Millimeter-Wave Beamforming Architectures, Channel Measurements and Modeling

ISART 2017
Mining Millimeter-Wave Capacity
Channel Measurements and Modeling Perspective Panel
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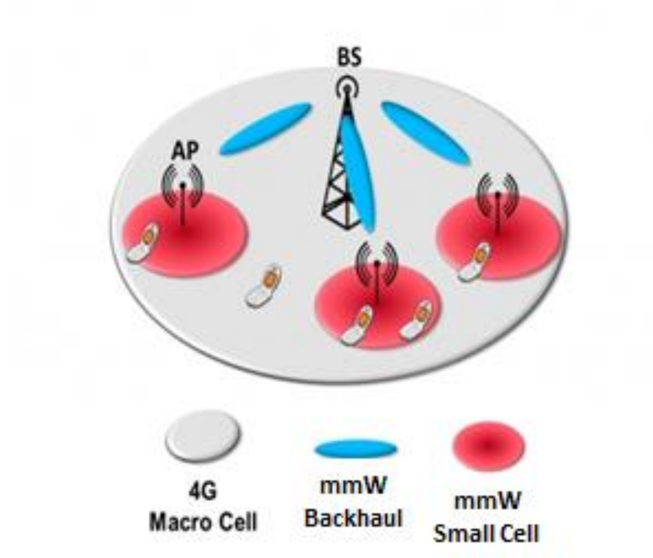
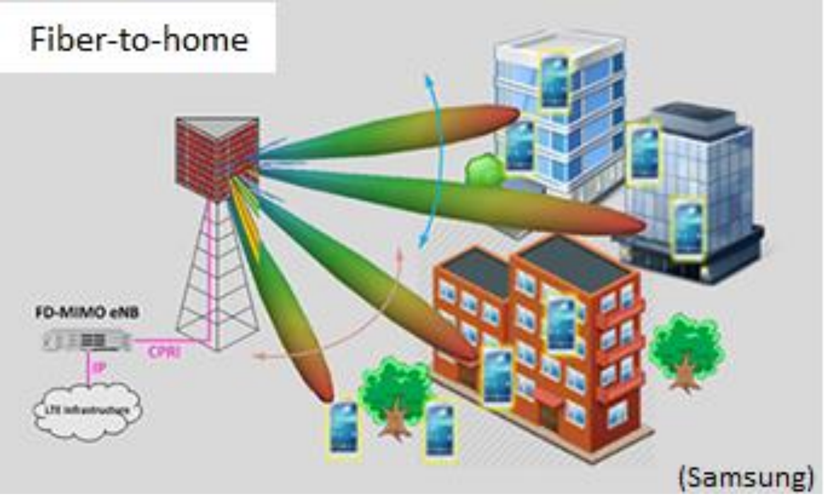
Exciting Times for mmW Research

- 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
- New FCC mmW allocations (July 2016)
  - Licensed (3.85 GHz): 28, 37, 39 GHz
  - Unlicensed (7 GHZ): 64-71 GHz
- New NSF Advanced Wireless Initiative
  - mmW Research Coordination Network
  - PAWR (Platforms for Advanced Wireless)





Questions for the Panel

- What is the state of mmW channel modeling and measurements? What needs to be done next?
- What the most cost effective way to enable multi-beamforming?
- Millimeter-wave was actively explored for fixed wireless in the late 1990s. What is different this time?

Channel Modeling and Measurements

- NIST 5G Channel Modeling Alliance
- Structure of channel models – in good shape
- Measurements – seriously lagging due to the current state of channel sounders
- Spatial dimension: current sounders limited to mechanically pointed antennas, or single-beam phased array of moderate sizes (8-64)
- Mobility: very limited

Critical Issues to Be Addressed

- Connection between measurements and models: How to incorporate measurements into models? What kind of measurements are needed?

- Sounder development: spatial resolutions and bandwidths comparable to actual systems

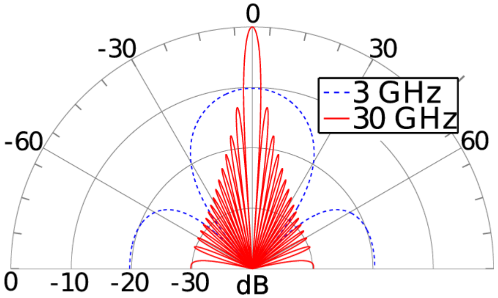
- What are models going to be used for? (comparison versus prediction)

Potential of mmW Wireless

Key Advantages of mmW: large bandwidth & narrow beams

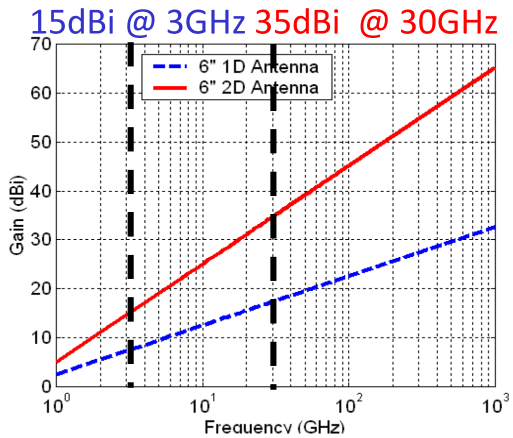
6" x 6" access point (AP) antenna array:

9 elements @3 GHz, 900 @ 30 GHz, 6000 @80 GHz vs.



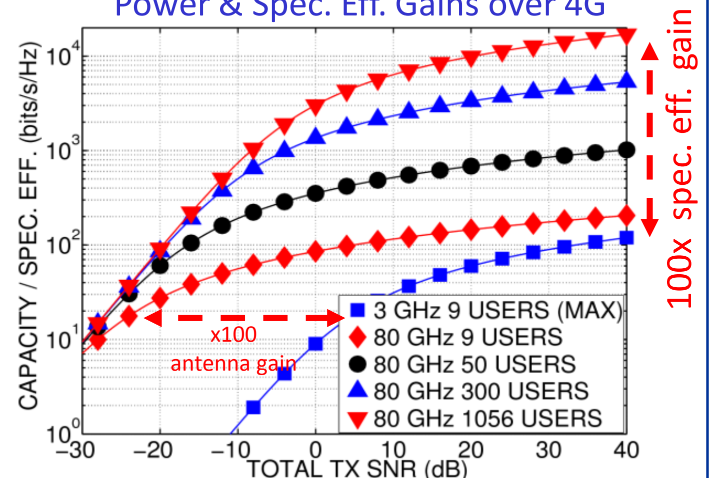
35 deg @ 3 GHz

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 & Computational Complexity (# T/R chains)

Conceptual and Analytical Framework: Beamspace MIMO

Beamspace Multiplexing

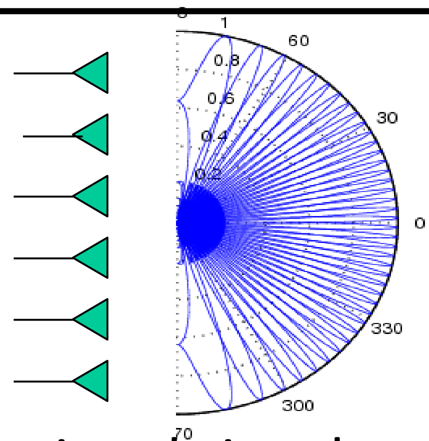
Multiplexing data into multiple beams

Discrete Fourier Transform (DFT)

Antenna space multiplexing

n-element array

($\frac{\lambda}{2}$ spacing)



