Wideband (and Massive) MIMO for Millimeter-Wave Mobile Networks: Recent Results on Theory, Architectures, and Prototypes

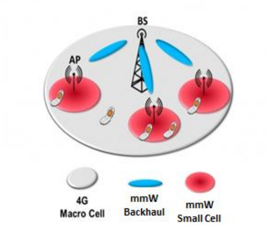
WCNC 2017
mmW5G Workshop
Millimeter Wave-Based Integrated Mobile Communications for 5G Networks
March 19, 2017

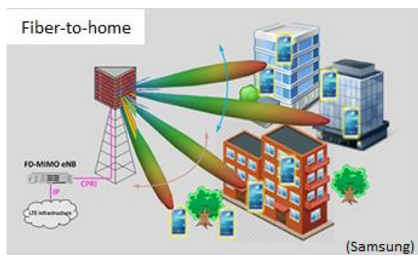
Akbar M. Sayeed
Wireless Communications and Sensing Laboratory
Electrical and Computer Engineering
University of Wisconsin-Madison
http://dune.ece.wisc.edu

Supported by the NSF and the Wisconsin Alumni Research Foundation

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
  - Licensed (3.85 GHz): 28, 37, 39 GHz
  - Unlicensed (7 GHZ): 64-71 GHz
- New NSF-led Advanced Wireless Initiative
  - mmW Research Coordination Network
  - 2nd Workshop Madison, WI; July 19-20, 2017.



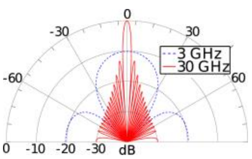


Potential of mmW Wireless

Key Advantages of mmW: large bandwidth & narrow beams

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

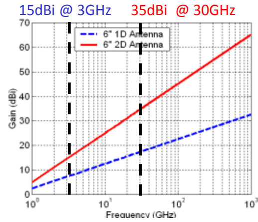
6000 elements @80GHz vs. 9 vs. elements @3GHz



35 deg @ 3 GHz

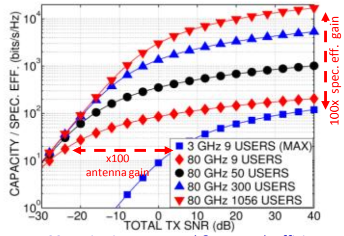
4 deg @ 30 GHz

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)

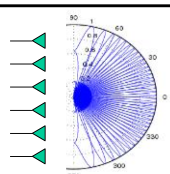
Conceptual and Analytical Framework: Beamspace MIMO

Beamspace MIMO

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

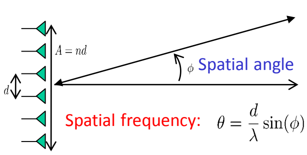
Antenna space multiplexing — Discrete Fourier Transform (DFT) — Beamspace multiplexing

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



n dimensional signal space

n orthogonal beams ⟷ n spatial channels

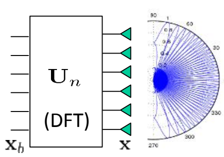


Spatial frequency: $\theta = \frac{d}{\lambda}\sin(\phi)$

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

steering/response vector

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



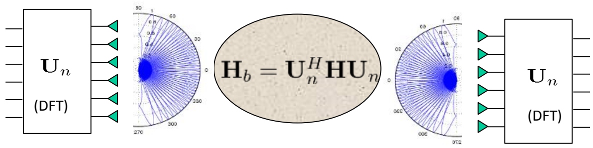
DFT matrix: Beamspace modulation

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

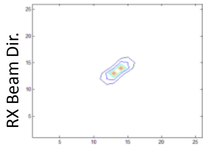
(AS TSP '02; AS & NB Allerton '10; JB, NB & AS TAPS '13) comm. modes in optics (Gabor '61, Miller '00, Friberg '07)

Beamspace Channel Sparsity

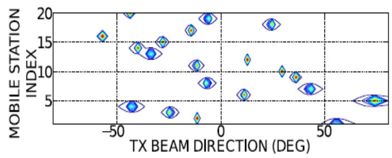
mmW propagation X-tics
- Directional, quasi-optical
- Predominantly line-of-sight
- Single-bounce multipath
- Beamspace sparsity



