Multi-Aperture Phased Arrays Versus Multi-beam Lens Arrays for Millimeter-Wave Multiuser MIMO

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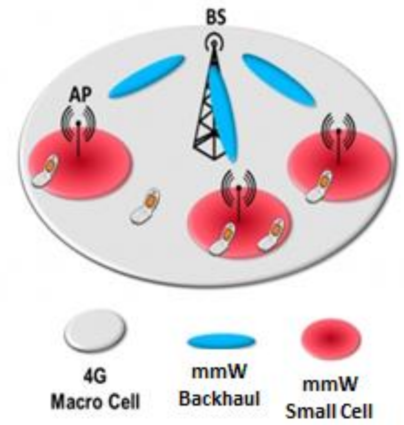
Exciting Times for mmW Research

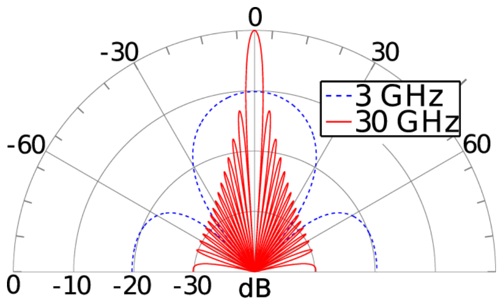
- A key component of 5G
  - Multi-Gigabits/s speeds
  - millisecond latency
- Key Gigabit use cases
  - Wireless backhaul
  - Wireless fiber-to-home (last mile)
  - Small cell access
  - Autonomous Vehicles
- New FCC mmW allocations
  - Licensed (3.85 GHz): 28, 37, 39 GHz
  - Unlicensed (7 GHZ): 64-71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



Two Key Advantages of mmW

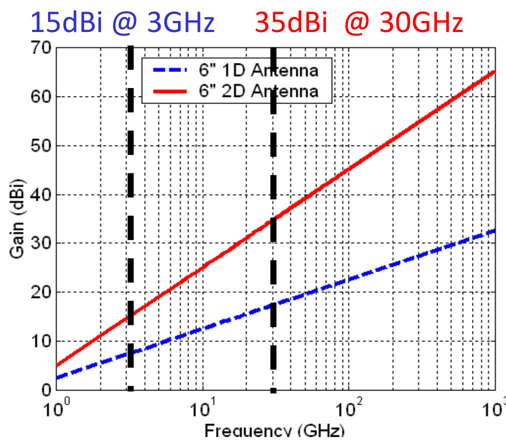
Large bandwidth & narrow beams

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



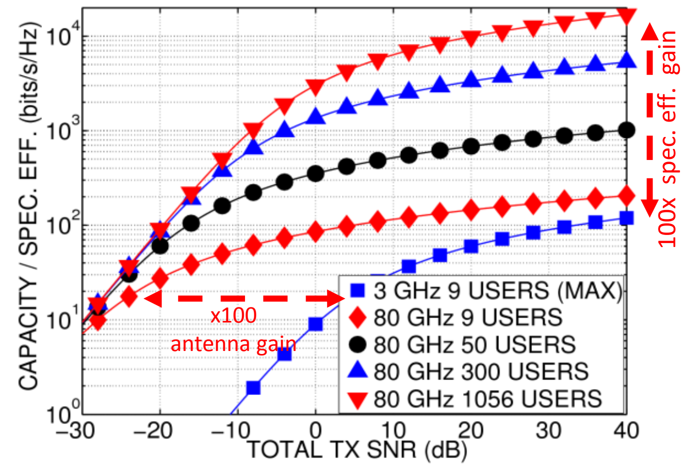
35 deg @ 3 GHz

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 & Comp. Complexity (# T/R chains)

Conceptual and Analytical Framework: Beamspace MIMO

Beamspace Multiplexing

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

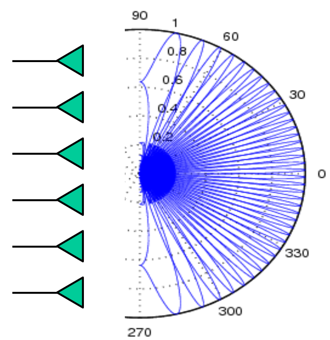
Antenna space multiplexing

Discrete Fourier Transform (DFT)

Beamspace multiplexing

n-element array

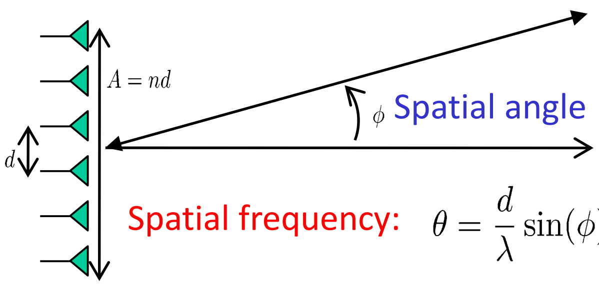
($\frac{\lambda}{2}$ spacing)



n dimensional signal space

n orthogonal beams

n spatial channels

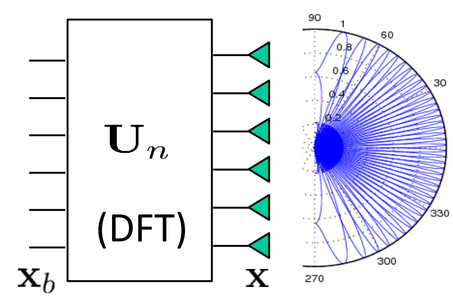


Spatial frequency: $\theta = \frac{d}{\lambda}\sin(\phi)$

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

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

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

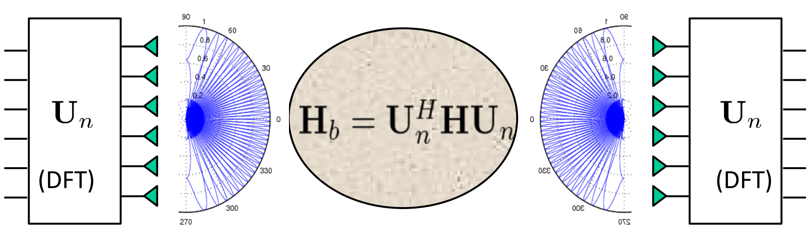
(AS TSP '02; AS & NB Allerton '10; JB, NB & AS TAPS '13) comm. modes in optics (Gabor '61, Miller '00, Friberg '07)

