Millimeter-Wave Beamforming Architectures, Channel Measurements and Modeling

ISART 2017
Mining Millimeter-Wave Capacity
Channel Measurements and Modeling Perspective Panel
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Akbar M. Sayeed
Wireless Communications and Sensing Laboratory
Electrical and Computer Engineering
University of Wisconsin-Madison
http://dune.ece.wisc.edu

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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

• New FCC mmW allocations (July 2016)
  – Licensed (3.85 GHz): 28, 37, 39 GHz
  – Unlicensed (7 GHZ): 64-71 GHz

• New NSF Advanced Wireless Initiative
  – mmW Research Coordination Network
  – PAWR (Platforms for Advanced Wireless)
Questions for the Panel

• What is the state of mmW channel modeling and measurements? What needs to be done next?

• What the most cost effective way to enable multi-beamforming?

• Millimeter-wave was actively explored for fixed wireless in the late 1990s. What is different this time?
Channel Modeling and Measurements

- NIST 5G Channel Modeling Alliance
- **Structure of channel models** – in good shape
- **Measurements** – seriously lagging due to the current state of channel sounders
- **Spatial dimension**: current sounders limited to mechanically pointed antennas, or single-beam phased array of moderate sizes (8-64)
- **Mobility**: very limited
Critical Issues to Be Addressed

- **Connection between measurements and models:** How to incorporate measurements into models? What kind of measurements are needed?

- **Sounder development:** spatial resolutions and bandwidths comparable to actual systems

- **What are models going to be used for?** (comparison versus prediction)
Potential of mmW Wireless

**Key Advantages of mmW:** large bandwidth & narrow beams

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

9 elements @3 GHz, 900 @ 30 GHz, 6000 @80 GHz vs.

![Antenna Gain Chart](image1)

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 & Computational Complexity (# T/R chains)

**Conceptual and Analytical Framework:** Beamspace MIMO
Beamspace Multiplexing

Multiplexing data into multiple beams

Discrete Fourier Transform (DFT)

Antenna space multiplexing

n-element array (λ/2 spacing)

n dimensional signal space

Beamspace multiplexing

n orthogonal beams

n spatial channels

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

DFT matrix:

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

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

steering/response vector

AMS ISART 2017 (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 at mmW

**mmW propagation X-tics**
- directional, quasi-optical
- mainly line-of-sight
- single-bounce multipath
- Beamspace sparsity

**LoS (P2P) Link**

**Multiuser (P2MP) link**

Action:  \( p \)-dim. subspace of the \( n \)-dim. spatial signal space; \( p \ll n \)

How to access the \( p \) active beams with \( O(p) \) complexity?

\[
H(f) = \sum_{n=1}^{N_P} \beta_n a_n(\theta_{R,n}) a_n^H(\theta_{T,n}) e^{-j2\pi n f}
\]
Conventional MIMO: Digital Beamforming

n: # of array elements (100’s-1000’s)

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

n T/R chains: prohibitive complexity
Hybrid MIMO: Phased Array Beamforming

n: # of array elements (100’s-1000’s)
p: # spatial channels/data streams (10-100’s)

Existing prototypes limited to single-beam phased arrays of modest size (<256 elements)
Hybrid MIMO: Lens Array Beamforming

Focal surface feed antennas: direct access to beamspace

mmW Lens computes analog spatial DFT

p data streams

Computational Complexity: $n \rightarrow p$ matrices

Hardware Complexity: $n \rightarrow p$ RF chains

Beam Selection

$p \ll n$ active beams

Data multiplexing through $p$ active beams

Scalable performance-complexity optimization

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(AS & NB Allerton ‘10, APS ‘11; JB, NB & AS TAPS ‘13)
4” x 3” AP Antenna: Multi-beam CAP-MIMO vs Single-beam Phased Arrays

\[ n \approx 285 \quad (19 \times 15) \quad \# \text{beams (cover)}: \quad n_b \approx 144 \quad (16 \times 9) \]

