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

- 15dBi @ 3GHz
- 35dBi @ 30GHz
- 35 deg @ 3 GHz
- 4 deg @ 30 GHz

Key Operational Functionality: Multibeam steering & data multiplexing

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

Conceptual and Analytical Framework: Beamspace MIMO

Potential of beamspace multiplexing
Power & Spec. Eff. Gains over 4G

> 100X gains in power and & spectral efficiency
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

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

\(-\frac{\pi}{2} \leq \phi \leq \frac{\pi}{2}\)
\(d = \frac{\lambda}{2}\)
\(-\frac{1}{2} \leq \theta \leq \frac{1}{2}\)

DFT matrix: Beamspace modulation

\[
U_n = \frac{1}{\sqrt{n}} \begin{bmatrix} a_n(\theta_0), & a_n(\theta_1), & \cdots, & a_n(\theta_{n-1}) \end{bmatrix}
\]

steering/response vector

\[
a_n(\theta) = \begin{bmatrix} 1 \\ e^{-j2\pi\theta} \\ \vdots \\ e^{-j2\pi\theta(n-1)} \end{bmatrix}
\]
Beamspace Channel Sparsity

**mmW propagation X-tics**
- Directional, quasi-optical
- Predominantly line-of-sight
- Single-bounce multipath
- Beamspace sparsity

**Point-to-multipoint MIMO link**

\[ H_b = U_n^H H U_n \]

**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:** \( n \rightarrow p \) dim.
- **Hardware Complexity:** \( n \rightarrow p \) RF chains
- **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

**Hardware parameters**
- \( N_{RF} = 1 \):
  - 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 architectures:

- **Extreme 1:** $N_{RF} = 1$: a single-beam phased array for analog beam-forming (ABF) is most cost effective.

- **Extreme 2:** $N_{RF} = n = \text{number of antennas}$: 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

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

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

Antenna size: $L_a \times L_e$

Antenna dimension:
$n = n_a \times n_e$
$n_a$ - azimuth , $n_e$ - elevation

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

AP or n_e
Antenna Aperture

L_a or n_a

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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 $n_b$, $\phi_e$, and $\phi_a$, how should we choose $n_a$, $n_e$?

Case 1: Equal number of beams in azimuth and elevation

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

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Optimum Phased Array Configuration

\[ C_{PA}(P, R) = \frac{WN_{RF}}{K} \log_2 \left( 1 + \frac{PnK\gamma}{N_{RF}^2 N_0 W} \right) \] bits/s (bps)

\[ = W_u \log_2 \left( 1 + \frac{Pn\gamma}{N_{RF}N_0 W_u} \right) \]

Per-user bandwidth:

\[ W_u = \frac{W}{K_{RF}} = \frac{WN_{RF}}{K} \]

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

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

\( \uparrow N_{RF} \implies \downarrow n_s = \frac{n}{N_{RF}} \) - size of sub-array

\( n_s = \frac{n}{N_{RF}} \) determines sub-array gain and \# orthogonal beams

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

\[ N_{s, opt} = \sqrt{n_b} = N_{RF} \]
PA Capacity Plot

![Graph showing Per User Capacity (Gbps) vs TX power (dBm) for different values of N (1, 5, 9, 12)]
Optimum Phased Array Configuration

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

\( n_b = 144 \)

**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:**
\( n = 240 \)
\( = n_{a} \times n_{e} \)
\( = 16 \times 15 \)

\( N_{s, opt} = \sqrt{n_b} = N_{RF} = 12 \)
\( \text{CAP-MIMO AP: Beamspace Sectoring} \)

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

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

**Phased Array**

Array partitioning

\[
n_a = N_{sa} \times n_{sa} = 16
\]

\[
N_{sa} = 4
\]

\[
n_{sa} = 4
\]

\[
n_{se} = \frac{n_c}{N_{se}} = \frac{15}{3} = 5
\]

\[
n_{b,se} = 4
\]

\[
n_{b,sa} = 3
\]

\[
n_b \approx 144 \text{ beams coverage}
\]

**CAP-MIMO**

Beamspace sectoring

\[
n_{ba} = N_{sa} \times n_{b,sa} = 12
\]

\[
N_{sa} = 4
\]

\[
N_{se} = 3
\]

\[
n_{b,se} = 12
\]

\[
n_b \approx 144 \text{ beams coverage}
\]
Idealized Per-User Capacity Expressions

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

\[ C = W_u \log_2 \left( 1 + \frac{PG\gamma}{N_oW_u} \right) \quad \text{bits/s (bps)} \]

\[ C_{PA} = \frac{WN_{RF}}{K} \log_2 \left( 1 + \frac{PnK\gamma}{N_{RF}^2N_oW} \right) \quad \text{bits/s (bps)} \]

\[ C_{CM} = \frac{WN_{RF}}{K} \log_2 \left( 1 + \frac{PnK\gamma}{N_{RF}N_oW} \right) \quad \text{bits/s (bps)} \]

