Millimeter Wave Cellular

A road to 5G

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NYU WIRELESS

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IEEE ICC Plenary Presentation

Agenda

- Motivation for mm-wave cellular for 5G
- Key Requirements for Channel Models:
  - Multipath Channel Statistics
  - Simulation/Beamforming
  - PHY/MAC prototyping
  - Cooperation
- NYU WIRELESS and industry first-movers are making new investments for mmWave

NYU WIRELESS Mission and Expertise

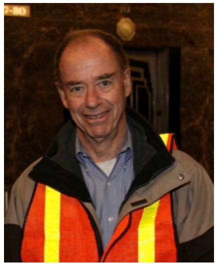
- **EXCITING NEW CENTER**: 25 faculty and 100 students across NYU

- Solving problems for industry, creating research leaders, and developing fundamental knowledge and new applications using wireless technologies
  - NYU-Poly (Electrical and Computer engineering)
  - NYU Courant Institute (Computer Science)
  - NYU School of Medicine (Radiology)

- 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:
  - ~ $10 Million/annually from NSF, NIH, and Corporate sponsors

NYU WIRELESS Faculty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Ryan Brown
RF Coils/Imaging
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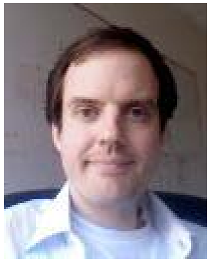
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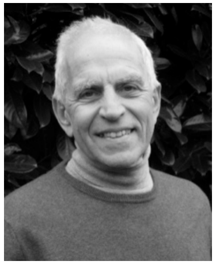
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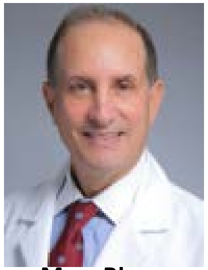
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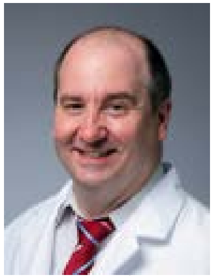
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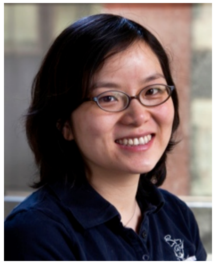
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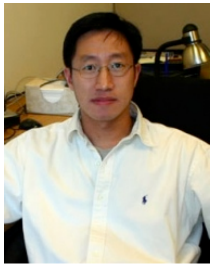
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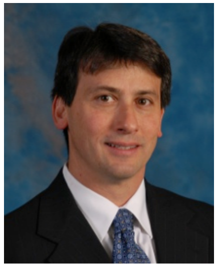
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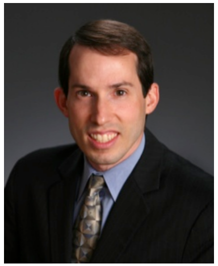
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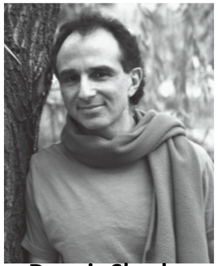
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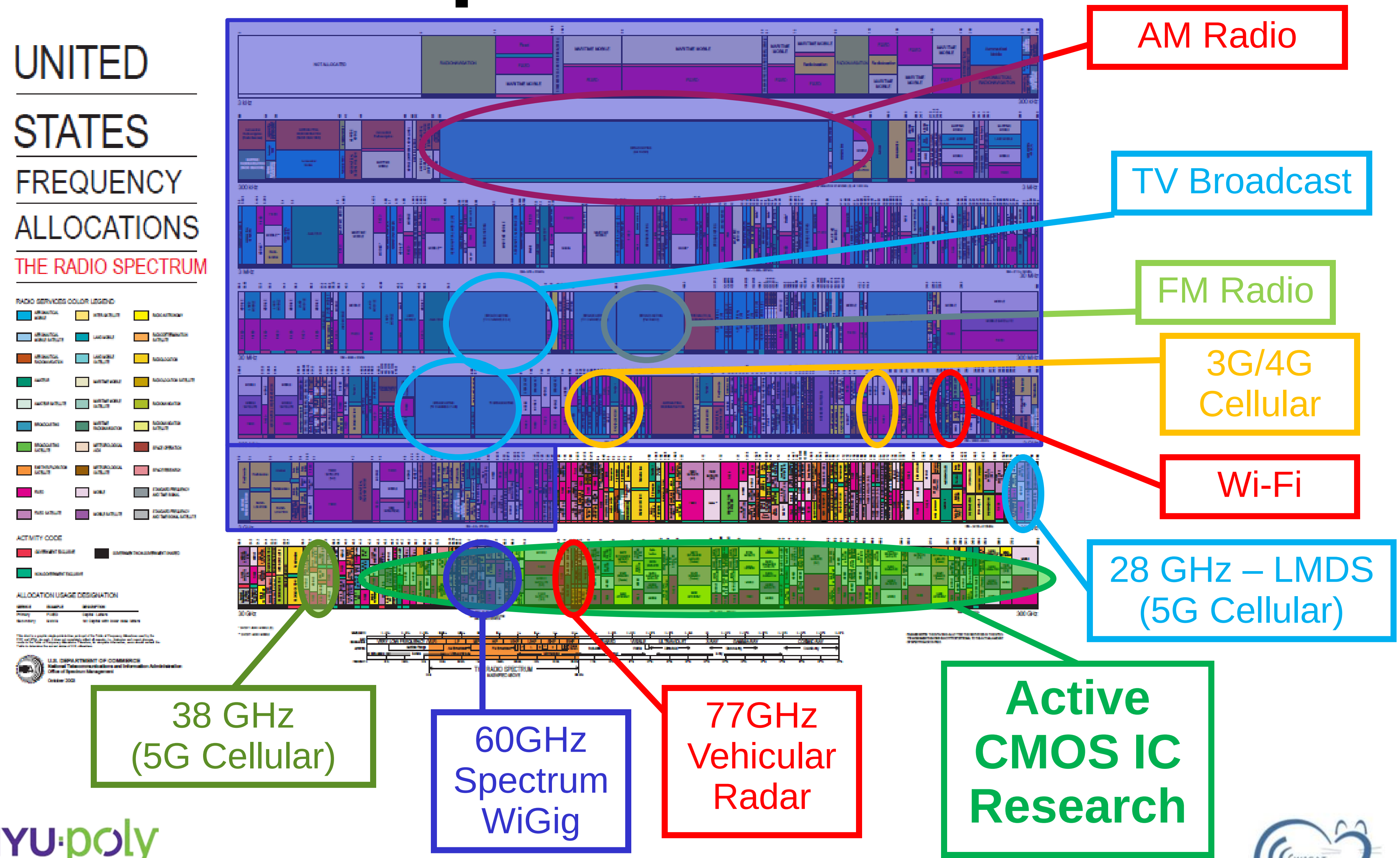
About NYU

- New York University
- One of the largest and oldest private universities in the USA (1831)
- Origins in Telecom: Samuel Morse (Morse Code) first faculty member
- Pioneering the Global Network University w/campuses in Abu Dhabi, Shanghai, Toronto, Buenos Aires, and 18 other countries
- Faculty have received 34 Nobel Prizes, 16 Pulitzer Prizes, 21 Academy Awards, 10 National of Science Medals
- New focus in Engineering for the Urban, Telecom, Bio-Med future
- NYU is ranked #32 in 2013 USNWR National University Ranking
  - (GA Tech is 36, UT Austin is 46)

Wireless Spectrum



AM Radio

TV Broadcast

FM Radio

3G/4G Cellular

Wi-Fi

28 GHz – LMDS (5G Cellular)

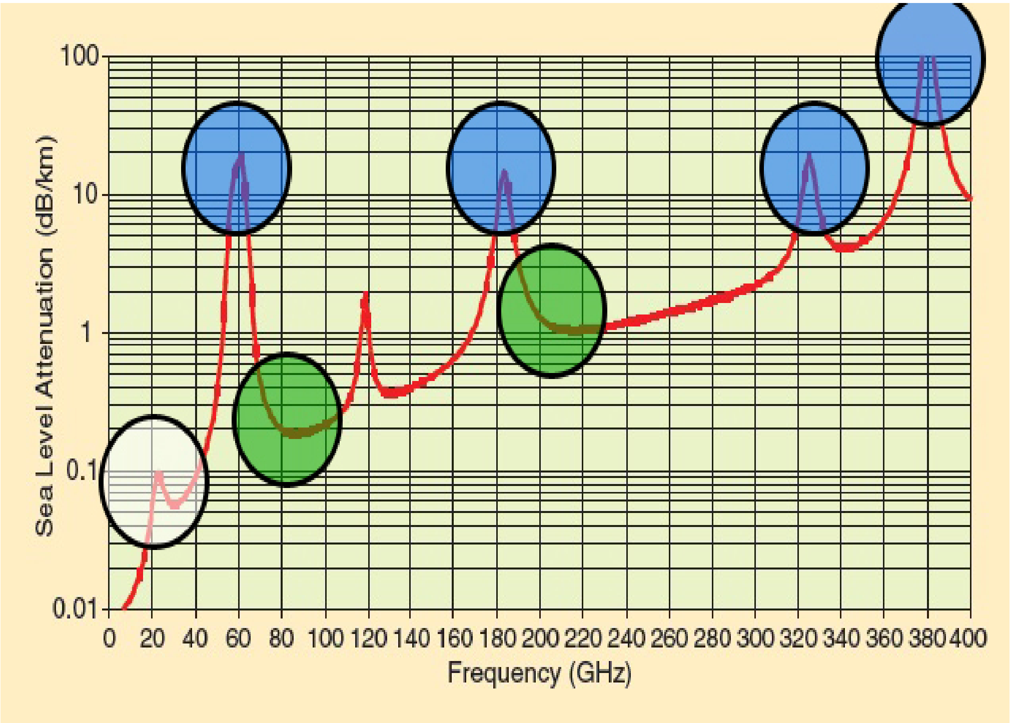
38 GHz (5G Cellular)

60GHz Spectrum WiGig

77GHz Vehicular Radar

Active CMOS IC Research

Atmospheric Attenuation: mm-waves



- 0.012 dB over 200 m at 28 GHz
- 0.016 dB over 200m at 38 GHz

- White
  - Current cellular frequencies and low mm-wave
- Blue
  - Short-range indoor communications, whisper radios of the future
    - Higher attenuation
- Green
  - Future backhaul and cellular frequencies
    - Low atmospheric attenuation
    - Multi-GHz Bandwidth
    - Directional Antenna Arrays with Beamsteering
    - CMOS: cost-effective with high frequency limits
    - Atmospherics are challenging

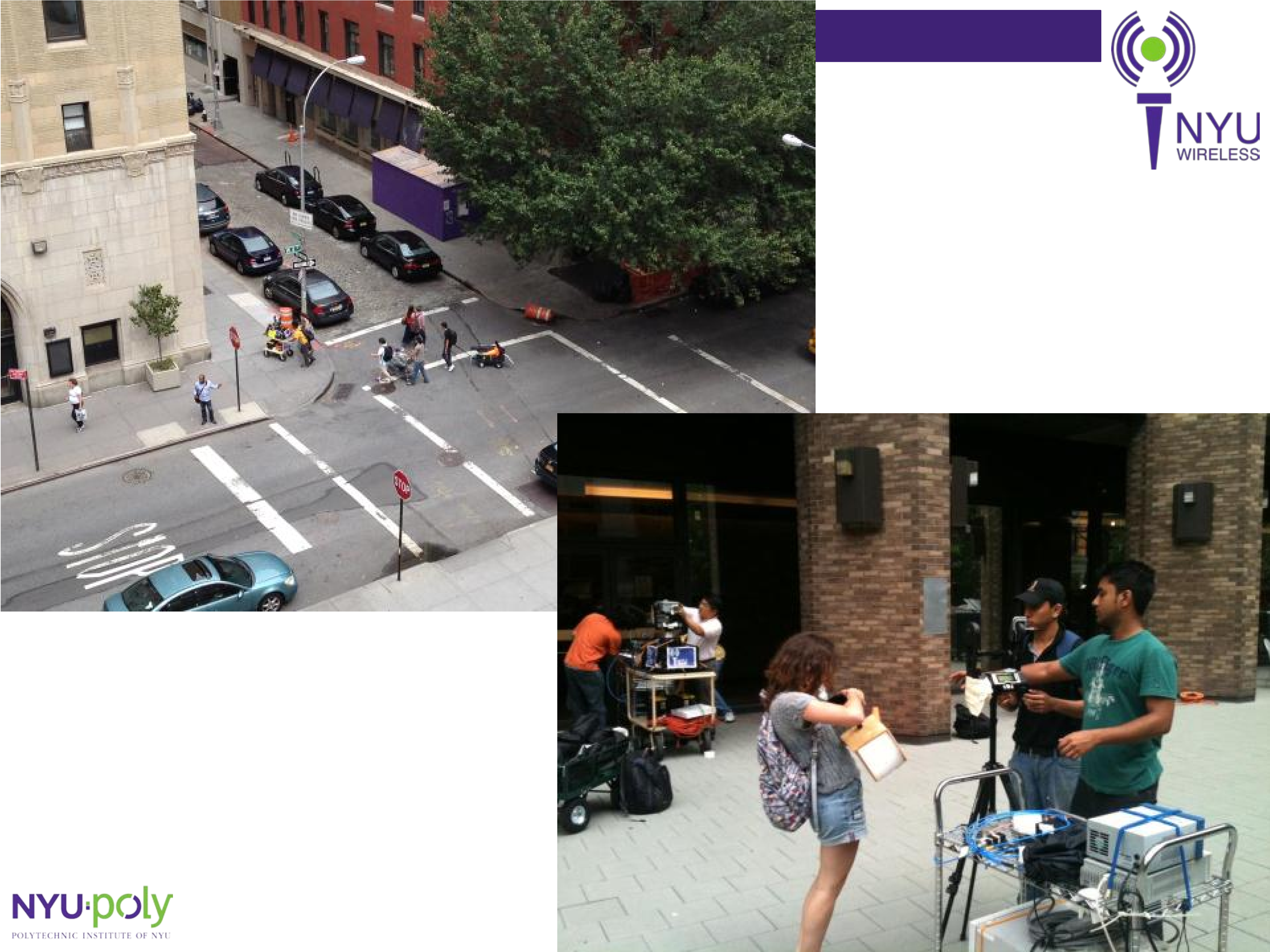
T. S. Rappaport, J. N. Murdock, and F. Gutierrez, “State of the Art in 60-GHz Integrated Circuits and Systems for Wireless Communications,” Proceedings of the IEEE, vol. 99, no. 8, pp. 1390–1436, August 2011.

