28 GHz Lens Array Multi-beam MIMO Testbed

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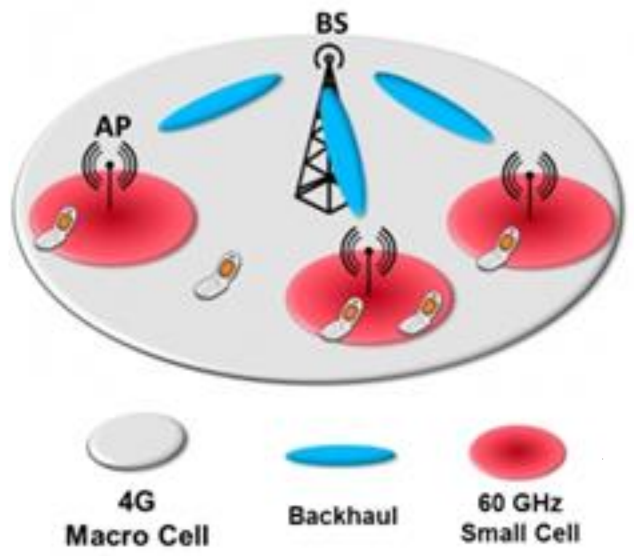
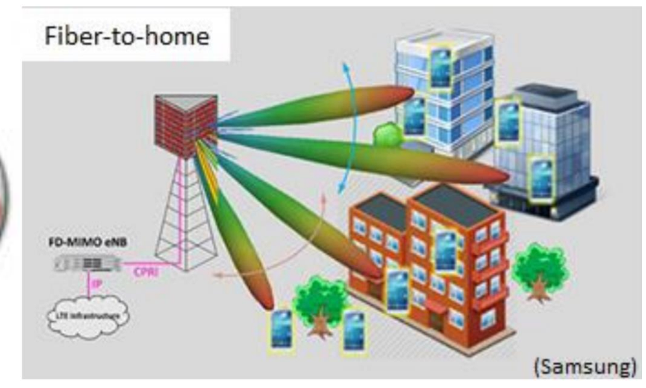
I. Beamspace MIMO for 5G Gigabit Applications

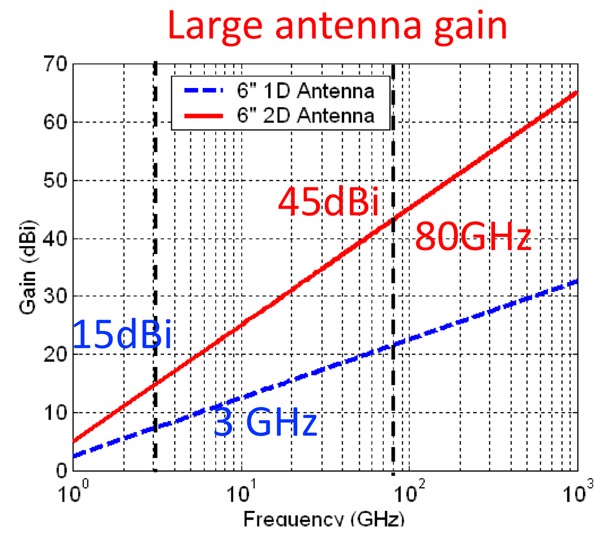
Key 5G Use Cases:
Backhaul
Last Mile
Small-Cell Mobile Access
Autonomous Vehicle

