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

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NYU Polytechnic School of Engineering, Brooklyn, New York, 11201

CEATEC JAPAN 2014
8 October 2014
10:00 – 10:30

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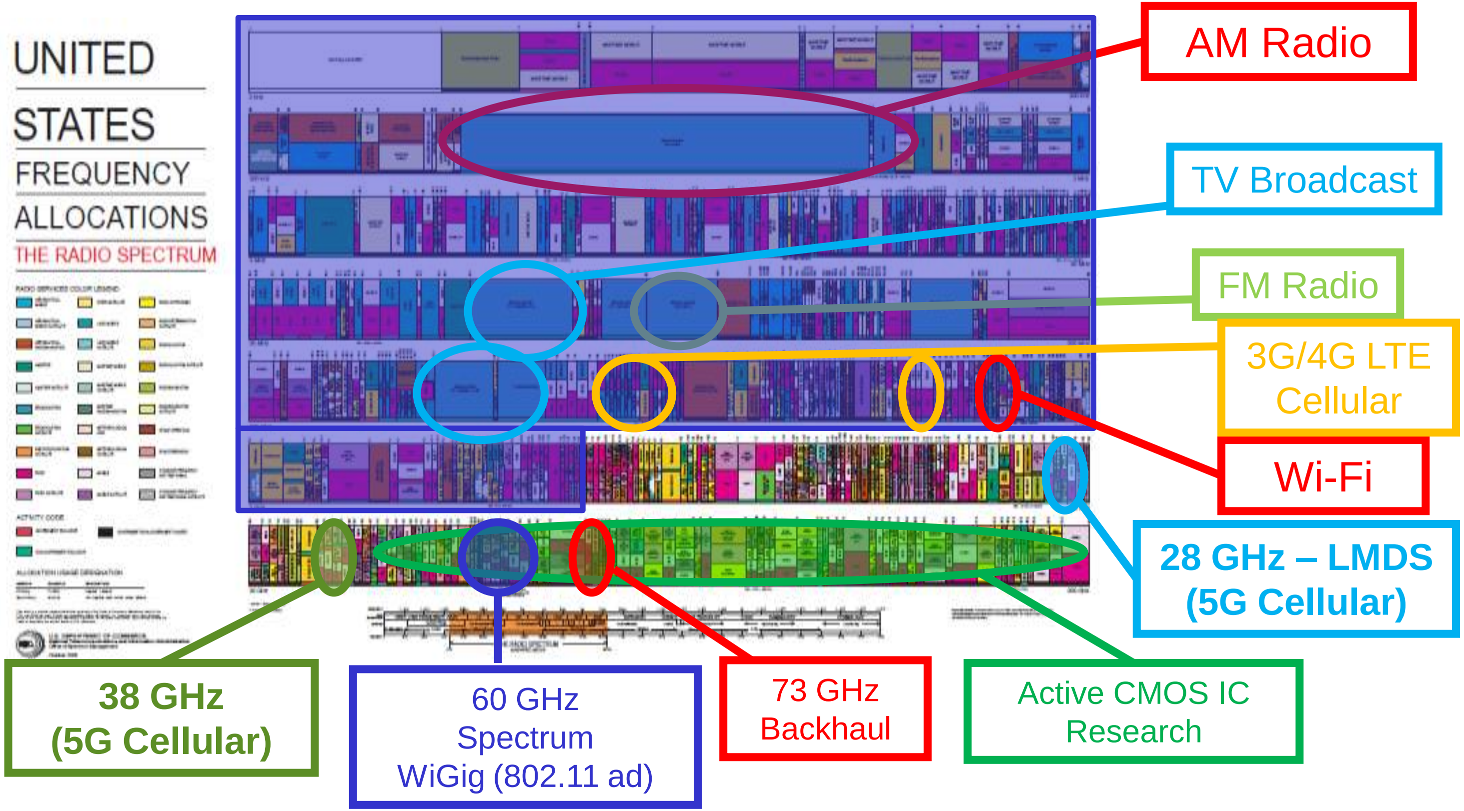
Agenda

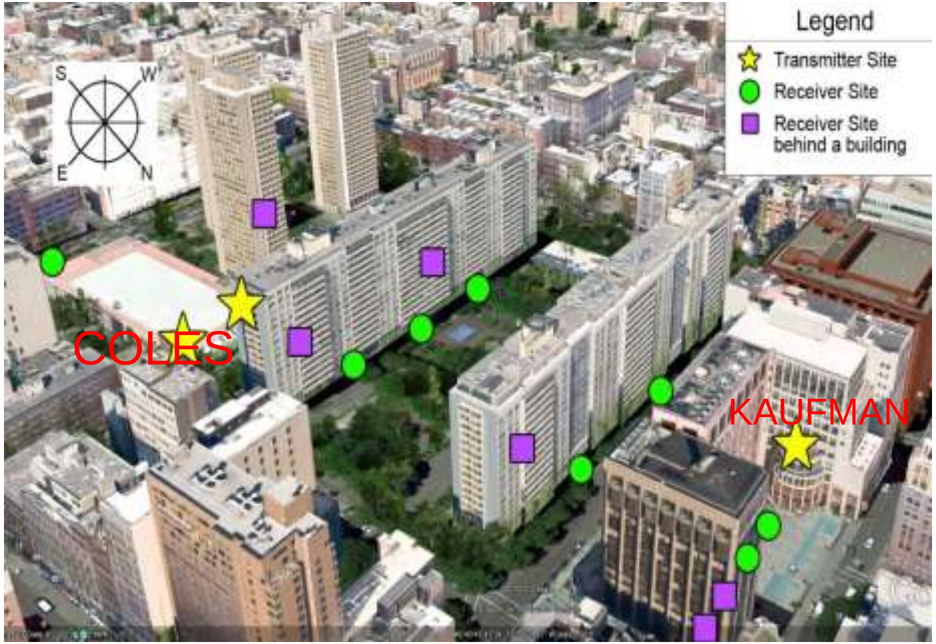
- 28 GHz and 73 GHz Mobile Measurements and Equipment (Summer 2012, Summer 2013, Ongoing)
- Omnidirectional Path Loss Models in LOS and NLOS
- 28 GHz Statistical Channel Models in LOS and NLOS
- Beamcombining Models at 28 GHz and 73 GHz
- Upgrades to Channel Sounder and Upcoming Measurements
- Joining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

The Wireless Spectrum Today



T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. Pearson/Prentice Hall, 2015.

28 GHz Propagation Measurement Campaign in Manhattan – Summer 2012

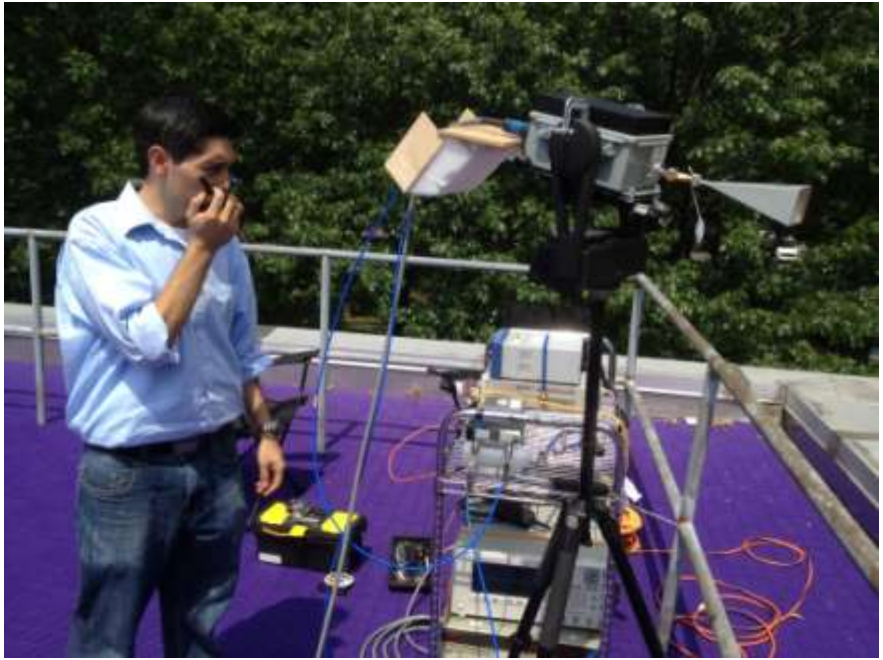


28 GHz Cellular Measurements Locations in Manhattan near NYU campus

- 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

T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEEE Access, vol.1, pp.335-349, 2013.

