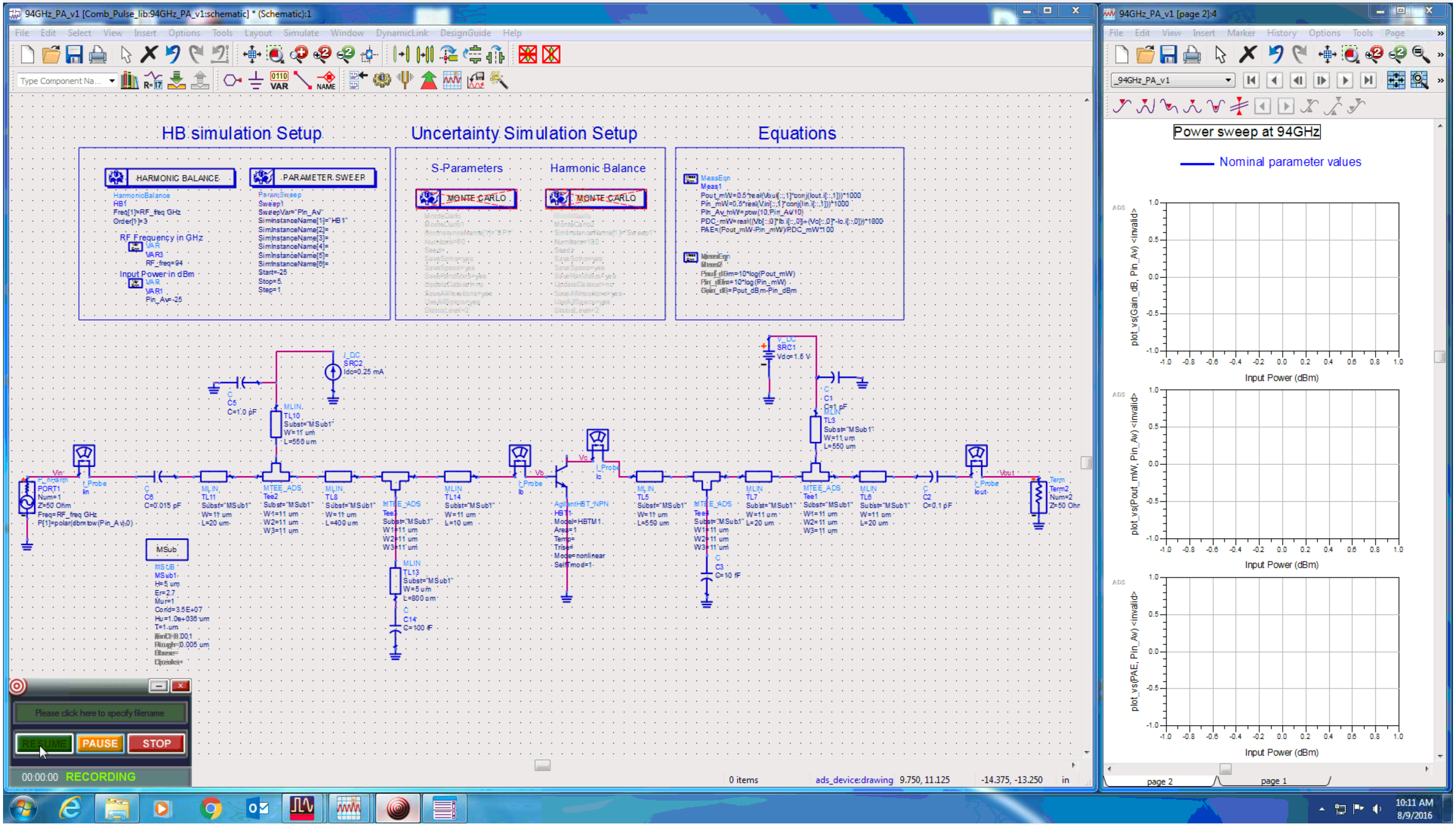
Small signal

Medium current

High current

Parameter	Unit	Nominal Value	Standard Uncertainty	Relative Uncertainty
IS	fA	1.39	± 0.09	6 %
CJC	fF	12.1	± 1.1	9 %
TFC0	fs	355	± 55	15 %
TCMIN	fs	74	± 43	58 %
IKRK	mA	46	± 161	350 %