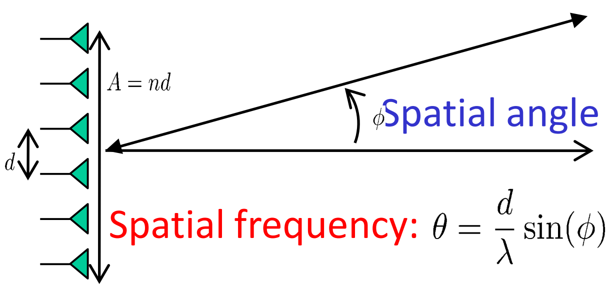
Beamspace multiplexing

n orthogonal beams

⇕

n spatial channels

n dimensional signal space

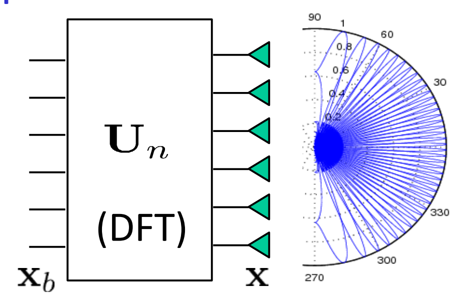


Spatial frequency: $\theta = \frac{d}{\lambda}\sin(\phi)$

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

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 at mmW

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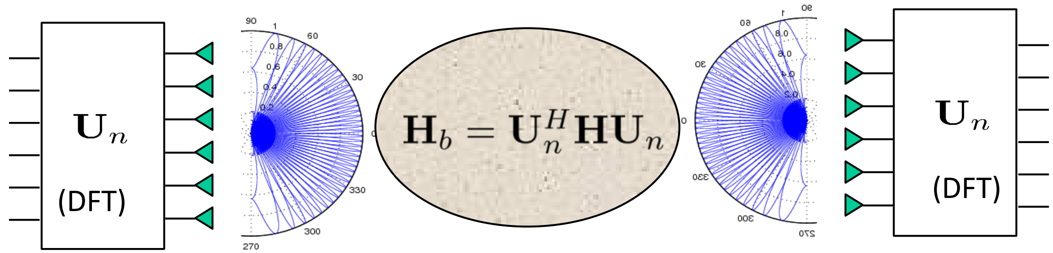
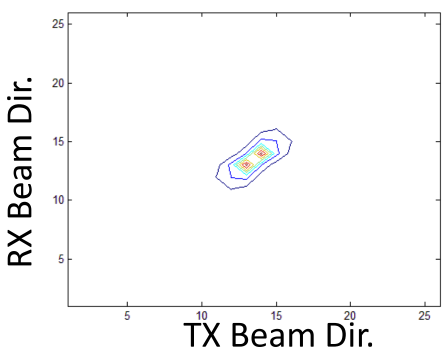
mmW propagation X-tics

- directional, quasi-optical
- mainly line-of-sight
- single-bounce multipath
- Beamspace sparsity

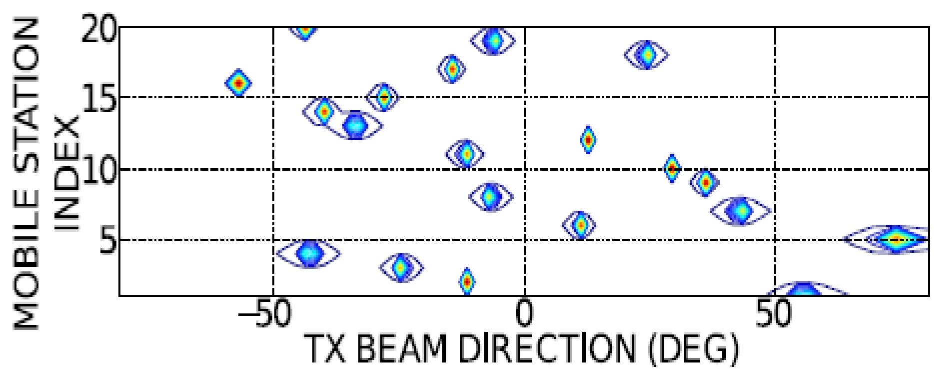


$$\mathbf{H}(f) = \sum_{n=1}^{N_p} \beta_n \mathbf{a}_n(\theta_{R,n}) \mathbf{a}_n^H(\theta_{T,n}) e^{-j2\pi\tau_n f}$$

LoS (P2P) Link



Multiuser (P2MP) link



Action: *p*-dim. subspace of the *n*-dim. spatial signal space; *p* << *n*

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

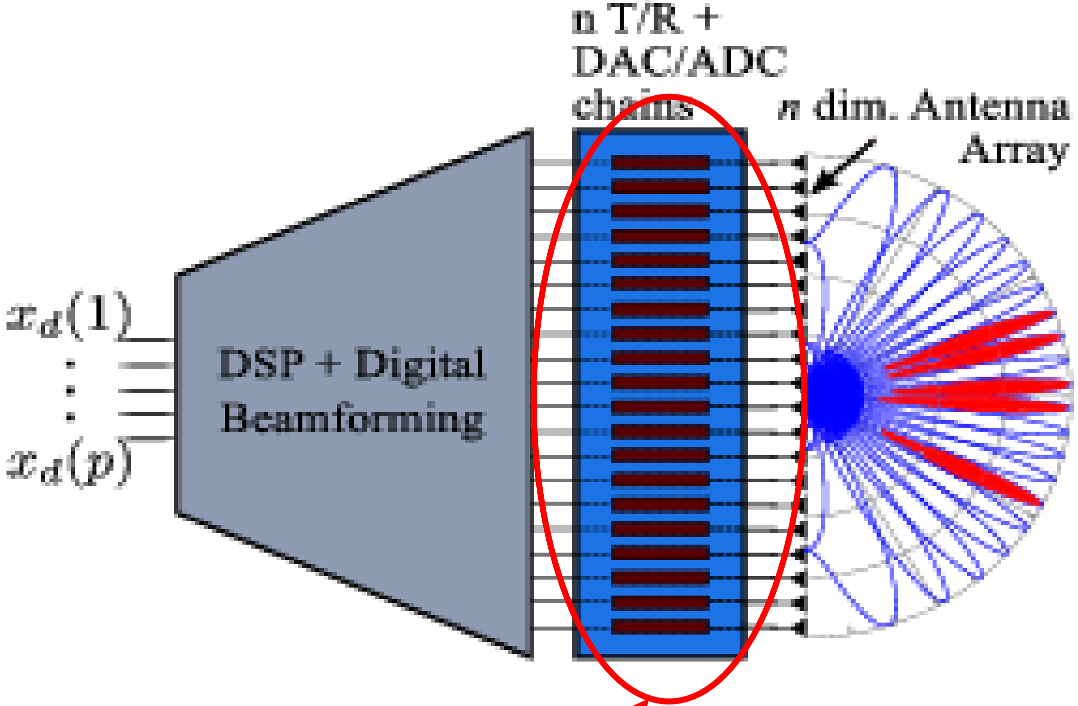
(AS & NB Allerton '10; Pi & Khan '11; Rappaport et. al, '13)

