Outdoor-to-Indoor 28 GHz Wireless Measurements in Manhattan: Path Loss, Location Impacts, and 90% Coverage

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[1]Columbia University; [2]Stuyvesant High School; [3]The City College of New York; [4]Universidad Tecnica Federico Santa Maria; [5]Nokia Bell Labs

ACM MobiHoc'22 October 20, 2022

Introduction

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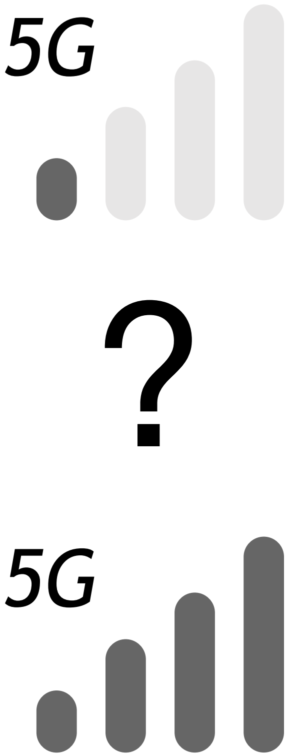
- As humans, we spend up to 80-90% of our time indoors, exacerbated in recent years by the COVID pandemic
- mmWave effective for outdoors use cases
    - Cellular users, V2X, backhaul etc.
- But what about for indoors users?
- What influences mmWave indoors coverage?
- Can the gold-standard gigabit data rates be achieved by indoors users?

Photo: Business Wire, 07/22/22

5G LinkNYC Kiosk



- A. Ferreira and N. Barros. 2022. COVID-19 and Lockdown: The Potential Impact of Residential Indoor Air Quality on the Health of Teleworkers. In *Int J Environ Res Public Health*

Outline

- **Research Questions and Methodology**
- The Outdoor-to-Indoor Measurement Campaign
- Path Gain and Link Rates in Different Scenarios
- Case Study of a Public Middle School + Dataset
- Closing Remarks

Research Questions and Methodology

Wireless & Mobile Networking Lab

- Singular overarching research question:

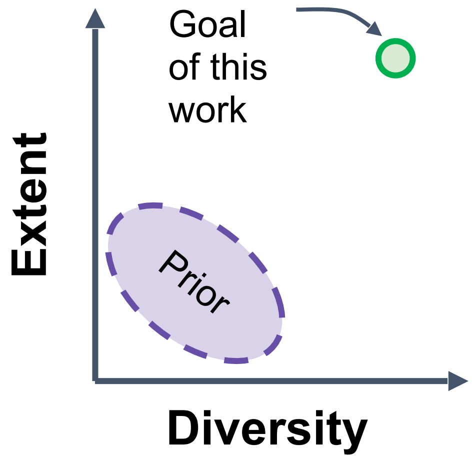
Is outdoor-to-indoor (OtI) coverage feasible in mmWave networks?

- **Feasible**: data rates in excess of 1 Gb/s achieved by 90% of users
- Effective way to answer this: *measure*, *measure*, *measure*…
- Measurements must be *diverse* and *extensive*
    - Measuring few sites leads to *bias*
    - Taking only a handful of measurements provides *anecdotes*
- Data diversity and volume → statistically relevant conclusions

Related Work

Ref.	Type	Frequency	Environment	Tx Design	Rx Design	Bandwidth	# Tx-Rx Links
Chizhik 2020	ItI	28 GHz	Urban	Stationary Horn	Rotating Horn	Narrowband	>1,500
Raghavan 2018	ItI, OtO	29 & 60 GHz	Urban & Suburban	Rotating Horn	Rotating Horn	200 MHz	785
K. Du 2021	ItI, OtO, OtI	28 GHz	Suburban	Stationary Horn	Stationary Horn	2 GHz	153
Jun 2020	ItI, OtI	60 GHz	Urban	8x1 MIMO Array	8x2 MIMO Array	4 GHz	150
Zhao 2013	ItI, OtI	28 GHz	Urban	Gimbal-mounted Horn	Gimbal-mounted Horn	400 Mcps	18
Aslam 2020	OtO	60 GHz	Urban	36x8 Phased Array	36x8 Phased Array	2.16 GHz	15
J. Du 2020	OtO	28 GHz	Suburban	Stationary Horn	Rotating Horn	Narrowband	>2,000
Chen 2019	OtO	28 GHz	Urban	Omnidirectional	Rotating Horn	Narrowband	>1,500
Diakhate 2017	OtI	60 GHz	Urban	Stationary Horn	Stationary Horn	125 MHz	76
Ntetsikas 2022	OtI	60 GHz	Suburban	Omnidirectional	Rotating Horn	Narrowband	160
Bas 2018	OtI	28 GHz	Urban	8x2 Phased Array	8x2 Phased Array	400 MHz	29
Larsson 2014	OtI	28 GHz	Suburban	Stationary Slot Array	Stationary Parabolic Dish	50 MHz	43
This work	OtI	28 GHz	Urban	Omnidirectional	Rotating Horn	Narrowband	>2,000

- Prior OtI measurements lack *extent* and *diversity*



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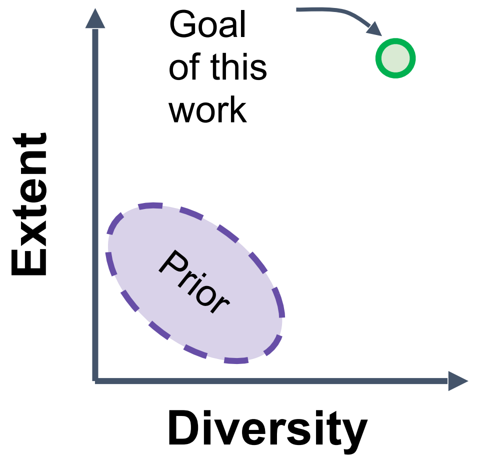
- Prior OtI measurements lack *extent* and *diversity*
- Leverage similar methodology from our past work with the desired *extent* and *diversity*
  - Want to repeat for OtI
  - Same measurement equipment used!



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Measurement Equipment

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- 28 GHz narrowband channel sounder with rotating Rx
- Rx spins at 120 RPM
- 740 power readings per second
- 20s measurements

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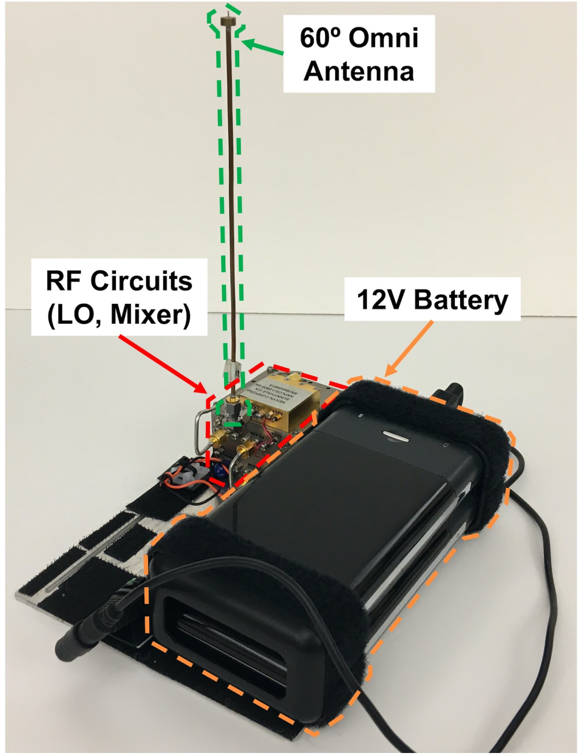
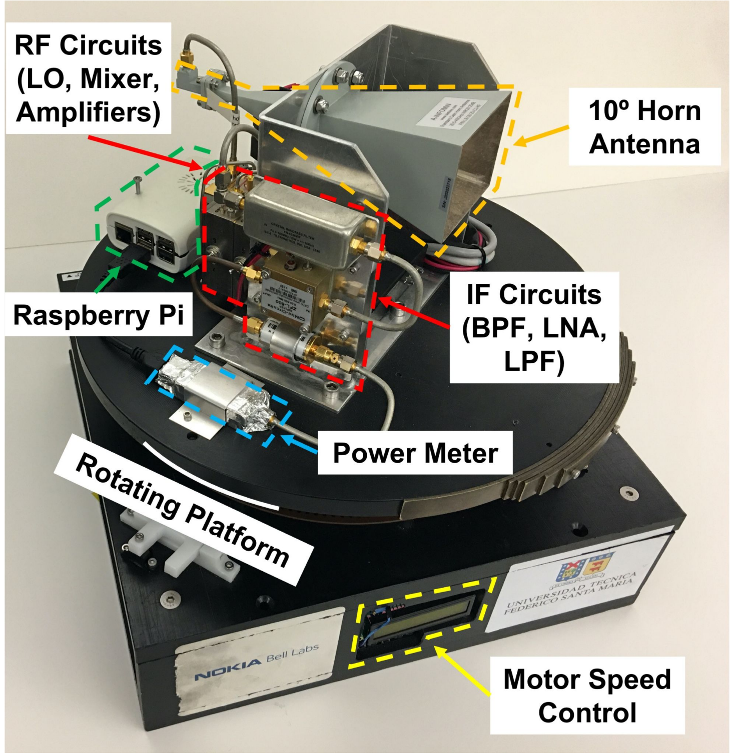