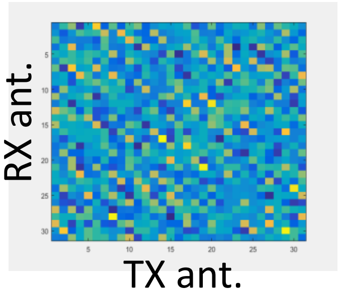
Beamspace Channel Sparsity

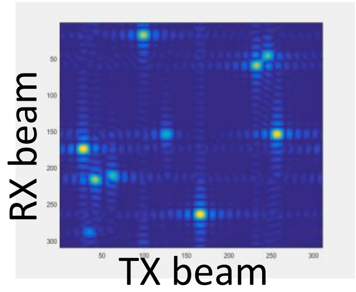
mmW propagation X-tics

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

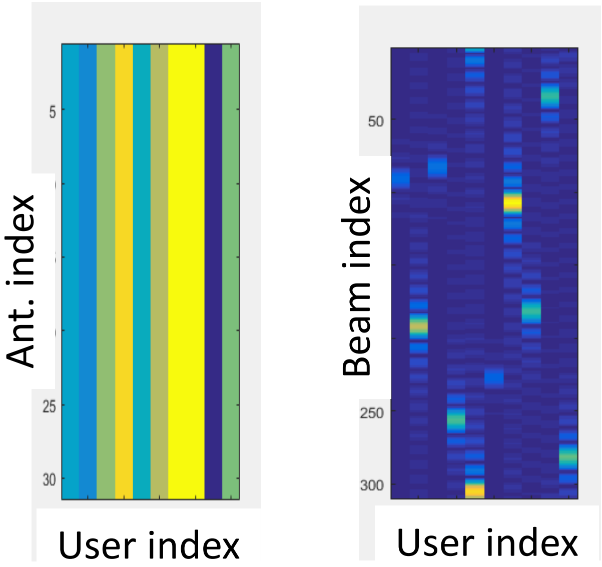
Point-to-multipoint MIMO link







Point-to-multipoint multiuser MIMO link



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

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

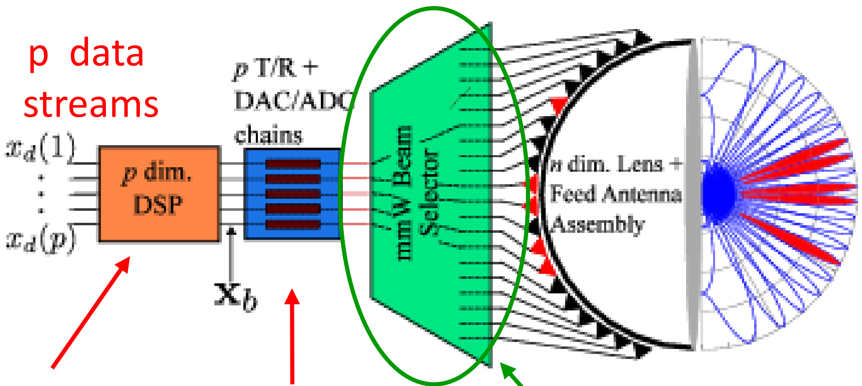
How to access the *p* active beams with the lowest - *O(p)* - transceiver complexity?

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

Hybrid Analog-Digital Beamforming

Lens Array Architecture

p data streams



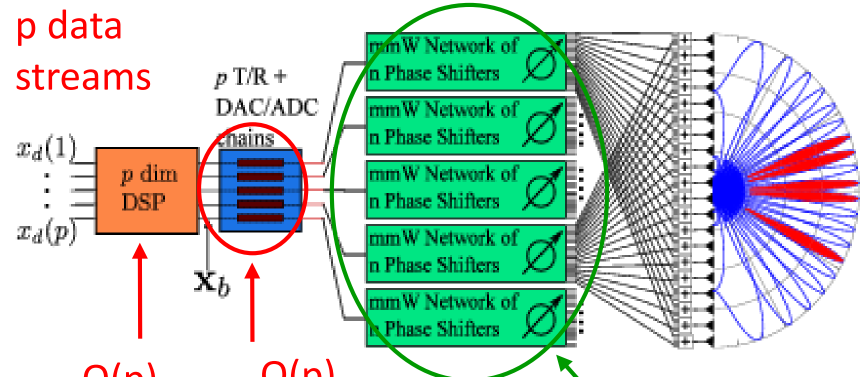
Comp. Complexity: n → p dim. matrix ops

Hardware Complexity: n → p RF chains

p → n Beam selector (switching) network

Phased Array Architecture

p data streams

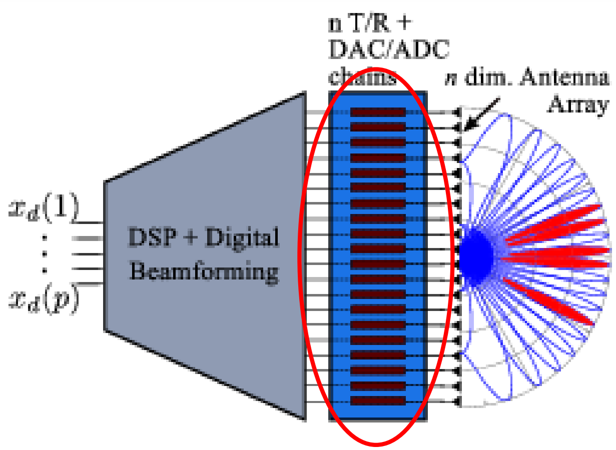


O(p) comp. complexity

O(p) T/R chains

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

Digital Beamforming Architecture



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

$N_{RF} = 1$: Analog beamforming

$N_{RF} = n$: Digital beamforming

$1 < N_{RF} < n$: Hybrid beamforming

(RH et al., JSTSP 2017)

Lens Array versus Phased Array for Multi-beam Forming

Key performance/complexity/cost metric: number of RF chains = N_{RF}

Three cases help differentiate between the three mmW MIMO arhitectures:

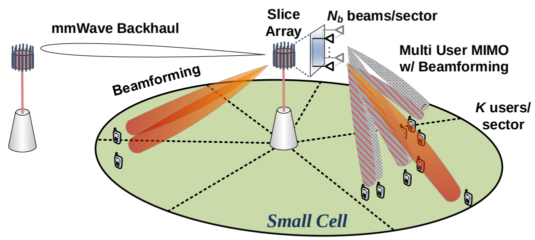
- **Extreme 1:** $N_{RF} = 1$: a single-beam phased array for **analog beamforming** (ABF) is most cost effective
- **Extreme 2:** $N_{RF} = n$ = number of antennas: A conventional (massive) MIMO system with **digital beamforming** (DBF) is most effective
- **Intermediate:** $1 < N_{RF} < n$: the practically most relevant case – **hybrid analog-digital beamforming** (HBF) is needed.

  Two main possibilities for generating N_{RF} beams:

  1) multi-beam CAP-MIMO architecture

  2) multi-aperture phased array architecture - one sub-array for each beam

Small Cell: AP and Coverage Parameters

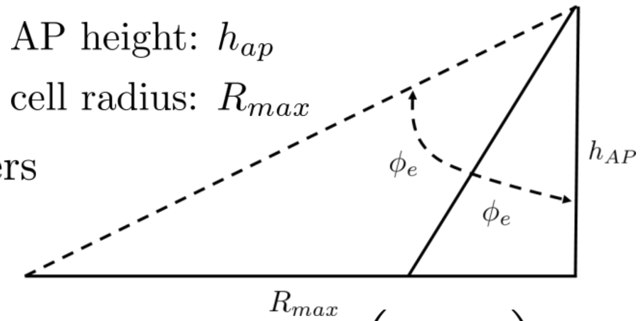


AP height: h_{ap}

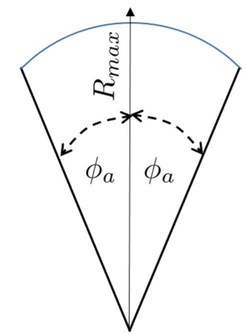
cell radius: R_{max}

$K = 100$ users

$W = 1$ GHz



$$\phi_e = \frac{1}{2}\tan^{-1}\left(\frac{R_{max}}{h_{ap}}\right)$$



ϕ_a azimuth spread

AP Antenna Aperture (L_a or n_a × L_e or n_e)

Antenna size: $L_a \times L_e$

Antenna dimension:

$n = n_a \times n_e$

n_a - azimuth , n_e - elevation

$n_a = \frac{2L_a}{\lambda}$, $n_e = \frac{2L_e}{\lambda}$

One-sided sector **angular spreads**:

azimuth, elevation: $\phi_a, \phi_e \in (0, \pi/2]$

Two-sided beam spreads:

$2\theta_a = \sin(\phi_a)$, $2\theta_e = \sin(\phi_e)$

Orthogonal beams over coverage area:

$n_b = n_{ba} \times n_{be}$, n_{ba} - azimuth , n_{be} - elevation

$$n_{ba} = \frac{2\theta_a}{\Delta\theta_a} = n_a \sin(\phi_a) \;,\; n_{be} = \frac{2\theta_e}{\Delta\theta_e} = n_e \sin(\phi_e)$$

beam spacing: $\Delta\theta_a = \frac{1}{n_a}$, $\Delta\theta_e = \frac{1}{n_e}$

AP Array Size and Aspect Ratio

Depends on:

- SNR requirements (cell size)
- K: # users
- n_b: # orthogonal beams in the coverage area

Fundamental relationship between n and n_b

$$n = \frac{n_b}{\sin(\phi_a)\sin(\phi_e)} = \frac{n_{b,a}}{\sin(\phi_a)} \times \frac{n_{b,e}}{\sin(\phi_e)} = n_a \times n_e$$

Need $n_b \geq N_{RF}$ larger $n_b \Rightarrow$ higher gain & lower interference

higher beam management complexity

Aspect ratio: $\alpha = \frac{n_a}{n_e}$

Given n_b, ϕ_e, and ϕ_a, how should we choose n_a, n_e?