28, 38 and 60 GHz Measurement Campaigns

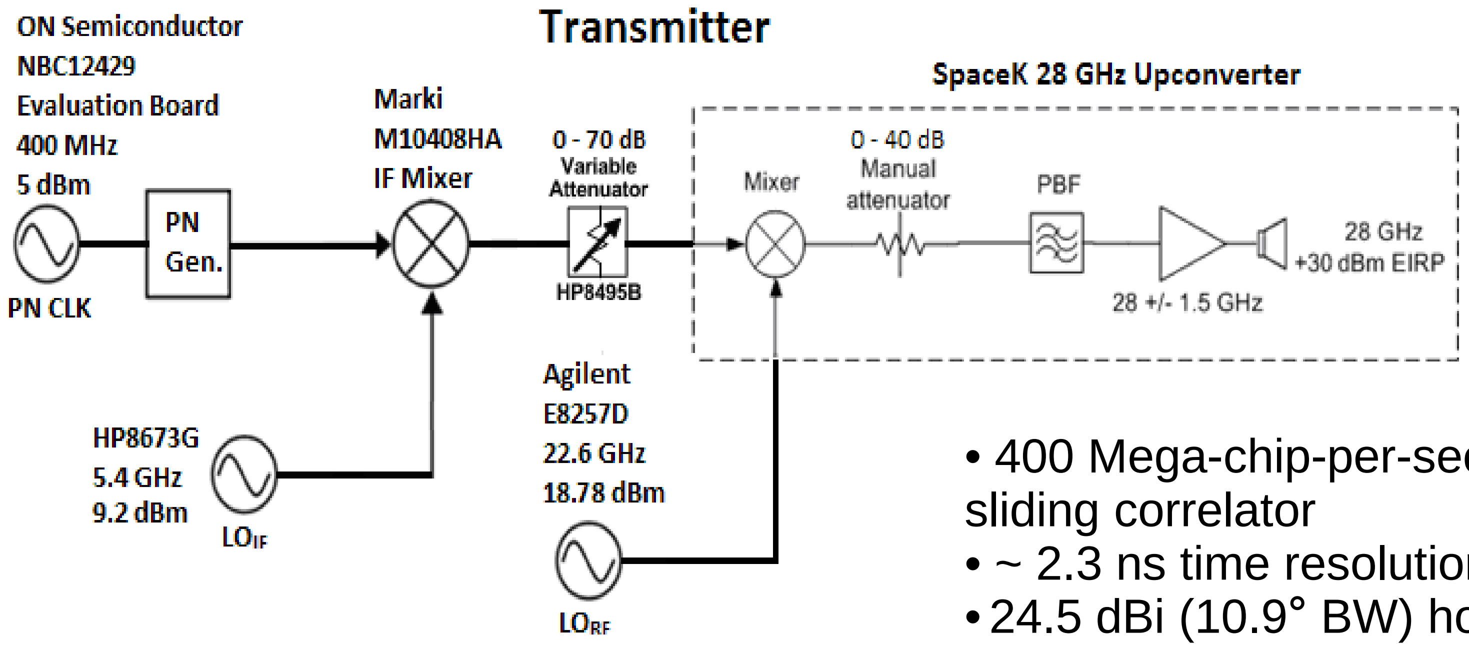
TX location: ROG1 (Rogers Hall NYU-Poly, Brooklyn, New York)

RX location: RX9 (Othmer Residence Hall, NYU-Poly, Brooklyn, New York)

- Sponsored by Samsung.
- NSN, Intel, NSF have added support, 28, 60, 72 GHz.


STOP
STOP

28 GHz Channel Sounder

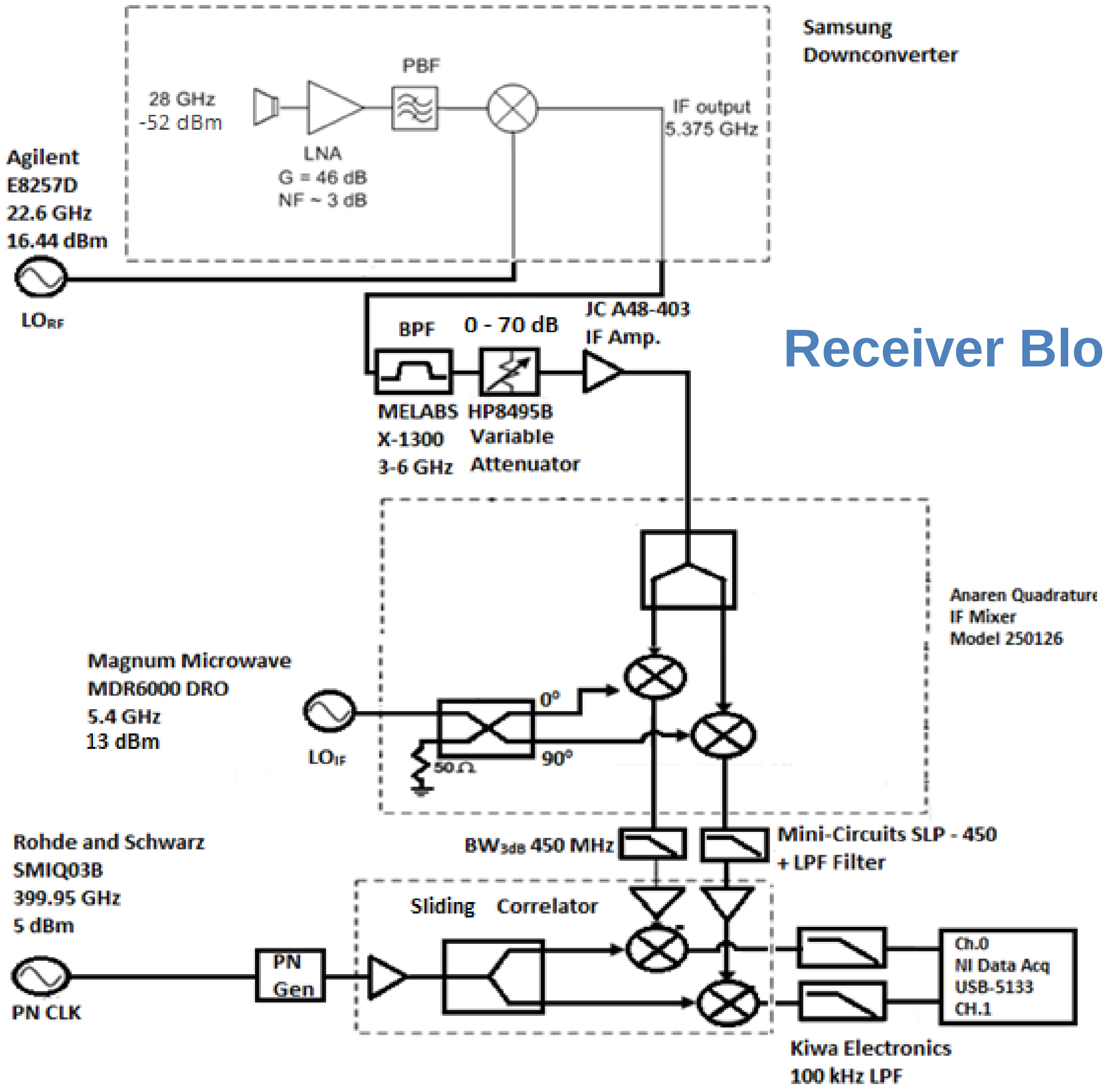


Transmitter Block Diagram

- 400 Mega-chip-per-second (Mcps) sliding correlator
- ~ 2.3 ns time resolution
- 24.5 dBi (10.9° BW) horn antennas
- 15 dBi (30° BW) horn antennas
- 30 dBm TX RF output
- 183 dB path loss dynamic range
- LabVIEW-controlled angular motor

28 GHz Channel Sounder

Receiver Block Diagram



28 GHz Channel Sounder

RX Hardware

TX Hardware

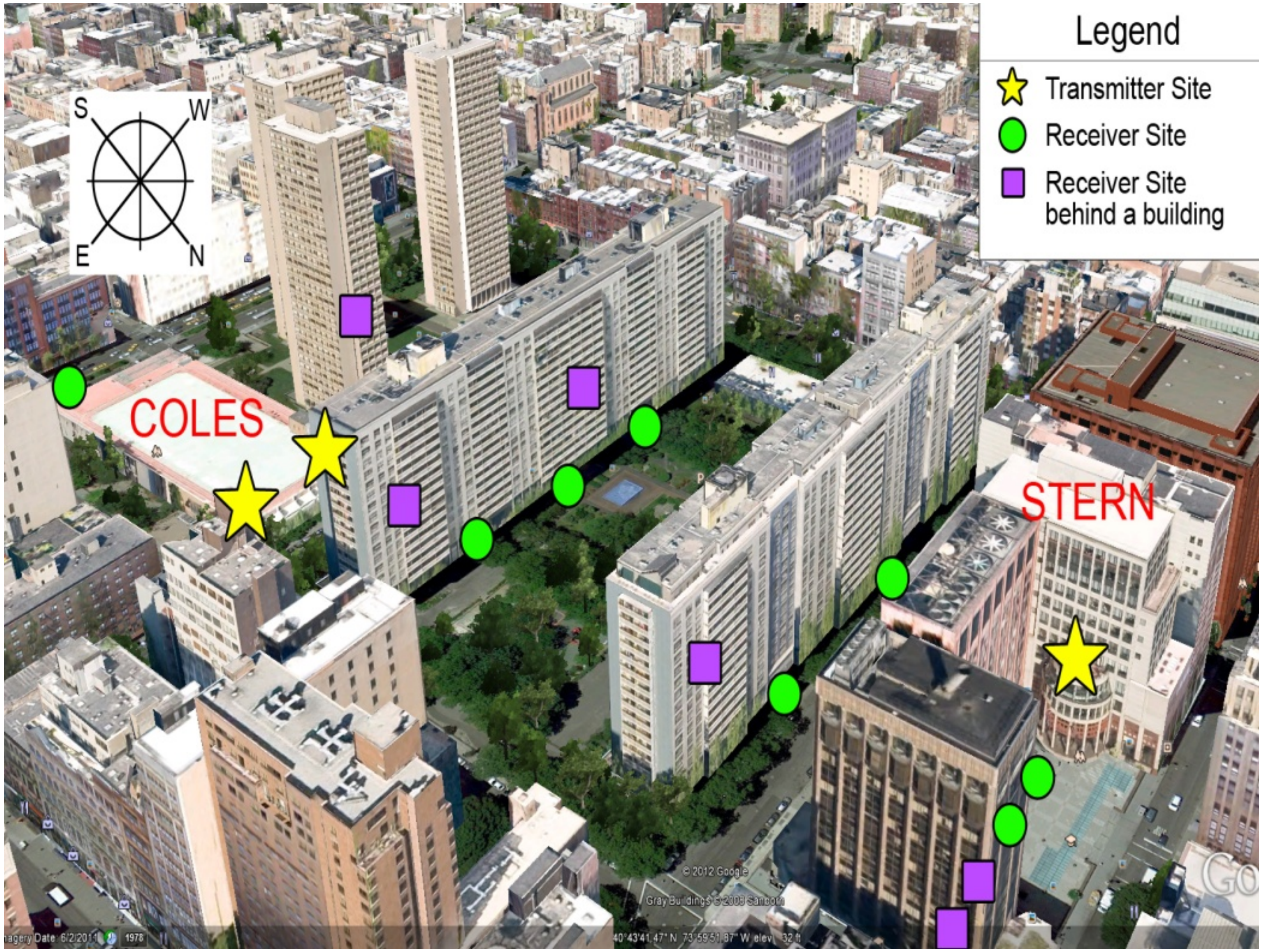
Manhattan Environment – Dense Urban

- 3 TX sites
- 25 RX sites

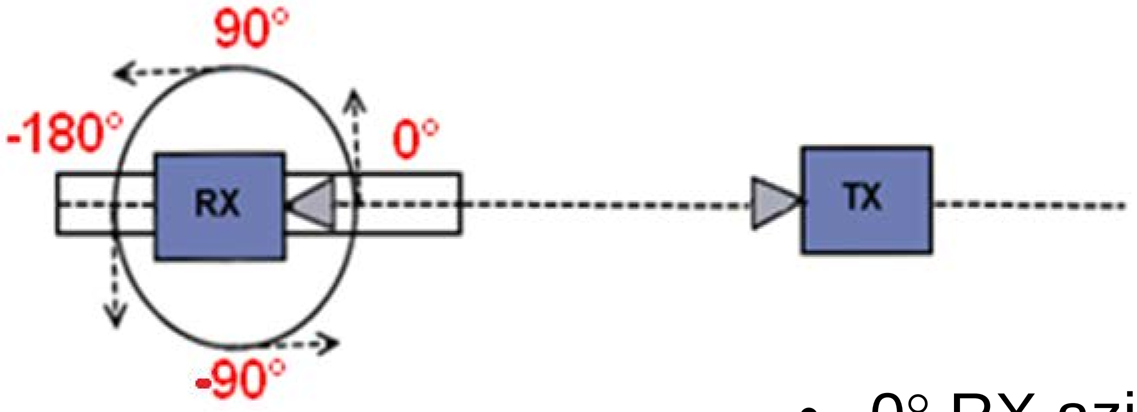
- Pedestrian and vehicular traffic
- High rise-buildings, trees, shrubs

