Lens Array Multi-beam MIMO Testbed for Real-Time mmWave Communication and Sensing

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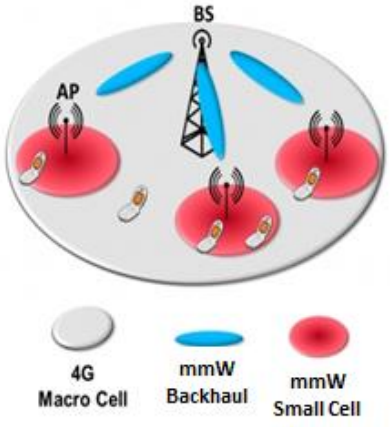
Outline

- Introduction
- Beamspace MIMO
- mmWave MIMO Transceiver Architectures
- Lens Array CAP-MIMO Testbed
- Measurement results & testbed functionality

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

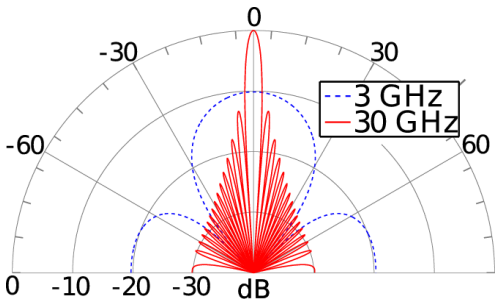


Potential of mmW Wireless

Key Advantages of mmW: large bandwidth & narrow beams

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

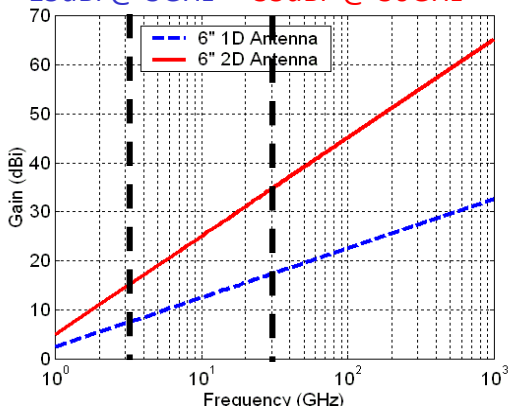
6000 elements @80GHz vs. 9 vs. elements @3GHz



35 deg @ 3 GHz

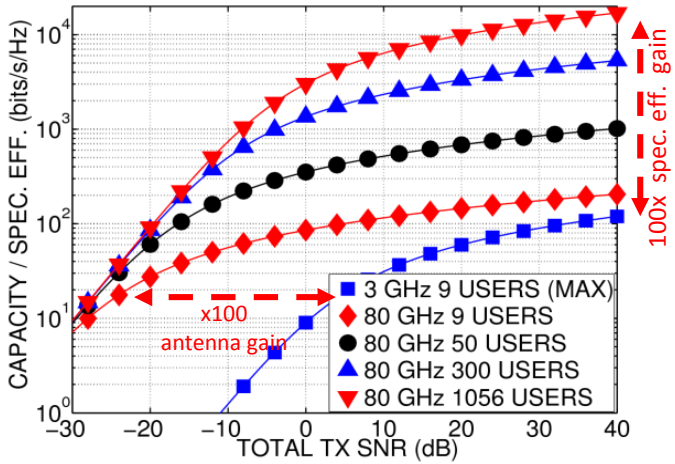
4 deg @ 30 GHz

15dBi @ 3GHz 35dBi @ 30GHz



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

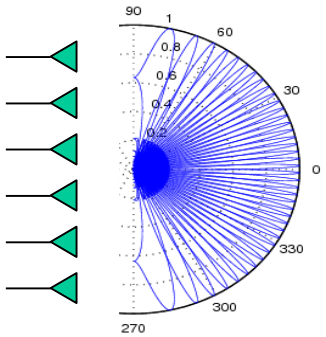
Multiplexing data into multiple highly-directional (high-gain) beams

Antenna space multiplexing

Discrete Fourier Transform (DFT)

Beamspace multiplexing

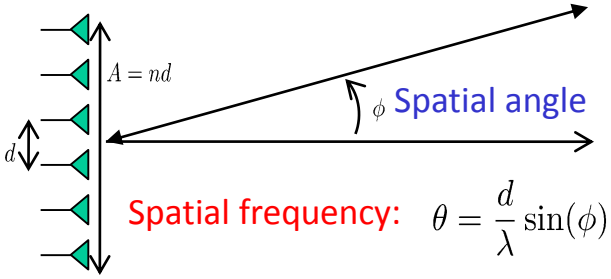
n-element array ($\frac{\lambda}{2}$ spacing)



