# Millimeter Wave Cellular Communications:

## Channel Models, Capacity Limits, Challenges and Opportunities

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and many, many dedicated students

May 26, 2014
IEEE Comm. Theory Workshop, Curacao



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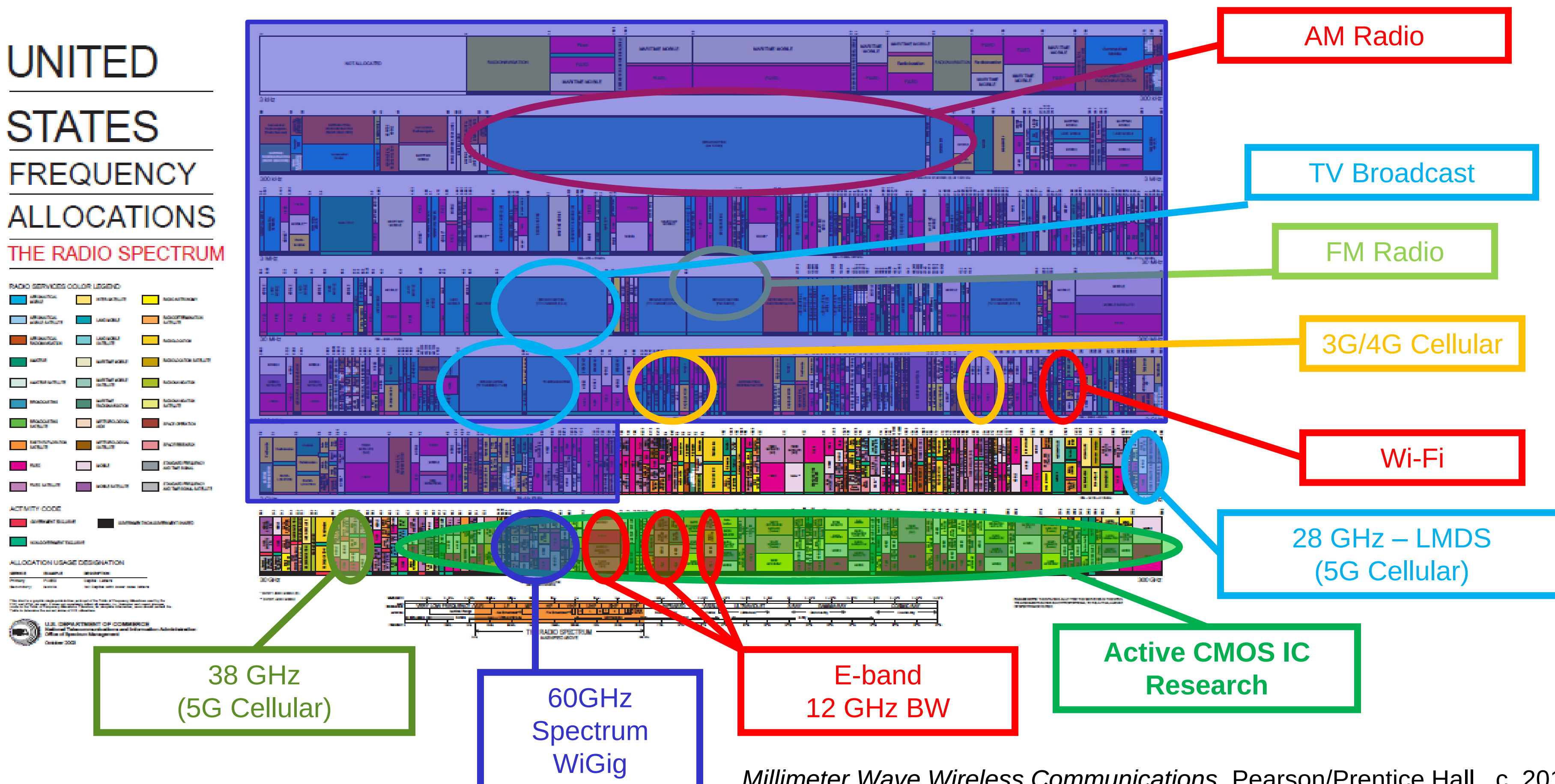
# Wireless Spectrum




*Millimeter Wave Wireless Communications*, Pearson/Prentice Hall, c. 2015

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# Early Work in Directional Channels



**Wideband Measurements of Angle and Delay Dispersion for Outdoor and Indoor Peer-to-Peer Radio Channels at 1920 MHz**

Durgin, et. al., IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 5, **MAY 2003**

**Spatial and temporal characteristics of 60-GHz indoor channels**

Xu, et. al., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL.. 20, NO. 3, **APRIL 2002**

.

1) Multipath Shape Factor Theory found new parameters to describe directional channels

2) RMS delay spreads and interference shrink dramatically for small cell **directional antennas**

.

4) A distinct trend shows how **angular spread increases as delay spread increases**.

5) **Multipath power is arriving from several discrete directions in azimuth** instead of across a smooth continuum of azimuthal angles in NLOS channels.

6) **What are the channel behaviors for outdoor, indoor, urban across mmWave bands?**



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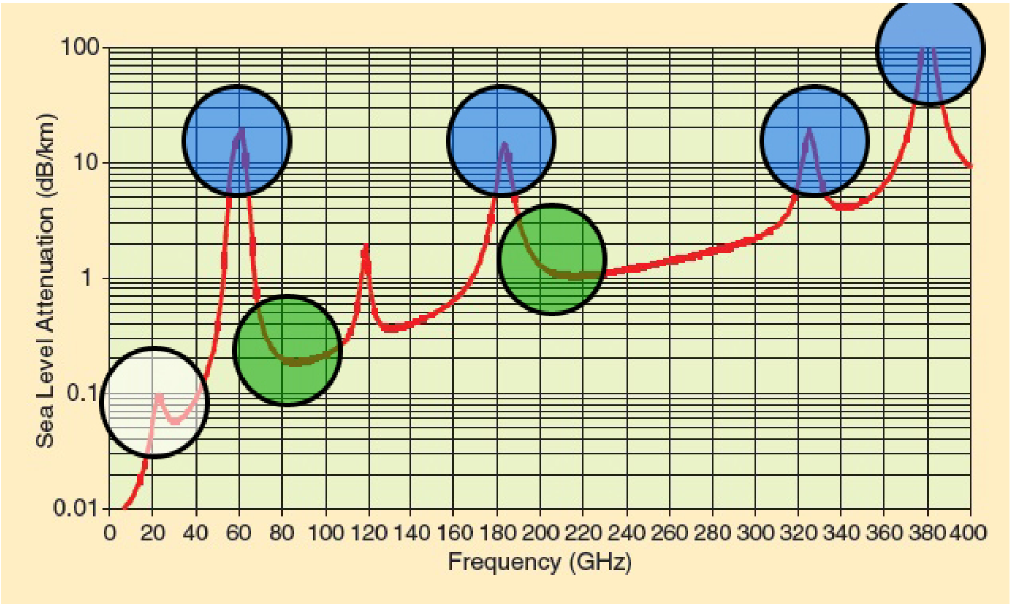
# Background – Atmospheric Attenuation




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.

- 0.012 dB over 200 m at 28 GHz
- 0.016 dB over 200 m at 38 GHz
- 4.000 dB over 200 m at 60 GHz
- 0.060 dB over 200 m at 73 GHz
- White
  - Very low air attenuation at 28 and 38 GHz
- Blue
  - Ultra-short-range indoor communications, "whisper" communications of the future
    - High Attenuation
- Green
  - Future backhaul and mobile at E-band
    - Low atmospheric attenuation
    - Multi-GHz bandwidth at 28, 39, 70 GHz
    - Directional antenna arrays with beamsteering and beam-combining
    - CMOS: cost-effective with high frequency limits



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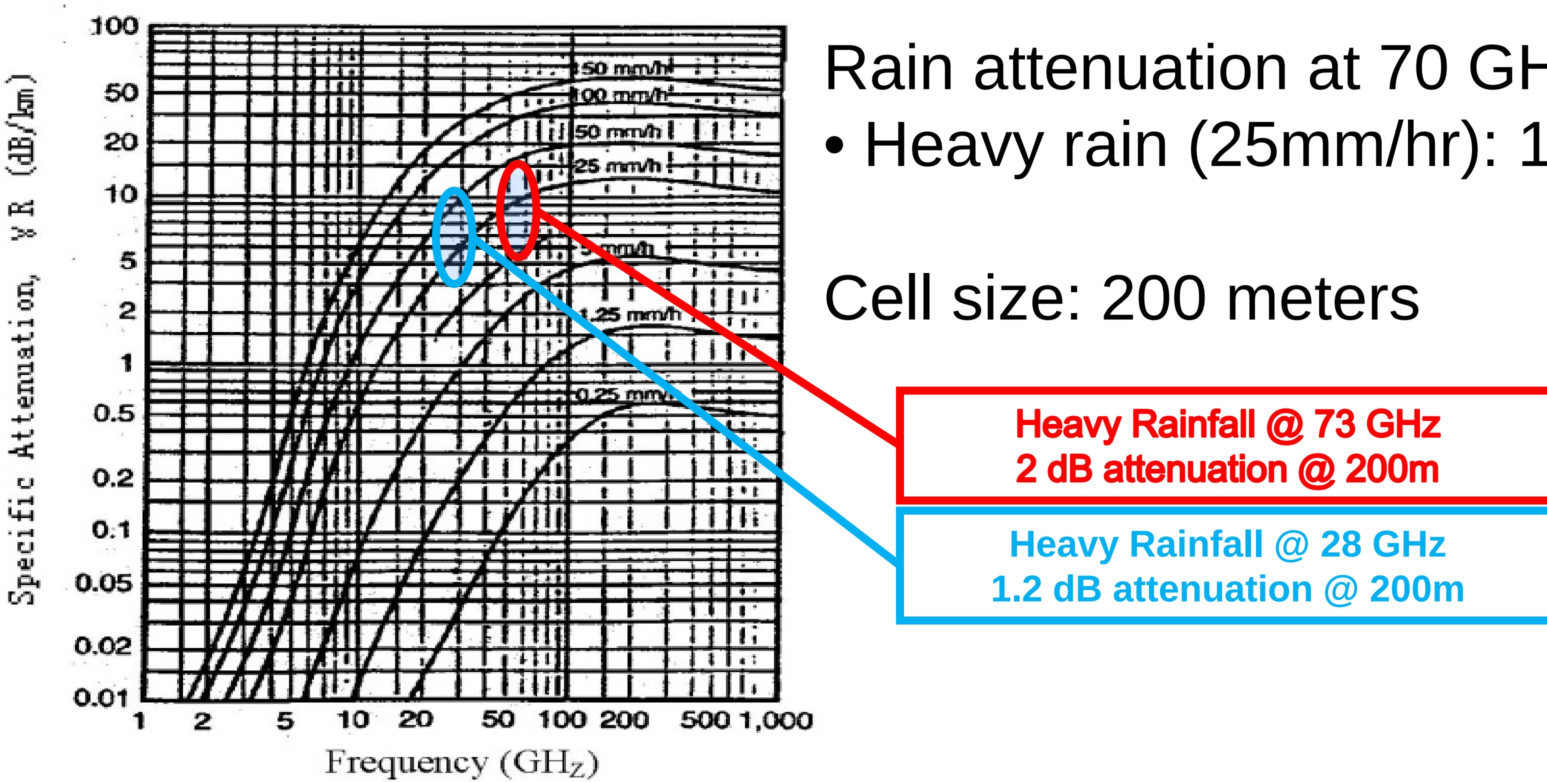
# Background – Rain Attenuation