Case 1: Equal number of beams in azimuth and elevation

$$n_{b,a} = n_{b,e} = \sqrt{n_b} \Longleftrightarrow \alpha = \frac{n_a}{n_e} = \frac{\sin(\phi_e)}{\sin(\phi_a)} \Longrightarrow n_a = \frac{\sqrt{n_b}}{\sin(\phi_a)}, n_e = \frac{\sqrt{n_b}}{\sin(\phi_e)}$$

Optimum Phased Array Configuration

$$C_{PA}(P,R) = \frac{W N_{RF}}{K} \log_2\left(1 + \frac{PnK\gamma}{N_{RF}^2 N_o W}\right) \text{ bits/s (bps)}$$

$$= W_u \log_2\left(1 + \frac{Pn\gamma}{N_{RF} N_o W_u}\right)$$

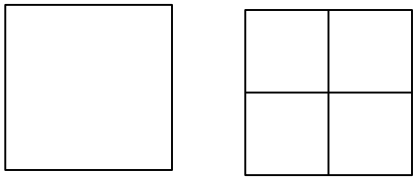
Per-user bandwidth:

$$W_u = \frac{W}{K_{RF}} = \frac{W N_{RF}}{K}$$

Two competing effects of $N_{RF} = N_s$ - the number of sub-arrays:

$\uparrow N_{RF}$ (number of sub-arrays) $\Longrightarrow \uparrow C_{PA}$

$\uparrow N_{RF} \Longrightarrow \downarrow n_s = \frac{n}{N_{RF}}$ - size of sub-array

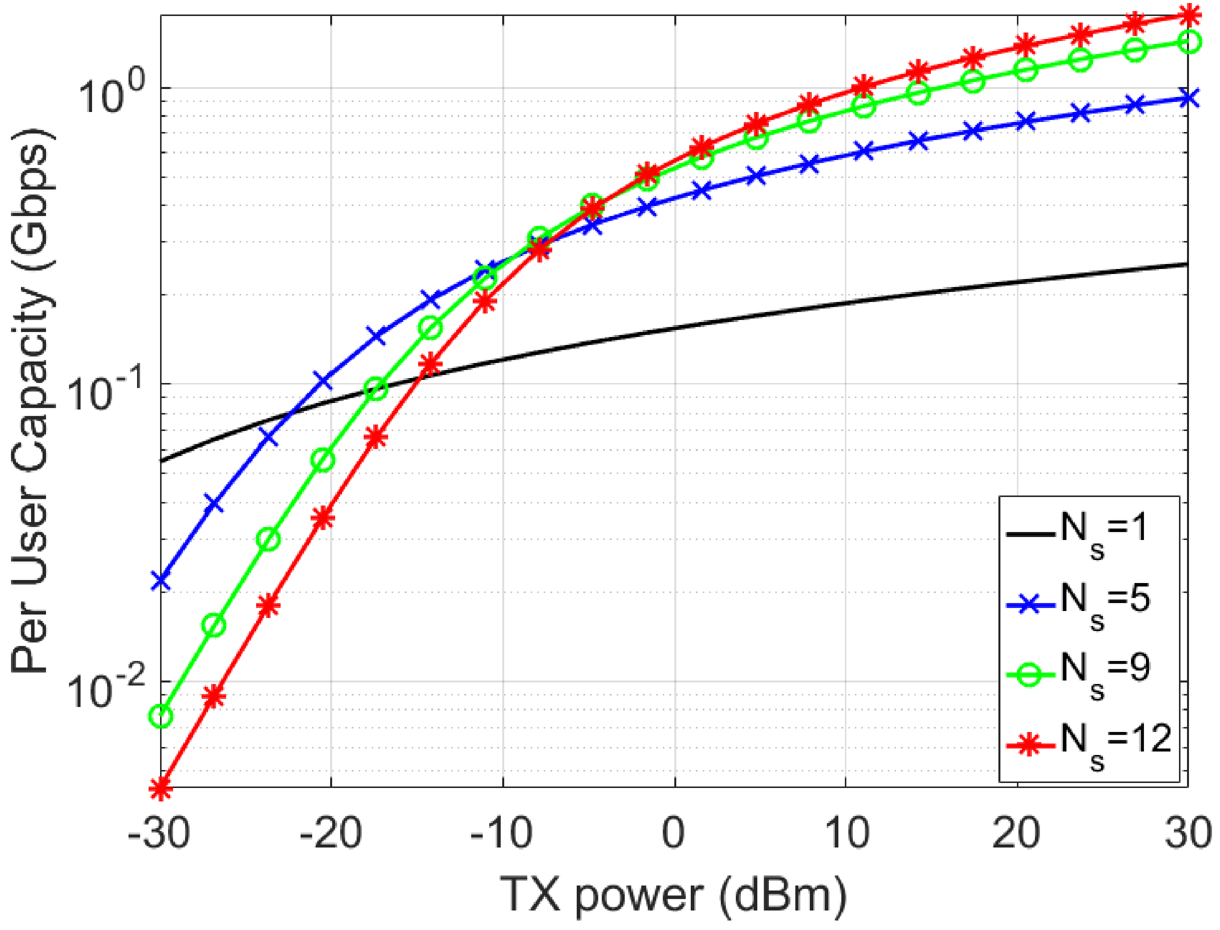


$n_s = \frac{n}{N_{RF}}$ determines sub-array gain and # orthogonoal beams

need: # $\perp$ beams from each sub-array $= \frac{n_b}{N_{RF}} \geq N_{RF} \Longrightarrow N_{RF} \leq \sqrt{n_b}$

$$N_{s,opt} = \sqrt{n_b} = N_{RF}$$

PA Capacity Plot



Optimum Phased Array Configuration

Ant. dim.: $n = N_s \times n_s = (N_{sa} \times N_{se}) \times (n_{sa} \times n_{se})$

$n_b = 144$

\# sub-arrays \# elements in sub-array

Multiple sub-arrays:

$n = 240$

$= N_s \times n_s$

$= 12 \times 20$

\# sub-arrays: $N_s = 12$

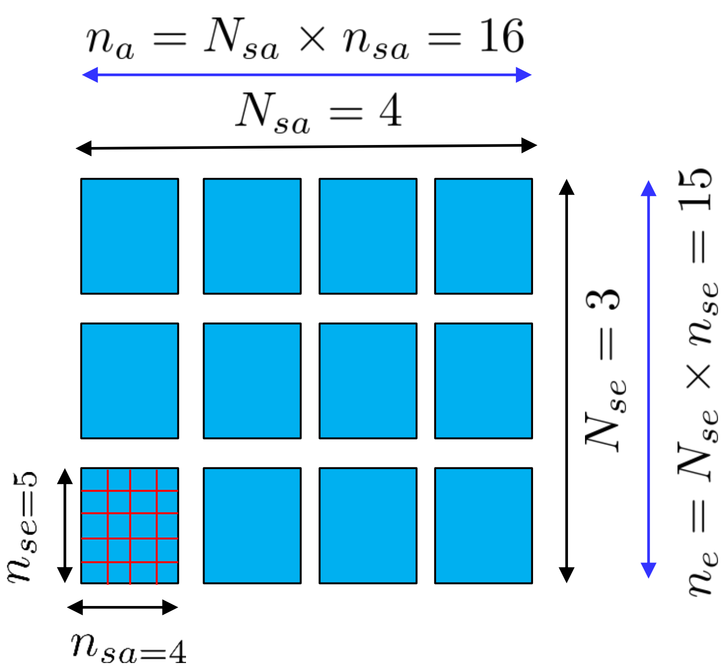
$= n_{sa} \times n_{se}$

$= 4 \times 3$

\# elements in sub-array: $n_s = 20$

$= n_{sa} \times n_{se}$

$= 4 \times 5$



Single array:

$n = 240$

$= n_a \times n_e$

$= 16 \times 15$

$$N_{s,opt} = \sqrt{n_b} = N_{RF} = 12$$

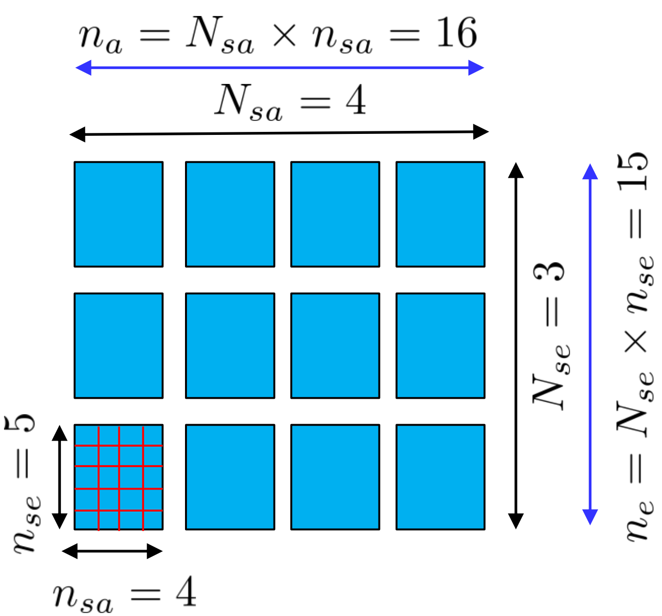
CAP-MIMO AP: Beamspace Sectoring

$$N_{so} = N_{RF} = \sqrt{n_b} = N_{sa} \times N_{se} - \#\text{ beamspace sectors}$$

$$n_{b,s} = \sqrt{n_b} = n_{b,sa} \times n_{b,se} - \#\text{beams per sector}$$

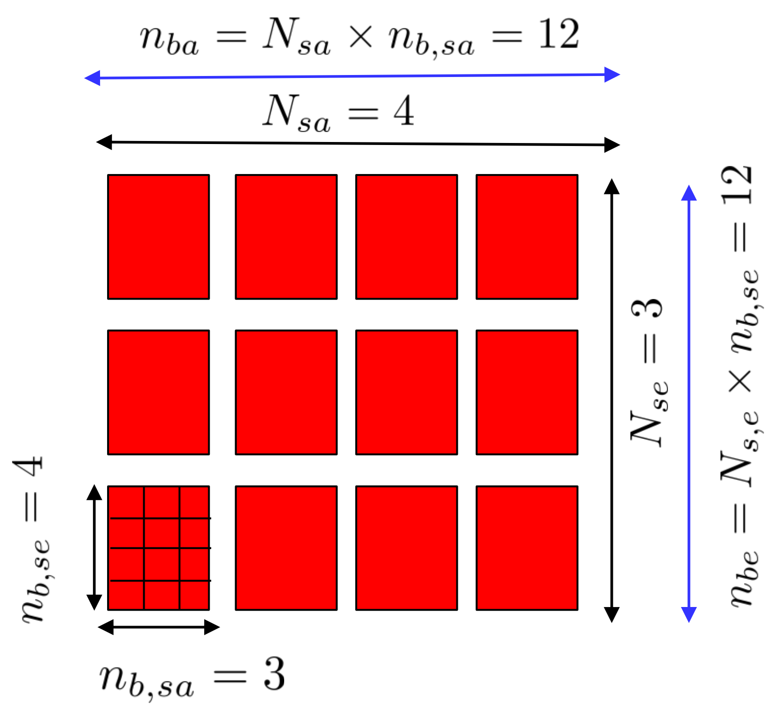
Phased Array

Array partitioning



$n_{b,s} = \sqrt{n_b} \approx 12$
beams coverage

CAP-MIMO
Beamspace sectoring



$n_b \approx 144$
beams coverage

Idealized Per-User Capacity Expressions

$$W_u = \frac{W}{K_{RF}} = \frac{WN_{RF}}{K} \text{ -- per-user bandwidth} \quad K_{RF} = \frac{K}{N_{RF}} \text{ -- users per RF chain}$$

$$C = W_u \log_2\left(1 + \frac{PG\gamma}{N_o W_u}\right) \text{ bits/s (bps)}$$

$$C_{PA} = \frac{WN_{RF}}{K}\log_2\left(1 + \frac{PnK\gamma}{N_{RF}^2 N_o W}\right) \text{ bits/s (bps)}$$

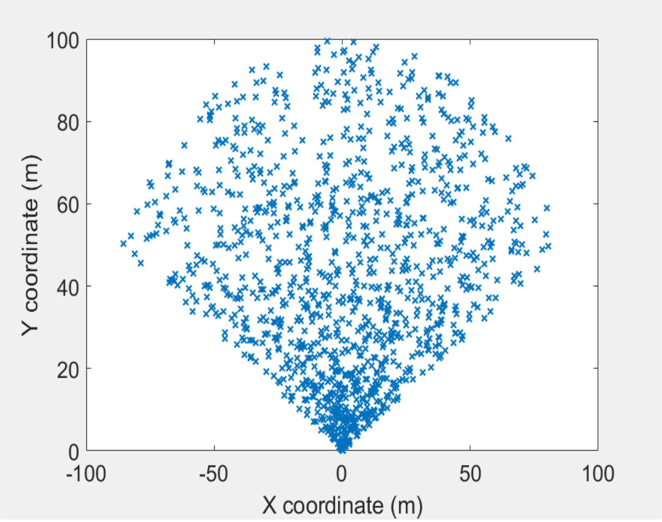
$$C_{CM} = \frac{WN_{RF}}{K}\log_2\left(1 + \frac{PnK\gamma}{N_{RF} N_o W}\right) \text{ bits/s (bps)}$$

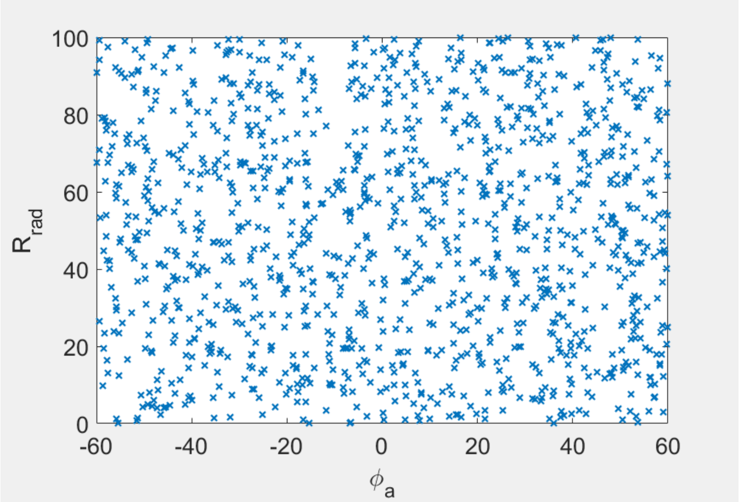
$$N_{RF,opt} = \sqrt{n_b} \qquad n_{s,opt} = \frac{n}{\sqrt{n_b}} \qquad \gamma = \left(\frac{\lambda}{4\pi R}\right)^2$$