12 RF chains; 100 users; 7.85 users/beam

**Phased Array**

- 4 x 3
- Array partitioning
- 5 x 5
  - Sub-array
  - \[ \sqrt{n_b} \approx 12 \] beams coverage

**CAP-MIMO**

- 4 x 3
- Beamspace sectoring
- 4 x 3
  - Sub-sector
  - \[ n_b \approx 144 \] beams coverage

- 2 beams/feed
  - \[ K_{RF} = 6 \] switch

**Small-Cell AP Design**

1 GHz bandwidth; includes Friis free-space path loss

**Graph**

- PER-USER CAPACITY (Gbps)
  - TX POWER (dBm)
- Opt. Ph. Array-\( N_{so} \) RF
- CMIMO-\( N_{so} \) RF, \( N_{so} \) SW
- CMIMO-\( N_{so} \) RF, \( K_{RF} \) SW
- CMIMO-K/4 RF
- C-MIMO-K RF
28 GHz Multi-beam CAP-MIMO Prototype

P2MP Link

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

CAP-MIMO AP Hardware

FPGA + DACs/ADCs for the CAP-MIMO AP supporting 4 complex (I/Q) data streams

CAP-MIMO AP RF Hardware and Lens Antenna Array

MS Hardware

FPGA + DACs/ADCs for MS 1 and MS 2

MS 1 RF Hardware

MS 2 RF Hardware
Directional Focusing by Lens Array

P2P link (154 feet): MS - CAP-MIMO AP

MS broadside  MS 11 ft left  MS 22 ft left, feeds moved

Temporal Filtering Result for User 1  Temporal Filtering Result for User 1

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Multiuser Communication

Two MSs (3 ft apart) to CAP-MIMO AP 29 ft away

unfiltered

Beam powers for the MSs

Spatial int. supp. & temp. eq.

Temporal equalization only
Channel Sounder with Unmatched Multi-beam Capability

Individual Beam PDPs

Aggregate PDP

Threshold Aggregate PDP for User 1

MS1

8ft

8ft

8ft

PDP (dB)

DISTANCE (FT)
What’s different this time? (vs 90’s)

LMDS (Local Multipoint Distribution Services)

- Lack of technology maturity and supporting infrastructure
- Lack of compelling use cases
- MIMO – invented in 1995; I-phone introduced in 2007

News | July 7, 1999

Ericsson Signs First LMDS Contract

“This LMDS network will deliver wireless access speeds of up to 37.5 Mb/s.”

Hope for LMDS Dwindles

By: eWeek Editors | August 06, 2001

“Users of the spectrum have faced a number of hurdles to deployment, including expensive gear, difficulties in securing roof rights for antennas, immature technology and signal interference from elements such as rain.”
mmW Wireless RCN
http://mmwrcn.ece.wisc.edu

- NSF research coordination network (RCN) on mmW wireless
  - Academia, industry & government agencies

- Cross-disciplinary research and technology challenges
  - CSP: communications & signal processing
  - HW: mmW hardware, including circuits, ADCs/DACs, antennas
  - NET: wireless networking

- Kickoff Workshop: Dec 2016, Washington, DC
- 2nd Workshop: July 19-20, 2017: Madison, WI
- 3rd Workshop: Jan 2017 (3rd week) – stay tuned!
Xtras
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!

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

28 GHz small cell design for supporting 100 users

Beamspace MIMO framework enables optimization of both architectures

CAP-MIMO has >8X higher energy and spectral efficiency over phased arrays (idealized analysis – even bigger gains expected with interference)
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: $N_{oh} \sim KN_{beams}$

E.g., for $N_{beams} = 50$, $K = 20$ to 80 users can be scanned with < 1% overhead

With $p$-beam capability: $N_{oh} \sim \frac{KN_{beams}}{p}$
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