- TX sites and heights:
  - TX-COL1 – 7 m
  - TX -COL2 – 7 m
  - TX-KAU – 16 m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors on or near sidewalks



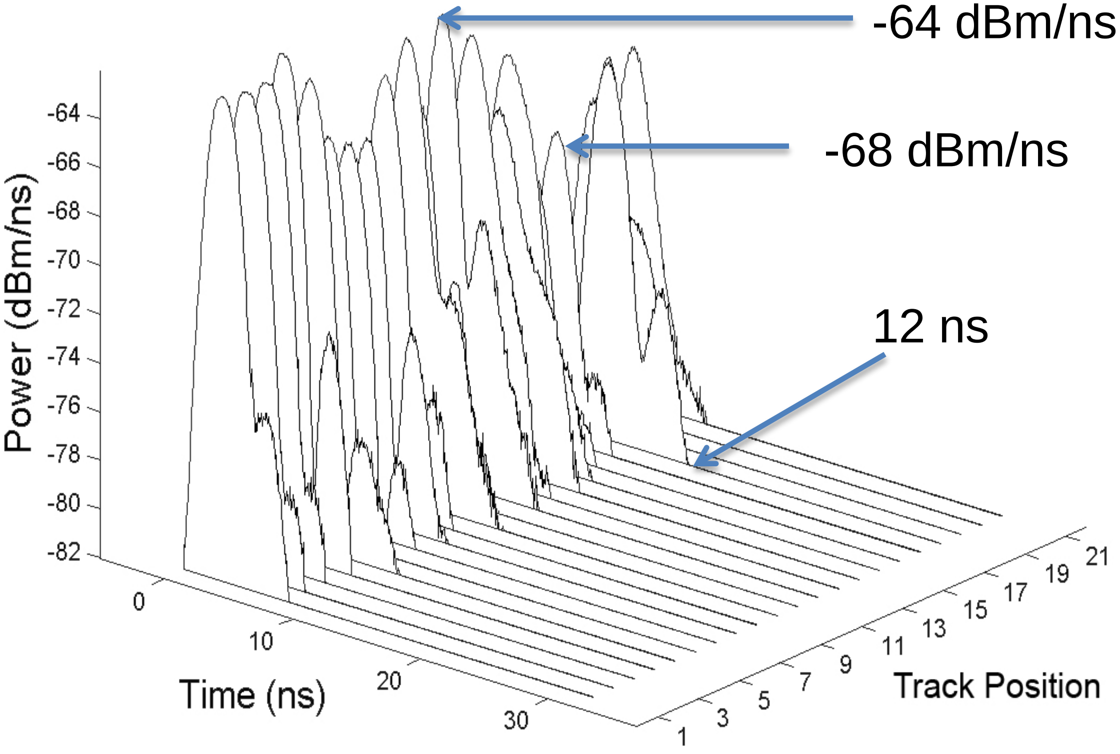
Small Scale Linear Track Measurements



Linear track setup in Brooklyn measurement campaign.

- 0° RX azimuth angle
  - RX directly points to TX
- Total track length: 107 mm (10λ)
- Step sizes: 5.35 mm (λ/2)

Small Scale Linear Steps - Power Delay Profiles (PDPs)



-64 dBm/ns

-68 dBm/ns

12 ns

Power delay profiles measured over a 10λ linear track. TX was on the rooftop of Rogers Hall in downtown Brooklyn. RX was on Bridge street (135 meters away from the TX). The TX and RX were pointed for maximum signal power. Track step size was λ/2 using 24.5 dBi horn antennas 10.9° 3-dB beamwidths at both TX and RX.

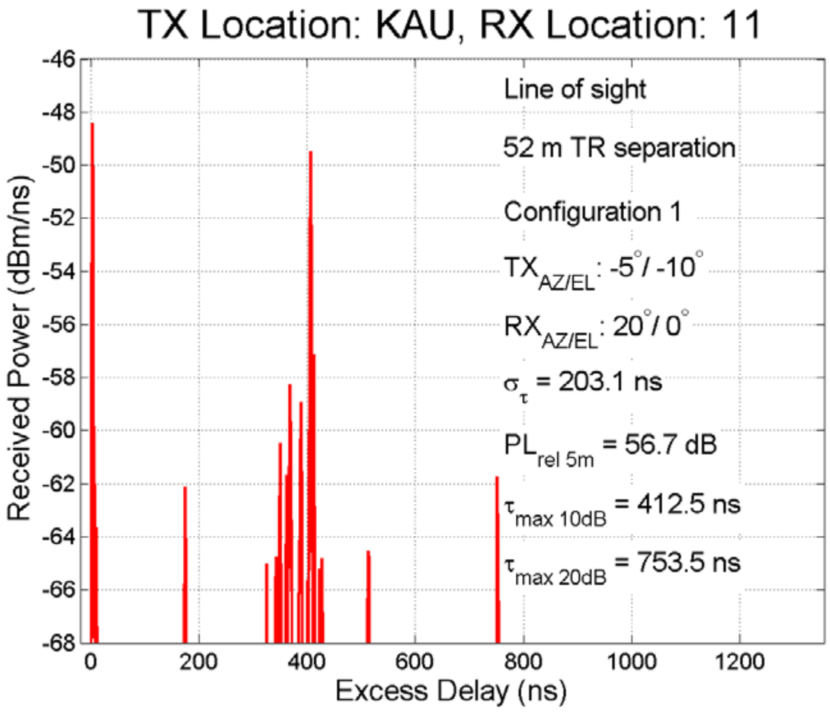
K. Wang., Y. Azar, T. S. Rappaport, *et al*, “28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications using Steerable-Beam Antennas in New York City,” *submitted to IEEE Vehicular Technology Conference (VTC)*, June 2013.

3-dimensional PDP at angles along a small-scale track.

Power Delay Profiles

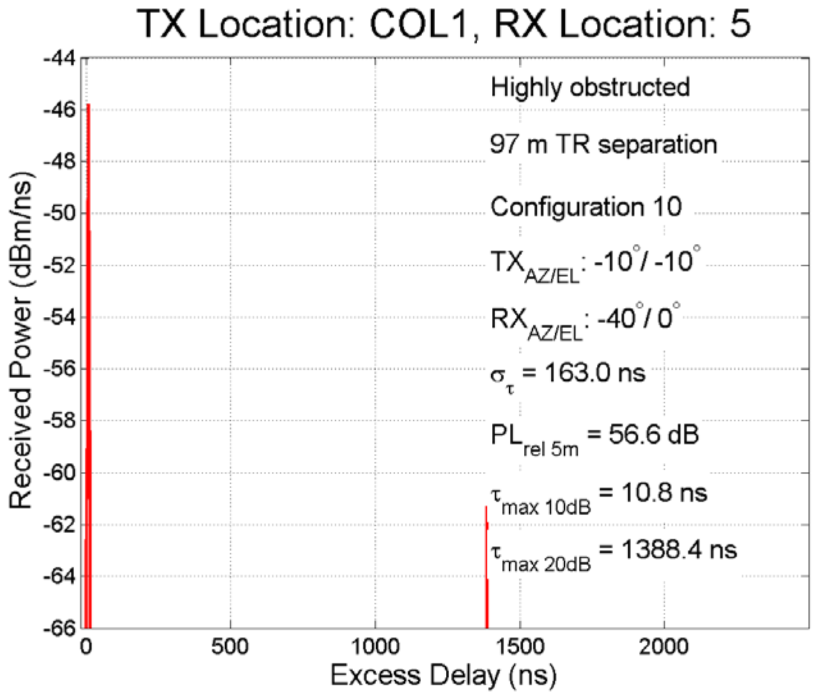
Largest Observed Multipath Excess Delay:

LOS: 753.5 ns



PDP in LOS environment.

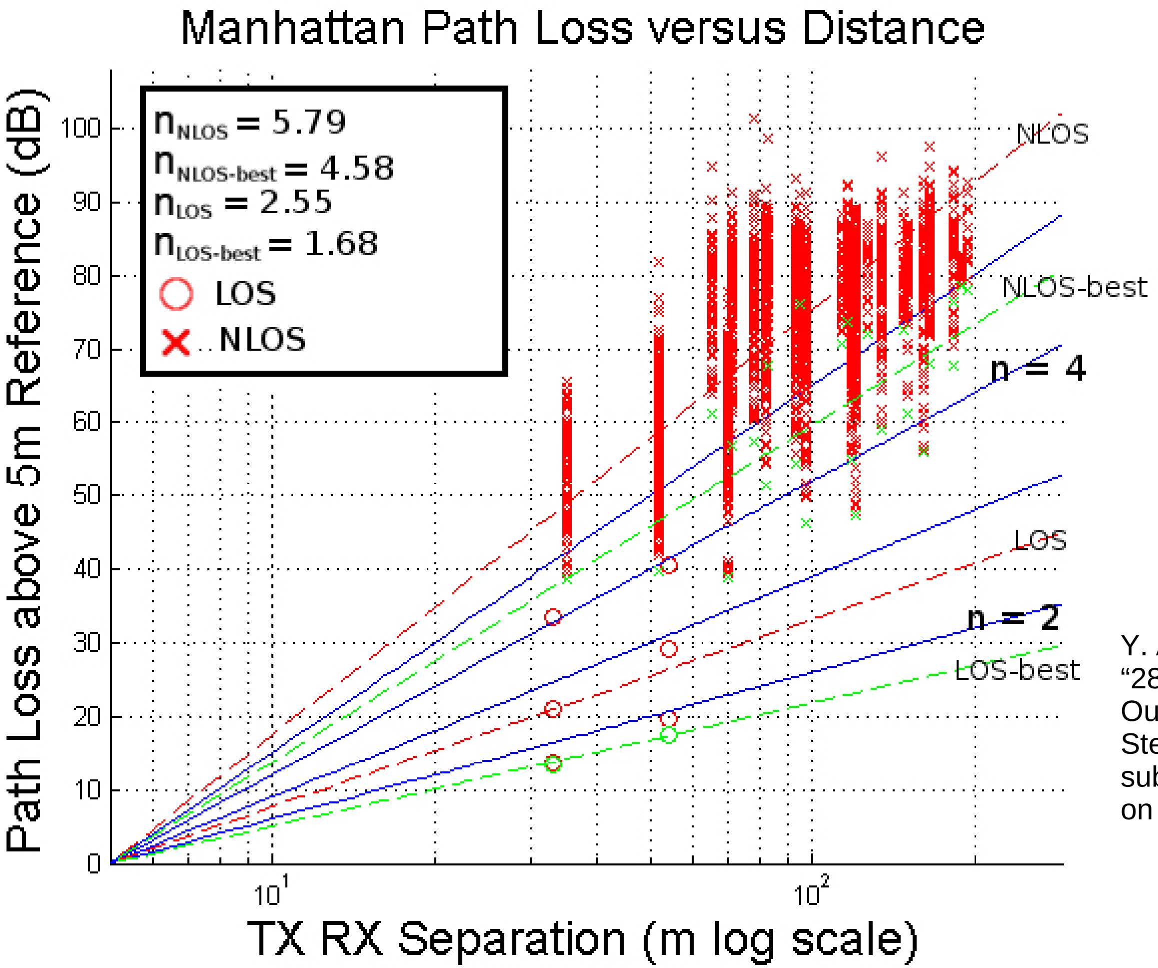
NLOS: 1388.4 ns



PDP in NLOS environment.

Y. Azar, G. N. Wong, T. S. Rappaport, *et al*, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," submitted to IEEE International Conference on Communications (ICC), June 9–13 2013.