28 GHz TX-RX Equipment

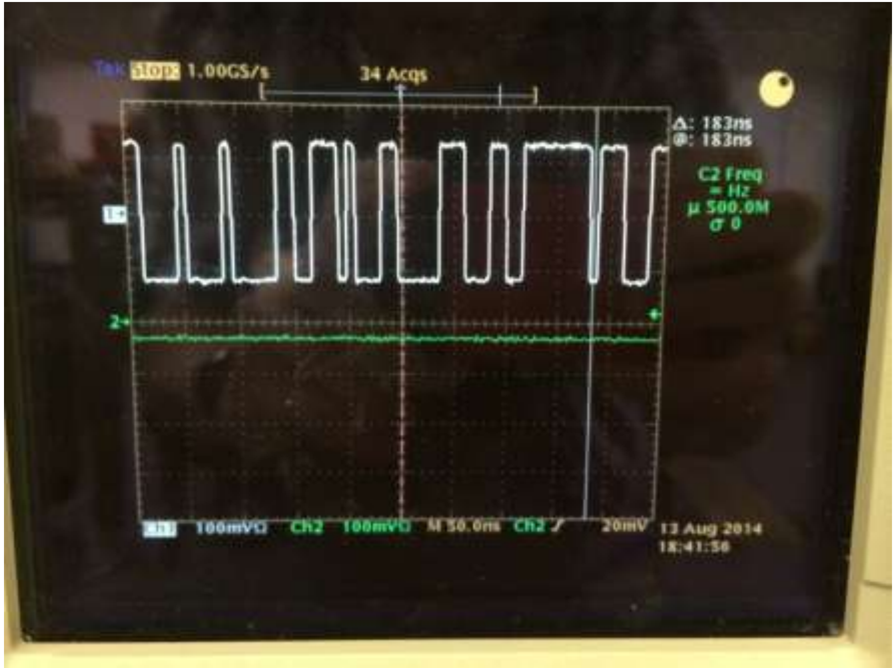


Transmitter

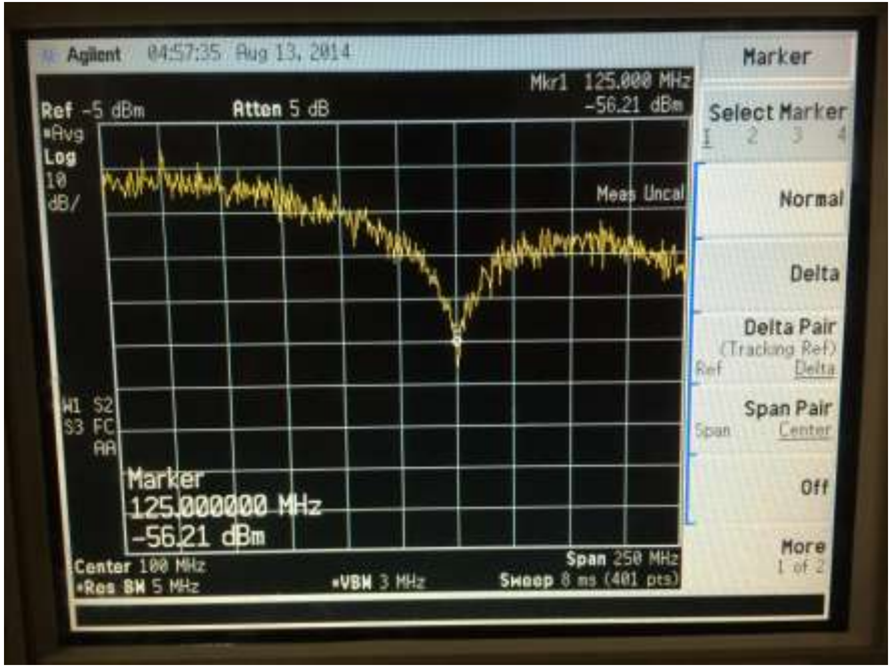
Receiver

PN Code Transmit Probing Signal

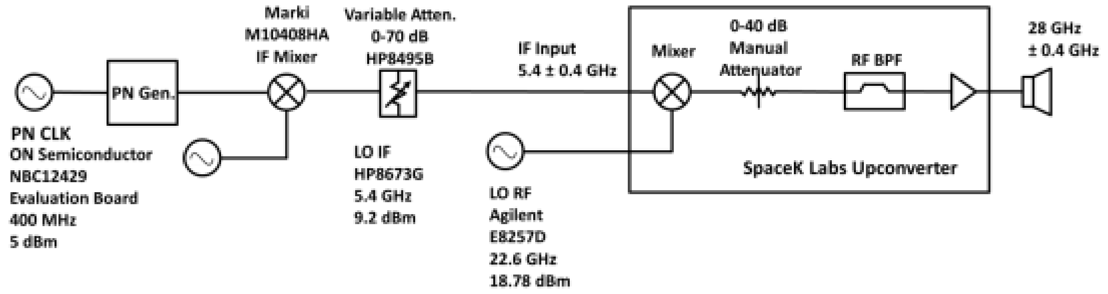
2^{11}-1 Length PN code



Spread Spectrum



28 GHz Channel Sounder Block Diagrams

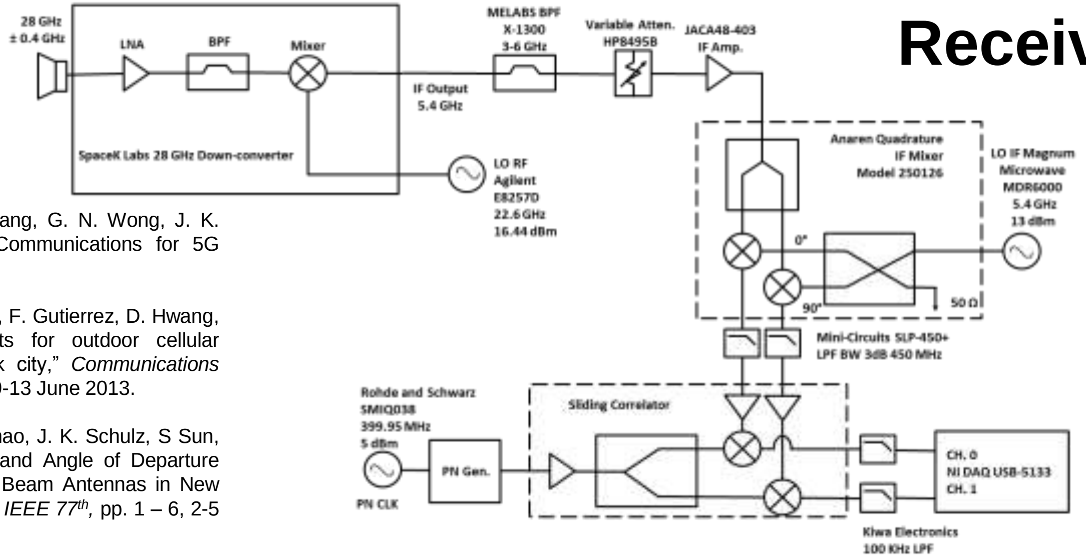


Transmitted Signal

Transmitter

Received Signal

Receiver



T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, F. Gutierrez, “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol.1, pp.335-349, 2013.

Y. Azar, G. N. Wong, K. Wang, R. Mayzus, J. K. Schulz, H. Zhao, F. Gutierrez, D. Hwang, and T. S. Rappaport, “28 GHz propagation measurements for outdoor cellular communications using steerable beam antennas in New York city,” *Communications (ICC), 2013 IEEE International Conference on*, pp. 5143 – 5147, 9-13 June 2013.

M. K. Samimi, K. Wang, Y. Azar, G. N. Wong, R. Mayzus, H. Zhao, J. K. Schulz, S Sun, F. Gutierrez, and T. S. Rappaport, “28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City,” *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, pp. 1 – 6, 2-5 June 2013.

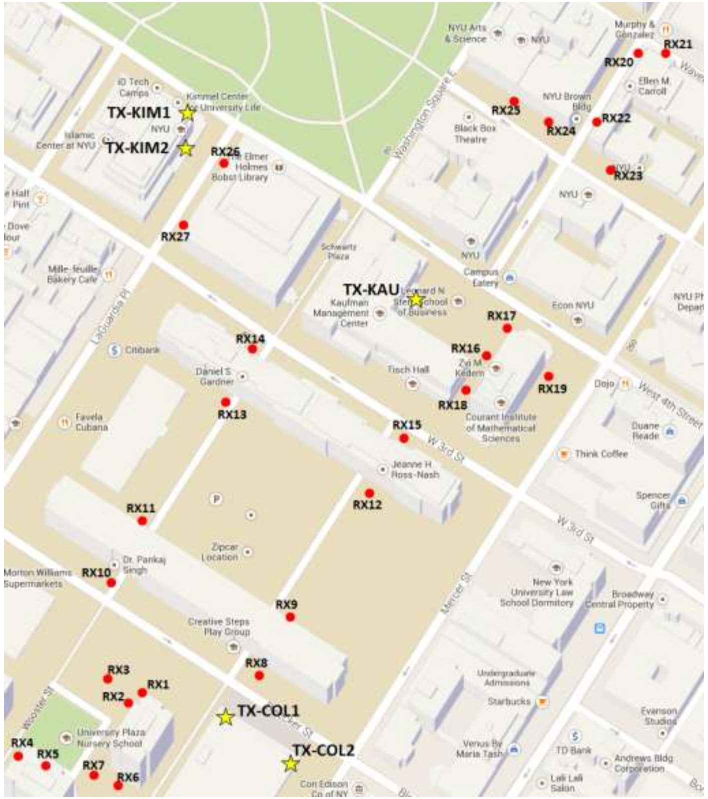
Manhattan Measurements at 73 GHz (Summer 2012)

- 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 – 7m
  - TX-KIM2 – 7m

- 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.

