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

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Agenda

- **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**

Background and Motivation I

❑ 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]

[1] T. S. Rappaport, “Wireless Communications: Principles and Practice”, Prentice Hall, Upper Saddle River, NJ, second edition, 2002.

[2] A. Goldsmith, Wireless Communications. Cambridge, U.K.: Cambridge Univ. Press, 2004.

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]

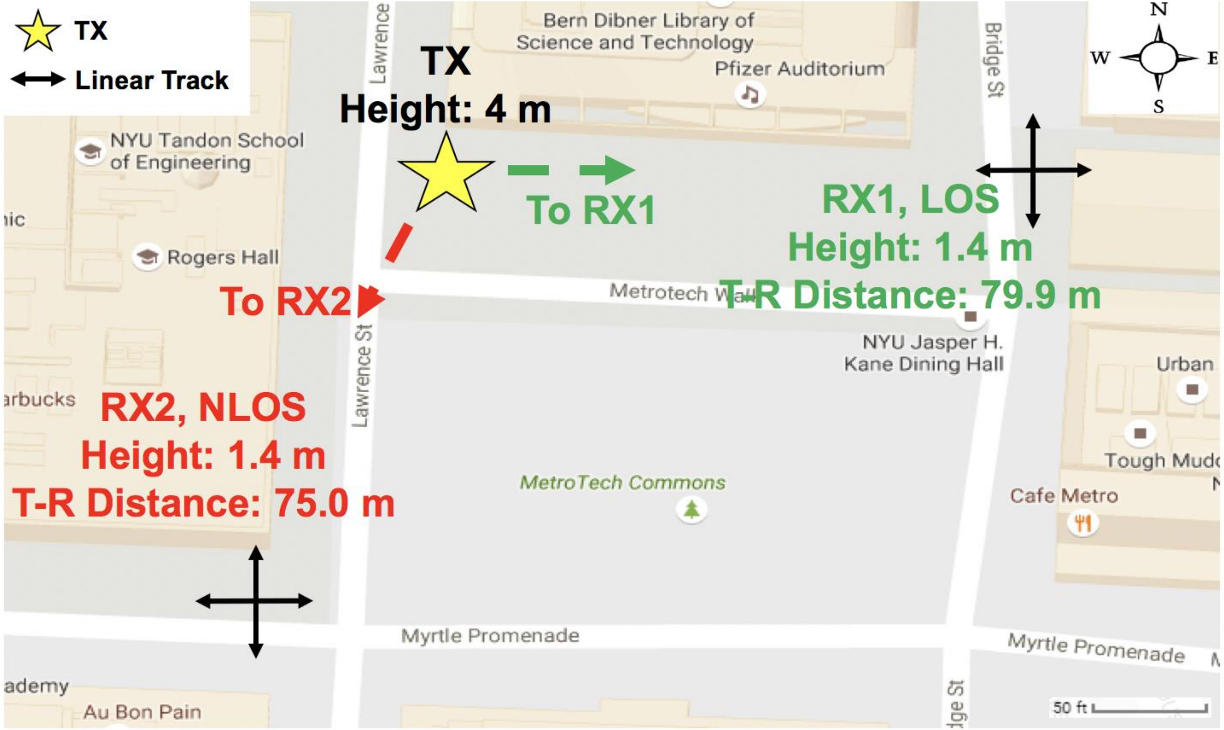
[1] R. Bultitude, "Measurement, characterization and modeling of indoor 800/900 MHz radio channels for digital communications," IEEE Communications Magazine, vol. 25, no. 6, pp. 5–12, June 1987. (received signal envelope of CW signals at 910 MHz, Ricean and Rayleigh)
[2] Q. Wang et al., "Ray-based analysis of small-scale fading for indoor corridor scenarios at 15 GHz," in 2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), May 2015, pp. 181–184. (received signal amplitude at 15 GHz with a bandwidth of 1 GHz, Ricean)
[3] T. F. C. Leao and C. W. Trueman, "Small-scale fading determination with a ray-tracing model, and statistics of the field," *Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation*, Chicago, IL, 2012, pp. 1-2. (Electric field strength of received signal at 2.45 GHz, Ricean)
[4] T. S. Rappaport et al., "Statistical channel impulse response models for factory and open plan building radio communicate system design," IEEE Transactions on Communications, vol. 39, no. 5, pp. 794–807, May 1991. (individual multipath component amplitudes at 1.3 GHz, log-normal distribution)
[5] H. Hashemi, "The indoor radio propagation channel," in *Proceedings of the IEEE*, vol. 81, no. 7, pp. 943-968, Jul 1993.
[6] H. Hashemi, "A study of temporal and spatial variations of the indoor radio propagation channel," 5th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Wireless Networks - Catching the Mobile Future., The Hague, 1994, pp. 127-134 vol.1. (CW envelope at 1.1 GHz, Nakagami and Weibull)
[7] W. Q. Malik et al., "Impact of bandwidth on small-scale fade depth," in IEEE GLOBECOM 2007 - IEEE Global Telecommunications Conference, Nov. 2007, pp. 3837–3841.
[8] G. D. Durgin and T. S. Rappaport, "Theory of multipath shape factors for small-scale fading wireless channels," IEEE Transactions on Antennas and Propagation, vol. 48, no. 5, pp. 682–693, May 2000.
[9] M. K. Samimi et al., "28 GHz millimeter-wave ultrawideband small-scale fading models in wireless channels," in 2016 IEEE 83rd Vehicular Technology Conference (VTC 2016-Spring), May 2016, pp. 1–6.