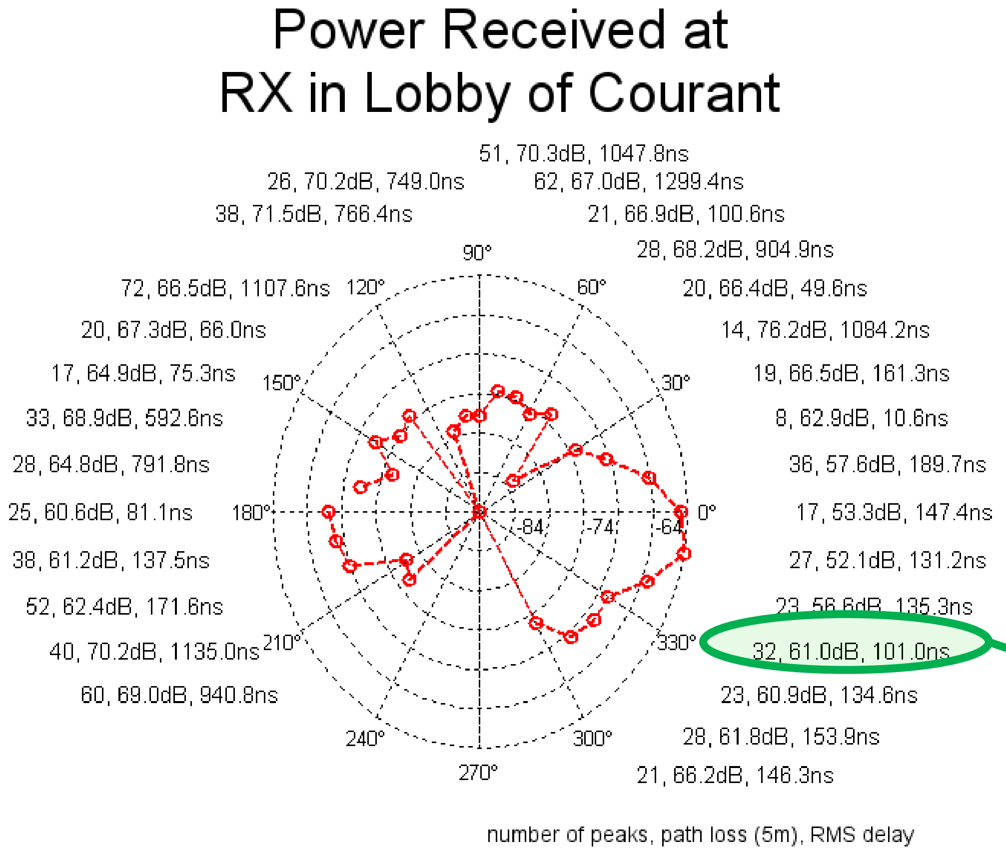
28 GHz Path Loss Exponent



Measured path loss values relative to 5 m free space in Manhattan.

Y. Azar, G. N. Wong, T. S. Rappaport, *et al*, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," submitted to IEEE International Conference on Communications (ICC), June 9–13 2013.

Received power, multipath, and RMS delay spread

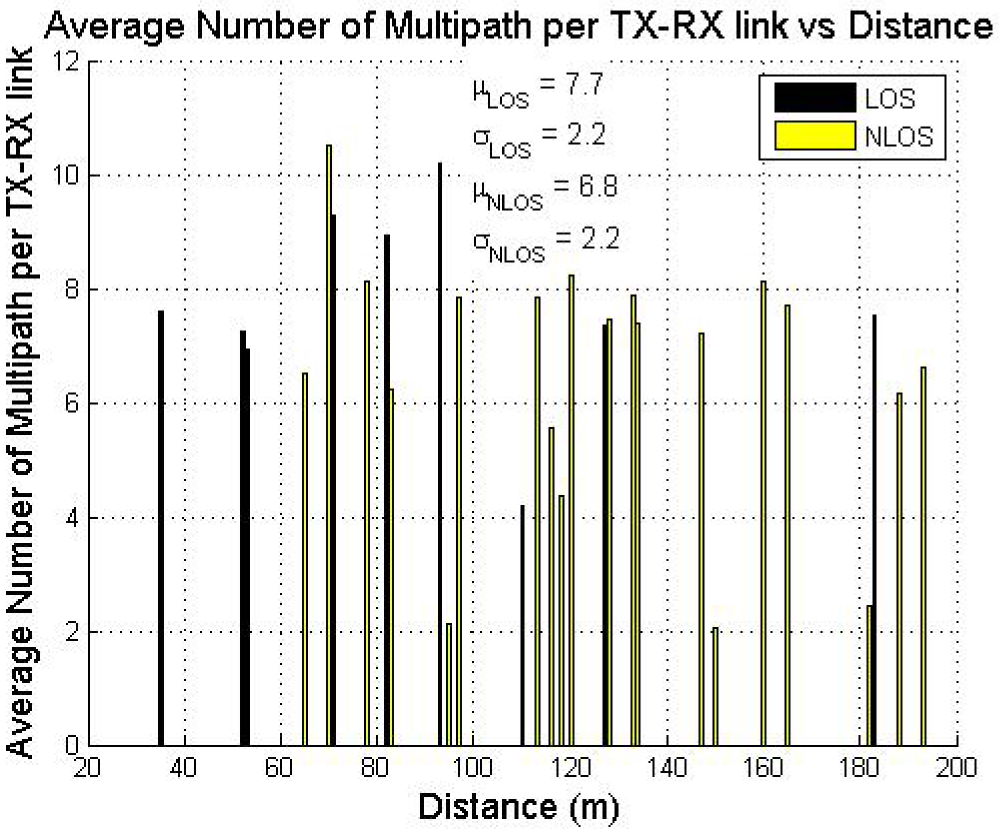

Power Received at RX in Lobby of Courant

Polar plot representing power received.

- NLOS Environment
- 78 m TX-RX separation
- Signal received in 28 of 36 angles (10° increments)
- Radius = Path loss relative to 5 m free space cal (dB)

- 32, 61.0 dB, 101.0 ns:
  - # of resolvable multipath
  - Path loss (relative to 5 meter free space cal)
  - Excess delay spread

Resolvable Multipath Components



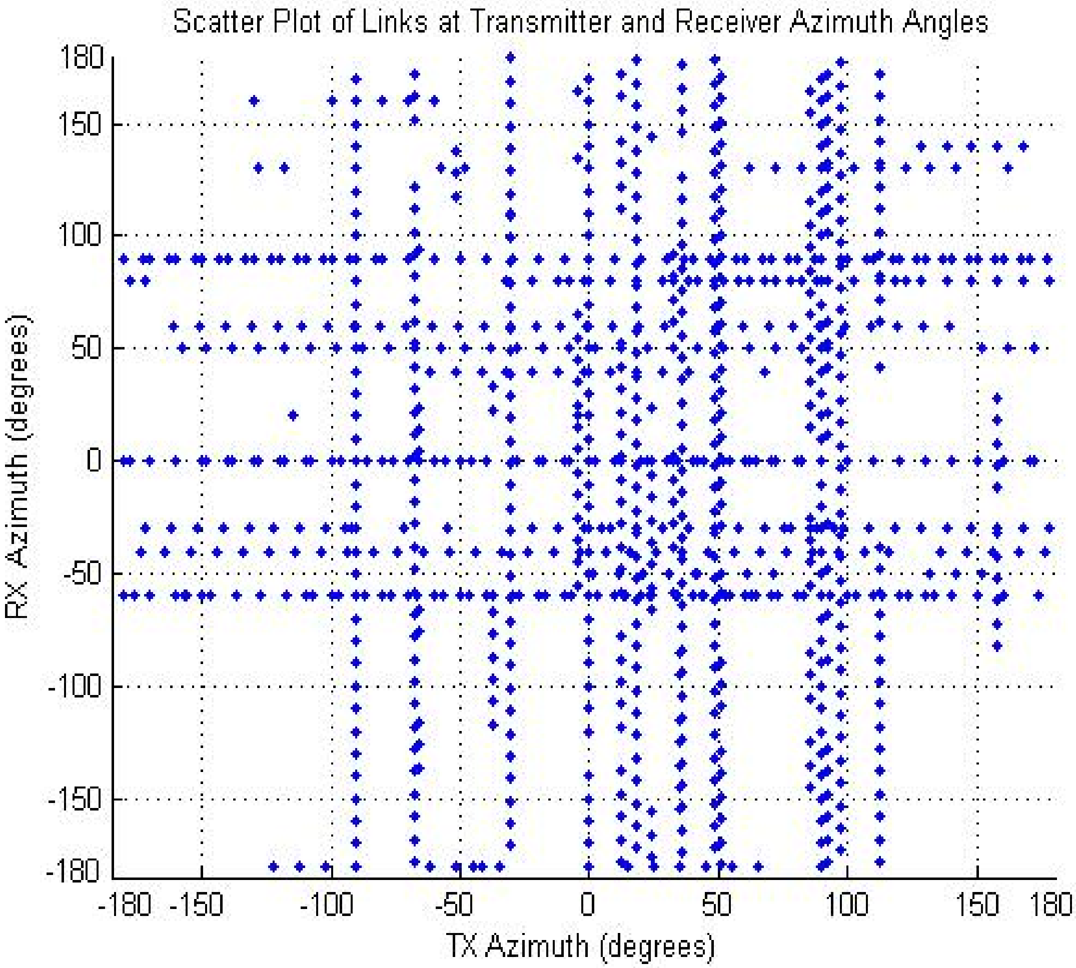
Average number of multipath **(X10)** in LOS and NLOS conditions.

Multipath in Urban Environment for each viable link:

- LOS: 72 resolvable multipath components on average when energy received
- NLOS: 68 resolvable multipath components on average when energy received
- **Key Finding:** Many resolvable multipath components in a specific directional link, regardless of environment

Y. Azar, G. N. Wong, T. S. Rappaport, *et al*, “28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City,” submitted to IEEE International Conference on Communications (ICC), June 9–13 2013.

28 GHz TX-RX Angular Links

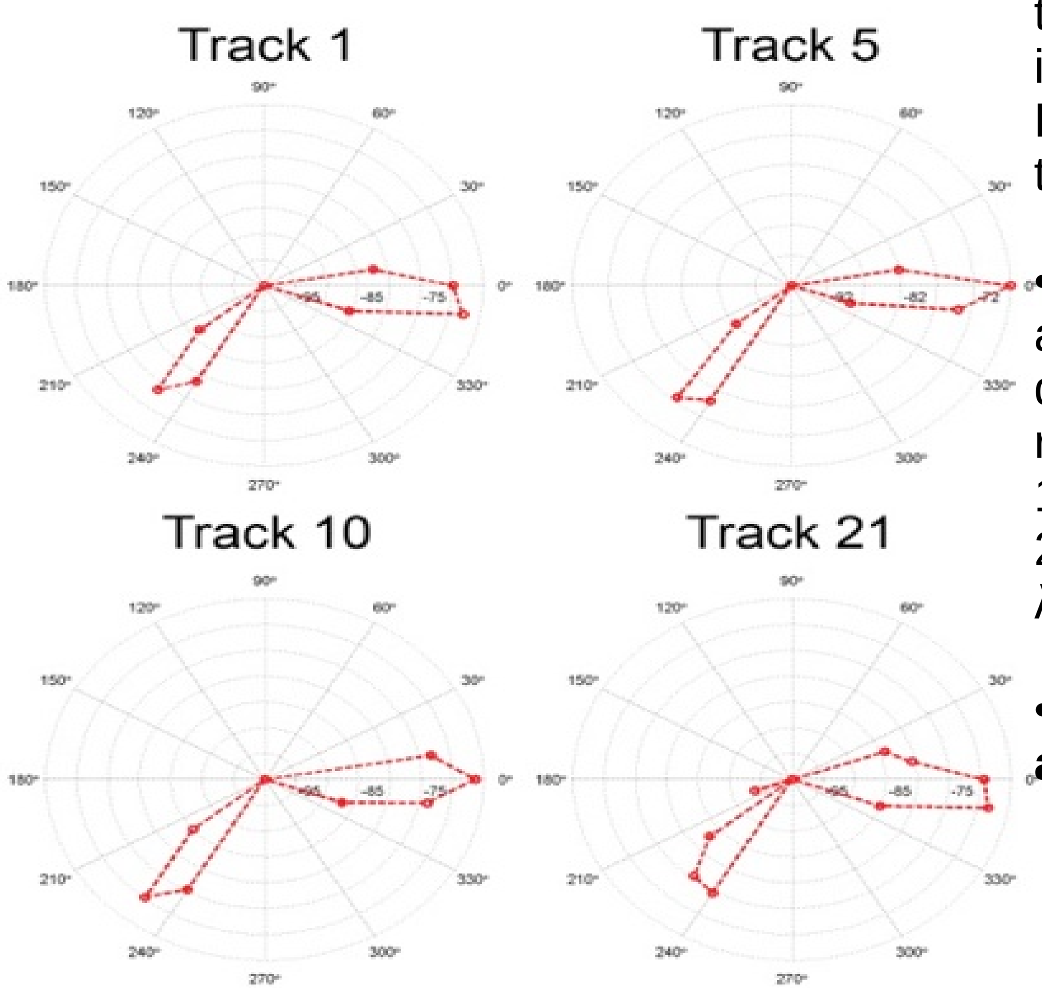


- Most links occurred
    - TX Az: -100°–100°
        - 91.6% of total links
    - RX Az: -160°–160°
        - 90.6% of total links

K. Wang., Y. Azar, T. S. Rappaport, *et al*, “28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications using Steerable-Beam Antennas in New York City,” *submitted to IEEE Vehicular Technology Conference (VTC)*, June 2013.

