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Indoor Office Wideband Penetration Loss Measurements at 73 GHz

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Agenda

- ❑ Motivation and Background for MmWave Penetration Loss
- ❑ Measurement System and Environment
- ❑ Penetration Loss Calculations
- ❑ Measurement Results and Analysis
- ❑ Conclusions and Noteworthy Observations

Motivation

- Why is mmWave penetration loss important?
  - Sub-6 GHz wireless communications **rely heavily on low penetration losses**
    - Indoor WiFi coverage between rooms
    - Outdoor-to-indoor UMi and UMa coverage
- Penetration loss models are used to **predict coverage**:
  - Into buildings; between floors; through partitions; and for outdoor-to-indoor scenarios [11]
- Models can be used to **supplement ray-tracing**, coverage, propagation, and **site-planning tools**
  - SMT PLUS [1]
  - SitePlanner [23],[24]
  - LANPlanner [23],[24]

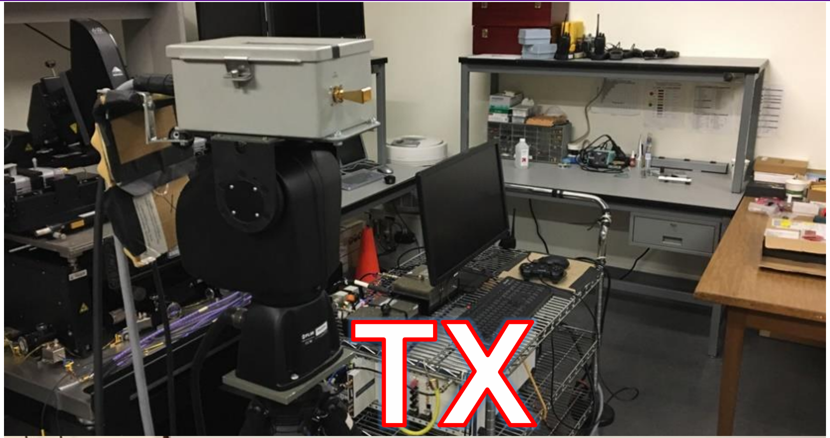
[1] R. R. Skidmore, T. S. Rappaport, and A. L. Abbott, "Interactive coverage region and system design simulation for wireless communication systems in multifloored indoor environments: SMT PLUS," in Proceedings of the 5th IEEE International Conference on Universal Personal Communications, vol. 2, Sept. 1996, pp. 646–650.
[11] G. D. Durgin, T. S. Rappaport, and H. Xu, "Measurements and models for radio path loss and penetration loss in and around homes and trees at 5.85 GHz," IEEE Transactions on Communications, vol. 46, no. 11, pp. 1484–1496, Nov. 1998.
[23] T. S. Rappaport and R. Skidmore, "System and method for ray tracing using reception surfaces," Dec. 2004, US Patent 10/830,445. [Online]. Available: https://www.google.com/patents/US20040259554
[24] Austin Business Journal, "Motorola buys wireless valley," Dec. 2005. [Online]. Available: http://www.bizjournals.com/austin/stories/2005/12/19/daily46.html

Motivation

- 900 MHz to 18 GHz penetration loss does **not** increase monotonically/linearly with frequency for V-V polarization [16]
- Floor Attenuation Factors (FAF) at 800 & 2000 MHz in an underground garage:
  - **5.2 dB/m of depth** [28]
- 914 MHz FAF in an office building: [5-7]
  - **16.2 dB, 27.5 dB**, and **31.6 dB** through 1, 2, and 3 floors, respectively
- 30 GHz to 50 GHz [21]:
  - Concrete slab: **4.50 dB/cm:** (VV / HH); Solid wood: **4.19 dB/cm:** (V-V) / **2.42 dB/cm** (H-H)
- 28 GHz [20]:
  - **Clear glass: 3.6 dB to 3.9 dB; Tinted Glass: 24.5 dB to 40 dB**

[5] S. Y. Seidel and T. S. Rappaport, “900 MHz path loss measurements and prediction techniques for in-building communication system design,” in 1991 Proceedings of the 41st IEEE Vehicular Technology Conference, May 1991, pp. 613–618.
[6] ——, “Path loss prediction in multifloored buildings at 914 MHz,” Electronics Letters, vol. 27, no. 15, pp. 1384–1387, July 1991.
[7] ——, “914 MHz path loss prediction models for indoor wireless communications in multifloored buildings,” IEEE Transactions on Antennas and Propagation, vol. 40, no. 2, pp. 207–217, Feb. 1992.
[16] Y. P. Zhang and Y. Hwang, “Measurements of the characteristics of indoor penetration loss,” in 1994 IEEE 44th Vehicular Technology Conference (VTC), vol. 3, June 1994, pp. 1741–1744.
[20] H. Zhao et al., “28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city,” in 2013 IEEE International Conference on Communications (ICC), June 2013, pp. 5163–5167.
[21] A. K. M. Isa, A. Nix, and G. Hilton, “Impact of diffraction and attenuation for material characterisation in millimetre wave bands,” in 2015 Loughborough Antennas and Propagation Conference (LAPC), Nov. 2015, pp. 1–4.
[28] H. C. Nguyen et al., “A simple statistical signal loss model for deep underground garage,” in 2016 IEEE 84th Vehicular Technology Conference (VTC2016-Fall), Sept. 2016, pp. 1–5.