Point-to-point
LoS Link



Point-to-multipoint
multiuser link



Communication occurs in a low *(p)*-dimensional subspace of the high *(n)*-dimensional spatial signal space

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

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

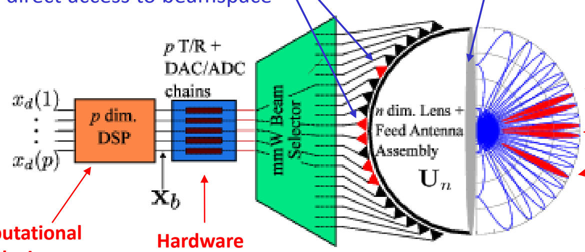
Continuous Aperture Phased (CAP) MIMO

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



Data multiplexing through p active beams

Computational Complexity:
n → p
matrix operations

Hardware Complexity:
n → p
RF chains

Beam Selection
p << n
active beams

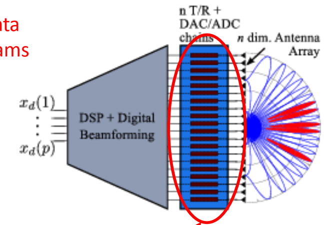
Scalable performance-complexity optimization

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

Competing mmW MIMO Architectures

Conventional MIMO:
Digital Beamforming

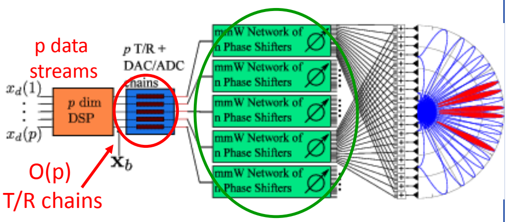
p data streams



n T/R chains: prohibitive complexity

Phased Array Architecture:
Analog mmW Beamforming

p data streams



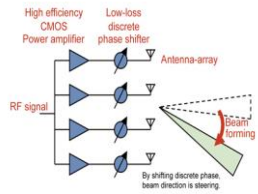
O(p) T/R chains

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)

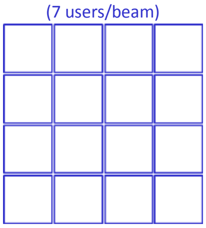
p: # spatial channels/data streams (10-100's)

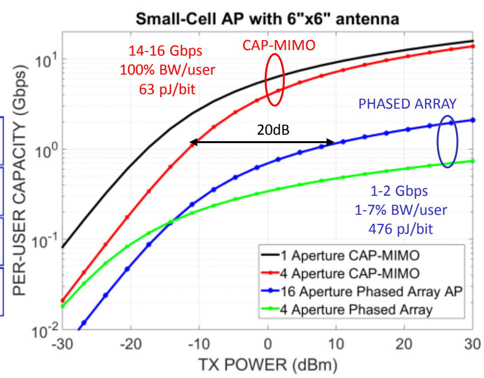


Multi-beam CAP-MIMO vs Single-beam Phased Arrays

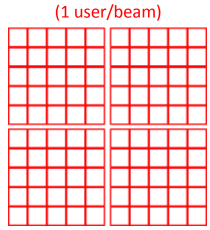
28 GHz small cell design for supporting 100 users

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

4” x 3.1” AP Antenna

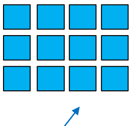
Ant. dim: $n \approx 285\ (19 \times 15)$ # beams (cover): $n_b \approx 144\ (16 \times 9)$

