Millimeter Wave MIMO: Opportunities and Challenges

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MIMO is a staple of modern wireless cuisine

- Widely used in WLAN and cellular at sub-6GHz frequencies
  - Valuable for spectral efficiency gains via spatial multiplexing
- All the signal processing action happens in the baseband
  - Not so many antennas are used (up to 8 are usually supported, but 2 is common)

MIMO is a building block for future WLAN and cellular wireless networks
Why mmWave & MIMO?

- several GHz of spectrum
- many separate bands

possible 5G cellular bands  automotive radar

30 GHz  38-49 GHz  unlicensed  70-90 GHz  300 GHz

isotropic radiator

mmWave aperture

TX  RX

sub-6GHz aperture

Beamforming for antenna gain

channels in some bands may be as small as 100 MHz

Spatial multiplexing for spectral efficiency

Past, present, and future consumer applications of mmWave
MmWave in the unlicensed bands

- Up to 7 GHz available worldwide in the 60 GHz unlicensed band
- Even more potential above 100 GHz as there are fewer regulations

60 GHz is a special case of mmWave, which is more generally licensed

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### Unlicensed bands

<table>
<thead>
<tr>
<th>Unlicensed bands</th>
<th>Total bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>900MHz</td>
<td>26 MHz</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>100 MHz</td>
</tr>
<tr>
<td>5.2 GHz</td>
<td>555 MHz</td>
</tr>
<tr>
<td>Total</td>
<td>676 MHz</td>
</tr>
</tbody>
</table>
WPAN at 60 GHz

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bandwidth</th>
<th>Rates</th>
<th>Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>WirelessHD 1.1</td>
<td>2.16 GHz</td>
<td>4 x 7.138 Gbps</td>
<td>Jan. 2010</td>
</tr>
</tbody>
</table>

- Wireless personal area networking (WPAN)
  - Multimedia streaming especially HDMI
  - Peripheral connections
  - Kiosk data transfer
- Compliant products already available
  - Dell Alienware laptops, Epson projectors, etc.
- Widely seen as the first 60 GHz consumer product

* http://www.wirelesshd.org/consumers/product-listing/
WLAN at 60 GHz

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bandwidth</th>
<th>Rates</th>
<th>Approval Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11ad</td>
<td>2.16 GHz</td>
<td>6.76 Gbps</td>
<td>Dec. 2012</td>
</tr>
</tbody>
</table>

- Wireless local area networking (WLAN)
  - Gbps peak throughputs
  - In-room local area networking
  - Cable replacement
- Chipsets are available and some products are shipping
- Next gen is currently in development (802.11ay)****
  - Will support MIMO spatial multiplexing
  - Channel bonding for even larger bandwidths
  - Targets 100 Gbps data rates

• [http://nitero.com/](http://nitero.com/)  
  ** [http://wilocity.com](http://wilocity.com)  
  **** [http://www.ieee802.org/11/Reports/ng60_update.htm](http://www.ieee802.org/11/Reports/ng60_update.htm)
Wearables at 60 GHz

- Multiple communicating devices in and around the body
  - 5 or more devices per person based on market trends
- MmWave solves two critical problems
  - High data rates for high-end devices, isolation for low-end devices
- Likely realized using IEEE 802.11ad/ay at 60 GHz

MmWave for cellular systems

Potential mmWave spectrum for cellular access channel

- Huge amount of spectrum possibly available in mmWave bands
- Advances in mmWave unlicensed enable low cost consumer devices

Most interest for cellular is in *licensed* bands
There is no specific allocation for 5G cellular at mmWave yet
- FCC released a notice of inquiry to start the conversation about mmWave

Not obvious that exclusive licensing will happen in mmWave
- Shared licensed access attractive due to reduced co-channel interference
- Cognitive radio techniques may allow co-existence with satellite or radar

Opportunities for light licensing, cognitive radio, other sharing models

See UT's response to comments here http://apps.fcc.gov/ecfs/comment/view?id=60001017585
Imagining a 5G cellular network with mmWave

- Many applications for mmWave
  - Access link from the user equipment to the base station
  - Backhaul between base stations

- Many interesting architectural features
  - Small cells, relays, use of sub 6 GHz and mmWave frequencies

MmWave for transportation

- MmWave radars widely used in automotive safety applications
- Connected vehicle is expected to drive 1.5GB monthly mobile data in 2017
  - May be handled with a combination of conventional cellular and DSRC
- Autonomous vehicle can generate up to 1 TB of data in a single trip
  - 4G and DSRC can not support these data rates

High sensing data rates are the key motivation for advanced communication

**Cisco, “The Internet of Cars: A Catalyst to Unlock Societal Benefits of Transportation,” Mar. 2013
MmWave for the connected car

- Vehicle-to-vehicle and vehicle-to-infrastructure allow sensor data exchange*
- Joint radar and communication is possible**
- Applications to safety, transportation operations, freight, and infotainment

