Fundamental measurements for wireless communications

Paul Hale
Chief, RF Technology Division

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

Communications Technology Laboratory

CTL mission

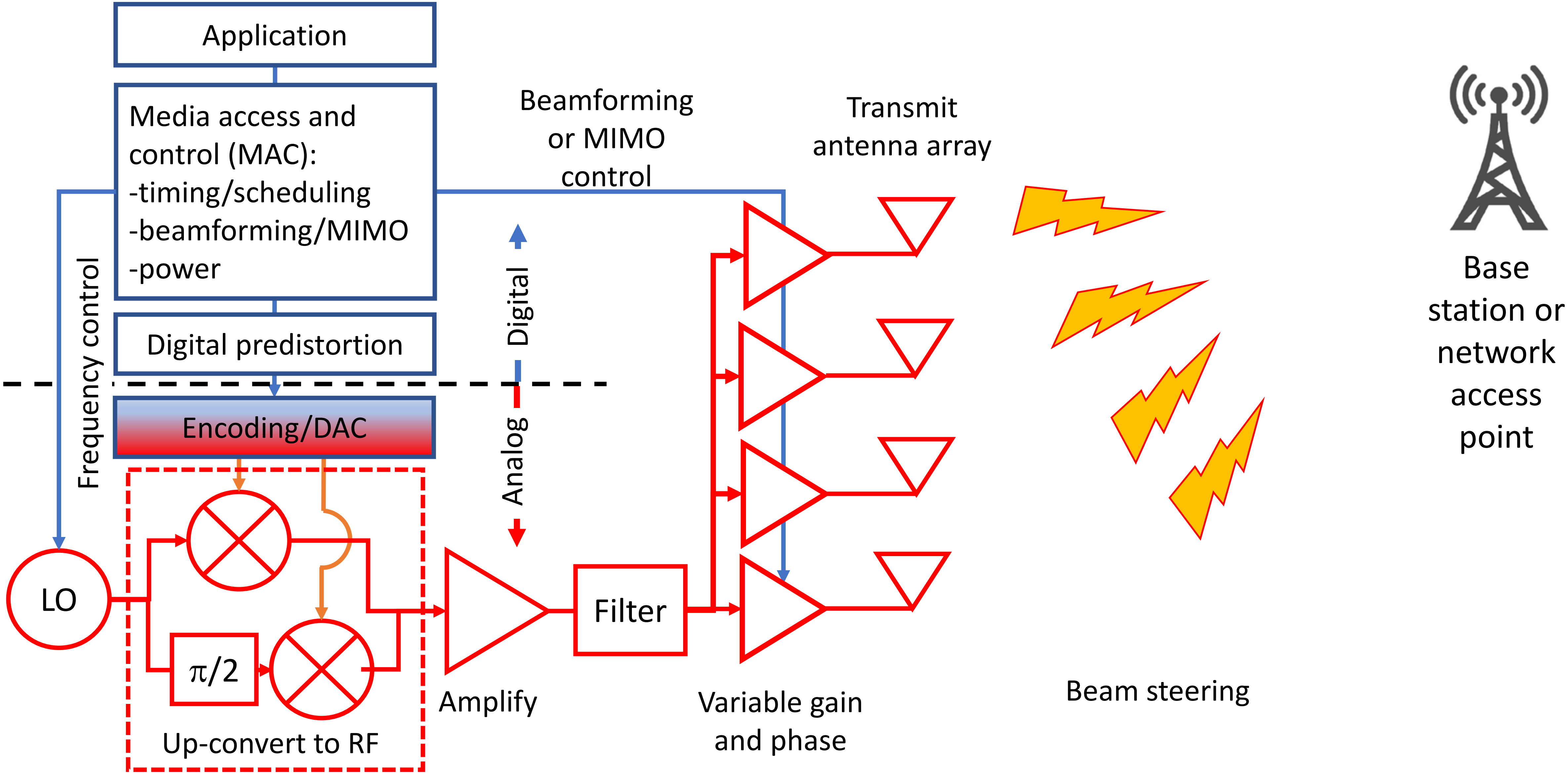
CTL promotes the development and deployment of ***advanced communications technologies*** *through dissemination of high-quality measurements, data, and research supporting U.S. innovation, industrial competitiveness, and public safety.*

CTL mission

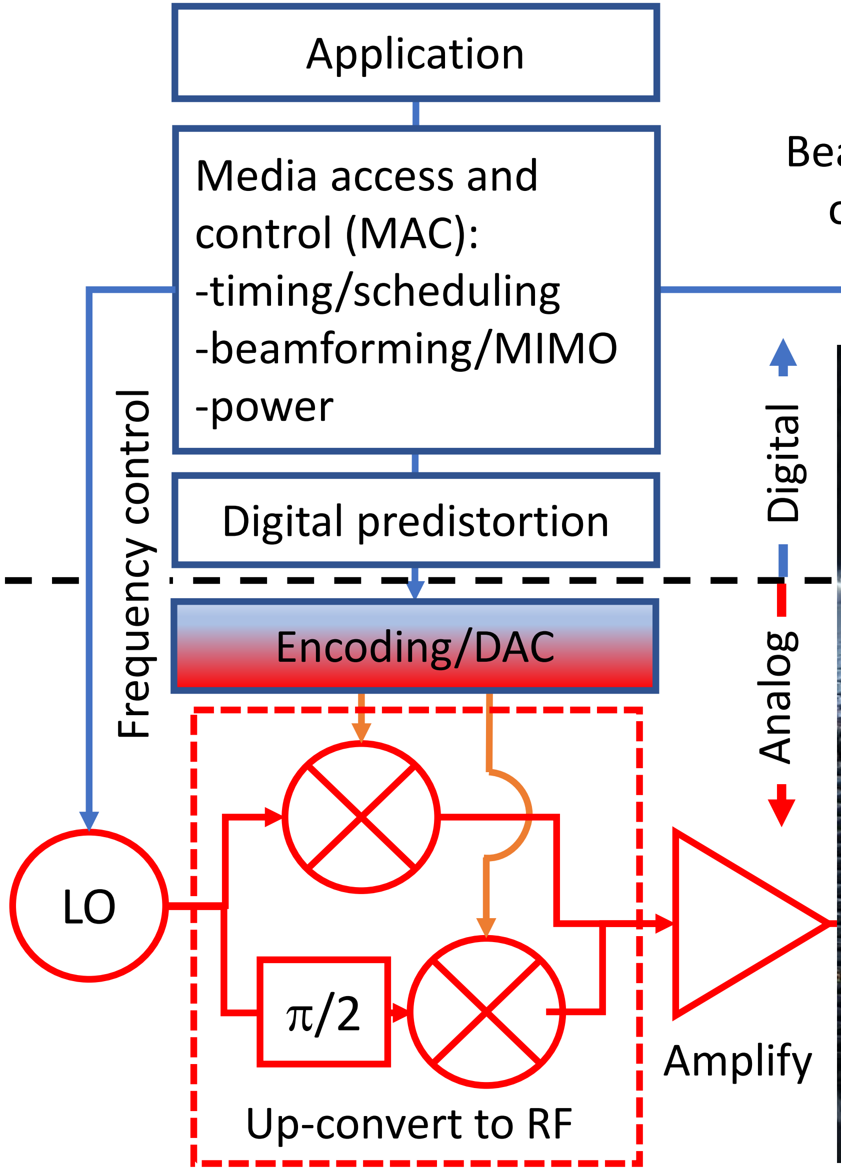
*CTL promotes the development and deployment of **advanced communications technologies** through dissemination of high-quality measurements, data, and research supporting U.S. innovation, industrial competitiveness, and public safety.*

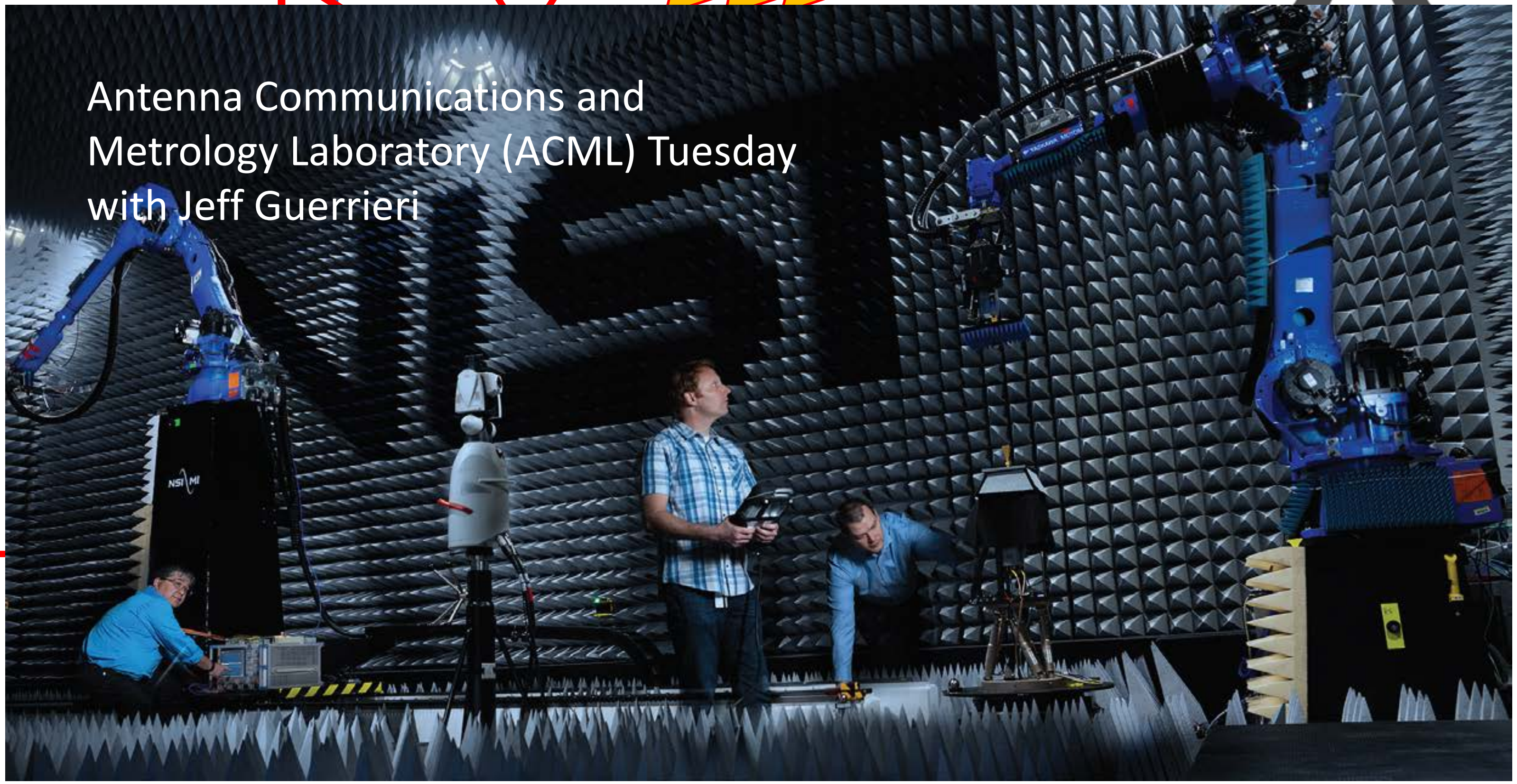
Wireless communications metrology, spanning from the component to system level, also impacts other forms of communications