$N_{so} = 12$ RF chains, $K = 100$ users, $K_{RF} = 7.85$ users/beam

Phased Array

4×3

Array partitioning

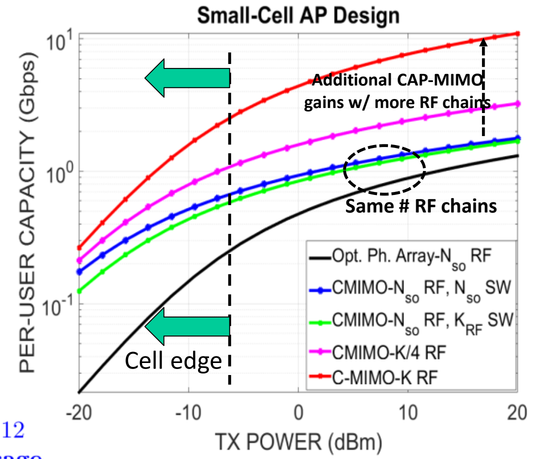


5×5

Sub-array

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

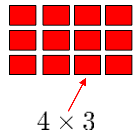
beams coverage



CAP-MIMO

4×3

Beamspace sectoring



4×3

Sub-sector

$n_{b,f} \approx 2$ beams/feed

$1 \mapsto K_{RF} = 6$ switch

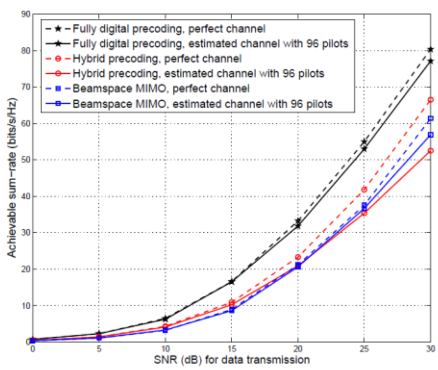
$n_b \approx 144$

beams coverage

1 GHz bandwidth; includes Friis free-space path loss

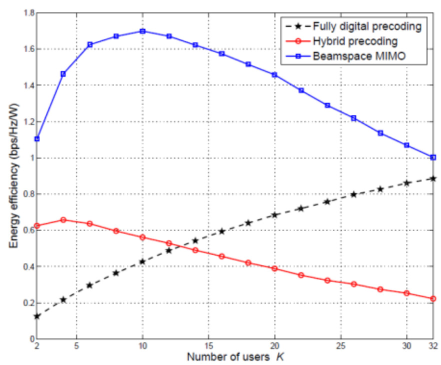
CAP-MIMO vs Multi-beam Phased Array

Spectral Efficiency



N=256, K=16 users, p = K =16 RF chains

Energy Efficiency

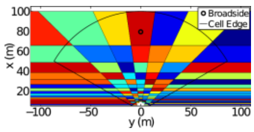


N=256, K=16 users, p = K=16 RF chains

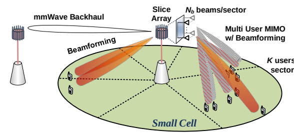
(X. Gao, L. Dai & AS ’16)

2D Arrays for 3D Beamforming

0.5" x 3" antenna
K=100 beam coverage



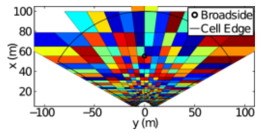
K=100 users



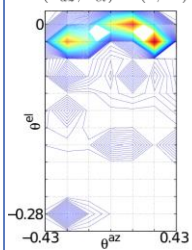
Cell radius: 100m, 120 deg sector

$(\phi_{el}, \phi_{az}) \in [0, -35°] \times [-60°, 60°]$

2.3" x 12" antenna
16K=1600 beam coverage



$n = 273$
$(n_{az}, n_{el}) = (7, 39)$



Beamspace
Multiuser Channel

2D steering vector: $\mathbf{a}_n(\theta^{az}, \theta^{el}) = \mathbf{a}_{n_{az}}(\theta^{az}) \otimes \mathbf{a}_{n_{el}}(\theta^{el})$

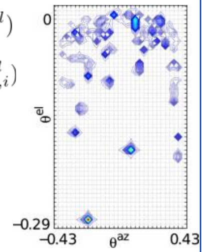
k-th user: $\mathbf{h}_k = \beta_{k,0}\mathbf{a}_n(\theta^{az}_{k,0}, \theta^{el}_{k,0}) + \sum_{i=1}^{N_p} \beta_{k,i}\mathbf{a}_n(\theta^{az}_{k,i}, \theta^{el}_{k,i})$

n x K Multiuser Beamspace Channel Matrix

$$\mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} = [\mathbf{h}_{b,1}, \cdots, \mathbf{h}_{b,K}]$$

$$\mathbf{U}_n = \mathbf{U}_{n_{az}} \otimes \mathbf{U}_{n_{el}} \quad \text{(2D DFT)}$$