n orthogonal beams

n spatial channels

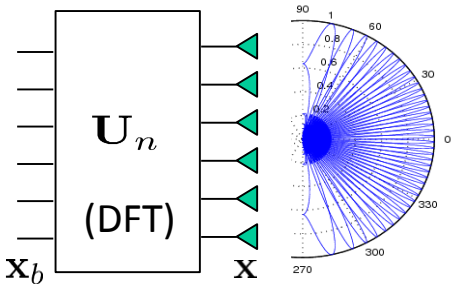
n dimensional signal space



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

steering/response vector

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



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

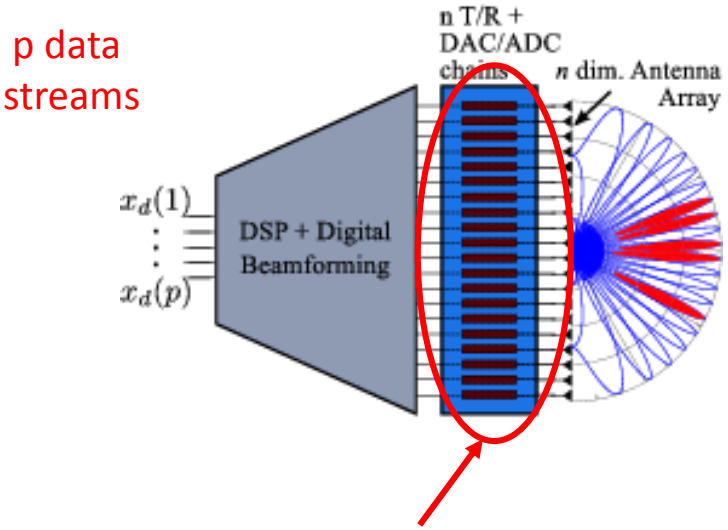
DFT matrix: Beamspace modulation

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

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

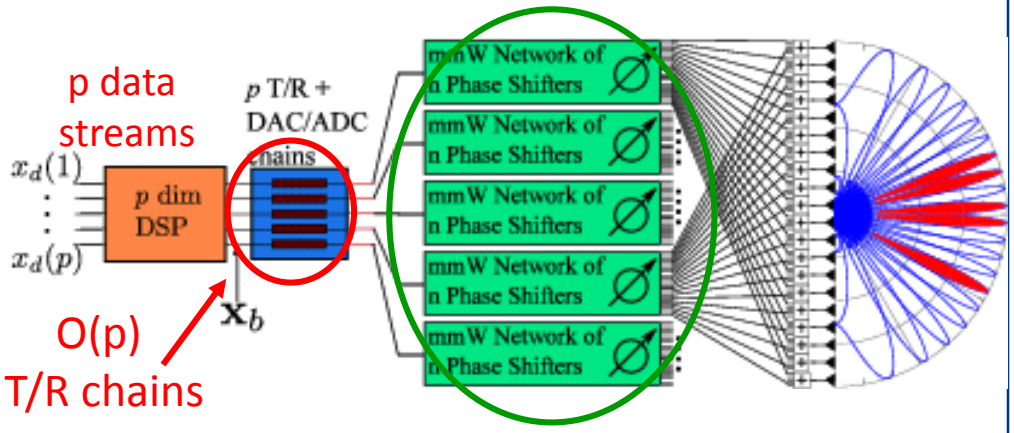
Two Common mmW MIMO Architectures

Conventional MIMO:
Digital Beamforming



n T/R chains: prohibitive complexity

Phased Array Architecture:
Analog mmW Beamforming

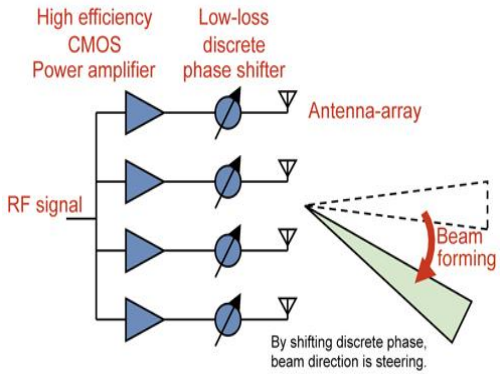


Phase Shifter **(np)** + Combiner Network

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

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

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



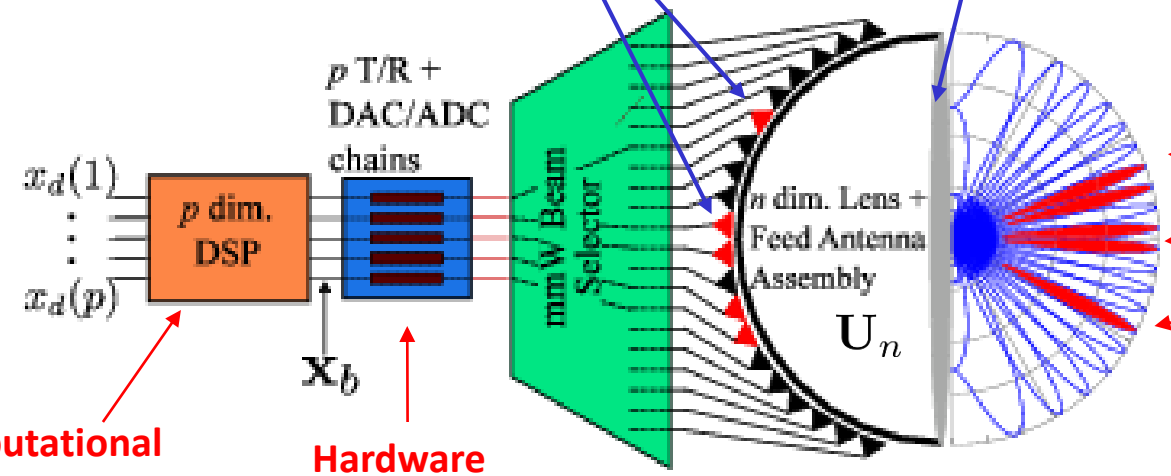
Continuous Aperture Phased (CAP) MIMO

Hybrid Analog-Digital Beamspace MIMO Architecture

Lens Array for Analog Multi-Beamforming

Focal surface feed antennas:
direct access to beamspace

mmW Lens computes
analog spatial DFT



p data
streams

Data multiplexing
through
p
active beams

Computational Complexity:
n → p
matrix operations

Hardware Complexity:
n → p
RF chains

Beam Selection
p << n
active beams

Scalable performance-complexity optimization

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

28 GHz Multi-beam CAP-MIMO Testbed

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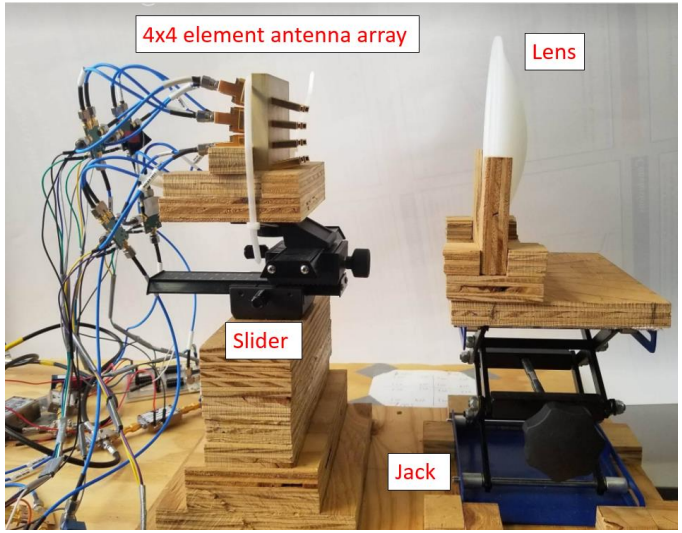
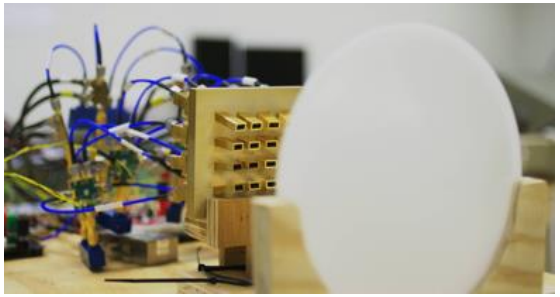
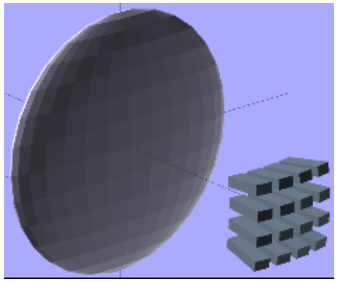
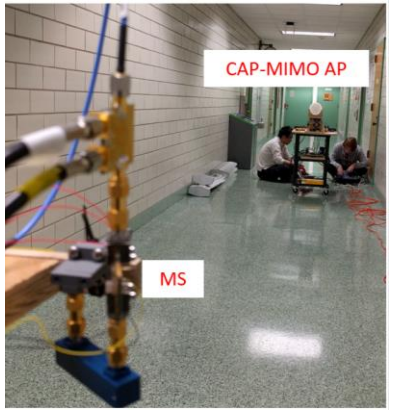
6” Lens with 16-feed Array



