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Millimeter-Wave Wireless: A Cross-Disciplinary View of Research and Technology Development

mmNets 2017

1st ACM Workhsop on Millimeter-Wave Networks and Sensing Systems

Snowbird, UT

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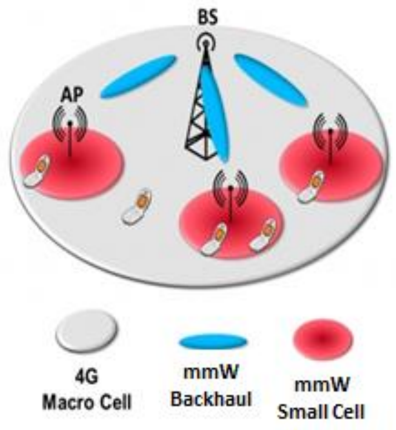
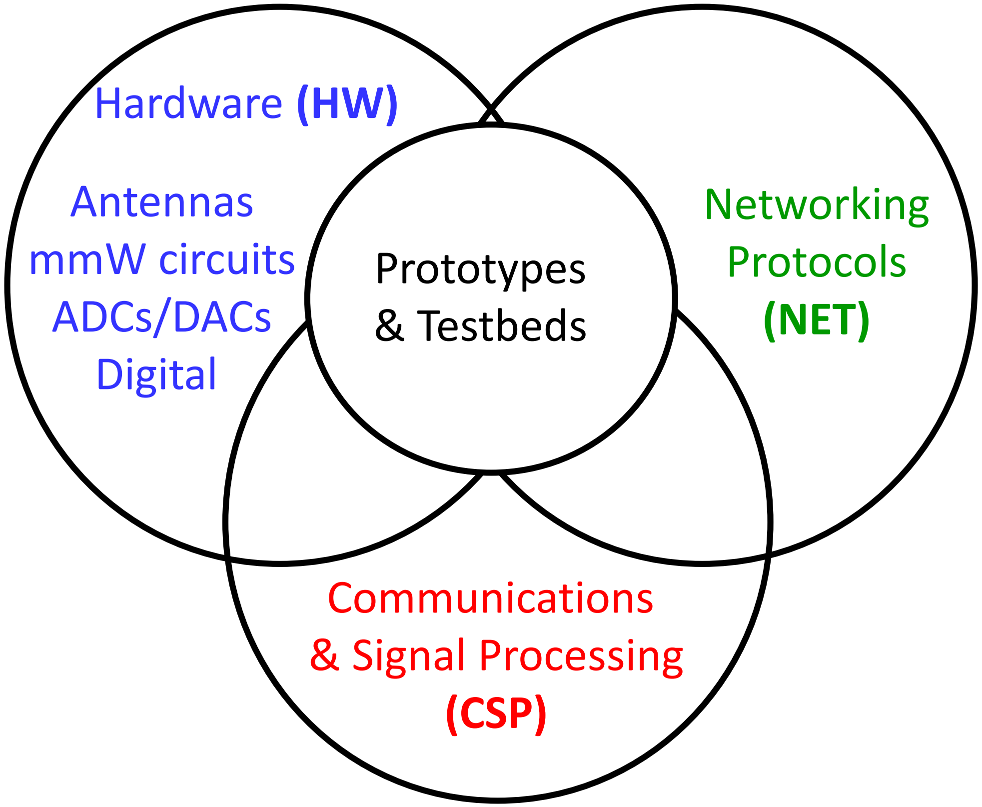
Exciting Times for mmW Research

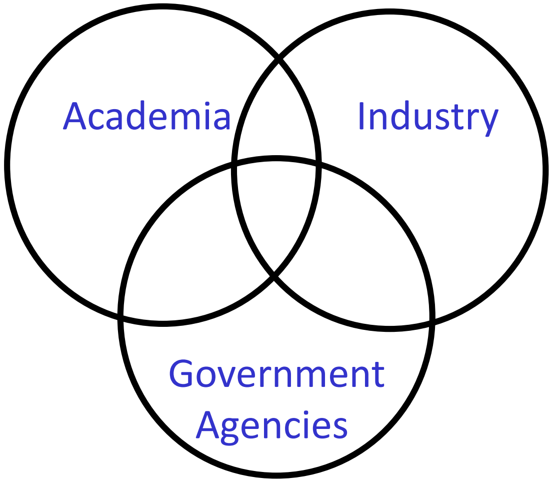
- A key component of 5G
  - Multi-Gigabits/s speeds
  - millisecond latency
- Key Gigabit use cases
  - Wireless backhaul
  - Wireless fiber-to-home (last mile)
  - Small cell access
  - Autonomous Vehicles
- New FCC mmW allocations
  - Licensed (3.85 GHz): 28, 37, 39 GHz
  - Unlicensed (7 GHZ): 64-71 GHz
- New NSF-led Advanced Wireless Initiative
  - mmW Research Coordination Network
  - 3rd Workshop Tucson, Jan 2018.



Cross-disciplinary view – informed by prototype development + RCN

mmW RCN: Rationale and Goals





Goal: Facilitate cross-fertilization of ideas, and to guide and accelerate the development of mmW wireless technology.

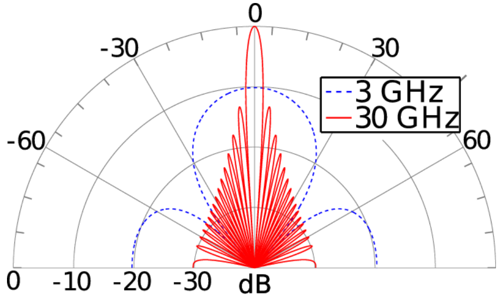
Main takeaway from the first two RCN workshops:

The key research challenges are at the interfaces: HW-CSP, CSP-NET

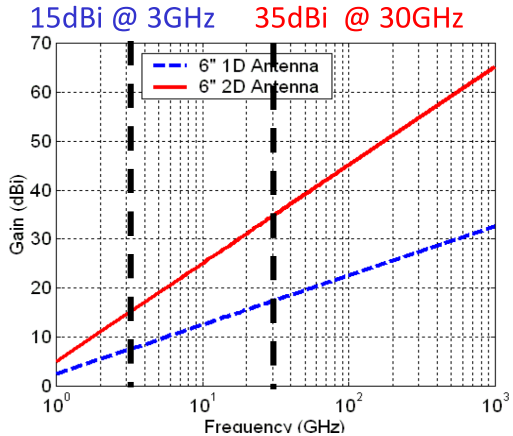
Two Key Advantages of mmW

Large bandwidth & narrow beams

6" x 6" access point (AP) antenna array: 9 elements @3GHz vs 6000 elements @80GHz