Enable the transition to automated driving and eventually full autonomy

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*Millimeter-wave Vehicular Communications Exploiting DSRC and Automotive Sensors*, Junil Choi, Robert C. Daniels and Robert W. Heath, submitted October 2015

Differentiating features of mmWave
Millimeter wave wireless communication

High frequency
Large bandwidth

Small factor arrays with many antennas
- array gain to overcome loss
- reduced sensitivity to interference
- more users via multiuser MIMO
- efficiency via spatial multiplexing MIMO

More spectrum
- easier to support low latency
- bandwidth to achieve Gbps rates
- spectrum to be shared

Different channel models
- fewer scattering clusters – more sparsity
- blockage

MmWave has applications to 5G cellular, WLAN, transportation, and wearables
Directional and adaptive antenna arrays

Prototype 64 element dielectric lens by Nokia [1]

16 element SiGe BiCMOS phased array from UCSD [4]

Prototype phased arrays by Samsung [2],[3]

Early mmWave devices will use simple adaptive beam steering

Observations on adaptive arrays:
Both transmit and receive beams need to be reconfigured

- Large number of antennas in each array, but in a small form factor
- Conventional MIMO signal processing, estimation, and feedback infeasible

Beam training is a source of overhead in a mmWave system

* Illustration of beam training from IEEE 802.11ad
Observations on adaptive arrays:
Narrower beams reduce Doppler spread but require pointing

- Coherence time increases as the beamwidth becomes smaller
- Optimum beamwidth is a tradeoff between pointing error and Doppler

Beams should be narrow but not too “pointy”

Observations on adaptive arrays:

Beamforming changes the effect of interference

- Interference becomes bursty, stronger flashlight effect, but weaker on average
- System can become noise limited with narrow beam and wide bandwidth

MmWave systems can have better SINR than lower frequency systems

Blockage is a major channel impairment

- **Blockage due to buildings**
  - Line-of-sight
  - Non-line-of-sight

- **Blockage due to people**
  - Hand blocking
  - Self-body blocking

Need models for blockage & system analysis including blockage
Observations on blockage:
Blockage mixes line-of-sight and non-line-of-sight links

- Distant-dependent blockage associated with each link
- Both the direct and interference links may be blocked
- Outdoor-indoor penetration high, need indoor infrastructure for indoor users

High density of infrastructure required relative to building density

Observations on blockage:

Body blockage further increases potential for outage

- Rapid switching between line-of-sight and non-line-of-sight paths
- Macro diversity where users associate with multiple base stations

System must be designed for resilience to each form of blockage

Observations on blockage:
Hand blockage may reduce mmWave viability

- Multiple arrays on handset if space is available (hard with multi-band)
- Train users not to block the arrays with their fingers (warning labels or shock)

Hand blockages and variable orientation require careful device engineering

Power consumption at mmWave in a MIMO receiver

For a receiver with 4 antennas, the power consumed by this front end at mmWave would be **2W** !!!

- **Carrier frequency and large bandwidth conspire together**

Alternative mmWave MIMO architectures are needed
Analog beamforming

- Implement all beamforming in the analog domain (at RF or IF freq.)
- Can be implemented with phase shifters, switches or lenses
- Lacks flexibility for multi-stream or multiuser MIMO processing

De facto approach for implementing simple adaptive beam steering
Hybrid precoding

- Approach to reduce the number of transceivers and ADCs/DCAs
- Digital precoder/combiner can correct for lack of precision in the analog

Different hardware leads to different tradeoffs performance-power consumption
Observations on hybrid precoding:
Allows multi-stream MIMO gains with less hardware

- Channel has 8 clusters
- Each cluster contributes with 10 rays
- Uniform planar arrays are assumed
- BS has 64 antennas (6 RF chains)
- MS has 16 antennas (6 RF chains)

- Hybrid structure introduces additional constraints on precoding
- Gains depend on dimensionality

Hybrid precoding has low loss in channels that are not “rich scattering”

Observations on hybrid precoding:
Also supports multiuser MIMO

- Training length and feedback overhead are important
- Configuring precoders in stages may be robust even with interference

Hybrid precoding provides the dimensionality for spatially separating users

Observations on hybrid precoding:
Precoding can be performed across different polarizations

- Several different ways to precode depending on cross-pole configuration
- Polarization adds signal processing complexity

Provides robustness against user misorientation

Low resolution ADCs

- A one-bit ADCs is built from a simple comparator
  - Works at high sampling rates with a very low power consumption

- Two ways to view ADCs:
  - As as impairment
  - Part of the design

**Model quantization as noise**
- simulate other distortion effects

**Account for ADC in signal design**
- explicitly model in RX algorithms
Observations about low resolution ADCs w/ mmWave:
Reasonable capacity can be achieved at moderate SNR values

- Performance improves with more receive antennas and TX CSI
- Baseband requires more signal processing complexity