Key 5G Requirements:
Multi-Gbps speeds
sub-millisecond latency





Large antenna gain

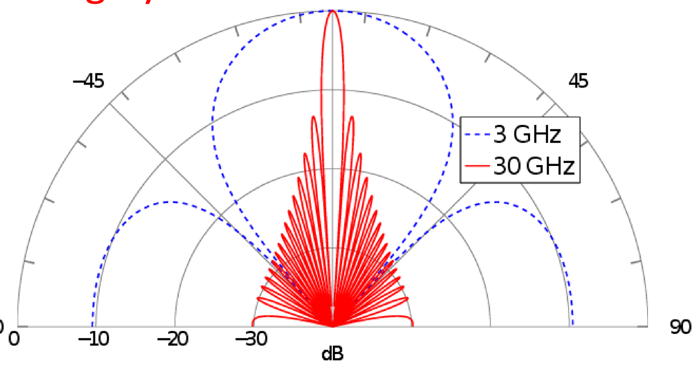


Highly directive narrow beams

6" antenna

35 deg @ 3GHz (15dBi Gain)

4 deg @ 30GHz (45dBi Gain)

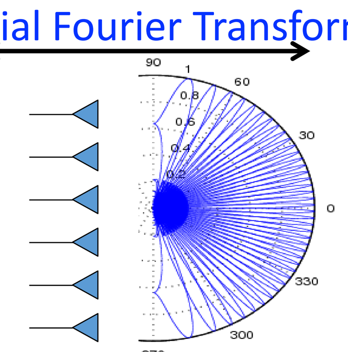


Beamspace MIMO: Multiplexing Data into Beams

Spatial Fourier Transform

Antenna space multiplexing

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



n orthogonal beams

Beamspace multiplexing

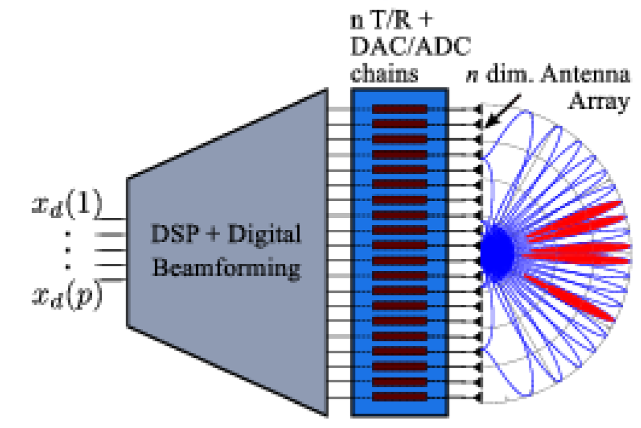
array steering vector

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

spatial freq. $-\frac{1}{2} \le \theta < \frac{1}{2}$ $\theta = \frac{1}{2}\sin(\phi)$ physical angle $-\frac{\pi}{2} \le \phi < \frac{\pi}{2}$

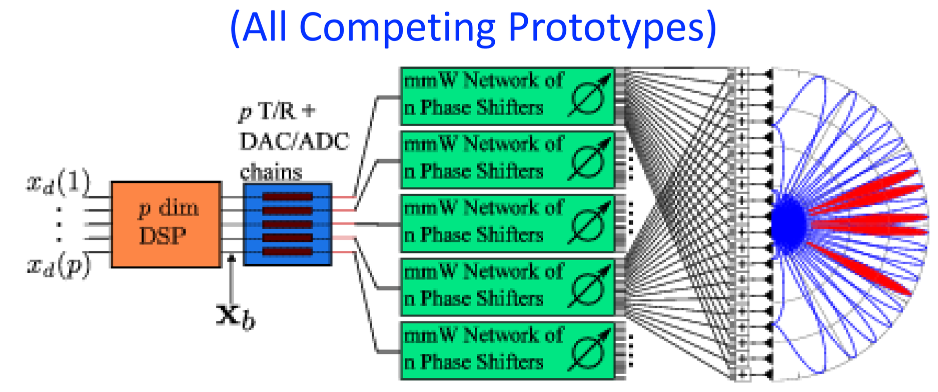
II. CAP-MIMO vs Competing Architectures

Conventional MIMO: Digital Beamforming

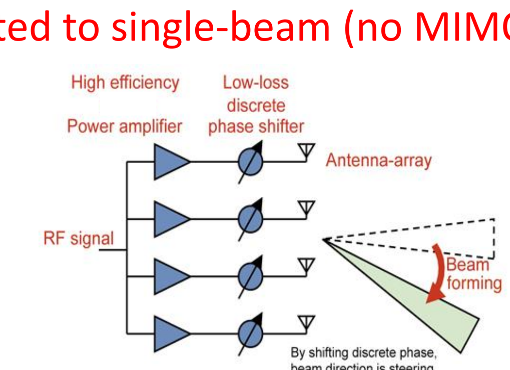


Prohibitive complexity

Phased Array Architecture (All Competing Prototypes)