DEVICE MODELS TO CIRCUIT DESIGN



HarmonicBalance
HB1
Freq[1]=RF_freq GHz
Order[1]=3

RF Frequency in GHz
VAR
VAR3
RF_freq=94

Input Power in dBm
VAR
VAR1
Pin_Av=-25

ParamSweep
Sweep1
SweepVar="Pin_Av"
SimInstanceName[1]="HB1"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=-25
Stop=5
Step=1

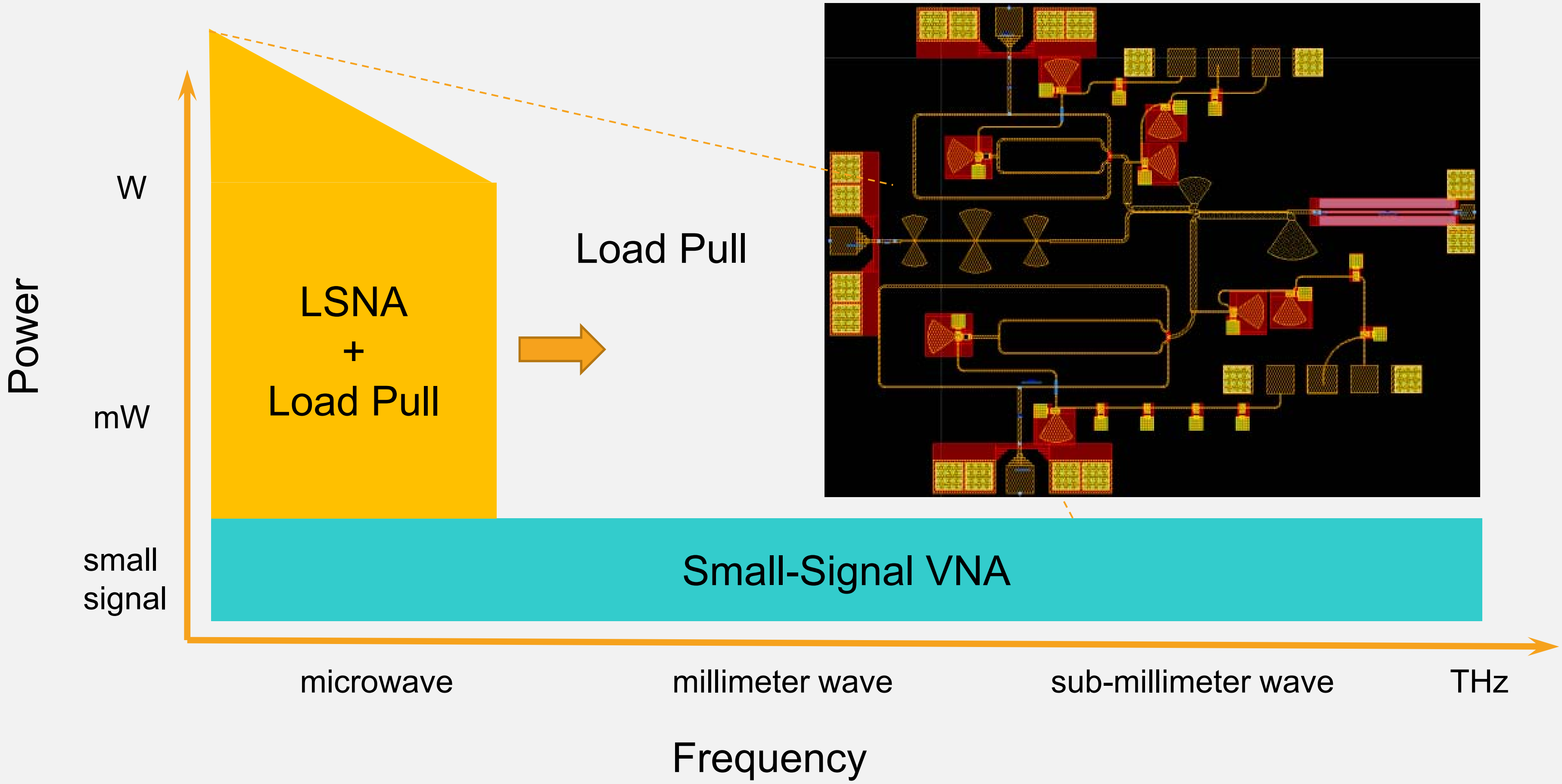
MeasEqn
Meas1
Pout_mW=0.5*real(Vout[::,1]*conj(Iout.i[::,1]))*1000
Pin_mW=0.5*real(Vin[::,1]*conj(Iin.i[::,1]))*1000
Pin_Av_mW=pow(10,Pin_Av/10)
PDC_mW=real((Vb[::,0]*Ib.i[::,0])+(Vc[::,0]*-Ic.i[::,0]))*1000
PAE=(Pout_mW-Pin_mW)/PDC_mW*100