Penetration Loss Measurement Hardware



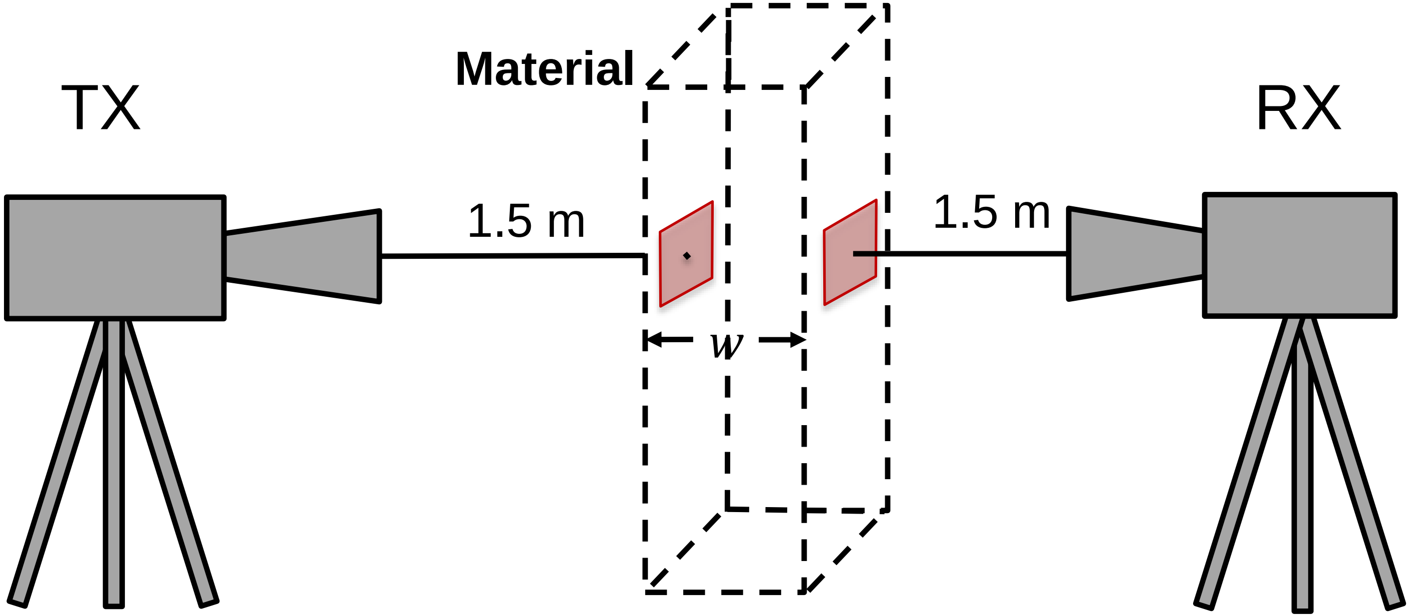
Broadband Sliding Correlator

Carrier Frequency	73.5 GHz
TX PN Code Chip Rate	500 Mcps
TX/RX IF Frequency	5.625 GHz
TX/RX LO Frequency	67.875 GHz
RF Bandwidth (Null-to-Null)	1 GHz
Max. TX Output Power	14.1 dBm
TX/RX Antenna Gain	20 dBi
TX and RX Azimuth/Elevation HPBW	15°/15°
TX and RX Antenna Height	1.5 m
Multipath Time Resolution	2 ns
TX Polarization	Vertical
RX Polarization	Vertical / Horizontal

[33] G. R. MacCartney, Jr. and T. S. Rappaport, “A flexible millimeter-wave channel sounder with absolute timing,” IEEE Journal on Selected Areas in Communications, June 2017.
[34] G. R. MacCartney, Jr. et al., “A flexible wideband millimeter-wave channel sounder with local area and NLOS to LOS transition measurements,” in 2017 IEEE International Conference on Communications (ICC), May 2017, pp. 1–7

Penetration Loss Setup

- 20 dBi, 15º HPBW antennas at TX and RX
- **1.5 m distance** (5 Fraunhofer distances) on either side of material
- At 1.5 m distance, antenna spread upon material is a **40 cm x 40 cm cross-section**
- Measured both co- and cross-polarized antenna configurations (**XPD = 27.1 dB**)