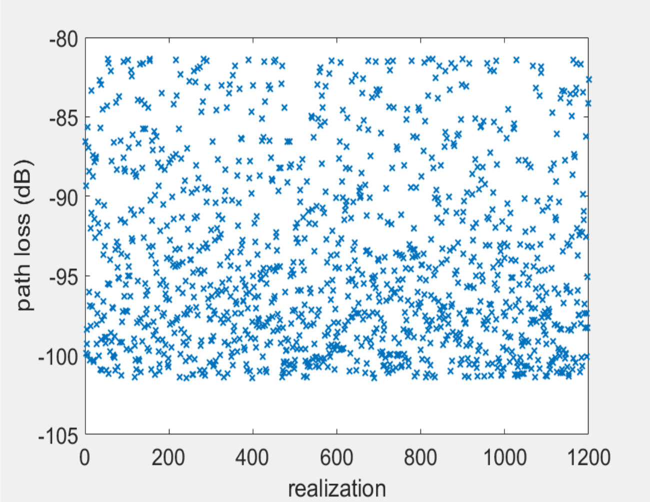
Free space path loss

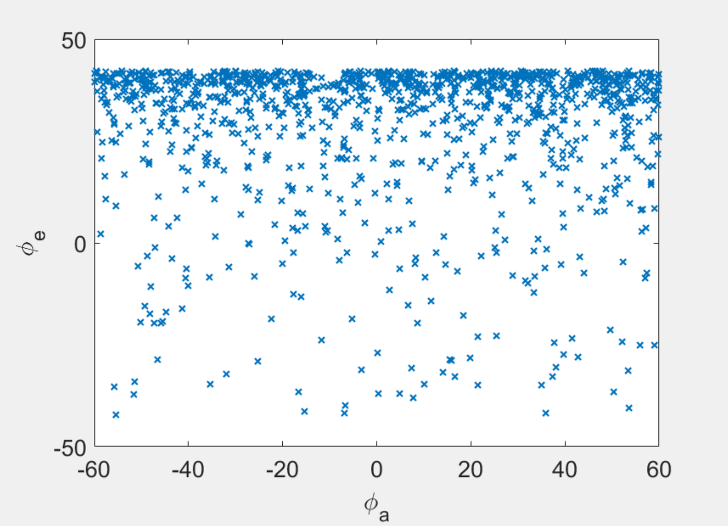
Simulation Parameters

$W = 1$ GHz, $K = 100$ users, $R_{max} = 100$m, $h_{AP} = 10$m $2\phi_a = 120^o$, $2\phi_e = 84^o$









3.4” x 3.2” AP with 144 Beam Coverage

$L_a = 3.4\text{”}\ \ L_e = 3.2\text{”}$ $\qquad 2\phi_a = 120^o\ ,\ 2\phi_e = 84^o$

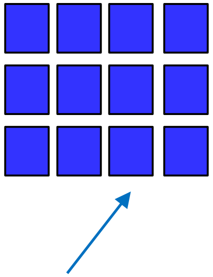
$n \approx 240\ (16 \times 15)$ $\qquad \#\ \text{beams (cover)}:\ n_b \approx 144\ (12 \times 12)$

$N_{RF} = 12$ RF chains; $K = 100$ users; $K_{RF} = 8.33$ users/beam

Phased Array

4×3

Array partitioning

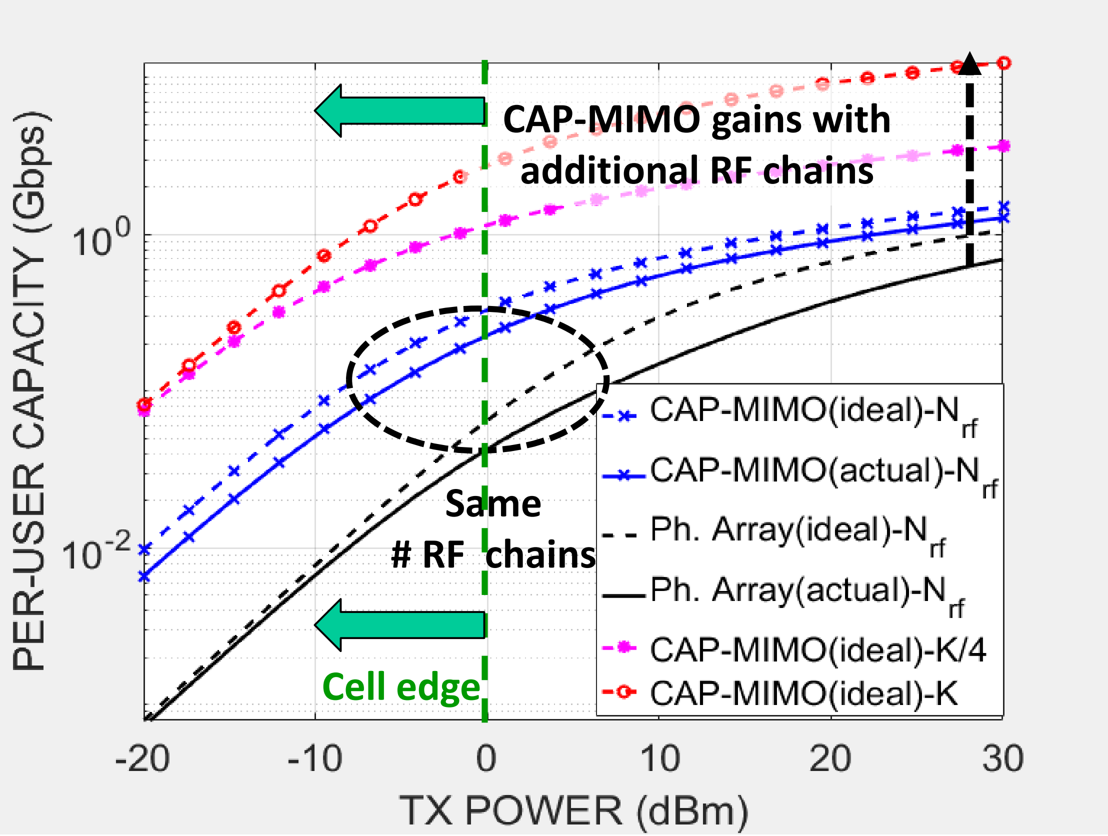


4×5

Sub-array

$\sqrt{n_b} \approx 12$

beams coverage

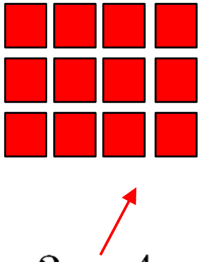


1 GHz bandwidth; includes Friis free-space path loss

CAP-MIMO

4×3

Beamspace sectoring



3×4

Sub-sector

$n_b \approx 144$

beams coverage

2 beams/feed

$1 \mapsto 6$ switch

5.3” x 5.9” AP with 400 Beam Coverage

$L_a = 5.3” \;\; L_e = 5.9”$ $2\phi_a = 120^o \;\; , \;\; 2\phi_e = 84^o$

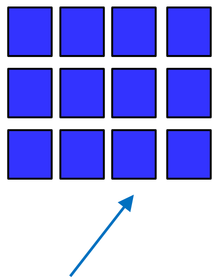
$n \approx 700 \; (25 \times 28)$ $\#$ beams (cover): $n_b \approx 400 \; (20 \times 20)$