Rain attenuation at 70 GHz

- Heavy rain (25mm/hr): 10 dB/km

Cell size: 200 meters

Q. Zhao; J. Li; "Rain Attenuation in Millimeter Wave Ranges," International Symposium on Antennas, Propagation, & EM Theory, Oct 26-29, 2006.

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# Key Challenge: Range



- Friis' Law: $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$
  - Free-space channel gain $\propto \lambda^2$, but antenna gains $\propto 1/\lambda^2$
  - For fixed physical size antennas in free space, frequency does not matter!
  - In principle, path loss can be overcome with beamforming, independent of frequency .
- Shadowing: Significant transmission losses possible:
  - Brick, concrete > 35 dB
  - Human body: Up to 35 dB
  - But channel is rich in scattering and reflection, even from people
- It works! NLOS propagation uses reflections and scattering

Rappaport, et. al, "Millimeter wave mobile communications for 5G cellular: It will work!" IEEE Access, 2013



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# 28 GHz Sliding Correlator Channel Sounder Specifications

| Description | Value |
|---|---|
| Carrier Frequency | 28 GHz |
| Sequence | $11^{th}$ order PN Code (Length = 2047) |
| Transmitted Chip Rate | 400 MHz |
| Receiver Chip Rate | 399.95 MHz |
| First null-to-null RF bandwidth | 800 MHz |
| Slide Factor | 8000 |
| System Measurement Range | 178 dB |
| Maximum TX Power | 30 dBm |
| TX/RX Antenna Gain | 24.5 dBi, 15 dBi |
| TX/RX Azimuth and Elevation HPBW | 10.9° /8.6° , 28.8° /30° |
| TX-RX Synchronization | Unsupported |

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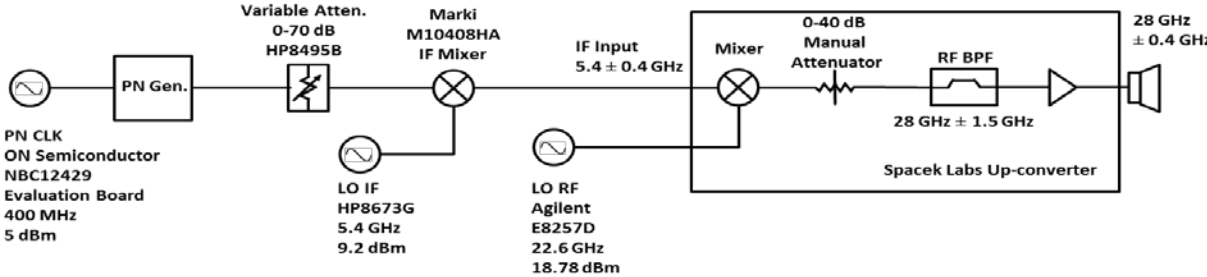
# 28 GHz Channel Sounder Block Diagrams

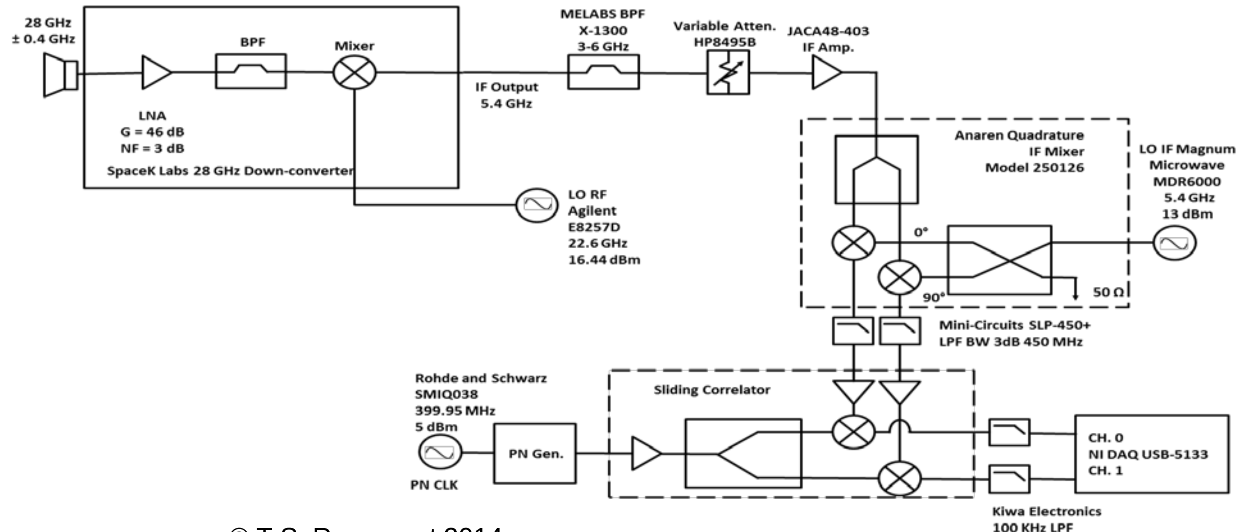





Transmitted Signal →

**Transmitter**

Received Signal →




**Receiver**

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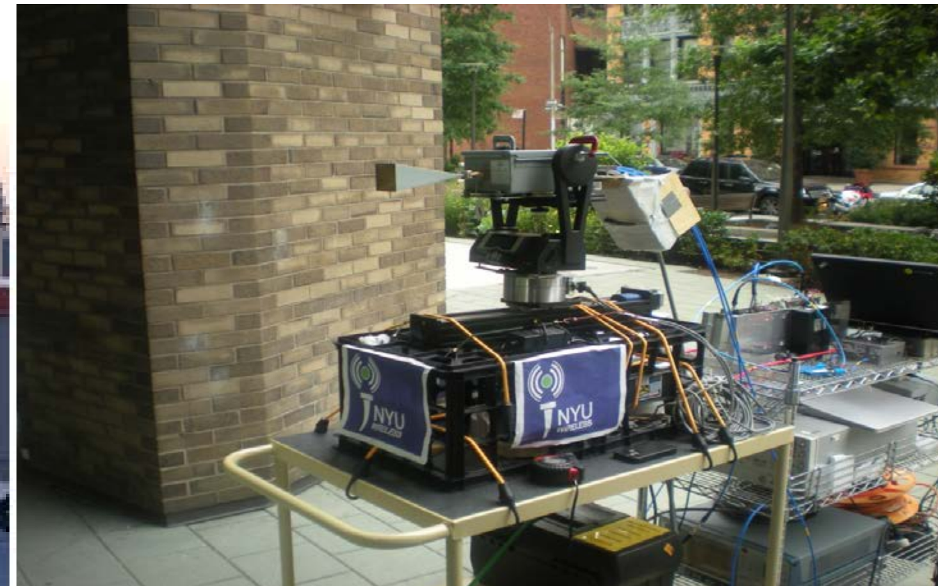
# 28 GHz Channel Sounder



TX Hardware




RX Hardware

Y. Azar, G. N. Wong, K. Wang, R. Mayzus, J. K. Schulz, H. Zhao, F. Gutierrez, D. Hwang, T. S. Rappaport, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City," *2013 IEEE International Conference on Communications (ICC)*, June 9-13, 2013.



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# 28 GHz Measurement Environment – Dense Urban NYC

