Millimeter Wave Cellular Communications:
Channel Models, Capacity Limits, Challenges and Opportunities

Prof. Ted Rappaport
NYU WIRELESS
NYU Polytechnic School of Engineering

Joint work with Sundeep Rangan and Elza Erkip (NYU-Poly)
and many, many dedicated students

May 26, 2014
IEEE Comm. Theory Workshop, Curacao
Millimeter Wave Wireless Communications, Pearson/Prentice Hall, c. 2015
Early Work in Directional Channels

Wideband Measurements of Angle and Delay Dispersion for Outdoor and Indoor Peer-to-Peer Radio Channels at 1920 MHz
Durgin, et. al., IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 5, MAY 2003

Spatial and temporal characteristics of 60-GHz indoor channels
Xu, et. al., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 20, NO. 3, APRIL 2002

1) Multipath Shape Factor Theory found new parameters to describe directional channels
2) RMS delay spreads and interference shrink dramatically for small cell directional antennas
4) A distinct trend shows how angular spread increases as delay spread increases.
5) Multipath power is arriving from several discrete directions in azimuth instead of across a smooth continuum of azimuthal angles in NLOS channels.
6) What are the channel behaviors for outdoor, indoor, urban across mmWave bands?
Background – Atmospheric Attenuation

- 0.012 dB over 200 m at 28 GHz
- 0.016 dB over 200 m at 38 GHz
- 4.000 dB over 200 m at 60 GHz
- 0.060 dB over 200 m at 73 GHz
- White
  - Very low air attenuation at 28 and 38 GHz
- Blue
  - Ultra-short-range indoor communications, “whisper” communications of the future
    - High Attenuation
- Green
  - Future backhaul and mobile at E-band
    - Low atmospheric attenuation
    - Multi-GHz bandwidth at 28, 39, 70 GHz
    - Directional antenna arrays with beamsteering and beam-combining
    - CMOS: cost-effective with high frequency limits

Background – Rain Attenuation

Rain attenuation at 70 GHz
- Heavy rain (25mm/hr): 10 dB/km

Cell size: 200 meters

Heavy Rainfall @ 73 GHz
2 dB attenuation @ 200m

Heavy Rainfall @ 28 GHz
1.2 dB attenuation @ 200m


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Key Challenge: Range

- **Friis’ Law:** $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$
  - Free-space channel gain $\propto \lambda^2$, but antenna gains $\propto 1/\lambda^2$
  - For fixed physical size antennas in free space, frequency does not matter!
  - In principle, path loss can be overcome with beamforming, independent of frequency.

- **Shadowing:** Significant transmission losses possible:
  - Brick, concrete $> 35$ dB
  - Human body: Up to 35 dB
  - But channel is rich in scattering and reflection, even from people

- **It works!** NLOS propagation uses reflections and scattering
  Rappaport, et. al, “Millimeter wave mobile communications for 5G cellular: It will work!” IEEE Access, 2013
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>28 GHz</td>
</tr>
<tr>
<td>Sequence</td>
<td>11th order PN Code (Length = 2047)</td>
</tr>
<tr>
<td>Transmitted Chip Rate</td>
<td>400 MHz</td>
</tr>
<tr>
<td>Receiver Chip Rate</td>
<td>399.95 MHz</td>
</tr>
<tr>
<td>First null-to-null RF bandwidth</td>
<td>800 MHz</td>
</tr>
<tr>
<td>Slide Factor</td>
<td>8000</td>
</tr>
<tr>
<td>System Measurement Range</td>
<td>178 dB</td>
</tr>
<tr>
<td>Maximum TX Power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>TX/RX Antenna Gain</td>
<td>24.5 dBi, 15 dBi</td>
</tr>
<tr>
<td>TX/RX Azimuth and Elevation HPBW</td>
<td>10.9° /8.6°, 28.8° /30°</td>
</tr>
<tr>
<td>TX-RX Synchronization</td>
<td>Unsupported</td>
</tr>
</tbody>
</table>
28 GHz Channel Sounder

TX Hardware

RX Hardware

• 4 TX sites
• 33 RX sites (35 w/ LOS)

• Pedestrian and vehicular traffic
• High rise-buildings, trees, shrubs

• TX sites:
  • TX-COL1 – 7 m
  • TX-COL2 – 7 m
  • TX-KAU – 17 m
  • TX-ROG – 40 m