A (simplified) wireless communications system

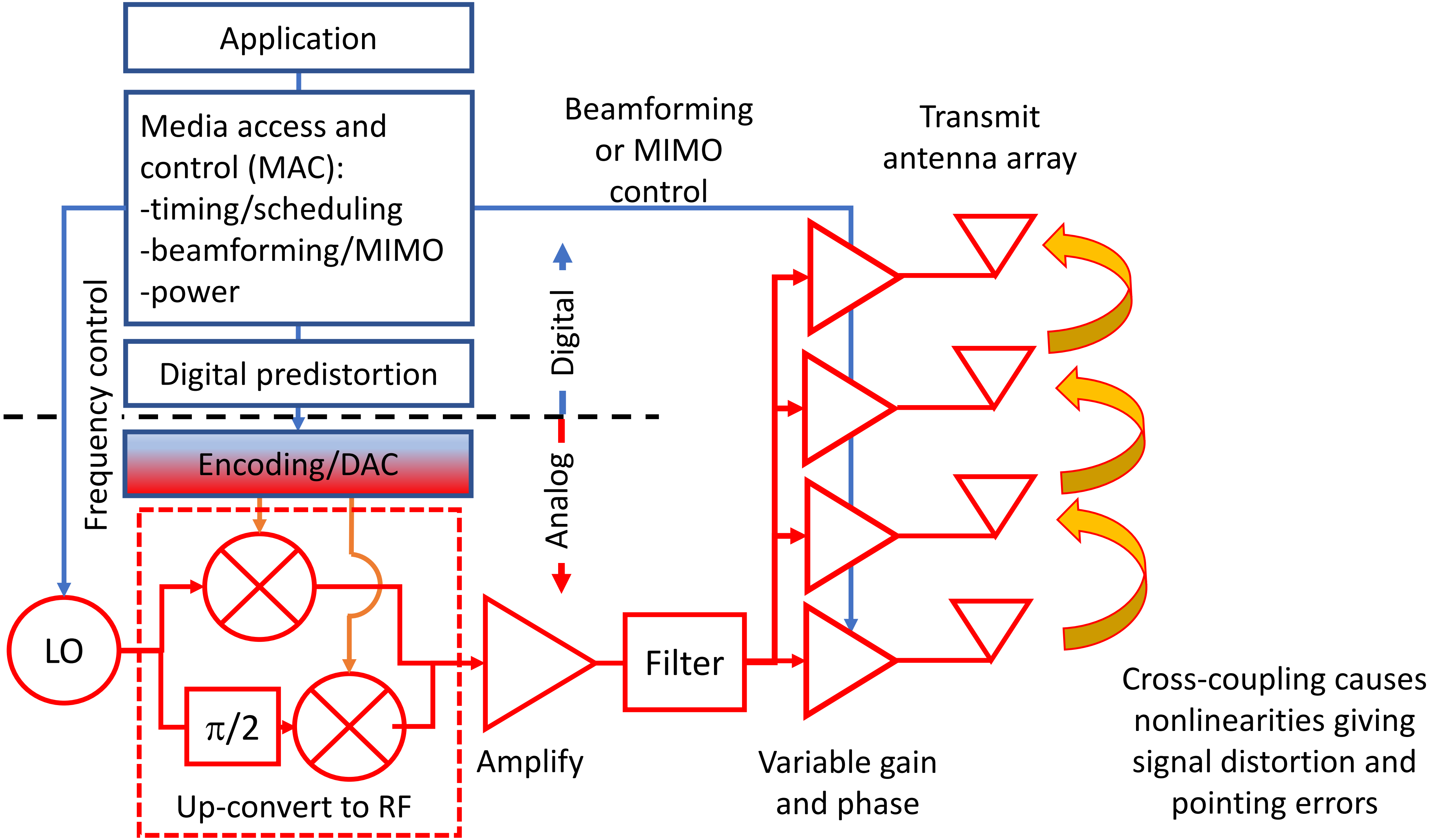


A (simplified) wireless communications system



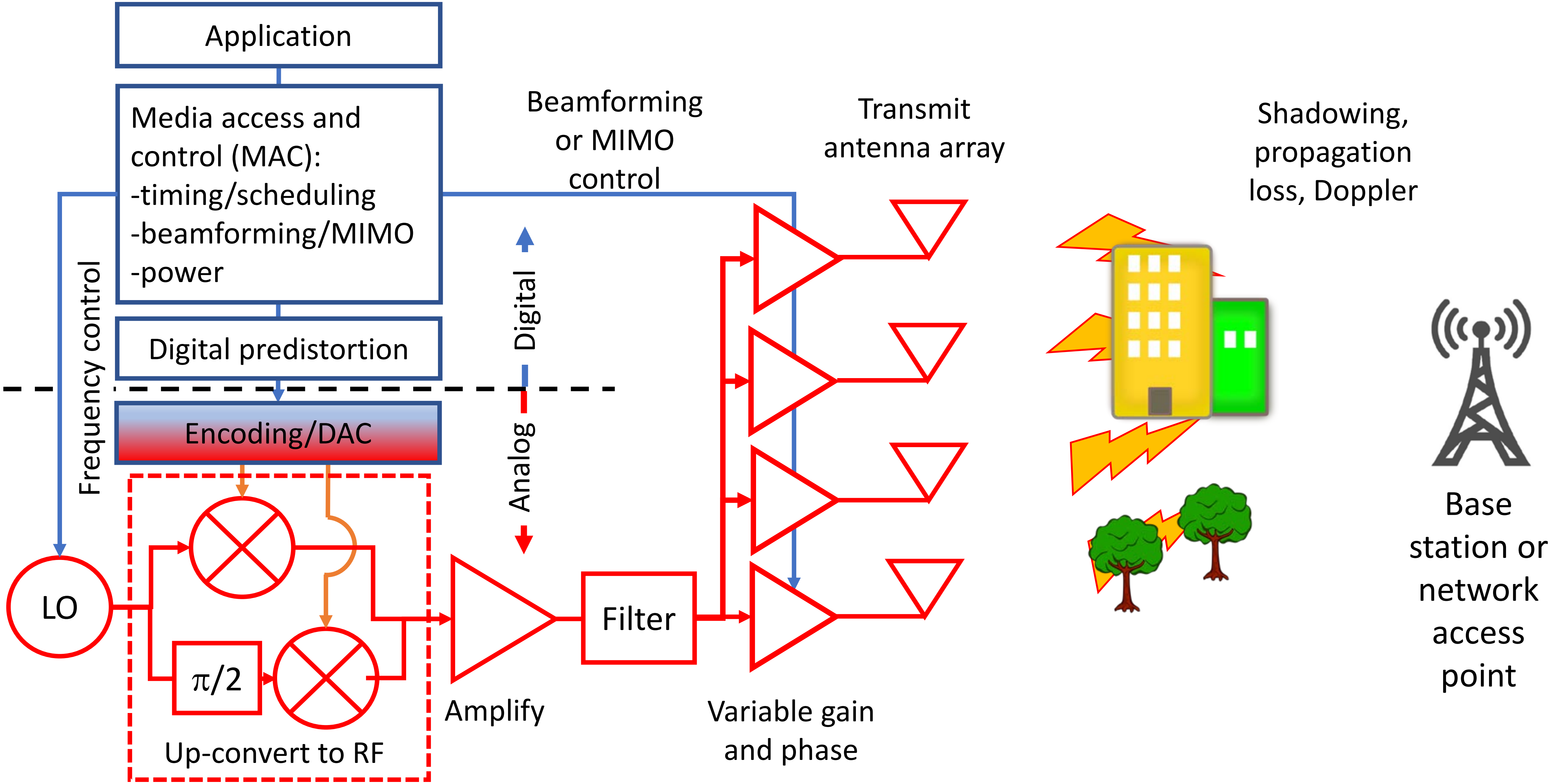


A (simplified) wireless communications system

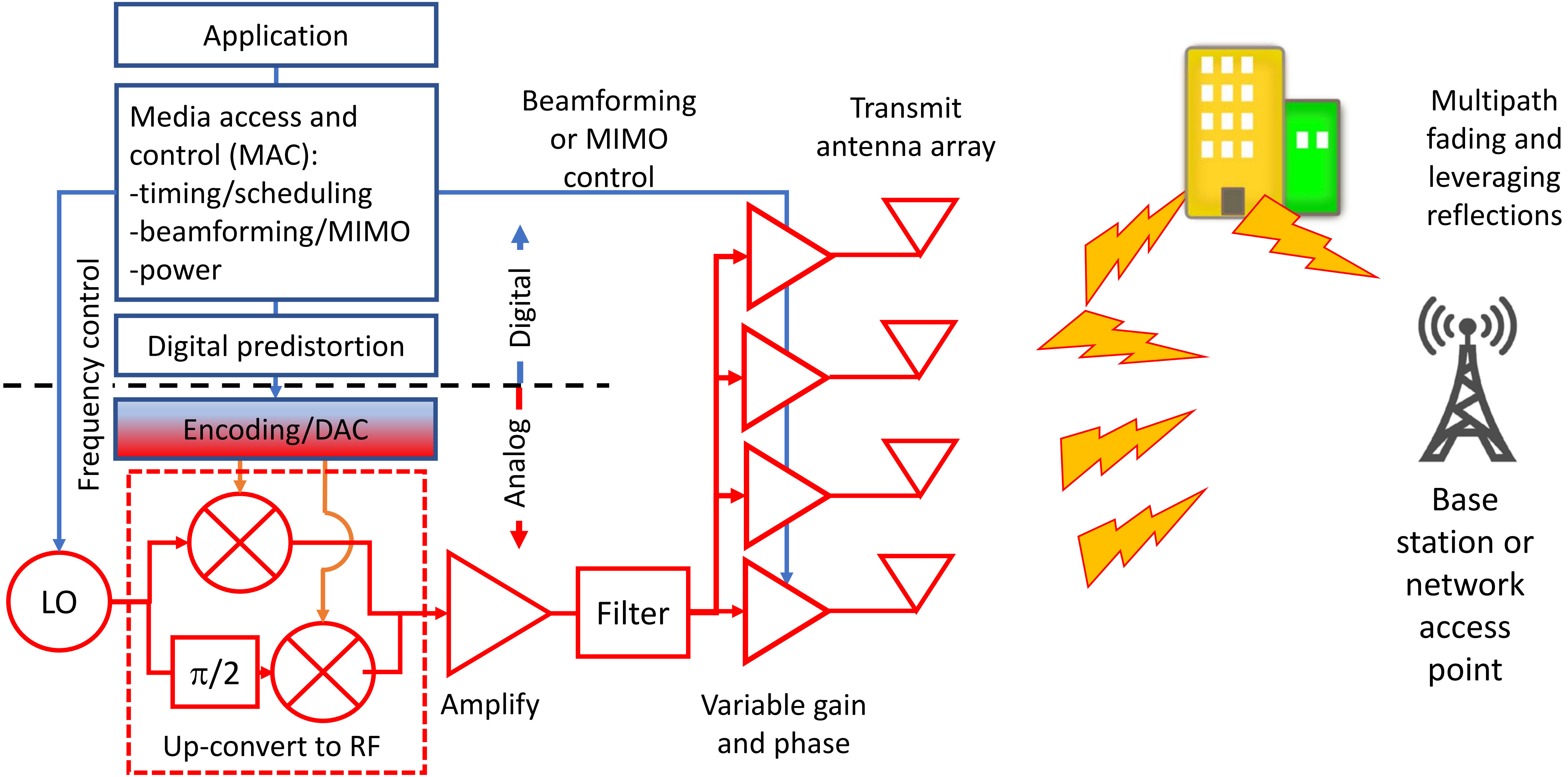


Base station or network access point

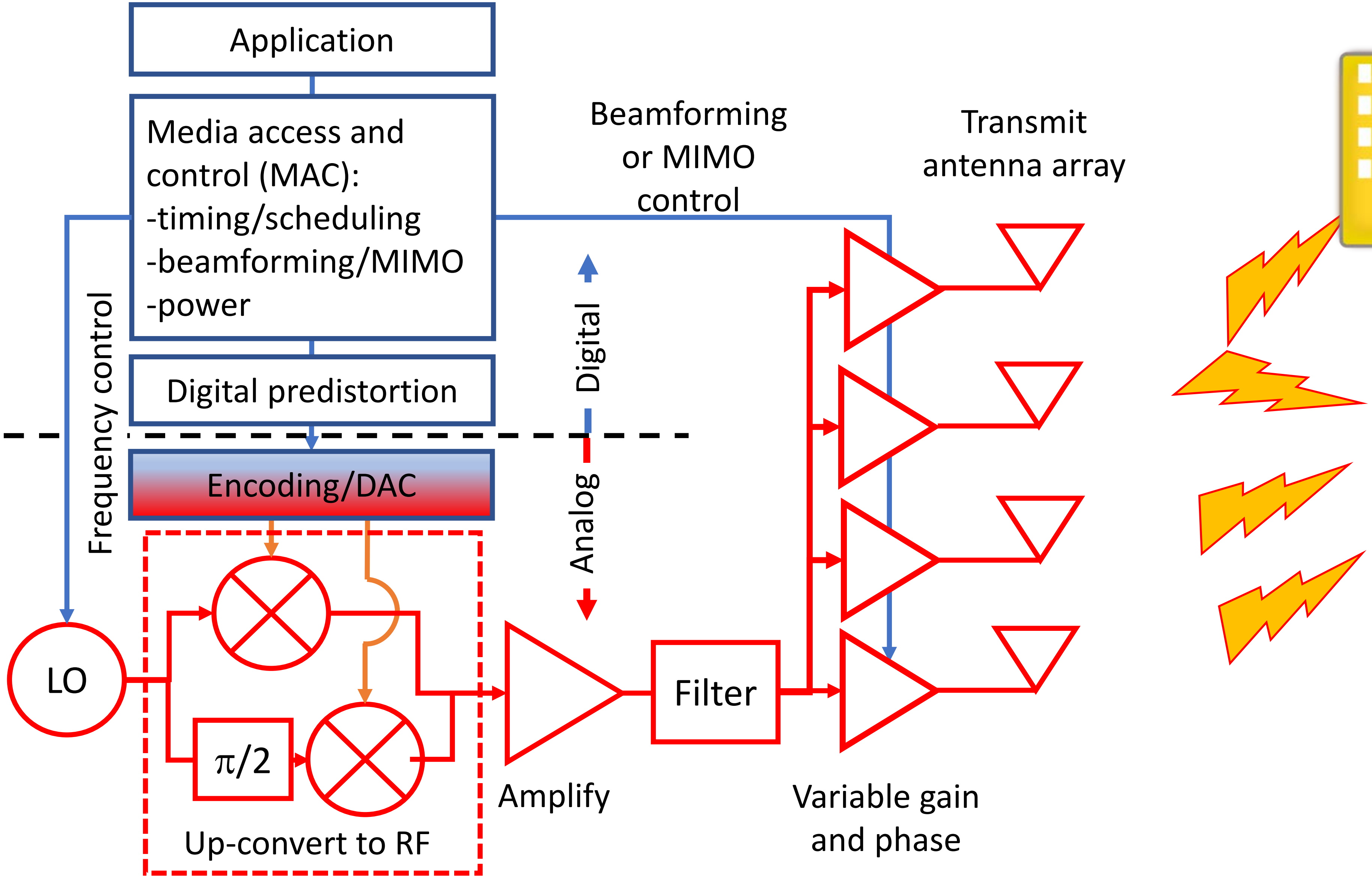
A (simplified) wireless communications system