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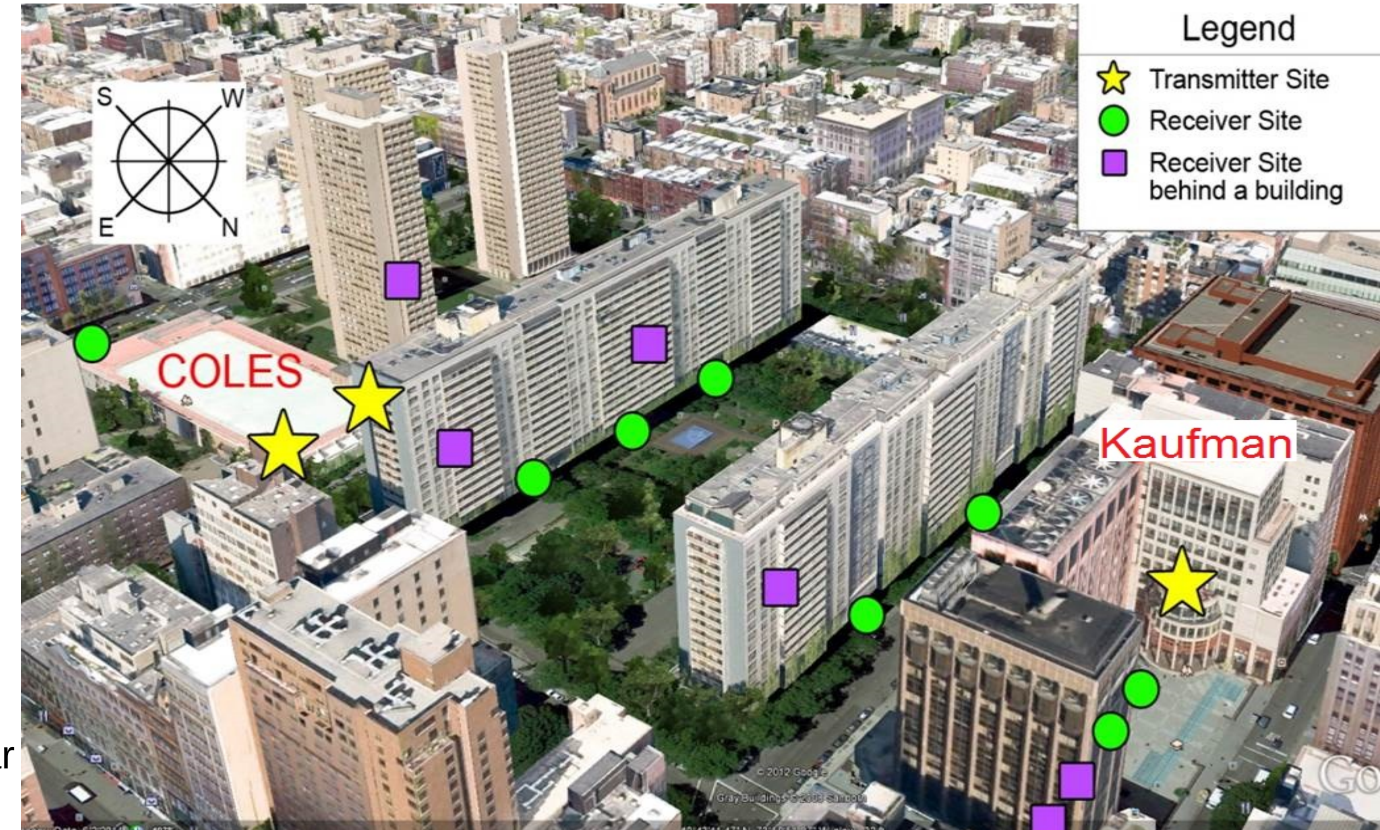
NYU WIRELESS

- 4 TX sites
- 33 RX sites (35 w/ LOS)

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

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-ROG – 40 m

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

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# 73 GHz Channel Sounder



| | |
|---|---|
| **Measurement Campaign** | 73 GHz |
| **Carrier Frequency** | 73.5 GHz |
| **RF Null-to-Null Bandwidth** | 800 MHz |
| **TX PN Code Chip Rate** | 11th order PN Code (Length = 2047 chips) |
| **Transmit Sequence** | 2047 chips |
| **TX PN Code Chip Rate** | 400 Mcps |
| **RX PN Code Chip Rate** | 399.95 Mcps |
| **Slide Factor** $\gamma$ | 8000 |
| **TX Power** | 14.6 dBm |
| **EIRP** | 41.6 dBm |
| **RX Antenna** | 27 dBi<br>$7^\circ$ half-power beamwidth<br>Vertically Polarized |
| **TX Antenna** | 27 dBi<br>$7^\circ$ half-power beamwidth<br>Vertically Polarized |
| **Maximum Measurable Path Loss (5 dB SNR)** | 181 dB |
| **Multipath Time Resolution** | 2.5 ns |

*Note: 20 dBi horn antenna on upconverter



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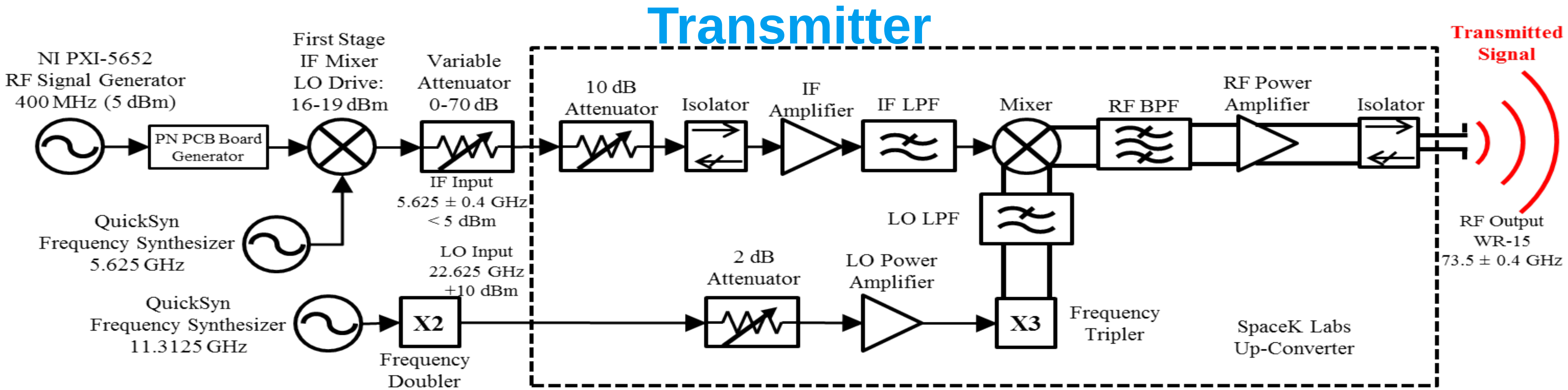
# 73 GHz Channel Sounder




- 400 Mega-chip-per-second (Mcps)
- 27 dBi (7° BW) horn antenna
- 14.6 dBm TX RF output
- LabVIEW-controlled gimbal (azimuth/elevation)

S. Nie, G. R. MacCartney, S. Sun, and T. S. Rappaport, “72 GHz millimeter wave indoor measurements for wireless and backhaul communications,” in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on*, Sept 2013, pp. 2429–2433.



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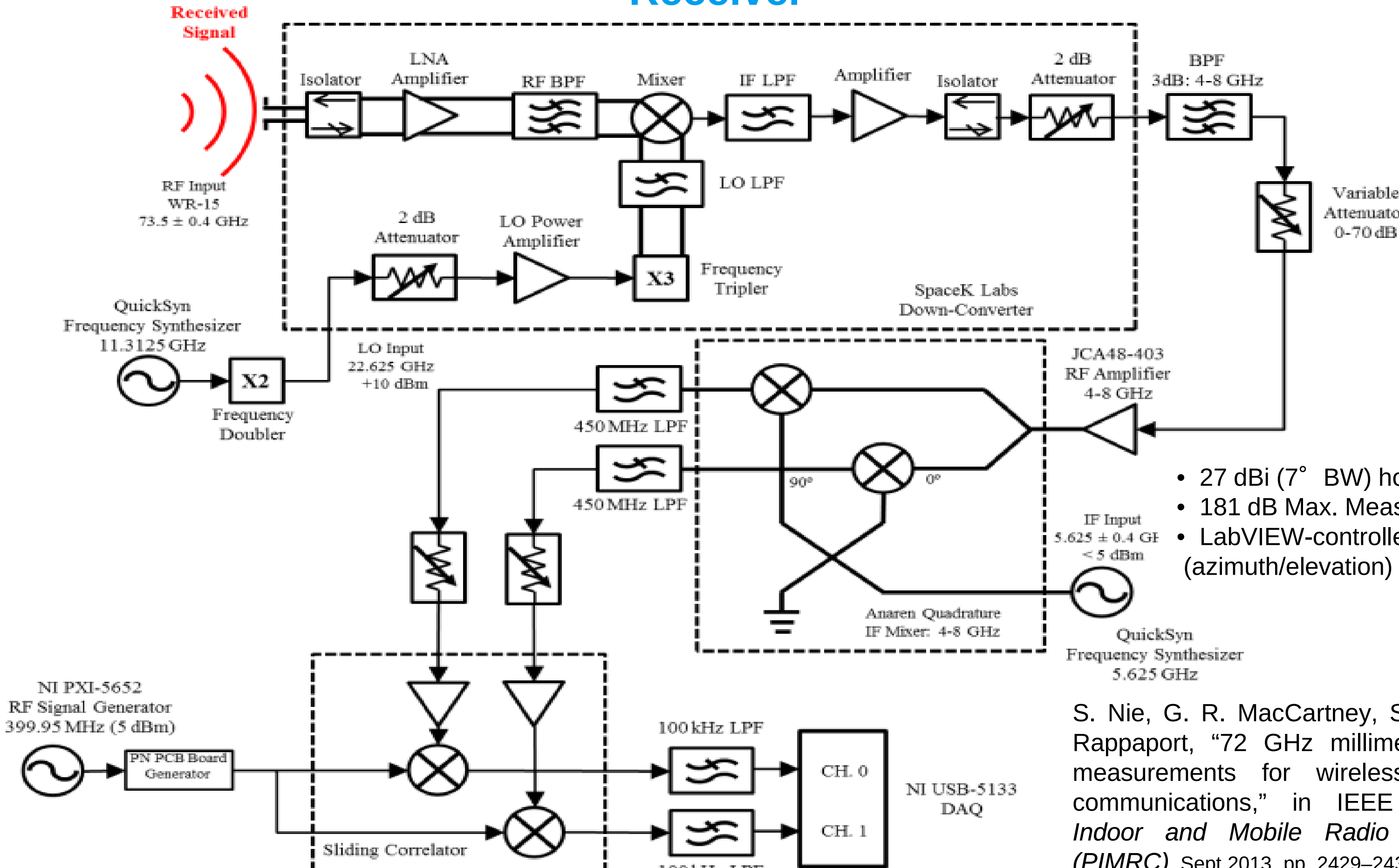
# 73 GHz Channel Sounder

## Receiver




- 27 dBi (7° BW) horn antenna
- 181 dB Max. Measurable Path Loss
- LabVIEW-controlled gimbal (azimuth/elevation)