Narrowband Tx



Rotating Rx

- J. Du, D. Chizhik, R. Feick, M. Rodriguez, G. Castro, and R. A. Valenzuela. 2020. Suburban Fixed Wireless Access Channel Measurements and Models at 28 GHz for 90% Outdoor Coverage. In *IEEE Trans. Antennas Propag.*

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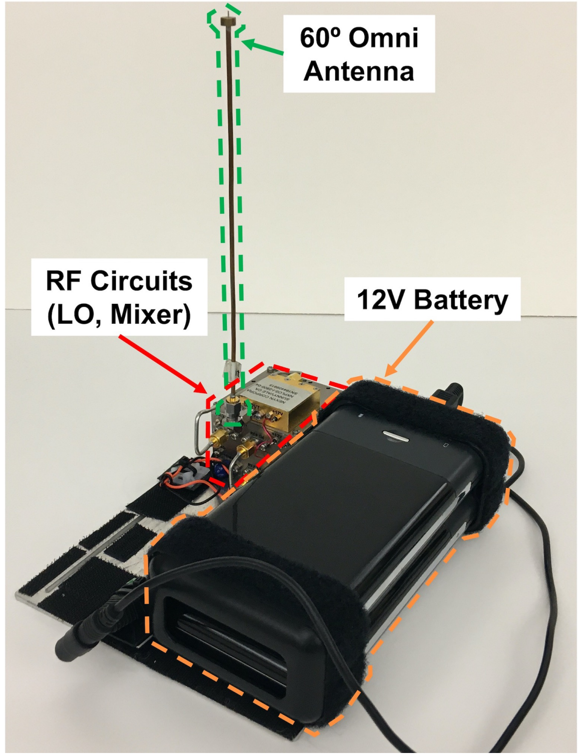

Narrowband Tx

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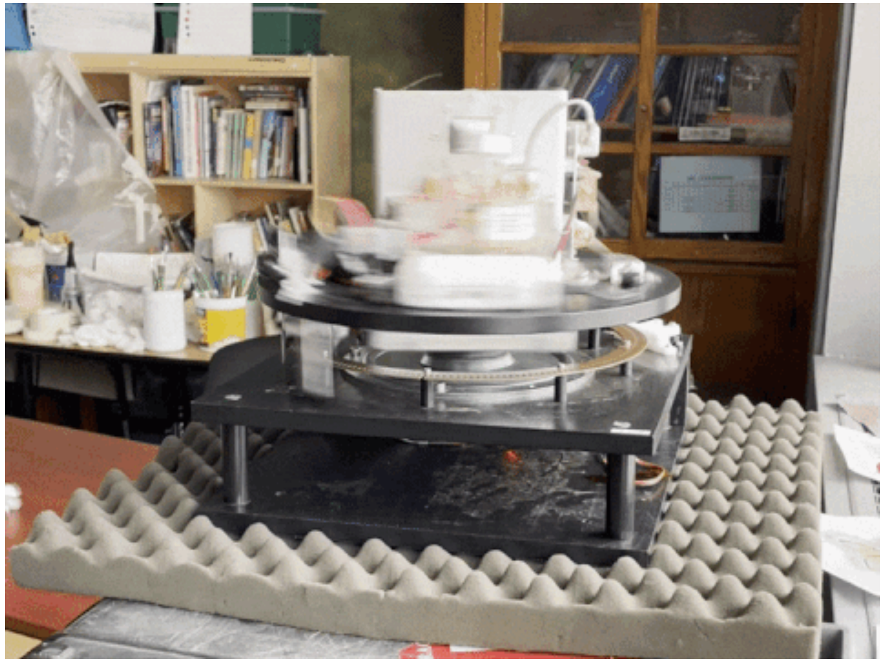
Measurement Setup

- Place rotating Rx indoors, 1m away from a window (emulating UE)
- Mount Tx on a tripod and cart: dipole is 11 ft off ground (emulating BS)
- Move the Tx on street sidewalks overlooked by Rx in fixed increments



Rx deployed indoors

Tx deployed outdoors → *Emulating* →

5G Lightpole gNB

Measurement Campaign

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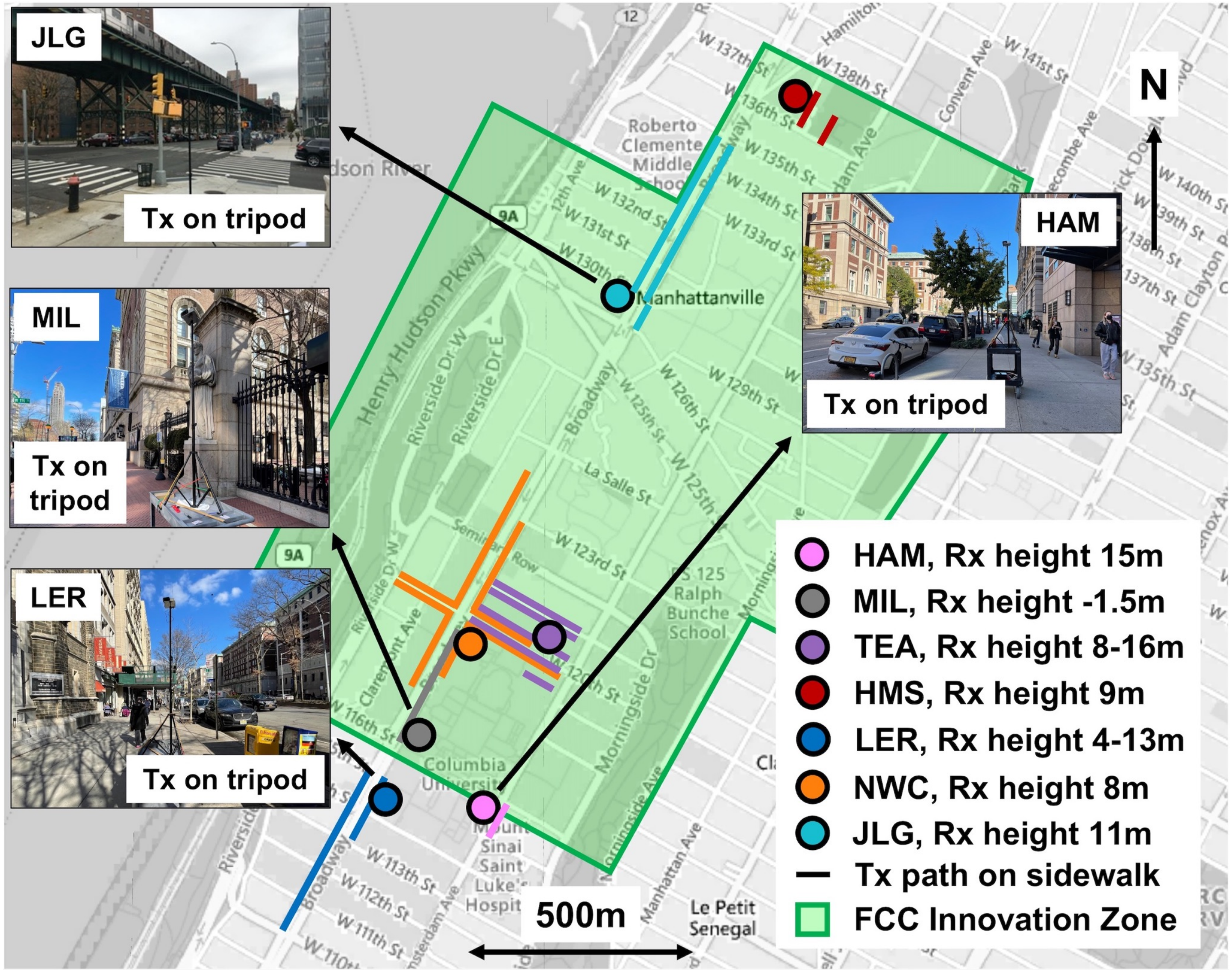
- Measure at 7 different buildings around West Harlem, NYC
- Area within the COSMOS FCC Innovation Zone
- Buildings range in construction date from 1903 to 2017
- Varied construction materials
  - Brick + concrete
  - Glass + metal
- *Different types of window glass*
- >2,000 Tx-Rx links measured
- >29 million power readings
- 35 OtI scenarios studied



Measurement Campaign

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- >2,000 Tx-Rx links
- >29 million power readings
- 35 OtI scenarios (building/sidewalk combo)