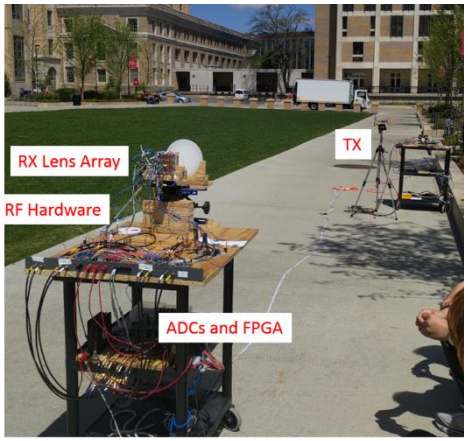




Indoor hallway



Outdoor link (up to 200 ft)



Indoor open atrium (LoS & NLoS)

Features

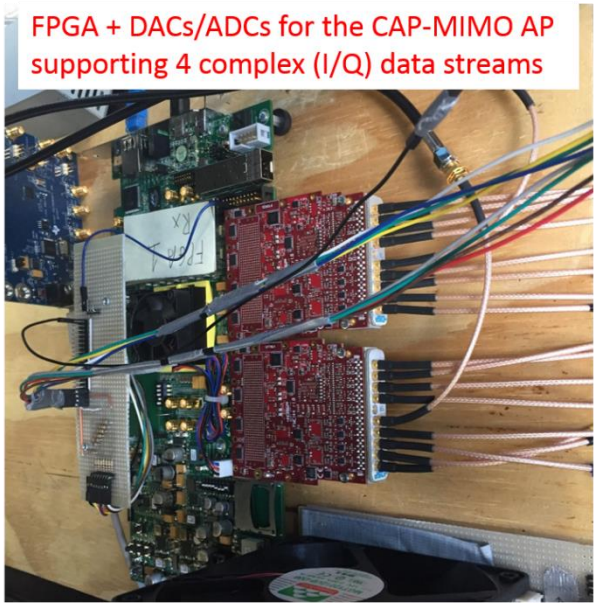
- **Unprecedented 4-beam steering & data mux.**
- RF BW: 1 GHz, Symbol rate: 370 MS/s
- AP – 4 MS bi-directional P2MP link
- FPGA-based backend DSP

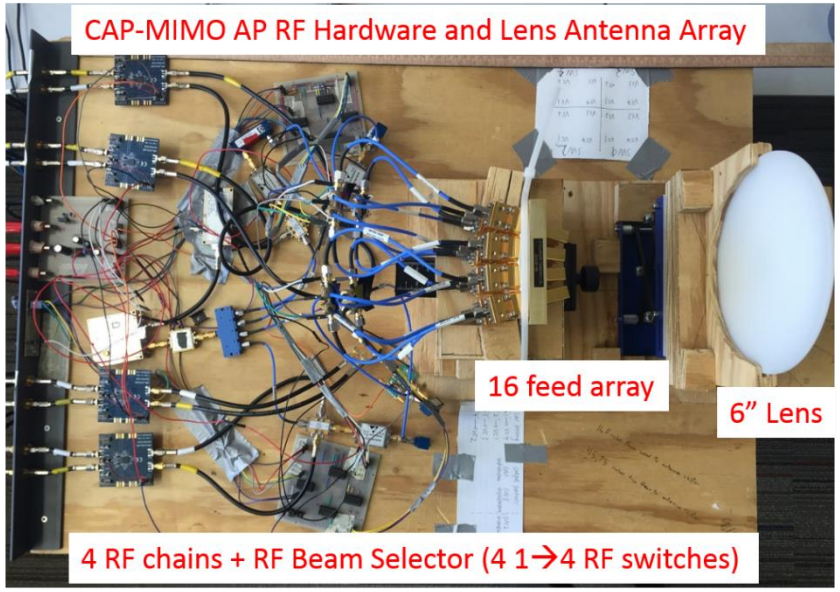
Use cases

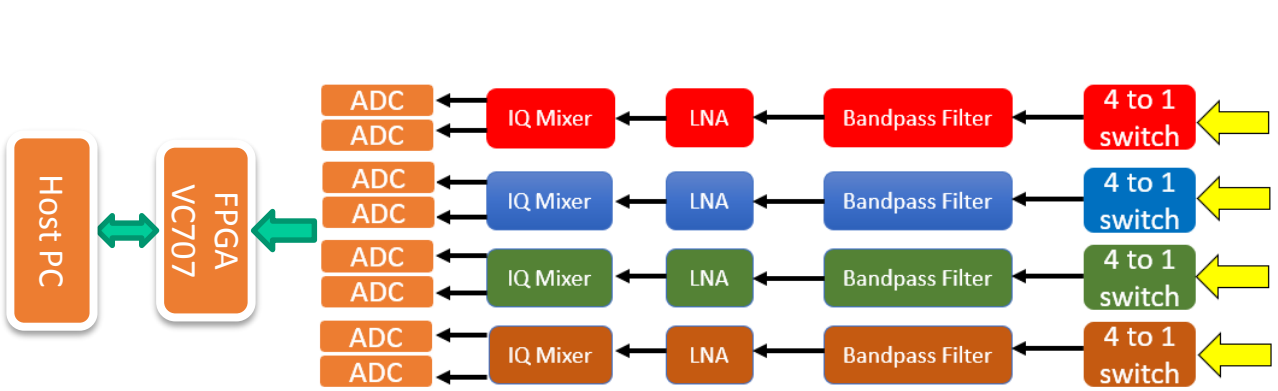
- Real-time testing of PHY-MAC protocols
- Multi-beam channel measurements
- Scaled-up testbed network

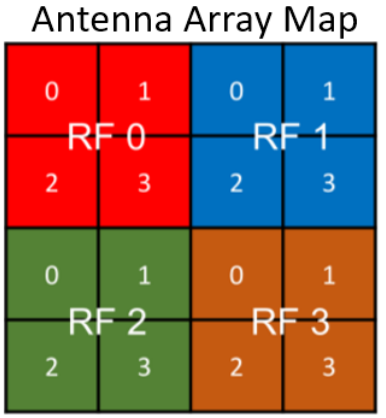
(JB, JH, AS, 2016 Globecom wkshop, 5G Emerg. Tech.)