Conventional MIMO: Digital Beamforming

n: # of array elements (100's-1000's)

p: # spatial channels/data streams (10-100's)

p data streams



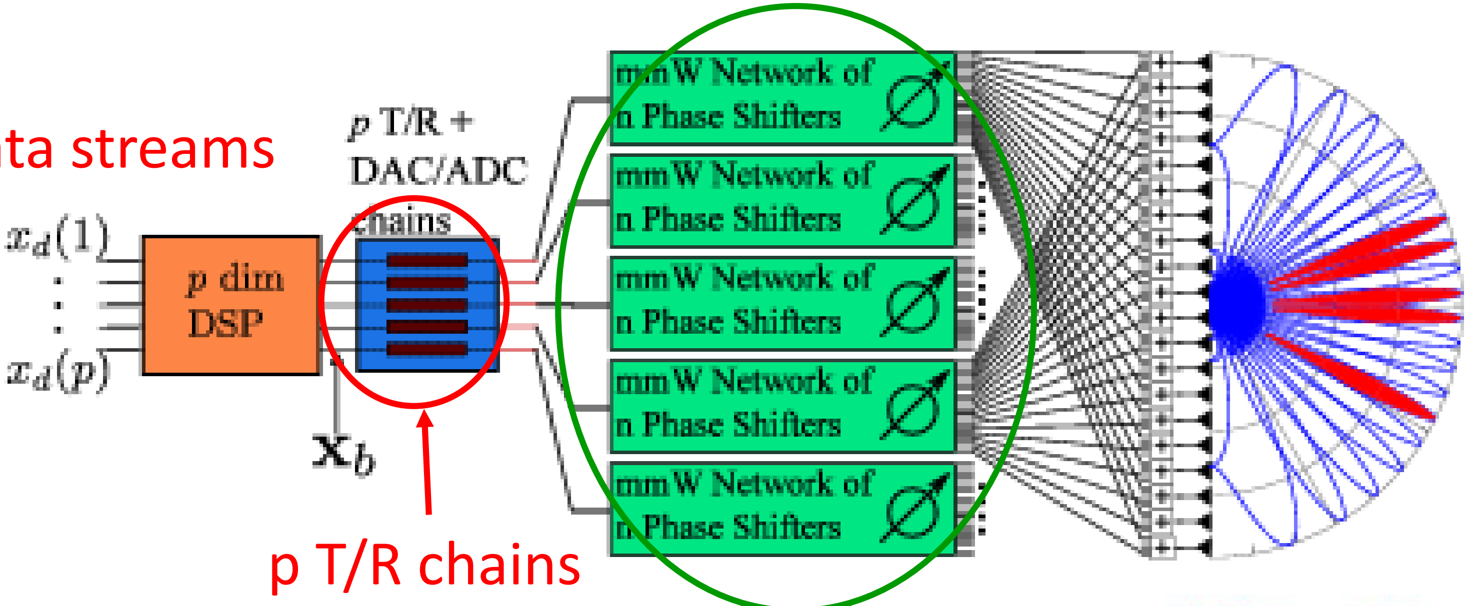
n T/R chains: prohibitive complexity

Hybrid MIMO: Phased Array Beamforming

n: # of array elements (100's-1000's)

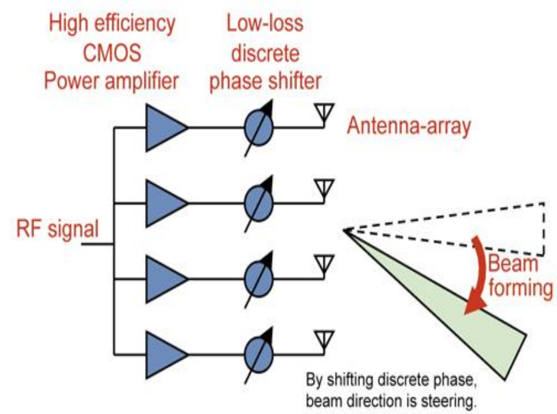
p: # spatial channels/data streams (10-100's)

p data streams



p T/R chains

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

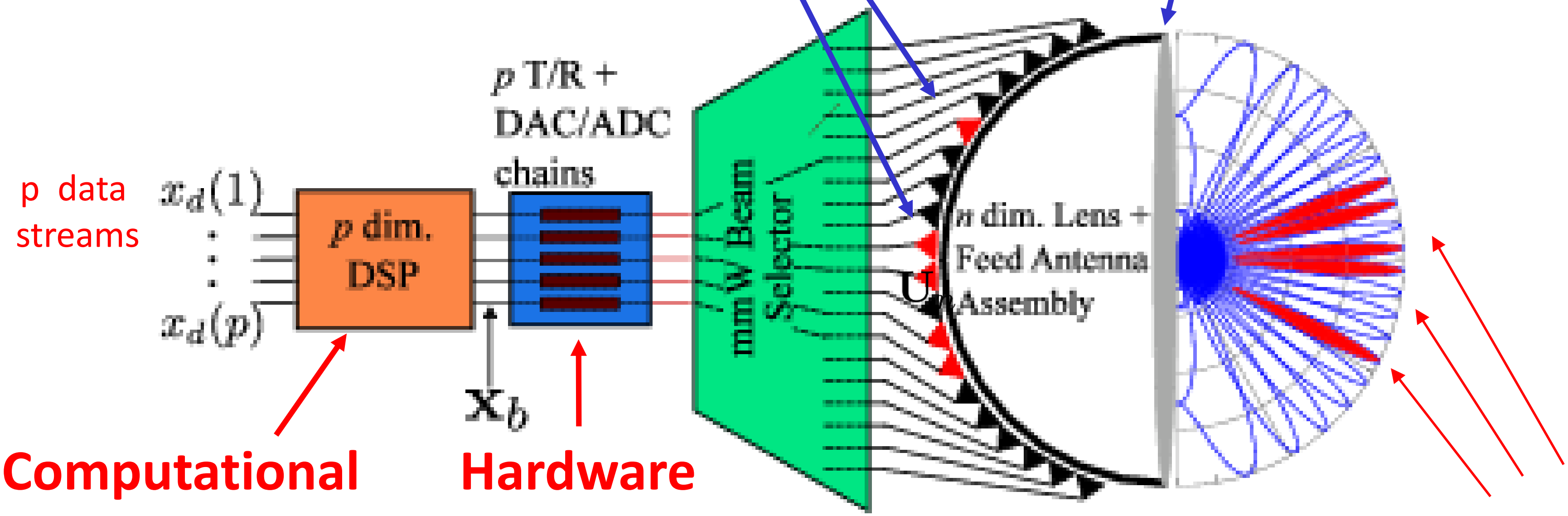


Existing prototypes limited to **single-beam** phased arrays of modest size (<256 elements)

Hybrid MIMO: Lens Array Beamforming

Focal surface feed antennas: direct access to beamspace

mmW Lens computes analog spatial DFT



Computational Complexity:
n → p
matrices

Hardware Complexity:
n → p
RF chains

Beam Selection
p << n
active beams

Data multiplexing through p active beams

Scalable performance-complexity optimization

(AS & NB Allerton ‘10, APS ‘11; JB, NB & AS TAPS ‘13)

4” x 3” AP Antenna: Multi-beam CAP-MIMO vs Single-beam Phased Arrays

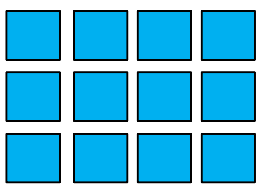
$n \approx 285 \ (19 \times 15)$ $\quad$ $\#$ beams (cover): $n_b \approx 144 \ (16 \times 9)$