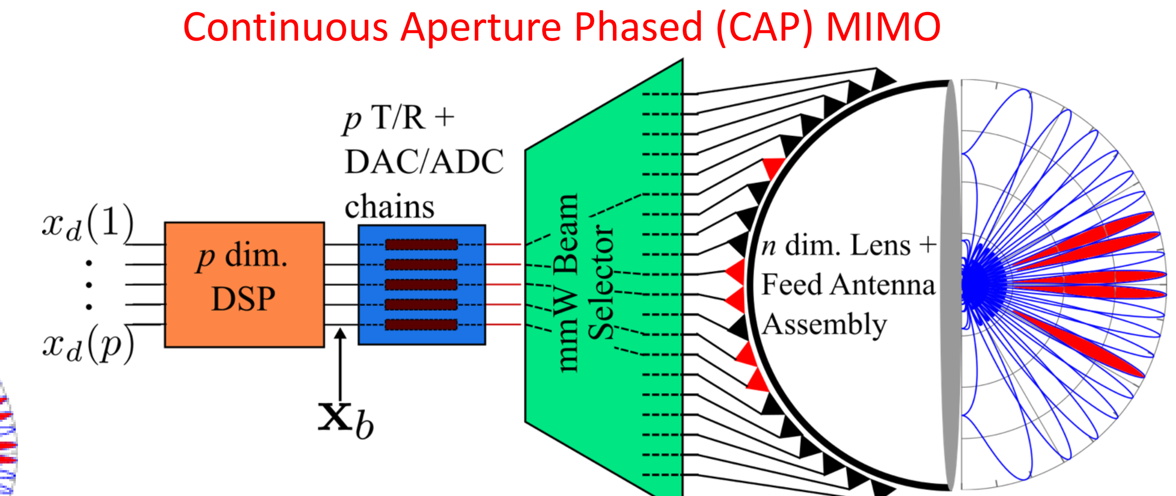
Limited to single-beam (no MIMO)



Key Functionality:
Multi-beam Steering & Data Multiplexing

Key Challenge:
Complexity (hardware & computational)

Continuous Aperture Phased (CAP) MIMO



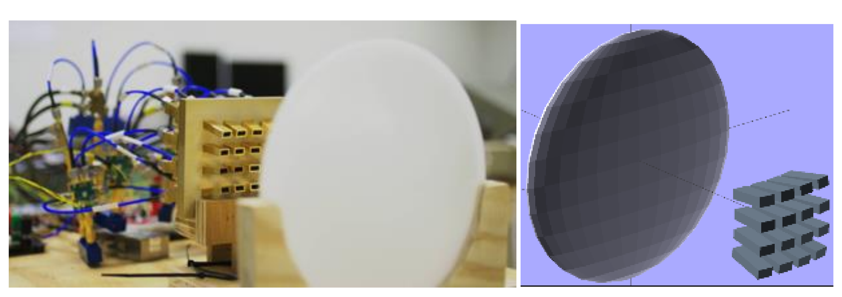
Scalable performance-complexity optimization