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)

Description	Specification
Broadcast Sequence	11^{th} order PN Code ($L = 2^{11} - 1 = 2047$)
TX and RX Antenna Type	Rotatable Pyramidal Horn Antenna
TX Chip Rate	500 Mcps
RX Chip Rate	499.9375 Mcps
Slide Factor γ	8 000
RF Null-to-Null Bandwidth	1 GHz
PDP Threshold	20 dB down from max peak
TX/RX Intermediate Frequency	5.625 GHz
TX/RX Local Oscillator	67.875 GHz (22.625 GHz×3)
Carrier Frequency	73.5 GHz
TX Power	14.2 dBm
TX Antenna Gain	27 dBi
TX Azimuth/Elevation HPBW	7°/7°
EIRP	41.2 dBm
TX Heights	4.0 m
RX Antenna Gain	9.1 dBi
RX Azimuth/Elevation HPBW	60°/60°
TX-RX Antenna Polarization	V-V (Vertical-to-Vertical)
RX Heights	1.4 m
Maximum Measurable Path Loss	168 dB

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:

- Placed in two orthogonal directions respectively
- RX antenna moved in half-wavelength steps (175 positions) for each fixed RX pointing angle
- 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

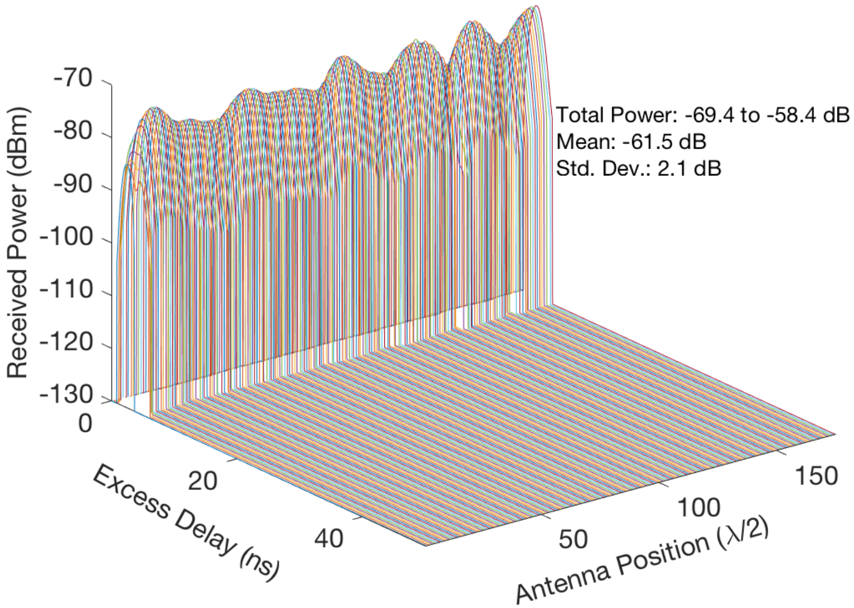
LOS Location

NLOS Location

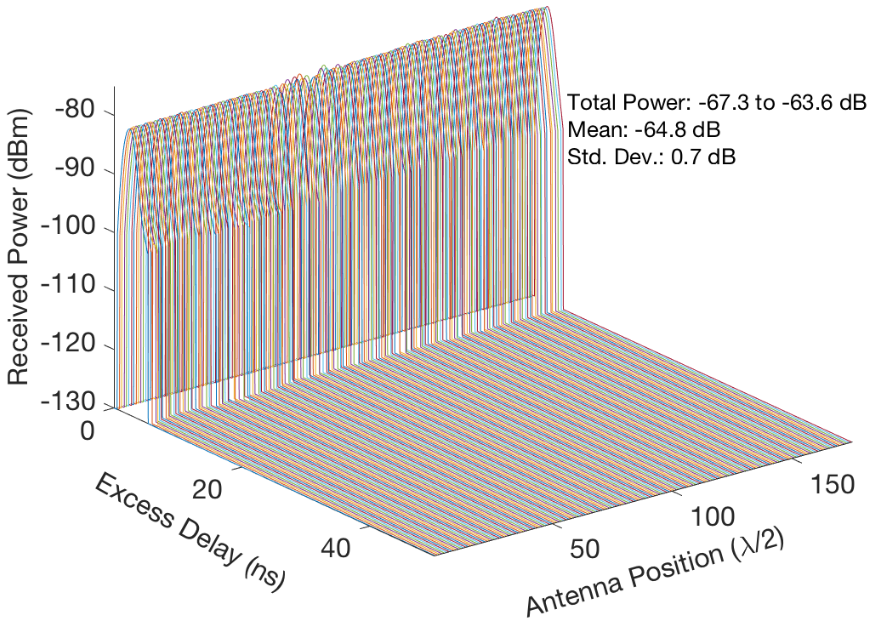
Measured LOS Small-Scale Power Delay Profiles at 73 GHz with 1 GHz RF Bandwidth

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



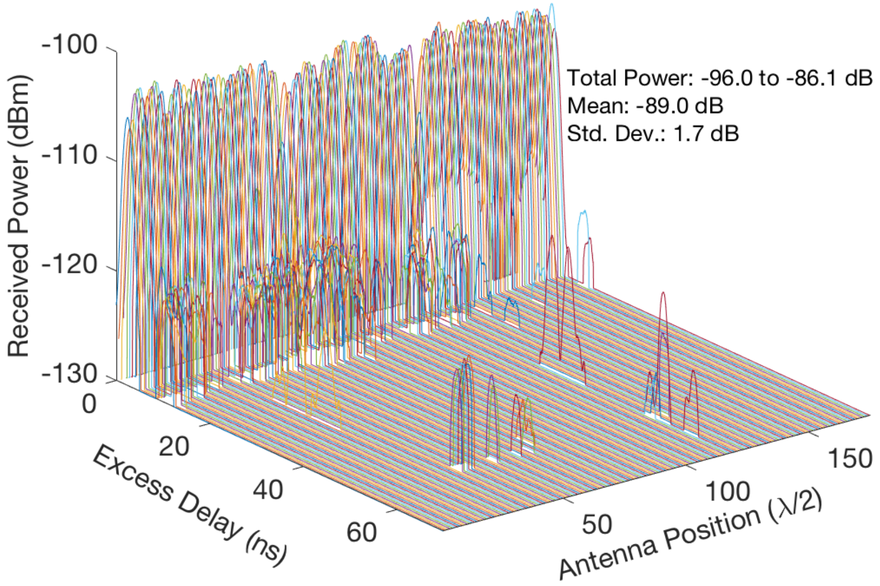
3.7 dB variation of signal power
Track orientation: parallel with T-R line
RX antenna pointing on boresight to TX