Name	Color	Group	Range (m)	Step (m)	# Links	Slope (dB)	Intercept (dB)	RMS (dB)	Median G_{az} (dBi)
HAM-S-E	Pink	HAM	61	1	62	-6.61	-23.7	3.5	11.1
MIL-N-E	Gray	MIL	155	2.5	76	-3.53	-59.1	2.8	11.0
TEA-S-N-1	Purple	TEA	230	6/8	35	-2.56	-95.3	5.6	11.0
TEA-S-S-1	Purple	TEA	228	4/8	45	-3.49	-75.1	4.8	10.9
TEA-S-S-2	Purple	TEA	155	3	52	-5.52	-40.5	2.6	7.7
TEA-S-S-3	Purple	TEA	232	3	77	-5.13	-36.1	3.3	8.8
TEA-S-Bal-1	Purple	TEA	85	3	29	-1.61	-107.9	4.7	9.7
TEA-S-Bal-2	Purple	TEA	85	3	29	-0.69	-111.3	4.2	7.8
TEA-S-Bal-3	Purple	TEA	37	3	13	-5.20	-33.6.	4.3	10.0
TEA-N-N	Purple	TEA	243	3	68	-4.45	-53.0	4.1	10.8
TEA-N-S	Purple	TEA	243	3	81	-4.80	-41.0	4.1	10.1
HMS-Lot-307	Maroon	HMS	62	1	63	-3.22	-60.4	1.6	10.4
HMS-Lot-317	Maroon	HMS	62	1	63	-3.48	-52.0	3.4	11.5
HMS-Lot-321	Maroon	HMS	62	1	63	-4.12	-44.1	3.4	11.8
HMS-Lot-323	Maroon	HMS	62	1	63	-4.10	-47.2	2.5	9.9
HMS-Lot-325	Maroon	HMS	62	3	22	-3.40	-54.8	2.5	10.8
HMS-Court-307	Maroon	HMS	42	1	43	-5.47	-3.9	2.9	13.3
HMS-Court-317	Maroon	HMS	39	1	40	-6.48	11.2	3.2	12.0
HMS-Court-321	Maroon	HMS	57	1	58	-8.50	51.1	3.1	11.0
HMS-Court-323	Maroon	HMS	57	1	58	-8.13	43.6	1.6	9.8
HMS-Court-325	Maroon	HMS	58	1	59	-1.88	-84.3	2.2	10.2
LER-S-W-5	Blue	LER	298	3	96	-5.29	-19.6	3.0	10.8
LER-S-W-2	Blue	LER	110	8	14	-6.72	-22.8	4.2	9.4
LER-S-E-2	Blue	LER	95	6	23	-3.97	-75.2	3.8	9.4
NWC-N-W	Orange	NWC	197	3/6	65	-3.03	-76.9	4.7	12.8
NWC-N-E	Orange	NWC	201	3	60	-3.52	-73.0	1.9	11.2
NWC-E-N	Orange	NWC	131	3	44	-4.83	-48.7	2.9	11.1
NWC-E-S	Orange	NWC	242	3	78	-3.08	-83.2	2.8	10.8
NWC-S-E	Orange	NWC	105	1	106	-3.30	-86.7	4.9	9.8
NWC-S-W	Orange	NWC	180	2/3/6	72	-3.36	-74.9	4.5	10.9
NWC-S-E	Orange	NWC	153	3	46	-4.36	-55.4	4.2	12.1
NWC-W-N	Orange	NWC	173	3	56	-2.02	-102.4	3.2	10.3
JLG-N-W	Cyan	JLG	291	3/6	75	-2.94	-72.5	2.5	10.8
JLG-N-E	Cyan	JLG	224	3	68	-3.20	-77.7	2.3	8.9
JLG-E-E	Cyan	JLG	49	3	17	11.61	-355.6	2.9	13.1

Measurement Campaign

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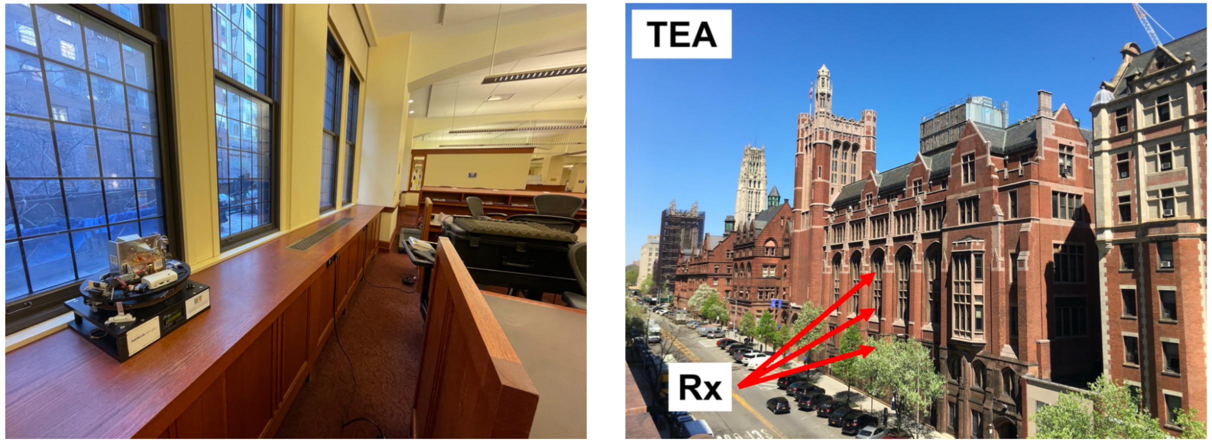
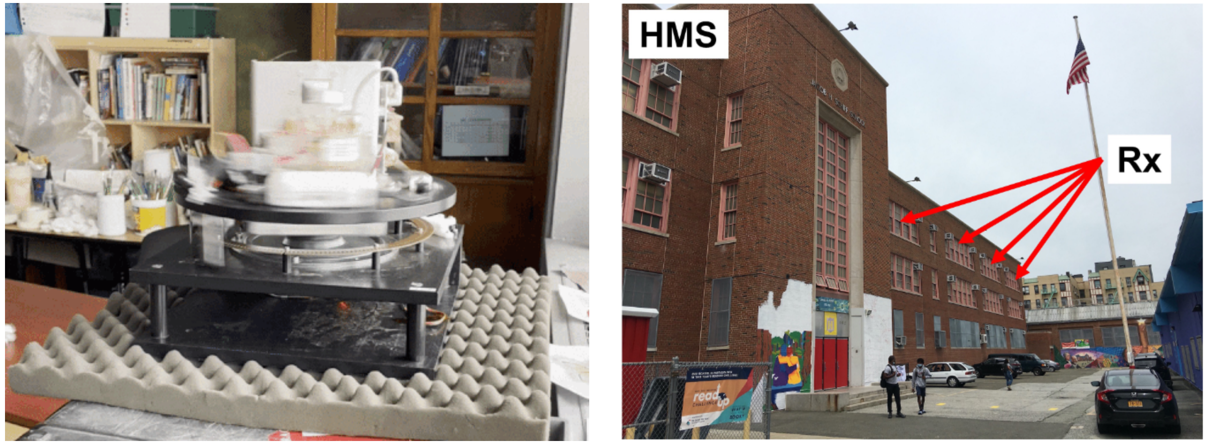
NWC: North**w**est **C**orner Building *(8 scenarios / 527 links)*