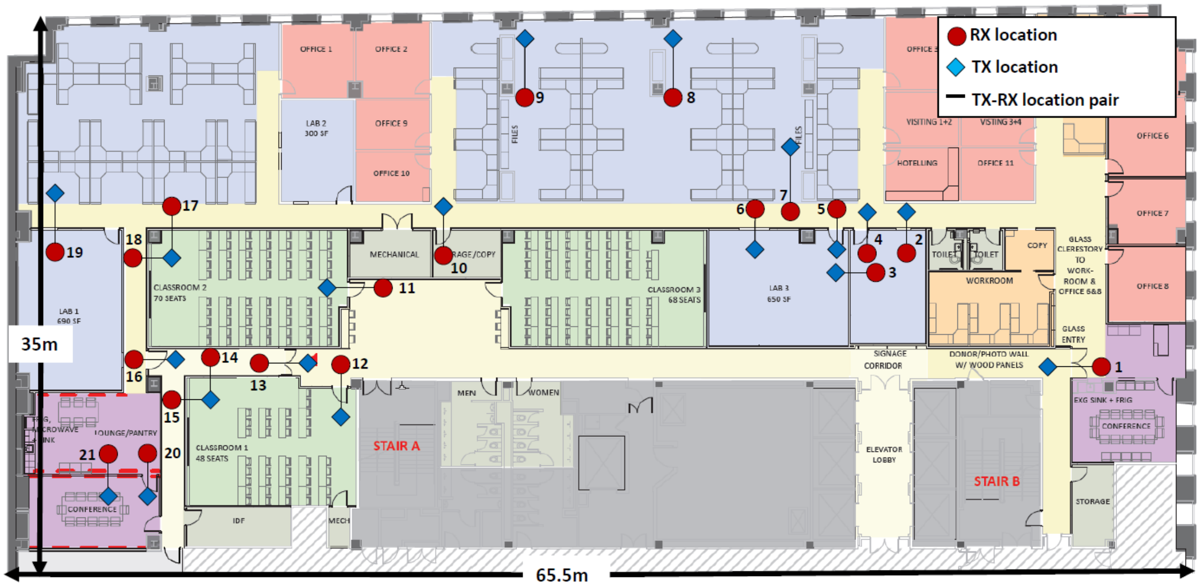


NOT DRAWN TO SCALE

Penetration Loss Setup

- 21 TX-RX Locations to measure partition loss with primary ray through material
- Typical open plan office and hallway with labs: 65.5 m x 35 m
- Materials tested: Plasterboard Walls, Whiteboard Writing Walls, Clear Glass, Glass Doors, Closet Doors, Steel doors

Material	Map Locations	Average Thickness
Plasterboard Walls	3; 14; 17; 21	13.7 cm
Whiteboard Writing Walls w/ Fiberboard	15; 18	21.4 cm
Clear Glass	2; 6; 19	1 cm
Glass Doors	1; 4; 5; 11; 12	1cm
Closet Doors – Medium Density Fiber (MDF)	7; 8; 9	7 cm
Steel Doors	10; 13; 16; 20	5.3 cm



[3] G. R. MacCartney, Jr. et al., “Indoor office wideband millimeter-wave propagation measurements and models at 28 GHz and 73 GHz for ultradense 5G wireless networks (Invited Paper),” IEEE Access, pp. 2388–2424, Oct. 2015.