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28 GHz and 73 GHz Sliding Correlator Channel Sounder Specifications

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

T. S. Rappaport, et. al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol.1, pp.335-349, 2013.

Y. Azar,et. Al., "28 GHz propagation measurements for outdoor cellular communications using steerable beam antennas in New York city," *Communications (ICC), 2013 IEEE International Conference on*, pp. 5143 – 5147, 9-13 June 2013.

M. K. Samimi, et. al, "28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, pp. 1 – 6, 2-5 June 2013.

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 θt and Φt in the azimuth and elevation plane angles respectively, and for RX arbitrary pointing angles θr and Φr 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. θr and Φr are the receiver azimuth and elevation planes respectively. θt and Φt are the transmitter azimuth and elevation planes respectively representing: $\widetilde{\mathrm{Pr}}_{\mathrm{i,j}}(\theta r, \Phi r, \theta t, \Phi t)$ for every individual measurement.
  - TX and RX antenna gains were removed from each received power level $\widetilde{\mathrm{Pr}}_{\mathrm{i,j}}(\theta r, \Phi r, \theta t, \Phi t)$ such that $\mathrm{Pr}_{\mathrm{i,j}}(\theta r, \Phi r, \theta t, \Phi t)[dBm] = \widetilde{\mathrm{Pr}}_{\mathrm{i,j}} - G_{TX} - G_{RX}$
  - 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:

$$\mathrm{PL}_{i,j}[\mathrm{dB}] = Pt_{i,j}[\mathrm{dBm}] - 10\log_{10}\left[\sum_z \sum_y \sum_x \sum_w \mathrm{Pr}_{i,j}\left(\theta r_w, \phi r_x, \theta t_y, \phi t_z\right)[\mathrm{mW}]\right]$$

G. R. MacCartney, Jr., M. K. Samimi, T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," Personal Indoor and Mobile Radio Communications (PIMRC), 2014 IEEE 25th International Symposium on, Sept. 2 – 5, 2014.

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

T. S. Rappaport, Wireless Communications: Principles and Practice, Chapter 4, 2nd Edition, Prentice Hall Communications Engineering and Emerging Technologies Series, 2002.

Floating Intercept Path Loss Model (Least-Squares Regression)

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

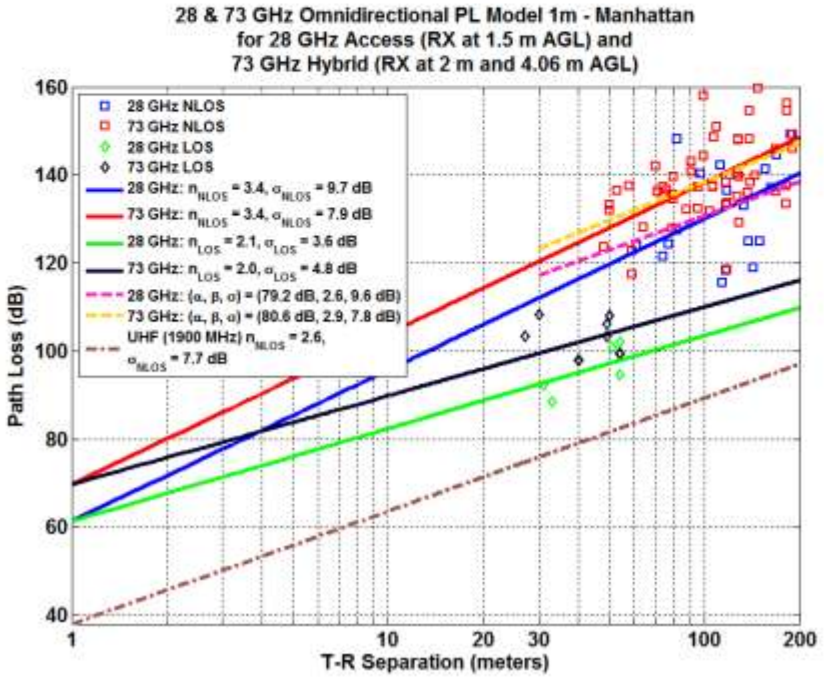
- α – intercept (dB)
- β – slope (different from PLE)
- χ_σ – lognormal R.V. $\sim N(0, \sigma)$
- d – T-R Separation distance (m)
- 30 m < d < 200 m (limited by measurements)

T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, J. N. Murdock, “Millimeter Wave Wireless Communications, Pearson/Prentice Hall, c. 2015

G. R. MacCartney, J. Zhang, S. Nie and T. S. Rappaport, "Path Loss Models for 5G Millimeter Wave Propagation Channels in Urban Microcells," *IEEE Global Communications Conference, Exhibition and & Industry Forum (GLOBECOM),* 9-13 December 2013.

28 GHz and 73 GHz Omnidirectional Path Loss

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:

$$PL_{28GHz}(LOS)[dB](d) = 61.4 + 21\log_{10}(d) + X_\sigma(\sigma = 3.6 \text{ dB})$$

$$PL_{73GHz\text{-}Hybrid}(LOS)[dB](d) = 69.8 + 20\log_{10}(d) + X_\sigma(\sigma = 4.8 \text{ dB})$$

NLOS Close-in Reference Model:

$$PL_{28GHz}(NLOS)[dB](d) = 61.4 + 34\log_{10}(d) + X_\sigma(\sigma = 9.7 \text{ dB})$$

$$PL_{73GHz\text{-}Hybrid}(NLOS)[dB](d) = 69.8 + 34\log_{10}(d) + X_\sigma(\sigma = 7.9 \text{ dB})$$

NLOS Floating Intercept Model:

$$PL_{28GHz}(NLOS)[dB](d) = 79.2 + 26\log_{10}(d) + X_\sigma(\sigma = 9.6 \text{ dB})$$

$$PL_{73GHz\text{-}Hybrid}(NLOS)[dB](d) = 80.6 + 29\log_{10}(d) + X_\sigma(\sigma = 7.8 \text{ dB})$$

G. R. MacCartney, Jr., M. K. Samimi, T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," Personal Indoor and Mobile Radio Communications (PIMRC), 2014 IEEE 25th International Symposium on, Sept. 2 – 5, 2014.

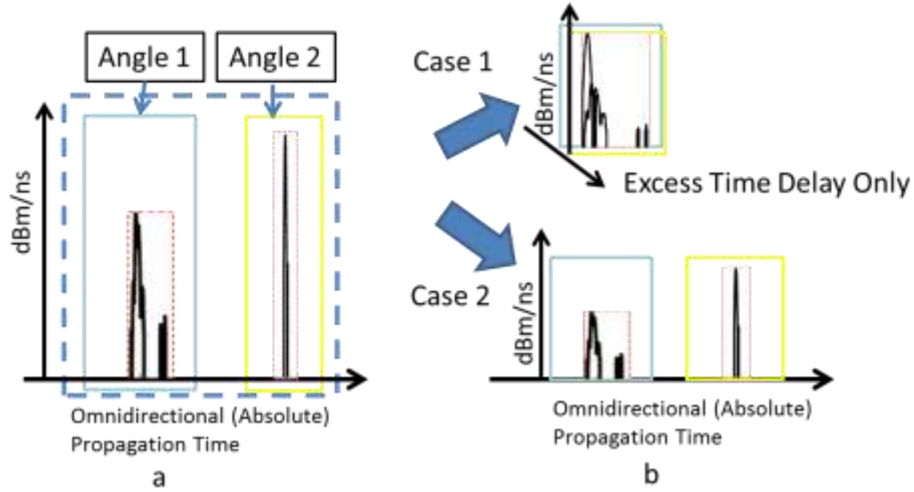
Current Channel Models: 3GPP and WINNER II

- 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

NYU Approach to Omni Statistical Channel Model

Multipath from different angles have different propagation time delays.



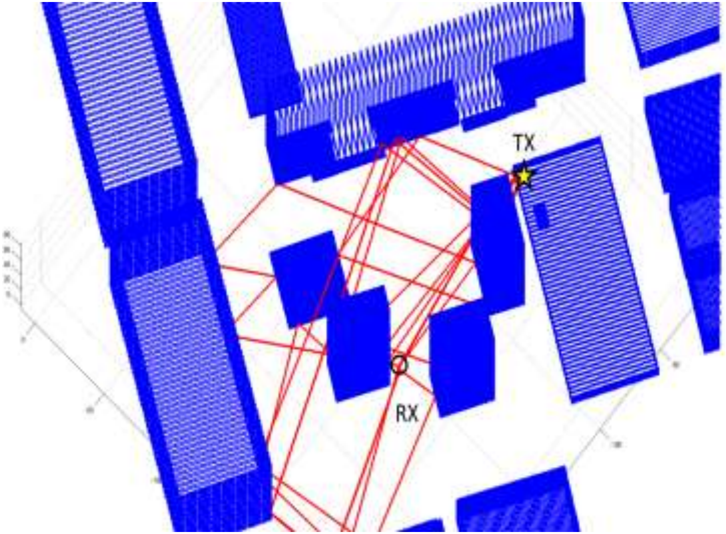
a) Superimposed PDPs of two individual PDPs, where each PDP comes from a different AOA at the same RX.