12 RF chains; 100 users; 7.85 users/beam

Phased Array

4×3

Array partitioning

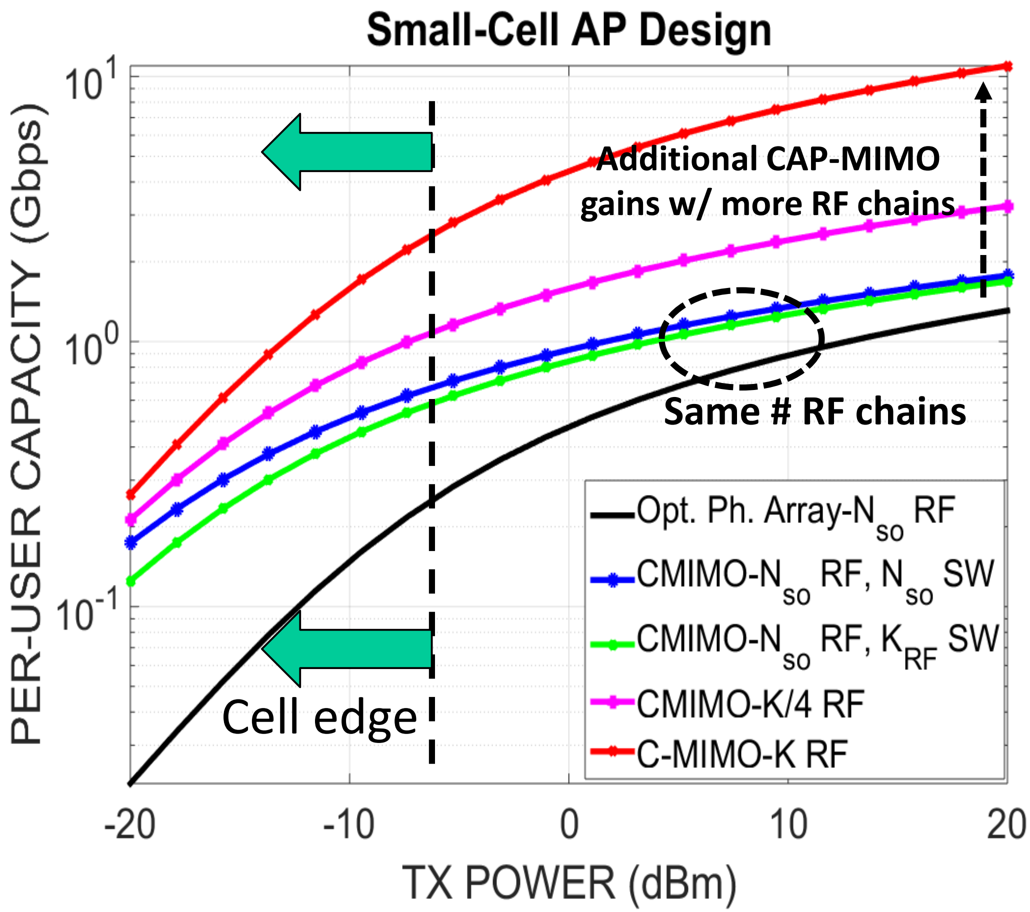


5×5

Sub-array

$\sqrt{n_b} \approx 12$

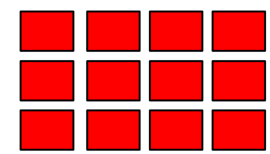
beams coverage



CAP-MIMO

4×3

Beamspace sectoring



4×3

Sub-sector

$n_b \approx 144$

beams coverage

2 beams/feed

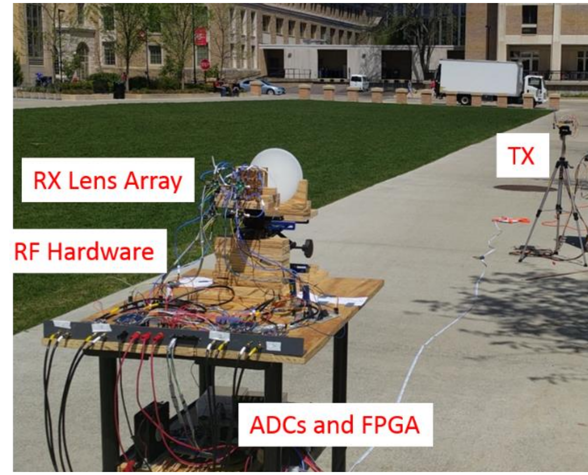
$\rightarrow K_{RF} = 6$ switch

1 GHz bandwidth; includes Friis free-space path loss

28 GHz Multi-beam CAP-MIMO Prototype

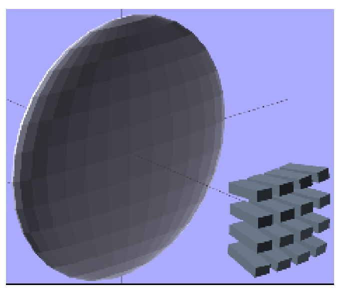
P2MP Link

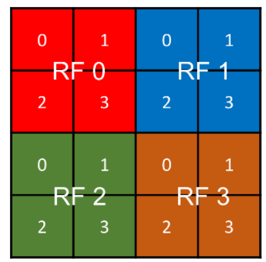
P2P Link



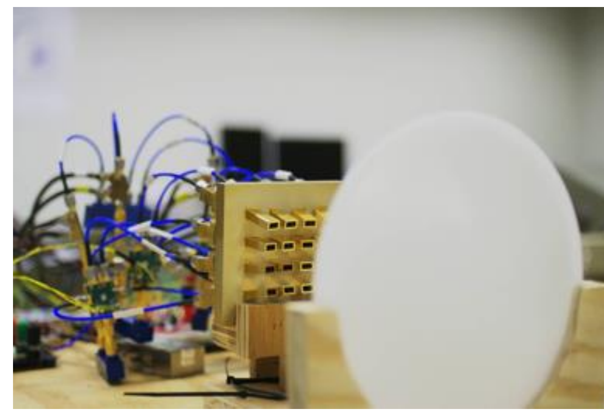
6” Lens with 16-feed Array

Equivalent to 600-element conventional array! Beamwidth=4 deg





1-4 switch for each T/R chain



Features

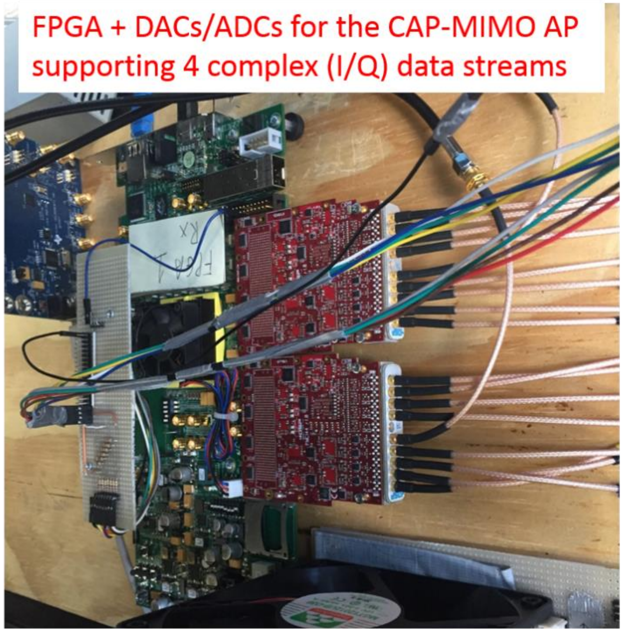
- **Unmatched 4-beam steering & data mux.**
- RF BW: 1 GHz, Symbol rate: 370 MS/s -1 GS/s
- Fully discrete mmW hardware
- FPGA-based backend DSP