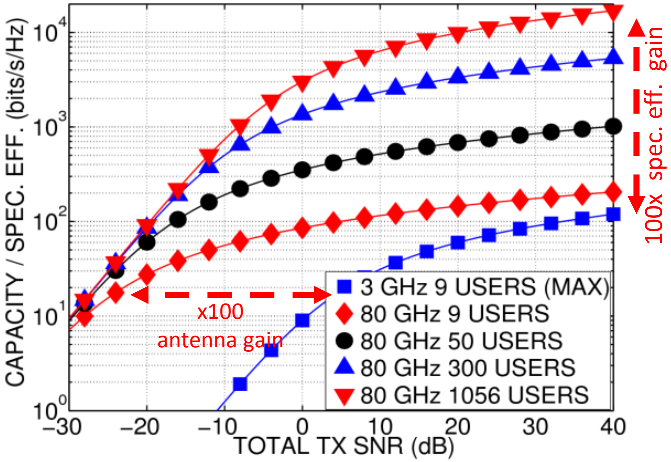


35 deg @ 3 GHz
4 deg @ 30 GHz



Potential of beamspace multiplexing

Power & Spec. Eff. Gains over 4G



> 100X gains in power and & spectral efficiency

Key Operational Functionality: Multibeam steering & data multiplexing

Key Challenge: Hardware Complexity & Computational Complexity (# T/R chains)

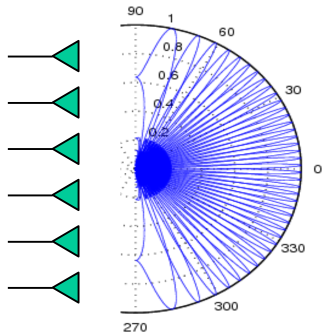
Conceptual and Analytical Framework: Beamspace MIMO

Beamspace Multiplexing

Multiplexing data into multiple highly-directional (high-gain) beams

Antenna space multiplexing — **Discrete Fourier Transform (DFT)** ⟷ — **Beamspace multiplexing**

n-element array ($\frac{\lambda}{2}$ spacing)

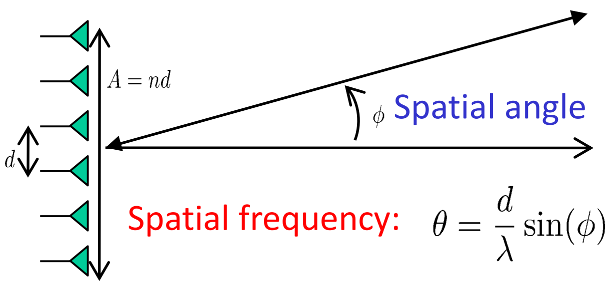


n dimensional signal space

n orthogonal beams

↕

n spatial channels

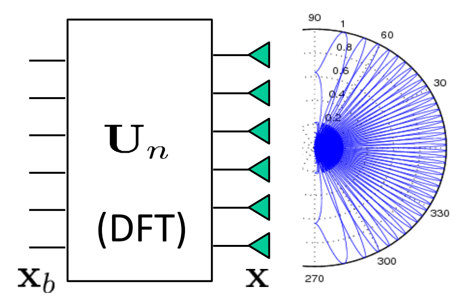


Spatial frequency: $\theta = \frac{d}{\lambda}\sin(\phi)$

$$-\frac{\pi}{2} \leq \phi \leq \frac{\pi}{2} \overset{d=\frac{\lambda}{2}}{\Longleftrightarrow} -\frac{1}{2} \leq \theta \leq \frac{1}{2}$$

steering/response vector

$$\mathbf{a}_n(\theta) = \begin{bmatrix} 1 \\ e^{-j2\pi\theta} \\ \vdots \\ e^{-j2\pi\theta(n-1)} \end{bmatrix}$$



DFT matrix:
Beamspace modulation

$$\mathbf{U}_n = \frac{1}{\sqrt{n}}\left[\mathbf{a}_n(\theta_0), \mathbf{a}_n(\theta_1), \cdots, \mathbf{a}_n(\theta_{n-1})\right]$$

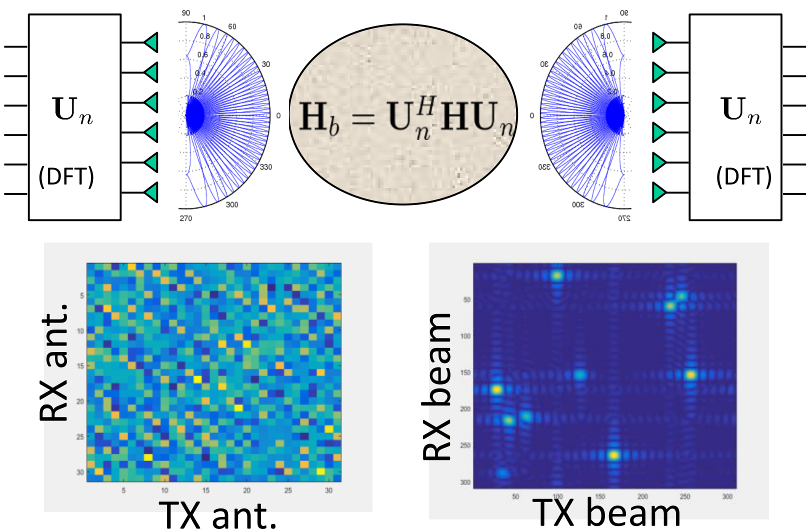
(AS TSP ’02; AS & NB Allerton ’10; JB, NB & AS TAPS ‘13) comm. modes in optics (Gabor ‘61, Miller ‘00, Friberg ‘07)

Beamspace Channel Sparsity

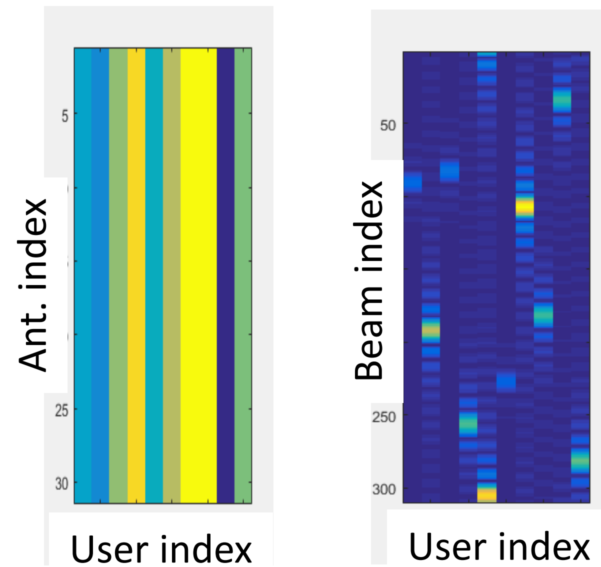
mmW propagation X-tics

- Directional, quasi-optical
- Predominantly line-of-sight
- Single-bounce multipath
- Beamspace sparsity