TEA: Teacher's College *(9 scenarios / 435 links)*

LER: Lerner Hall *(3 scenarios / 133 links)*



HMS: Hamilton Grange **M**iddle **S**chool *(10 scenarios / 532 links)*

Measurement Campaign

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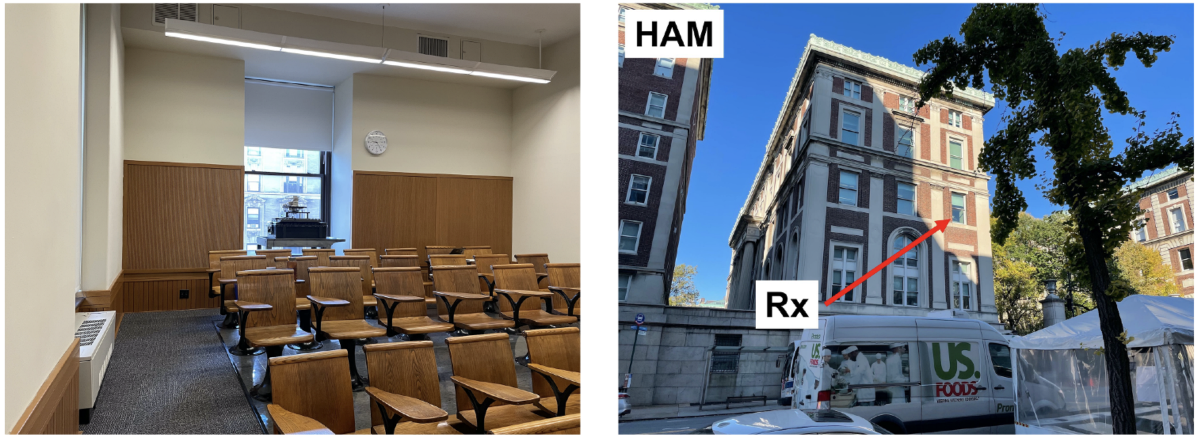
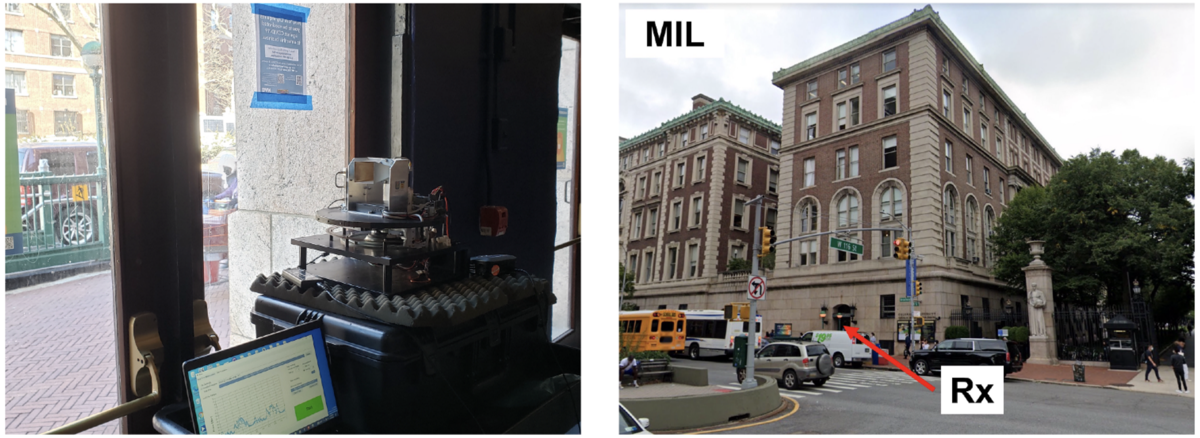


HAM: Hamilton Hall *(1 scenario / 62 links)*



MIL: Miller Theatre *(1 scenario, 76 links)*

JLG: Jerome **L**. **G**reene *(3 scenarios, 160 links)*

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Measured Parameters

Measured Power

$P_{\text{horn}}(d, \phi)$

Tx-Rx dist. d

Azim. angle ϕ

- Sounder records the measured power at link distance *d*, azim. angle *φ*

Measured Parameters

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Measured Power

$P_{\text{horn}}(d, \phi)$

Tx-Rx dist. d

Azim. angle ϕ

Equivalent Omnidirectional Received Power

$$P_{\text{omni}}(d) = \frac{1}{2\pi} \int_0^{2\pi} P_{\text{horn}}(d, \phi) d\phi$$

- Sounder records the measured power at link distance *d*, azim. angle φ
- Compute the equivalent omnidirectional received power

Measured Parameters

Measured Power

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Equivalent Omnidirectional Received Power

$$P_{\text{omni}}(d) = \frac{1}{2\pi}\int_0^{2\pi} P_{\text{horn}}(d, \phi)\, d\phi$$

Path Gain

$$G_{\text{path}}(d) = \frac{P_{\text{omni}}(d)}{P_{\text{Tx}} \cdot G_{\text{el}}(d)}$$

- Sounder records the measured power at link distance *d*, azim. angle *φ*
- Compute the equivalent omnidirectional received power
- Compute the path gain

Measured Parameters

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$$G_{\text{path}}(d) = \frac{P_{\text{omni}}(d)}{P_{\text{Tx}} \cdot G_{\text{el}}(d)}$$

Power Angular Spectrum

$$S(d, \phi) = \frac{1}{N} \sum_{i=1}^{N} P_{\text{horn}}^{(i)}(d, \phi)$$

- Sounder records the measured power at link distance *d*, azim. angle *φ*
- Compute the power angular spectrum

Measured Parameters

Measured Power

$$P_{\text{horn}}(d, \phi)$$

$\text{Tx-Rx dist. } d$

$\text{Azim. angle } \phi$

Equivalent Omnidirectional Received Power

$$P_{\text{omni}}(d) = \frac{1}{2\pi} \int_0^{2\pi} P_{\text{horn}}(d, \phi) d\phi$$

Path Gain

$$G_{\text{path}}(d) = \frac{P_{\text{omni}}(d)}{P_{\text{Tx}} \cdot G_{\text{el}}(d)}$$

Power Angular Spectrum

$$S(d, \phi) = \frac{1}{N} \sum_{i=1}^{N} P_{\text{horn}}^{(i)}(d, \phi)$$

Azim. Beamforming Gain

$$G_{\text{az}}(d) = \frac{\max_{\phi}\{S(d, \phi)\}}{P_{\text{omni}}(d)}$$

- Sounder records the measured power at link distance *d*, azim. angle *φ*
- Compute the power angular spectrum
- Compute the azimuth beamforming gain

Path Gain for Different Buildings

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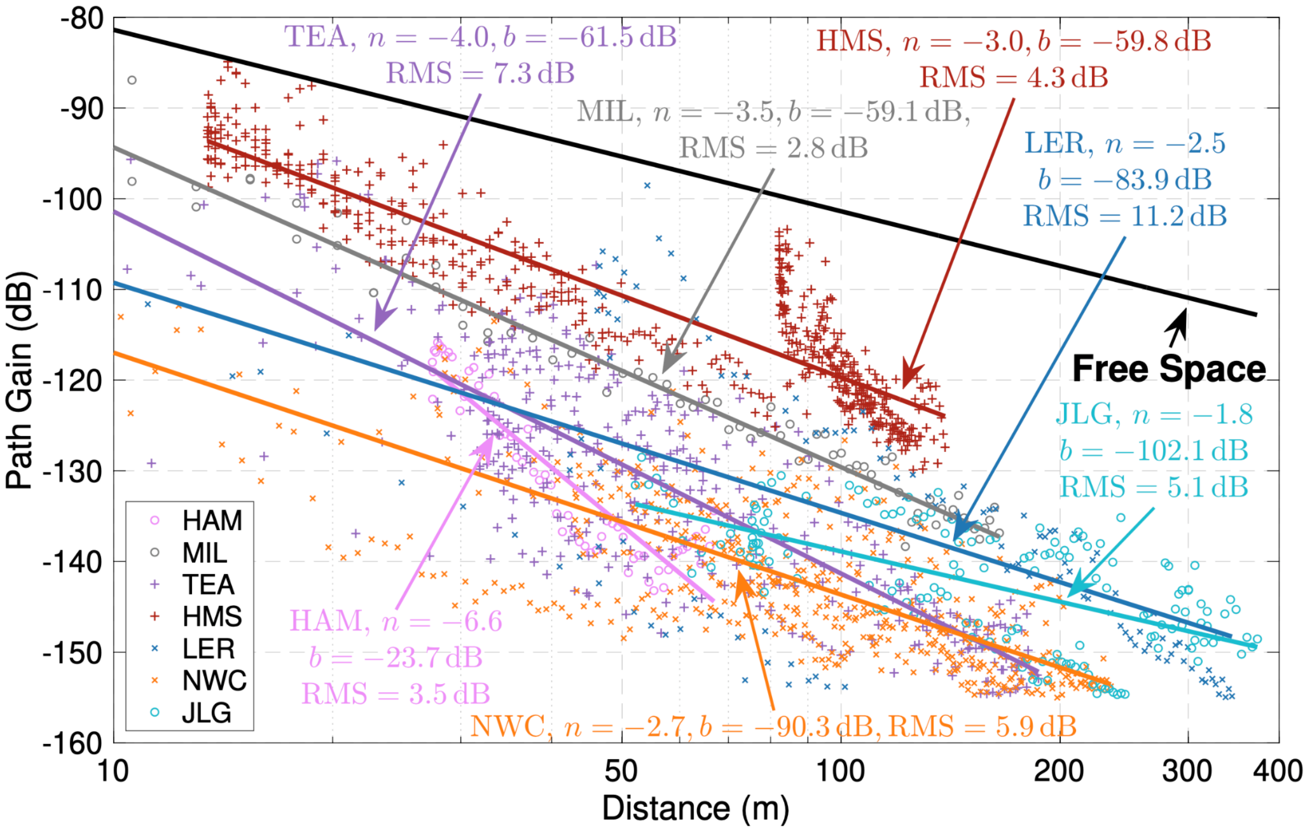
- Path gain plotted as a function of distance
- Best-fit exponential path gain model fitted to point cloud
- Very different models for all seven buildings measured
- *Takeaway: Impossible to predict path loss from building exterior*
- Note: newer buildings typically have lower path gain (JLG, NWC)



$$G_{\text{path}}(d) = b + n \cdot 10 \log_{10} d + \sigma \mathcal{N}(0,1)$$

b = path gain at 1m (dB), n = slope of best-fit line, σ = RMS fitting error (dB)