RX Azimuth vs. TX Azimuth.

28 GHz Small Scale AoA Measurements



- AOA measurements from the TX on the rooftop of NYU-Poly's Rogers Hall in downtown Brooklyn to the RX on Bridge street (135 meters away from the TX)

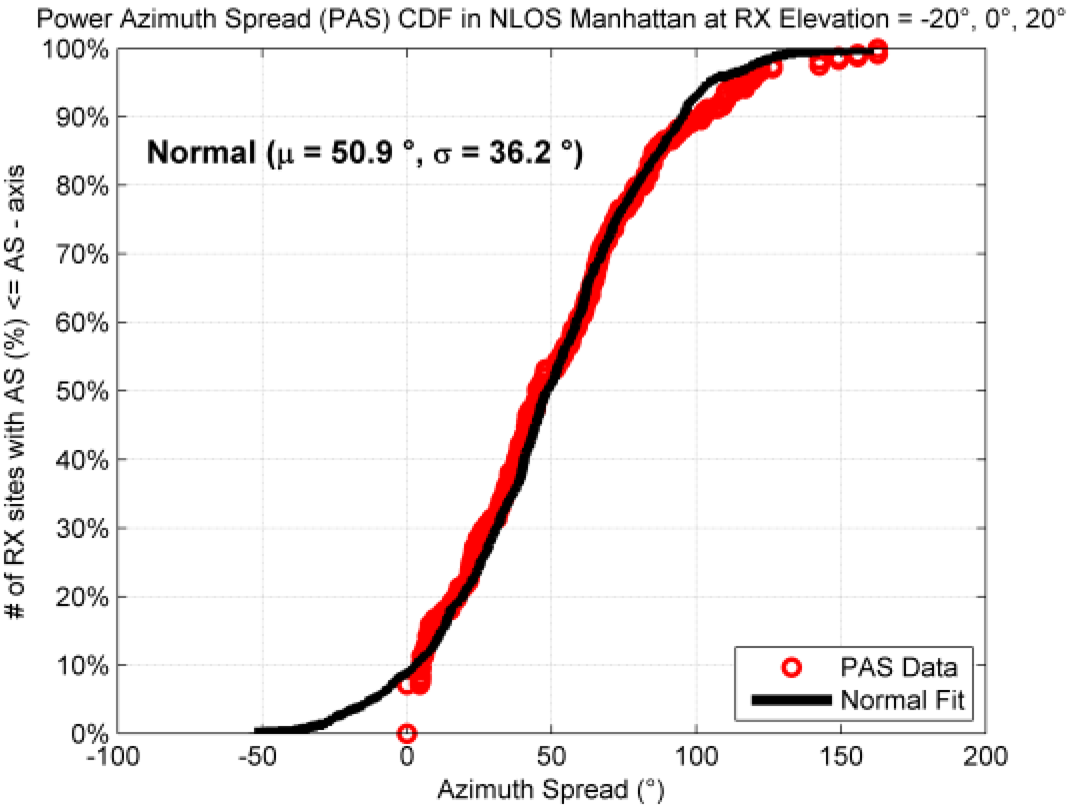
- Received power versus receiver antenna azimuth angle using a 24.5 dBi horn antenna. Each plot represents a position (Track Location 1, 5, 10, and 21) along a small-scale 21-step linear track with step sizes of λ/2 and a total length of 10λ

- **Small scale movement does not affect AOA**

K. Wang., Y. Azar, T. S. Rappaport, *et al*, "28 GHz Angle of Arrival and Angle of Departure Analysis for Outdoor Cellular Communications using Steerable-Beam Antennas in New York City," *submitted to IEEE Vehicular Technology Conference (VTC)*, June 2013.

Power received vs. receiver antenna azimuth angle.

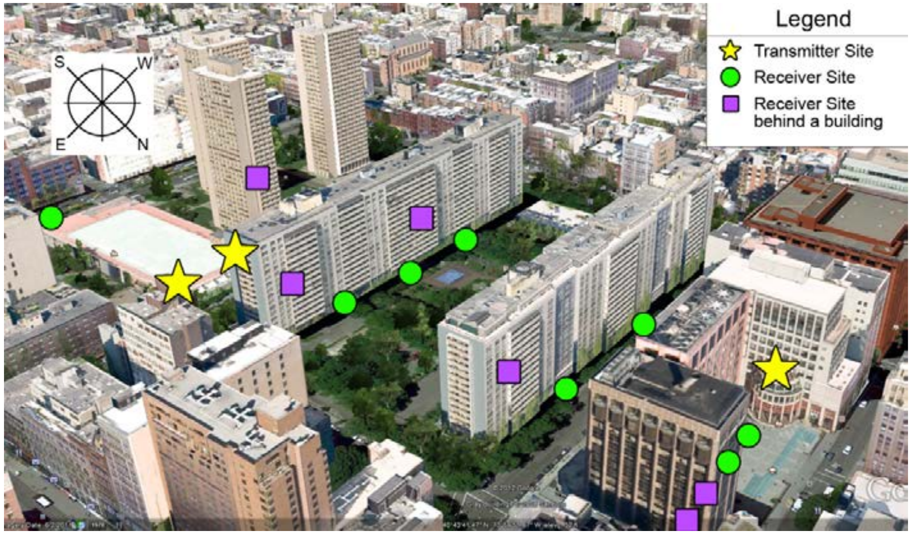
Cumulative RX Distribution Function of AOA Power Azimuth Spread



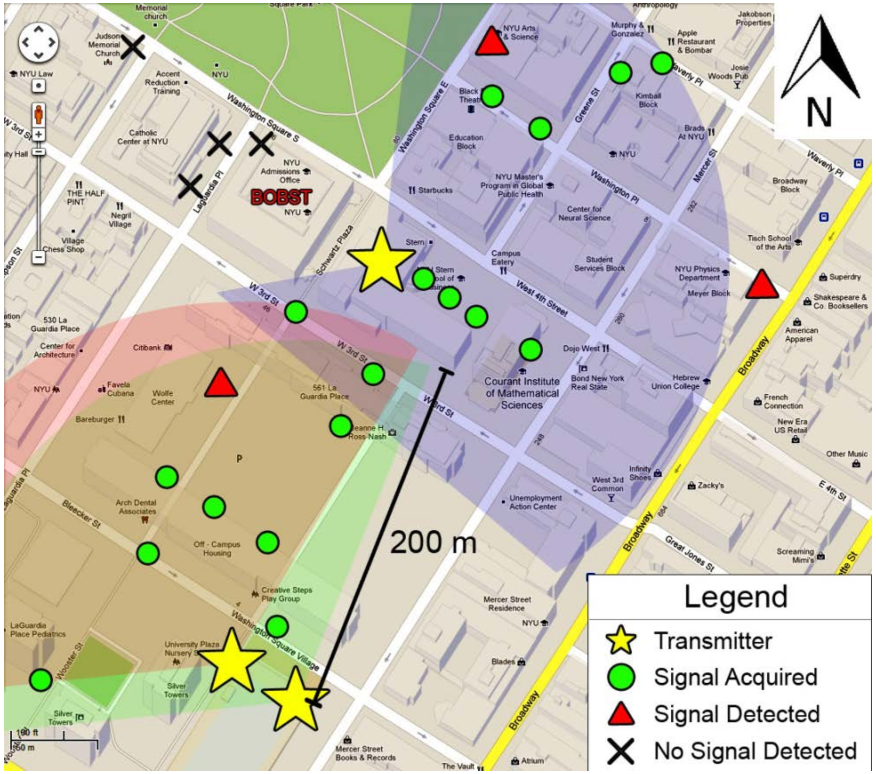
CDF of the AOA power azimuth spread (PAS) about the RX 0° azimuth angle (pointing directly at TX) in NLOS Manhattan, combining RX elevations of -20°, 0° and 20°, for 28 GHz and with TX and RX antenna gains of 24.5 dBi. The red circles represent the experimental PAS data, and the black line represents the Gaussian fit to the experimental data.

Signal Outage in Manhattan

- Signal acquired up to 200 m TX-RX separation
- For outage: total path loss > 170 dB
- 57% of all locations found to be outages (up to 500 m)
- Only 16% of locations within 200 m were found to be outages (massive building)



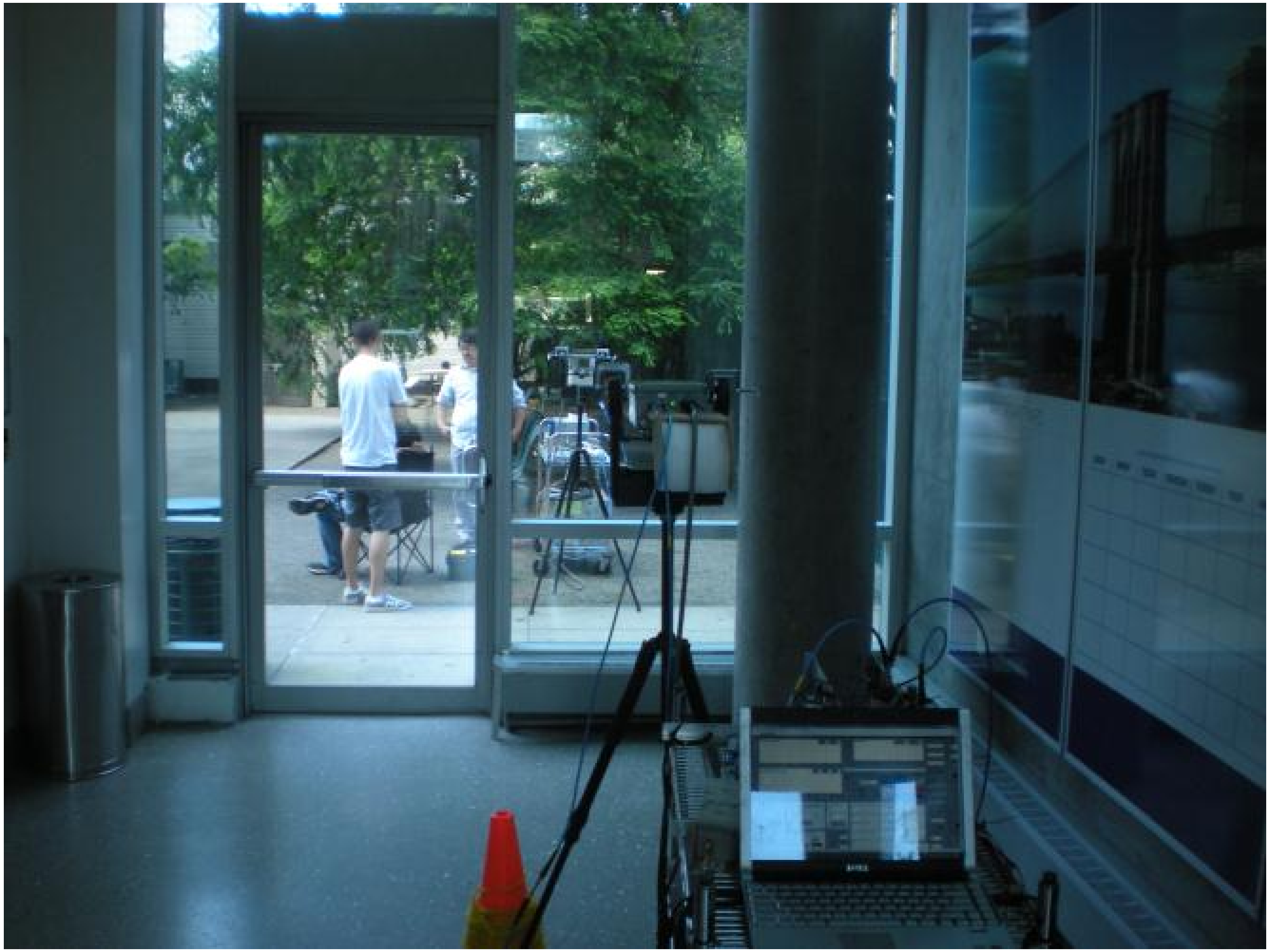
3-Dimensional view of downtown Manhattan.



Sectorized view of cellular coverage.

Y. Azar, G. N. Wong, T. S. Rappaport, *et al*, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," submitted to IEEE International Conference on Communications (ICC), June 9–13 2013.