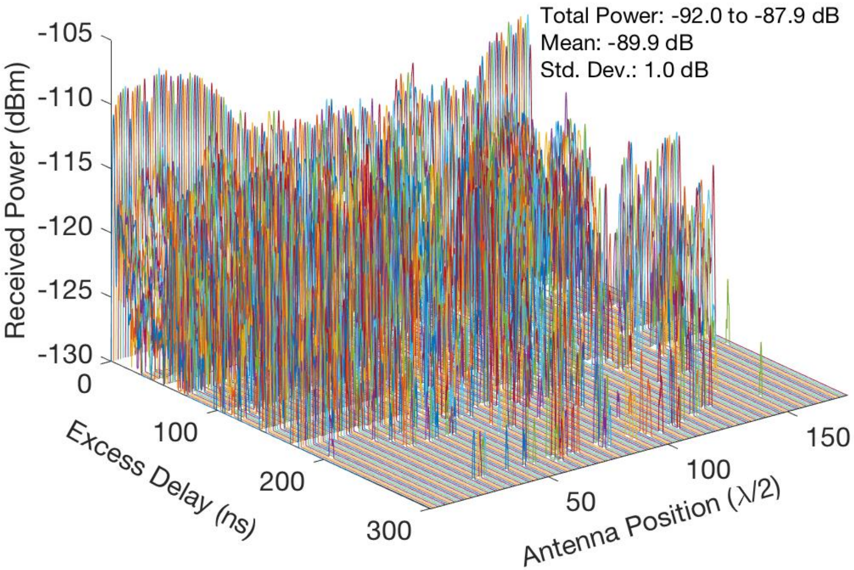
Measured NLOS Small-Scale Power Delay Profiles at 73 GHz with 1 GHz RF Bandwidth

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



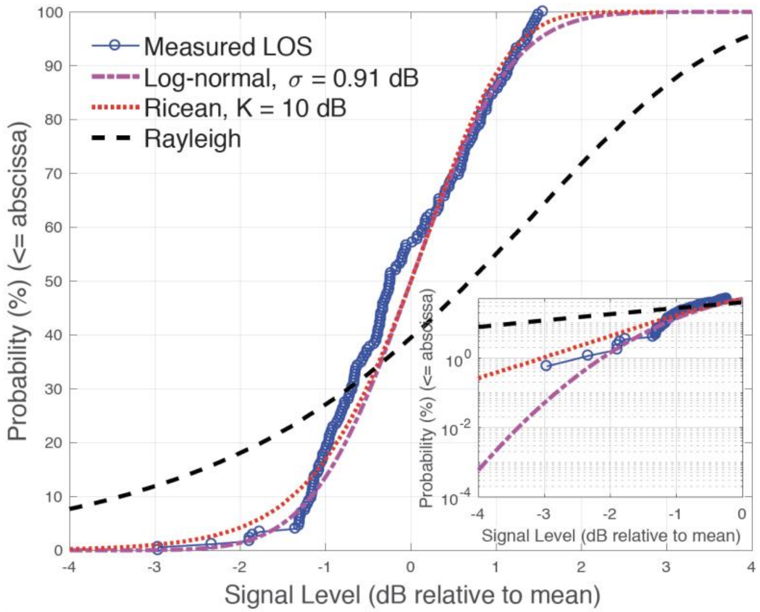
Omnidirectional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth

Omnidirectional received power was synthesized from the directional received power using the approach presented in [1], over all RX antenna pointing directions

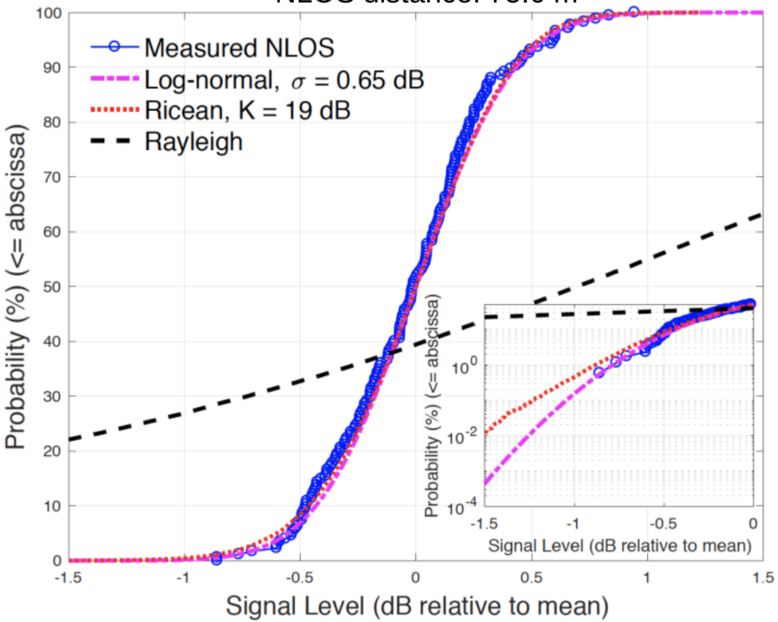
Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)