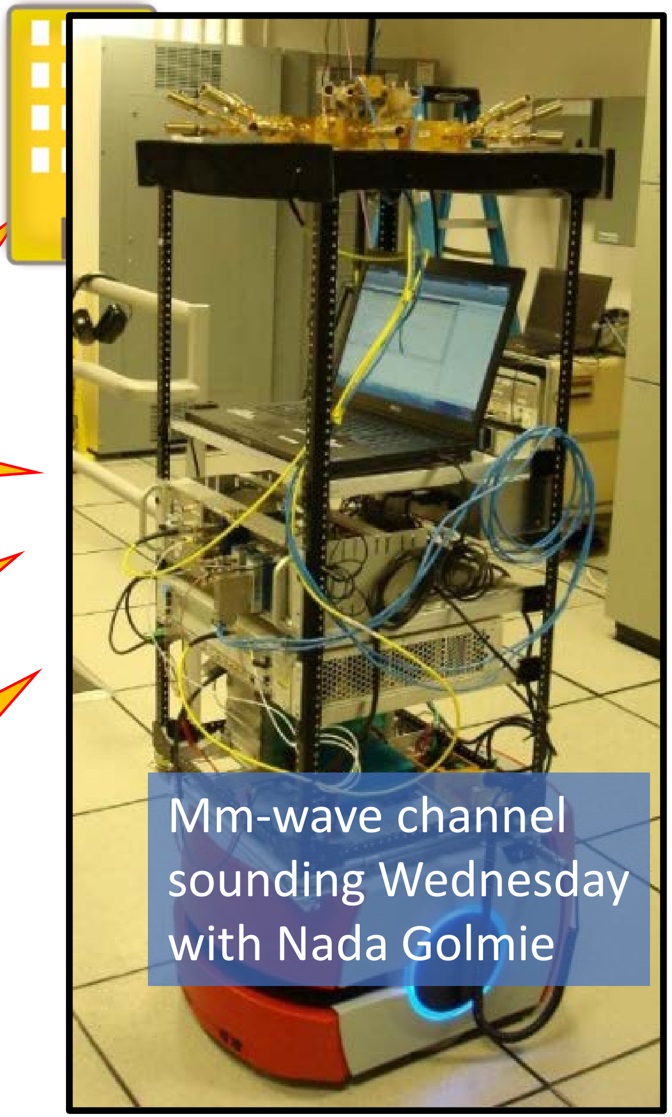


A (simplified) wireless communications system

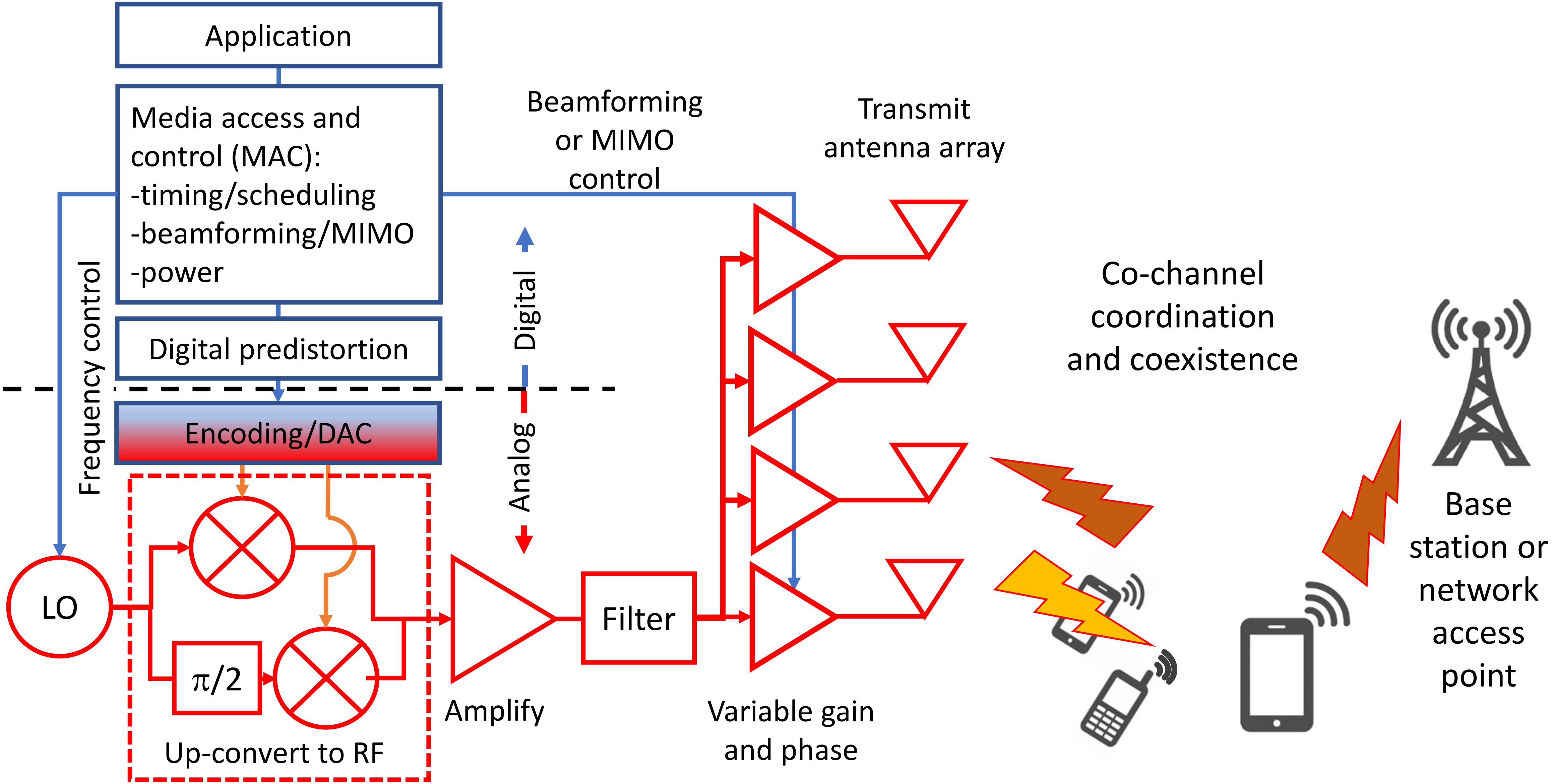


A (simplified) wireless communications system

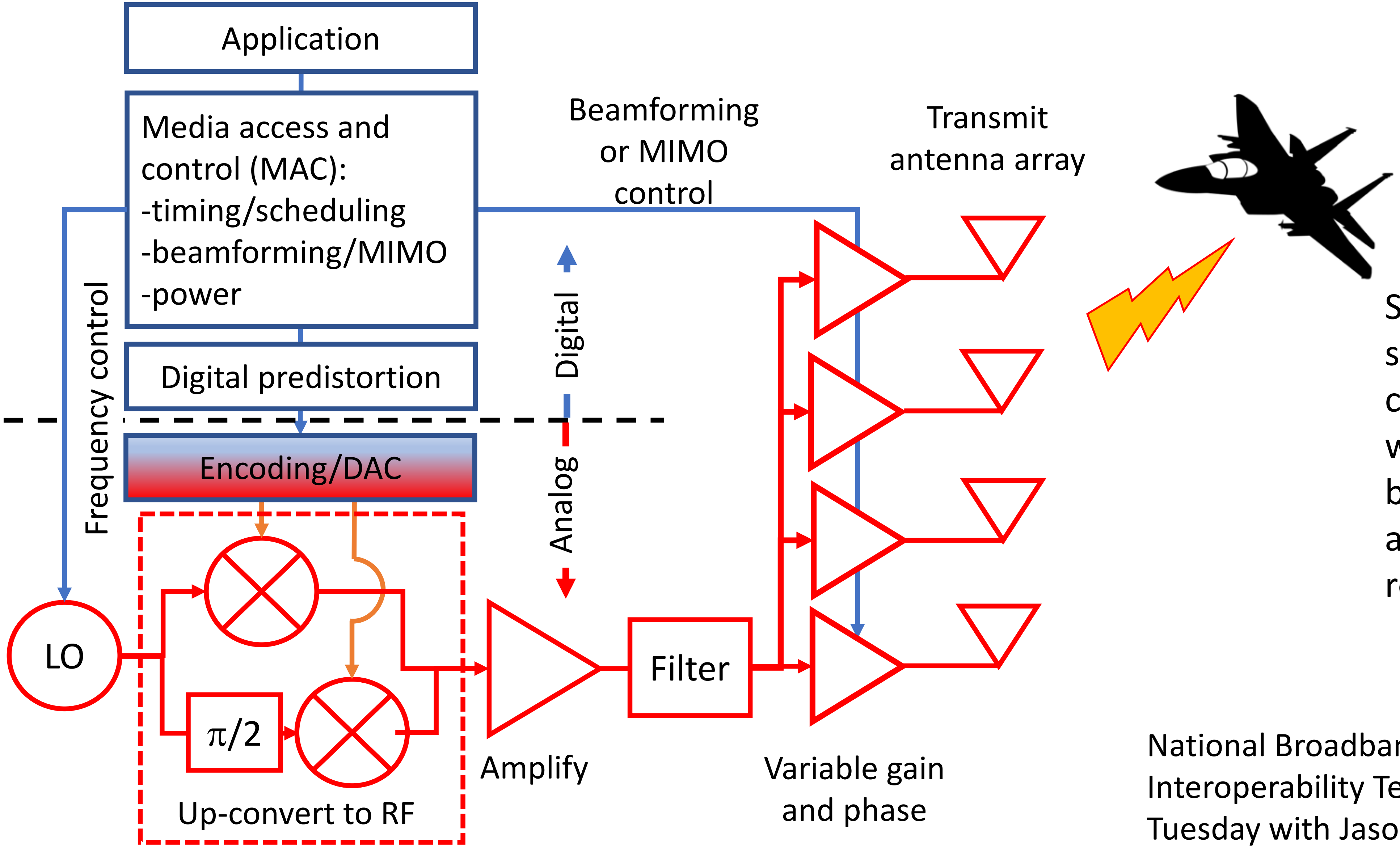




A (simplified) wireless communications system



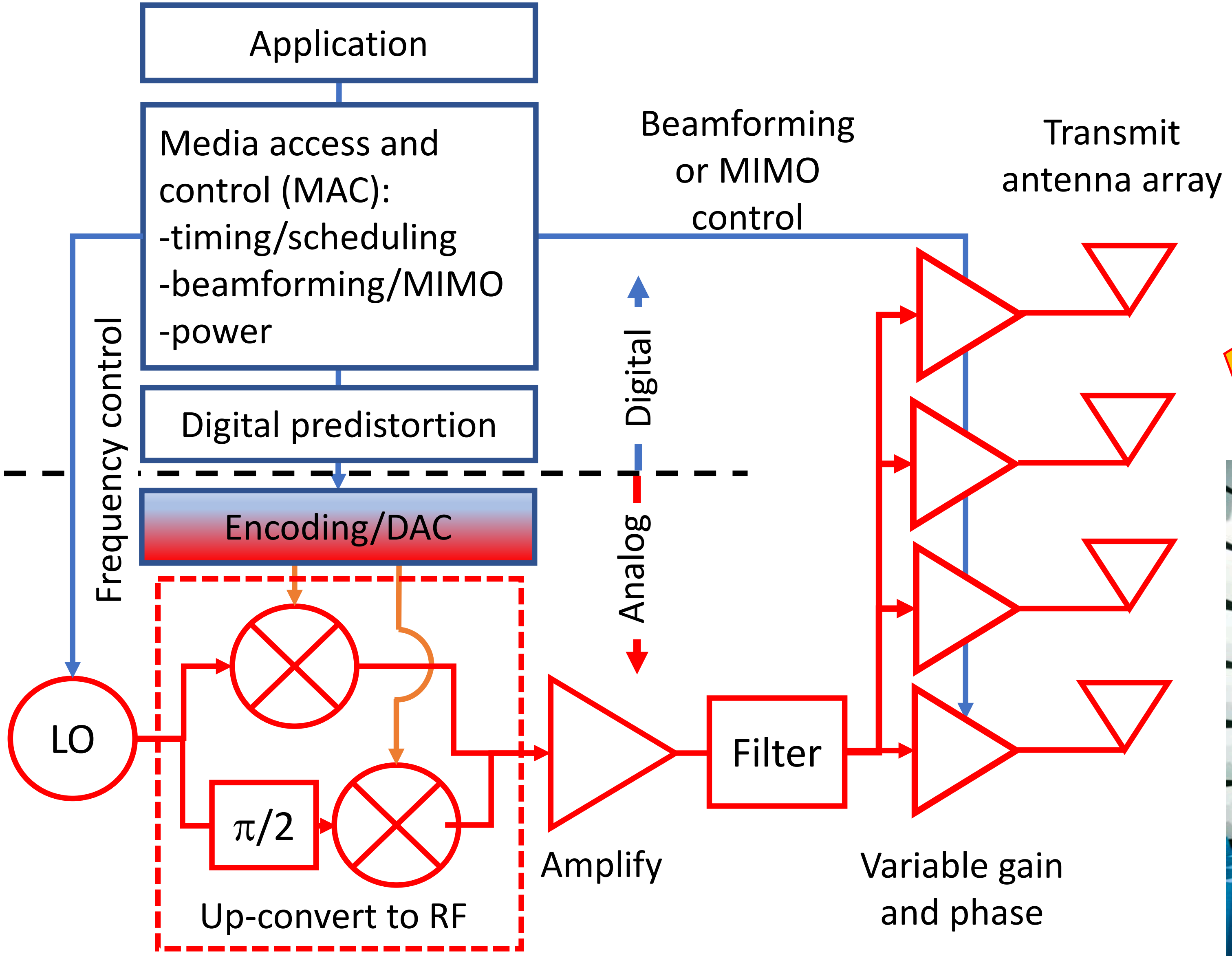
A (simplified) wireless communications system

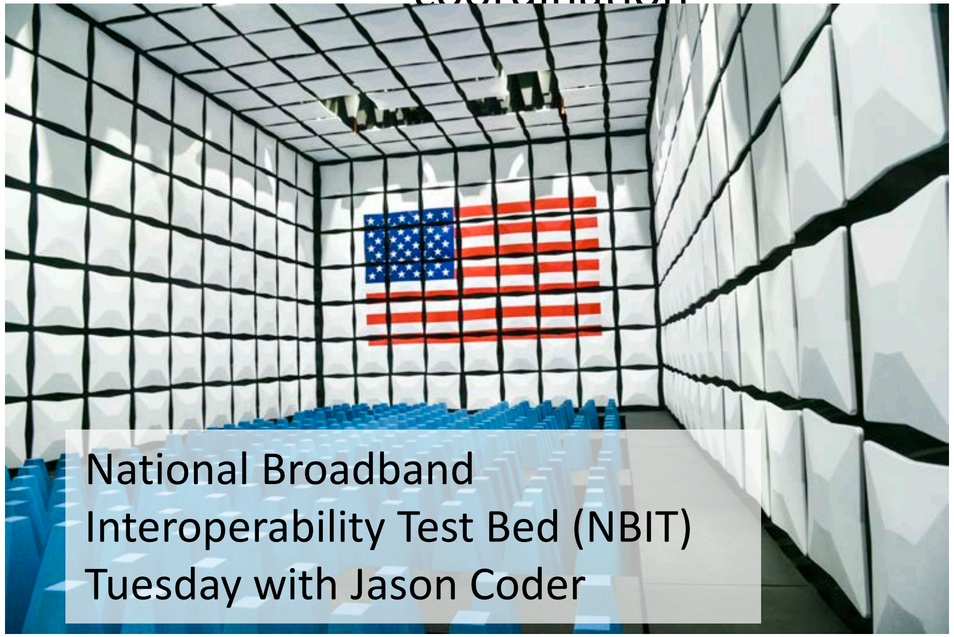


Spectrum sharing or coordination with priority in-band and adjacent- band receivers

National Broadband Interoperability Test Bed (NBIT) Tuesday with Jason Coder

A (simplified) wireless communications system





Cell phone design and test considerations

From www.ifixit.com, April 13, 2019

Challenges: Efficiency, test without connectors

Large battery
- Power efficiency

Digital and RF ICs mounted on multiple boards
- Massive integration
- IC test
- Interconnect/circuit board test

No RF connectors in assembled system
- Over-the-air test
- Digital / propagating field test ports

Support for multiple LTE bands, 802.11 a/b/g/n/ac WiFi w/ MIMO, Bluetooth, NFC
- Multiple (active) antennas and antenna control, filters, amplifiers
- Inference and coexistence must be considered for all bands

Industry moving to mm-wave frequencies

Implication for propagation:

- Propagation loss increases
- Mm-waves are blocked by trees, buildings, and people
  - ⇒ Overcome losses with beam steering
- Channels tend to be more reflective than diffractive
  - ⇒ Beam steering must be dynamic

Implication for circuits:

- Parasitics increase with frequency
- Linear and nonlinear distortion (in circuit and measurement) increases with frequency
