Millimeter Wave Small-Scale Spatial Statistics in an Urban Microcell Scenario

Shu Sun, Hangsong Yan, George R. MacCartney, Jr., and Theodore S. Rappaport
{ss7152,hy942,gmac,tsr}@nyu.edu

IEEE International Conference on Communications (ICC)
Paris, France, May 22, 2017
Background and Motivation for Small-Scale Channel Behavior

Small-Scale Fading Measurements at 73 GHz with 1 GHz RF Bandwidth

Omnidirectional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth
  - Omnidirectional Small-Scale Spatial Fading of Received Signal Voltage Amplitude
  - Omnidirectional Small-Scale Spatial Autocorrelation of Received Signal Voltage Amplitude

Directional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth
  - Directional Small-Scale Spatial Fading of Received Signal Voltage Amplitude
  - Directional Small-Scale Spatial Autocorrelation of Received Signal Voltage Amplitude

Conclusions
What is small-scale fading?

- The fluctuation of the **amplitude of a radio signal (received voltage)** or the **envelope of an individual multipath component (MPC)** over a short period of time or travel distance, caused by interference between two or more versions of the transmitted signal which arrive at slightly different times [1]

- The variation in **received signal envelope** due to the constructive and destructive addition of multipath signal components over very short distances, on the order of the signal wavelength [2]


Background and Motivation II

- Small-scale fading at sub-20 GHz bands over small distances or time periods
  - Ricean [1][2][3][5], Rayleigh [1][5], log-normal [4][5], Nakagami [5][6], Weibull [5][6], etc.

- Impact of RF bandwidth on small-scale fading
  - Fade depth generally decreases as the bandwidth increases [7][8]

- Little is known about small-scale fading and autocorrelation at millimeter-wave (mmWave) frequencies
  - 28 GHz small-scale statistics measurements in [9]:
    - Small-scale spatial fading of individual multipath voltage amplitudes for an RF bandwidth of 800 MHz: Ricean distribution [9]
    - Small-scale spatial autocorrelation: exponential function plus a constant term [9]

Small-Scale Fading Measurements at 73 GHz with 1 GHz RF Bandwidth

Note: measurement set with a linear track of length 35.31-cm (about 87 wavelengths at 73.5 GHz)

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast Sequence</td>
<td>11th order PN Code ($L = 2^{11} - 1 = 2047$)</td>
</tr>
<tr>
<td>TX and RX Antenna Type</td>
<td>Rotatable Pyramidal Horn Antenna</td>
</tr>
<tr>
<td>TX Chip Rate</td>
<td>500 Mcps</td>
</tr>
<tr>
<td>RX Chip Rate</td>
<td>499,9375 Mcps</td>
</tr>
<tr>
<td>Slide Factor $\gamma$</td>
<td>8000</td>
</tr>
<tr>
<td>RF Null-to-Null Bandwidth</td>
<td>1 GHz</td>
</tr>
<tr>
<td>PDP Threshold</td>
<td>20 dB down from max peak</td>
</tr>
<tr>
<td>TX/RX Intermediate Frequency</td>
<td>5.625 GHz</td>
</tr>
<tr>
<td>TX/RX Local Oscillator</td>
<td>67.875 GHz (22,625 GHz x 3)</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>73.5 GHz</td>
</tr>
<tr>
<td>TX Power</td>
<td>14.2 dBm</td>
</tr>
<tr>
<td>TX Antenna Gain</td>
<td>27 dBi</td>
</tr>
<tr>
<td>TX Azimuth/Elevation HPBW</td>
<td>$7^\circ/7^\circ$</td>
</tr>
<tr>
<td>EIRP</td>
<td>41.2 dBm</td>
</tr>
<tr>
<td>TX Heights</td>
<td>4.0 m</td>
</tr>
<tr>
<td>RX Antenna Gain</td>
<td>9.1 dBi</td>
</tr>
<tr>
<td>RX Azimuth/Elevation HPBW</td>
<td>$60^\circ/60^\circ$</td>
</tr>
<tr>
<td>TX-RX Antenna Polarization</td>
<td>V-V (Vertical-to-Vertical)</td>
</tr>
<tr>
<td>RX Heights</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Maximum Measurable Path Loss</td>
<td>168 dB</td>
</tr>
</tbody>
</table>
Small-Scale Fading Measurements at 73 GHz with 1 GHz RF Bandwidth

TX: 7° azimuth & elevation HPBW directional antenna

RX: 60° azimuth & elevation HPBW directional antenna to emulate mobile phones in small-scale areas