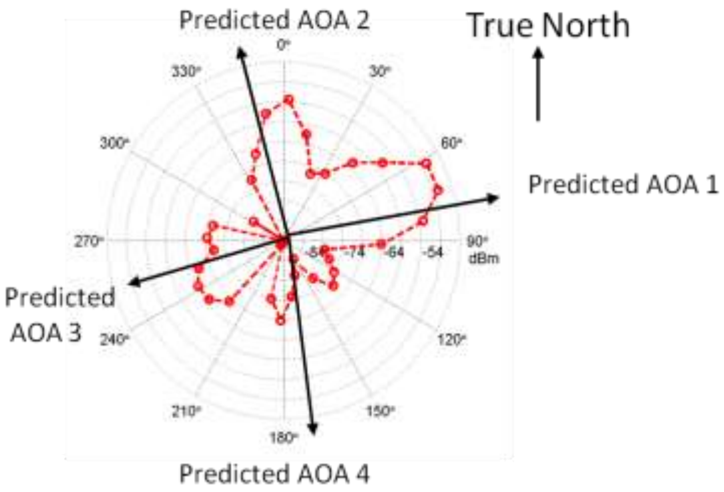
b) Case 1: Superimposed PDPs at excess delay t = 0 ns.
Case 2: Superimposed PDPs according to absolute time = 0 ns (using ray-tracing methods).

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

3-D Ray-Tracing to Synthesize Omni. PDP

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

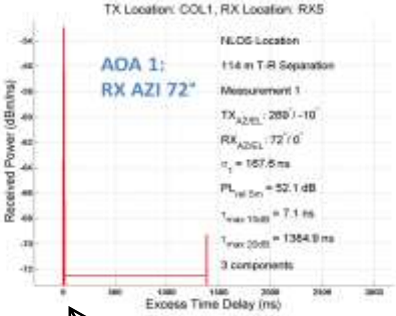




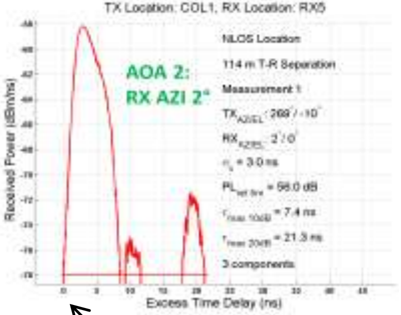
- 4 Strongest AOA's predicted to synthesize omni PDP
- Minor angle skew does not impact statistical model

M. K. Samimi, T. S. Rappaport, "Characterization of the 28 GHz Millimeter-Wave Dense Urban Channel for Future 5G Mobile Cellular," NYU WIRELESS TR 2014-001, June 2014.

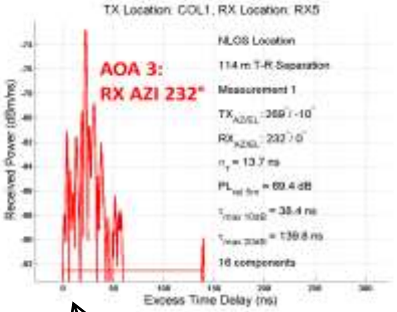
Example of Four Strongest Measured PDPs to Create Omni. PDP



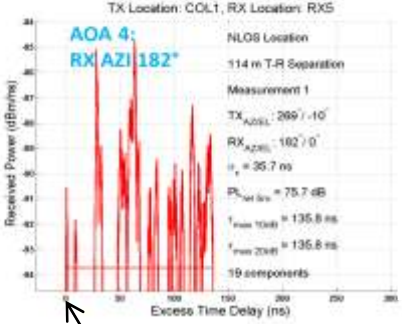
T1 = 381 ns



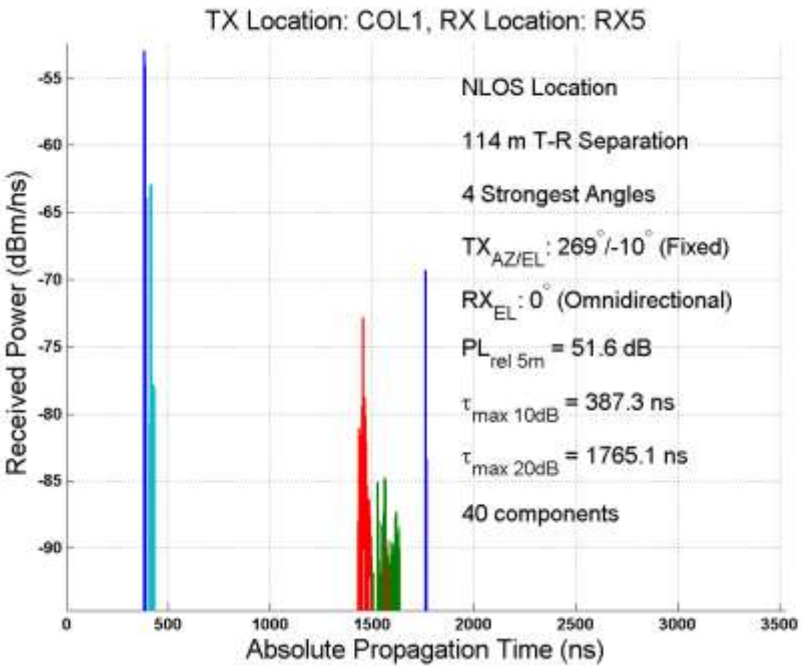
T2 = 407 ns



T3 = 1433 ns



T4 = 1500 ns

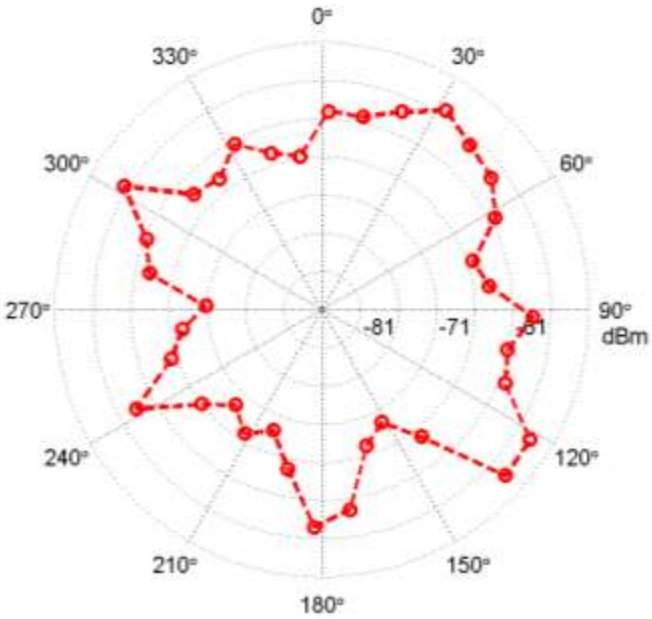


M. K. Samimi, T. S. Rappaport, "Characterization of the 28 GHz Millimeter-Wave Dense Urban Channel for Future 5G Mobile Cellular," NYU WIRELESS TR 2014-001, June 2014.

28 GHz LOS VS NLOS Spectra

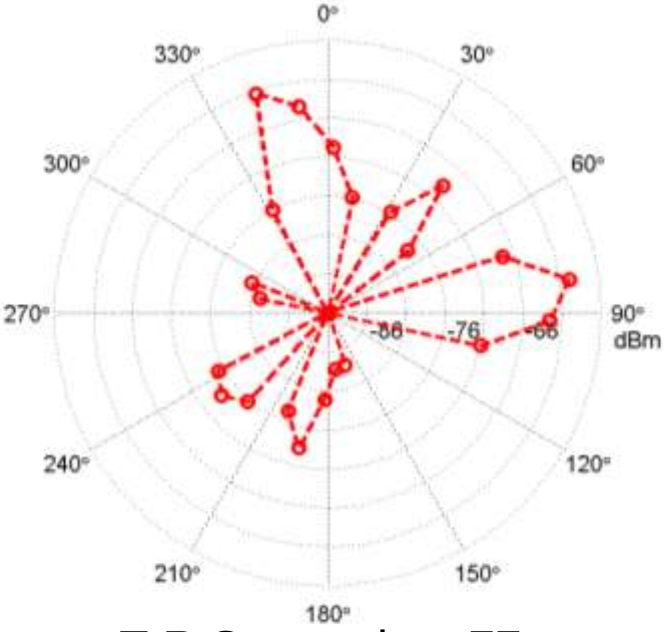
In LOS: Power arriving from all AOA angles (Large RMS Delay Spread)
In NLOS: Power arriving from distinct AOA angles (Smaller RMS Delay Spread)