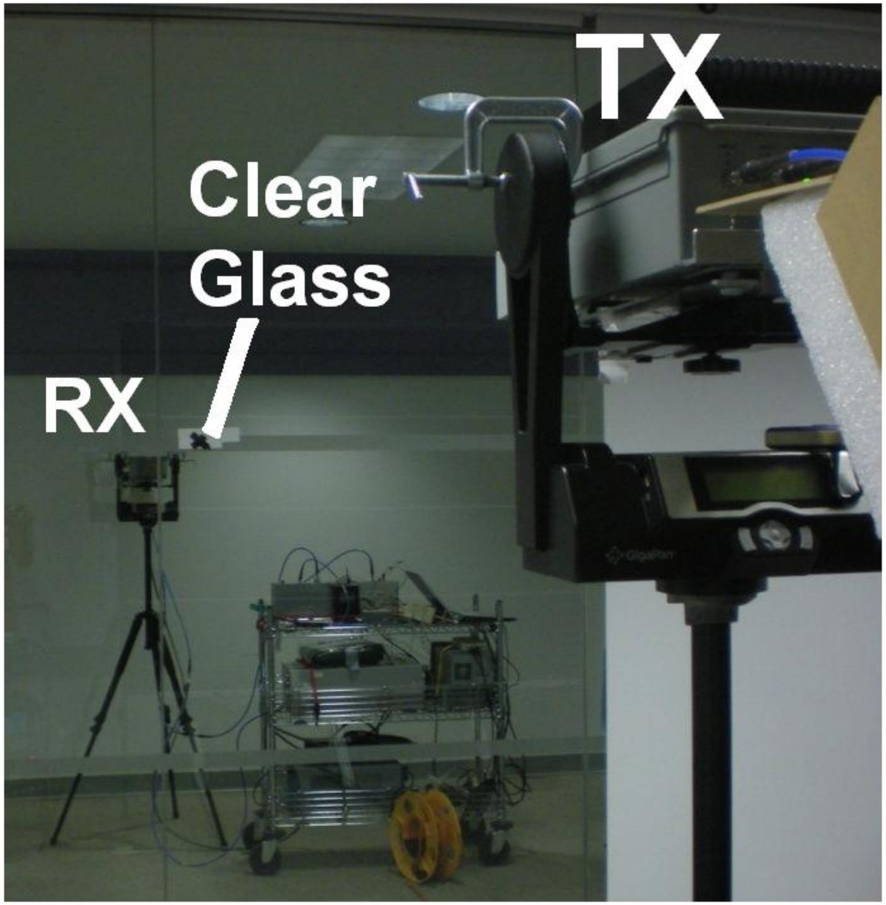
Reflection and Penetration Measurements

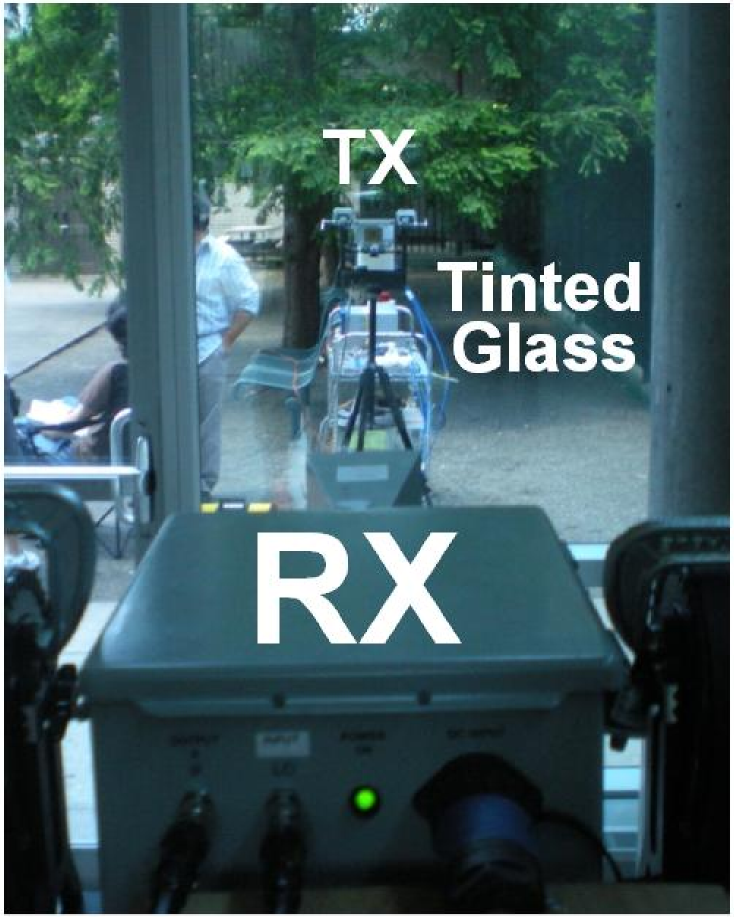


Channel Sounder Equipment–Reflection

Photographs for reflection measurements

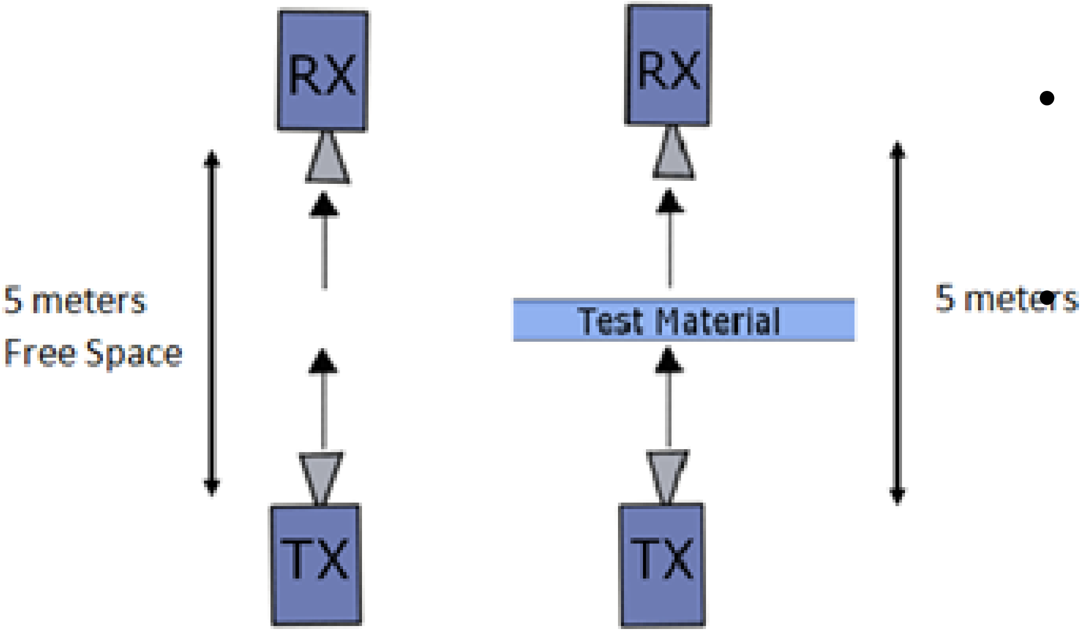
Channel Sounder Equipment–Penetration





Photographs for penetration loss measurements.

Channel Sounder Equipment– Penetration



Setup for penetration loss measurements.

- TX-RX separation distance: 5m
  - Free space
  - Test Material
- TX and RX horn antennas:
  - 24.5 dBi gains
  - 10° half power beamwidth
  - 1.5 m heights

Penetration Loss Equation

- Penetration Loss:

$$P_R = P_T + G_T + G_R - 20log_{10}(\frac{4\pi d_o}{\lambda})$$

P_R: Received power

P_T: Transmitted power

[P_T values used: -8.55 dBm, +11.63 dBm and +21.37 dBm]

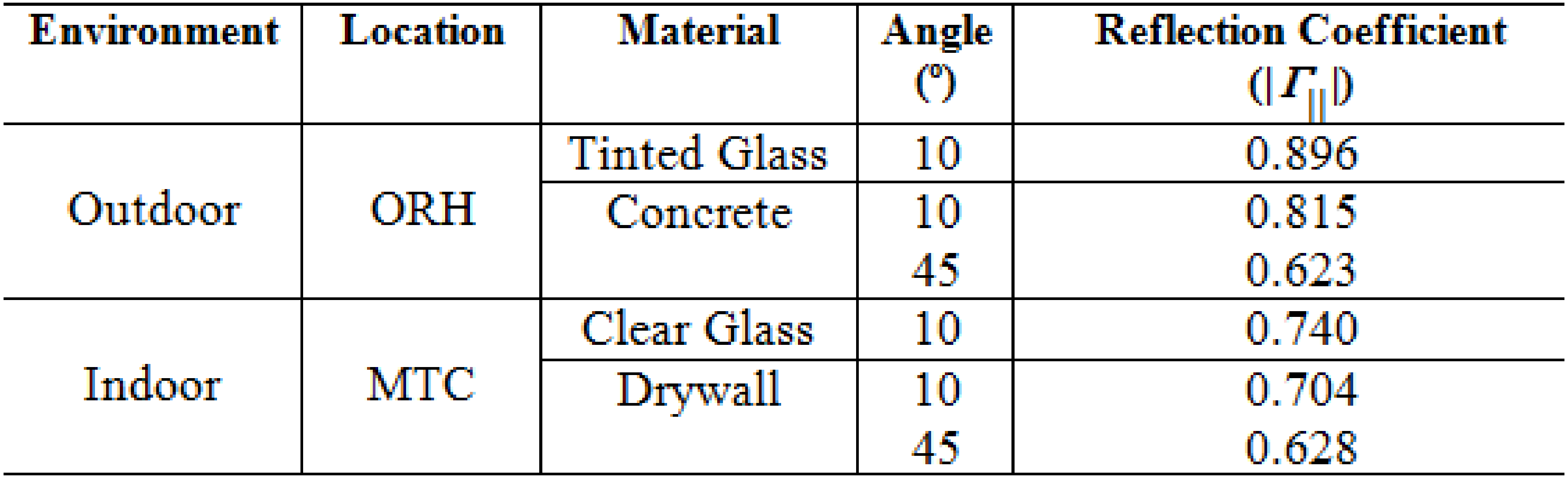
G_T, G_R: Transmitter and receiver antenna gains (24.5 dBi each)

λ : Wavelength of the carrier wave (10.71 mm at 28 GHz)

d_0: Far field close-in reference distance (5 m)

H. Zhao, R. Mayzus, T. S. Rappaport, *et al*, "28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City," submitted to IEEE International Conference on Communications (ICC), June 9–13 2013

Reflectivity of Materials at 28 GHz

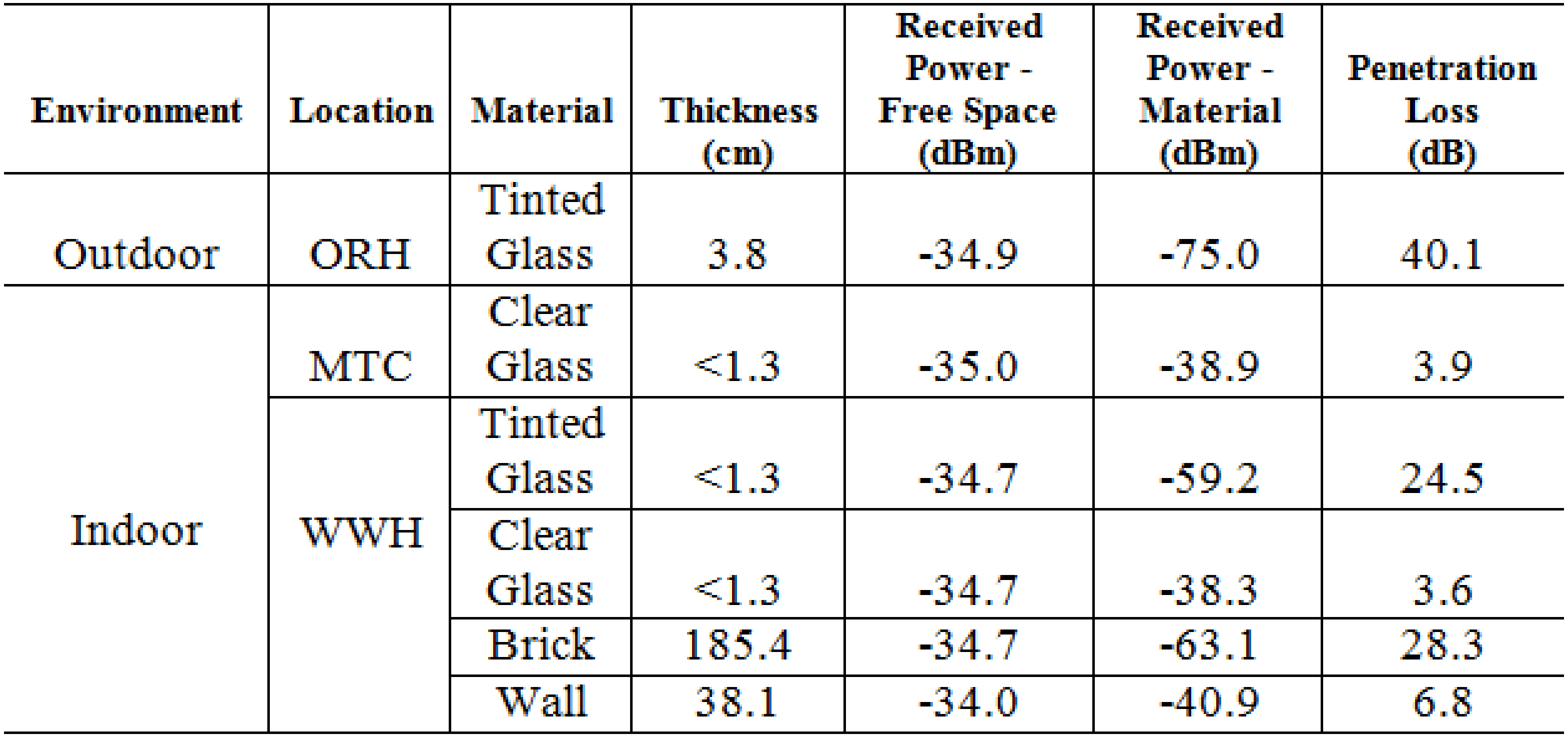


Environment	Location	Material	Angle (°)	Reflection Coefficient ($|\Gamma_{\|}|$)
Outdoor	ORH	Tinted Glass	10	0.896
		Concrete	10	0.815
			45	0.623
Indoor	MTC	Clear Glass	10	0.740
		Drywall	10	0.704
			45	0.628

Reflectivity for different common building materials.