MeasEqn
Meas2
Pout_dBm=10*log(Pout_mW)
Pin_dBm=10*log(Pin_mW)
Gain_dB=Pout_dBm-Pin_dBm

V_DC
SRC1
Vdc=1.5 V

I_DC
SRC2
Idc=0.25 mA

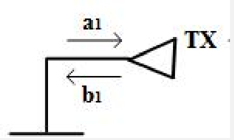
ON-WAFER, MMWAVE LARGE-SIGNAL-NETWORK-ANALYSIS MEASUREMENT LANDSCAPE



OTA MEASUREMENT LANDSCAPE

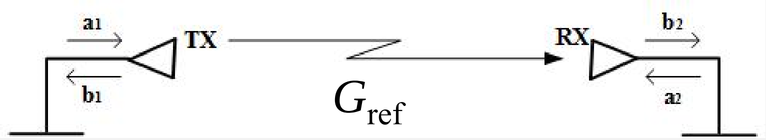
- **DUT with accessible antenna terminals**

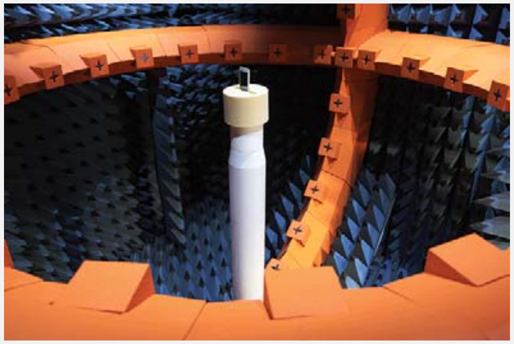
$$P_{\mathrm{rad,direct}} = \left\langle |a_1|^2 - |b_1|^2 \right\rangle \eta_{\mathrm{TX}}$$



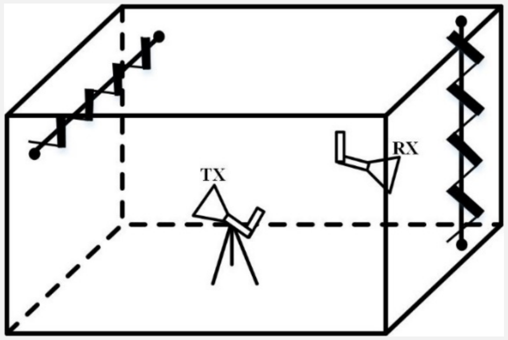
- **DUT with integrated antenna**

$$P_{\mathrm{rad,integrated}} = \frac{P_{\mathrm{rec}}}{G_{\mathrm{ref}}} = \frac{\left\langle |b_2|^2 - |a_2|^2 \right\rangle}{G_{\mathrm{ref}}}$$