Point-to-multipoint MIMO link



Point-to-multipoint multiuser MIMO link



high *(n)*-dim. spatial signal space

low *(p)*-dim. comm. subspace

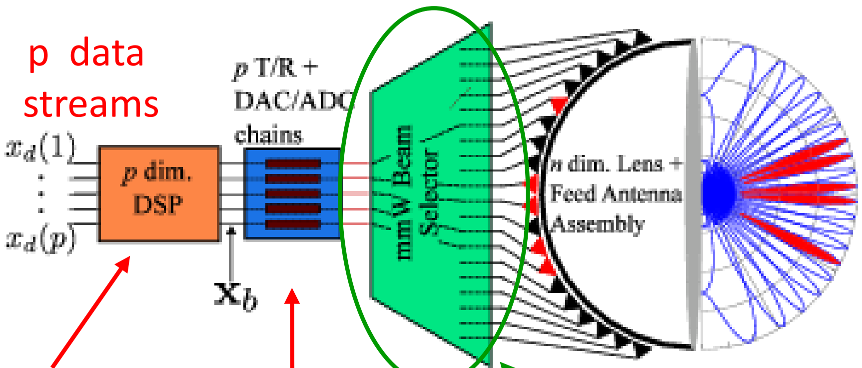
How to access the *p* active beams with the lowest - *O(p)* - transceiver complexity?

(AS & NB Allerton '10; Pi & Khan '11; Rappaport et. al, '13)

Hybrid Analog-Digital Beamforming (HW-CSP)

Lens Array Architecture

p data streams



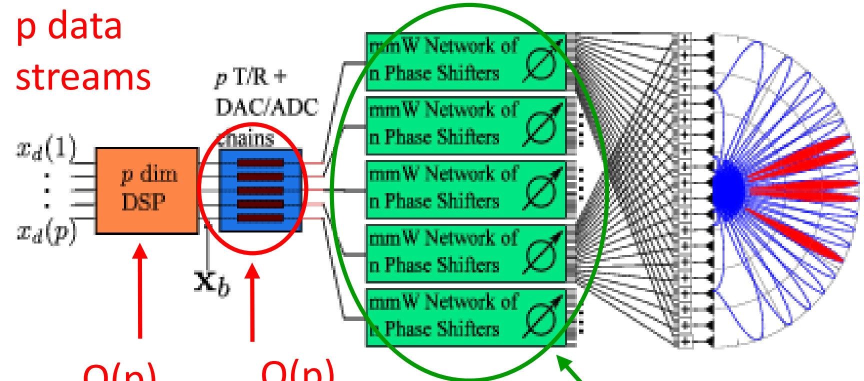
Comp. Complexity: n → p dim. matrix ops

Hardware Complexity: n → p RF chains

p → n Beam selector (switching) network

Phased Array Architecture

p data streams

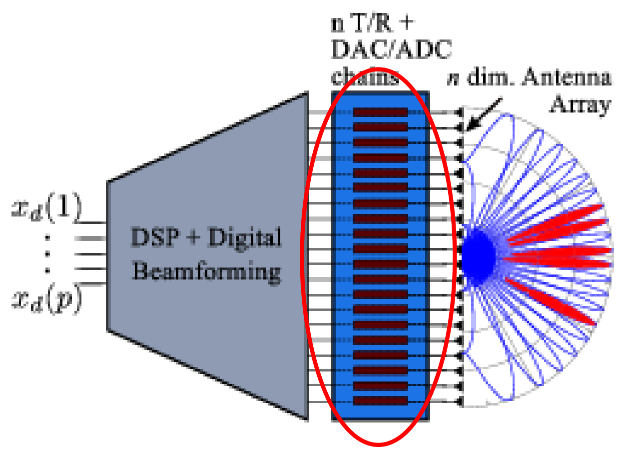


O(p) comp. complexity

O(p) T/R chains

Phase Shifter **(np)** + Combiner Network

Digital Beamforming Architecture



n T/R chains: prohibitive hardware + comp. complexity

28 GHz Multi-beam CAP-MIMO Testbed (CSP-HW-NET)

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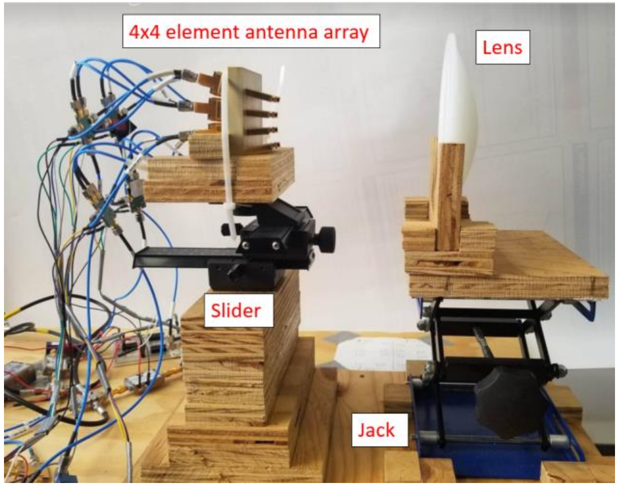
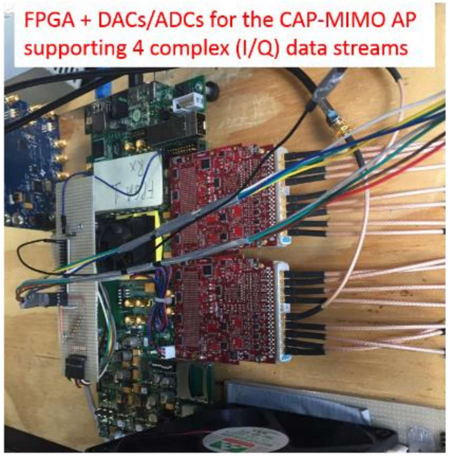
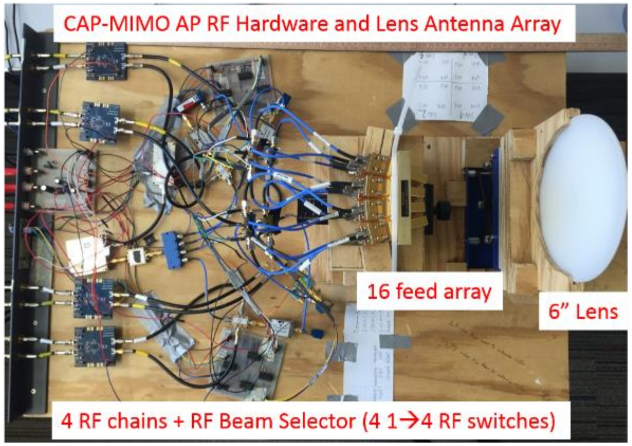
6" Lens with 16-feed Array