H. Zhao, R. Mayzus, T. S. Rappaport, *et al*, “28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City,” submitted to IEEE International Conference on Communications (ICC), June 9–13 2013

Penetration Loss of Materials at 28 GHz



Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
	WWH	Tinted Glass	<1.3	-34.7	-59.2	24.5
		Clear Glass	<1.3	-34.7	-38.3	3.6
		Brick	185.4	-34.7	-63.1	28.3
		Wall	38.1	-34.0	-40.9	6.8

Penetration loss for different common building materials.

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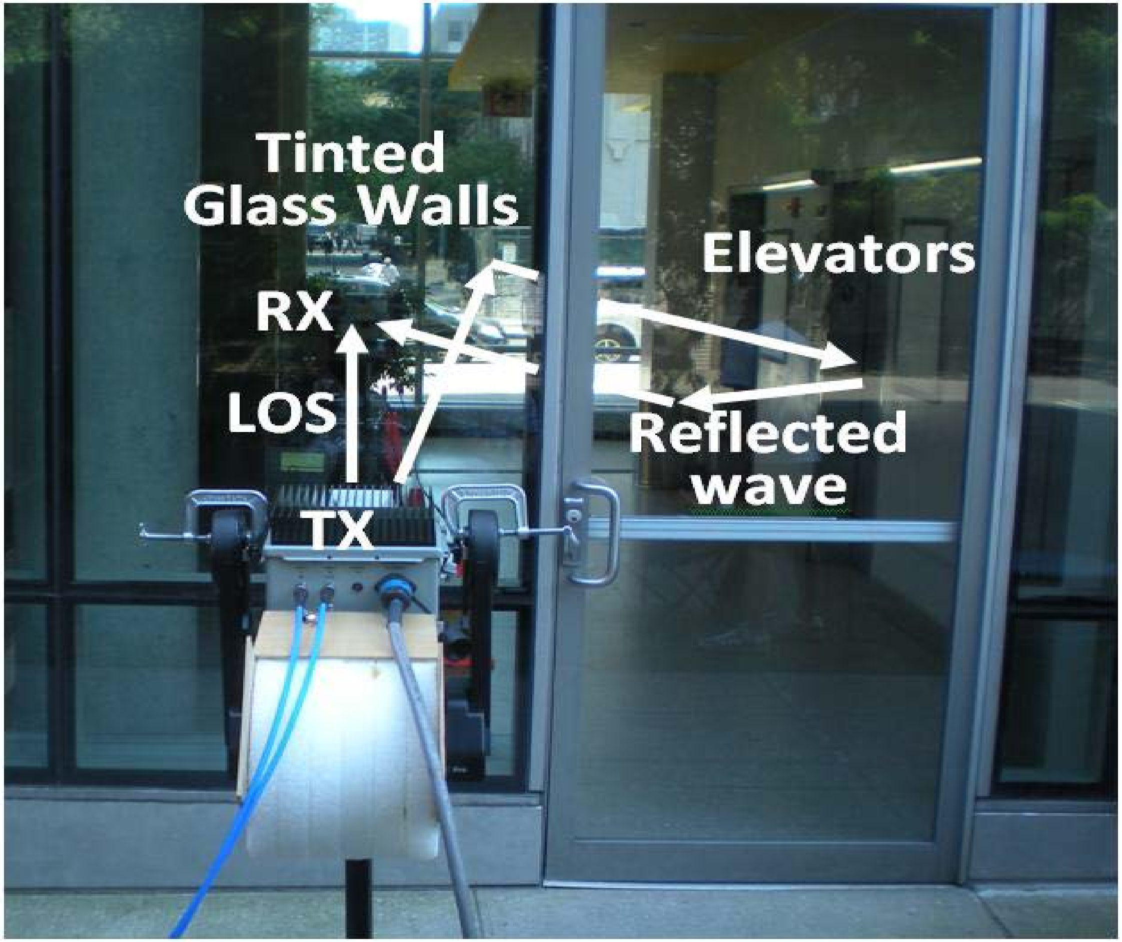
In-Building Reflections @ ORH

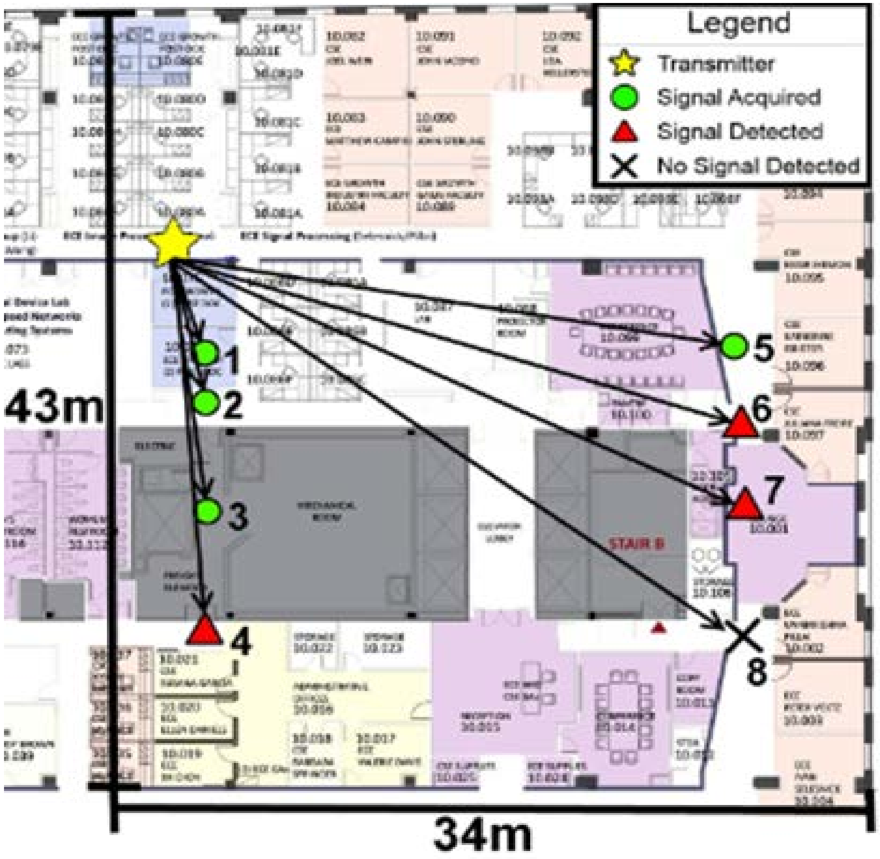


Possible in-building reflection paths.

- Possible reflector after wave penetration:
  - Elevator (metallic)

H. Zhao, R. Mayzus, T. S. Rappaport, *et al*, “28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City,” submitted to IEEE International Conference on Communications (ICC), June 9–13 2013

Indoor Penetration Loss

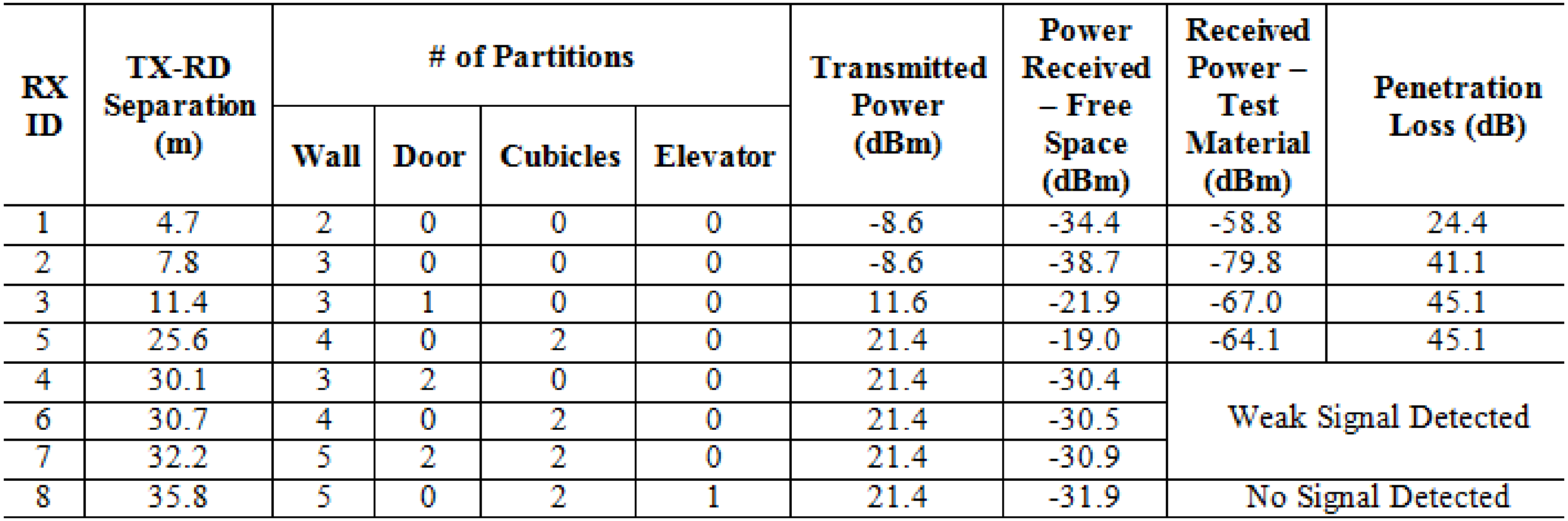


Outage map for penetration loss of multiple obstructions in an office environment.

- Signal acquired
  - SNR sufficiently high for accurate acquisition
  - Penetration loss (relative to a 5 m free space test) : < 64 dB
- Signal detected:
  - SNR is high enough to distinguish signal from noise
  - Penetration loss (relative to a 5 m free space test): between 64 and 74 dB
- No signal detected:
  - Outage
  - Penetration loss (relative to a 5 m free space test): >74 dB

H. Zhao, R. Mayzus, T. S. Rappaport, *et al*, "28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City," submitted to IEEE International Conference on Communications (ICC), June 9–13 2013

Penetration Loss of Multiple Obstructions at 28 GHz



RX ID	TX-RD Separation (m)	# of Partitions				Transmitted Power (dBm)	Power Received – Free Space (dBm)	Received Power – Test Material (dBm)	Penetration Loss (dB)
		Wall	Door	Cubicles	Elevator				
1	4.7	2	0	0	0	-8.6	-34.4	-58.8	24.4
2	7.8	3	0	0	0	-8.6	-38.7	-79.8	41.1
3	11.4	3	1	0	0	11.6	-21.9	-67.0	45.1
5	25.6	4	0	2	0	21.4	-19.0	-64.1	45.1
4	30.1	3	2	0	0	21.4	-30.4	Weak Signal Detected	
6	30.7	4	0	2	0	21.4	-30.5		
7	32.2	5	2	2	0	21.4	-30.9		
8	35.8	5	0	2	1	21.4	-31.9	No Signal Detected	

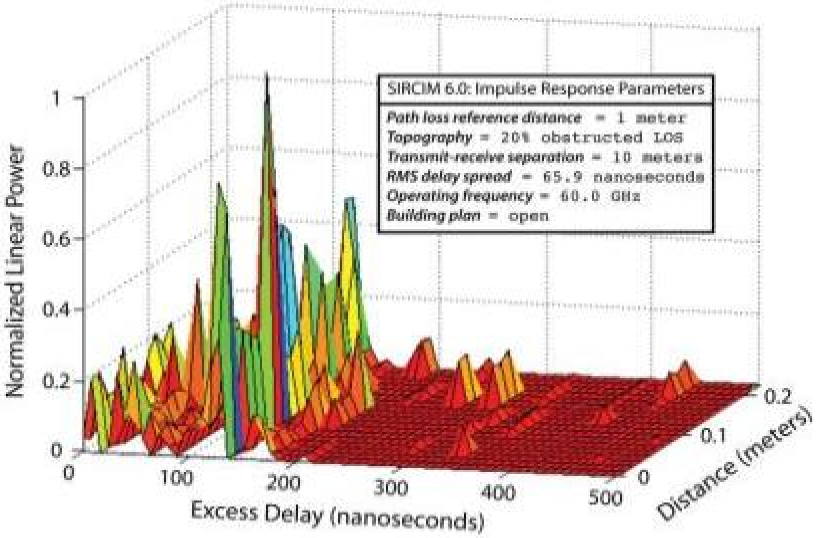
Penetration loss for multiple obstructions in an office environment.

