3GPP-Style Statistical Channel Models and Directional Beamforming Models for Outdoor Millimeter-Wave Wireless Communications

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• 28 GHz and 73 GHz Mobile Measurements and Equipment (Summer 2012, Summer 2013, Ongoing)
• Omnidirectional Path Loss Models in LOS and NLOS
• 28 GHz Statistical Channel Models in LOS and NLOS
• Beamcombining Models at 28 GHz and 73 GHz
• Upgrades to Channel Sounder and Upcoming Measurements
• Joining the Industry Affiliates Program at NYU WIRELESS
The Wireless Spectrum Today

AM Radio

FM Radio

3G/4G LTE Cellular

Wi-Fi

28 GHz – LMDS (5G Cellular)

38 GHz (5G Cellular)

60 GHz Spectrum WiGig (802.11 ad)

73 GHz Backhaul

Active CMOS IC Research

28 GHz Propagation Measurement Campaign in Manhattan – Summer 2012

- 400 Mcps Broadband Sliding Correlator Channel Sounder
- BS to MS measurements
- 3 BS Locations (yellow stars):
  - Kaufman Center – 17m
  - Coles Sports Center – 7m (x2)
- 25 RX Locations (green dots, purple squares):
  - TR Distances 30 m – 500 m
- 3 TX Sites: 3 AOD, 1 sweep
- 25 RX Sites: 3 EL, 9 sweeps

28 GHz Cellular Measurements Locations in Manhattan near NYU campus

28 GHz TX-RX Equipment

Transmitter

Receiver
2^{11}-1 Length PN code

Spread Spectrum
28 GHz Channel Sounder Block Diagrams

Transmitted Signal

Transmitter

Received Signal

Receiver


Manhattan Measurements at 73 GHz (Summer 2012)

- 5 TX sites
- 27 RX sites

- 74 total TX-RX combinations tested
  - 36 BS to MS (access)
  - 38 BS to BS (backhaul).
  - 2 AOD and 10 AOA sweeps for each combination with varying elevations between sweeps

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

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways

G. R. MacCartney and T. S. Rappaport, “73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City,” accepted to the IEEE International Conference on Communications (ICC), 10-14 June 2014.
## 28 GHz and 73 GHz Sliding Correlator Channel Sounder Specifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>28 GHz</td>
<td>73.5 GHz</td>
</tr>
<tr>
<td>Sequence</td>
<td>11th order PN Code (Length = 2047)</td>
<td></td>
</tr>
<tr>
<td>Transmitter Chip Rate</td>
<td>400 Mcps</td>
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</tr>
<tr>
<td>Receiver Chip Rate</td>
<td>399.95 Mcps</td>
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</tr>
<tr>
<td>RF Bandwidth (First Null)</td>
<td>800 MHz</td>
<td></td>
</tr>
<tr>
<td>Slide Factor</td>
<td>8000</td>
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<tr>
<td>Multipath Time Resolution</td>
<td>2.5 ns</td>
<td></td>
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<tr>
<td>Maximum Measurable Path Loss (5 dB SNR)</td>
<td>178 dB</td>
<td>181 dB</td>
</tr>
<tr>
<td>Maximum TX Output</td>
<td>30 dBm</td>
<td>14.6 dBm</td>
</tr>
<tr>
<td>TX/RX Antenna Gain</td>
<td>24.5/15 dBi</td>
<td>27 dBi</td>
</tr>
<tr>
<td>TX/RX Antenna Azimuth and Elevation HPBW</td>
<td>10.9°/8.6°, 28.8°/30°</td>
<td>7°</td>
</tr>
</tbody>
</table>


73 GHz TX-RX Equipment

TX Hardware

RX Hardware
Creation of an Omnidirectional Path Loss Model

Our work measured path loss at unique pointing angles for directional channel models. Here, we present the world’s first omnidirectional path loss models suitable for 3GPP/ITU.

- Steps for obtaining omnidirectional path loss
  - Note: Original TX and RX antennas were directional at the “i” transmitter locations and “j” receiver locations for TX arbitrary pointing angles $\theta t$ and $\Phi t$ in the azimuth and elevation plane angles respectively, and for RX arbitrary pointing angles $\theta r$ and $\Phi r$ in the azimuth and elevation plane angles respectively.
  - Received power (area under PDP) was measured at each and every unique azimuth/elevation TX and RX angle combinations for every distinct TX-RX location pair. $\theta r$ and $\Phi r$ are the receiver azimuth and elevation planes respectively. $\theta t$ and $\Phi t$ are the transmitter azimuth and elevation planes respectively representing: $P_{R_{i,j}}(\theta r, \Phi r, \theta t, \Phi t)$ for every individual measurement.
  - TX and RX antenna gains were removed from each received power level $P_{R_{i,j}}(\theta r, \Phi r, \theta t, \Phi t)$ such that $P_{R_{i,j}}(\theta r, \Phi r, \theta t, \Phi t)[dBm] = P_{R_{i,j}} - G_{TX} - G_{RX}$
  - Sum each and every resulting power (in mW) at all measured unique pointing angle combinations ($\theta r, \Phi r, \theta t, \Phi t$) for each TX-RX location pair.
  - For each TX-RX location pair, omnidirectional path loss is given by the following equation:

$$PL_{i,j}[dB] = P_{l_{i,j}}[dBm] - 10\log_{10} \left[ \sum \sum \sum \sum Pr_{i,j}(\theta r, \Phi r, \theta t, \Phi t)[mW] \right]$$

Path Loss Models

Close-in Free Space Reference Distance Path Loss Model (MMSE Fit)

\[ PL[dB](d) = 20 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right) + 10\bar{n} \log_{10} \left( \frac{d}{d_0} \right) + \chi_{\sigma} \]

- \( d_0 = 1 \text{ m, free space reference distance} \)
- \( \lambda \) – carrier wavelength
- \( \bar{n} \) – path loss exponent w.r.t. \( d_0 \)
- \( \chi_{\sigma} \) – lognormal R.V. \( \sim N(0, \sigma) \)
- \( d \) – T-R Separation distance (m)

Path Loss Models

Floating Intercept Path Loss Model (Least-Squares Regression)

\[ PL[dB](d) = \alpha + 10\beta \log_{10}(d) + \chi_\sigma \]

- \( \alpha \) – intercept (dB)
- \( \beta \) – slope (different from PLE)
- \( \chi_\sigma \) – lognormal R.V. \( \sim N(0, \sigma) \)
- \( d \) – T-R Separation distance (m)
- \( 30 \text{ m} < d < 200 \text{ m} \) (limited by measurements)


The following models are for 28 GHz access measurements (RX: 1.5 m), and 73 GHz hybrid measurements (RX: 2 m and 4.06 m)

**LOS Close-in Reference Model:**
\[
\begin{align*}
\text{PL}_{28\text{GHz}}(\text{LOS})[\text{dB}](d) &= 61.4 + 21\log_{10}(d) \\
+ X_\sigma (\sigma = 3.6 \text{ dB}) \\
\text{PL}_{73\text{GHz-Hybrid}}(\text{LOS})[\text{dB}](d) &= 69.8 + 20\log_{10}(d) \\
+ X_\sigma (\sigma = 4.8 \text{ dB})
\end{align*}
\]

**NLOS Close-in Reference Model:**
\[
\begin{align*}
\text{PL}_{28\text{GHz}}(\text{NLOS})[\text{dB}](d) &= 61.4 + 34\log_{10}(d) \\
+ X_\sigma (\sigma = 9.7 \text{ dB}) \\
\text{PL}_{73\text{GHz-Hybrid}}(\text{NLOS})[\text{dB}](d) &= 69.8 + 34\log_{10}(d) \\
+ X_\sigma (\sigma = 7.9 \text{ dB})
\end{align*}
\]

**NLOS Floating Intercept Model:**
\[
\begin{align*}
\text{PL}_{28\text{GHz}}(\text{NLOS})[\text{dB}](d) &= 79.2 + 26\log_{10}(d) \\
+ X_\sigma (\sigma = 9.6 \text{ dB}) \\
\text{PL}_{73\text{GHz-Hybrid}}(\text{NLOS})[\text{dB}](d) &= 80.6 + 29\log_{10}(d) \\
+ X_\sigma (\sigma = 7.8 \text{ dB})
\end{align*}
\]

• 1 – 6 GHz RF propagation
• 5 – 100 MHz RF bandwidth
• 20 ns multipath time resolution (best)
• High spatial (angular) resolution
• **Inappropriate for describing millimeter-wave propagation**

V11.0.0, 3GPP TR 25.996, "Spatial Channel Model for Multipath Input Multiple Output (MIMO) Simulations," September 2012
Multipath from different angles have different propagation time delays.

a) Superimposed PDPs of two individual PDPs, where each PDP comes from a different AOA at the same RX.

b) Case 1: Superimposed PDPs at excess delay $t = 0$ ns.
Case 2: Superimposed PDPs according to absolute time $= 0$ ns (using ray-tracing methods).