$N_{RF} = 20$ RF chains; $K = 100$ users; $K_{RF} = 5$ users/beam

Phased Array

5×4

Array partitioning

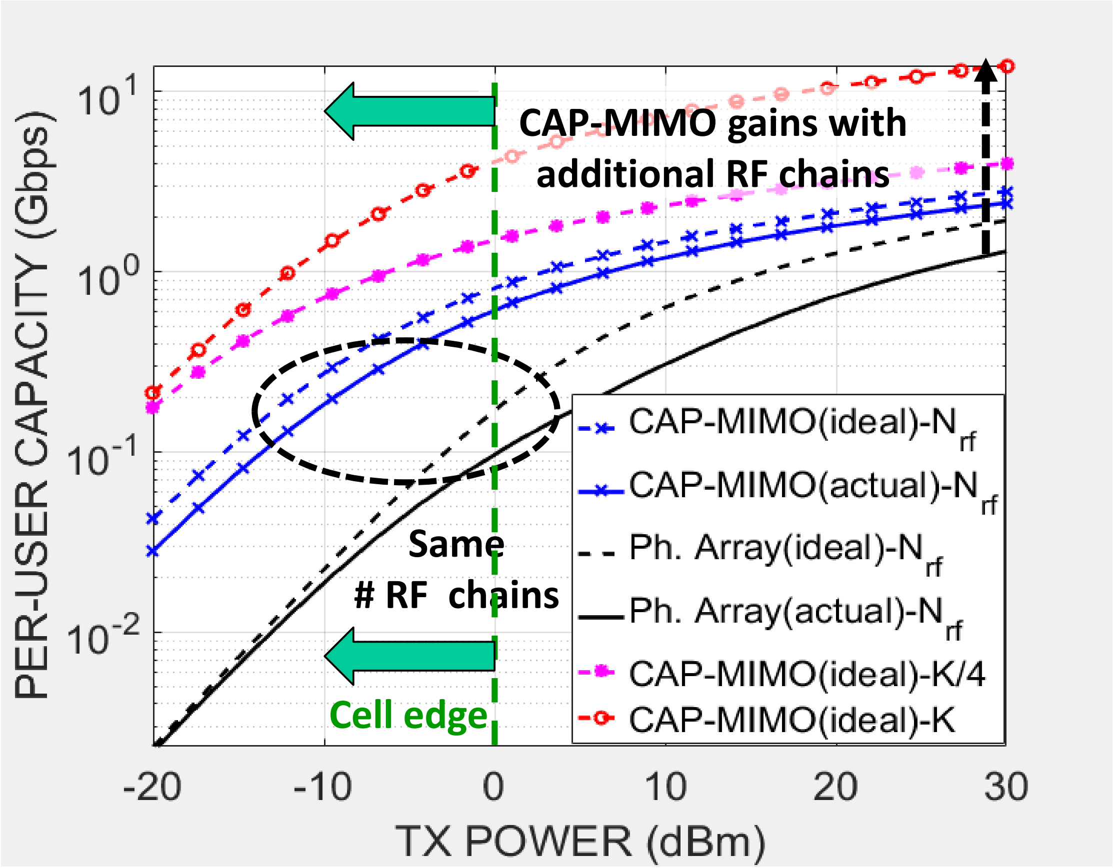


5×7

Sub-array

$\sqrt{n_b} \approx 20$

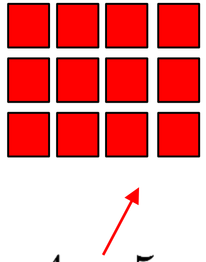
beams coverage



CAP-MIMO

5×4

Beamspace sectoring



4×5

Sub-sector

$n_b \approx 400$

beams coverage

4 beams/feed

$1 \mapsto 5$ switch

1 GHz bandwidth; includes Friis free-space path loss

Key Observation

CAP-MIMO AP spans the coverage area with n_b beams

Phased Array AP spans the coverage area with $n_{b,s} = \sqrt{n_b}$ beams

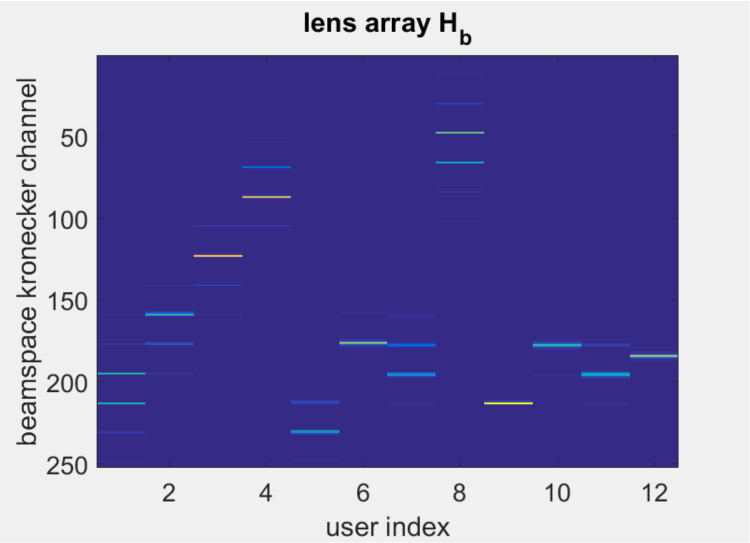
$$\Rightarrow \frac{\text{Phased Array Beamwidth}}{\text{CAP-MIMO Beamwidth}} \approx \sqrt{n_b}$$

The idealized comparison accounts for this in SNR/array gain only
Would also impact multiuser interference

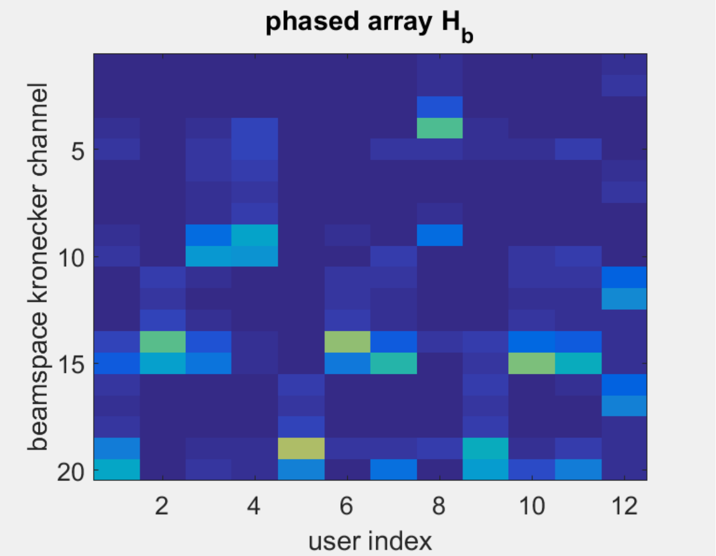
For the $n_b = 144$ example:
Phased array beamwidths: 28^o in azimuth and 23^o in elevation
Lens Array beamwidths: 7^o in azimuth and 7.5^o in elevation
Overall a factor of $\sqrt{n_b} = 12 = 4 \times 3$ **larger beam area** for phased array