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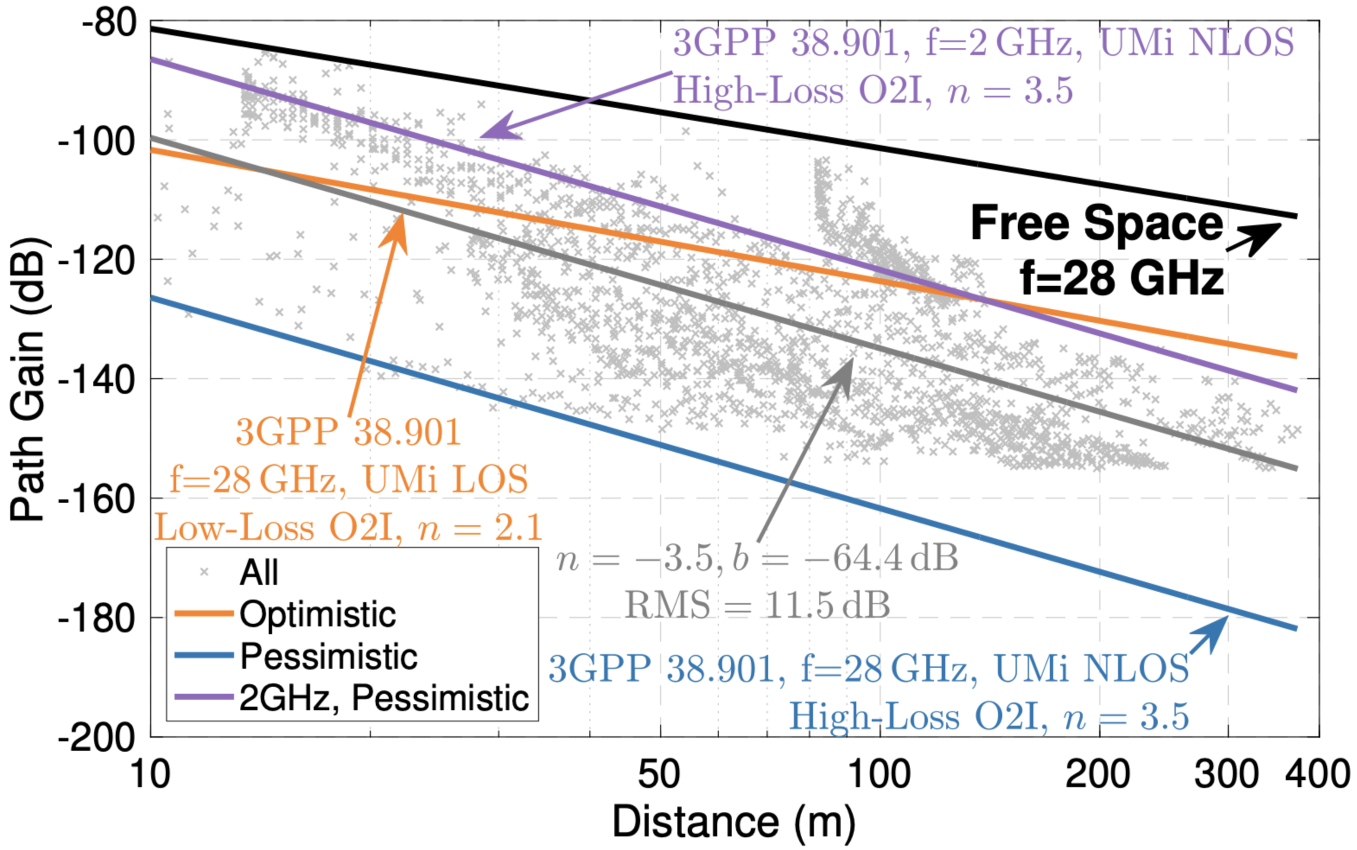

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Considering the Type of Glass

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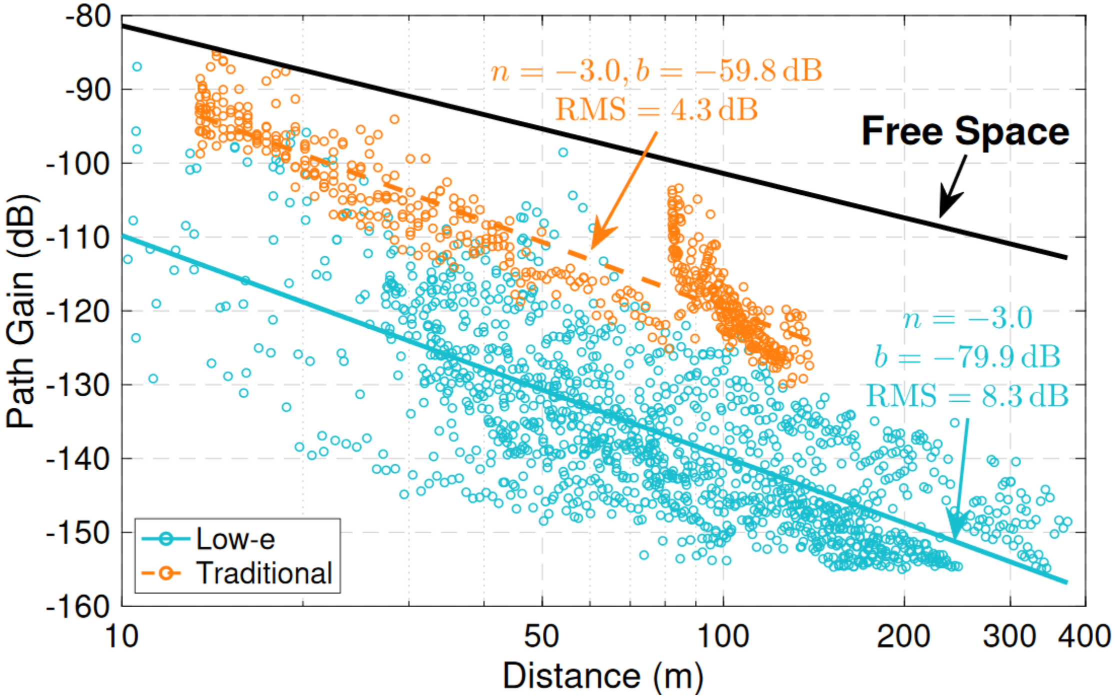
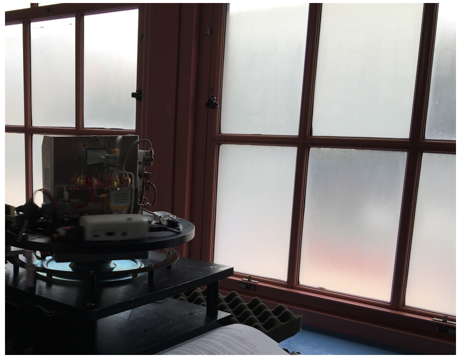
- mmWave signal experiences in excess of 50 dB loss through walls
- Majority of signal will enter indoors space via the building windows
- Categorize buildings by glass type
  - Low-e: double glazing with coating
  - “Traditional”: single glazed, plain
- Observe uniform 20 dB penalty for Low-e buildings at all link distances
- *Worse OtI coverage for Low-e?*



Low-e



Traditional

- C. Vargas, L. da Silva Mello, and C. R. Rodriguez. 2017. Measurements of Construction Materials Penetration Losses at Frequencies From 26.5 GHz to 40 GHz, in *Proc. IEEE PACRIM*