• RX sites:
  • Randomly selected near AC outlets
  • Located outdoors in walkways
**Measurement Campaign** 73 GHz  
**Carrier Frequency** 73.5 GHz  
**RF Null-to-Null Bandwidth** 800 MHz  
**TX PN Code Chip Rate** 11th order PN Code (Length = 2047 chips)  
**Transmit Sequence** 2047 chips  
**TX PN Code Chip Rate** 400 Mcps  
**RX PN Code Chip Rate** 399.95 Mcps  
**Slide Factor $\gamma$** 8000  
**TX Power** 14.6 dBm  
**EIRP** 41.6 dBm  
**RX Antenna** 27 dBi  
7° half-power beamwidth  
Vertically Polarized  
**TX Antenna** 27 dBi  
7° half-power beamwidth  
Vertically Polarized  
**Maximum Measurable Path Loss (5 dB SNR)** 181 dB  
**Multipath Time Resolution** 2.5 ns

*Note: 20 dBi horn antenna on upconverter*
• 400 Mega-chip-per-second (Mcps)
• 27 dBi (7° BW) horn antenna
• 14.6 dBm TX RF output
• LabVIEW-controlled gimbal (azimuth/elevation)

73 GHz Channel Sounder

Receiver

- 27 dBi (7° BW) horn antenna
- 181 dB Max. Measurable Path Loss
- LabVIEW-controlled gimbal (azimuth/elevation)

73 GHz Channel Sounder

TX Hardware

RX Hardware
NYC Measurements – Dense Urban
Mobile and Backhaul at 73 GHz

- 5 TX sites
- 27 RX sites

- 74 total TX-RX combinations tested
  - 36 BS to MS
  - 38 BS to BS (backhaul).

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-KIM1 – 7m
  - TX-KIM2 – 7m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways
### Summary of Measurement Locations in NYC

#### 28 GHz Campaign in Manhattan for 200 m cell (2012)

<table>
<thead>
<tr>
<th>TX Location</th>
<th>TX Height (meters)</th>
<th>Number of RX Locations</th>
<th>RX Height (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL1</td>
<td>7</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>COL2</td>
<td>7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>KAU</td>
<td>17</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

#### 73 GHz Campaign in Manhattan for 200 m cell (2013)

<table>
<thead>
<tr>
<th>TX Location</th>
<th>TX Height (meters)</th>
<th>Number of RX Locations (Cellular)</th>
<th>RX Height (Cellular) (meters)</th>
<th>RX Height (Backhaul) (meters)</th>
<th>Number of RX Locations (Backhaul)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COL1</td>
<td>7</td>
<td>11</td>
<td>2</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>COL2</td>
<td>7</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAU</td>
<td>17</td>
<td>11</td>
<td>2</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>KIM1</td>
<td>7</td>
<td>3</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>KIM2</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
• 75 TX-RX separation distances range from 19 m to 425 m

• Signal acquired up to 200 m TX-RX separation

• 14% of 35 TX-RX location combinations within 200 m are found to be outage

• For outage, path loss > 178 dB (5 dB SNR per multipath sample) for all unique pointing angles


Signal Outage at 73 GHz in NYC for All Unique Pointing Angles at Each Site

- 74 TX-RX separation distance range from 27 m to 216 m
- 17% of 36 TX-RX location combinations were outage in mobile scenario; 16% of 38 TX-RX location combinations found to be outages in backhaul scenario
- For outage, path loss > 181 dB (5 dB SNR per multipath sample) for all unique pointing angles
- Receiver locations chosen based on previous 28 GHz campaign


* Only a limited amount of RX selected for KIM1 and KIM2

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At 28 GHz in cellular measurements the estimated outage probability is 14% for all RX locations within 200 meters;

At 73 GHz the outage probabilities are 16% and 17% within 216 meters cell size for backhaul and cellular access scenarios, respectively;

Site-specific propagation planning easily predicts outage.

*Published ICC '14 paper erroneously stated 20% and 50% for distances up to 425 m– corrected here.
Signals were received at 23 out of 36 RX azimuth angles (10 degree increments)
Average number of multipath components (MPCs) per distance:
First increases and then decreases with the increasing distance

Average number of MPCs per PDP:
Nearly identical for both the narrow-beam (10.9-degree HPBW) and wide-beam (28.8-degree HPBW) antenna measured cases

Measured RMS delay spread vs. T-R separation distance:
Smaller RMS delay spreads at larger distances (near 200 m) due to large path loss

CDF of RMS delay spread:
Average and maximum RMS delay spreads are slightly smaller for wide-beam antenna case due to lower antenna gain thus smaller detectable path loss range

Average RMS delay spread values are only slightly larger than those for 38 GHz in suburban environments

• Each point on scatter lot represents a unique pointing angle for TX and RX horn antennas
RX (UE) Beam combining results using 1 m free space reference distance for the 7-m high TX antenna, where “PLE” is path loss exponent, “STD” is the shadowing standard deviation, “NC” means noncoherent combining, and “C” denotes coherent combining.