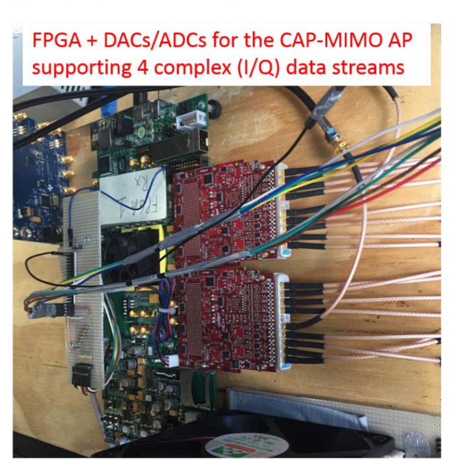
Key CAP MIMO differentiators

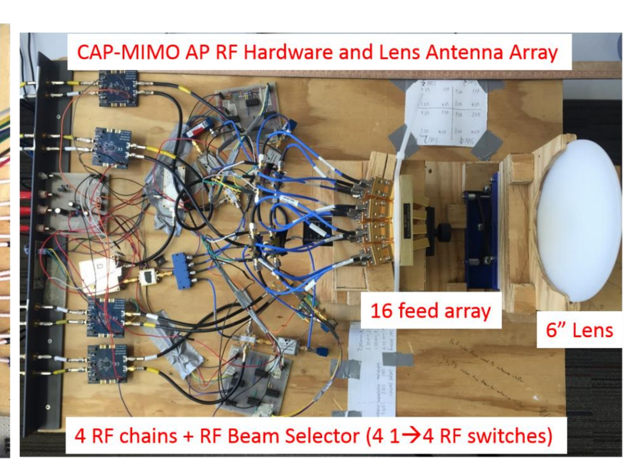
- Electronic multi-beam steering & data multiplexing
- Dramatic reduction in hardware & computational complexity
- Scalable performance-complexity optimization