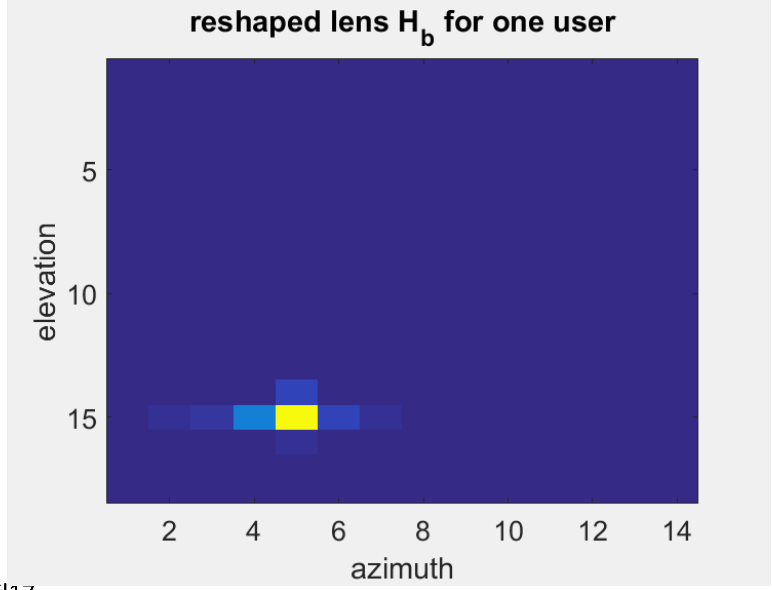
Beamspace Channels

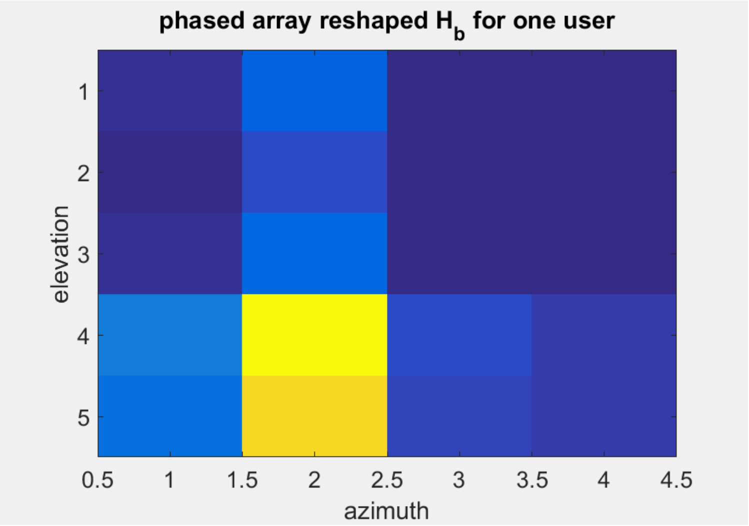
Lens Array $n_b = 144$



Phased Array $n_{b,s} = 12$





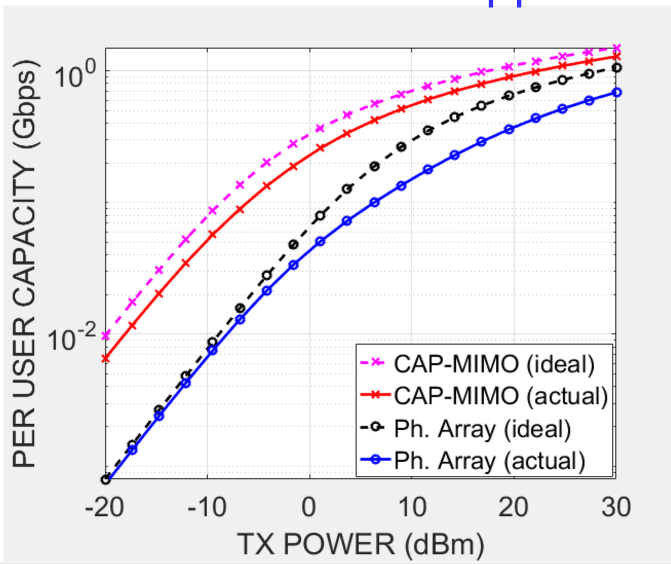


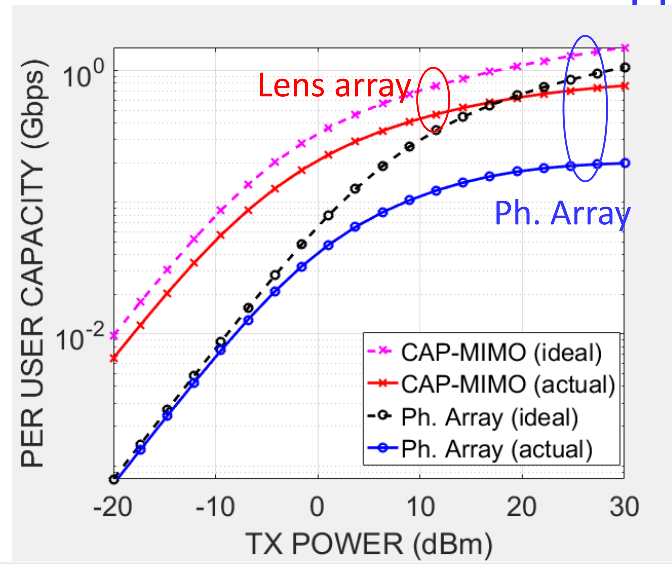
With or Without Interference Suppression

MMSE – int. supp.

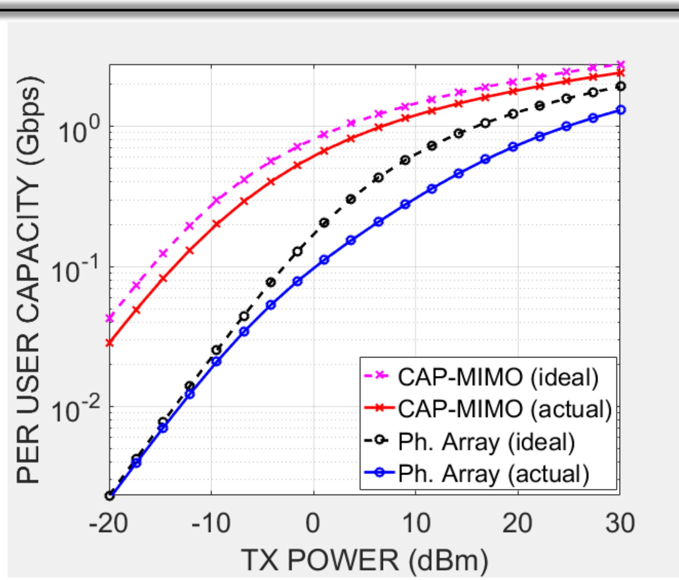
matched filter – no int. supp.

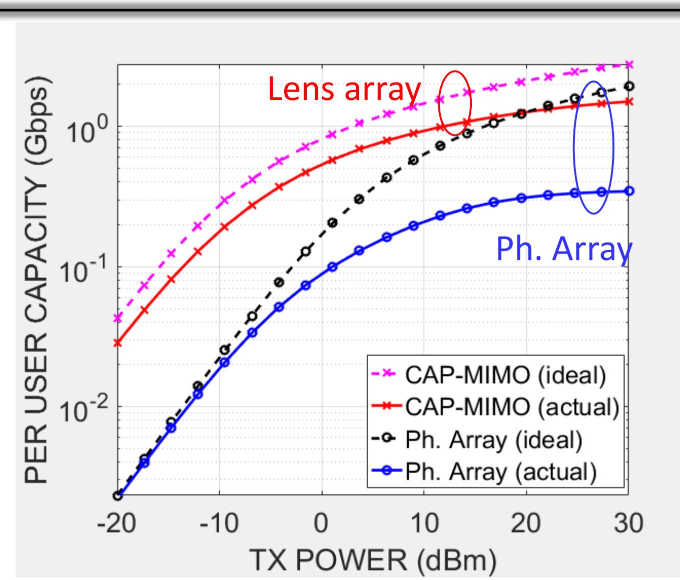
$$n_b = 144$$
$$N_{RF} = 12$$
$$K_{RF} = 8.33$$





$$n_b = 400$$
$$N_{RF} = 20$$
$$K_{RF} = 5$$





MMSE vs MF Spatial Processing

Antenna domain Uplink model:

$$\mathbf{r} = \sum_{k=1}^{K} s_k \beta_k \mathbf{h}_k + \mathbf{w} = \mathbf{H}\beta\mathbf{s} + \mathbf{w}$$

$$\beta = \mathrm{diag}(\beta_1, \cdots, \beta_K) \ , \ \beta_k = \frac{e^{j\psi_k}\lambda}{4\pi R_{min}} \quad \mathbf{H} = [\mathbf{h}_1, \cdots, \mathbf{h}_K] \ , \ \mathbf{h}_k = \mathbf{a}_{n_a}(\theta_{a,k}) \otimes \mathbf{a}_{n_e}(\theta_{e,k})$$

Beamspace:

LoS user channels

$$\mathbf{r}_b = \mathbf{U}^H \mathbf{r} = \mathbf{H}_b \beta \mathbf{s} + \mathbf{w}_b \qquad \mathbf{h}_{b,k} = \mathbf{U}^H \mathbf{h}_k$$

$$\mathbf{H}_b = \mathbf{U}^H \mathbf{H} = [\mathbf{h}_{b,1}, \cdots, \mathbf{h}_{b,K}] \qquad = [\mathbf{U}_{n_a}^H \mathbf{a}_{n_a}(\theta_{a,k})] \otimes [\mathbf{U}_{n_e}^H \mathbf{a}_{n_e}(\theta_{e,k})]$$