S. Nie, G. R. MacCartney, S. Sun, and T. S. Rappaport, "72 GHz millimeter wave indoor measurements for wireless and backhaul communications," in IEEE 2013 *Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept 2013, pp. 2429–2433.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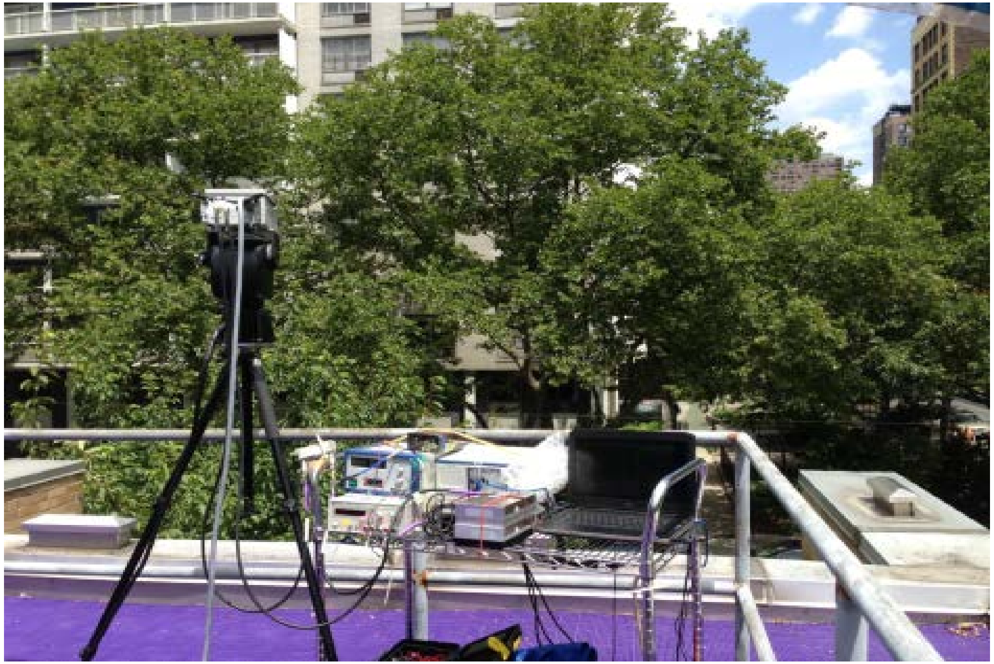
# 73 GHz Channel Sounder





TX Hardware

RX Hardware



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# NYC Measurements – Dense Urban Mobile and Backhaul at 73 GHz

- 5 TX sites
- 27 RX sites

- 74 total TX-RX combinations tested
    - 36 BS to MS
    - 38 BS to BS (backhaul).

- 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


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# Summary of Measurement Locations in NYC



## 28 GHz Campaign in Manhattan for 200 m cell (2012)

| TX Location | TX Height (meters) | Number of RX Locations | RX Height (meters) |
|---|---|---|---|
| COL1 | 7 | 10 | 1.5 |
| COL2 | 7 | 10 | |
| KAU | 17 | 15 | |

## 73 GHz Campaign in Manhattan for 200 m cell (2013)

| TX Location | TX Height (meters) | Number of RX Locations (Cellular) | RX Height (Cellular) (meters) | Number of RX Locations (Backhaul) | RX Height (backhaul) (meters) |
|---|---|---|---|---|---|
| **COL1** | 7 | 11 | 2 | 7 | 4.06 |
| **COL2** | 7 | 9 | | 14 | |
| **KAU** | 17 | 11 | | 11 | |
| **KIM1** | 7 | 3 | | 3 | |
| **KIM2** | 7 | 2 | | 3 | |



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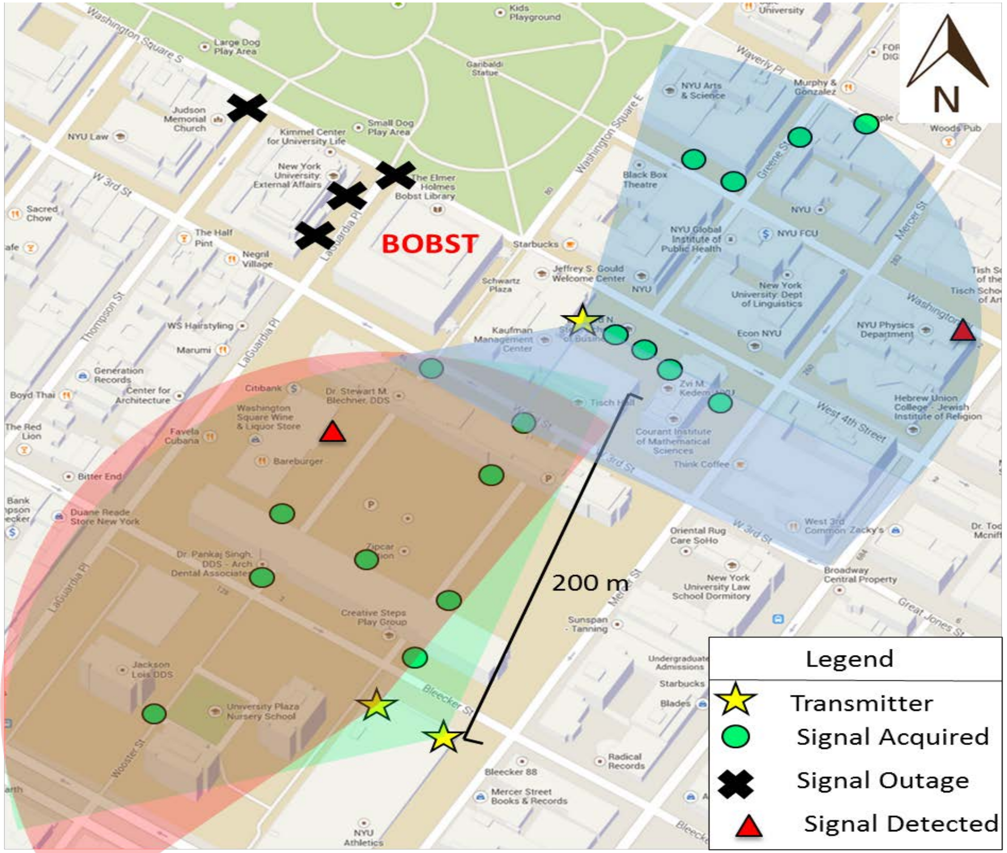
# Signal Outage at 28 GHz in NYC for All Unique Pointing Angles at Each Site

- 75 TX-RX separation distances range from 19 m to 425 m
- Signal acquired up to 200 m TX-RX separation
- 14% of 35 TX-RX location combinations within 200 m are found to be outage
- For outage, path loss > 178 dB (5 dB SNR per multipath sample) for all unique pointing angles

-S. Nui, G. MacCartney, S. Sun, T. S. Rappaport, "28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications," 2014 IEEE Int.. Conf. on Comm. (ICC), Sydney, Australia.

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



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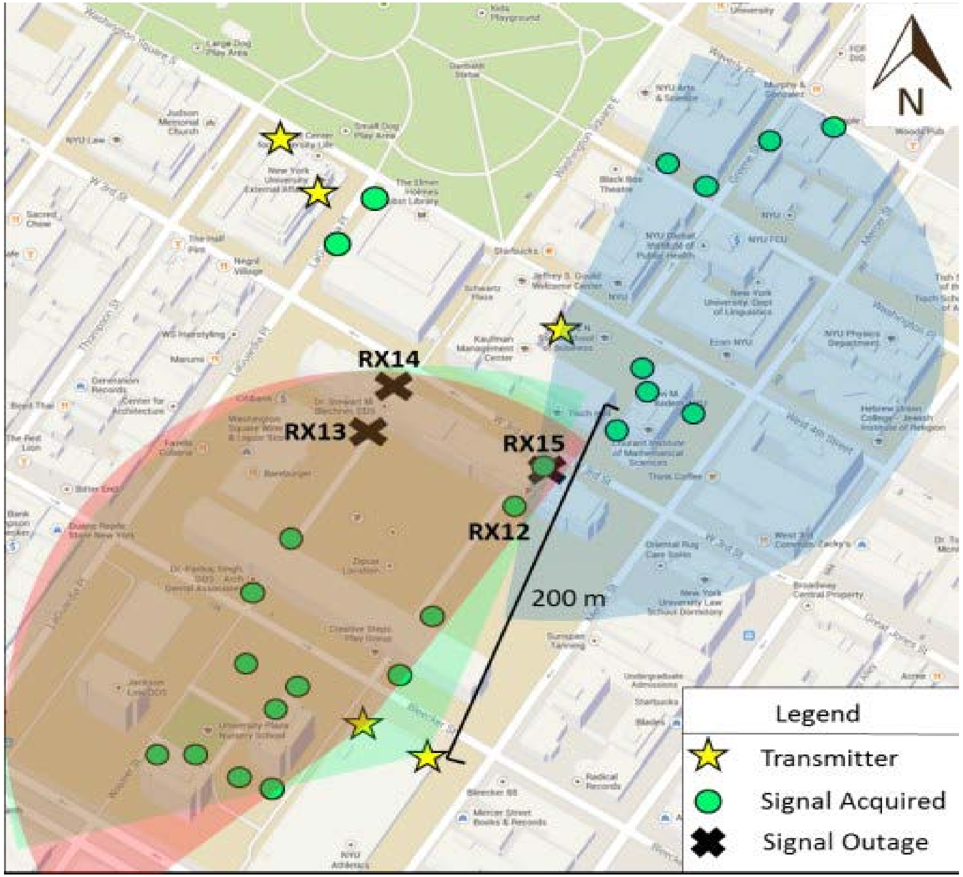
# Signal Outage at 73 GHz in NYC for All Unique Pointing Angles at Each Site

- 74 TX-RX separation distance range from 27 m to 216 m
- 17% of 36 TX-RX location combinations were outage in mobile scenario; 16% of 38 TX-RX location combinations found to be outages in backhaul scenario
- For outage, path loss > 181 dB (5 dB SNR per multipath sample) for all unique pointing angles
- Receiver locations chosen based on previous 28 GHz campaign




* Only a limited amount of RX selected for KIM1 and KIM2


S. Nui, G. MacCartney, S. Sun, T. S. Rappaport, "28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications," 2014 IEEE Int.. Conf. on Comm. (ICC), Sydney, Australia.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# Signal Outage (200 m Cell) in NYC using Adaptive Single Beam Antennas



| Transmitter Locations | Transmitter Height (m) | Percentage of Outage for >Max. Measurable Path Loss | | |
|---|---|---|---|---|
| | | 28 GHz | 73 GHz | |
| | | Cellular | Cellular | Backhaul |
| COL1 | 7 | 10%* | 27% | 42% |
| COL2 | 7 | 10% | 33% | 15% |
| KAU | 17 | 20%* | 0% | 0% |
| KIM1 | 7 | N/A | 0% | 0% |
| KIM2 | 7 | N/A | 0% | 0% |
| Overall | | 14% | 17% | 16% |

At 28 GHz in cellular measurements the estimated outage probability is 14% for all RX locations within 200 meters;

At 73 GHz the outage probabilities are 16% and 17% within 216 meters cell size for backhaul and cellular access scenarios, respectively;

Site-specific propagation planning easily predicts outage.