CAP-MIMO Access Point (AP) Architecture









Single Antenna Mobile Stations (MSs)

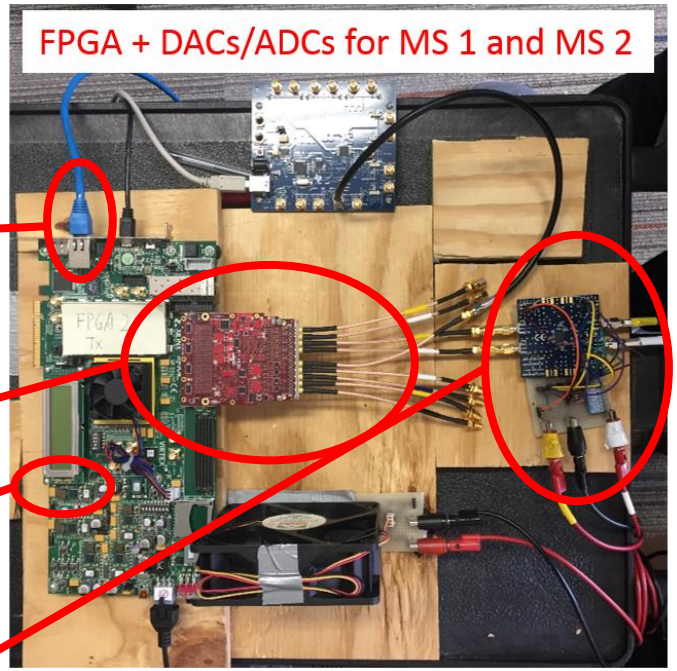
Xilinx VC707
4DSP FMC 144
DACs/ADCs

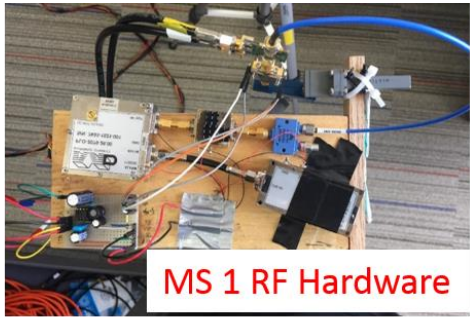
Ethernet port for FPGA configuration and data offloading (PC)

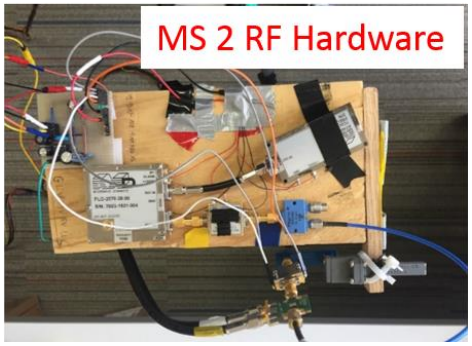
DACs and ADCs
370 MS/s symbol rate

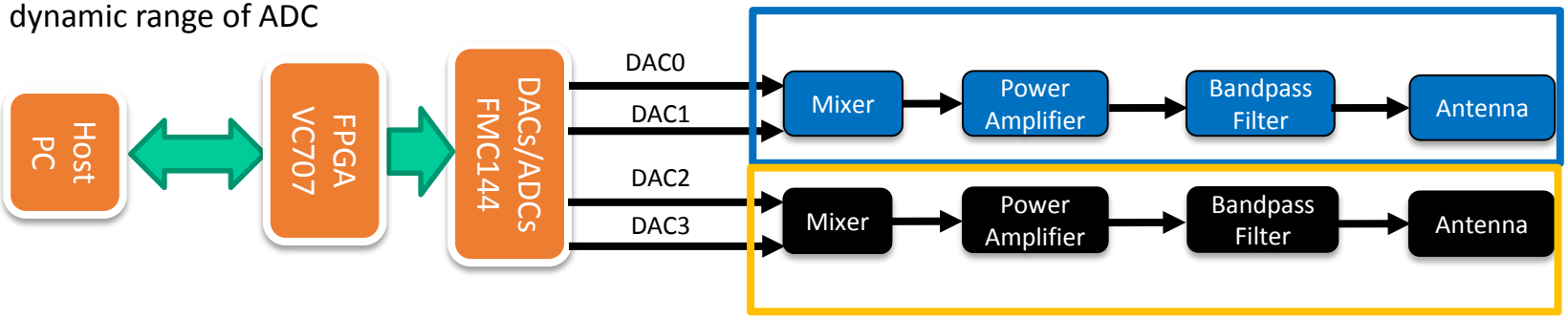
GPIO Pins drive the RF Switching circuitry