Glass-Dependent Link Rates

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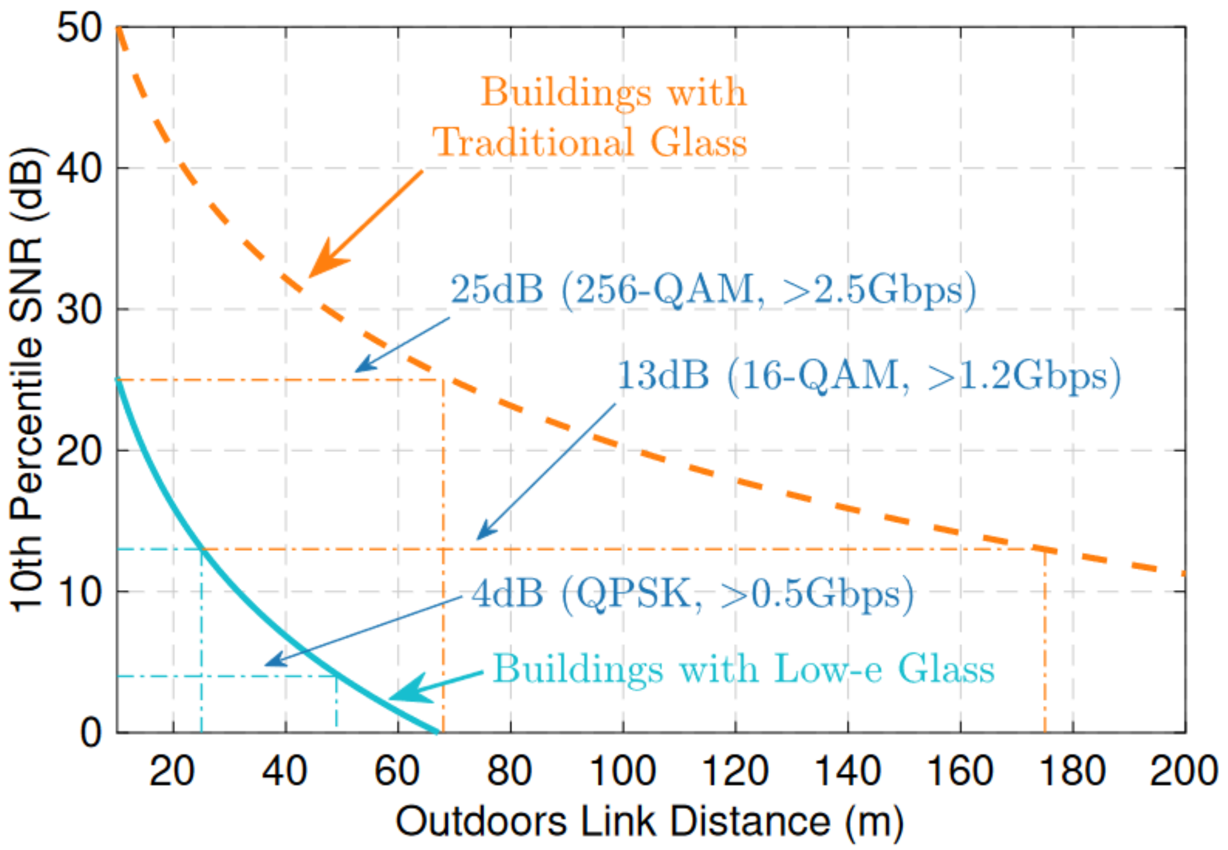
- Apply the best-fit exponential path gain models for two types of glass

$$G_{\mathrm{path}}(d) = b + n \cdot 10 \log_{10} d + \sigma \mathcal{N}(0,1)$$

- Compute 10th percentile signal-to-noise ratio, compute impaired Shannon capacity
- Traditional glass: 256QAM out to 68m, 16QAM to 175m **(> 1Gb/s)**
- Low-e glass: 16QAM out to 25m, QPSK out to 49m **(< 1 Gb/s)**

Bandwidth: 800 MHz, state-of-the-art system parameters (UE LNA, BS PA, UE Antenna Gain etc.)



Locational Effects - Subway Track

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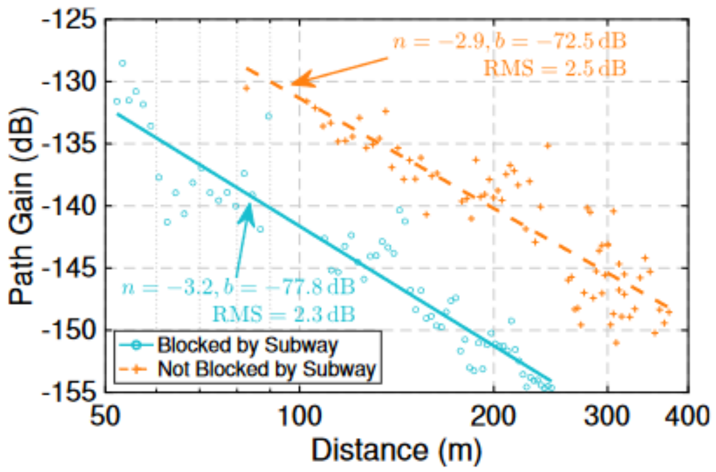
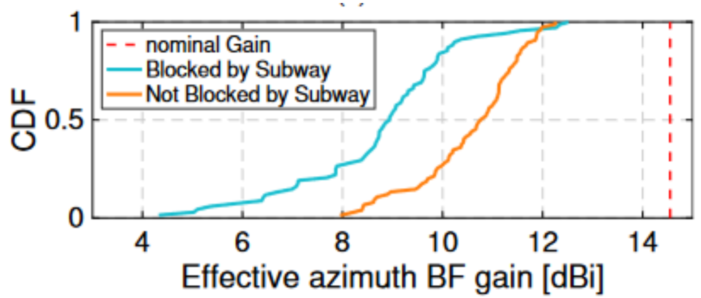
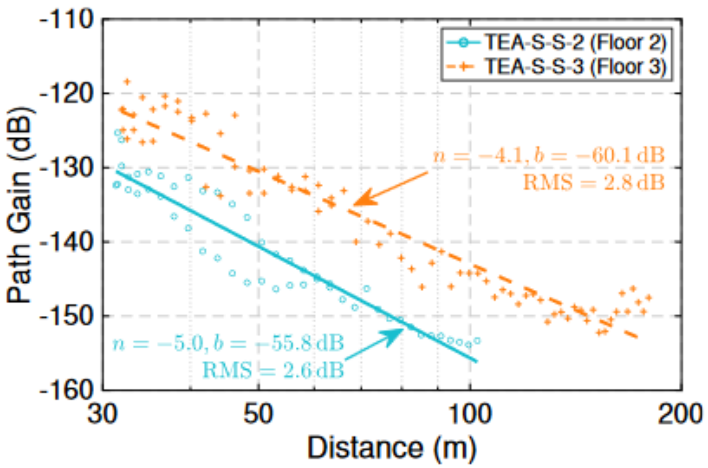