$n = 5216$
$(n_{az}, n_{el}) = (32, 163)$

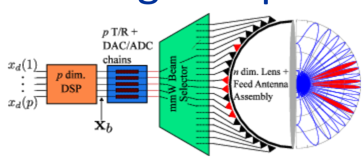


Beamspace
Multiuser Channel

(JB & AS SPAWC '14)

Beam Selection for Taming Complexity

Beam selection:
Power-based thresholding



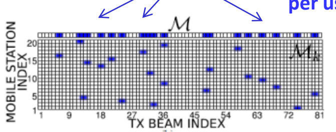
k-th user mask: $\gamma \in (0, 1)$

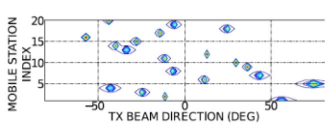
$$\mathcal{M}_k = \left\{ i : |h_{b,k}(i)|^2 > \gamma \max_{\ell} |h_{b,k}(\ell)|^2 \right\}$$

Beam sparsity mask

$$\mathcal{M} = \bigcup_{k=1}^{K} \mathcal{M}_k$$

few (1-4) dominant beams per user





Full-dimensional channel matrix *(n x K)*

$$\mathbf{H}_b = \mathbf{U}_n^H \mathbf{H} = [\mathbf{h}_{b,1}, \cdots, \mathbf{h}_{b,K}]$$

$p = |\mathcal{M}|$ beams - rows of $\mathbf{H}_b$ - selected

Low-dim channel matrix *(p x K)*

$$\tilde{\mathbf{H}}_b = [\mathbf{H}_b(\ell, :)]_{\ell \in \mathcal{M}}$$

K x p downlink channel

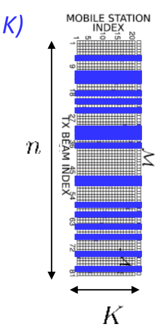
$$\mathbf{r} = \tilde{\mathbf{H}}_b^H \tilde{\mathbf{G}}_b \mathbf{s} + \mathbf{w}$$

K x p   *p x K*

p x K uplink channel

$$\mathbf{z}_b = \tilde{\mathbf{F}}_b \tilde{\mathbf{H}}_b \mathbf{x} + \tilde{\mathbf{F}}_b \mathbf{w}_b$$

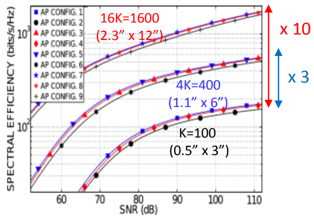
p x K   *K x p*



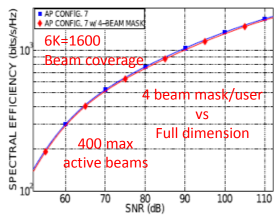
(AS & JB GCOM '13, JB & AS SPAWC '14, JG & AS CISS '16)

Performance vs Complexity

Impact of Antenna Size



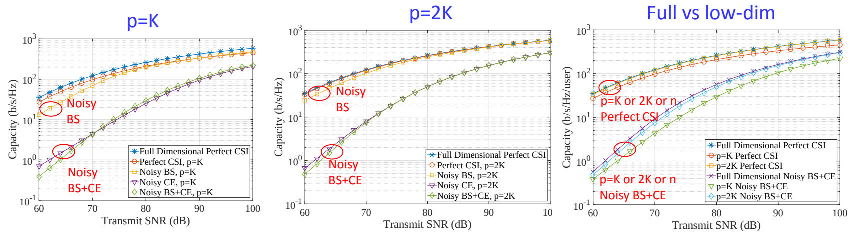
Full dim. vs low-dim.