VGA for matching dynamic range of ADC





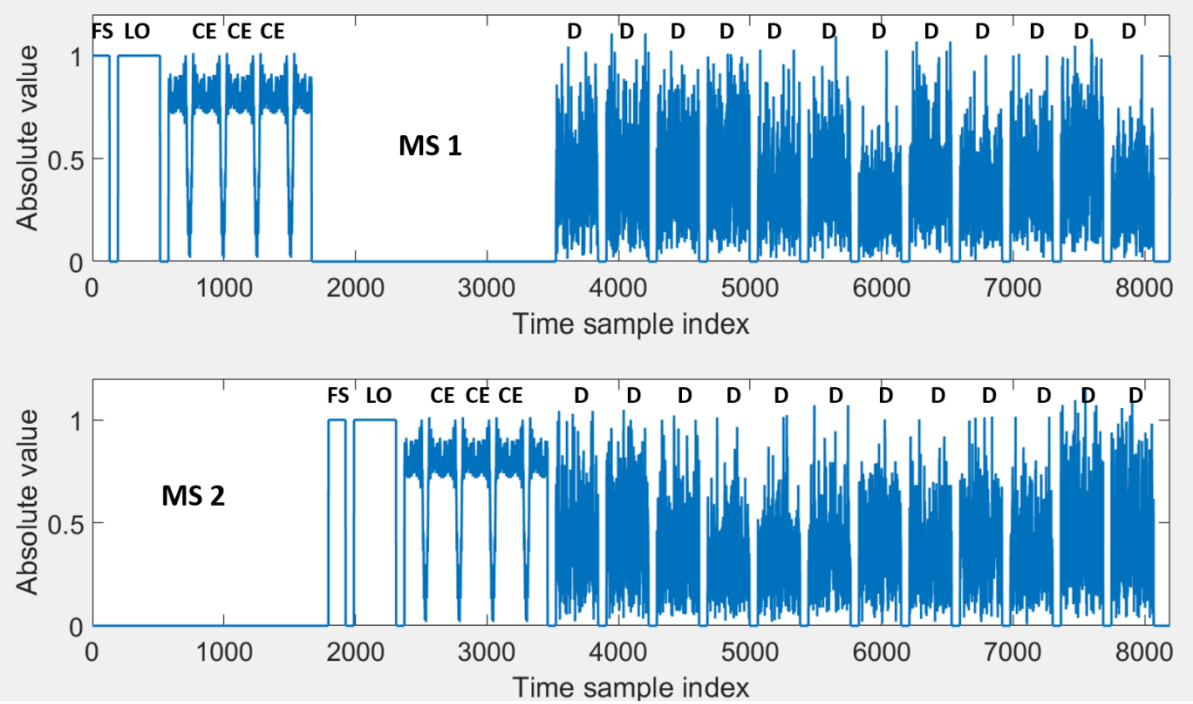




Signaling Frame Structure

MS 1

MS 2

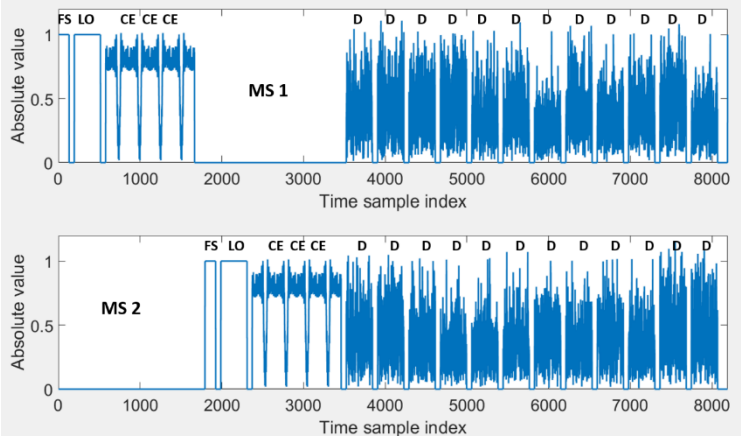


- Single user (SU) and multi-user (MU) scenarios
- Frame Sync (FS) block: time aligns the frame
- Local oscillator (LO) offset block: for LO offset estimation
- Channel Estimation (CE) block: for beam-frequency channel est.
- Data (D) block: data symbols (simultaneous from both MSs in MU)

Data and Computation Requirements

- Sampling rate (per ch.): 370 MS/s (16 chs - 6 GS/s)
- Communication rate (per ch.): 740 Mb/s
- 4 channel throughput: 3 Gb/s (16 chs - 12 Gb/s)
- Raw bit rate (per ADC ch (I+Q) - 16 b/samp): 12 Gb/s (16 chs. – 192 Gb/s)

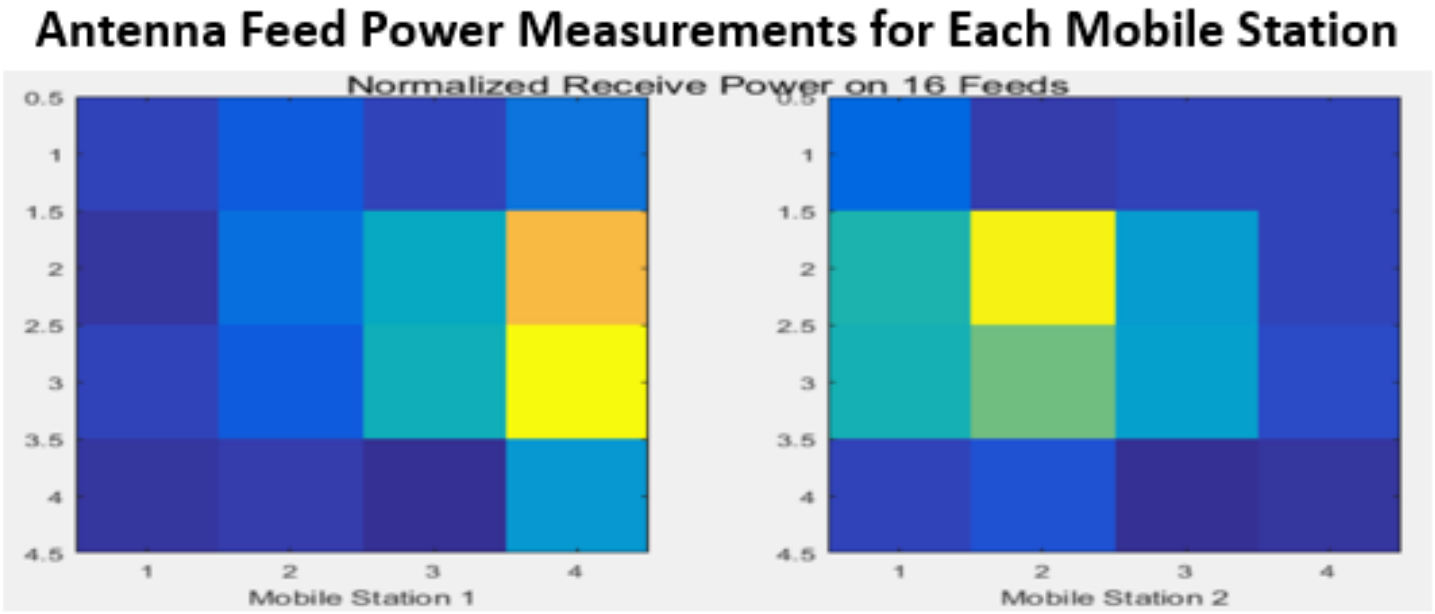
Frame Payload



- Frame duration: 22 micro seconds
- Raw frame size for each (I+Q) channel: 16 K samples = 256 Kb
- Raw frame size for all 16 channels: 256 K samples = 4 Mb
- Raw frame size for 4 selected channels: 64 K samples = 1 Mb

Measurement Analysis Capabilities

- Beam Power Maps
- Channel Estimates
- Constellation Diagrams
- Power Delay Profiles (PDPs)
- Power Spectral Densities (PSDs)
- Measurement forensics & pruning