LOS Polar Plot



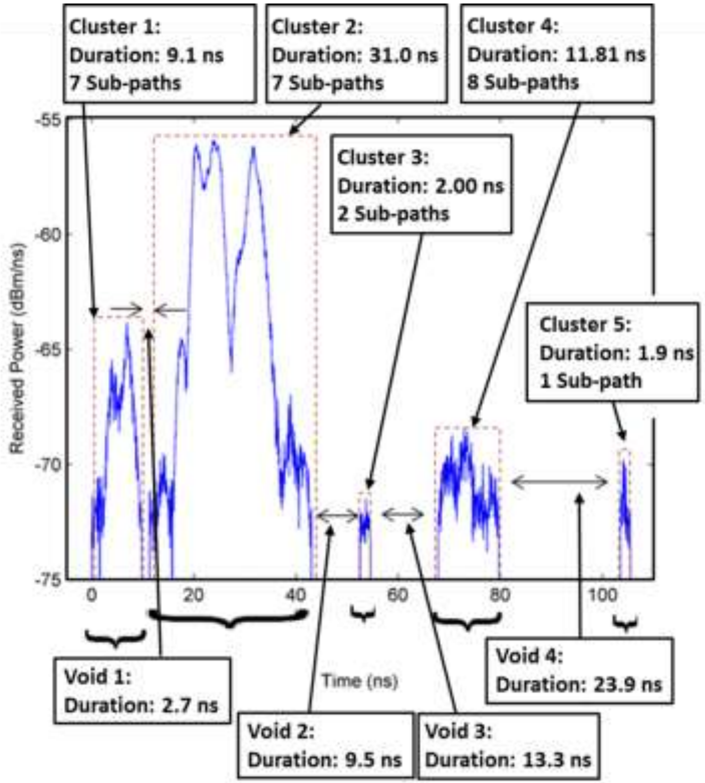
T-R Separation: 54 m

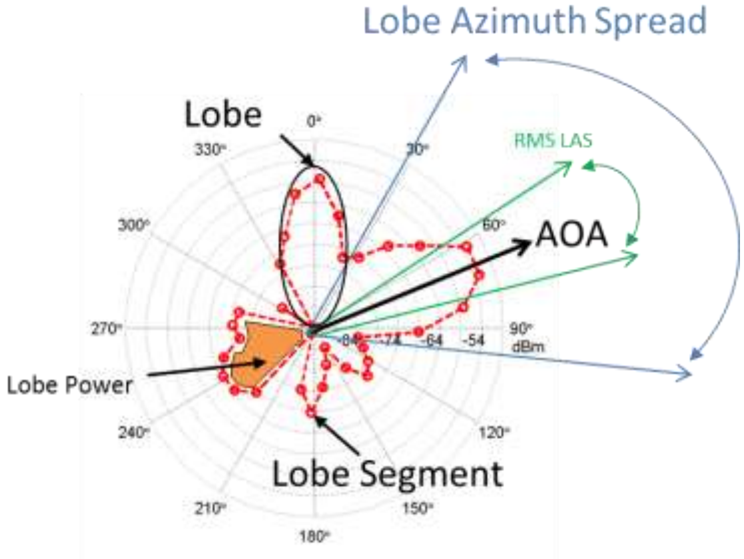
NLOS Polar Plot



T-R Separation: 77 m

Omnidirectional Statistical Spatial Channel Model





Example PDP at one pointing angle

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. Pearson/Prentice Hall, 2015.

Temporal Channel Modeling

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

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Spatial Channel Modeling

Primary Statistics:

Quantities needed to reproduce mmWave PAS (Polar Plot):

- Number of Lobes
- AOAs
- Lobe Azimuth Spreads
- Lobe Segment Powers

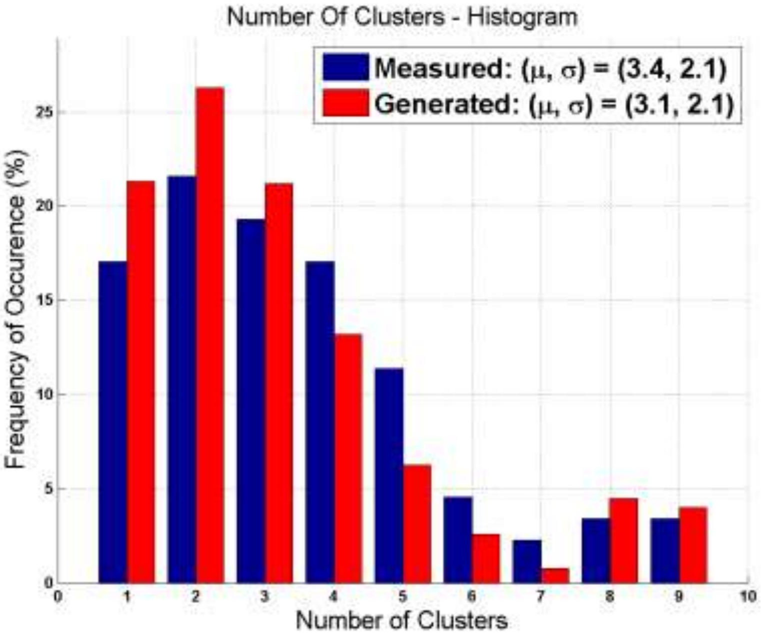
Secondary Statistics:

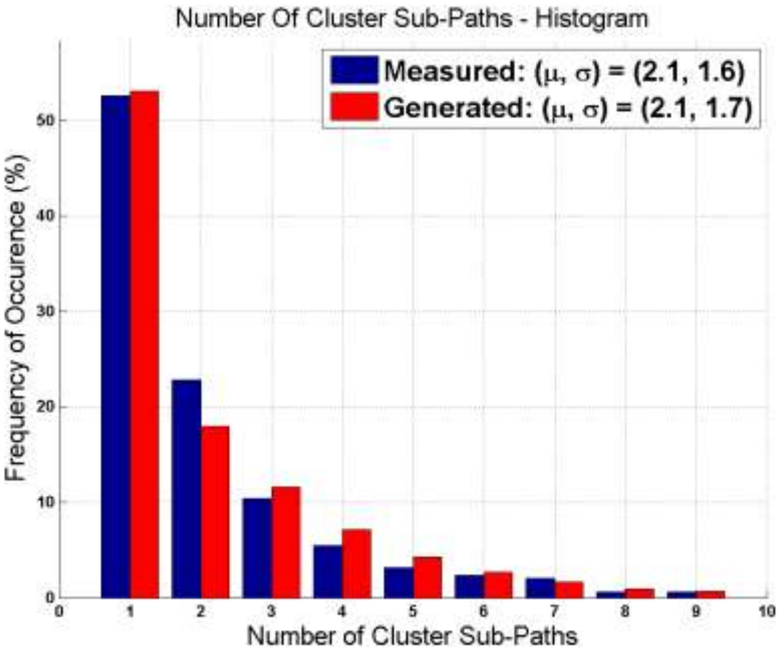
Quantities needed to validate simulator:

- RMS Lobe Azimuth Spread

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Number of clusters and cluster subpaths in NLOS





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

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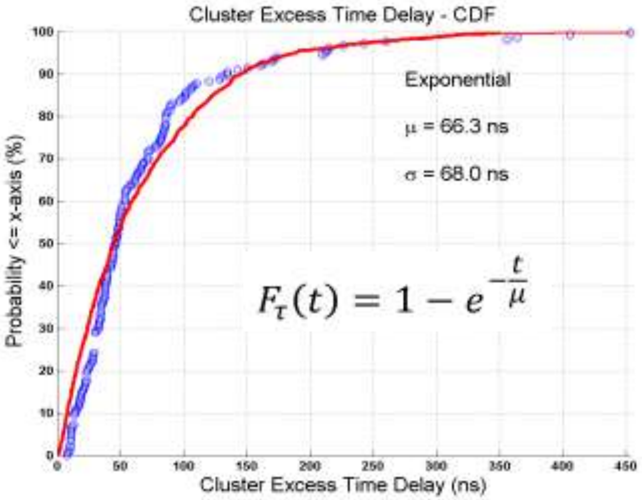
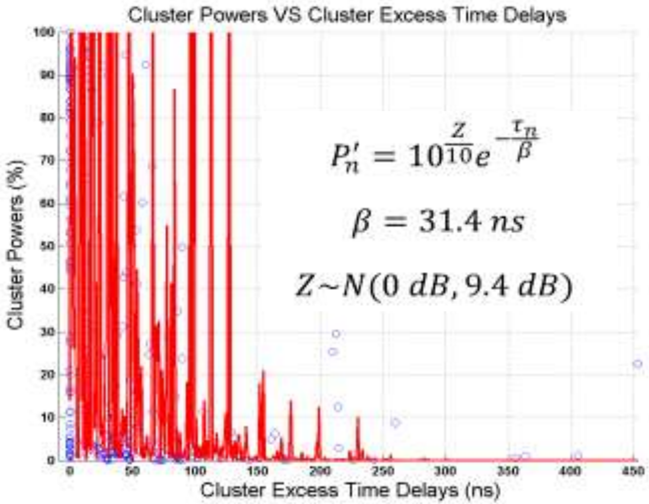
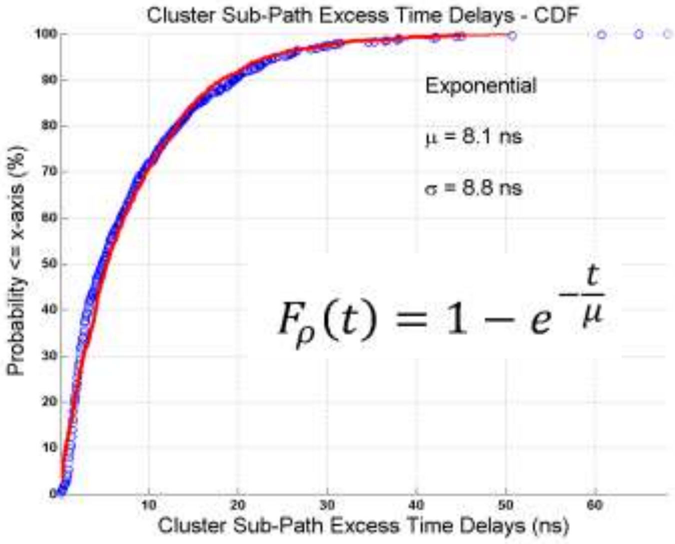
Clusters delays and powers in NLOS