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 σ of 0.65 dB

LOS distance: 79.9 m



NLOS distance: 75.0 m



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

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

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

ρ: the autocorrelation coefficient of the received signal voltage amplitudes
A_k: received signal voltage amplitude at the *k*th position on the linear track
X_k: *k*th position on the linear track
ΔX: the spacing between different RX antenna positions on the linear track
$E[\ ]$: the expectation taken over all the positions on the linear track

T. S. Rappaport et al., “Statistical channel impulse response models for factory and open plan building radio communicate system design,” *IEEE Transactions on Communications*, vol. 39, no. 5, pp. 794–807, May 1991.
M. K. Samimi et al., “28 GHz millimeter-wave ultrawideband small-scale fading models in wireless channels,” *2016 IEEE 83rd Vehicular Technology Conference (VTC 2016 Spring)*, Nanjing, May 2016, pp. 1–6.

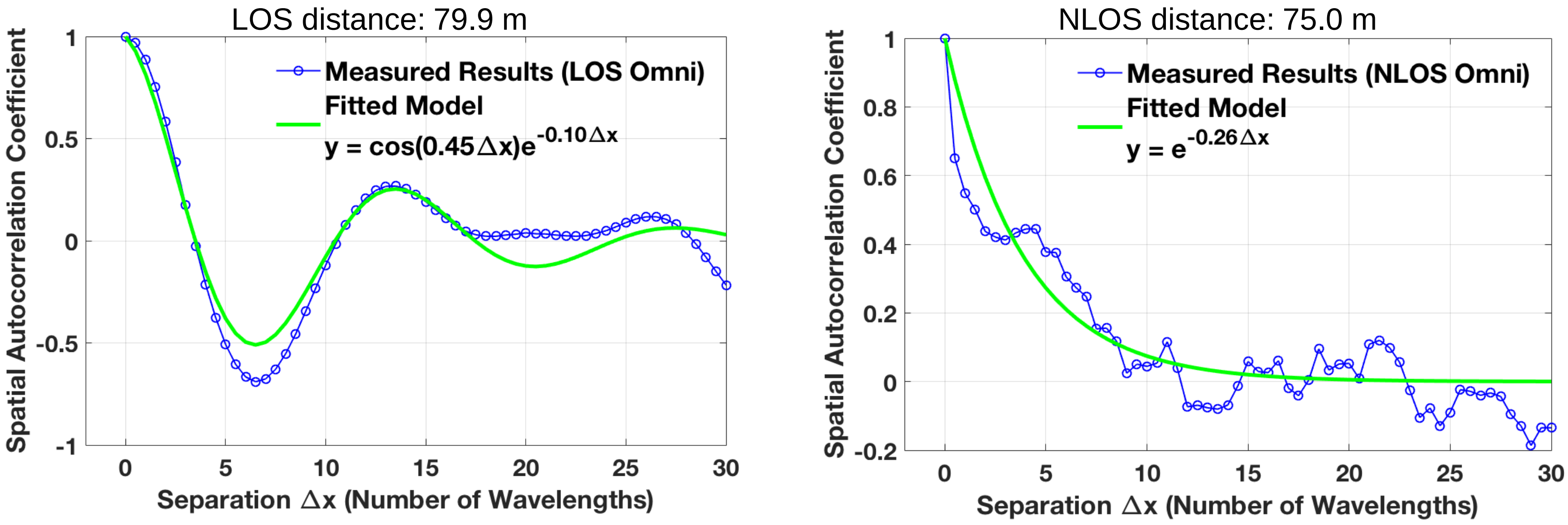
Omnidirectional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth

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



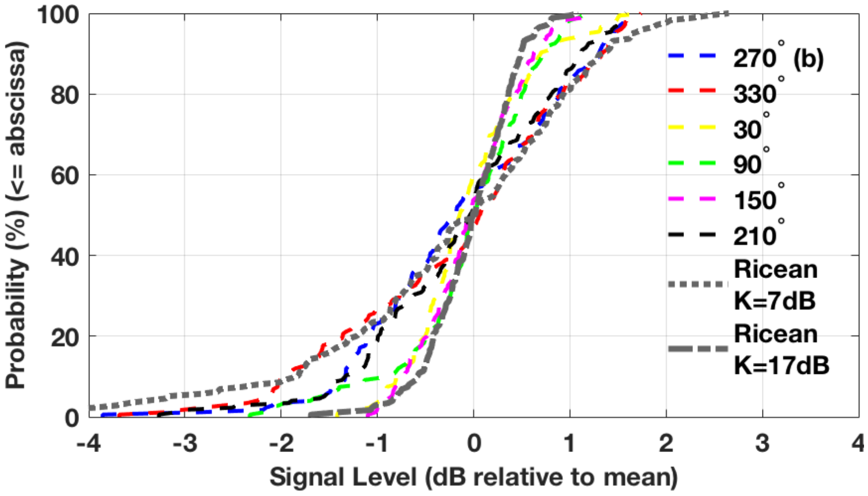
Omnidirectional small-scale spatial autocorrelation of received signal voltage amplitudes

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

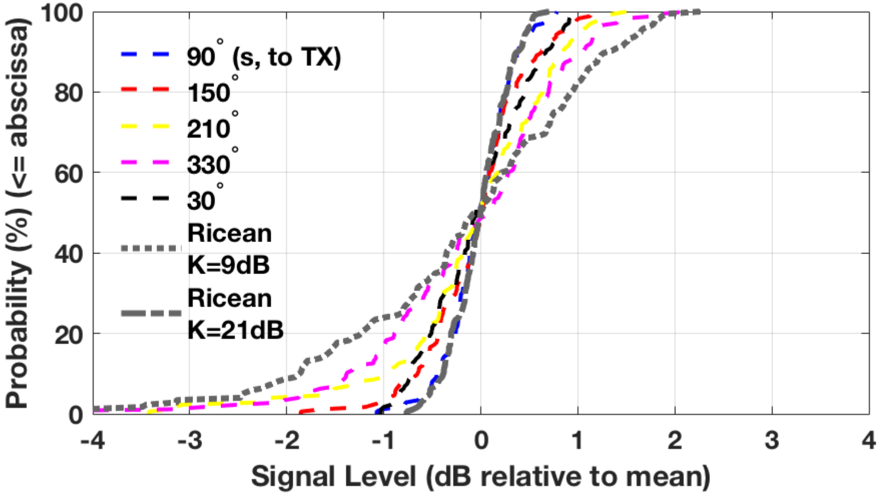
Track length: 35.31-cm (about 87 wavelengths at 73.5 GHz)

LOS directional small-scale spatial 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 distance: 79.9 m