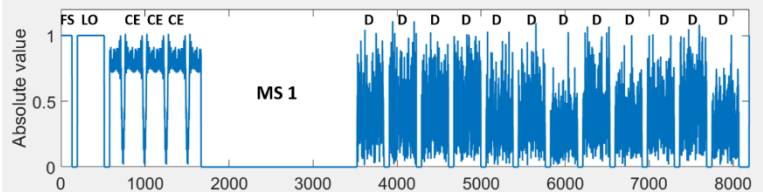


Directional focusing capability of the lens array

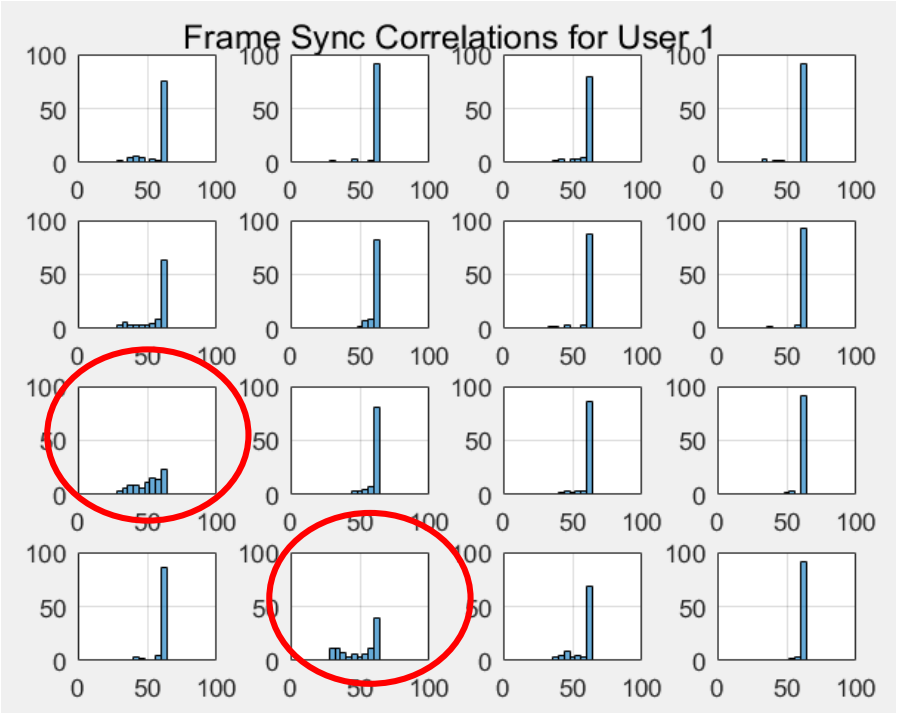
Data Forensics Example: Frame Sync Correlation Values

Frame sync: correlate the received signal with a known frame sync pseudo-random signal

$$y[n] = \sum_{k=0}^{N_{sync}-1} r[n+k]s_{sync}[k] \qquad \text{sync index} = \arg\max_{n} |y[n]|$$



Histogram of frame sync correlation values |y[n]|

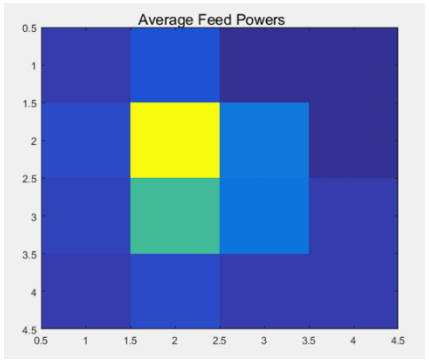


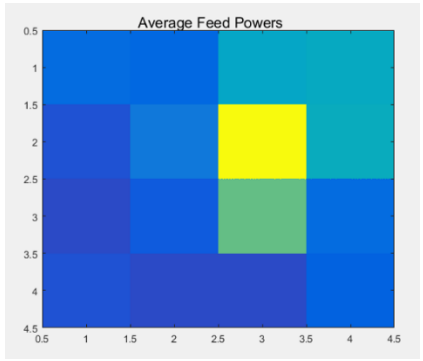
Maximum possible correlation value is 64

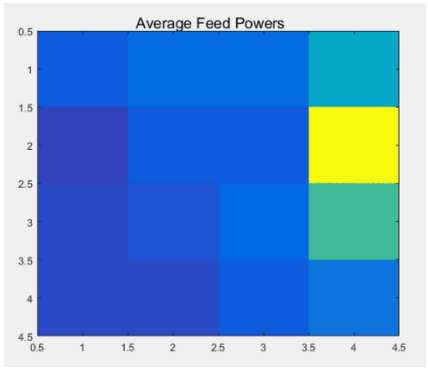
- One measurement: 100 frame captures for each antenna feed
- Can prune measurements based on values of a specific metric, e.g.:
  - LO Offset estimate
  - Frame sync correlation value
  - SNR/SINR
- Identify erroneous measurements
- More reliable data analysis, e.g.:
  - channel impulse response
  - PDPs
  - PSDs

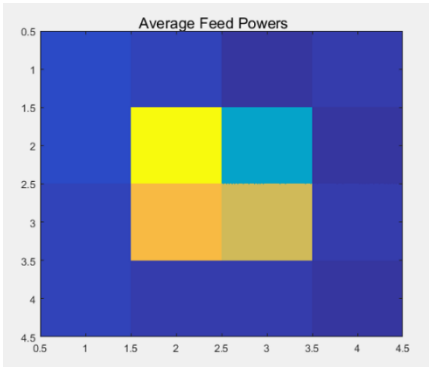
Directional Focusing of Lens Array: Outdoor LoS Measurements