  - ⇒ Better measurements and models are required
- Efficiency decreases with frequency
  - ⇒ Better design practices are required

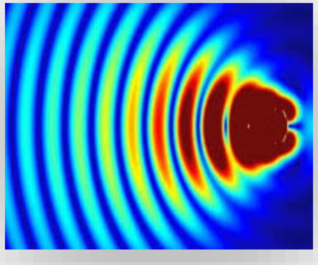
Traceable measurements for communications

- Fundamental measurements: Measurements of the properties of a physical system that can be made traceable to the SI
- Traceability: "...property of a measurement result whereby the result can be related to a reference through a **documented unbroken chain of calibrations**, each contributing to the **measurement uncertainty** [VIM]."*
- NIST is *the* National Metrology Institute (NMI) for the USA; providing traceability to the SI is a core NIST mission.
- SI traceability for communications
  - Scattering parameters
  - RF power
  - RF noise
  - Antenna parameters
  - Dielectric constant
  - Cross-frequency phase
- Validated methodology for measurements required for design, development, and deployment of advanced communications systems

**JCGM 200:2008, International vocabulary of metrology - Basic and general concepts and associated terms (VIM Third Edition, 2008).*

Fundamental measurements

- Instrumentation industry and DoD rely on NIST/CTL for providing traceability to the SI for RF quantities.
- Traceability is primarily to the meter, coulomb, volt, and ohm through partners in other parts of NIST
- Traceable calibration is needed for unbiased validation of experimental data
- Traceable calibration supports current and future services
- NIST research includes developing better ways to provide traceability and developing new measurement techniques to address tomorrow's needs