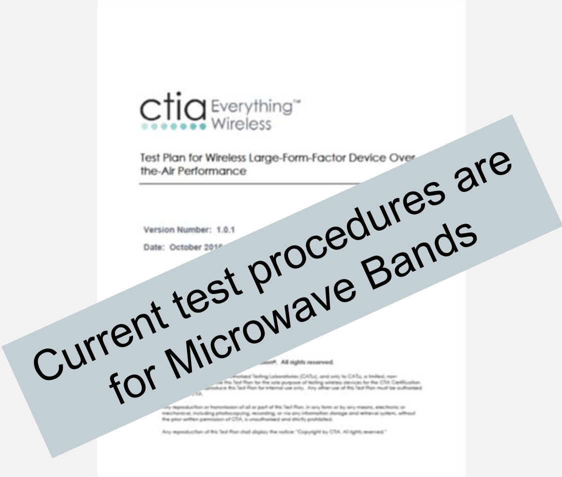




Anechoic chamber



Reverberation chamber



ctia Everything™ Wireless

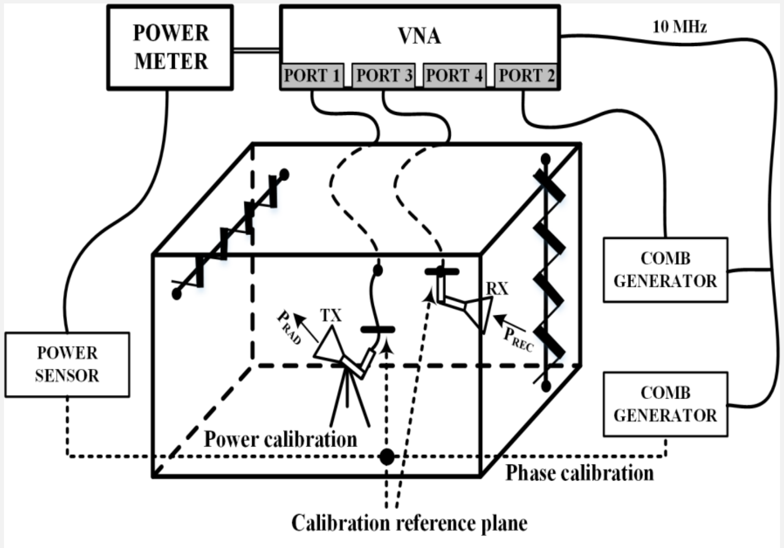
Test Plan for Wireless Large-Form-Factor Device Over-the-Air Performance

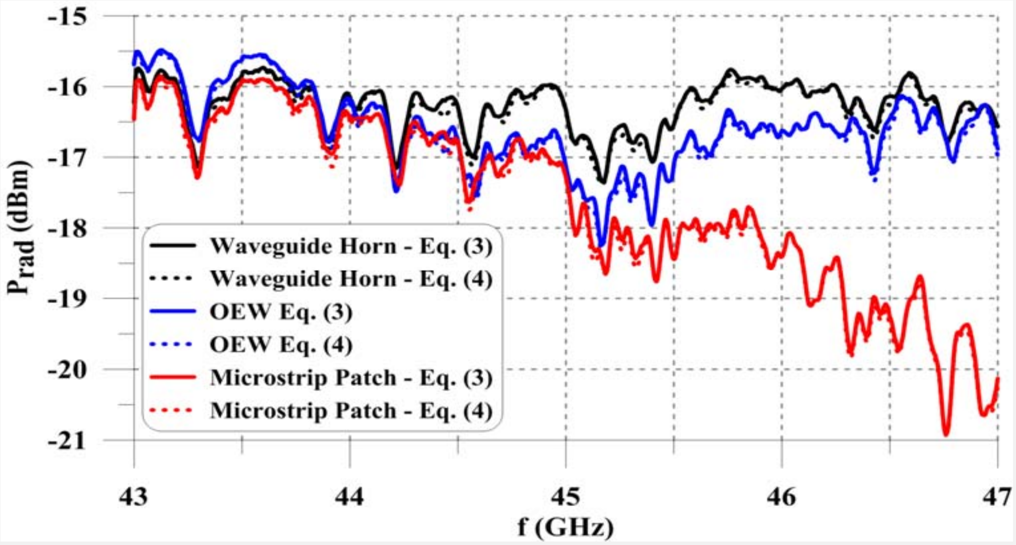
Version Number: 1.0.1

Date: October 201

Current test procedures are for Microwave Bands

OTA MMWAVE MEASUREMENT LANDSCAPE





OTA test at mmWave in reverberation chamber

- Open-ended waveguide
- Waveguide horn antenna
- Microstrip patch antenna

MEASUREMENT QUESTIONS UNDER CONSIDERATION

- **The Elephant in the Room:**
  - How to determine meaningful evaluation metrics from on-wafer-to-OTA test?
- **Large-Signal Device and Circuit Characterization**
  - What are prospects for large-signal network analysis at mmWave frequencies?
  - What are issues with impedance tuning of mmWave harmonics?
- **mmWave Signal Characterization:**
  - How to cascade nonideal, distortion-inducing instruments (e.g., “Additive EVM”)?
  - How to conduct free-field measurements with spatial as well as electronic distortion (e.g., off-axis EVM)?
- **OTA Test at mmWave Frequencies:**
  - What new uncertainties are related to the testing of integrated devices?
  - How to repeatably test under free-field multipath conditions?
  - Are new statistics needed for testing arrays that operate in more states than you can count?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