*Published ICC '14 paper erroneously stated 20% and 50% for distances up to 425 m– corrected here.

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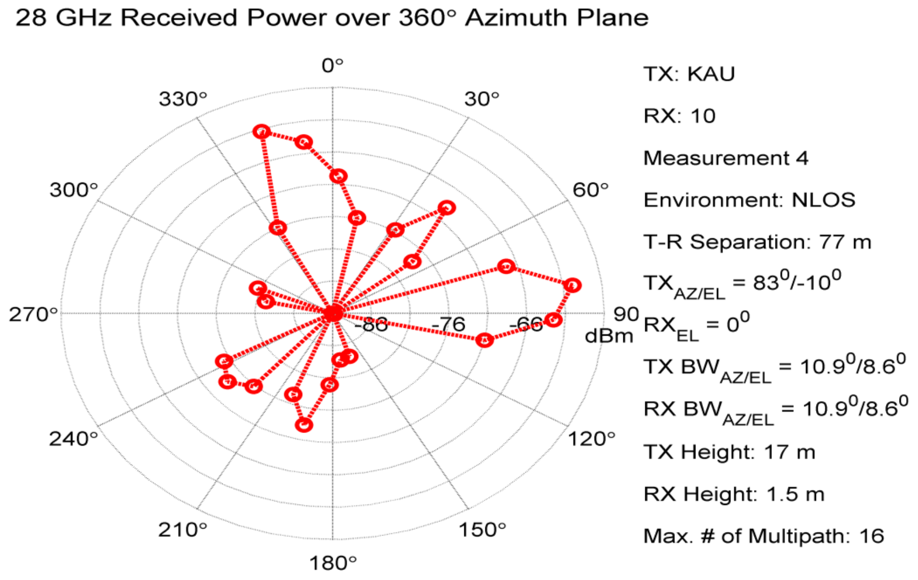
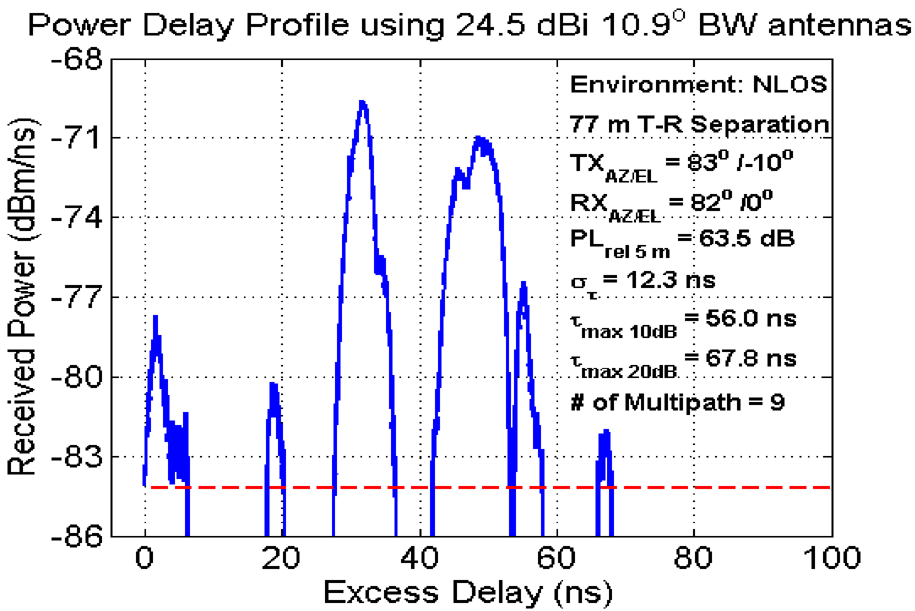
# Typical Measured Polar Plot and PDP at 28 GHz




Signals were received at 23 out of 36 RX azimuth angles (10 degree increments)



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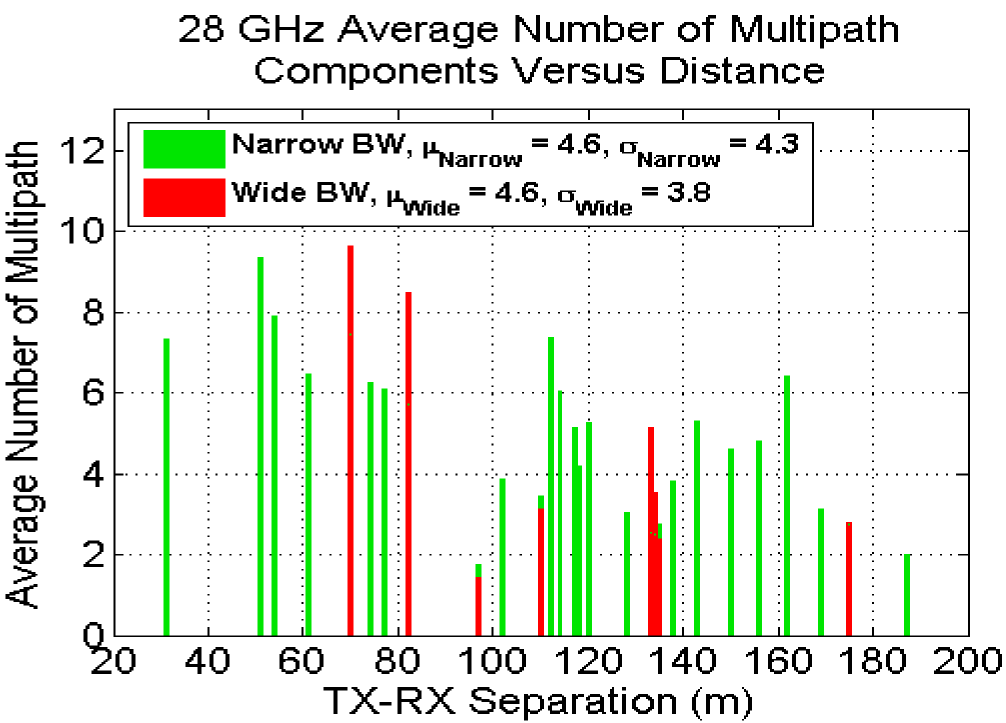
# No. of Multipath Components at 28 GHz for Unique Directional Angle Combinations




Average number of multipath components (MPCs) per distance: First increases and then decreases with the increasing distance

Average number of MPCs per PDP: Nearly identical for both the narrow-beam (10.9-degree HPBW) and wide-beam (28.8-degree HPBW) antenna measured cases

S. Sun, T. S. Rappaport, "Wideband mmWave Channels: Implications for Design and Implementation of Adaptive Beam Antennas ," IEEE 2014 Intl. Microwave Symp. (IMS), June 2014, Tampa Bay.

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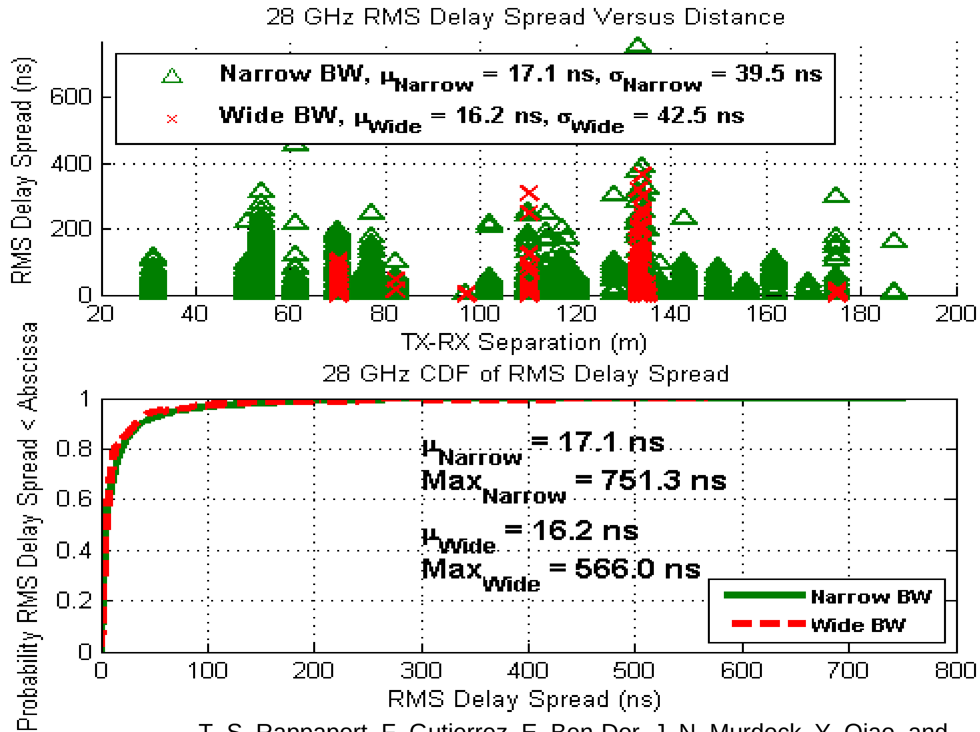
# RMS Delay Spread at 28 GHz

Measured RMS delay spread vs. T-R separation distance:
Smaller RMS delay spreads at larger distances (near 200 m) due to large path loss

CDF of RMS delay spread:
Average and maximum RMS delay spreads are slightly smaller for wide-beam antenna case due to lower antenna gain thus smaller detectable path loss range

Average RMS delay spread values are only slightly larger than those for 38 GHz in suburban environments




T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao, and J. I. Tamir, "Broadband millimeter wave propagation measurements and models using adaptive beam antennas for outdoor urban cellular communications," *IEEE Trans. Antennas Prop.*, vol. 61, no. 4, pp. 1850-1859, Apr. 2013.