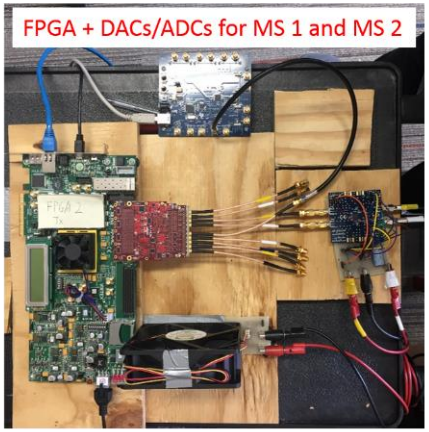


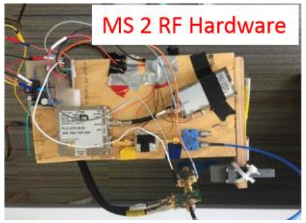
CAP-MIMO Access Point (AP)





Two Mobile Stations (MSs)





Features

- **Unmatched 4-beam steering & data mux.**
- RF BW: 1 GHz, Symbol rate: >370 MS/s
- AP – 4 MS bi-directional P2MP link
- FPGA-based backend DSP

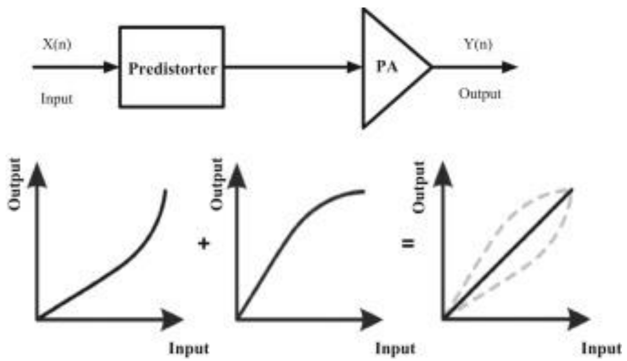
Use cases

- Real-time testing of PHY-MAC protocols
- Hi-res multi-beam channel meas.
- Scaled-up testbed network

(JB, JH, AS, 2016 Globecom wksp, 5G Emerg. Tech.)

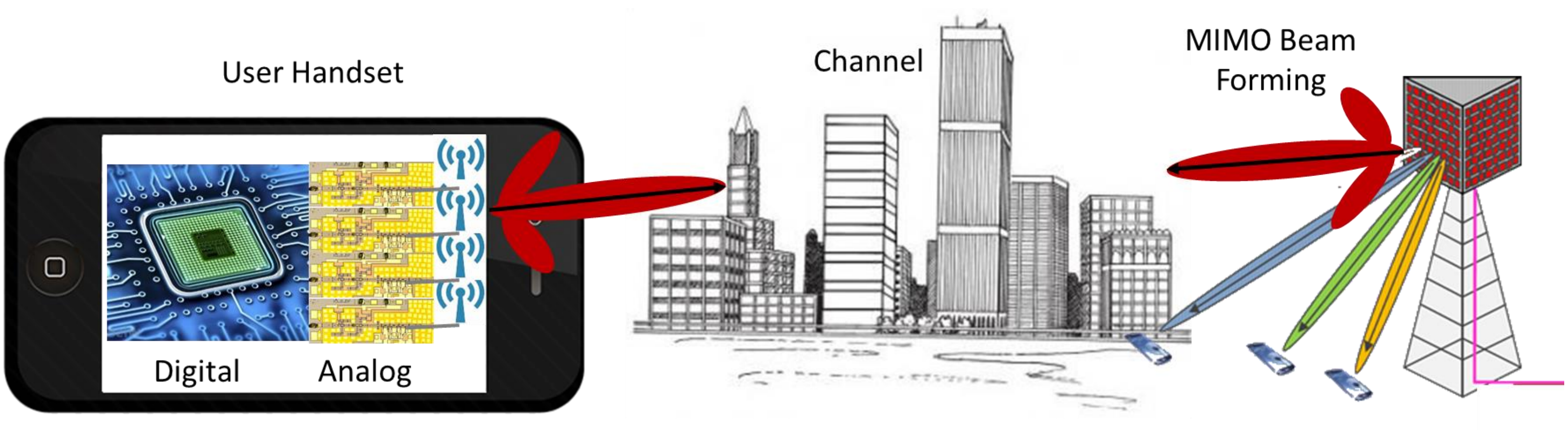
CSP-HW Interface Challenges

- **Energy-performance-complexity tradeoffs**
- Analog vs Digital Signal Processing
  - Hybrid beamforming
  - Hybrid interference suppression? (spatial nulling)
  - Hybrid temporal signaling/filtering? (OFDM)



- PA efficiency – digital predistortion
- Non-ideal device characteristics over large bandwidth:
  - Non-flat frequency response of components
  - I/Q mismatch
  - Phase noise
- Need for new models - signal processing to address the non-idealities

mmWave Testing & Measurement (HW-CSP)



mmWave Transistor and NL-Device Measurements

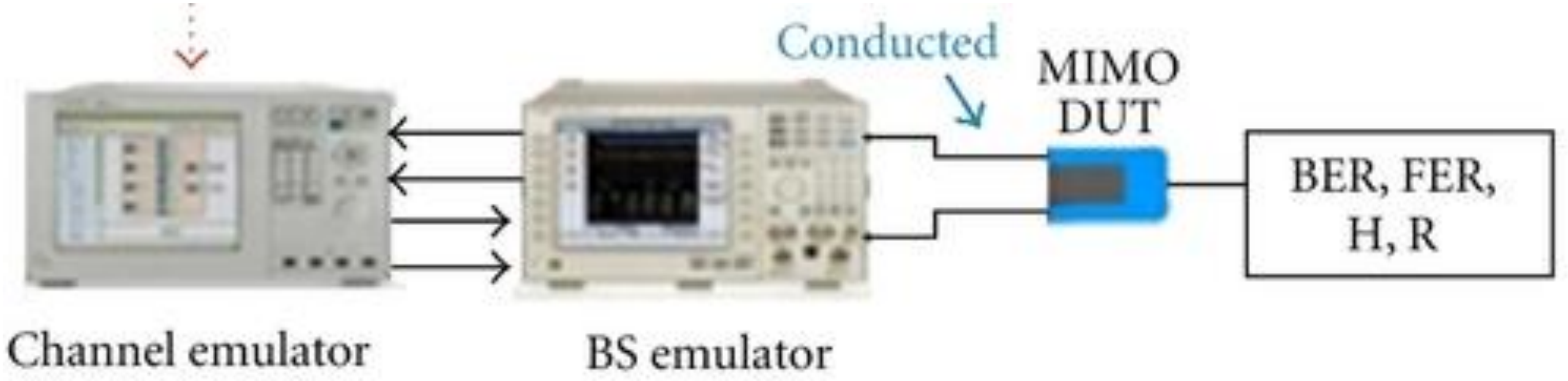
mmWave Signal Characterization

Channel Measurement and Modeling

Massive MIMO and Over-the-Air Test

Kate Remley, NIST

Existing RF Hardware Testing Paradigm: Channel Emulators + Conductive measurements

