Millimeter wave as the future of 5G

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12 PhD students

- mmWave precoding
- mmWave for tactical ad hoc networks
- mmWave wearables
- mmWave for infrastructure-to-car
- mmWave communication and radar for car-to-car
- next generation mmWave LAN
- mmWave licensed shared access for 5G
- mmWave 5G performance
Why millimeter wave for 5G?

- Huge amount of spectrum possibly available in mmWave bands
- Technology advances make mmWave possible for cheap consumer devices
- mmWave research is as old as wireless, e.g. Bose 1895 and Lebedew 1895
MmWave is coming for consumers

<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>

- Standards developed @ unlicensed 60 GHz band
  - WirelessHD: Targeting HD video streaming
  - IEEE 802.11ad: Targeting Gbps WLAN
- Compliant products already available
  - Dell Alienware laptops, Epson projectors, etc.
  - 11ad Chipset available from Wilocity, Tensorcom, Nitero
- Only single stream MIMO beamforming
  - Next generation will likely support multi-stream (>20 Gbps)*

Spectrum considerations

- There is no specific allocation for 5G cellular at millimeter wave yet
- Some candidate bands and their bandwidth (many shared with fixed and mobile satellite, and federal / non-federal users)

<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 GHz (LMDS)</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>39 GHz</td>
<td>1.4 GHz</td>
</tr>
<tr>
<td>37 / 42 GHz</td>
<td>2.1 GHz</td>
</tr>
<tr>
<td>71-76 GHz 81-86 GHz (E-Band)</td>
<td>10 GHz</td>
</tr>
</tbody>
</table>

- FCC released a notice of inquiry to start the conversation about mmWave
  - NOI posses many questions that are being addressed by research at UT
- Not obvious that exclusive licensing will happen in mmWave
  - Shared licensed access may be attractive due to reduced co-channel interference
  - Cognitive radio techniques may allow co-existence with satellite or radar

See UT’s response to comments here http://apps.fcc.gov/ecfs/comment/view?id=60001017585
How does mmWave enable ultrafast broadband?

#1 spectrum
- more spectrum (10x or more)
- larger channels (5-100x)

#2 large arrays & narrow beams
- reduced interference (better SINR)
- spectrum reuse (multiple users share same channel)
Role of MIMO for mmWave

millimeter wave band

| 1.3 GHz | 2.1 GHz | 7 GHz (unlic) | 10 GHz |

28 GHz 37 / 42 GHz 60GHz E-Band … to 300 GHz

spatial multiplexing & beamforming just beamforming

Spatial multiplexing for spectral efficiency

multiple data streams

Beamforming for antenna gain

isotropic radiator

mmWave aperture

sub-6GHz aperture

TX RX

Observations about antenna arrays

- Large number of antennas used at the base station and mobile station
  - Antennas will be small -> no form factor challenges at the base station
- Directionality of the patterns changes many aspects of system design
  - Physical layer signal processing
  - Mobility management (e.g. initial access and handoff)
  - Interference management
Blockages will become more severe

- blockage due to buildings
- line-of-sight
- non-line-of-sight
- blockage due to people
- hand blocking
- self-body blocking

many forms of blockage have yet to be modeled and analyzed
Observations about blockage

- **Building blockage**
  - High density of infrastructure required to cover areas around buildings

- **Body blockage and self-body blockage**
  - Need rapid switching between line-of-sight and non-line-of-sight paths
  - Macro diversity where users associate with multiple base stations

- **Hand blockage**
  - Array diversity on the handset
Analytical model for mmWave cellular systems

Random building model for LOS/NLOS links

- Exponent proportional to building density

Simplified model for directional beamforming

- Back lobe gain
- Main lobe array gain
- Main lobe beamwidth

Interfering Transmitters

Buildings

Typical Receiver

LOS path

NLOS Path

 Associated Transmitter

Main lobe beamwidth

Main lobe array gain

Back lobe gain

Random building model

$e^{-\beta d}$

Exponentially decaying LOS prob.


### Performance calculations

<table>
<thead>
<tr>
<th>scenario</th>
<th>5% rate (Mbps)</th>
<th>avg rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF with 1TX 1RX</td>
<td>1.26</td>
<td>67.53</td>
</tr>
<tr>
<td>UHF with 4TX 4RX</td>
<td>13.22</td>
<td>148.95</td>
</tr>
<tr>
<td>mmWave with low density and building blockages</td>
<td>2.95</td>
<td>2579.62</td>
</tr>
<tr>
<td>mmWave with high density and building blockages</td>
<td>2427.2</td>
<td>3716.41</td>
</tr>
<tr>
<td>mmWave with high density and building / body blockages</td>
<td>2106.53</td>
<td>3682.32</td>
</tr>
<tr>
<td>UHF &amp; mmWave with high density and building blockages</td>
<td>2434.1</td>
<td>3733.3</td>
</tr>
</tbody>
</table>

**UHF (2 GHz) parameters:**
- Carrier frequency: 2 GHz
- BW: 50 MHz
- ISD: 500 m
- TX power: 46 dBm
- MIMO with ZF receiver

**MmWave parameters:**
- Carrier frequency: 28 GHz
- BW: 500 MHz
- ISD: 100 m (Dense)
- 200m (Sparse)
- TX power: 30 dBm
- BS beamwidth: 10 degree
- BS beamforming gain: 20 dB
- MS beamwidth: 90 degree
- MS beamforming gain: 6 dB
- Body blocking loss: 30 dB
- Body blocking prob.: 1/6

**Building statistics:**
- LOS range: 200 m (Austin downtown)

**Rate computation:**
- 5 dB gap from Shannon
- SINR clipped by 30 dB
- Maximum rate from two bands all outdoor users
Conclusion

mmWave BS

Microwave Macro BS

Multiple-BS access for fewer handovers and high rate

Buildings

Wireless backhaul

Data center

LOS links

Control signals

Indoor user

Femtocell

Non-line-of-sight (NLOS) link

mmWave D2D

mmWave will impact every aspect of cellular communication


https://www.youtube.com/watch?v=BQ45FuGpFQ0