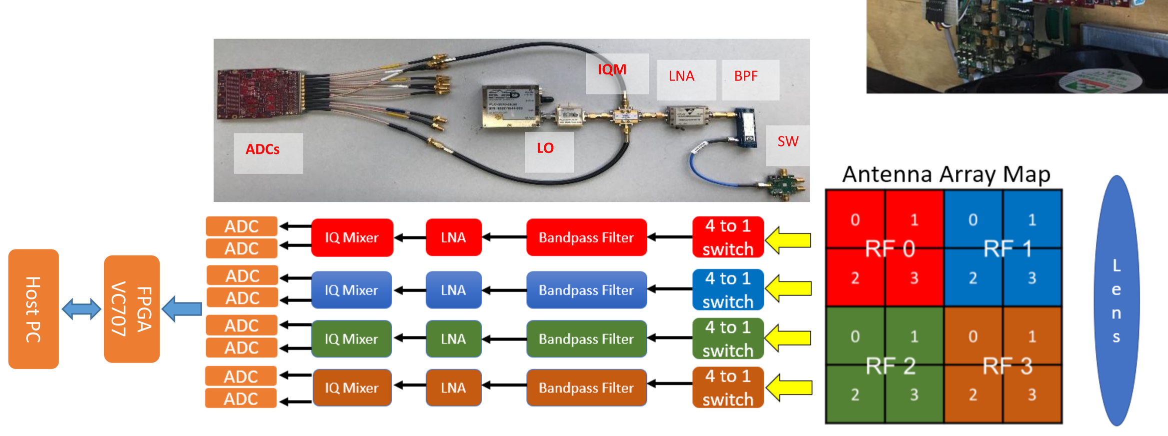
III. Multi-beam CAP-MIMO Testbed

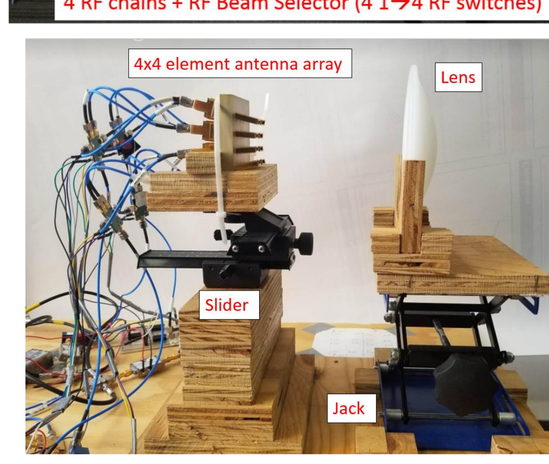
Access Point Architecture



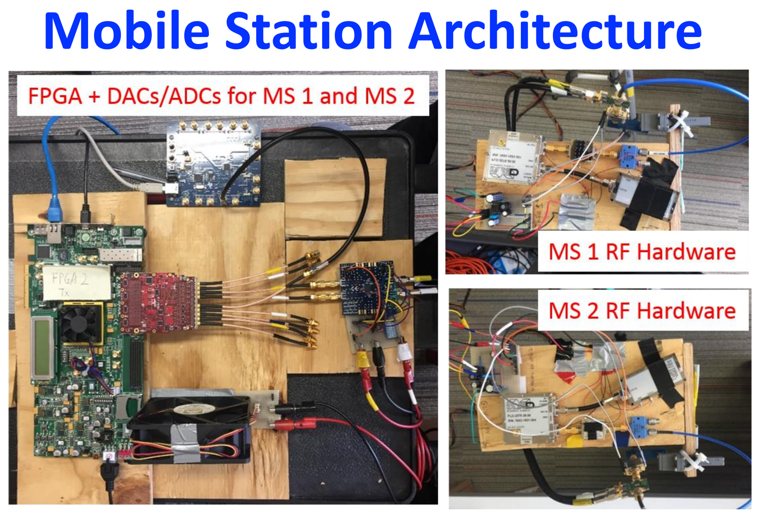


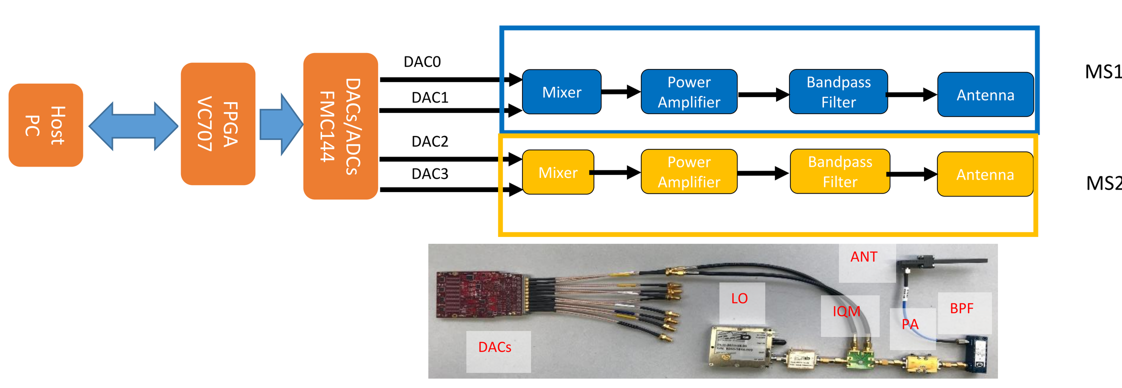






Mobile Station Architecture





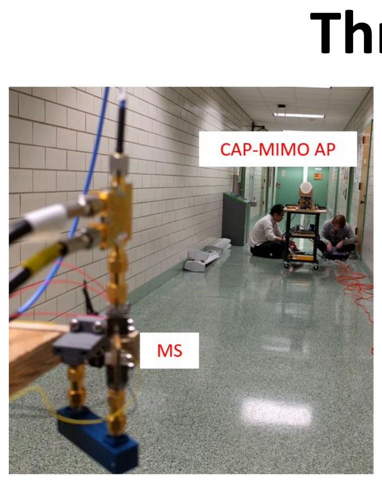
Features

- **Unprecedented 4-beam steering & data mux.**
- **Lens Size : 6 in diameter.**
- RF BW: 1 GHz, Symbol rate: 370 MS/s
- AP – 4 MS bi-directional P2MP link
- FPGA-based backend DSP