I-bit ADCs are a power efficient option for mmWave systems

Observations about low resolution ADCs w/ mmWave
Channel can be estimated even with 1-bit ADCs at low SNR

I-bit CS problem

\[ \text{vec}(Y) = \text{sign}( (Z^T \otimes U_{N_t}) \text{vec}(H_b) + \text{vec}(Q) ) \]

- Estimation is possible if there is channel structure

Sparsity in the channel and one-bit CS tools may be leveraged

1-bit CS problem

- \( N_t \times N_t \) training symbols
- Training precoding matrix
- Noise matrix

Sparse matrix which contains the path gains of the quantized spatial frequencies

Structure can be exploited in channel estimation

Physical channel model

Spatial resolution

Virtual angles fixed a priori

Virtual channel model

- Only a few clusters exist due to the propagation characteristics at mmWave

Channel power is concentrated in a few entries of the virtual channel matrix
Observations about mmWave channel estimation:

Conventional MIMO channel estimation is not applicable

- Channel dimensionality is high and bandwidth is large
- Direct access to the channel is compromised by RF processing

Need to exploit channel structure to enable efficient estimation

Observations about mmWave channel estimation:

Sparsity can be exploited

- Hybrid architectures with switches and phase shifters are comparable

CS tools can be used for efficient channel recovery with different RF hardware

Observations about mmWave channel estimation:

MU channel estimation is possible

- Need to achieve a balance between training overhead & estimation quality
- Sparsity and other channel structure may be exploited

Combinations between estimation and beam training are possible

MmWave has application for cellular systems

- **self-backhauled networks**
- **network diversity**
- **impact of blockages on system performance**
- **self body blocking**

**mmWave BS** vs **Conventional BS at sub-6 GHz**
- LOS links
- Control signals
- Multiple-BS access for fewer handovers and high rate
- NLOS interference

**Data center**
- Buildings

**Femtocell**
- Indoor user

**Non-line-of-sight (NLOS) link**

Observations on mWave cellular:

Coverage and rate are high with dense mmWave networks

<table>
<thead>
<tr>
<th>scenario</th>
<th>5% rate</th>
<th>avg rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 GHz 1x1 50 MHz</td>
<td>1.3</td>
<td>68</td>
</tr>
<tr>
<td>2 GHz 4x4 50 MHz</td>
<td>13</td>
<td>149</td>
</tr>
<tr>
<td>28 GHz 500 MHz sparse</td>
<td>4.7</td>
<td>1560</td>
</tr>
<tr>
<td>28 GHz 500 MHz dense</td>
<td>500</td>
<td>8300</td>
</tr>
<tr>
<td>73 GHz 2 GHz sparse</td>
<td>8.2</td>
<td>4200</td>
</tr>
<tr>
<td>73 GHz 2 GHz dense</td>
<td>830</td>
<td>14500</td>
</tr>
</tbody>
</table>

- Better SINR is possible with enough density
- Sparse networks are noise limited but subject to coverage holes

MmWave can provide high quality and high rate links for outdoor users

MmWave massive MIMO

- Increase peak cell throughput and provide service to multiple users

Large arrays are a natural application of massive MIMO techniques

Observations result on mmWave massive MIMO:
Massive MIMO implementation is different at mmWave

- Both hybrid precoding concepts and few bit ADCs can be used
- Number of users supported is limited by the RF configuration chosen

Choice of carriers depends on base station density
Observations result on mmWave massive MIMO: Massive MIMO may co-exist at sub 6 GHz and mmWave

Need to train arrays at user equipment, and account for blockage in analysis

Strong dependence between performance and density for mmWave


Future research directions
Research challenges

Signal processing algorithms

- Compressive channel estimation in broadband channels
- SU and MU hybrid precoding in broadband channels
- MU hybrid precoding with out of cell interference
- Multi stream beam training
- Hybrid codebooks design

Application specific measurements

- Broadband channel models
- Propagation

Communication theory

- Stochastic geometric analysis of mmWave cellular
- Performance in broadband channels
- Overcoming blockage
- Multicell beamforming
- Multicell beamforming

Information theory

- Capacity with low resolution ADCs
- Non-coherent or wideband capacity
- Going beyond 120 GHz
- RF impairment models
- Device architectures

Other
Research directions

**Signal processing algorithms**
- Compressive channel estimation
- Hybrid precoding for single and multiple users
- Beam training and feedback

**Channel measurements**
- Blockage models
- Channel models

**Propagation**
- Stochastic geometric analysis of mmWave cellular systems
- Performance in broadband channels

**Communication theory**
- Device architectures
- Device architectures

**Information theory**
- Capacity with low resolution ADCs
- Non-coherent or wideband capacity

**Other**
- Going beyond 120 GHz
- RF impairment models

**Cellular systems**
Questions?

mmWave

5G

WLAN

Wearables

Transportation

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