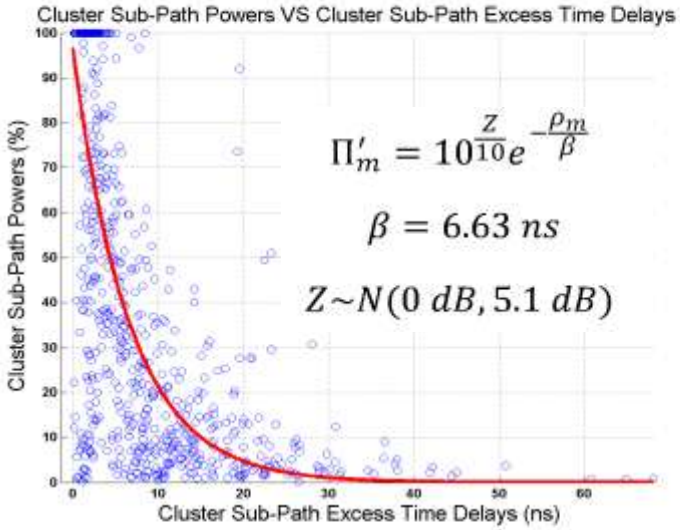




M. K. Samimi, T. S. Rappaport, "Characterization of the 28 GHz Millimeter-Wave Dense Urban Channel for Future 5G Mobile Cellular," NYU WIRELESS TR 2014-001, June 2014.

Clusters subpath delays and powers in NLOS





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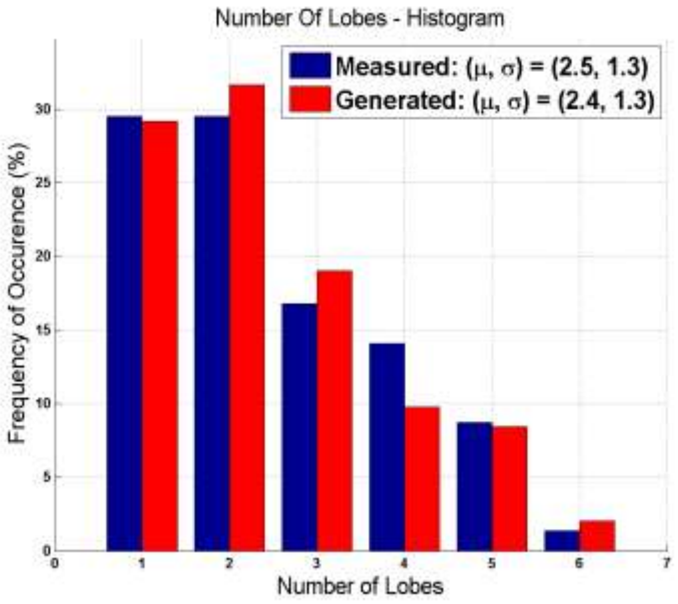
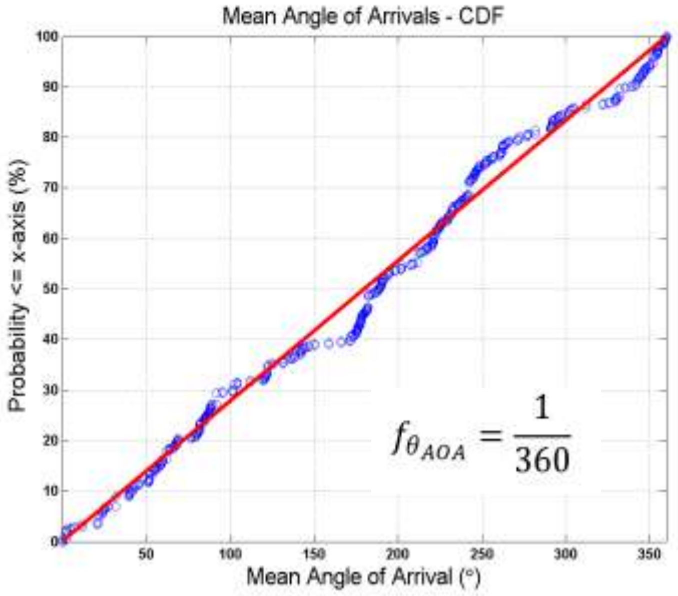
Number of Lobes and AOAs in NLOS





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

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Statistical Modeling for Omnidirectional mmWave Power Spectra

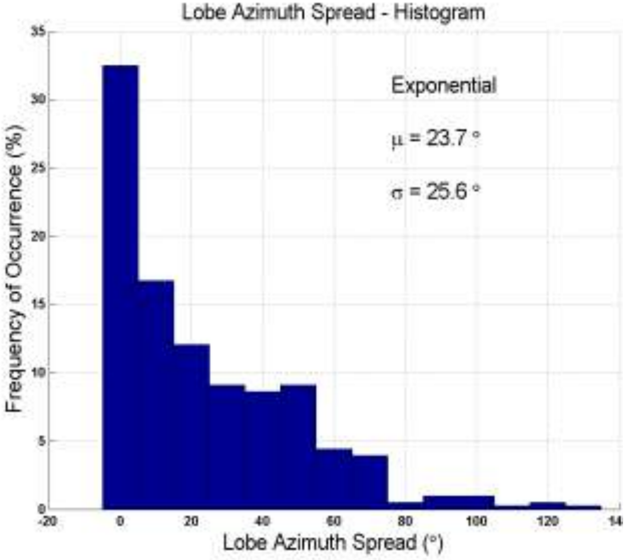
Lobe Azimuth Spreads and Lobe Segment Powers in NLOS

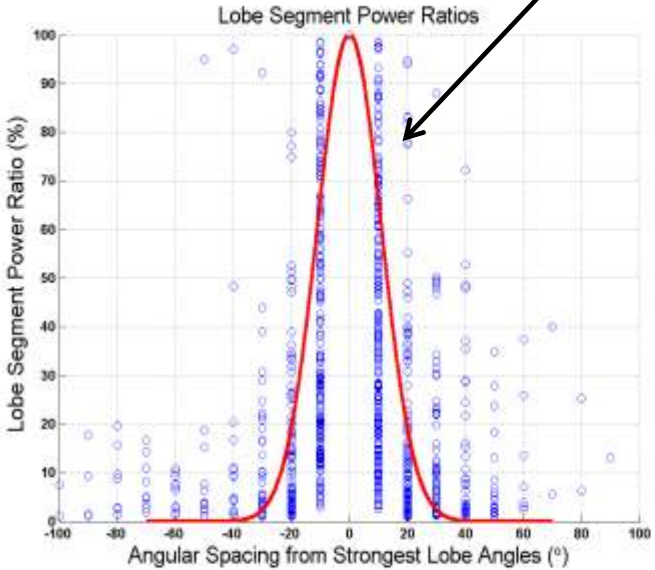
Key step for unifying temporal and spatial statistics

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

$$\sigma = 2\sigma_{RMS,AOA} = 2 * 5.5° = 11°$$

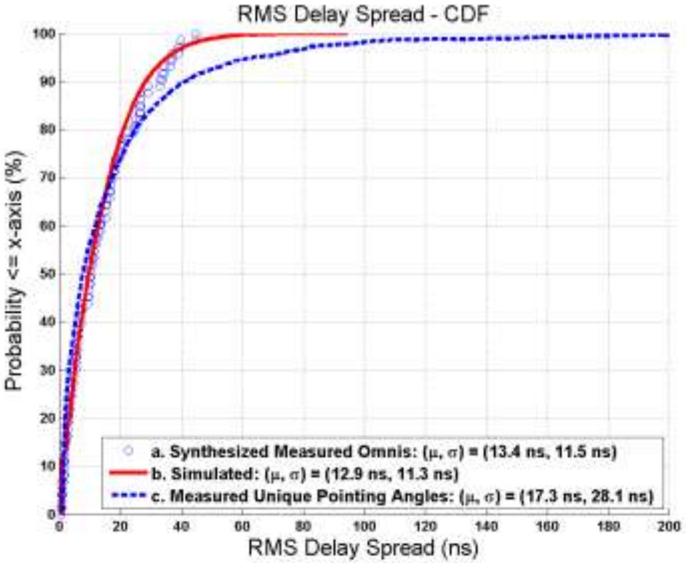
$$= Antenna\ 3dB\ BW$$





M. K. Samimi, T. S. Rappaport, "Characterization of the 28 GHz Millimeter-Wave Dense Urban Channel for Future 5G Mobile Cellular," NYU WIRELESS TR 2014-001, June 2014.