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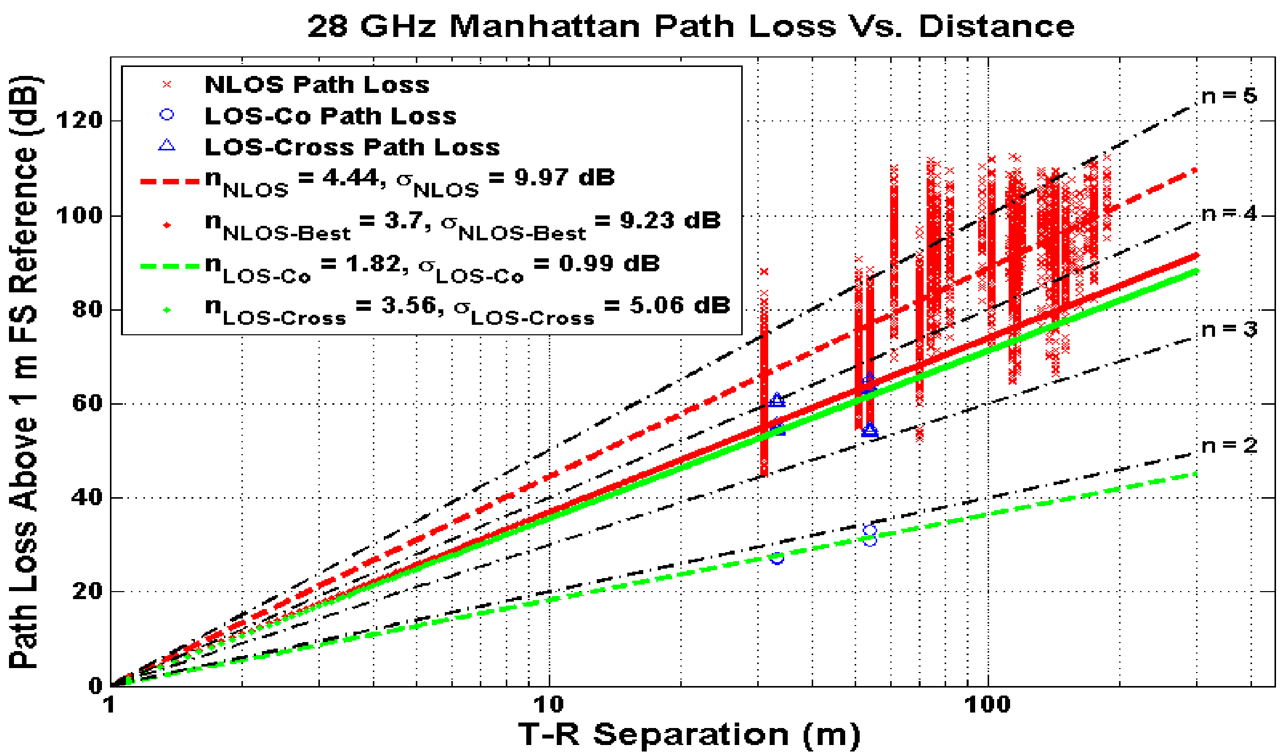
# 28 GHz Directional Path Loss Models




- Each point on scatter lot represents a unique pointing angle for TX and RX horn antennas

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.

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# Equal-Gain Combining for Different Pointing Angels at 28 GHz

| | PLE | STD (dB) |
|---|---|---|
| Overall | 4.47 | 10.20 |
| One best beam | 3.68 | 8.76 |
| Two best beam (NC) | 3.55 | 8.96 |
| Two best beam (C) | 3.41 | 9.03 |
| Three best beam (NC) | 3.49 | 9.12 |
| Three best beam (C) | 3.26 | 9.25 |
| Four best beam (NC) | 3.44 | 9.21 |
| Four best beam (C) | 3.15 | 9.39 |

S. Sun, T. S. Rappaport, "Wideband mmWave Channels: Implications for Design and Implementation of Adaptive Beam Antennas ," IEEE 2014 Intl. Microwave Symp. (IMS), June 2014, Tampa Bay

RX (UE) Beam combining results using 1 m free space reference distance for the 7-m high TX antenna, where "PLE" is path loss exponent, "STD" is the shadowing standard deviation, "NC" means noncoherent combining, and "C" denotes coherent combining.

**Coherent combining of 2 beams (n=3.41) < Noncoherent combining of 4 beams (n=3.44)**

**Coherent combining of 4 beams (n=3.15) < single best beam (n=3.68)**

Path gain: 13.2 dB/decade in distance w/ 4 strongest beams coherently combined at different pointing angles compared to randomly pointed single beam.

Path gain: 5.3 dB/decade w/4 beams over single best beam (1.4X range increase)



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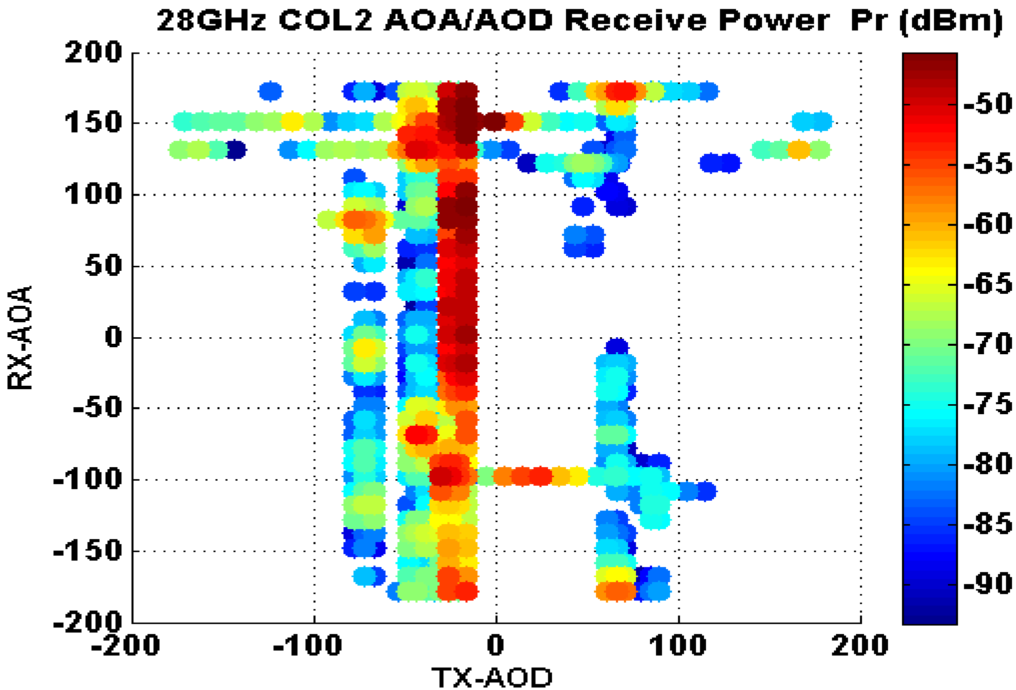
# AOA/AOD at 28 GHz

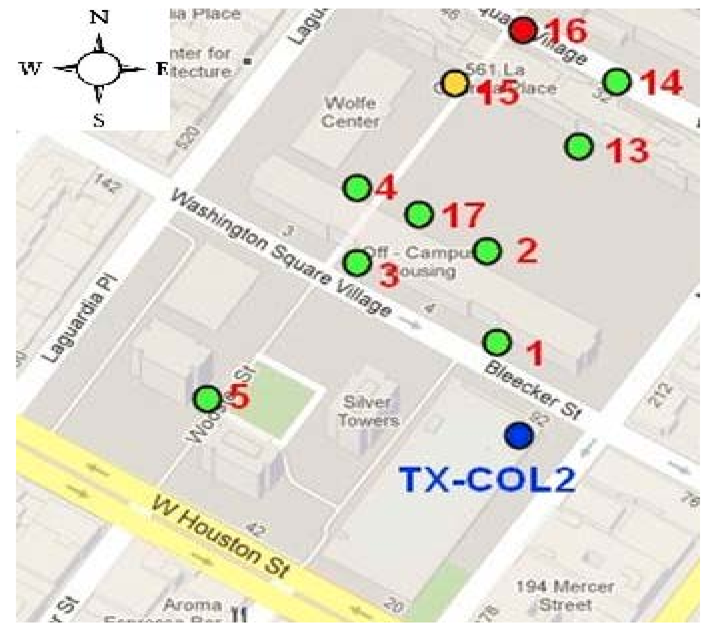





Distributions of AOA/AOD and received power for one TX location and 8 RX locations at 28 GHz

- AODs are concentrated between -80 degrees and -10 degrees with AOAs distributed uniformly from -180 degrees to 180 degrees over this AOD range.

Also confirmed in: "Broadband millimeter wave propagation measurements and models using adaptive beam antennas for outdoor urban cellular communications," IEEE Trans. Antennas Prop., vol. 61, no. 4, pp. 1850-1859, Apr. 2013.




- Strongest signals are received when the TX antenna points in a narrow span of -20 degrees to -10 degrees.
- Beamforming at the TX should focus in a narrow sector of space (60 to 90 degrees is adequate at base station).