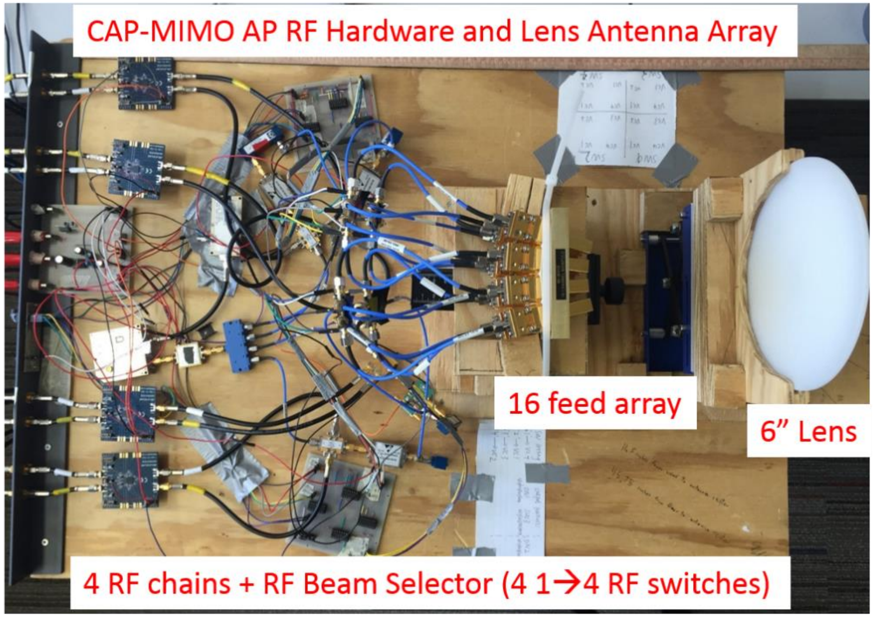
Use cases

- Real-time testing of PHY-MAC protocols
- Multi-beam channel measurements
- Scaled-up testbed network

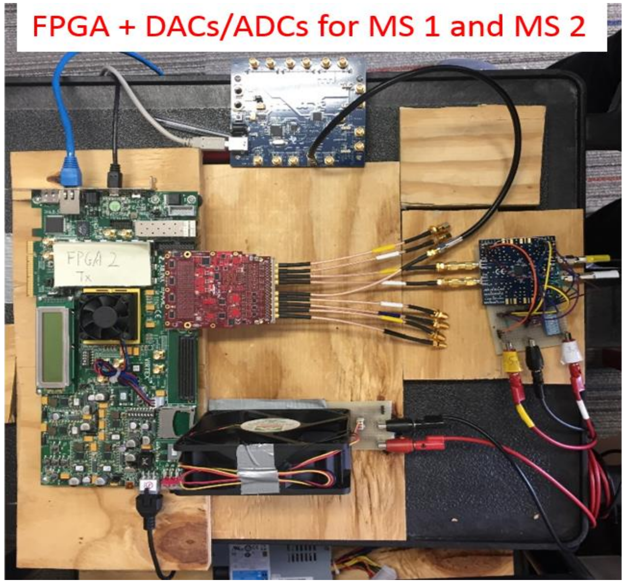
(JB, JH, AS, 2016 Globecom wkshop, 5G Emerg. Tech.)