H. Zhao, R. Mayzus, T. S. Rappaport, *et al*, “28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City,” submitted to IEEE International Conference on Communications (ICC), June 9–13 2013

Key Requirement: Channel Simulation Software for Modems

- Based roughly on the previously-developed “Simulation of Indoor Radio Channel Impulse-Response Models” a.k.a. “SIRCIM” program

- Make use of experimentally calculated statistics to simulate the effect a channel might have on a broadcasted signal



SIRCIM 6.0: Impulse Response Parameters

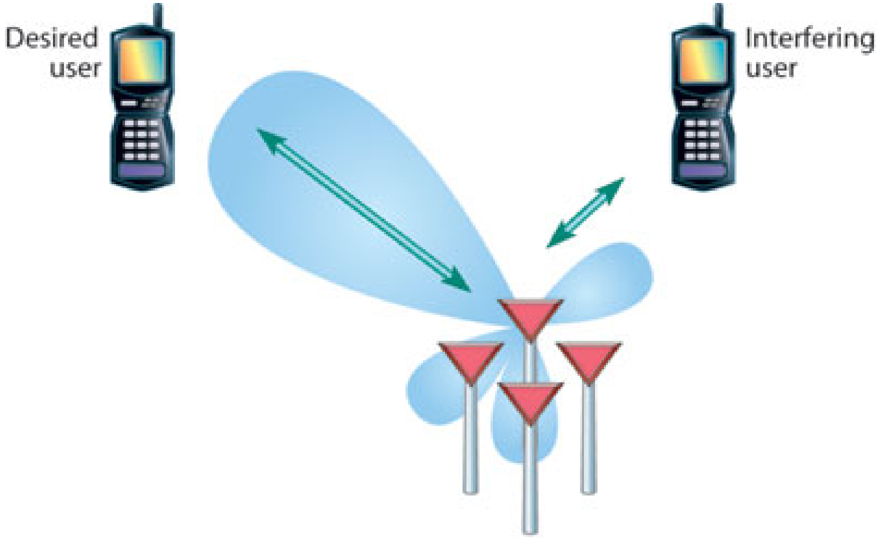
Path loss reference distance = 1 meter
Topography = 20% obstructed LOS
Transmit-receive separation = 10 meters
RMS delay spread = 65.9 nanoseconds
Operating frequency = 60.0 GHz
Building plan = open

- Criteria such as environment (LOS / NLOS), transmitter-receiver separation, precipitation, angle of arrival (AOA), angle of departure (AOD) used to specify type of channel to model

- Simulate delay spread / power delay profile, small scale fading, etc.

Concepts and Applications of Beamforming

Beamforming or spatial filtering, is the method of creating the radiation pattern of the antenna array by adding constructively the phase of the signals in the direction of the targets/mobiles desired, and nulling the pattern of the targets/mobiles that are undesired.



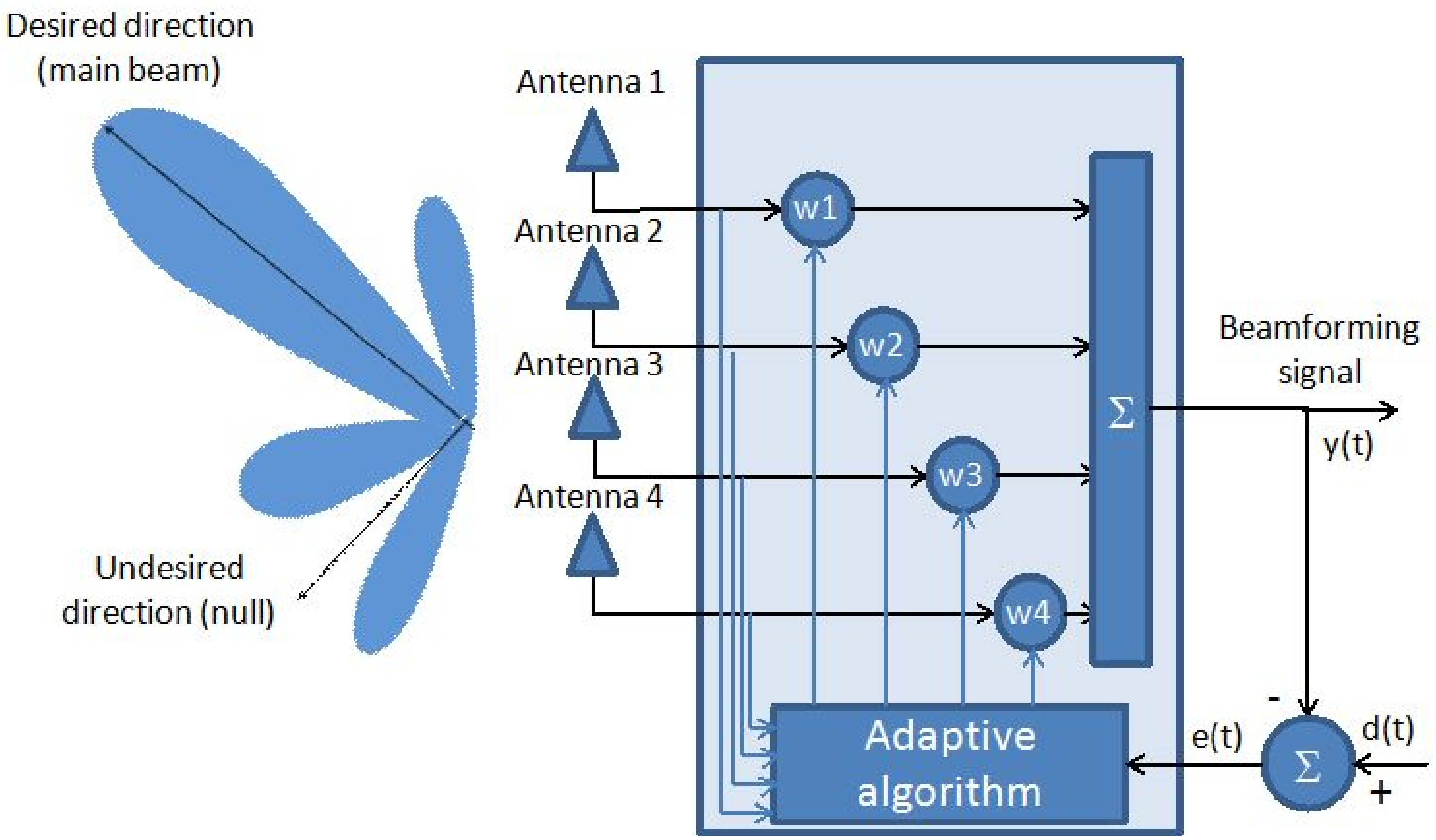
5G can exploit smart antenna systems, with more focus being placed on pointing in the direction of maximum signal levels using multiple beams (for simplicity, first ignore interference)

Beamforming history in cellular standards

- Passive mode: (almost) non-standardized solutions
  - Wideband Code Division Multiple Access (WCDMA) supports direction of arrival (DOA) based beamforming

- Active mode: mandatory standardized solutions
  - 2G — Transmit antenna selection as an elementary beamforming
  - 3G — WCDMA: Transmit antenna array (TxAA) beamforming
  - 4G evolution — LTE/UMB: MIMO precoding based beamforming with partial Space-Division Multiple Access (SDMA)
  - Beyond 3G (4G, 5G, …) — More advanced beamforming solutions to support SDMA such as closed loop beamforming and multi-dimensional beamforming are expected

Beamforming Architecture



Possibility of performing beamforming and beam-combining

The PDP in the figure to the right shows the type of diversity of multipath at 28 GHz, where strong RF energy may be received and combined to improve link budget and MIMO capacity.

A different pointing angle at the same RX location yields a completely different channel PDP. There is rich diversity in the different beams, themselves, and from beam to beam.

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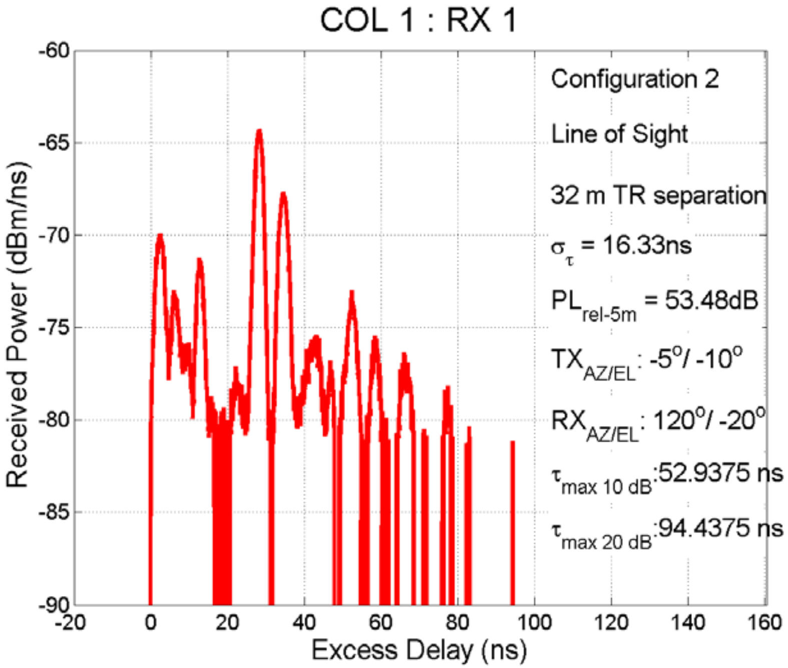


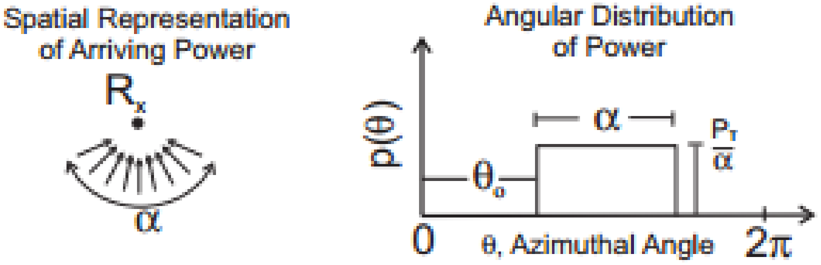
Measured Power Delay Profiles (PDPs) at 28 GHz for a LOS cellular channel in New York City using steerable beam 24.5 dBi antennas with 32 meter distance separation between transmitter and receiver

Requirement: Adaptive Algorithms for Beamforming

- Non-blind adaptive algorithms
- Wiener Solution
- Steepest-Descent Method
- Least-Mean-Squares Algorithm
- Recursive Least-Squares Algorithm
- Blind Adaptive Algorithms
- Algorithms based on estimation of DOAs of received signals (MUSIC, ESPRIT)
- Constant Modulus Algorithm (CMA) (including Steepest-Descent CMA and Least-Squares CMA)
- Marquardt Method

Multipath shape factor theory

- We are exploring the multipath shape factor theory (by Durgin) to find the pointing angles of multipath using very low overhead CW pilots received at multiple elements of an adaptive array



Angular distribution of power, p(θ), for a sector of arriving multipath components

The multipath shape factor theory showed that the cross correlation of narrowband fading across an antenna manifold can accurately predict both the physical direction and the angular spread of multipath

G.D. Durgin and T.S. Rappaport, "Effects of Multipath Angular Spread on the Spatial Cross Correlation of Received Envelope Voltages," in *IEEE Vehicular Technology Conference*, vol. 2, 1999, pp. 996-1000. Also see subsequent journal papers.

28 GHz conclusion (1)

- ✓ Small-scale fading measurements along a track (limited number)
  - ❖ Movement along a small-scale track does not induce much fading.
    - Power received has only 4 dB/ns variance, maximum of 12 ns excess delay variation
    - AOA does not change along a 107 mm track (10λ)
- ✓ Path Loss Exponent (NLOS conditions)
  - ❖ Overall: n = 5.76
  - ❖ Strongest power received angles only: n=4.58
  - ❖ Cross Polarization diversity may allow independent signals
- ✓ Link distributions (more data to come this month)
  - ❖ AOA link: Sinusoidal
  - ❖ AOD link: Gaussian
- ✓ Signal outage: Maximum radial cell size for urban environment is ~ 200m

28 GHz Conclusion (2)

- ✓ Outdoor building materials
  - ❖ Excellent reflectors
    - Largest reflection coefficient: 0.896 (tinted glass)
  - ❖ Highly attenuation from inside to outside of buildings
    - Largest penetration loss: 40.1 dB (tinted glass)
- ✓ Indoor building materials
  - ❖ Less attenuation / Less reflective
    - Penetration Loss: 3.6 dB – clear glass; 6.8 dB – drywall
    - Reflection Coefficient: 0.62 – clear glass; 0.74 – drywall
- ✓ Penetration loss for multiple obstructions
  - ❖ Material dependent
  - ❖ Distance dependent

RECENT JOURNAL PAPERS:

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- NEW TEXTBOOK: **Millimeter Wave Wireless Communications,** Pearson Prentice Hall, coming this summer! Rappaport, Heath, Daniels, Murdock.