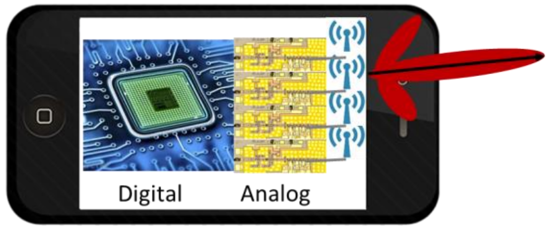


mmW technology: conductive measurements not possible

- Integrated modules
- Antenna arrays

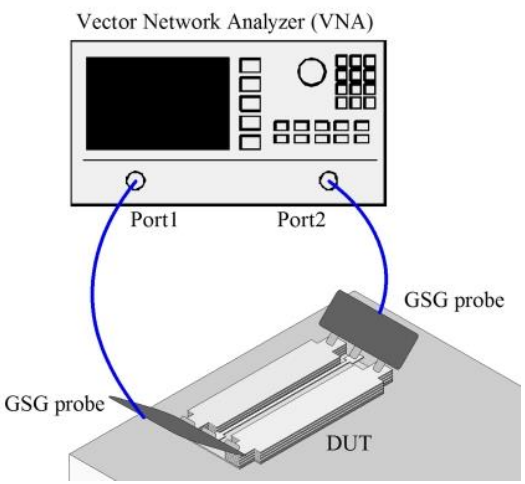
Figure credit: MIMO Over-The-Air Research, Development and Testing, M. Rumney et. al., *International Journal on Antennas and Propagation* 2012.

The Measurement Elephant In the Room



Courtesy:
Kate Remley
NIST

On wafer meas.



Intech (T. Hirano, K. Okada, J. Hirokawa and M. Ando)

On-Wafer to OTA – no connectors

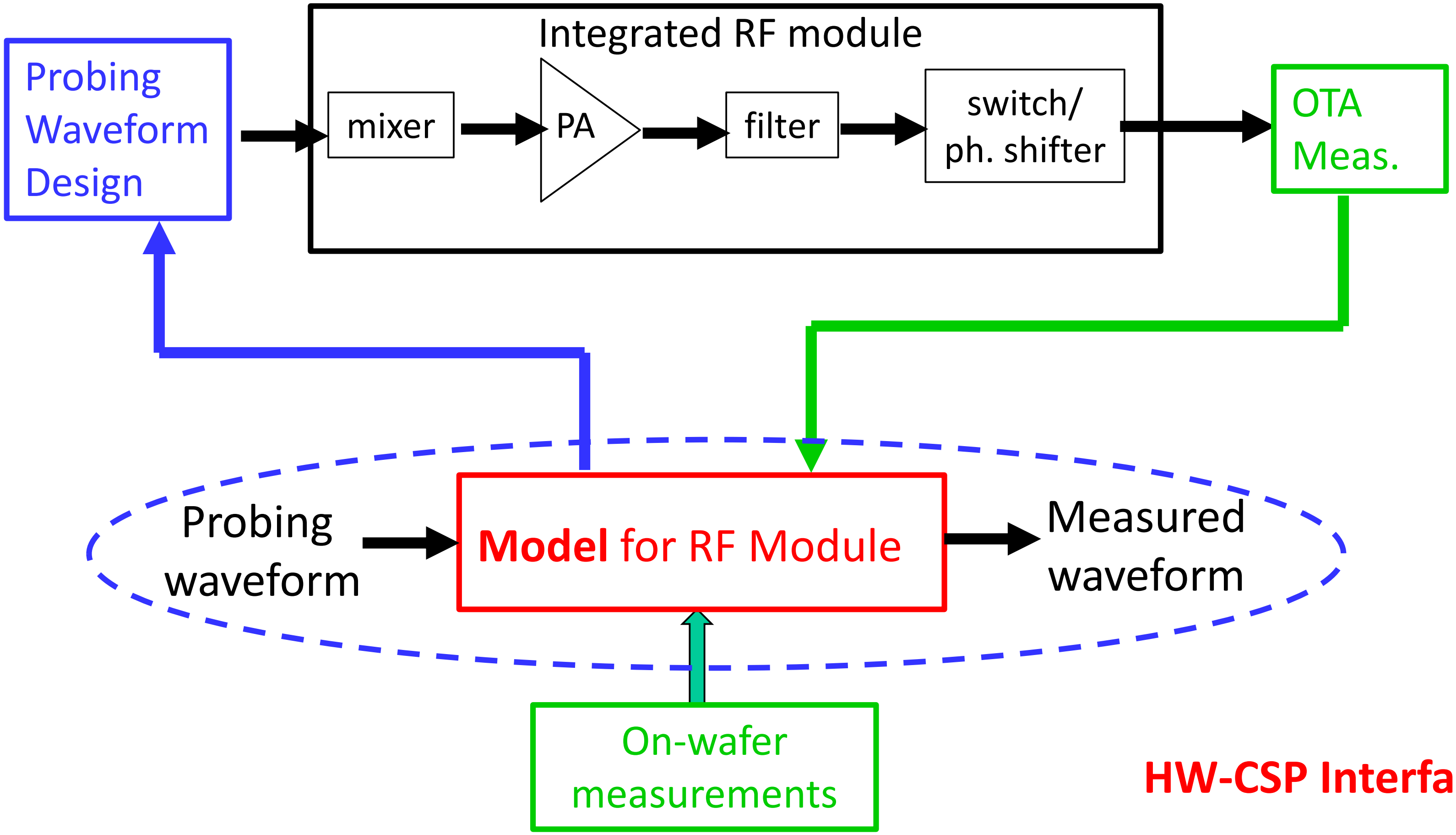
- Efficiency
- Distortion
- Troubleshooting stages

Over-the-air testing

Cisco

How to merge on-wafer and OTA tests to verify performance?