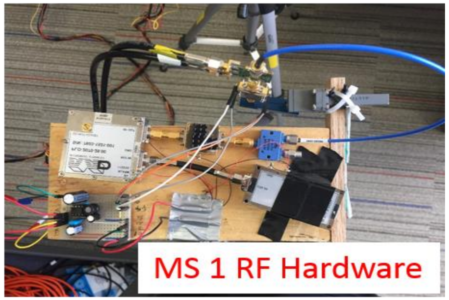
CAP-MIMO AP Hardware

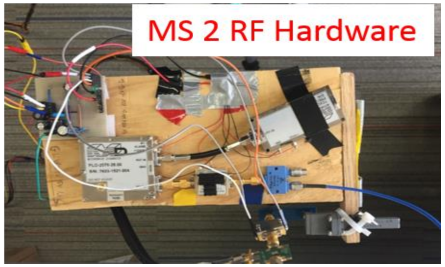




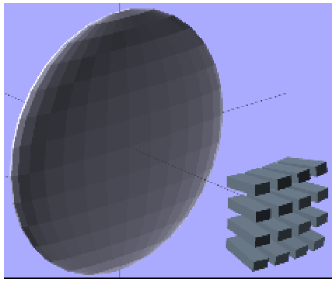
MS Hardware





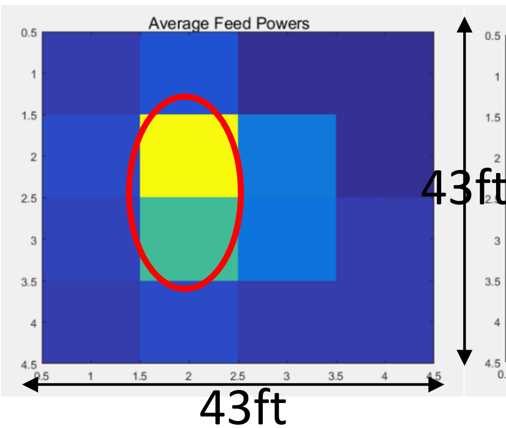


Directional Focusing by Lens Array

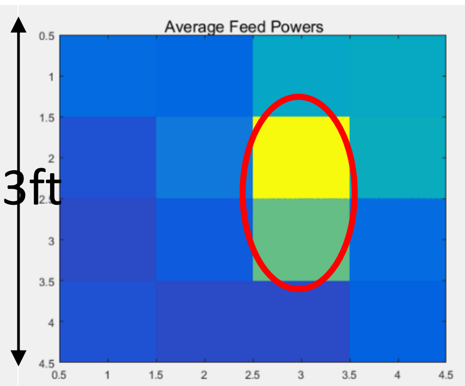


P2P link (154 feet): MS - CAP-MIMO AP

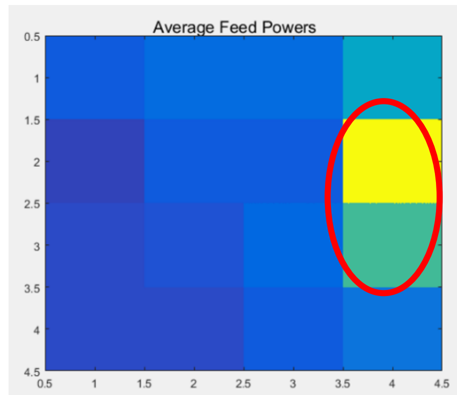
MS broadside



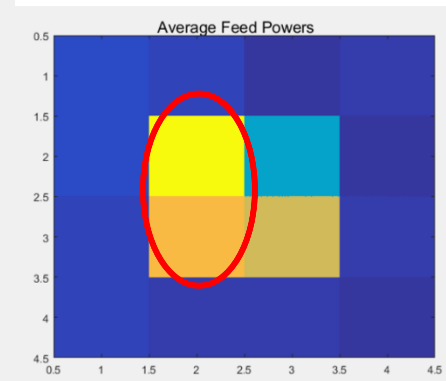
MS 11 ft left

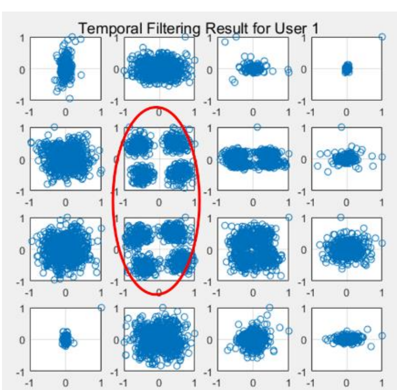


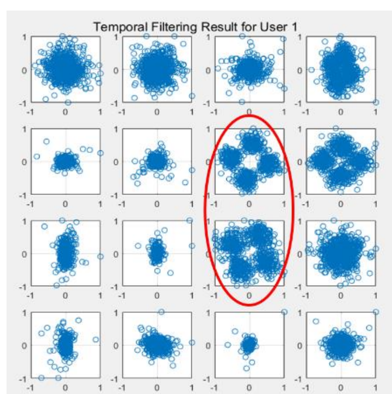
MS 22 ft left

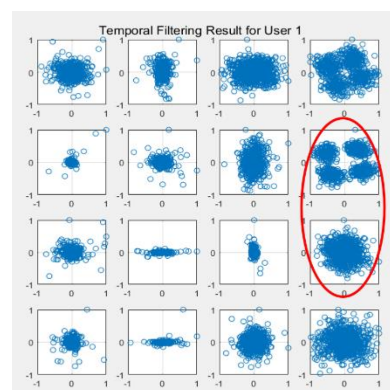


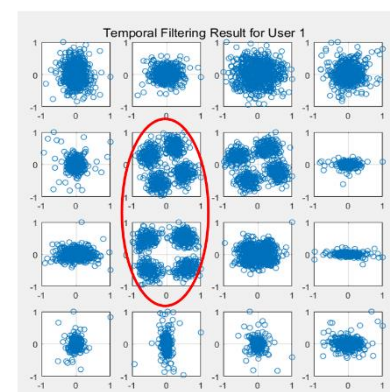
MS 22 ft left, feeds moved







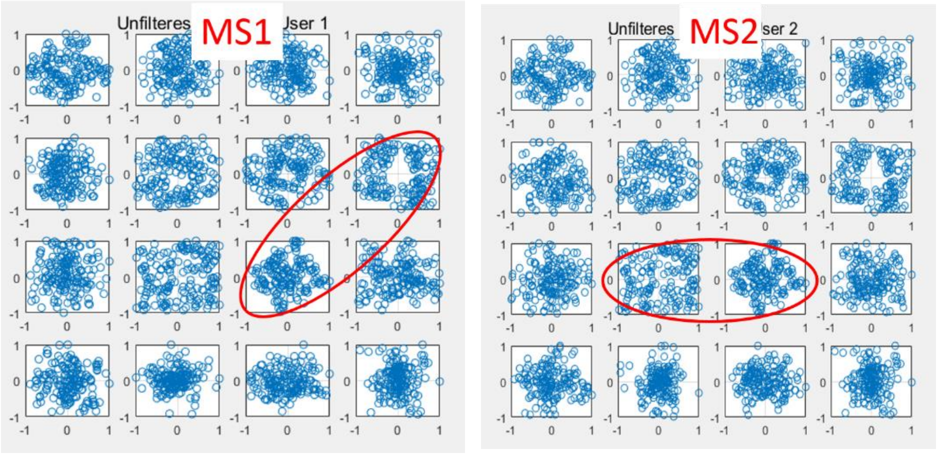




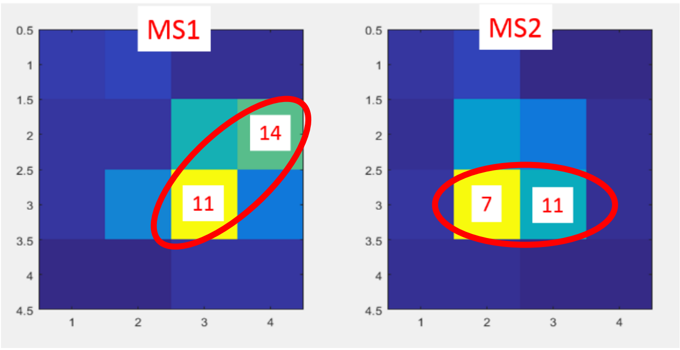
Multiuser Communication

Two MSs (3 ft apart) to CAP-MIMO AP 29 ft away

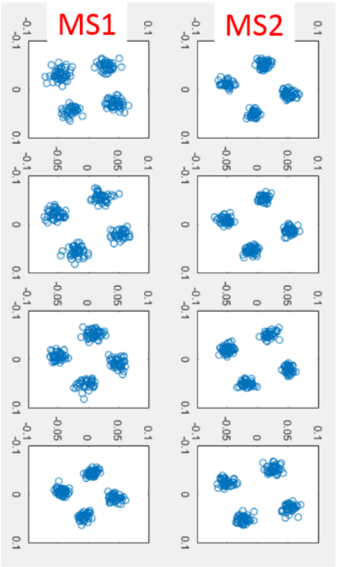
unfiltered



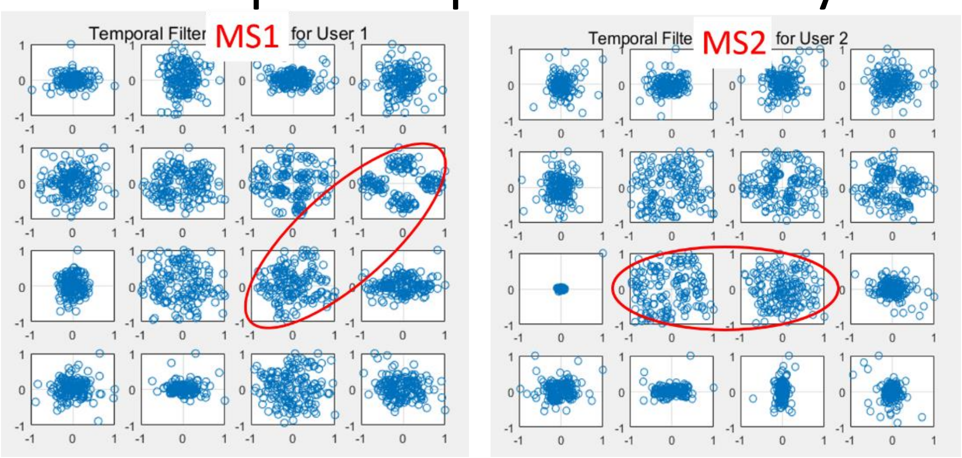
Beam powers for the MSs



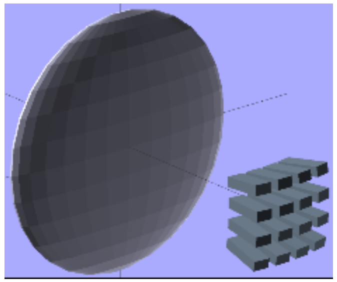
Spatial int. supp. & temp. eq.