**Coherent combining of 2 beams (n=3.41) < Noncoherent combining of 4 beams (n=3.44)**

**Coherent combining of 4 beams (n=3.15) < single best beam (n=3.68)**

Path gain: 13.2 dB/decade in distance w/ 4 strongest beams coherently combined at different pointing angles compared to randomly pointed single beam.

Path gain: 5.3 dB/decade w/4 beams over single best beam (**1.4X range increase**)
Distributions of AOA/AOD and received power for one TX location and 8 RX locations at 28 GHz

- AODs are concentrated between -80 degrees and -10 degrees with AOAs distributed uniformly from -180 degrees to 180 degrees over this AOD range.


- Strongest signals are received when the TX antenna points in a narrow span of -20 degrees to -10 degrees.

- Beamforming at the TX should focus in a narrow sector of space (60 to 90 degrees is adequate at base station).

73 GHz Omnidirectional Models for (Hybrid) Backhaul/Mobile RX Scenario


Isotropic Path Loss Comparison

- Isotropic NLOS path loss measured in NYC
  - ~ 20 - 30 dB worse than 3GPP urban micro model for fc=2.5 GHz

- Beamforming will offset this loss.

- **Bottom line:** mmW omni channels do not experience increased path loss beyond the simple free space frequency dependence in urban New York City

Hybrid LOS-NLOS-Outage Model

- mmW signals susceptible to severe shadowing.
  - Not incorporated in standard 3GPP models, but needed for 5G
- New three state link model: LOS-NLOS-outage
  - Other Outage modeling efforts (Bai, Vaze, Heath ‘13)
- Outages significant only at $d > 150m$
  - Will help smaller cells by reducing interference

Simulations: SNR Distribution

- Simulation assumptions:
  - 200m ISD
  - 3-sector hex BS
  - 20 / 30 dBm DL / UL power
  - 8x8 antenna at BS
  - 4x4 (28 GHz), 8x8 (73 GHz) at UE

- A new regime:
  - High SNR on many links
  - Better than current macro-cellular
  - Interference is non dominant
Comparison to Current LTE

- Initial results show significant gain over LTE
  - Further gains with spatial mux, subband scheduling and wider bandwidths

<table>
<thead>
<tr>
<th>System antenna</th>
<th>Duplex</th>
<th>fc (GHz)</th>
<th>Antenna</th>
<th>Cell throughput (Mbps/cell)</th>
<th>Cell edge rate (Mbps/user, 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DL</td>
<td>UL</td>
</tr>
<tr>
<td>mmW TDD</td>
<td>1 GHz</td>
<td>28</td>
<td>4x4 UE</td>
<td>1514</td>
<td>1468</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8x8 eNB</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>73</td>
<td>8x8</td>
<td>8x8 eNB</td>
<td>1435</td>
<td>1465</td>
</tr>
<tr>
<td>Current LTE</td>
<td>20+20 MHz FDD</td>
<td>2.5</td>
<td>(2x2 DL, 2x4 UL)</td>
<td>53.8</td>
<td>47.2</td>
</tr>
</tbody>
</table>

10 UEs per cell, ISD=200m, hex cell layout
LTE capacity estimates from 36.814

~ 25x gain ~ 10x gain


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Recent Results by NSN for 73 GHz

* Assumes RF BW of 2.0 GHz, NCP-SC Modulation
* Symbol Rate 1.536 Gigasymbols/sec (50 X LTE)
* Access Point Array: 4 sectors, dual 4X4 polarization
* Ideal Channel State estimator and Fair Scheduler
* Beamforming using uplink signal

Simulation Results:

4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage
8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage

Outage can be reduced by denser cells, smart repeaters/relays

Multihop Relaying for mmW

- Significant work in multi-hop transmissions for cellular
- Gains have been minimal
- Why?
  - Current cellular systems are bandwidth-limited; mmWave is noise-limited
- Millimeter wave may be different
  - Overcome outage via macrodiversity
  - Many degrees of freedom
Multihop Relays (D2D)

- Network discovery?
- Directional isolation
- Dynamic duplexing

Interference-to-noise

Qualcomm FlashLinQ frame structure
• mmW systems offer orders of magnitude capacity gains
• Experimental confirmation in NYC
  • 200 m cell radius very doable
  • Greater range extension through beam combining
  • Orders of magnitude capacity gains from increased bandwidth
  • Early days for channel modeling and adaptive arrays – a new frontier
  • NYU WIRELESS has created a Statistical Spatial Channel Model for 28 GHz – complete simulator

• Systems enter new regime:
  • Links are directionally isolated, high SNR, noise-limited channel
  • Links rely heavily on beamforming
  • Cooperation and base station diversity should offer big improvements

• Multi-hop relaying
  • Revisiting a mature concept but now in a noise-limited environment
Thank you!

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