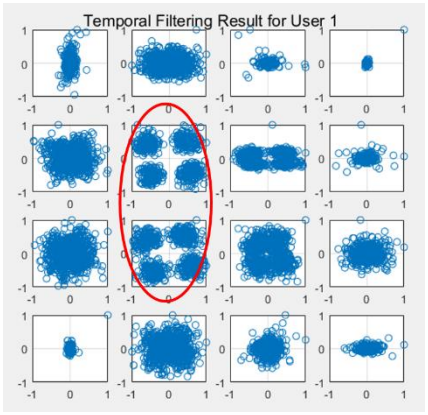
150 feet link length

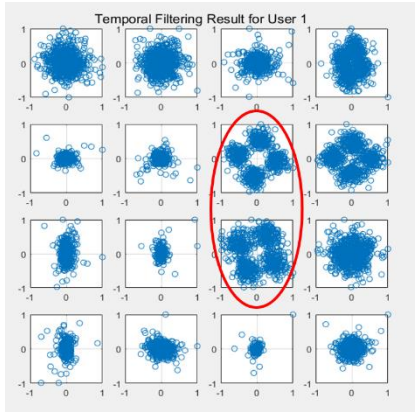


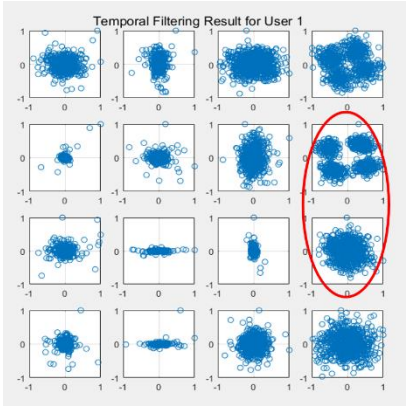


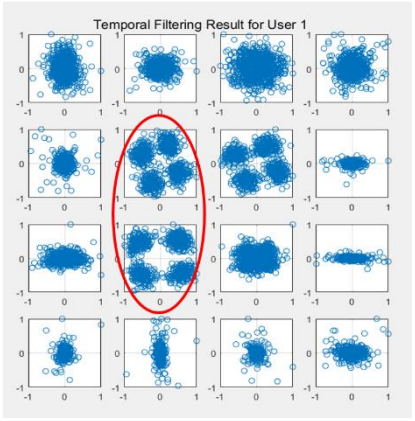












MS broadside

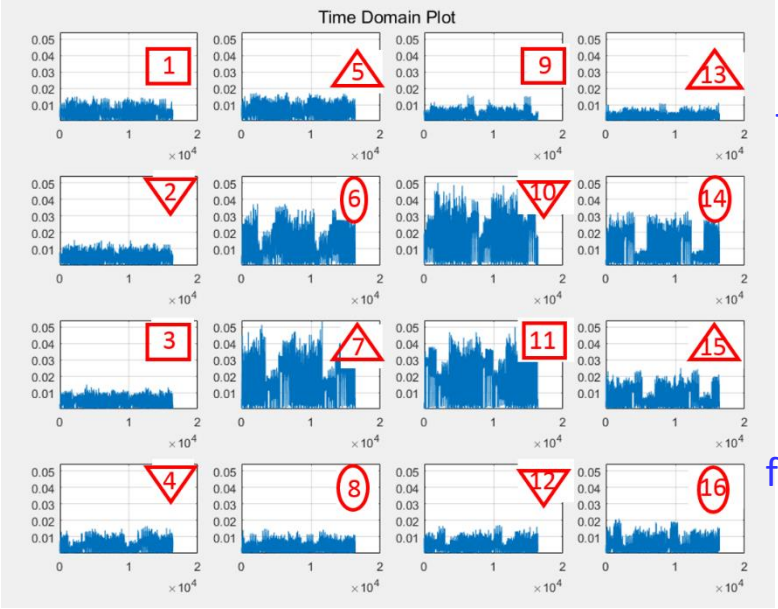
MS 11 feet
left of broadside
(one beamwidth)

MS 22 feet
left of broadside
(two beamwidths)

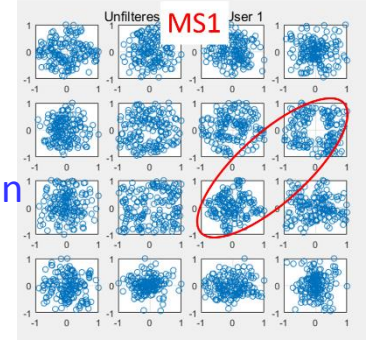
MS 22 feet
left of broadside
feed array moved

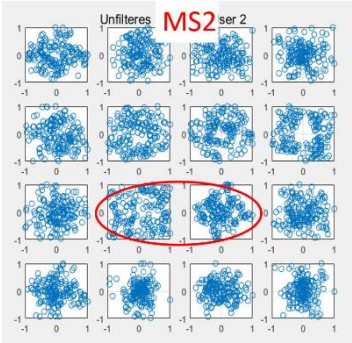
Multiuser (MU) Communication: Indoor Hallway Measurements

Time-domain frame signals (MU)

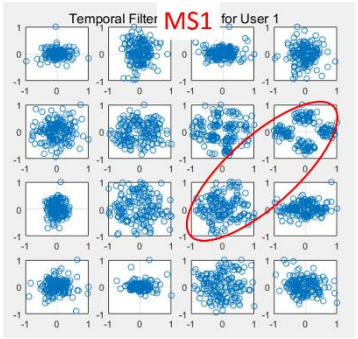


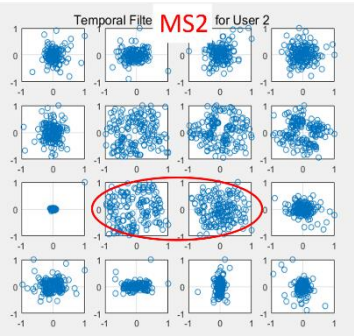
Raw frequency domain data samples

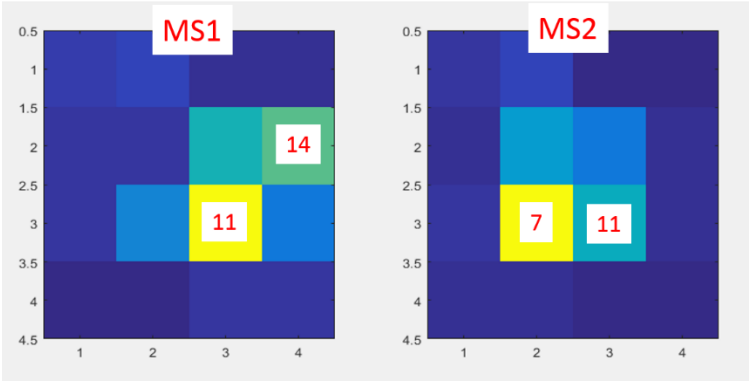




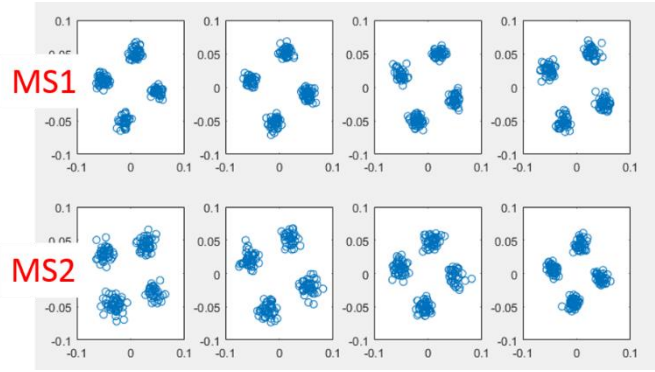
Temporally Filtered frequency domain data samples







Spatially combined & temporally filtered frequency domain data samples



Link length=28 feet, MS separation = 3ft

Power Delay Profiles (Hallway Channel Measurements)