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

Free space path loss
Simulation Parameters

\( W = 1 \text{ GHz}, K = 100 \text{ users}, R_{max} = 100\text{m}, h_{AP} = 10\text{m} \quad 2\phi_a = 120^\circ, 2\phi_e = 84^\circ \)
3.4” x 3.2” AP with 144 Beam Coverage

\[ L_a = 3.4” \quad L_e = 3.2” \]
\[ n \approx 240 \quad (16 \times 15) \]
\[ 2\phi_a = 120^\circ \quad , \quad 2\phi_e = 84^\circ \]
\[ \# \text{ beams (cover)}: \quad n_b \approx 144 \quad (12 \times 12) \]
\[ N_{RF} = 12 \quad \text{RF chains}; \quad K = 100 \quad \text{users}; \quad K_{RF} = 8.33 \quad \text{users/beam} \]

Phased Array

\[ 4 \times 3 \]
Array partitioning

\[ 4 \times 5 \]
Sub-array

\[ \sqrt{n_b} \approx 12 \]
beams coverage

1 GHz bandwidth; includes Friis free-space path loss

CAP-MIMO

\[ 4 \times 3 \]
Beamspace sectoring

\[ 3 \times 4 \]
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

\[ L_a = 5.3\" \quad L_e = 5.9\" \]
\[ n \approx 700 \ (25 \times 28) \]
\[ 2\phi_a = 120^\circ \quad , \quad 2\phi_e = 84^\circ \]
\[ \# \text{ beams (cover)}: \ n_b \approx 400 \ (20 \times 20) \]
\[ N_{RF} = 20 \text{ RF chains}; \ K = 100 \text{ users}; \ K_{RF} = 5 \text{ users/beam} \]

**Phased Array**
- 5 × 4 Array
  - 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 → 5 switch

1 GHz bandwidth; includes Friis free-space path loss

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Key Observation

CAP-MIMO AP spans the coverage area with $n_b$ beams

Phased Array AP spans the coverage area with $n_{bs} = \sqrt{n_b}$ 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:** $28^\circ$ in azimuth and $23^\circ$ in elevation

**Lens Array beamwidths:** $7^\circ$ in azimuth and $7.5^\circ$ 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

$\begin{align*}
n_b &= 144 \\
N_{RF} &= 12 \\
K_{RF} &= 8.33 \\
n_b &= 400 \\
N_{RF} &= 20 \\
K_{RF} &= 5
\end{align*}$
MMSE vs MF Spatial Processing

Antenna domain

Uplink model:

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

\[ \beta = \text{diag}(\beta_1, \cdots, \beta_K), \quad \beta_k = \frac{e^{j \psi_k} \lambda}{4\pi R_{\text{min}}} \]

\[ \mathbf{H} = [\mathbf{h}_1, \cdots, \mathbf{h}_K], \quad \mathbf{h}_k = \mathbf{a}_{n_a}(\theta_{a,k}) \otimes \mathbf{a}_{n_e}(\theta_{e,k}) \]

Beamspace:

LoS user channels

\[ \mathbf{r}_b = \mathbf{U}^H \mathbf{r} = \mathbf{H}_b \beta \mathbf{s} + \mathbf{w}_b \]

\[ \mathbf{h}_{b,k} = \mathbf{U}^H \mathbf{h}_k \]

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

beamspace processing: 

\[ \mathbf{z}_b = \mathbf{L}^H \mathbf{r}_b = \mathbf{L}^H \mathbf{H}_b \beta \mathbf{s} + \mathbf{L}^H \mathbf{w}_b \]

Sum rate: 

\[ C(\mathbf{L}_b) = E_H \left[ \frac{WN_{\text{RF}}}{K} \sum_{k=1}^{N_{\text{RF}}} \log_2(1 + \text{SINR}_k(\mathbf{L}_b, \mathbf{H}_b)) \right] \text{ bps} \]
28 GHz Multi-beam CAP-MIMO Testbed

P2MP Link

CAP-MIMO AP

P2P Link

MS 1

MS 2

6” Lens with 16-feed Array

Equivalent to 600-element conventional array!

Beamwidth=4 deg

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

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

6” Lens with 16-feed Array

CAP-MIMO Access Point (AP)

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

Conclusion

• 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)

Thank You!

• 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.
• A. Sayeed and J. Brady, Beamspace MIMO for High-Dimensional Multiuser Communication at Millimeter-Wave Frequencies, IEEE Globecom, Dec. 2013.