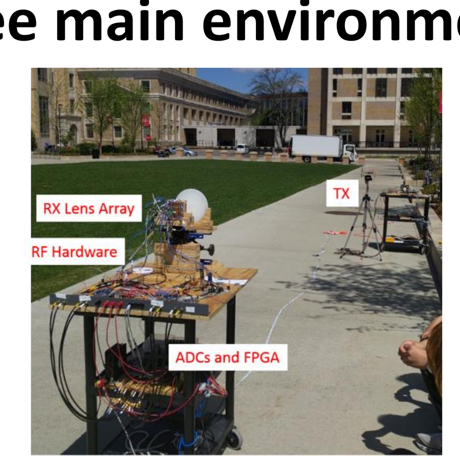
Use cases

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

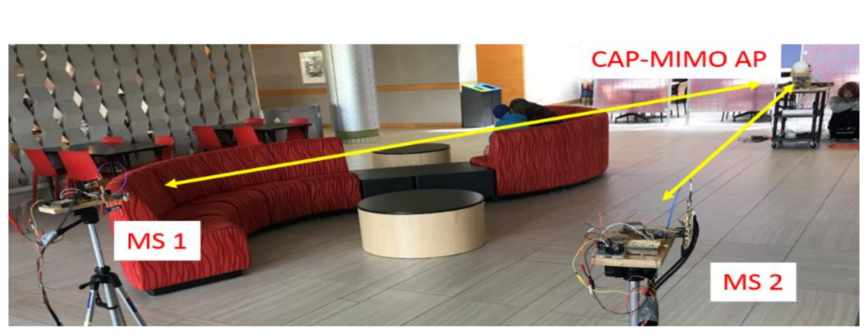
Three main environments for measurements



Indoor hallway



Outdoor link (up to 200 ft)



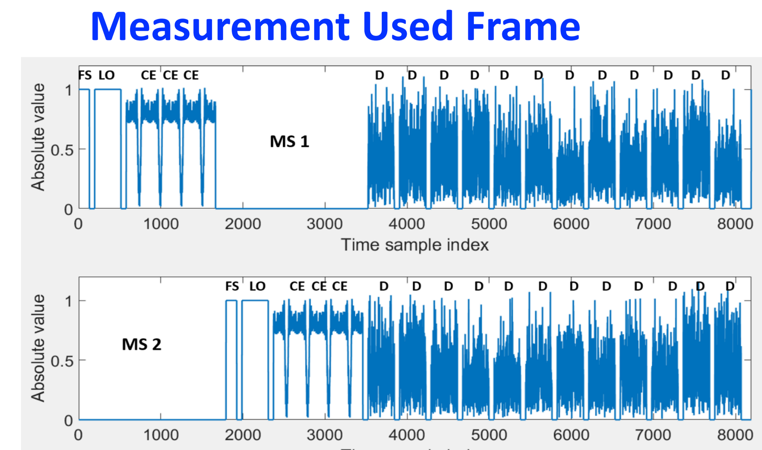
Indoor open atrium (LoS & NLoS)

IV. Measurement Results

Measurement Analysis Capability

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

Measurement Used Frame



- 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)

1. Data Forensics Example: Frame Sync Correlation Values

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

100 captures / measurement/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

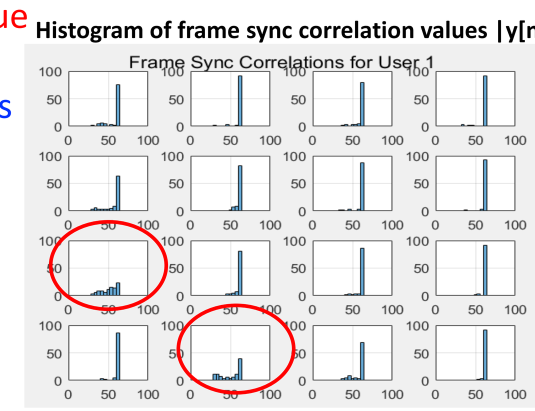
More reliable data analysis, e.g.:

- channel impulse response
- PDPs
- PSDs

$$y[n] = \sum_{k=0}^{N_{sync}-1} r[n+k]\, s_{sync}[k]$$

$$\text{sync index} = \arg\max_n |y[n]|$$

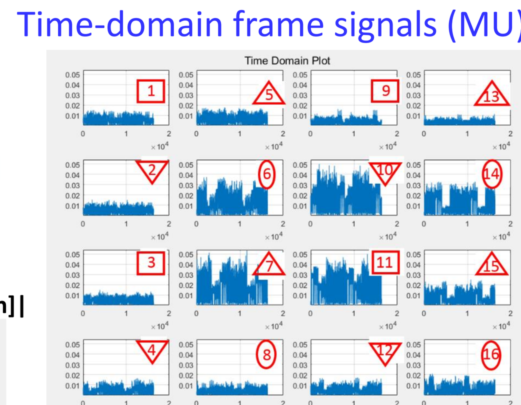
Histogram of frame sync correlation values |y[n]|



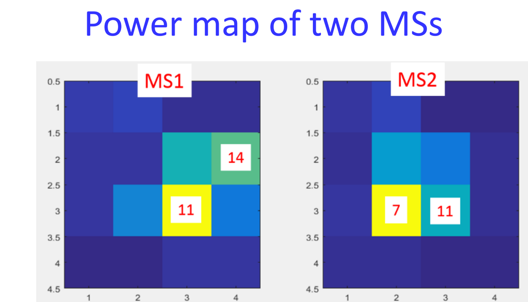
Maximum possible correlation value is 64

2. Multiuser Communication: Indoor Hallway Measurements

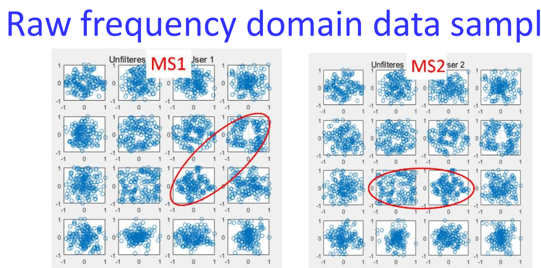
Time-domain frame signals (MU)