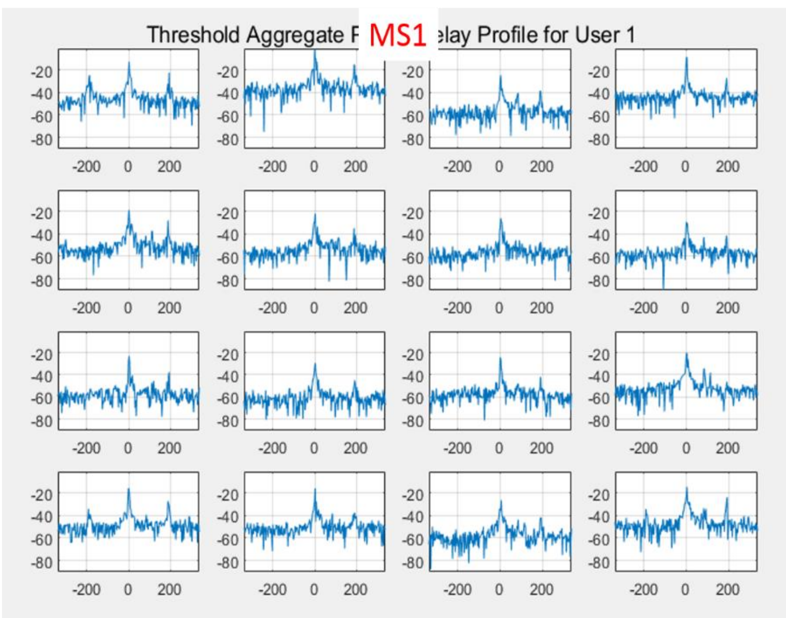
Temporal equalization only



Channel Sounder with Unmatched Multi-beam Capabilty



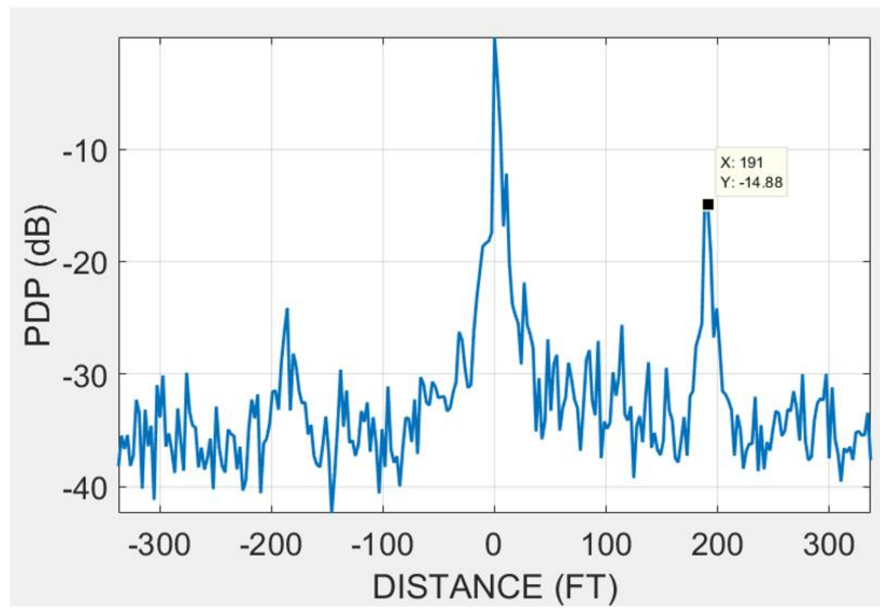
Individual Beam PDPs



8ft

8ft

Aggregate PDP



What's different this time? (vs 90's)

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LMDS (Local Multipoint Distribution Services)

- Lack of technology maturity and supporting infrastructure
- Lack of compelling use cases
- MIMO – invented in 1995; I-phone introduced in 2007

News | July 7, 1999

Ericsson Signs First LMDS Contract

RF Globalnet

"This LMDS network will deliver wireless access speeds of up to 37.5 Mb/s."

Hope for LMDS Dwindles

By: eWeek Editors | August 06, 2001

"Users of the spectrum have faced a number of hurdles to deployment, including expensive gear, difficulties in securing roof rights for antennas, immature technology and signal interference from elements such as rain."

mmW Wireless RCN
http://mmwrcn.ece.wisc.edu

- NSF research coordination network (RCN) on mmW wireless
  - Academia, industry & government agencies

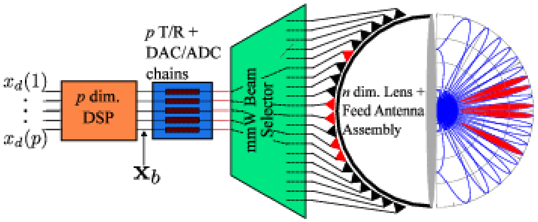
- Cross-disciplinary research and technology challenges
  - CSP: communications & signal processing
  - HW: mmW hardware, including circuits, ADCs/DACs, antennas
  - NET: wireless networking

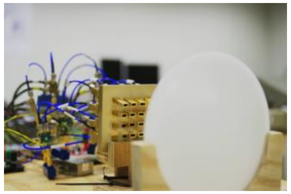
- Kickoff Workshop: Dec 2016, Washington, DC
- 2nd Workshop: July 19-20, 2017: Madison, WI
- 3rd Workshop: Jan 2017 (3rd week) – stay tuned!

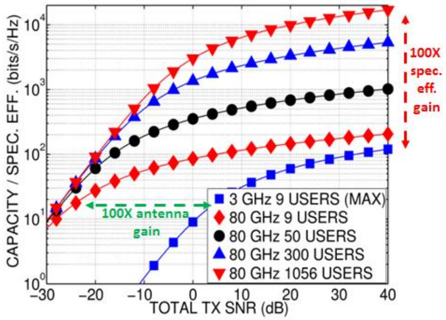
Xtras

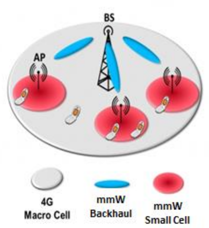
Conclusion

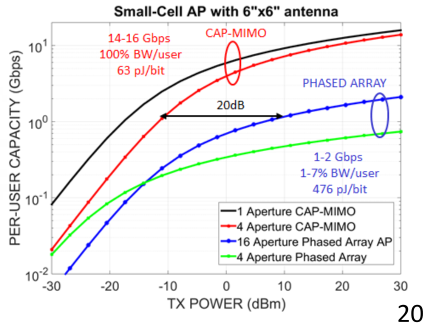
- Beamspace mmW MIMO: Versatile theoretical & design framework
- CAP-MIMO: practical architecture
  - Scalable perf.-comp. optimization
- Compelling advantages over state-of-the-art
  - Capacity/SNR gains
  - Operational functionality
  - Electronic multi-beam steering & data multiplexing
- Timely applications (Gbps speeds & ms latency)
  - Wireless backhaul: fixed point-to-multipoint links
  - Smart Access Points: dynamic beamspace multiplexing
  - Last-mile connectivity, vehicular comm, M2M, satcom
- Prototyping & technology development
  - Multi-beam CAP-MIMO vs Phased arrays?