Vector Network Analysis

- Vector network analyzer
  - S-parameter calibration

Air lines

$$S_{21} = \frac{b_2}{a_1}$$

Normalized, dimensionless

$$S_{11} = \frac{b_1}{a_1}$$

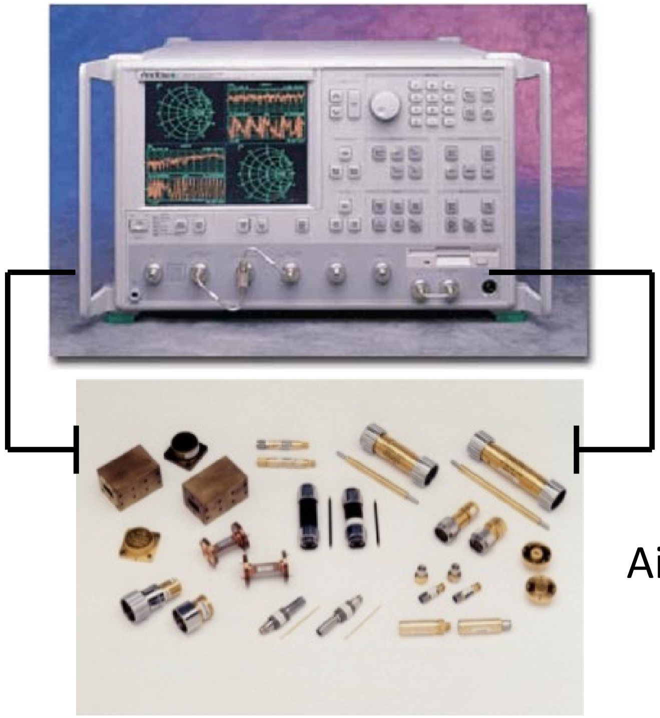
Where we are going: Vector Network Analysis

- Same vector network analyzer
  - S-parameter calibration
  - **Power calibration**
  - **Cross-frequency phase calibration**

NIST is only NMI to provide all three

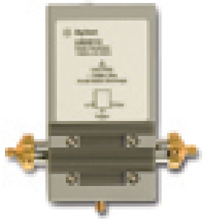
$$v = \sqrt{Z_0}\,(a + b)$$

$$i = \frac{1}{\sqrt{Z_0}}\,(a - b)$$



Air lines

Power meter

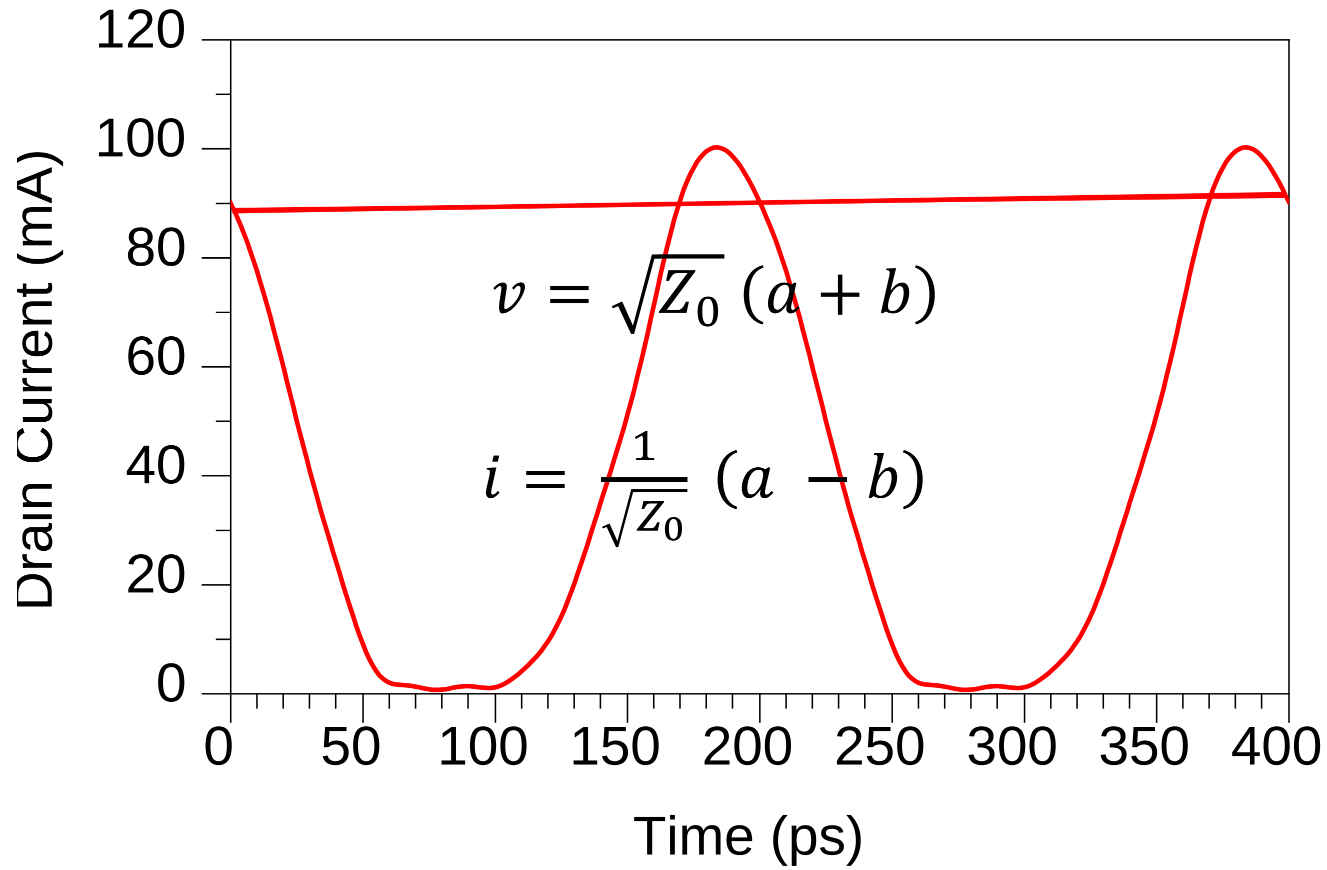


Comb generator

Where we are going: Vector Network Analysis

- Same vector network analyzer
  - S-parameter calibration
  - **Power calibration**
  - **Cross-frequency phase calibration**

NIST is only NMI to provide all three

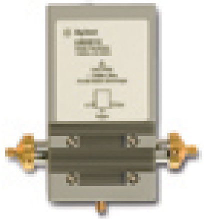


$$v = \sqrt{Z_0}\,(a + b)$$

$$i = \frac{1}{\sqrt{Z_0}}\,(a - b)$$

Air lines

Power meter



Comb generator

What is cross-frequency phase?

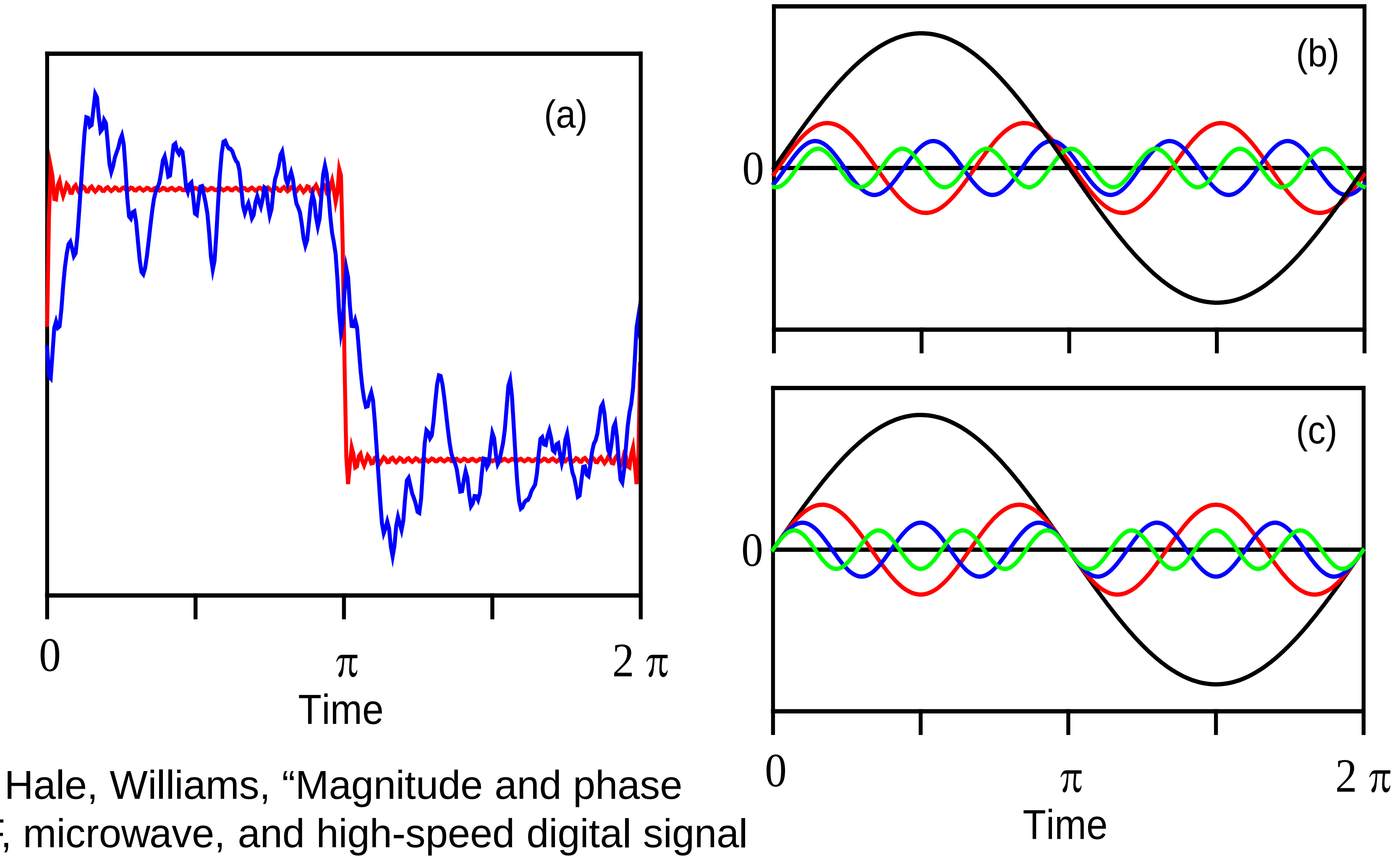
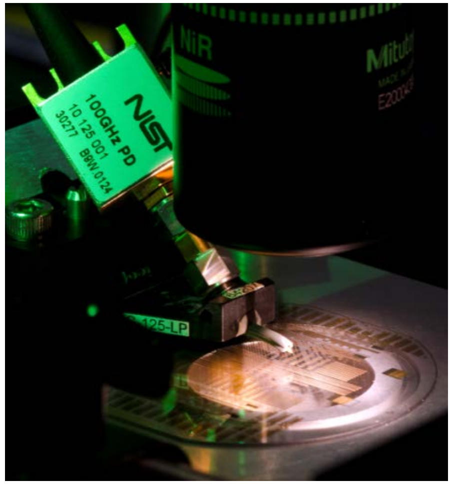
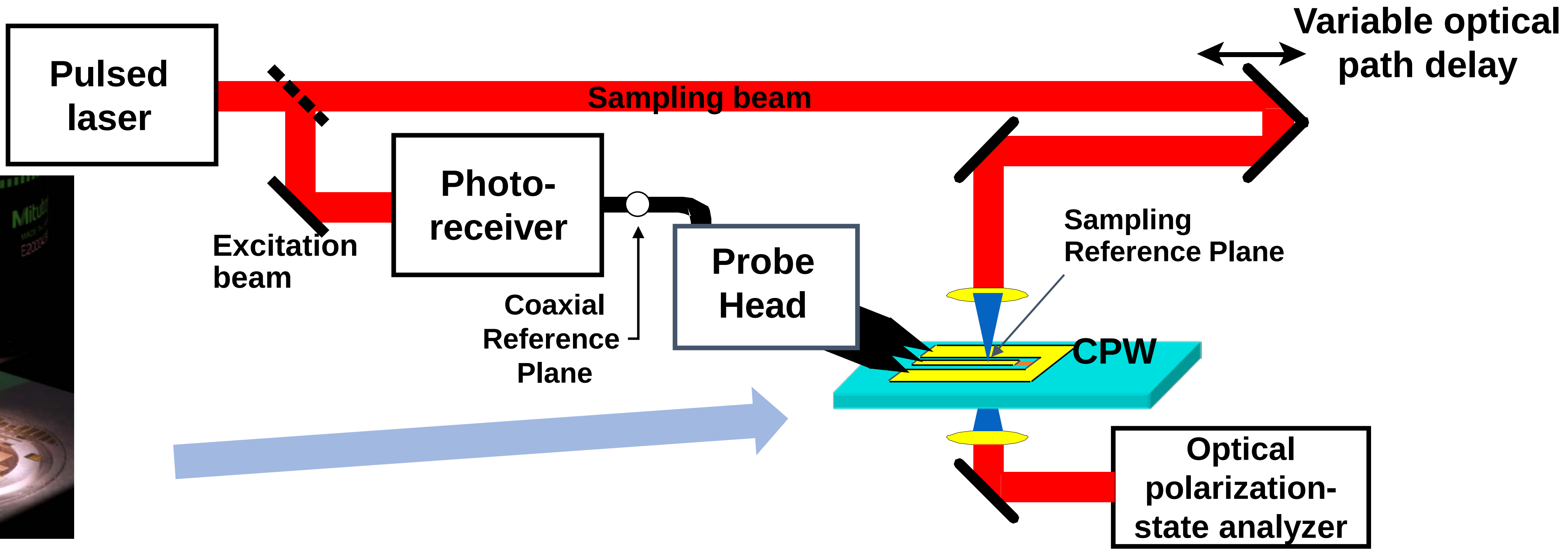