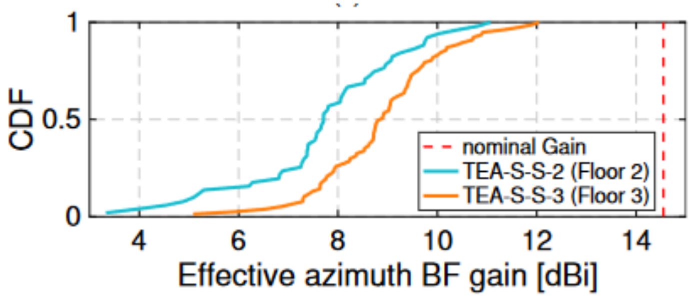


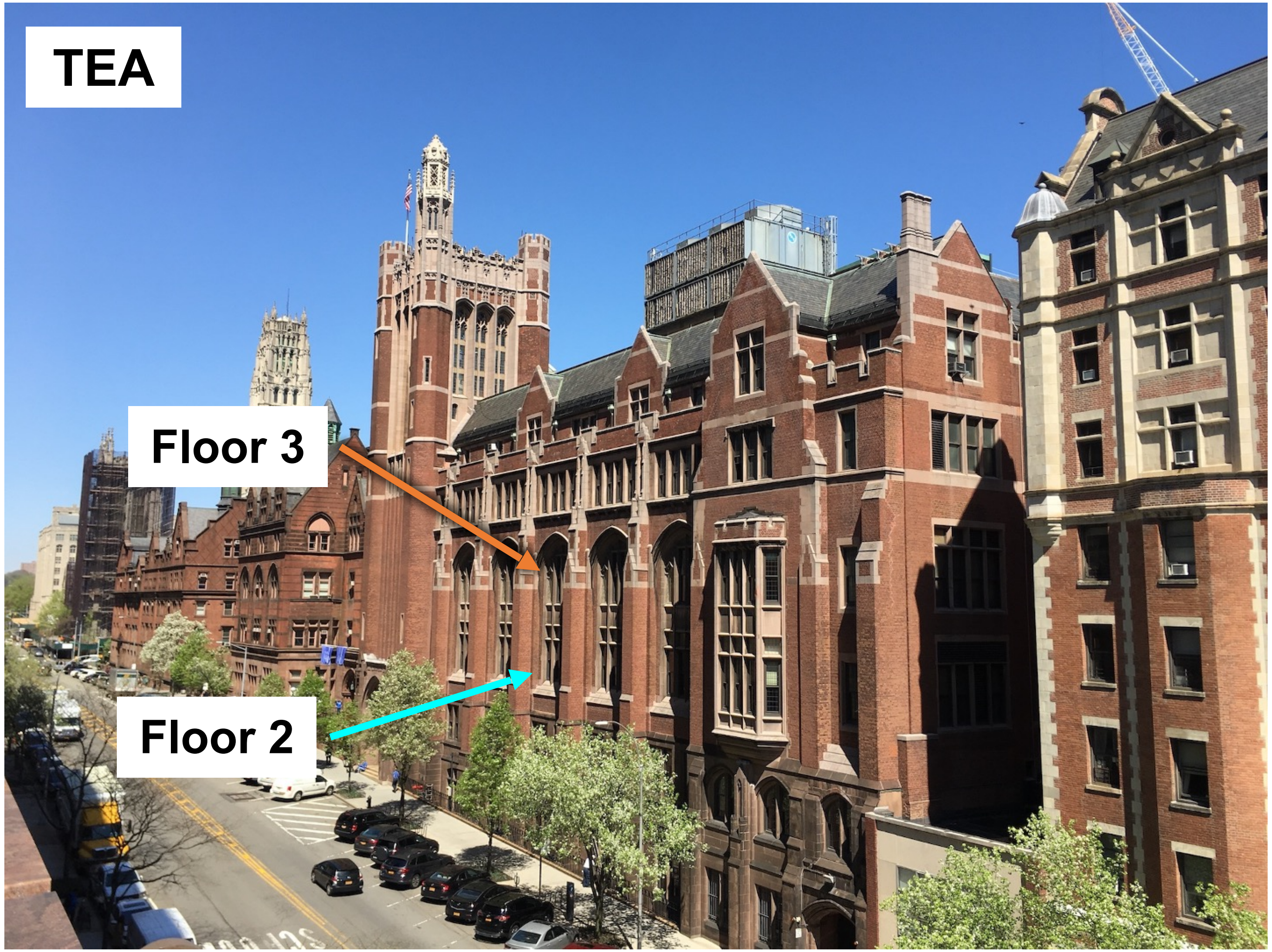
Blockage by Subway Track

- 10 dB lower path gain
- 2dB lower beamforming gain

Locational Effects - Building Floors



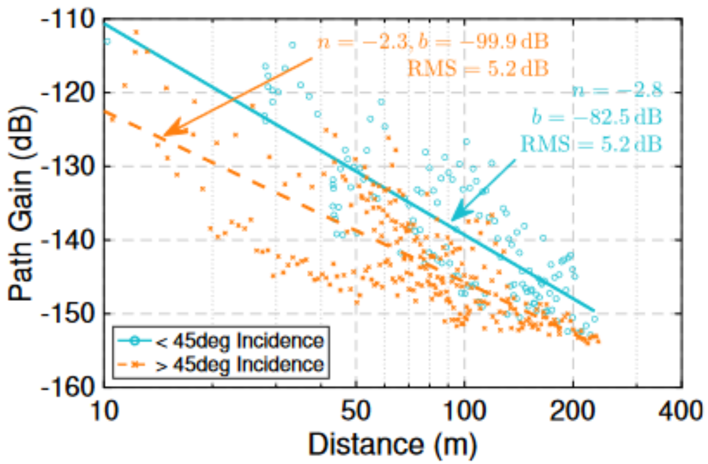


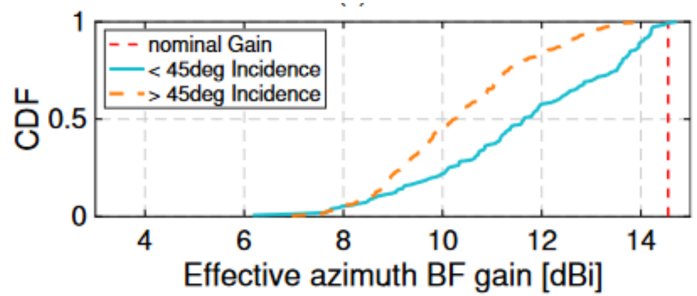


2nd vs. 3rd Floor

- 2nd: 10 dB lower path gain & 1 dB lower beamforming gain

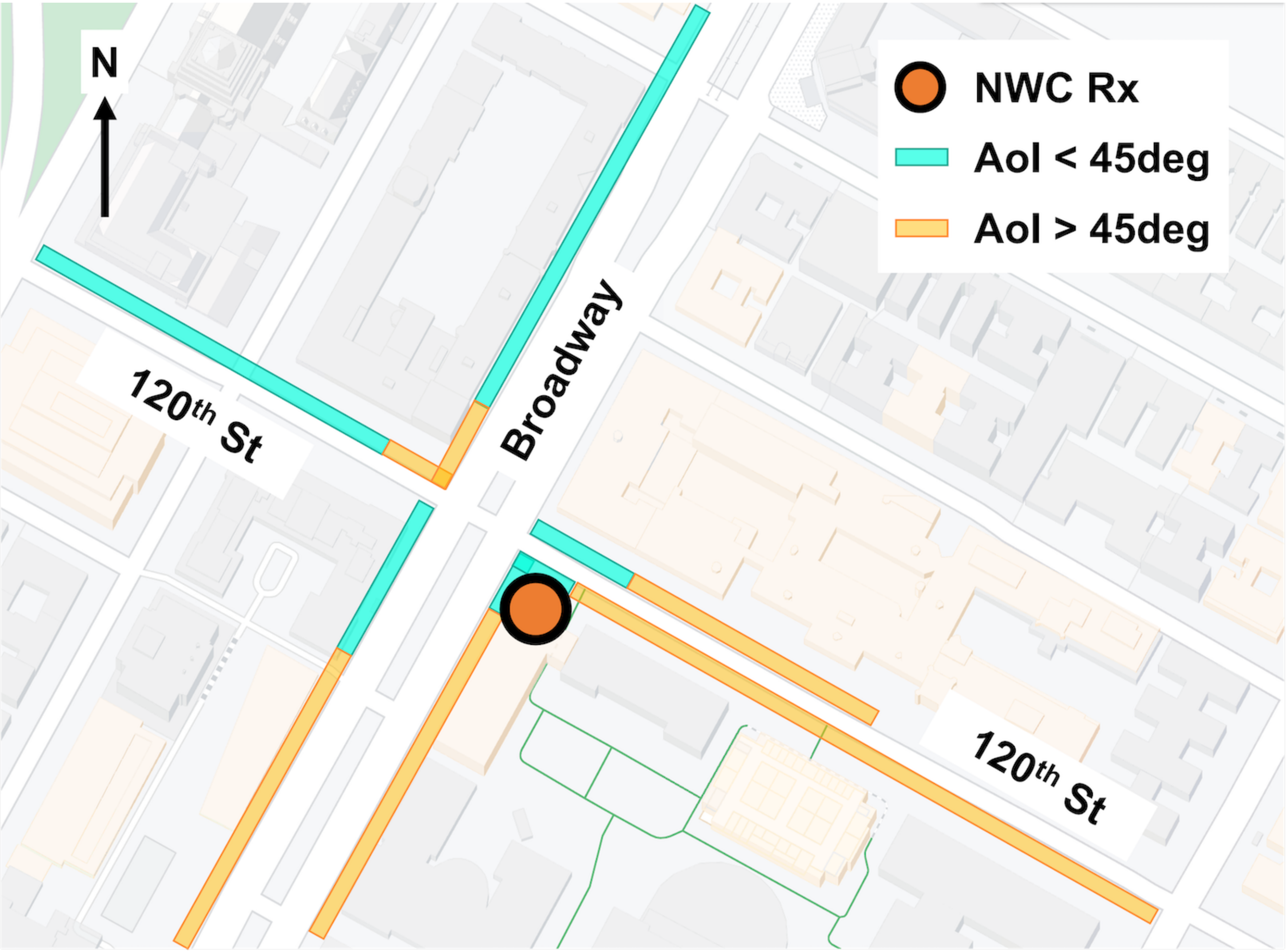
Locational Effects - Angle of Incidence





Angle of Incidence

- ~10 dB difference in path gain at close range
- Decreases with range



Additional Results

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- Additional results/discussion (omitted for time/space)
- MU-MIMO capability for users at far distance from a BS
- Environmental effects: scaffolding at building with UE, tree foliage
- Full report available at arXiv:2205.09436 [eess.SP]

Scaffolding at NWC

Typical Street Foliage around NWC

arXiv

Outline

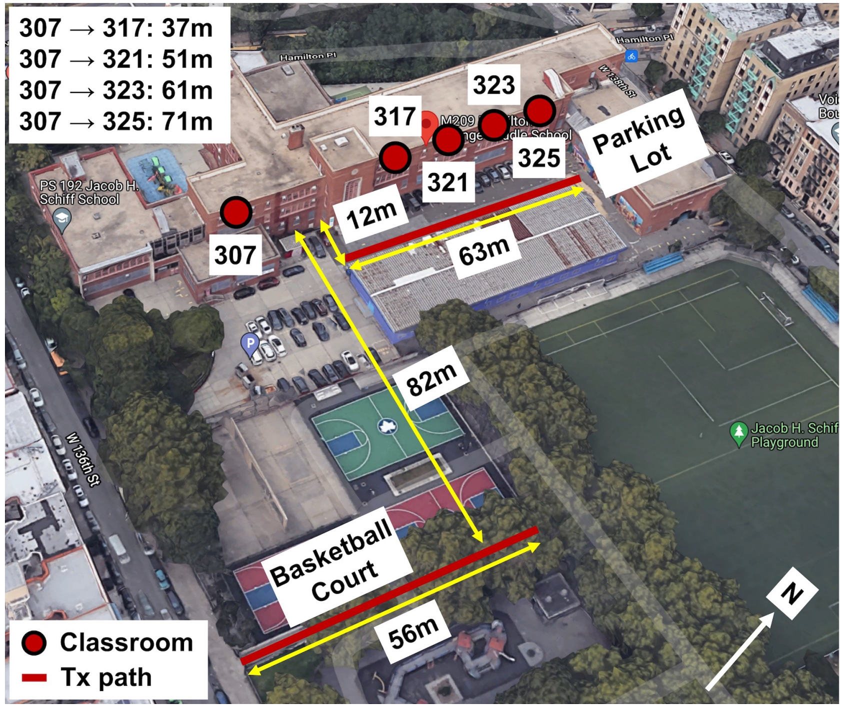
wim.net
Wireless & Mobile Networking Lab