3-D Ray-Tracing to Synthesize Omni. PDP

Numerical Database:
- Google SketchUp
- 250 m x 250 m
- ~ 5 m accuracy

- 4 Strongest AOA's predicted to synthesize omni PDP
- Minor angle skew does not impact statistical model

Example of Four Strongest Measured PDPs to Create Omni. PDP

T1 = 381 ns  
T2 = 407 ns  
T3 = 1433 ns  
T4 = 1500 ns

28 GHz LOS VS NLOS Spectra

In LOS: Power arriving from all AOA angles (Large RMS Delay Spread)
In NLOS: Power arriving from distinct AOA angles (Smaller RMS Delay Spread)

LOS Polar Plot

NLOS Polar Plot

T-R Separation: 54 m
T-R Separation: 77 m
Omnidirectional Statistical Spatial Channel Model

Example PDP at one pointing angle


Primary Statistics:
Quantities needed to reproduce mmWave omni-PDP:

• Omni-directional path loss model
• # of time clusters
• # of cluster sub-paths in time clusters
• Cluster and cluster sub-path arrival times
• Power in clusters and cluster sub-paths

Secondary Statistics:
Quantities needed to validate simulator:

• Cluster durations
• Inter-cluster void duration
• RMS delay spread

Primary Statistics:
Quantities needed to reproduce mmWave PAS (Polar Plot):
  • Number of Lobes
  • AOAs
  • Lobe Azimuth Spreads
  • Lobe Segment Powers

Secondary Statistics:
Quantities needed to validate simulator:
  • RMS Lobe Azimuth Spread

Number of clusters and cluster subpaths in NLOS

- Inter-cluster Minimum Void Duration of 2.7 ns
- Cluster Partitioning Scheme Optimized using $\chi^2$ criterion

Clustering delays and powers in NLOS

\[ F_t(t) = 1 - e^{-\frac{t}{\mu}} \]

\[ P_n' = 10^{10} e^{-\frac{\tau_n}{\beta}} \]

\[ \beta = 31.4 \text{ ns} \]

\[ Z \sim N(0 \text{ dB}, 9.4 \text{ dB}) \]

Clusters subpath delays and powers in NLOS

\[ F_\rho(t) = 1 - e^{-\frac{t}{\mu}} \]

\[ \Pi'_m = 10^{10e^{-\frac{\rho_m}{\beta}}} \]

\[ \beta = 6.63 \text{ ns} \]

\[ Z \sim N(0 \text{ dB}, 5.1 \text{ dB}) \]

Number of Lobes and AOAs in NLOS

- Lobe threshold -20 dB below maximum PAS segment power
- AOA ~ Uniform(0,360)

Lobe Azimuth Spreads and Lobe Segment Powers in NLOS

Key step for unifying temporal and spatial statistics

\[ R(\Delta \theta) = e^{\frac{-\frac{\Delta \theta^2}{2\sigma^2}}{}} \]

\[ \sigma = 2\sigma_{RMS, AOA} = 2 \times 5.5^\circ = 11^\circ \]

= Antenna 3dB BW

10,000 Simulated PDPs VS Synthesized Measured RMS Delay Spreads in NLOS

Note: more careful noise thresholding yields lower RMS delay spreads than published

Path Loss Model in NLOS:

Summary of the measured statistics were obtained from synthesized measured 28 GHz omnidirectional wideband PDPS, and the simulated statistics were generated from 10,000 PDPS and PAS. (P) and (S) stand for primary and secondary, respectively.

<table>
<thead>
<tr>
<th>Path Loss Model</th>
<th>Measured ((n, \sigma))</th>
<th>Simulated ((n, \sigma))</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omnidirectional (P)</td>
<td>(3.4, 9.7 dB)</td>
<td>(3.4, 9.8 dB)</td>
<td>(0,1.0)</td>
</tr>
</tbody>
</table>

Statistical Simulator Results

Temporal Statistics in NLOS: All primary statistics within 10% error

**SUMMARY OF THE MEASURED STATISTICS WERE OBTAINED FROM TIME-SYNTHESIZED MEASURED 28 GHz OMNIDIRECTIONAL WIDEBAND PDPs, AND THE SIMULATED STATISTICS WERE GENERATED FROM 10,000 PDPs AND PAS. (P) AND (S) STAND FOR PRIMARY AND SECONDARY, RESPECTIVELY.**