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



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

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Statistical Simulator Results

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.

Path Loss Model	Measured (n, σ)	Simulated (n, σ)	Error (%)
Omnidirectional (P)	(3.4, 9.7 dB)	(3.4, 9.8 dB)	(0,1.0)

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

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.

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

T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. Pearson/Prentice Hall, 2015.

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Statistical Simulator Results

Spatial Statistics in NLOS:

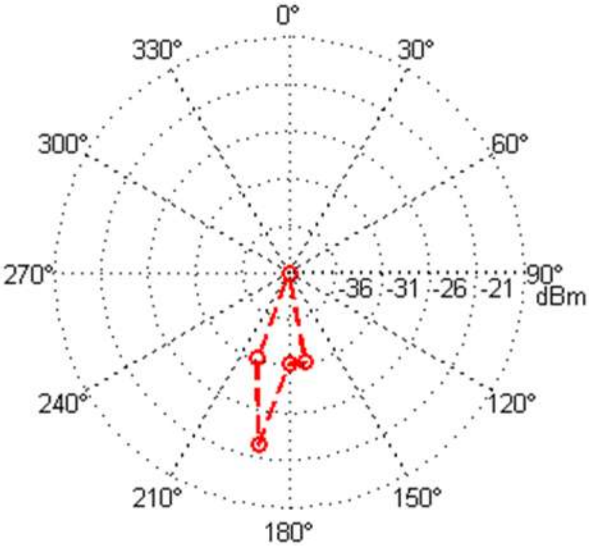
SUMMARY OF THE MEASURED STATISTICS WERE OBTAINED FROM SYNTHESIZED MEASURED 28 GHZ OMNIDIRECTIONAL WIDEBAND PDPS, AND THE SIMULATED STATISTICS WERE GENERATED FROM 10,000 PDPS AND PAS. (P) AND (S) STAND FOR PRIMARY AND SECONDARY, RESPECTIVELY.

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

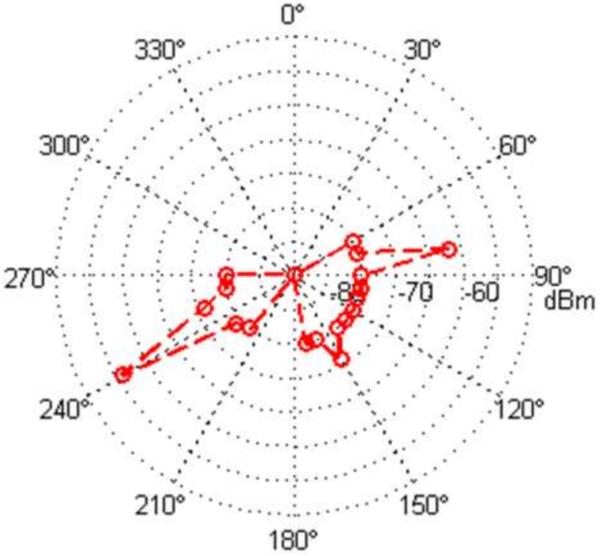
T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. Pearson/Prentice Hall, 2015.

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Typical Polar Plots for TX at 28 GHz (Simulated)



TX LOS AOD for 28 GHz

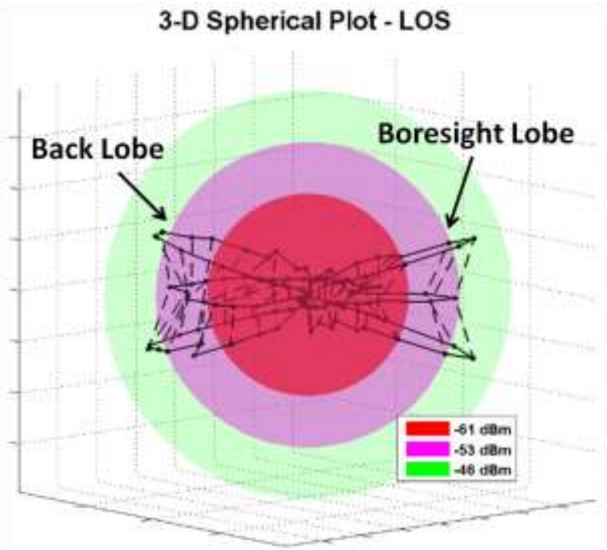


TX NLOS AOD at 28 GHz

"MIMO for Millimeter Wave Wireless Communications: Beamforming, Spatial Multiplexing, or Both?" S. Sun, et. al., IEEE Comm. Mag., Dec. 2014, to appear.

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

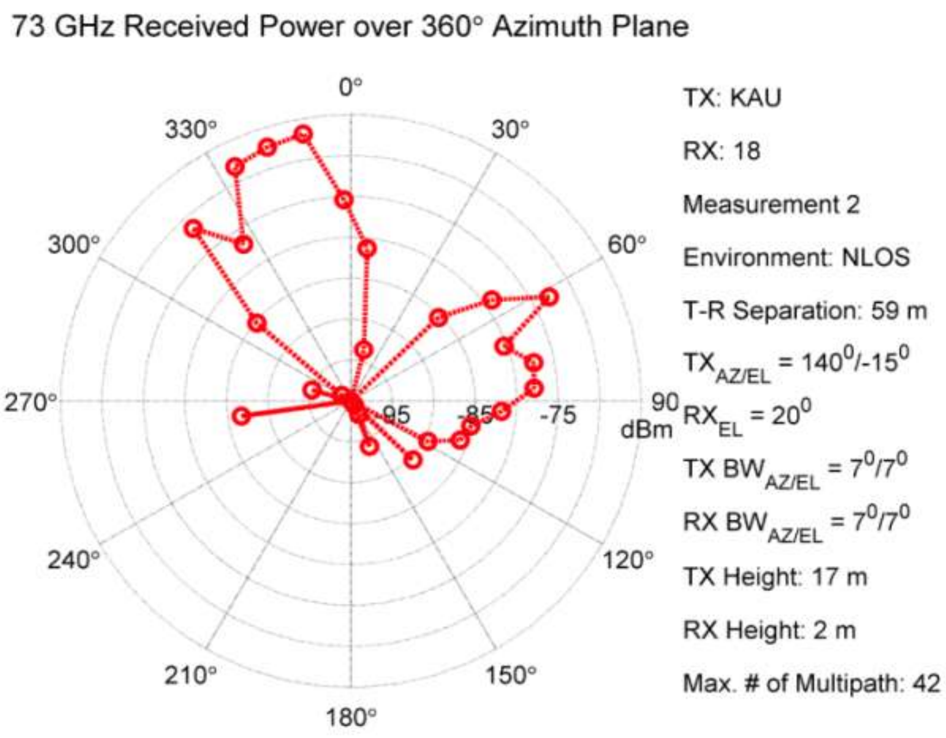


Opportunity for Beamforming and Beam Combining

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



S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter Wave Multi-beam Antenna Combining for 5G Cellular Link Improvement in New York City," *2014 IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 10-14, 2014.