Potential New mmW Testing Paradigm

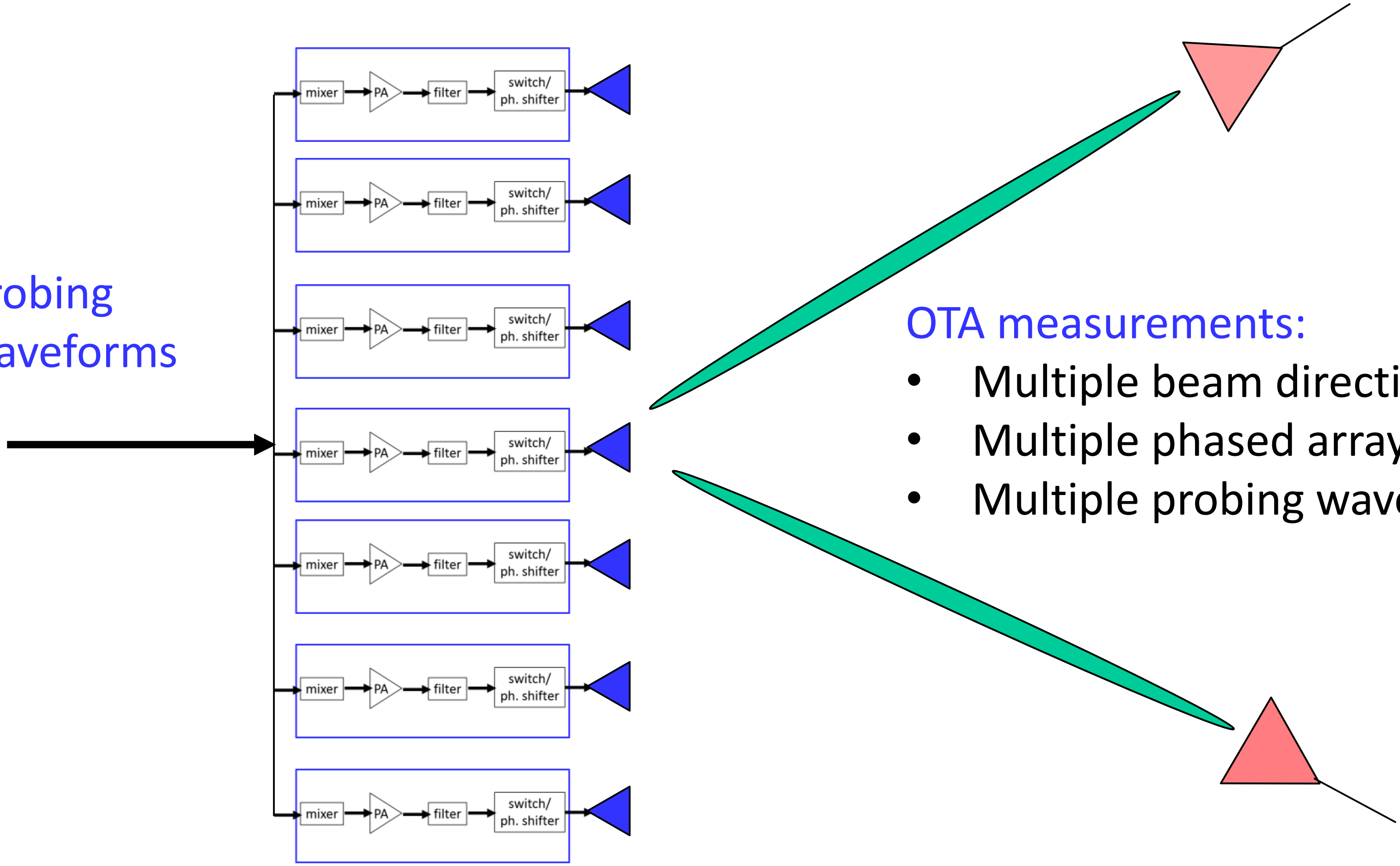


HW-CSP Interface

- **RF model:** what kind of on-wafer measurements?
- **OTA testing**: probing waveforms and measurements?

Ex.: OTA Testing of Phased Arrays

probing
waveforms



phase shifter configurations
(beamforming codebook)

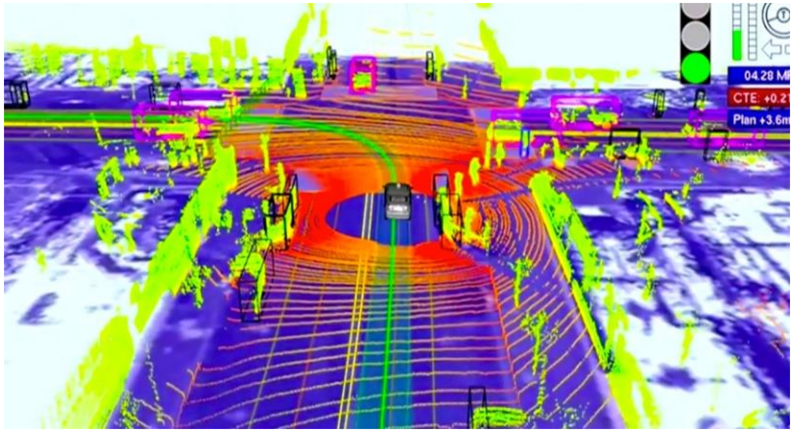
OTA measurements:

- Multiple beam directions
- Multiple phased array configs.
- Multiple probing waveforms

Channel Measurements to Modeling to Network Simulators & Emulators (HW-CSP-NET)

- **Accurate** performance prediction prior to network deployment very beneficial
- Current network models (e.g., ns-3) are limited
  - Multi-beam PHY capabilities
- Current mmW channel models limited:
  - sounders and measurements
  - models for beam dynamics & blocking
- Opportunity: Meas.+ comp.
  - Multi-beam sounders & measurements
  - Ray tracing (combined with LIDAR, e.g.)
  - → accurate channel models
- → Accurate Network Simulators & Emulators

Google's self-driving car use lidar to create 3D images

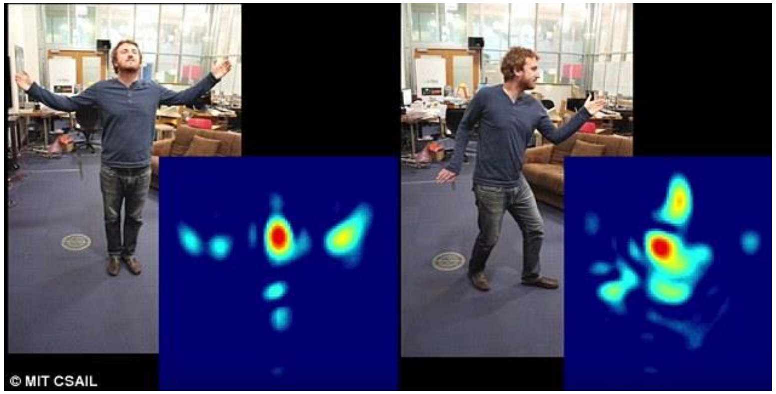


Sebastian Thrun & Chris Urmson/Google (IEEE Spectrum)