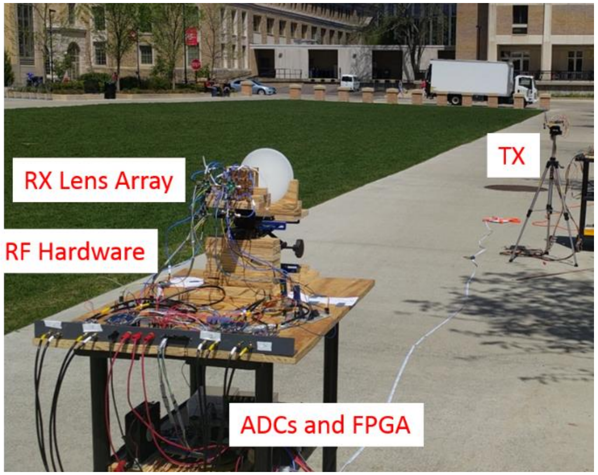
$$\text{beamspace processing: } \mathbf{z}_b = \mathbf{L}^H \mathbf{r}_b = \mathbf{L}^H \mathbf{H}_b \beta \mathbf{s} + \mathbf{L}^H \mathbf{w}_b$$

$$\text{Sum rate: } C(\mathbf{L}_b) = E_{\mathbf{H}} \left[\frac{W N_{RF}}{K} \sum_{k=1}^{N_{RF}} \log_2(1 + \mathrm{SINR}_k(\mathbf{L}_b, \mathbf{H}_b)) \right] \text{ bps}$$

28 GHz Multi-beam CAP-MIMO Testbed

P2MP Link

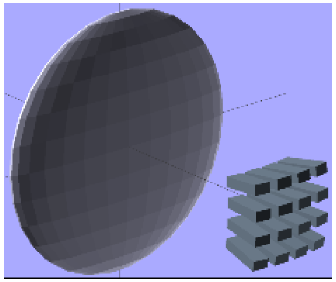
P2P Link

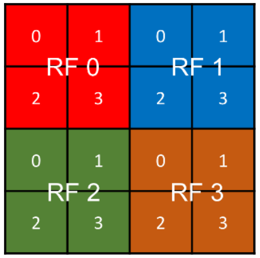


6” Lens with 16-feed Array

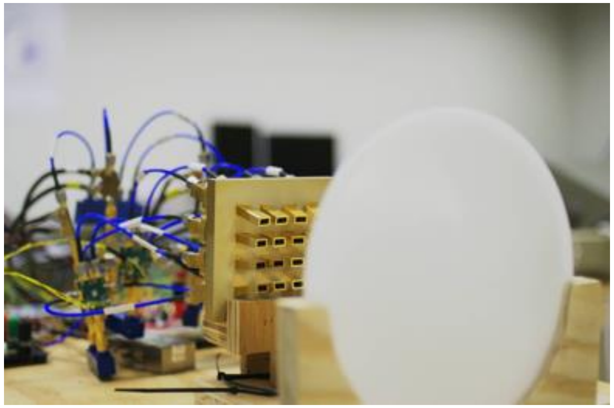
Equivalent to 600-element conventional array!

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.; AS, CH, YZ, mmNets 2017)

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

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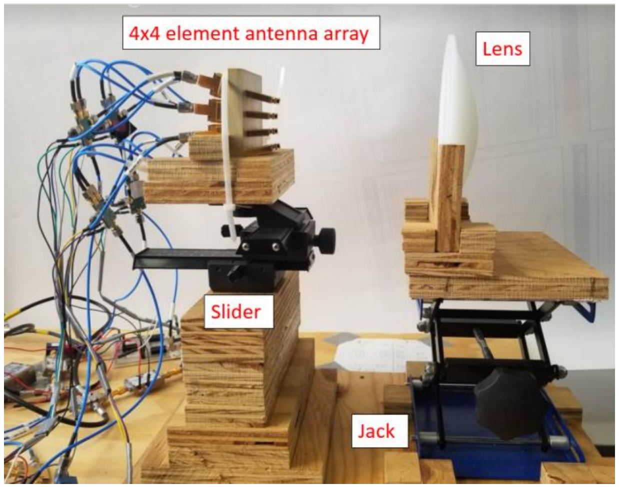
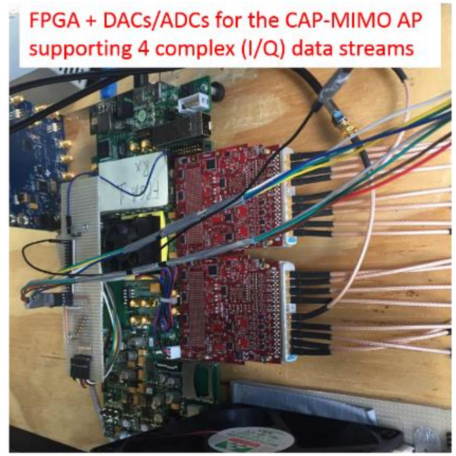
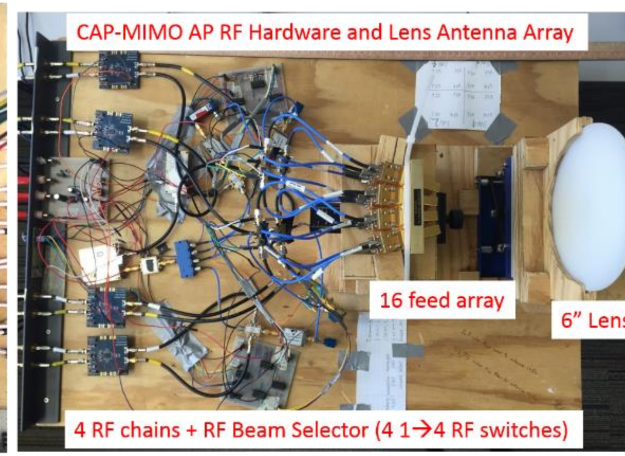
6” Lens with 16-feed Array

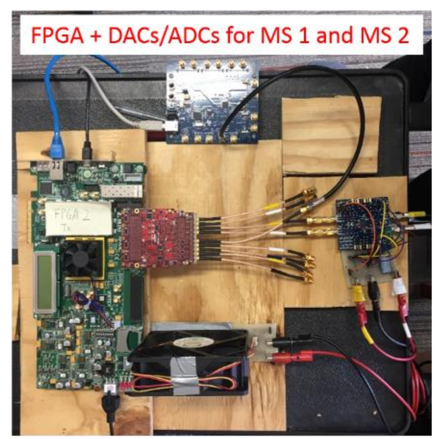


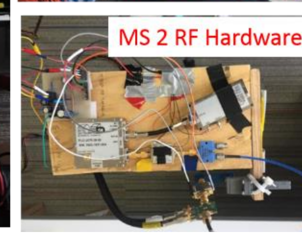
CAP-MIMO Access Point (AP)





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.)

Conclusion

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- Phased arrays limited to single beam/RF chain per aperture
- Sub-arrays for multiple beams:
  - Wider beams
  - Lower array gain & higher interference
- Lens arrays do not have the limitation
  - Significantly improved performance for same # RF chains
  - Flexibility to add more RF chains for even higher capacity
- Future work
  - Explicitly addressing frequency domain multiplexing
  - Hardware non-idealities & losses (phase shifters, switches)

Some Relevant Publications

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

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Thank You!

- A. Sayeed, C. Hall and Y. Zhu, *A Lens Array Multi-beam MIMO Testbed for Real-Time mmWave Communication and Sensing*, invited paper, First ACM mmNets workshop, Snowbird, UT, Oct. 16, 2017.
- 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.
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- 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.