<table>
<thead>
<tr>
<th>Type of Statistic</th>
<th>Quantity</th>
<th>Measured ($\mu, \sigma$)</th>
<th>Simulated ($\mu, \sigma$)</th>
<th>Error (%)</th>
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</thead>
<tbody>
<tr>
<td><strong>Temporal</strong></td>
<td>Number of Clusters (P)</td>
<td>Poisson (3.4, 2.1)</td>
<td>(3.2, 2.1)</td>
<td>(5.9, 0)</td>
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<td></td>
<td>Number of Cluster Sub-Paths (P)</td>
<td>Exponential (2.1, 1.6)</td>
<td>(2.2, 1.7)</td>
<td>(4.7, 6.3)</td>
</tr>
<tr>
<td></td>
<td>Cluster Excess Time Delay (ns) (P)</td>
<td>Exponential (66.3, 68.0)</td>
<td>(71.8, 62.1)</td>
<td>(8.3, 8.7)</td>
</tr>
<tr>
<td></td>
<td>Cluster Sub-path Excess Time Delay (ns) (P)</td>
<td>Exponential (8.1, 8.8)</td>
<td>(8.6, 8.0)</td>
<td>(6.2, 9.1)</td>
</tr>
<tr>
<td></td>
<td>RMS Delay Spread (ns) (S)</td>
<td>Exponential (13.4, 11.5)</td>
<td>(12.9, 11.3)</td>
<td>(3.7, 1.7)</td>
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<tr>
<td></td>
<td>Cluster RMS Delay Spread (ns) (S)</td>
<td>Exponential (2.0, 2.0)</td>
<td>(2.4, 1.7)</td>
<td>(20.0, 15.0)</td>
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<td>Cluster Duration (ns) (S)</td>
<td>Exponential (8.9, 8.7)</td>
<td>(10.7, 8.4)</td>
<td>(20.2, 3.5)</td>
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<td>Inter-cluster Void Duration (ns) (S)</td>
<td>Exponential (16.8, 17.2)</td>
<td>(21.5, 15.9)</td>
<td>(28.0, 7.5)</td>
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</tbody>
</table>


Spatial Statistics in NLOS:

Summary of the measured statistics were obtained from synthesized measured 28 GHz omnidirectional wideband PDPs, and the simulated statistics were generated from 10,000 PDPs and PAS. (P) and (S) stand for primary and secondary, respectively.

<table>
<thead>
<tr>
<th>Type of Statistic</th>
<th>Quantity</th>
<th>AOA/AOD</th>
<th>Measured (μ,σ)</th>
<th>Simulated (μ,σ)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Lobes (P)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>AOA</td>
<td></td>
<td>Poisson (2.4, 1.3)</td>
<td>(2.3, 1.1)</td>
<td>(4.2, 15.4)</td>
</tr>
<tr>
<td></td>
<td>AOD</td>
<td></td>
<td>Poisson (2.0, 1.3)</td>
<td>(1.8, 0.9)</td>
<td>(10.0, 30.0)</td>
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<td></td>
<td>Mean Pointing</td>
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<tr>
<td></td>
<td>AOA</td>
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<td>Uniform(0,360)</td>
<td>Uniform(0,360)</td>
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<tr>
<td></td>
<td>AOD</td>
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<td>Uniform(0,360)</td>
<td>Uniform(0,360)</td>
<td>0</td>
</tr>
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<td></td>
<td>Lobe Azimuth Spread (°) (P)</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>AOA</td>
<td></td>
<td>Normal (34.8, 25.7)</td>
<td>(34.6, 27.8)</td>
<td>(0.2, 9.0)</td>
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<tr>
<td></td>
<td>AOD</td>
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<td>Normal (42.5, 25.2)</td>
<td>(43.6, 26.1)</td>
<td>(2.6, 3.6)</td>
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<tr>
<td></td>
<td>RMS Lobe Azimuth Spread (°) (S)</td>
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<td></td>
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<tr>
<td></td>
<td>AOA</td>
<td></td>
<td>Exponential (6.1, 5.8)</td>
<td>(8.3, 6.8)</td>
<td>(36.0, 17.0)</td>
</tr>
<tr>
<td></td>
<td>AOD</td>
<td></td>
<td>Normal (7.7, 5.3)</td>
<td>(8.0, 7.0)</td>
<td>(4.0, 32.0)</td>
</tr>
</tbody>
</table>


Typical Polar Plots for TX at 28 GHz (Simulated)

TX LOS AOD for 28 GHz

TX NLOS AOD at 28 GHz

Upcoming 3-D Channel Models

- 3-D Channel Models include Elevation
- 3-D Modeling of Power Spherical Spectra at TX and RX
- 3-D Modeling of Omnidirectional PDPs
- Active Research Area at NYU WIRELESS – Close Collaboration with Industrial Affiliates
Opportunity for Beamforming and Beam Combining

Typical polar plot showing received power at different angles of arrival (AOAs)

Signals were received at 26 out of 45 RX azimuth angles

Signals coming from a myriad of beams can be combined to enhance the received signal level

Beam Combining Procedure

- Non-coherent Combining

$$P_{NC} = \sum_{i=1}^{N} P_i$$

- Coherent Combining

$$P_C = \left( \sum_{i=1}^{N} \sqrt{P_i} \right)^2$$

$P_{NC}$ and $P_C$: the non-coherently and coherently combined powers in Watts

$P_i$ (i=1,2,…, N): the i\textsuperscript{th} strongest received power in Watts.