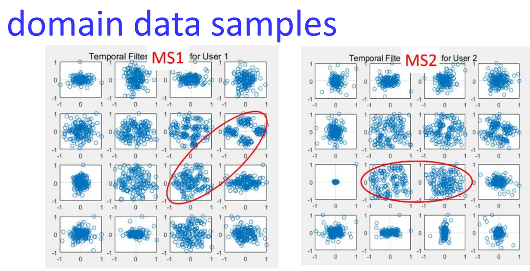
Power map of two MSs



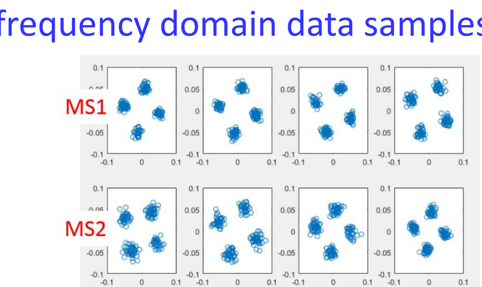
Raw frequency domain data samples



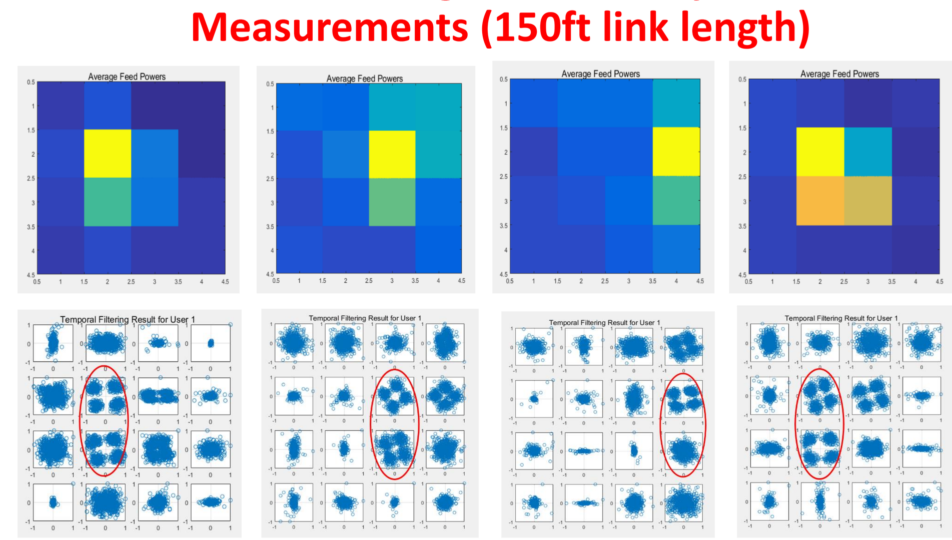
Temporally Filtered frequency domain data samples



Spatially & temporally filtered frequency domain data samples



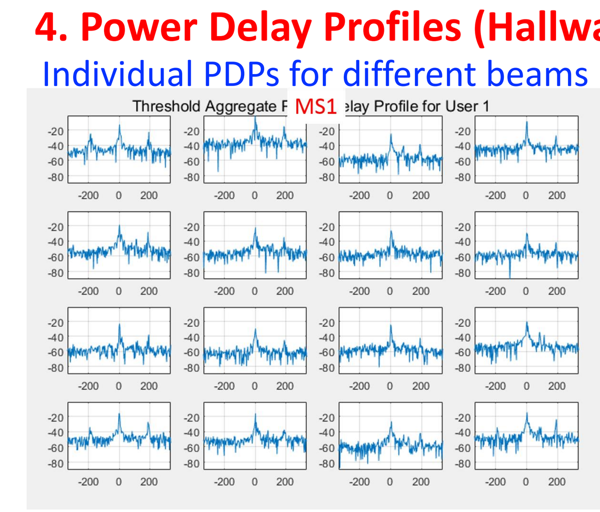
3. Directional Focusing of Lens Array: Outdoor LoS Measurements (150ft link length)



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

4. Power Delay Profiles (Hallway Channel Measurements)

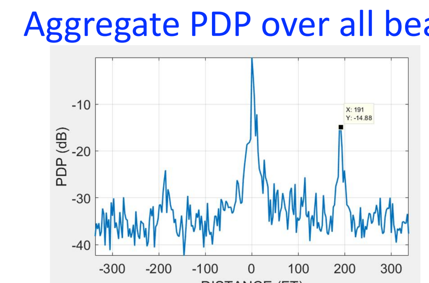
Individual PDPs for different beams



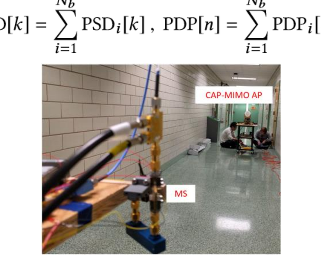
$PSD_i[k] = |\hat{h}_{b,i}[k]|^2$, $PDP_i[n] = |\hat{g}_{b,i}[n]|^2$

Frequency response (i-th beam) Impulse response (i-th beam)

Aggregate PDP over all beams



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



Potential Applications and Impact

- Disruptive 5G technology
- Multi-Gigabit speeds
- Millisecond latency
- Key use cases: Backhaul, Last Mile, & Mobile Access
- Scalability to meet performance metrics with minimum complexity
- New channel sounding architecture for multi-beam measurements