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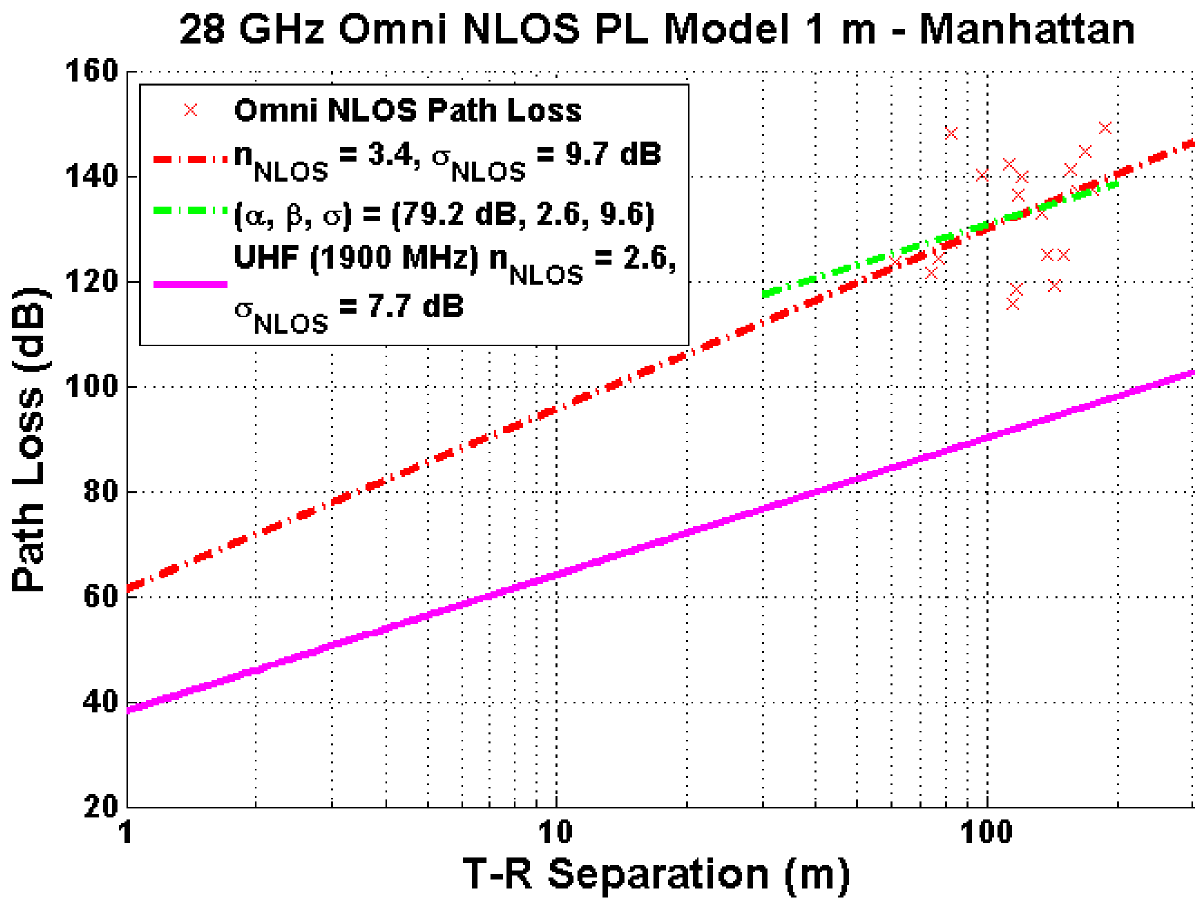
# 28 GHz NLOS Omnidirectional Path Loss Models







G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," IEEE *2014 Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2014, Washington, DC

K. Blackard, M. Feuerstein, T. Rappaport, S. Seidel, and H. Xia,"Path loss and delay spread models as functions of antenna height for microcellular system design," in *Vehicular Technology Conference, 1992, IEEE 42nd*, May 1992, pp. 333–337 vol.1.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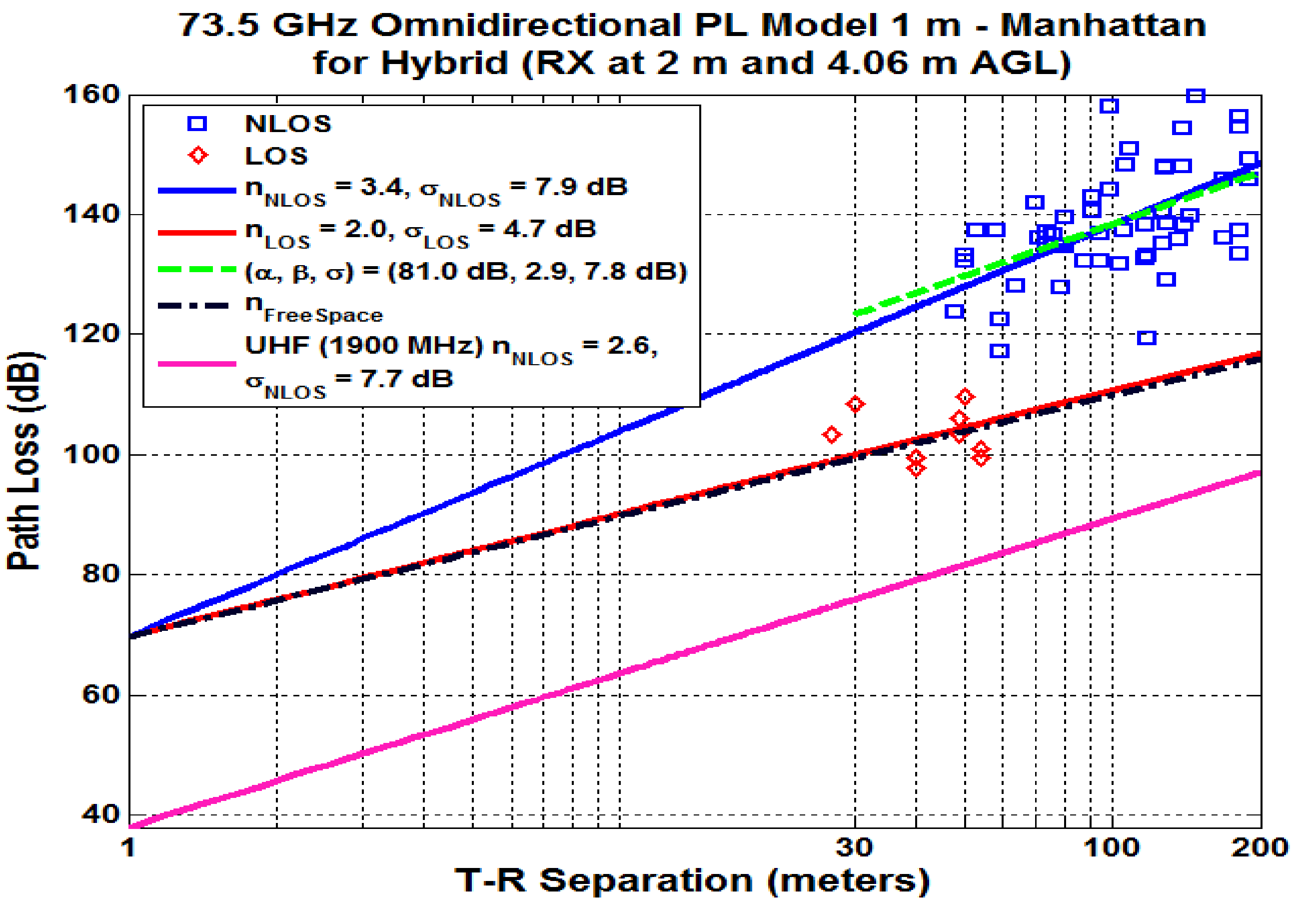
# 73 GHz Omnidirectional Models for (Hybrid) Backhaul/Mobile RX Scenario





S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

K. Blackard, M. Feuerstein, T. Rappaport, S. Seidel, and H. Xia,"Path loss and delay spread models as functions of antenna height for microcellular system design," in 1992 IEEE *Vehicular Technology Conference,* May 1992, pp. 333–337 vol.1.

G. R. MacCartney, M. K. Samimi, and T. S. Rappaport, "Omnidirectional Path Loss Models in New York City at 28 GHz and 73 GHz," IEEE 2014 Personal Indoor and Mobile Radio Communications (PIMRC), Sept. 2014, Washington, DC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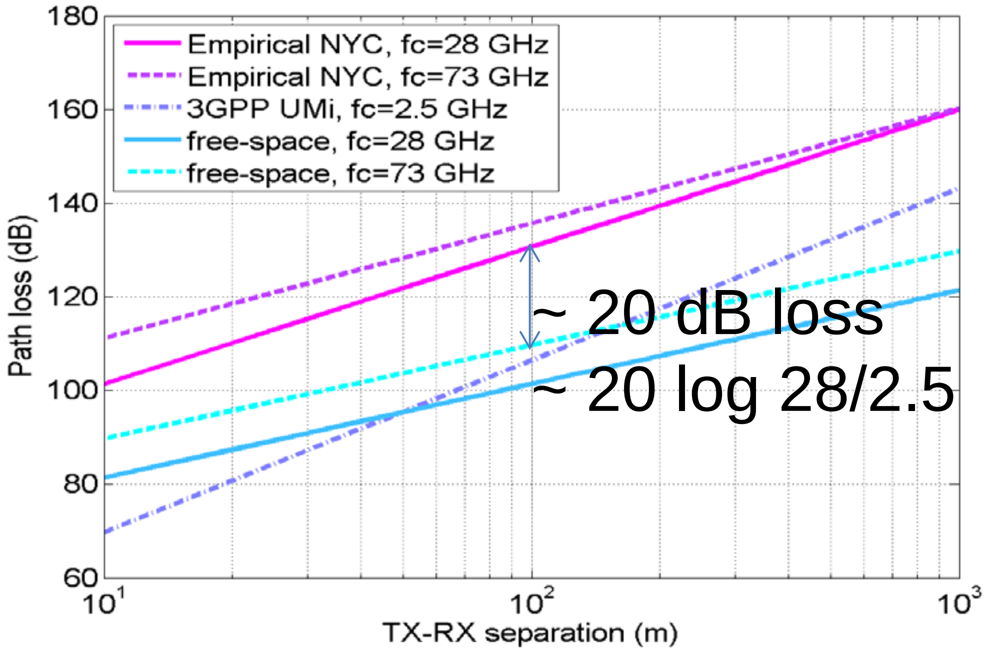
# Isotropic Path Loss Comparison




S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges," Proceedings of the IEEE, vol. 102, no. 3, pp. 366-385, March 2014.