Beam Combining Procedure

- Non-coherent Combining

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

- Coherent Combining

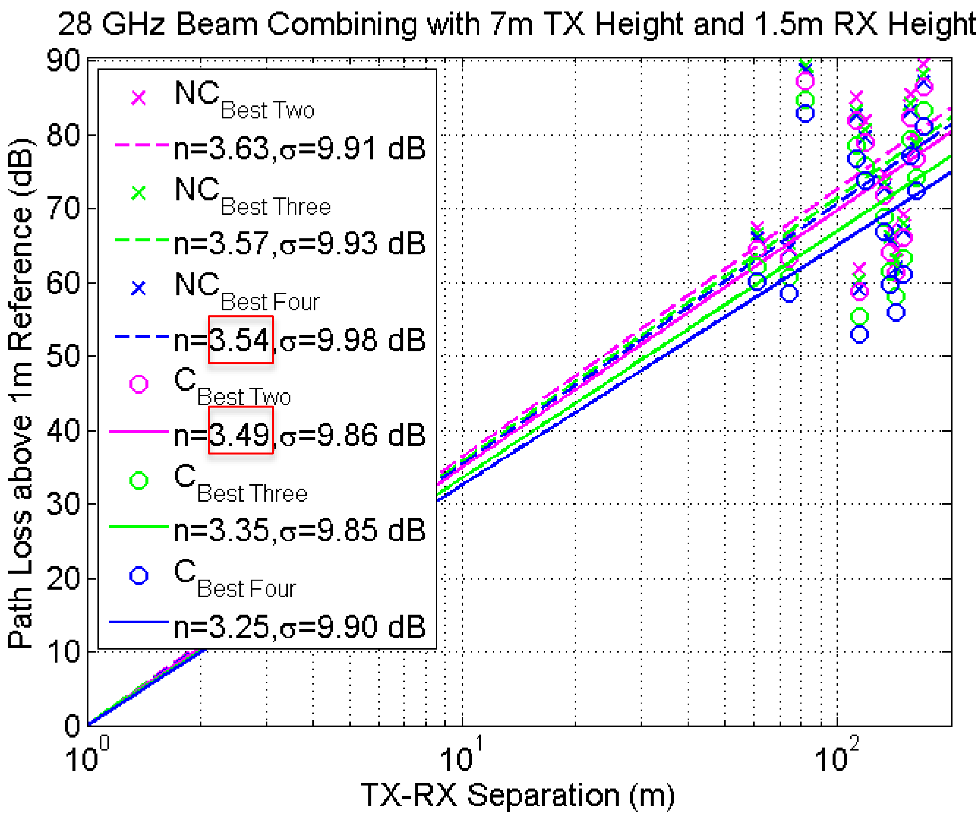
$$P_C = \left(\sum_{i=1}^{N} \sqrt{P_i}\right)^2$$

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

P_i (i=1,2,…, N): the ith strongest received power in Watts.

S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter Wave Multi-beam Antenna Combining for 5G Cellular Link Improvement in New York City," *2014 IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 10-14, 2014.

Beam Combining Results at 28 GHz



NLOS (Co-Polarization):

Overall: n = 4.5

σ_{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

σ_{SF} = 9.5 dB

"NC": Non-coherent Combining
"C": Coherent Combining

Beam combining can significantly improve path loss exponents (PLEs)

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

S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter Wave Multi-beam Antenna Combining for 5G Cellular Link Improvement in New York City," *2014 IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 10-14, 2014.

Comparison of Path Loss between 28 GHz and 73 GHz

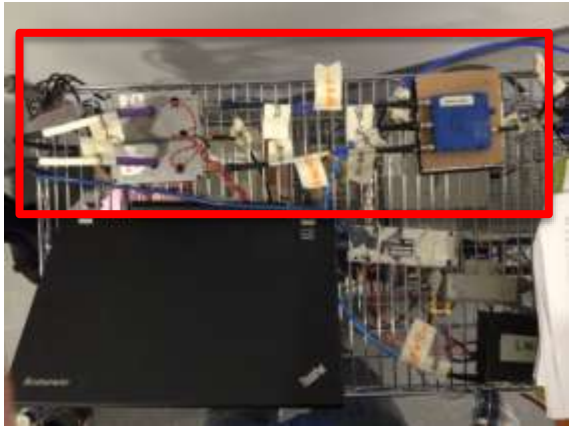
Environment: NLOS

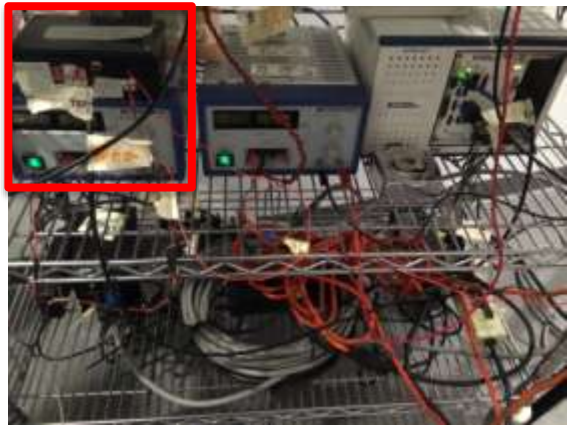
Comparable path Loss exponents (PLEs) at 28 GHz and 73 GHz

Frequency (GHz)	TX, RX Antenna Gains (dBi)	TX Height (m)	RX Height (m)	# of Combined Beams	Coherent		Noncoherent	
					Path Loss Exponent	Shadow Factor (dB)	Path Loss Exponent	Shadow Factor (dB)
28	24.5, 24.5, vertically polarized	7, 17	1.5	Arbitrary Angle	4.5	10.0	4.5	10.0
				1	3.8	9.1	3.8	9.1
				2	3.5	9.1	3.7	9.2
				3	3.4	9.2	3.6	9.2
				4	3.3	9.2	3.6	9.2
73	27, 27, vertically polarized	7, 17	2	Arbitrary Angle	4.6	11.3	4.6	11.3
				1	3.7	7.6	3.7	7.6
				2	3.5	7.3	3.6	7.4
				3	3.3	7.2	3.6	7.3
				4	3.2	7.2	3.5	7.3
			4.06	Arbitrary Angle	4.6	10.7	4.6	10.7
				1	3.8	8.9	3.8	8.9
				2	3.6	8.6	3.7	8.7
				3	3.4	8.3	3.7	8.5
				4	3.3	8.0	3.6	8.3

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

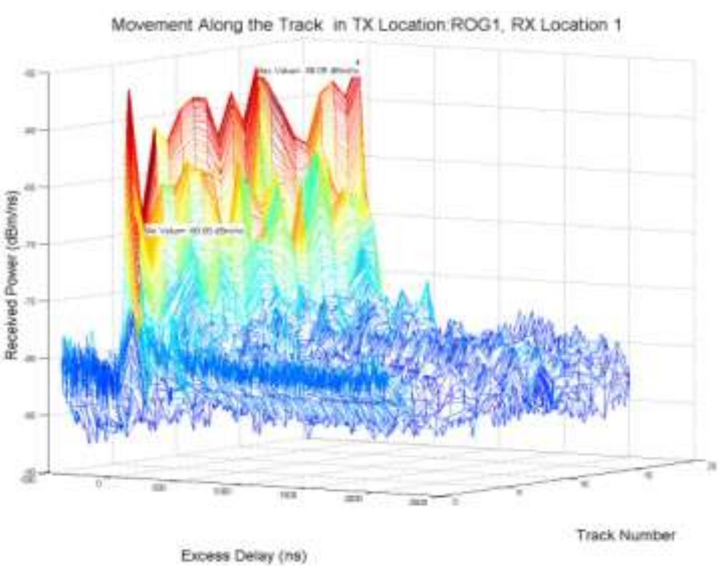
Future mmWave Measurements at NYU

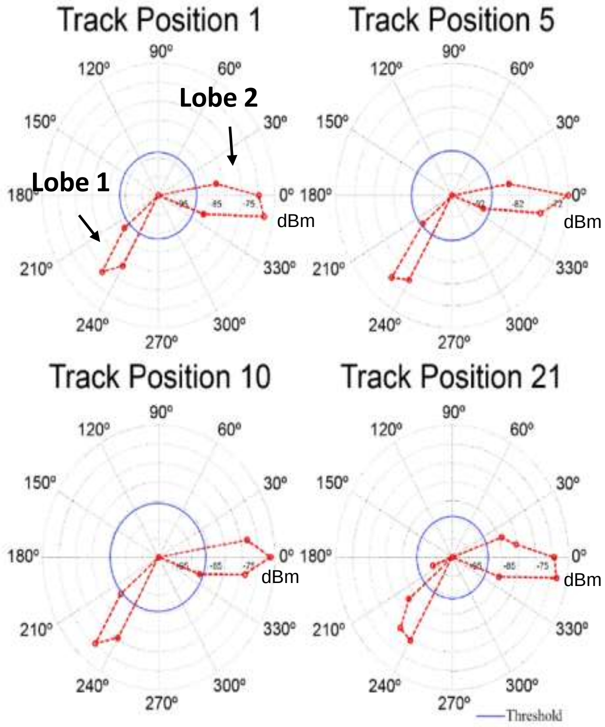
Large scale and small scale propagation measurements:

- Linear track (small scale)
- Different RX locations, separated by a few meters (large scale)

Future mmWave Measurements at NYU

Understanding Spatial and Temporal Correlation: How does the channel change with small displacements in position and time?





M. K. Samimi, K. Wang, Y. Azar, G. N. Wong, R. Mayzus, J. K. Schulz, S. Sun, F. Gutierrez and T. S. Rappaport, "28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications using Steerable Beam Antennas in New York City," *IEEE Vehicular Technology Conference (VTC),* 2-5 June 2013

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:
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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

M. K. Samimi, T. S. Rappaport, "Ultra-Wideband Statistical Channel Model for 28 GHz Millimeter-Wave Urban NLOS Environments," IEEE Global Communications Conference, Exhibition & Industry Forum (GLOBECOM), 8 – 12 Dec., 2014.

Conclusion

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**

S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter Wave Multi-beam Antenna Combining for 5G Cellular Link Improvement in New York City," *2014 IEEE International Conference on Communications (ICC)*, Sydney, Australia, June 10-14, 2014.

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ありがとうございました
Arigatoo Gozaimashta!

Questions?