NYU, U. Padova, Bristol, NCSU, CRC, UW, NIST, SIRADEL ….

mmWave Sensing (HW-CSP-NET)

- RF signatures – unique to device
- Channel Signatures – environment + device location
- mmWave accentuates the signatures (large bandwidth + small wavelength)
- Untapped opportunity for:
  - Device localization and identification
  - Environmental sensing
  - Network optimization
  - Comm + radar principles
  - Leveraging machine learning tools



D. Katabi, X. Zhang, P. Mohapatra, H. Zheng, U. Madhow, others

Prototype & Testbeds: A Microcosm of Challenges and Opportunities (HW-CSP-NET)

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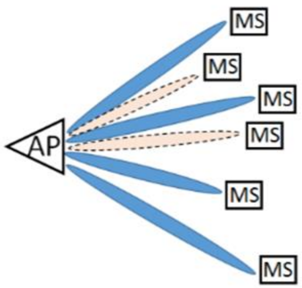
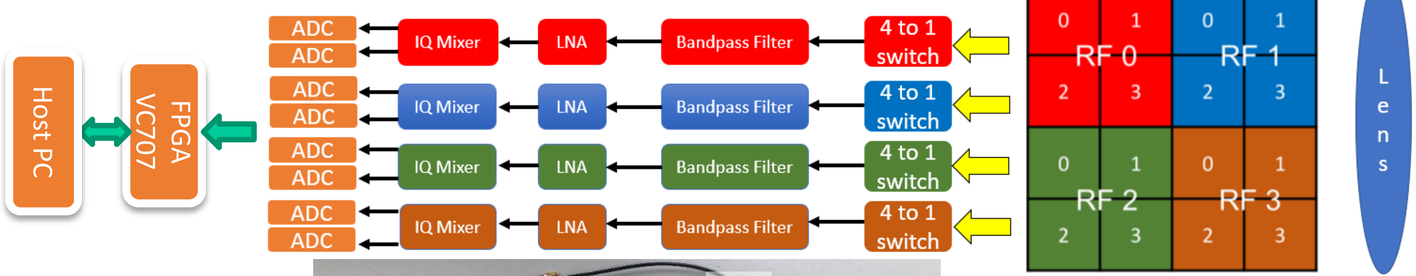
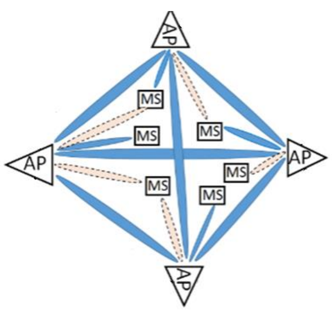
Multi-node
Multi-beam
CAP-MIMO
Testbed Network

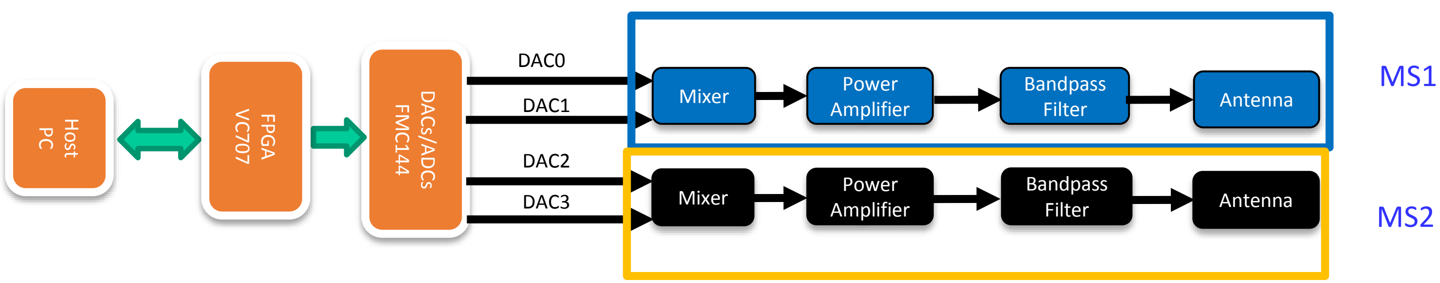


CAP-MIMO Access Point



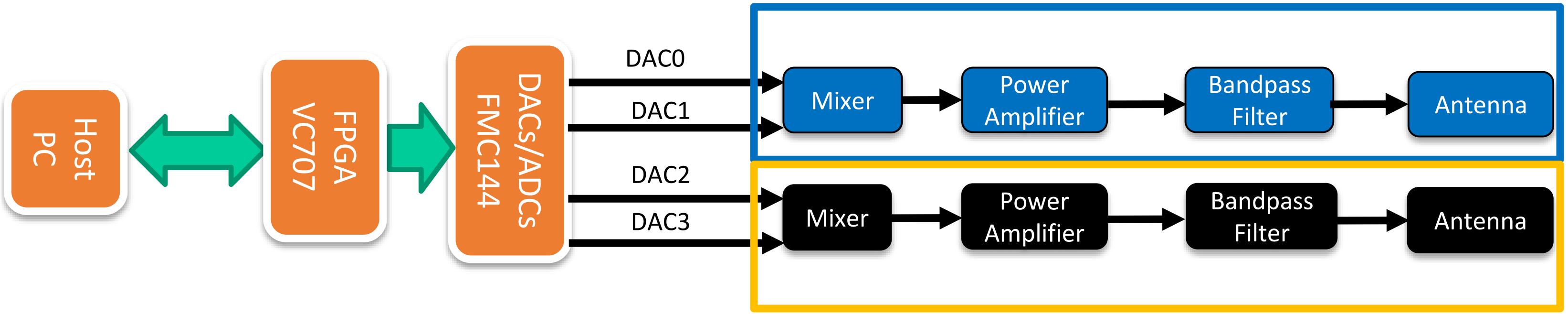


Single antenna Mobile Stations



- Real-time testing of PHY-MAC protocols
- Hi-res multi-beam channel measurements

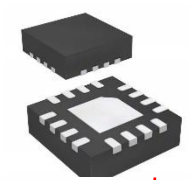
Reducing the Cost of Prototyping: A Timely Opportunity for Academic-Industrial Innovation