Beam combining can significantly improve path loss exponents (PLEs)

The performance of coherent combining is superior to that of non-coherent combining

NLOS (Co-Polarization):
Overall: \( n = 4.5 \)
\( \sigma_{SF} = 10.8 \) dB

Strongest power at each T-R distance for best angle combination using 24.5 dBi 10.9-degree beamwidth antennas at both TX and RX:
\( n = 3.7 \)
\( \sigma_{SF} = 9.5 \) dB

“NC”: Non-coherent Combining
“C”: Coherent Combining

### Comparison of Path Loss between 28 GHz and 73 GHz

**Environment: NLOS**

**Comparable path Loss exponents (PLEs) at 28 GHz and 73 GHz**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>TX, RX Antenna Gains (dBi)</th>
<th>TX Height (m)</th>
<th>RX Height (m)</th>
<th># of Combined Beams</th>
<th>Coherent Path Loss Exponent</th>
<th>Shadow Factor (dB)</th>
<th>Noncoherent Path Loss Exponent</th>
<th>Shadow Factor (dB)</th>
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</thead>
<tbody>
<tr>
<td>28</td>
<td>24.5, 24.5, vertically polarized</td>
<td>7, 17</td>
<td>1.5</td>
<td>Arbitrary Angle</td>
<td>4.6</td>
<td>11.3</td>
<td>4.6</td>
<td>11.3</td>
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<td>7.6</td>
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<td>7.6</td>
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<td></td>
<td>2</td>
<td>3.5</td>
<td>7.3</td>
<td>3.6</td>
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<td>7.2</td>
<td>3.6</td>
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<td>4</td>
<td>3.2</td>
<td>7.2</td>
<td>3.5</td>
<td>7.3</td>
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<tr>
<td>73</td>
<td>27, 27, vertically polarized</td>
<td>7, 17</td>
<td>2</td>
<td>Arbitrary Angle</td>
<td>4.6</td>
<td>10.7</td>
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<td></td>
<td>4</td>
<td>3.3</td>
<td>8.0</td>
<td>3.6</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Future Channel Sounding System

Old Sounder

New Sounder

- Going from Analog to Digital: Faster Data Rates (Larger Bandwidth Up to 1 Gbps)
- TX-RX Time Synchronization using 1PPS GPS
- Accurate RX Location Positioning using GPS
- More Compact, More Reliable than PCB and Analog Components
Large scale and small scale propagation measurements:
- Linear track (small scale)
- Different RX locations, separated by a few meters (large scale)
Understanding Spatial and Temporal Correlation: How does the channel change with small displacements in position and time?

NYU WIRELESS Mission and Expertise

• **EXCITING NEW CENTER**: 25 faculty and 100 students across NYU

• Solving problems for industry, creating research leaders, and developing fundamental knowledge and new applications using wireless technologies
  - NYU Polytechnic (Electrical and Computer Engineering)
  - NYU Courant Institute (Computer Science)
  - NYU School of Medicine (Radiology) and world class hospital

• NYU WIRELESS faculty possess a diverse set of knowledge and expertise:
  - Communications (DSP, Networks, RF/Microwave, Antennas, Circuits)
  - Medical applications (Anesthesiology, EP Cardiology, MRI, Compressed sensing)
  - Computing (Graphics, Data mining, Algorithms, Scientific computing)
  - Current in-force funding:
    - Over $10 Million/annually from NSF, NIH, and Corporate sponsors
NYU WIRELESS Industrial Affiliates
Conclusion

- mmWave offers new spatial channel models with high temporal and narrow spatial resolutions
  - Multiple temporal clusters per AOA
  - Multiple subpath components per temporal cluster (intra-cluster statistics)
  - Omnidirectional LOS offers greater RMS delay spreads than NLOS in 2-D

Path Loss:

- Comparable path loss at 28 GHz and 73 GHz in dense urban environments

Beam Combining:

- Coherent combining is superior to non-coherent combining
- Higher signal quality and lower path loss
  - Up to 28 dB of link budget improvement at 73 GHz and 24 dB at 28 GHz when combining the four strongest beams coherently
- Better signal coverage and link margin

References


ありがとうございます！

Arigatoo Gozaimashta!

Questions?