Orthogonal linear tracks (35.31-cm (about 87 wavelengths at 73.5 GHz)) at each RX

Measure total signal voltage amplitude, i.e., square root of area under PDP

TX: one location, 4 m above ground
- RX: two locations, 1.4 m above ground
  - LOS location: 79.9 m T-R separation distance (TX antenna fixed at 90°/0° azimuth/elevation)
  - NLOS location: 75.0 m T-R separation distance (TX antenna fixed at 200°/0° azimuth/elevation)
Small-Scale Fading Measurements at 73 GHz with 1 GHz RF Bandwidth

35.31-cm (about 87 wavelengths at 73.5 GHz) linear track at each RX location:
  o Placed in two orthogonal directions respectively
  o RX antenna moved in half-wavelength steps (175 positions) for each fixed RX pointing angle
  o 6 RX antenna azimuth pointing angles per track orientation, with adjacent azimuth angles separated by a HPBW (60°), covering 360° azimuth plane for synthesizing omnidirectional received power
LOS small-scale directional power delay profiles (PDPs) over 35.31-cm (about 87 wavelengths at 73.5 GHz) linear track

11.0 dB variation of signal power
Track orientation: orthogonal to T-R line
RX antenna pointing on boresight to TX

3.7 dB variation of signal power
Track orientation: parallel with T-R line
RX antenna pointing on boresight to TX
NLOS small-scale directional power delay profiles (PDPs) over 35.31-cm (about 87 wavelengths at 73.5 GHz) linear track

9.9 dB variation of signal power
Track orientation: parallel with street
RX antenna pointing to building with pillars

4.1 dB variation of signal power
Track orientation: parallel with street
RX antenna pointing to TX but obstructed by building corner

Measured NLOS Small-Scale Power Delay Profiles at 73 GHz with 1 GHz RF Bandwidth
Omnidirectional received power was synthesized from the directional received power using the approach presented in [1], over all RX antenna pointing directions.

Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)

 LOS omnidirectional small-scale spatial fading: Ricean distribution with $K = 10$ dB
 NLOS omnidirectional small-scale spatial fading: Log-normal distribution with a standard deviation $\sigma$ of 0.65 dB

LOS distance: 79.9 m  
NLOS distance: 75.0 m

We used empirical measurements to determine the small-scale spatial autocorrelation of received signal voltage amplitude for both omnidirectional and directional RX antennas.

Equation for calculating small-scale spatial autocorrelation of received signal voltage amplitudes

\[
\rho = \frac{E \left[ (A_k(X_k) - \bar{A}_k(X_k)) (A_k(X_k + \Delta X) - \bar{A}_k(X_k + \Delta X)) \right]}{\sqrt{E \left[ (A_k(X_k) - \bar{A}_k(X_k))^2 \right] E \left[ (A_k(X_k + \Delta X) - \bar{A}_k(X_k + \Delta X))^2 \right]}}
\]

\(\rho\): the autocorrelation coefficient of the received signal voltage amplitudes
\(A_k\): received signal voltage amplitude at the kth position on the linear track
\(X_k\): kth position on the linear track
\(\Delta X\): the spacing between different RX antenna positions on the linear track
\(E[\ ]\): the expectation taken over all the positions on the linear track


Omnidirectional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth

Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz) (6 RX pointing angles covering 360° azimuth plane)

LOS omnidirectional small-scale spatial autocorrelation: Sinusoidal-exponential distribution
- Phase differences among individual multipath components oscillate as the separation distance of track positions increases due to alternating constructive and destructive combining of the multipath phases

NLOS omnidirectional small-scale spatial autocorrelation: Exponential distribution

![Graphs showing spatial autocorrelation](image)

Omnidirectional small-scale spatial autocorrelation of received signal voltage amplitudes
Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)

LOS directional small-scale spatial fading (over individual RX antenna pointing angles):
Ricean distribution with $K = 7$ to 17 dB depending on RX pointing angle

NLOS directional small-scale spatial fading (over individual RX antenna pointing angles):
Ricean distribution with $K = 9$ to 21 dB depending on RX pointing angle
LOS Directional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth

Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)
LOS directional small-scale spatial autocorrelation (over individual RX antenna pointing angles): Sinusoidal-exponential distribution in most cases
Interesting LOS directional cases: for track parallel with T-R line
• 270°: large correlation distance larger than 30 wavelengths; RX antenna pointing directly at TX
• 330° and 210°: RX antenna pointing at a large reflector and one multipath component in PDP; autocorrelation oscillates over 200-wavelength distance (extrapolated from measured 30-wavelength distance range)
Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)