Full dim: ñ = 158

Impact of **Beam Selection** and **Channel Estimation**

K=50



Estimation SNR = communication SNR

(JB & AS GCOM'13, SPAWC '14; JH & AS CISS'16)

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: $N_{oh} \sim \frac{K N_{beams}}{p}$

Beam Selection & Channel Estimation Overhead

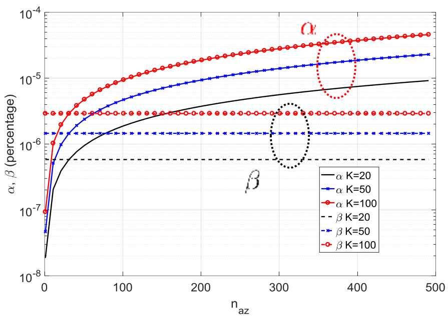
Beam Selection Overhead:

$$\alpha = \frac{T_{bs}}{T_{b,coh}} = T\frac{K(N_s+N_{sw})n_{az}v_{max}}{2R_{min}}\frac{n_{beams}}{p}$$

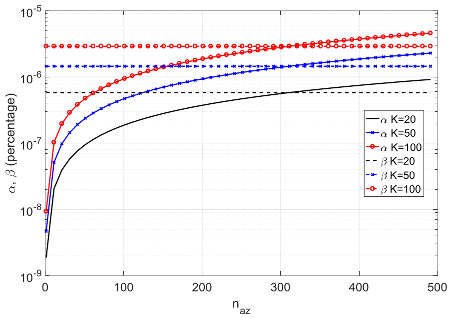
Channel Estimation Overhead:

$$\beta = \frac{T_{ce}}{T_{coh}} = \frac{K\tau}{c/f_c v_{max}} = \frac{K\tau f_c v_{max}}{c}$$

p=1 simultaneous beams



p=10 simultaneous beams



(J. Hogan & AS, CISS '16)

Simultaneous Beams != # RF Chains

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

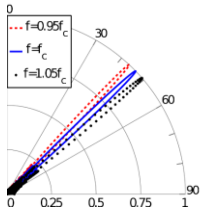
Existing phased array (single-beam)
Limiting factor: **phased shifter network** (not RF chains)

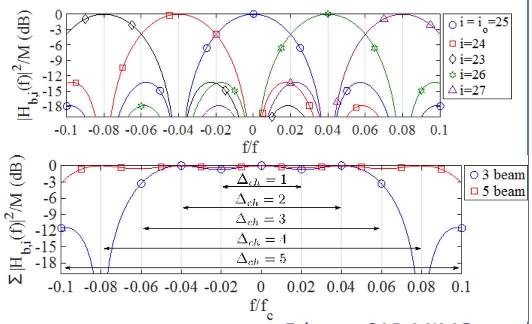
Lens arrays: multi-beam steering and data mux (# RF chains)
Limiting factor: beam selection network

Wideband mmW MIMO: Beam Squint Problem & Multi-beam Solution

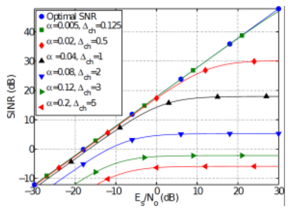
Channel Dispersion Factor:

$$\Delta_{ch} = M\alpha|\theta_o| = \frac{\Delta\tau_{ch}}{\Delta\tau} = \frac{\Delta\theta_{ch}}{\Delta\theta}$$

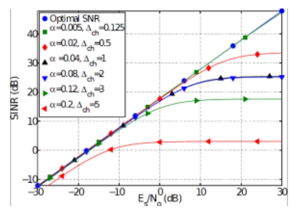




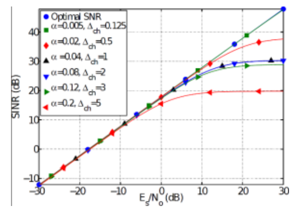
Phased array



3-beam CAP-MIMO



5-beam CAP-MIMO

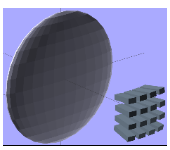


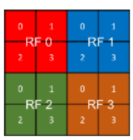
(JB & AS ICC '15)