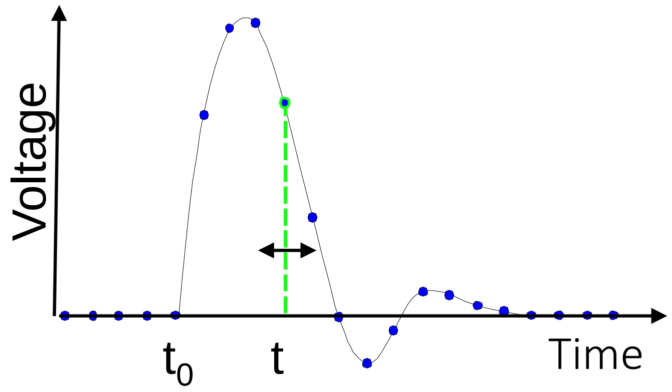
Fig. from Remley, Hale, Williams, “Magnitude and phase calibrations for RF, microwave, and high-speed digital signal measurements,” *RF and Microwave Circuits, Measurements, and Modeling,* CRC Press, Taylor and Francis Group, Boca Raton, 2007.

NIST electro-optic sampling: A THz bandwidth oscilloscope

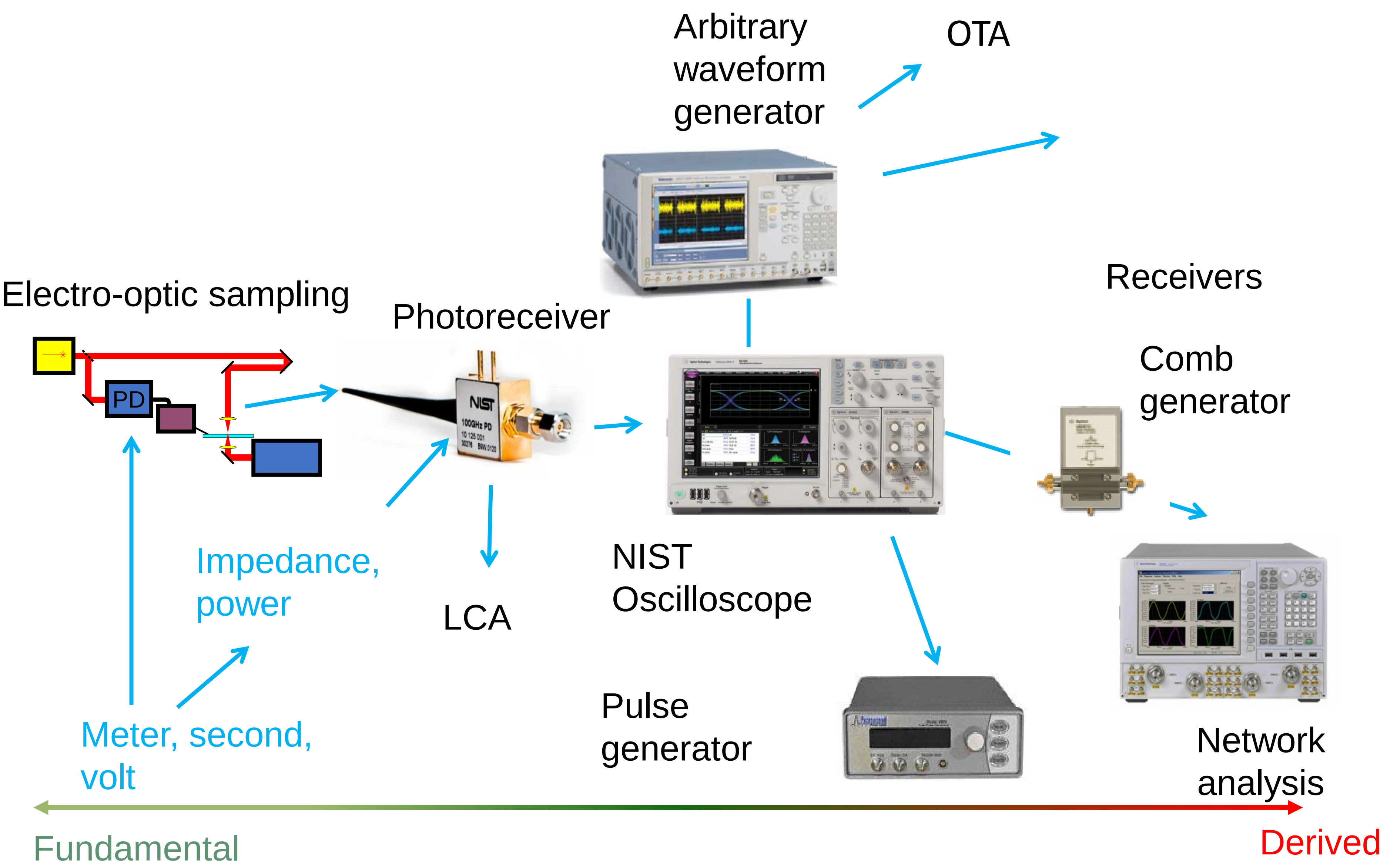




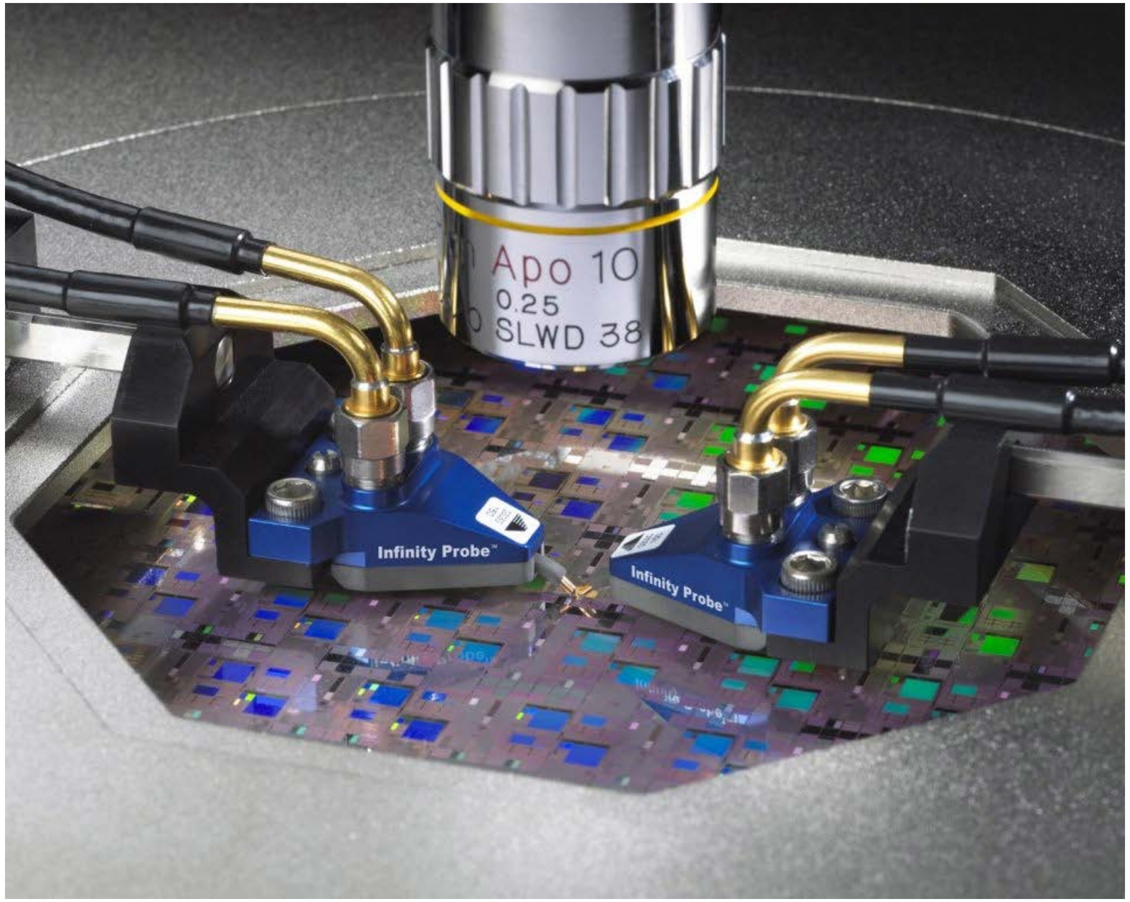
- Fourier transform of waveform includes cross-frequency phase relationships
- Use electro-optic (Pockels) effect in $LiTaO_3$, InP, or GaAs, but other materials possible
- Response time given by phonon resonances and propagation effects
- > 10 THz bandwidth possible
- Optical signal generation and electro-optic signal measurement are being leveraged for mm-wave device characterization in other projects



Traceability for modulated signals and network analysis



Where we are going: Network analysis for connector-less test



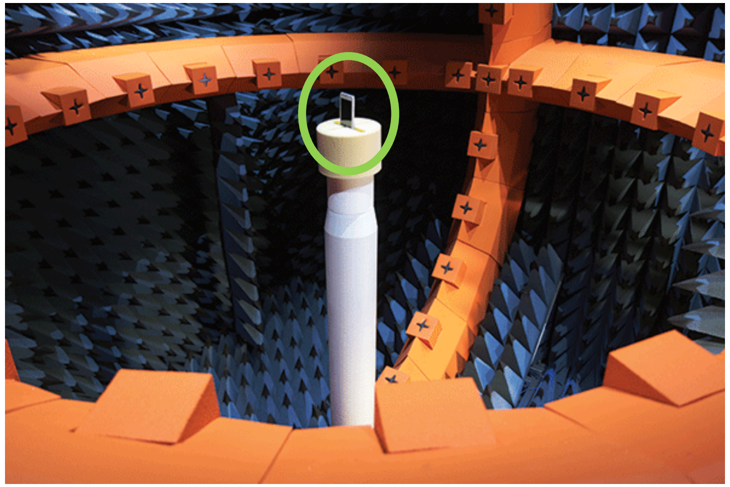
Chip-level and board-level test

- ICs in cell phones are 100% tested
- Errors increase with frequency
- Tour stop Wednesday with Dylan Williams and Nate Orloff