- Isotropic NLOS path loss measured in NYC
  - ~ 20 - 30 dB worse than 3GPP urban micro model for fc=2.5 GHz
- Beamforming will offset this loss.
- Bottom line:
  **mmW omni channels do not experience increased path loss beyond the simple free space frequency dependence in urban New York City**

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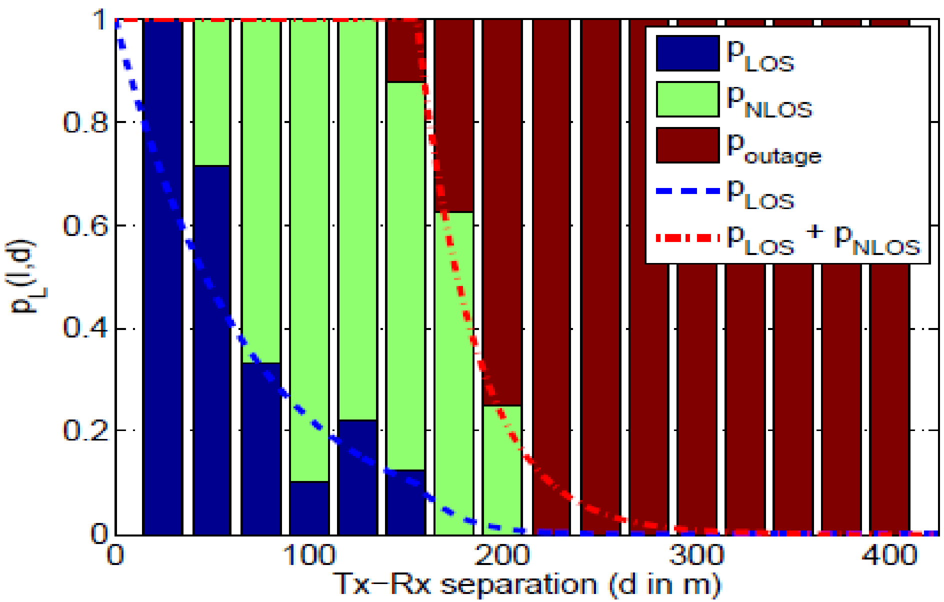
# Hybrid LOS-NLOS-Outage Model






M. R. Akdeniz, Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, E. Erkip, "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," IEEE. J. Sel. Areas on Comm., Aug. 2014

- mmW signals susceptible to severe shadowing.
  - Not incorporated in standard 3GPP models, but needed for 5G
- New three state link model: LOS-NLOS-outage
  - Other Outage modeling efforts (Bai, Vaze, Heath '13)
- Outages significant only at d > 150m
  - Will help smaller cells by reducing interference

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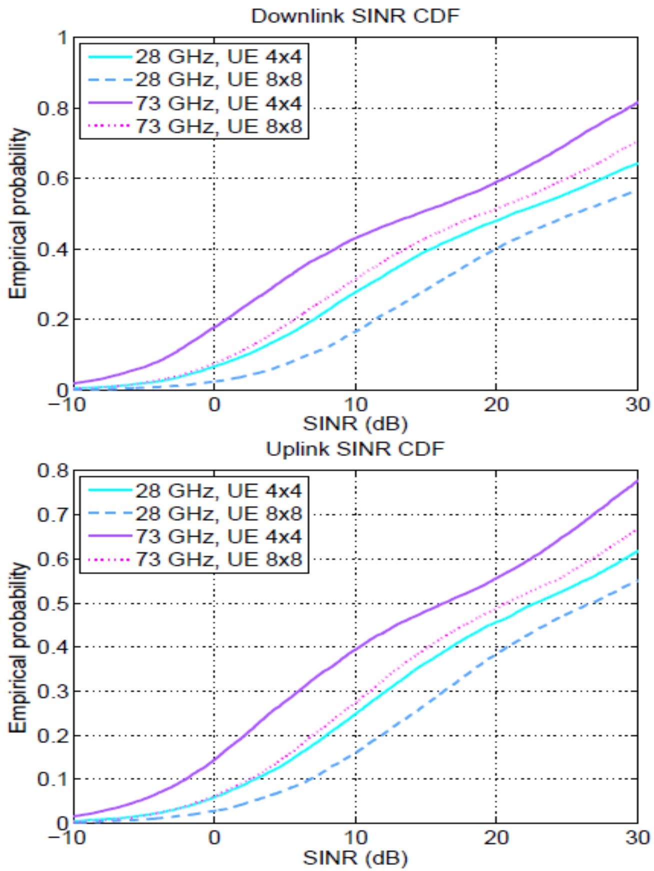
# Simulations: SNR Distribution




- Simulation assumptions:
  - 200m ISD
  - 3-sector hex BS
  - 20 / 30 dBm DL / UL power
  - 8x8 antenna at BS
  - 4x4 (28 GHz), 8x8 (73 GHz) at UE
- A new regime:
  - **High SNR on many links**
  - **Better than current macro-cellular**
  - **Interference is non dominant**



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# Comparison to Current LTE



- Initial results show significant gain over LTE
  - Further gains with spatial mux, subband scheduling and wider

| System antenna | Duplex BW | fc (GHz) | Antenna | Cell throughput (Mbps/cell) | | Cell edge rate (Mbps/user, 5%) | |
|---|---|---|---|---|---|---|---|
| | | | | DL | UL | DL | UL |
| mmW | 1 GHz TDD | 28 | 4x4 UE 8x8 eNB | 1514 | 1468 | 28.5 | 19.9 |
| | | 73 | 8x8 UE 8x8 eNB | 1435 | 1465 | 24.8 | 19.8 |
| Current LTE | 20+20 MHz FDD | 2.5 | (2x2 DL, 2x4 UL) | 53.8 | 47.2 | 1.80 | 1.94 |

~ 25x gain (cell throughput)

~ 10x gain (cell edge rate)

10 UEs per cell, ISD=200m,
hex cell layout
LTE capacity estimates from 36.814

M. R. Akdeniz,Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, E. Erkip, "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," IEEE. J. Sel. Areas on Comm., Aug. 2014

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# Recent Results by NSN for 73 GHz



* Assumes RF BW of 2.0 GHz, NCP-SC Modulation
* Symbol Rate 1.536 Gigasymbols/sec (50 X LTE)
* Access Point Array: 4 sectors, dual 4X4 polarization
* Ideal Channel State estimator and Fair Scheduler
* Beamforming using uplink signal

Simulation Results:

4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage

8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage

Outage can be reduced by denser cells, smart repeaters/relays

A. Ghosh,T. A. Thomas,M. Cudak, R. Ratasuk,P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, Jr., S. Sun, S. Nie, “Millimeter Wave Enhanced Local Area Systems: A High Data Rate Approach for Future Wireless Networks,” IEEE J. on Sel. Areas on Comm., Aug. 2014.



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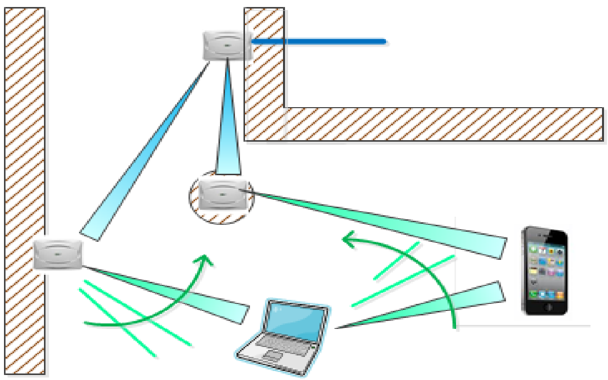
# Multihop Relaying for mmW





- Significant work in multi-hop transmissions for cellular
- Gains have been minimal
- Why?
  - **Current cellular systems are bandwidth-limited; mmWave is noise-limited**
- Millimeter wave may be different
  - Overcome outage via macrodiversity
  - Many degrees of freedom

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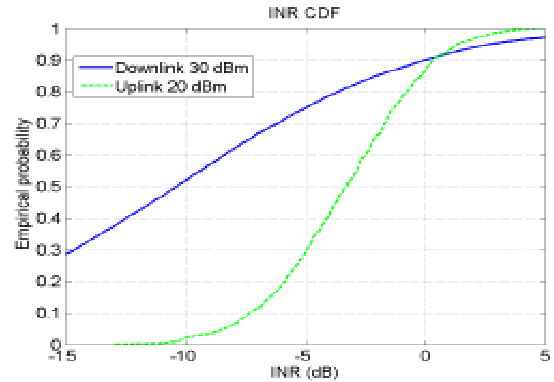
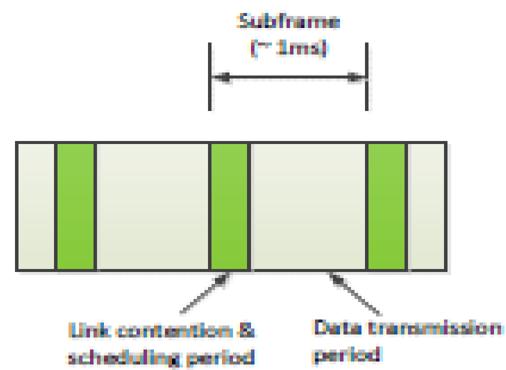
# Multihop Relays (D2D)



- Network discovery?
- Directional isolation
- Dynamic duplexing

Interference-to-noise




Qualcomm FlashLinQ frame structure

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# Challenges and Opportunities



- mmW systems offer orders of magnitude capacity gains
- Experimental confirmation in NYC
  - 200 m cell radius very doable
  - Greater range extension through beam combining
  - Orders of magnitude capacity gains from increased bandwidth
  - Early days for channel modeling and adaptive arrays – a new frontier
  - NYU WIRELESS has created a Statistical Spatial Channel Model for 28 GHz – complete simulator
- Systems enter new regime:
  - Links are directionally isolated, high SNR, noise-limited channel
  - Links rely heavily on beamforming
  - Cooperation and base station diversity should offer big improvements
- Multi-hop relaying
  - Revisiting a mature concept but now in a noise-limited environment



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- Measurements recorded under U.S. FCC Experimental License 0040-EX-ML-2012.


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