MS1

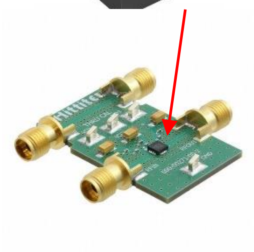
MS2

Surface mountable chip



$30

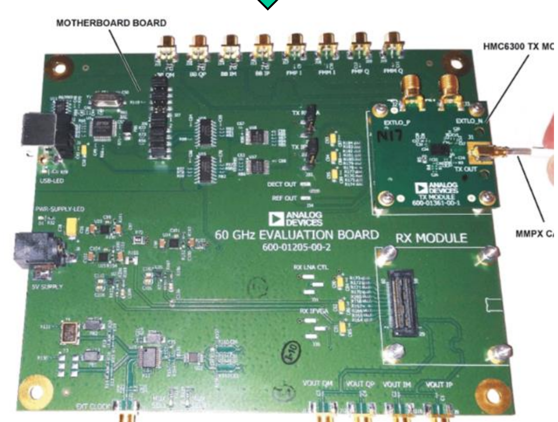
PCB packaging



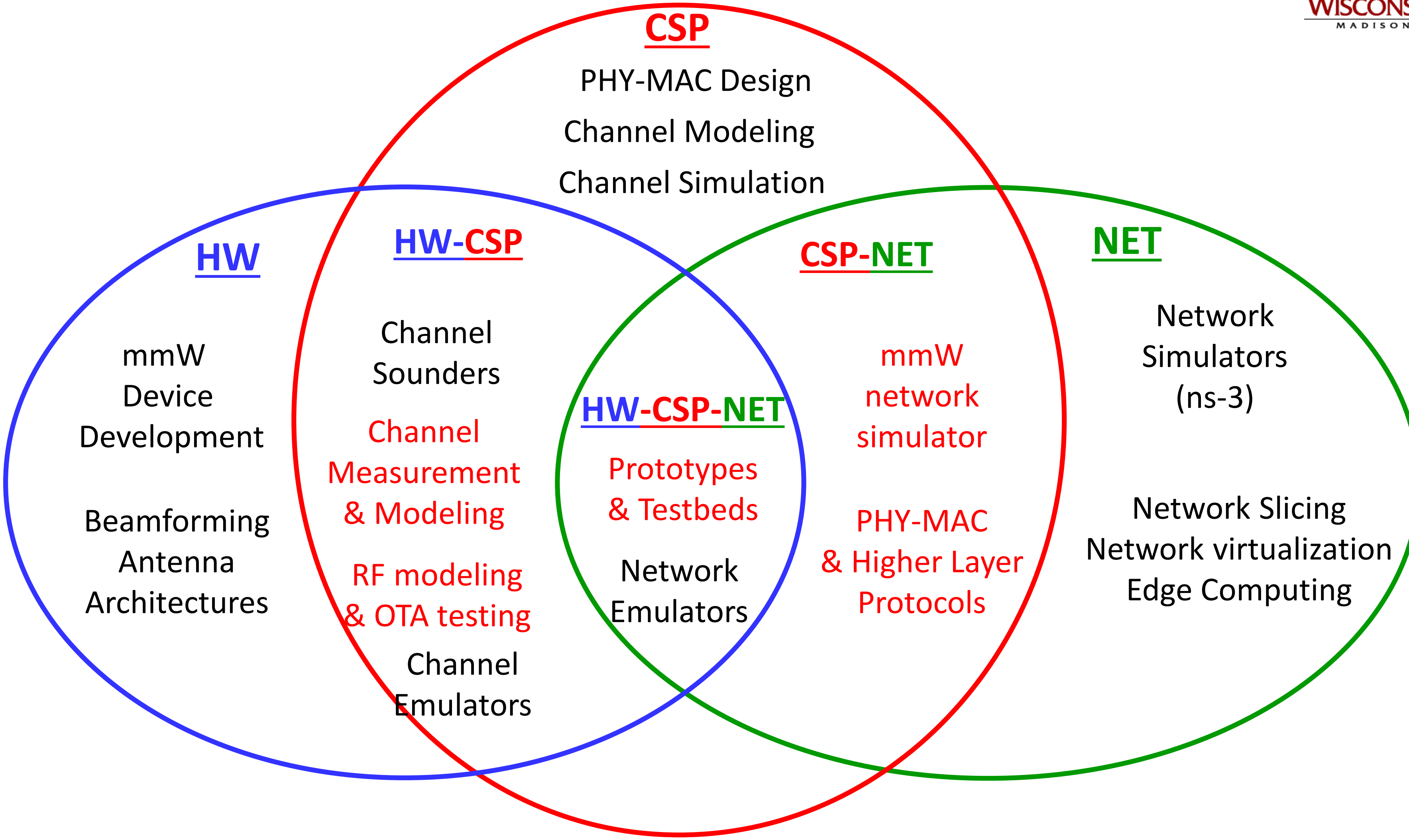
$300

Connectorized Module

$3000



Summary



Multi-beamforming, steering and data multiplexing

Some Relevant Publications

(http://dune.ece.wisc.edu)

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Thank You!

- A. Sayeed and J. Brady, *Beamspace MIMO Channel Modeling and Measurement: Methodology and Results at 28 GHz,* IEEE Globecom Workshop on Millimeter-Wave Channel Models, Dec. 2016.
- J. Brady, John Hogan, and A. Sayeed, *Multi-Beam MIMO Prototype for Real-Time Multiuser Communication at 28 GHz*, IEEE Globecom Workshop on Emerging Technologies for 5G, Dec. 2016.
- J. Hogan and A. Sayeed, Beam Selection for Performance-Complexity Optimization in High-Dimensional MIMO Systems, 2016 Conference on Information Sciences and Systems (CISS), March 2016.
- J. Brady and A. Sayeed, Wideband Communication with High-Dimensional Arrays: New Results and Transceiver Architectures, IEEE ICC, Workshop on 5G and Beyond, June 2015.
- J. Brady and A. Sayeed, Beamspace MU-MIMO for High Density Small Cell Access at Millimeter-Wave Frequencies, IEEE SPAWC, June 2014.
- J. Brady, N. Behdad, and A. Sayeed, Beamspace MIMO for Millimeter-Wave Communications: System Architecture, Modeling, Analysis, and Measurements, IEEE Trans. Antennas & Propagation, July 2013.
- A. Sayeed and J. Brady, Beamspace MIMO for High-Dimensional Multiuser Communication at Millimeter-Wave Frequencies, IEEE Globecom, Dec. 2013.
- A. Sayeed and N. Behdad, Continuous Aperture Phased MIMO: Basic Theory and Applications, Allerton Conference, Sep. 2010.
- A. Sayeed and T. Sivanadyan, Wireless Communication and Sensing in Multipath Environments Using Multiantenna Transceivers, Handbook on Array Processing and Sensor Networks, S. Haykin & K.J.R. Liu Eds, 2010.
- A. Sayeed, Deconstructing Multi-antenna Fading Channels, IEEE Trans. Signal Proc., Oct 2002.