Over-the-air test (OTA) for IoT today

NIST

- Handset and base-station performance verified under radiated conditions
  - Total Radiated Power, Receiver Sensitivity
  - Isotropic quantities
  - *Every new model is tested over-the-air (OTA), thousands every year!*
- NIST has led development of efficient, rigorous reverberation-chamber tests for large-form-factor IoT devices
  - CTIA test plan released July 2018



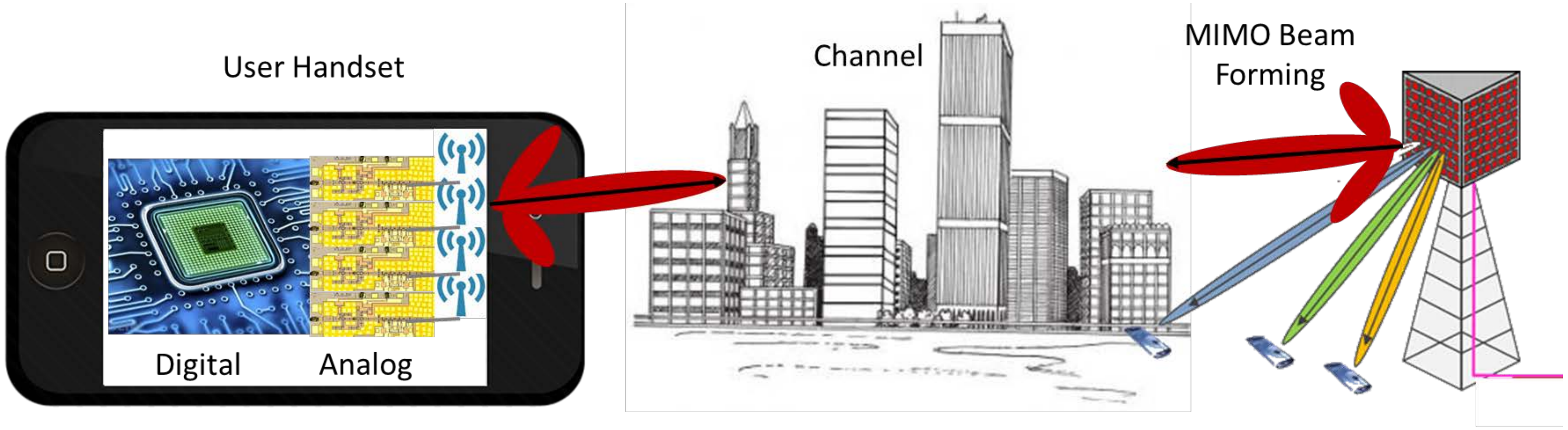
ctia™

Where we are going: mm-waves for IoT

NIST

All 3GPP tests that were conducted must now be OTA:

- Still no RF connectors
- Large phased arrays with narrow steerable beams
- Hardware errors scale with frequency



3GPP

ctia

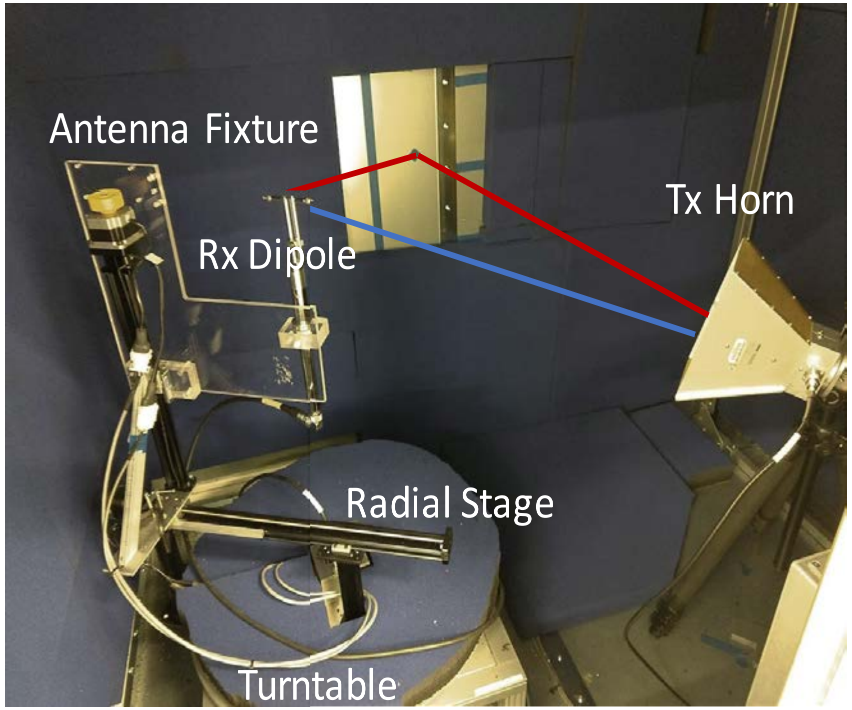
5G Millimeter-Wave
Channel Model Alliance

OTA testing of mmWave devices with integrated antennas is challenging in all phases: design, production, and system-level verification

Where we are going: Better metrology for mm-wave IoT

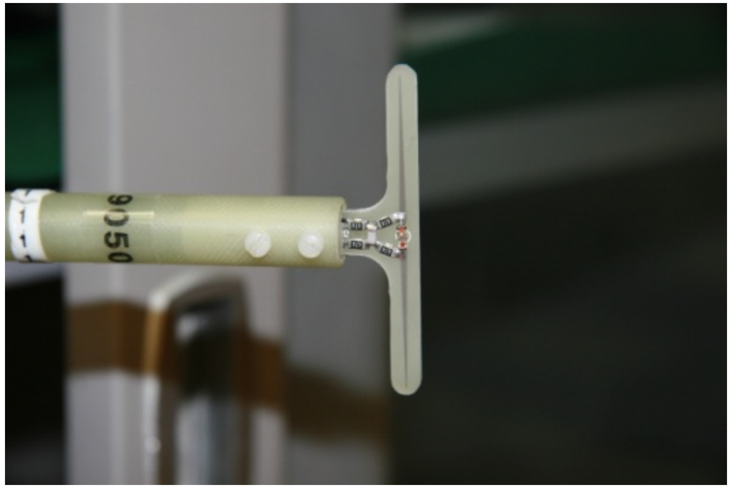
- Wireless device verification: Apply known field at OTA test plane
  - Traceably calibrated chamber
  - Precise angles-of-arrival (AoAs), timing, and power
- Tests for active antenna arrays that do not have RF connectors
  - Test at IF
  - Calibrated dynamic test environment
- Correlated uncertainty analysis for key metrics
  - Error vector magnitude
  - Channel models with uncertainties
- Requires modern network analysis tools
- Non-invasive probes are key
- Recently received NIST seed funding jointly with Engineering Lab

- Tour stop Wednesday with Kate Remley



NIST-characterized OTA testbed for IoT devices

E-field measurement today



Probe limitations:

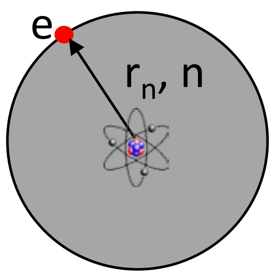
- Field-levels: about 100 mV/m
- Requires calibration
- Perturbs the field (due to metal)
- Relatively large in size
- Narrow frequency range

To calibrate the probe, we need a “known” field.

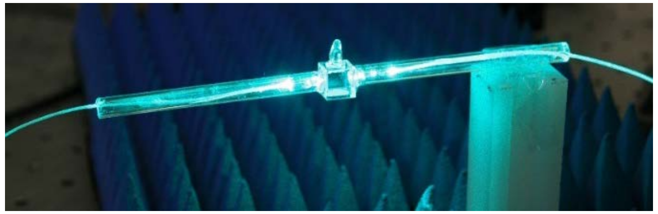
Probe manufacturers at the 2015 EMC Europe conference stated that their probes only allow them to measure fields ≥10 % uncertainty.

Where we are going: Rydberg-based field and power measurements

- Rydberg atoms are atoms with one electron excited to a very high principal quantum number *n, i.e.,* r_n *is very large*.
- Rydberg states have very large dipole moments: Meaning they are very sensitive to RF E-fields (making for good RF E-field sensors).
- Energy levels of the atom are changed the Autler-Townes effect or AC Stark shifts effect.
- Changes in energy levels are detected by laser spectroscopy
- **Quantum traceable and non-invasive (for E-field sensors)**
- **Expected uncertainty ~0.1%: Two orders of magnitude better than state-of-the-art**



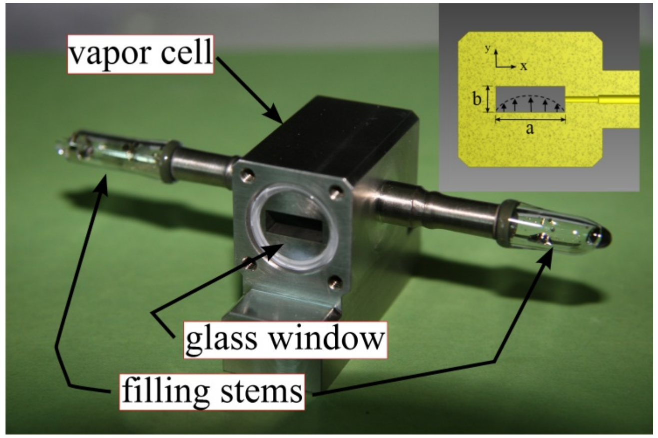
- Electric field measurement implemented in a compact probe