Some Relevant Publications

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

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.
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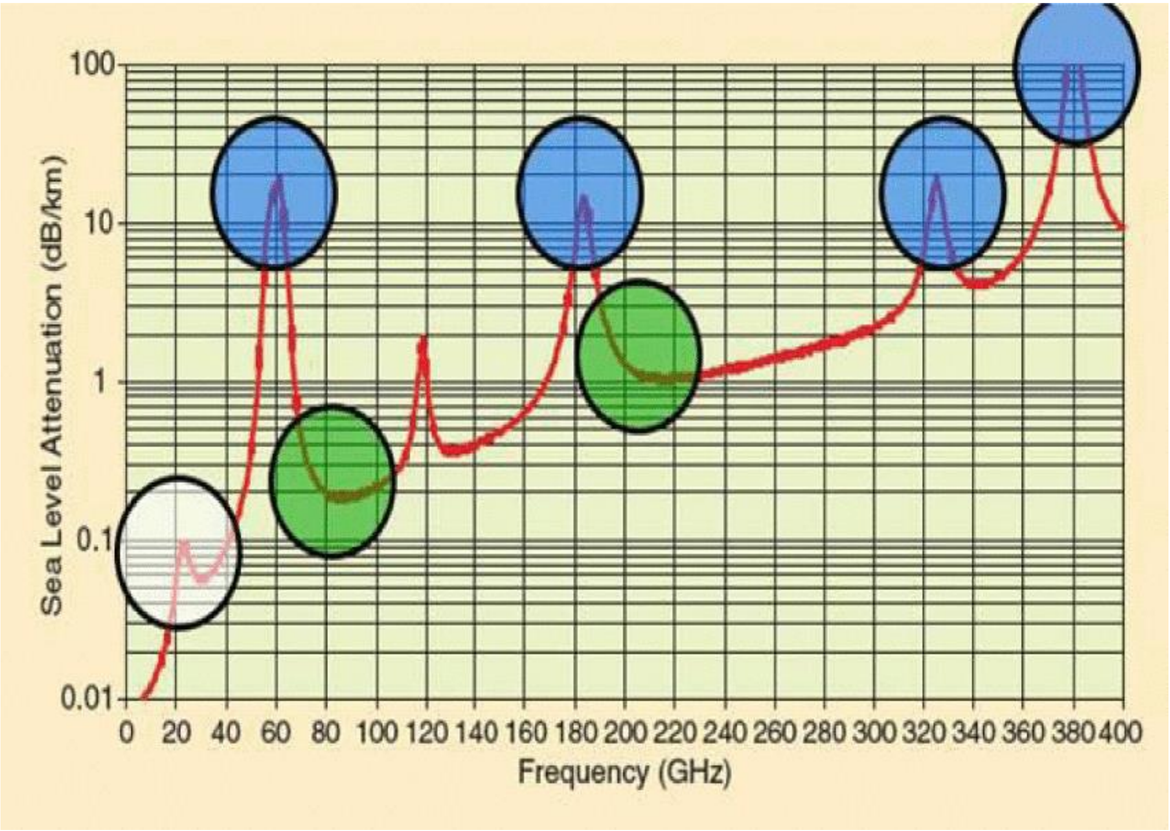
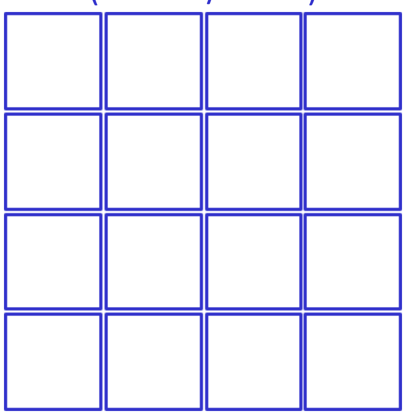


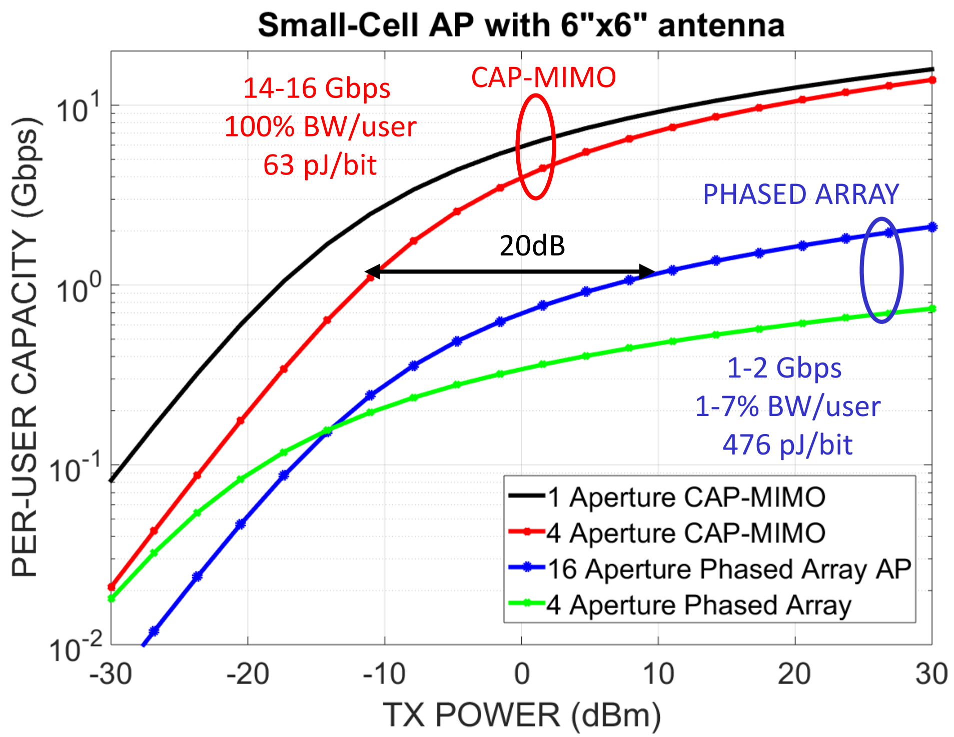
100
10
1
0.1
0.01
Sea Level Attenuation (dB/km)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Frequency (GHz)

Multi-beam CAP-MIMO vs Single-beam Phased Arrays

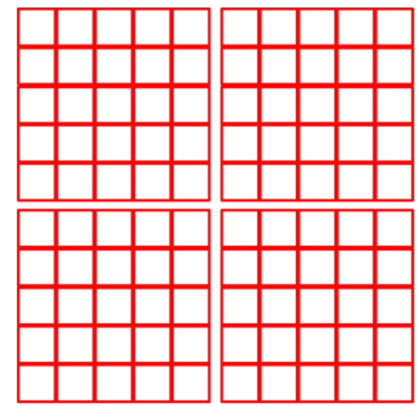
28 GHz small cell design for supporting 100 users

16, Single-beam
Phased Arrays
(16 total beams)
(7 users/beam)





4, 25-beam
CAP-MIMO Arrays
(100 total beams)
(1 user/beam)



CAP-MIMO has >8X higher energy and spectral efficiency over phased arrays
(idealized analysis – even bigger gains expected with interference)

Beamspace MIMO framework enables optimization of both architectures

Beam Selection Overhead: A Myth?

Countless papers claim that the beam selection overhead is prohibitive at mmW. Is it?

70 mph (30 m/s) speed $\Rightarrow f_d = 2800\text{Hz} \Rightarrow T_{coh} = 0.36\text{ms}$

Sampling interval $T_s = 1\text{ns}$ for $W = 1\text{GHz}$

$\Rightarrow N_{coh} = \frac{T_{coh}}{T_s} \approx 400,000$ samples (or $100,000$ for 250 MHz bandwidth)

Loss in spectral efficiency due to beam selection overhead: $\frac{N_{oh}}{N_{coh}}$

$N_{oh} \leq 1000 - 4000$ for a 1% loss

Brute force overhead: $N_{oh} \sim K N_{beams}$

E.g., for $N_{beams} = 50$, $K = 20$ to 80 users can be scanned with $< 1\%$ overhead

With p-beam capability: $N_{oh} \sim \frac{K N_{beams}}{p}$

Simultaneous Beams != # RF Chains

Multiple RF chains are necessary but not sufficient for multi-beam steering and data multiplexing

Existing phased array (single-beam)
Limiting factor: **phased shifter network** (not RF chains)

Lens arrays: multi-beam steering and data mux (# RF chains)
Limiting factor: beam selection network