NLOS distance: 75.0 m



Directional small-scale spatial fading of received signal voltage amplitudes

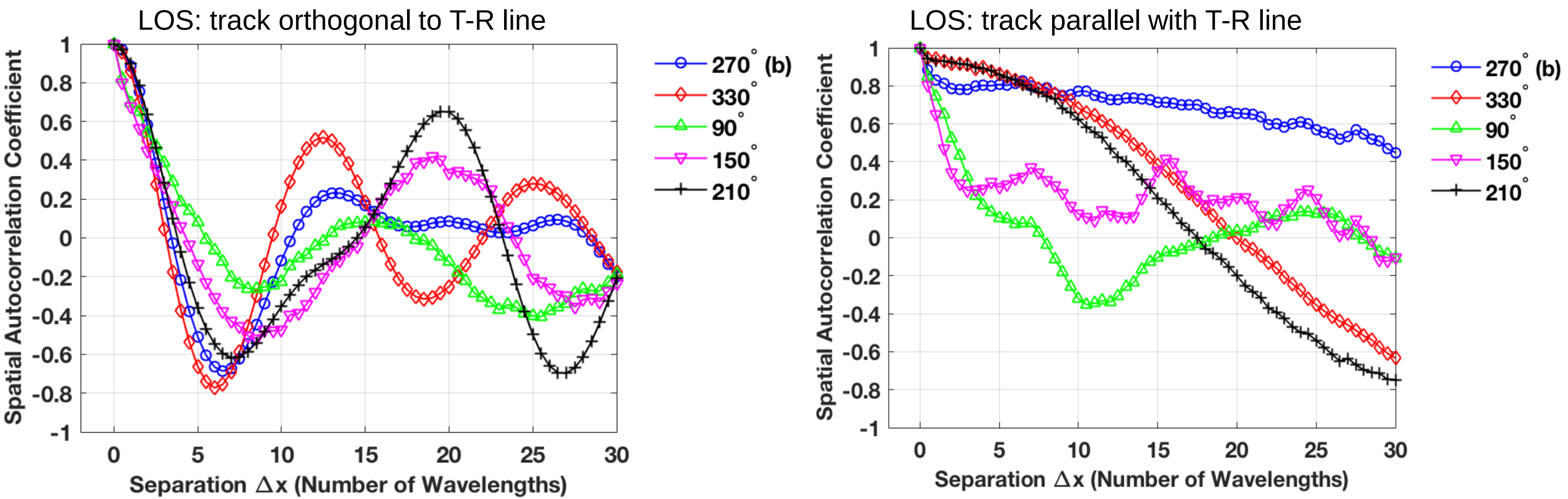
LOS Directional Small-Scale Spatial Statistics at 73 GHz with 1 GHz RF Bandwidth

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)



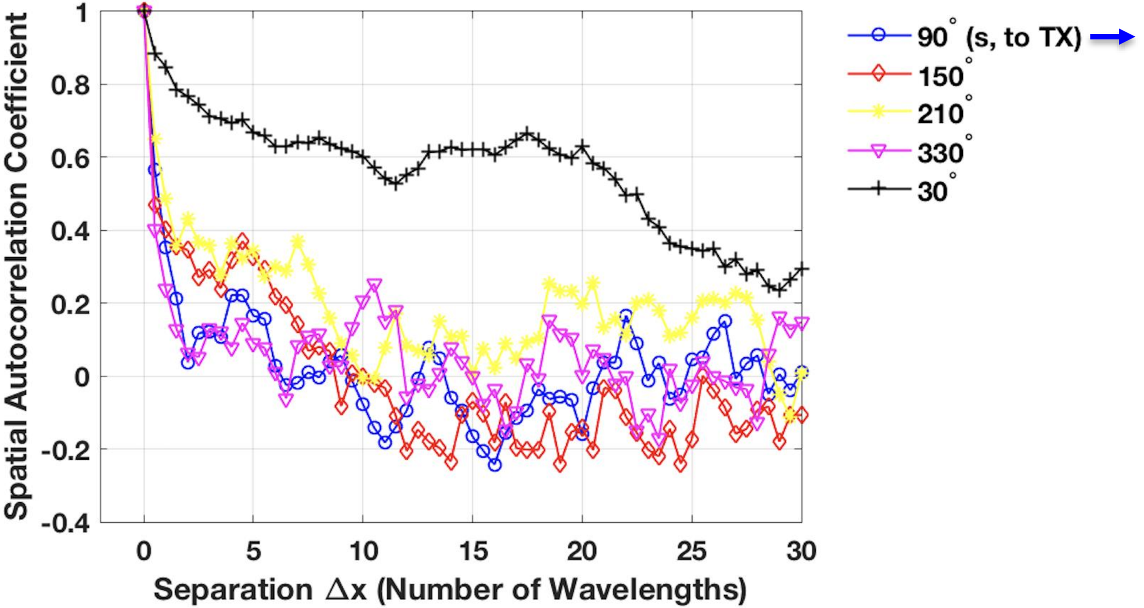
Directional small-scale spatial autocorrelation of received signal voltage amplitudes

NLOS 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)

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

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



Directional small-scale spatial autocorrelation of received signal voltage amplitudes

Small-Scale Spatial Autocorrelation Summary at 73 GHz with 1 GHz RF Bandwidth

Proposed autocorrelation fit: $f(\Delta X) = \cos(a\Delta X)e^{-b\Delta X}$

Decorrelation distance

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

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

Conclusion I

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 N**LOS**

- 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

Conclusion II

- 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

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Questions