- Microwave power in a waveguide

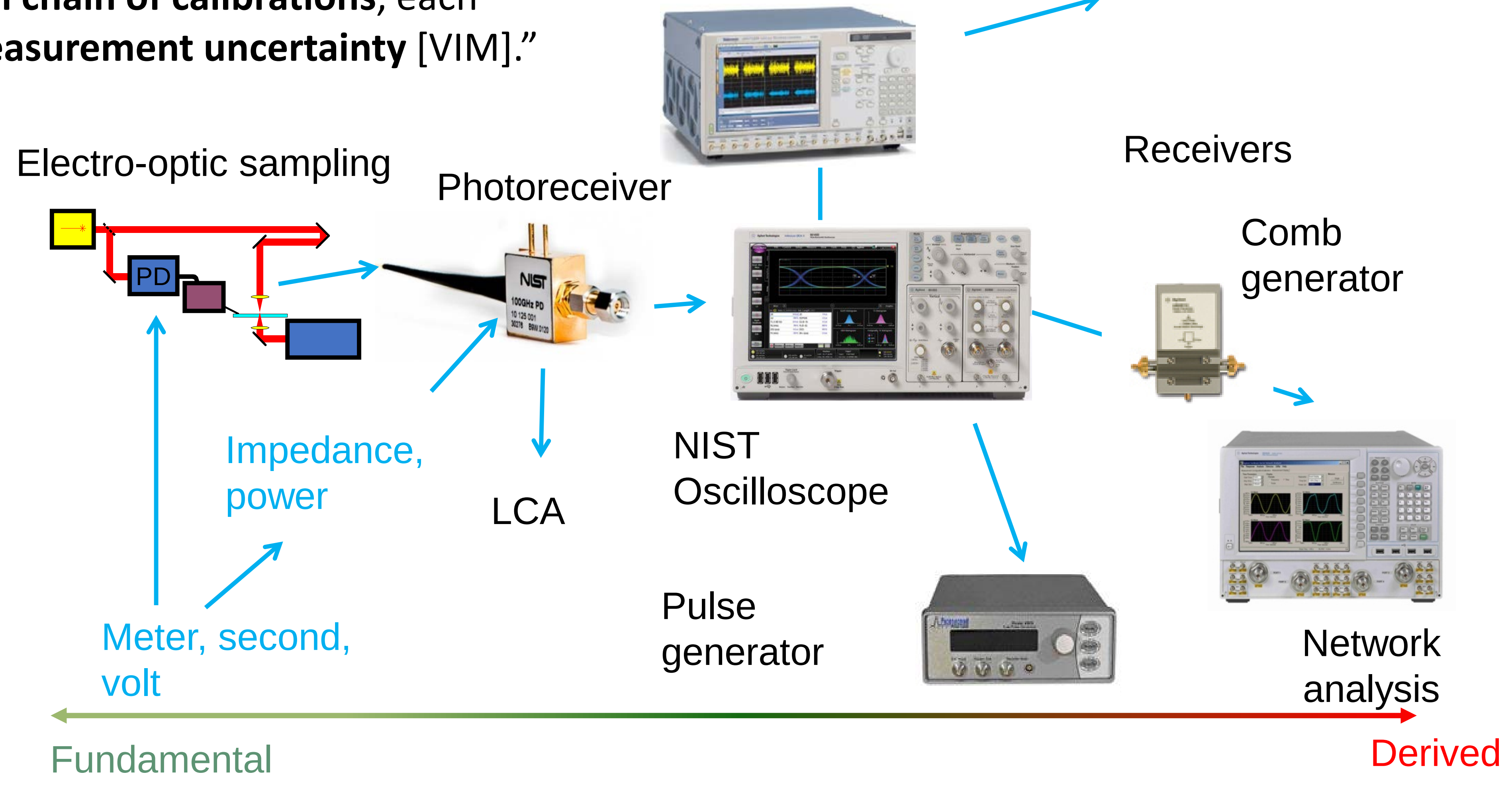
- Useful for…
  - Stand alone probe
  - Calibration of existing sensors and test facilities

- Tour stop Wednesday with Chris Holloway

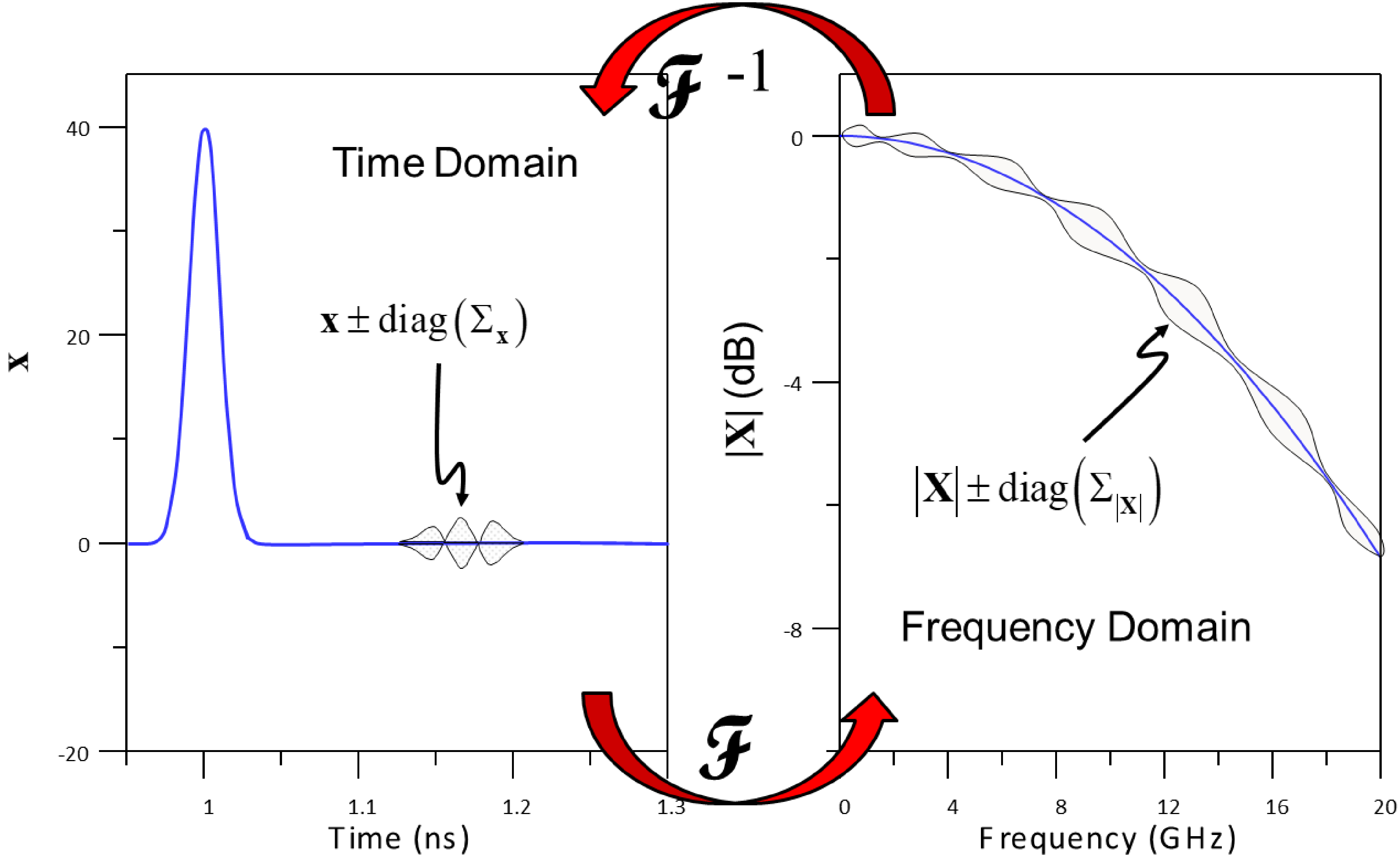


Tying them all together: The NIST Microwave Uncertainty Framework

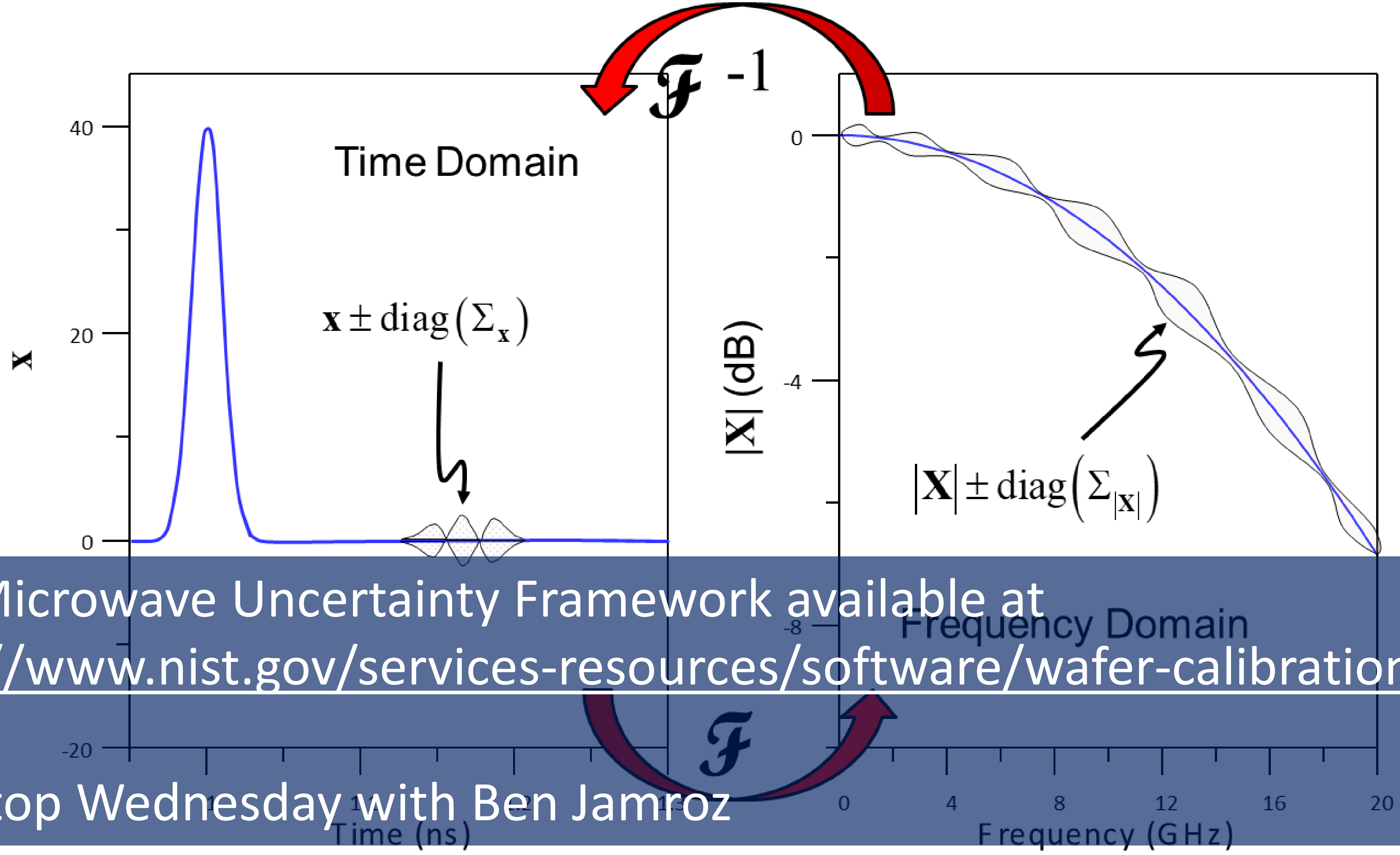
- Traceability: "...property of a measurement result whereby the result can be related to a reference through a documented **unbroken chain of calibrations**, each contributing to the **measurement uncertainty** [VIM]."



Uncertainty correlated across times and frequencies



Uncertainty correlated across times and frequencies



NIST Microwave Uncertainty Framework available at
https://www.nist.gov/services-resources/software/wafer-calibration-software

Tour stop Wednesday with Ben Jamroz

CTL is small: Leverage key expertise and stakeholders

- NIST partners
  - Engineering Laboratory: Industrial IoT
  - Information Technology Laboratory: Mathematical and statistical analysis, machine learning, optical networks, quantum optics
  - Physical Measurement Laboratory: Precision optical sources, quantum optics, traceability to the meter, second, volt, ohm
- External interactions to inform and disseminate our work
  - IEEE, 3GPP, ANSI, 5G Channel Model Alliance, DoD Primary Standards Labs, NSF, CTIA, BIPM, FCC
  - Test equipment manufacturers
  - Wireless device manufacturers
  - Test labs
  - Academia
  - Participation in numerous conferences
  - Publish and lead numerous journals

Summary

NIST is providing traceable measurements for RF communications by

- Improving upon traditional measurement services
- Developing new measurement techniques and services for dynamic, connector-less, high-frequency systems
- Developing and providing an uncertainty analysis framework that includes correlations and is extensible to a complicated calibration chain