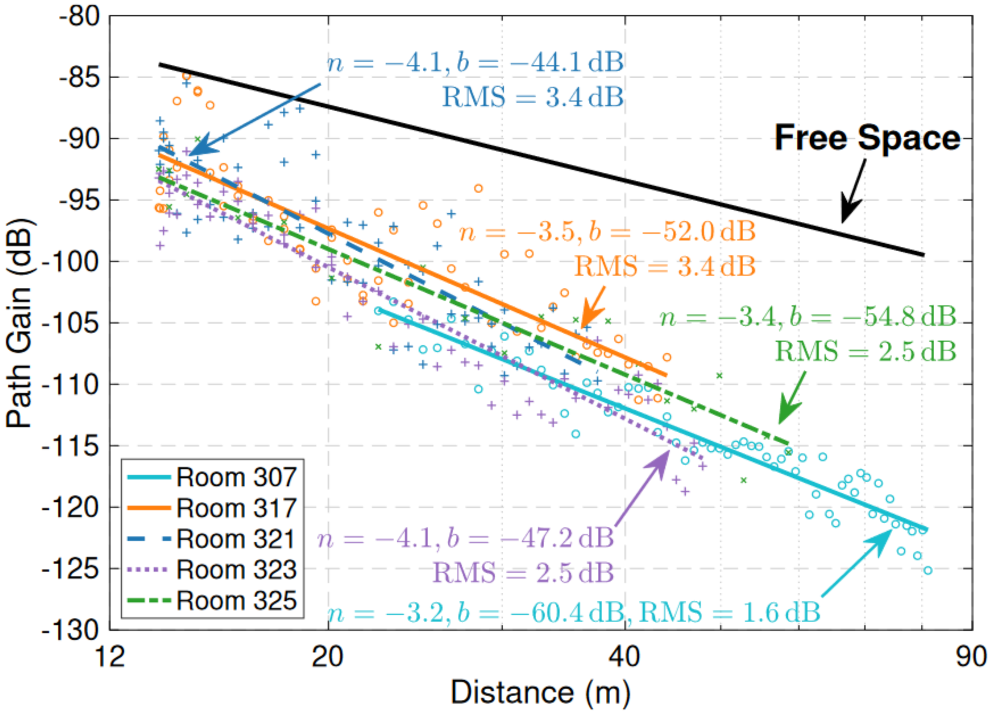
- Research Questions and Methodology
- The Outdoor-to-Indoor Measurement Campaign
- Path Gain and Link Rates in Different Scenarios
- **Case Study of a Public Middle School + Dataset**
- Closing Remarks

Hamilton Grange Middle School (HMS)

NYC Public Middle School in West Harlem

Work w/COSMOS RET Program Teachers





- Higher path gain at HMS than other locations - thin, “traditional” glass
- Good potential for service provided by mmWave fixed wireless access
- Uniform path gain for all five classrooms measured

Hamilton Grange Middle School (HMS)

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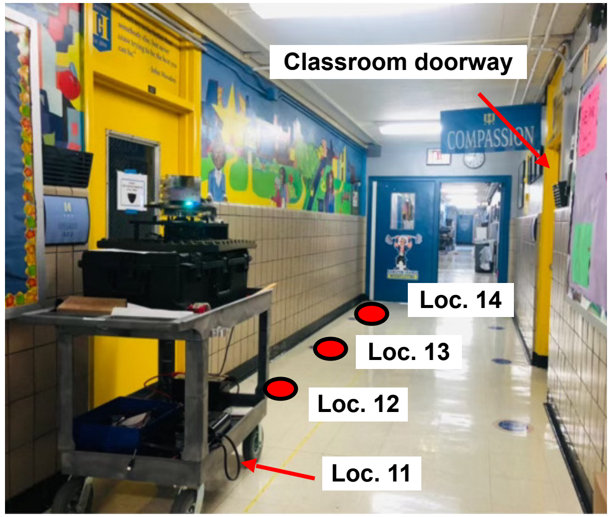
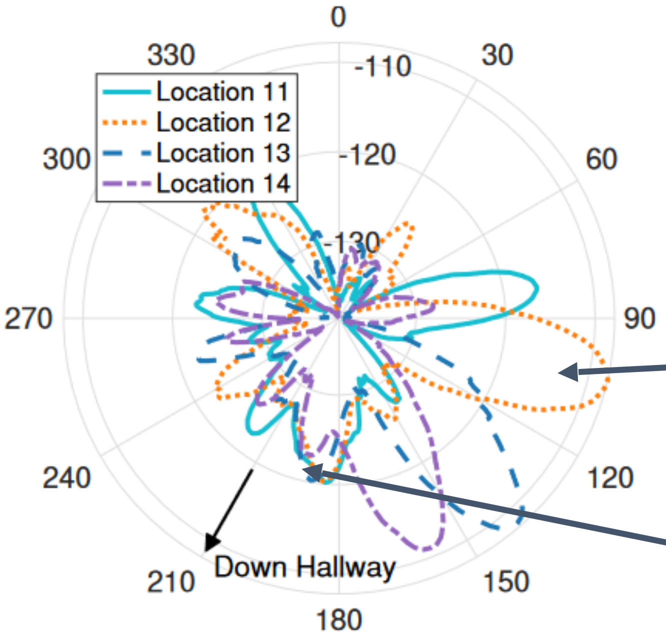
- Also performed “swapped” measurement: Tx stationary, Rx moved
- Rx moved along interior hallway in fixed 1m increments
- Power angular spectra can describe signal propagation to deep interior space



Hallway Measurement



Power angular spectra

- Two candidate signal paths
  - From end of hallway
  - From closest doorway

Peak angle “swings” around the doorway as Rx moves past it (doorway between L12 and L13)

No discernible peaks from the end of hallway

• D. Chizhik, J. Du, and R. A. Valenzuela. 2021. Universal Path Gain Laws for Common Wireless Communication Environments. In *IEEE Trans. Antennas Propag*

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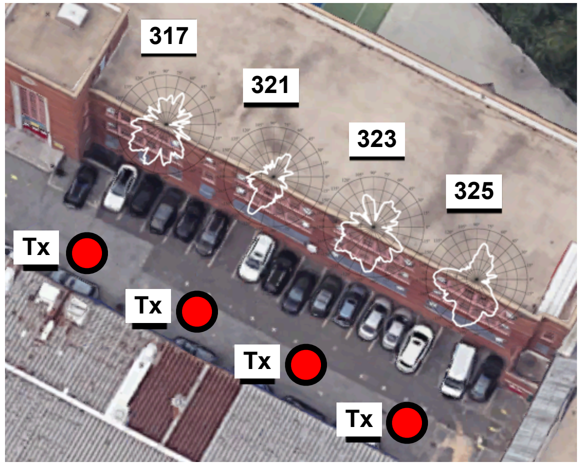
- Back to the original research question…
- OtI coverage looks promising in buildings with less lossy window glass
- ~20 dB benefit over Low-e windows lessens beamforming requirements
  - Important: power angular spectra show greatly imparied azimuth beamforming gain in some cases



BS-per-classroom

Hamilton Grange Dataset is Available!

Available at NIST: https://nextg.nist.gov/submissions/131

Also: https://wimnet.ee.columbia.edu/wp-content/uploads/2022/10/hms_data.zip

NIST

Closing Remarks

Is outdoor-to-indoor (OtI) coverage feasible in mmWave networks?

- Yes, but your (building's) mileage may vary…
- Measured >2,000 Tx-Rx links across 7 locations in West Harlem, NYC
- Type of window glass used can have up to 20 dB of impact on path loss
- Other impacts such as mid-street blockages, height of indoors user: 10-12dB of potential impacts
- Buildings with low-loss glass and line-of-sight to the BS: strong potential for OtI coverage at multi-Gb/s link rates
  - Bridge the digital divide through fixed wireless service provisioning

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Thank you!

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Columbia University in the City of New York · Nokia Bell Labs · Stuyvesant High School · The City College of New York · Universidad Tecnica Federico Santa Maria