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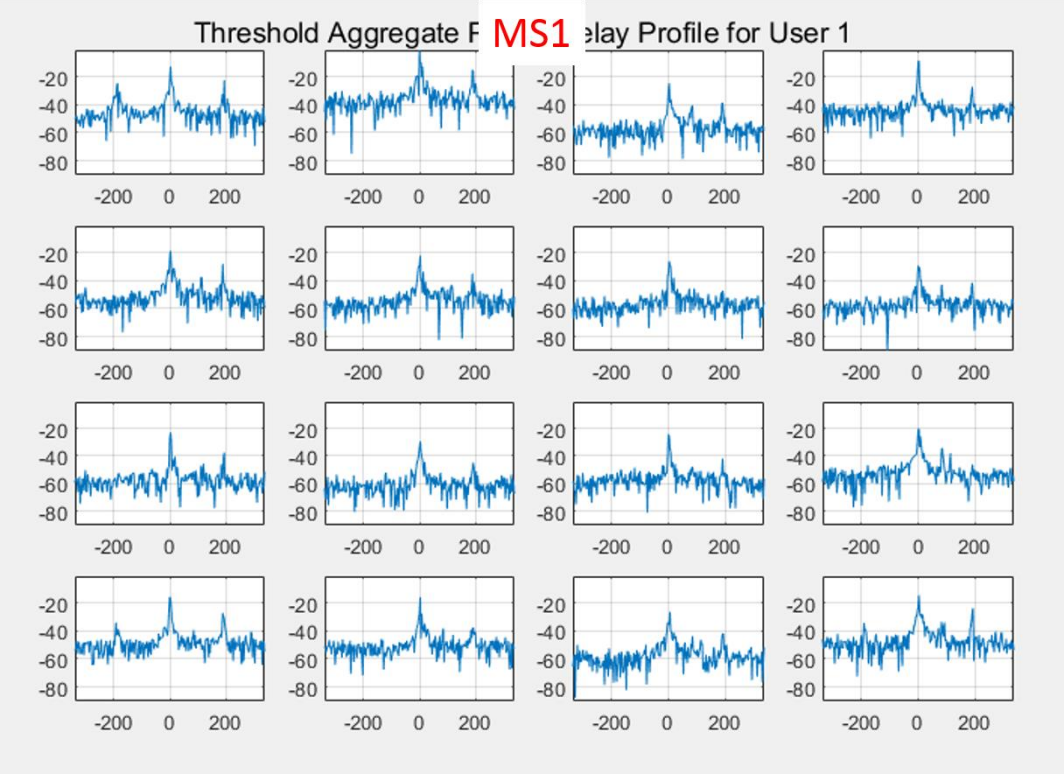
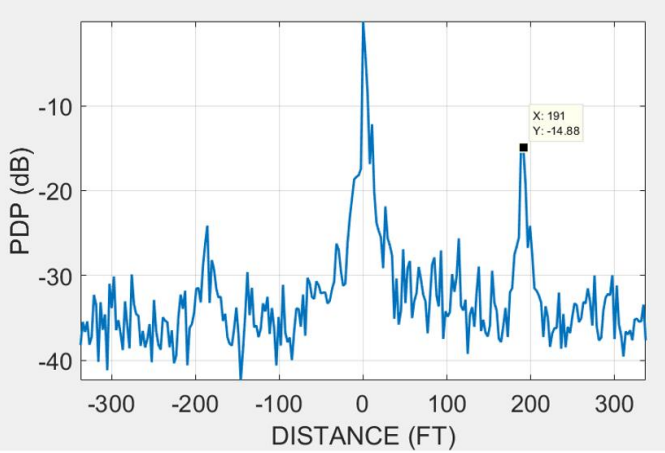
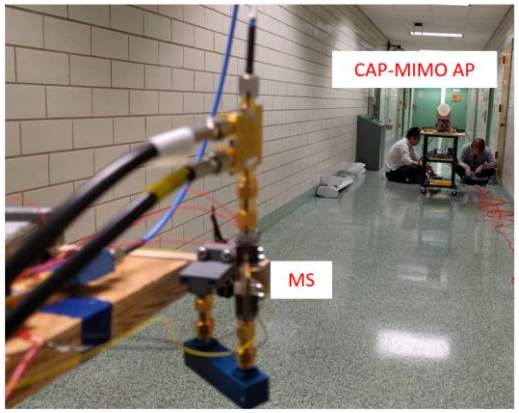
Individual PDPs for different beams



Aggregate PDP over all beams



$$\mathrm{PSD}[k] = \sum_{i=1}^{N_b} \mathrm{PSD}_i[k]\,,\ \mathrm{PDP}[n] = \sum_{i=1}^{N_b} \mathrm{PDP}_i[n]$$



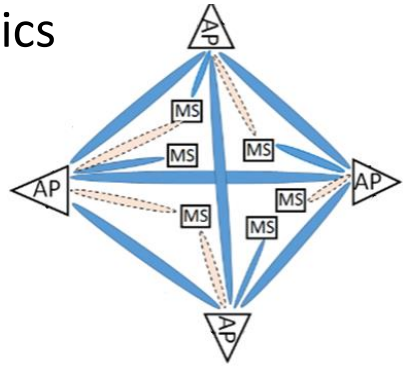
$$\mathrm{PSD}_i[k] = |\bar{h}_{b,i}[k]|^2\,,\ \mathrm{PDP}_i[n] = |\bar{g}_{b,i}[n]|^2$$

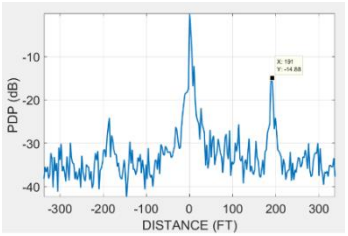
Frequency response (i-th beam)

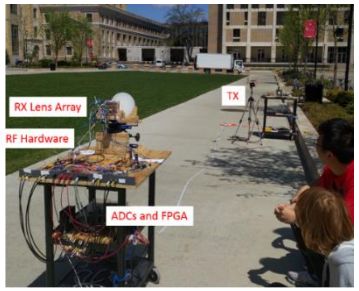
Impulse response (i-th beam)

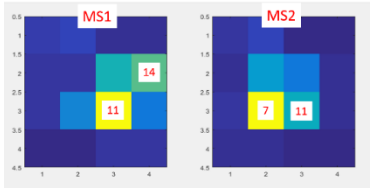
Conclusion

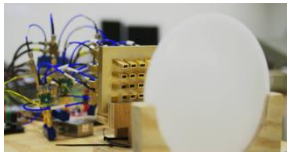
- CAP-MIMO testbed: lens array architecture for multi-beamforming & mux.
- Fully modular hardware design for reconfiguration and experimentation
- Flexible FPGA design for real-time experimentation and measurements
- MATLAB-based offline processing for data analysis and forensics
- Future Work:
  - FPGA design for real-time experimentation
  - AP – 4 MS bi-directional P2MP links
  - Remote access and control of the testbed network
  - Analysis of wide band operating characteristics including beamsquint

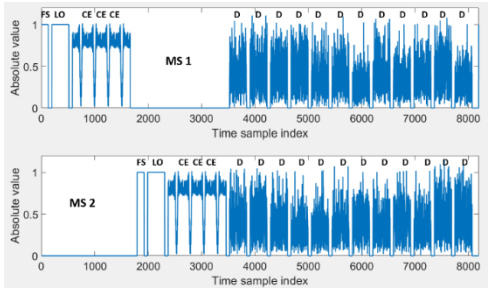


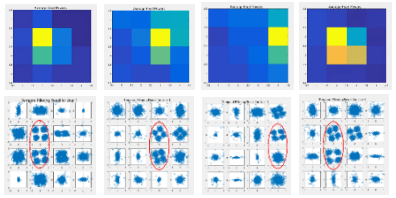












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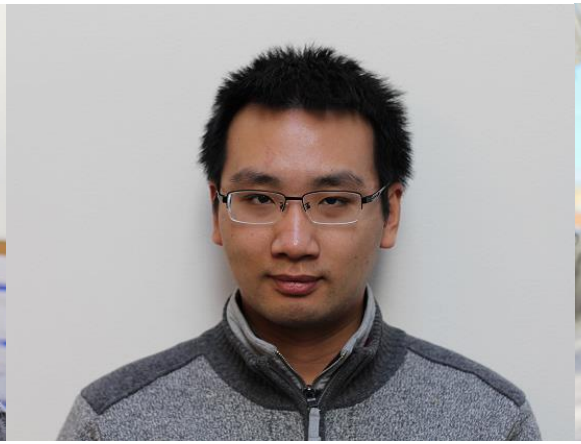


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