28 GHz Multi-beam CAP-MIMO Prototype

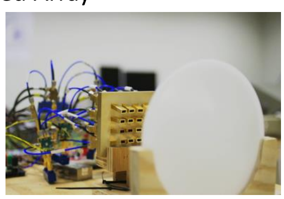
6" Lens with 16-feed Array

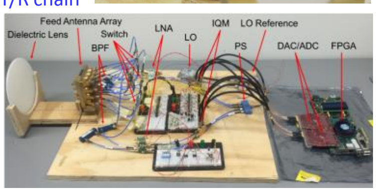
P2MP Link

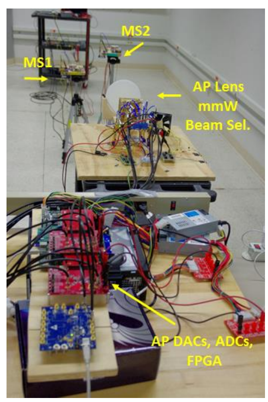




1-4 switch for each T/R chain







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

Features

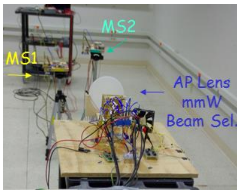
- **Unprecedented 4-beam steering & data mux.**
- RF BW: 1 GHz, Symbol rate: 125-370 MS/s
- AP – 4 MS bi-directional P2MP link
- TX power – 15 dBm
- FPGA-based backend DSP

Use cases

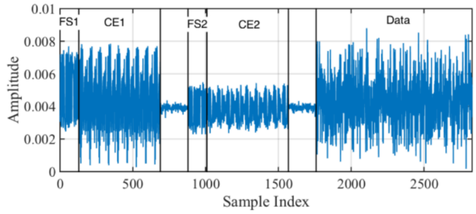
- Real-time testing of PHY protocols
- Multi-beam channel measurements
- Scaled-up testbed network

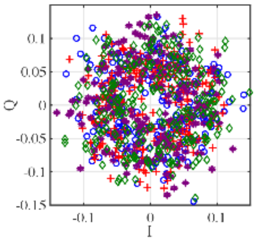
(JB, JH, AS, 2016 Globecom wkshop, 5G Emerg. Tech.)

P2MP Link: Space-Time Filtering & Coherent Detection

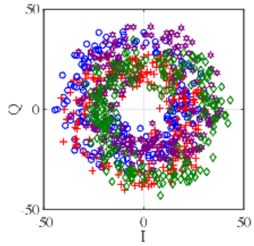


MS1 Transmitting RX Frame (MS 1 ch)

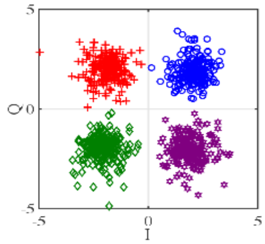




Raw RX I/Q samples



spatial filtering



Spatial + temporal filtering

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

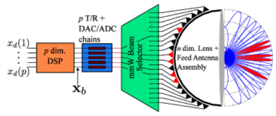
- NSF research coordination network (RCN) on mmW wireless
  - Academia, industry & government agencies
- Cross-disciplinary research challenges
  - CSP: communications & signal processing
  - HW: mmW hardware, including circuits, ADCs/DACs, antennas
  - NET: wireless networking
- Kickoff Workshop: Dec 2016
- 2nd Workshop: July 19-20, 2017: Madison, WI

Ongoing Work

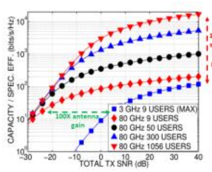
- Innovations in basic theory & technology development
- Gen 2 prototype: 28 GHz, advanced multi-beam functionality
- Channel measurements: massive, beamspace, and multi-beam
- Lens array and beam selector network optimization
- Spatial analog-digital interface design (CSP+HW)
  - Gigabit-rate DSP power hungry; more analog processing?
- Wideband high-dimensional MIMO
  - “beam-squint” problem
  - Waverforms: OFDM, SC, SC-OFDM? Short-Time Fourier
- Scaled up CAP-MIMO testbed & commercialization

Conclusion

- Beamspace mmW MIMO: Versatile theoretical & design framework

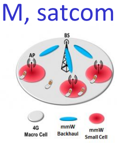


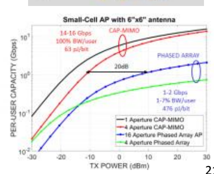
- CAP-MIMO: practical architecture
  - Scalable perf.-comp. optimization
- Compelling advantages over state-of-the-art
  - Capacity/SNR gains
  - Operational functionality
  - Electronic multi-beam steering & data multiplexing



- 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.
- A. Sayeed, Deconstructing Multi-antenna Fading Channels, IEEE Trans. Signal Proc., Oct 2002.