NLOS directional small-scale spatial autocorrelation (over individual RX antenna pointing angles): Exponential distribution

Interesting case: 30°: large correlation distance greater than 30 wavelengths;

Parallel with street, pointing to TX side

Directional small-scale spatial autocorrelation of received signal voltage amplitudes
Proposed autocorrelation fit: \( f(\Delta X) = \cos(a\Delta X) e^{-b\Delta X} \)

<table>
<thead>
<tr>
<th>Condition</th>
<th>( a ) (rad/( \lambda ))</th>
<th>( T = 2\pi /a )</th>
<th>( b ) (( \lambda^{-1} ))</th>
<th>( d = 1/b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS Omnidirectional</td>
<td>0.45</td>
<td>14.0( \lambda ) (5.71 cm)</td>
<td>0.10</td>
<td>10.0( \lambda ) (4.08 cm)</td>
</tr>
<tr>
<td>NLOS Omnidirectional</td>
<td>0</td>
<td>Not used</td>
<td>0.26</td>
<td>3.85( \lambda ) (1.57 cm)</td>
</tr>
<tr>
<td>LOS Directional</td>
<td>0 - 0.50</td>
<td>12.6( \lambda ) - ( \infty ) (5.14 cm - ( \infty ))</td>
<td>0.005 - 0.195</td>
<td>5.13( \lambda ) - 200( \lambda ) (2.09 cm - 81.6 cm)</td>
</tr>
<tr>
<td>NLOS Directional</td>
<td>0</td>
<td>Not used</td>
<td>0.04 - 1.49</td>
<td>0.67( \lambda ) - 25.0( \lambda ) (0.27 cm - 10.2 cm)</td>
</tr>
</tbody>
</table>

LOS decorrelation distance at 73 GHz: 5.13 to 200 wavelengths (2.09 cm to 81.6 cm)
NLOS decorrelation distance at 73 GHz: 0.67 to 25.0 wavelengths (0.27 cm to 10.2 cm)
Maximum decorrelation distance: RX antenna points directly at the TX or at a major reflector, and moves along a line between the TX and RX
Minimum decorrelation distance: RX antenna points roughly to the opposite direction of the TX and without major reflectors
For received signal voltage amplitudes over a 35.31-cm (about 87 wavelengths) linear track at 73 GHz with 1 GHz RF bandwidth:

- Omnidirectional received signal voltage amplitude varies by -3 dB to 1.5 dB relative to mean level for LOS, and -0.9 dB to 0.9 dB relative to mean level for NLOS.

- Directional received signal voltage amplitudes vary less severely than the Rayleigh fading
  - LOS: -4 dB to 1.5 dB relative to mean level over all 6 RX pointing angles
  - NLOS: -4 dB to 2 dB relative to mean level over all 6 RX pointing angles
  - Extent of variation at individual pointing angles depends on the physical geometry and does not have a general law

- Small-scale spatial autocorrelation
  - Maximum decorrelation distance: RX antenna points directly at TX or at a major reflector, and moves in a parallel manner with respect to T-R line
  - Minimum decorrelation distance: RX antenna points roughly to the opposite direction of TX and without major reflectors
Small-scale spatial fading of received signal voltage amplitudes over a 35.31-cm (about 87 wavelengths) linear track at 73 GHz with 1 GHz RF bandwidth

- LOS omnidirectional: Ricean distribution with $K = 10$ dB
- NLOS omnidirectional: Log-normal distribution with a standard deviation of 0.65 dB
- LOS directional: Ricean distribution varies between $K = 7 - 17$ dB
- NLOS directional: Ricean distribution varies between $K = 9 - 21$ dB

Small-scale spatial autocorrelation of received signal voltage amplitudes over a 35.31-cm (about 87 wavelengths) linear track at 73 GHz with 1 GHz RF bandwidth

Autocorrelation function: $f(\Delta X) = \cos(a\Delta X)e^{-b\Delta X}$

- LOS: Sinusoidal-exponential distribution
- NLOS: Exponential distribution
- LOS decorrelation distance: 5.13 – 200 wavelengths (2.09 cm – 81.6 cm)
- NLOS decorrelation distance: 0.67 – 25.0 wavelengths (0.27 cm – 10.2 cm)

The short correlation distance in most cases is favorable for spatial multiplexing in MIMO, since it allows for uncorrelated spatial data streams to be transmitted from closely-spaced (a fraction to several wavelengths) antennas
Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF
References