Examples of Materials

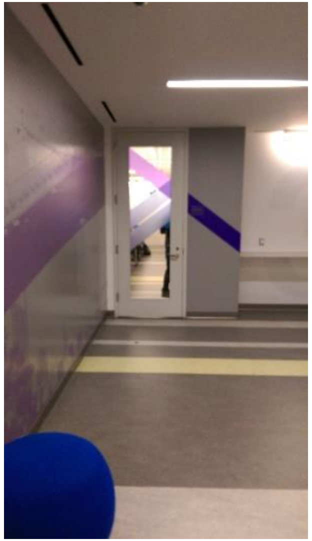
❑Glass Door

Location 1

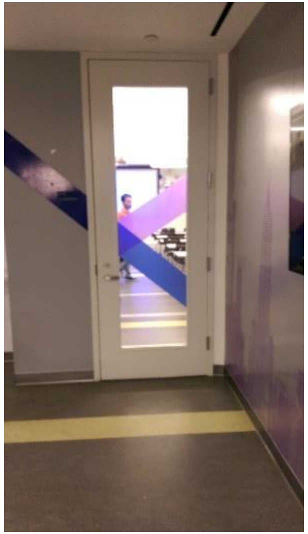
Location 4

Lights off; not tinted

Location 5



Location 11



Location 12

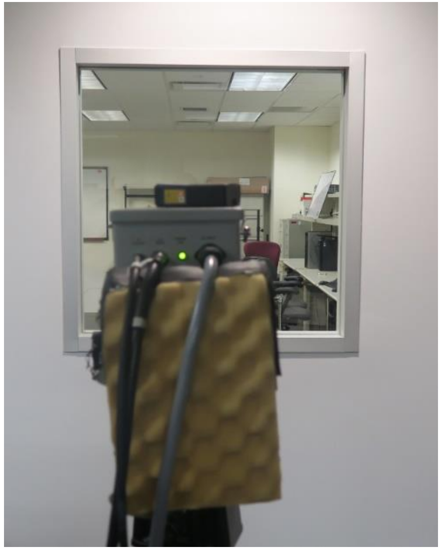
Examples of Materials

- Clear Glass

Location 2

Lights off; not tinted

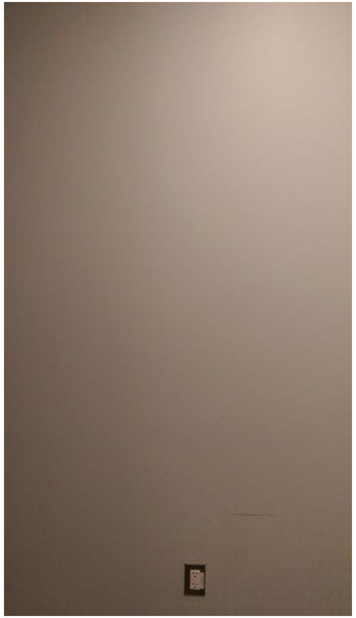
Location 6



Location 19

Examples of Materials

- Plasterboard Walls



Location 17

Location 3

Location 21

Examples of Materials

- Closet Door: Medium-Density Fibreboard (MDF)

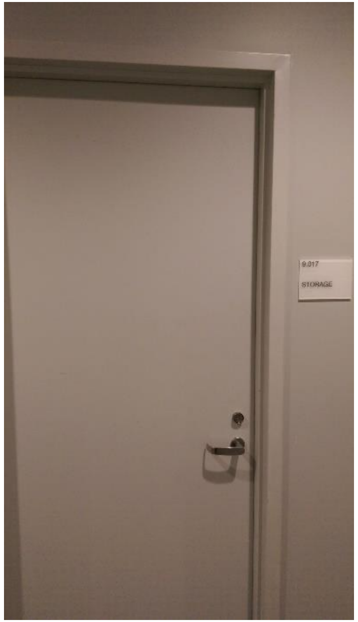
Location 7

Location 8

Location 9

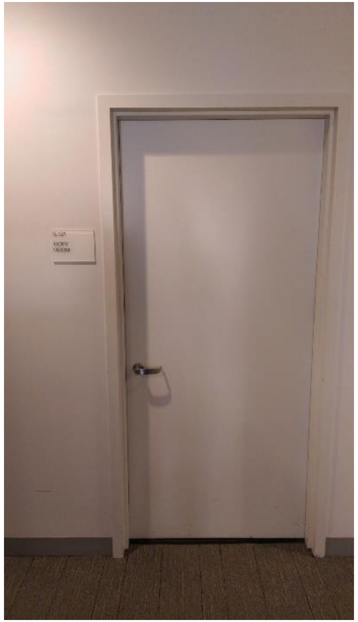
Examples of Materials

- Steel Door



Location 16

Location 13



Location 10

Examples of Materials

- Whiteboard Writing Walls

Location 15

Location 18

Penetration Loss Calculation

- 10 measured power delay profiles (PDPs) at each TX-RX location pair:
  - 5 redundant V-V measurements for consistency
  - 5 redundant V-H measurements for consistency
- Each measured PDP is an average of 20 PDPs to improve SNR
- Penetration Loss L (for f_c = 73.5 GHz):

$$L\ [\text{dB}] = P_{r,\text{FS}} - P_{r,\text{meas.}}$$

$$P_{r,\text{FS}}[\text{dBm}] = P_t + G_t + G_r + 20\log_{10}\left(\frac{c}{4\pi d f_c}\right)$$

where:	d:	T-R separation distance (including material width) typically > 3m
	P_t:	Transmit power in dBm
	G_t:	TX antenna gain in dB
	G_r:	RX antenna gain in dB
	c:	Speed of light in air
	f_c:	Carrier frequency
	$P_{r,\text{FS}}$:	Theoretical received power in free space using Friis' formula

[41] H. T. Friis, "A note on a simple transmission formula," Proceedings of the IRE, vol. 34, no. 5, pp. 254–256, May 1946.

Penetration Loss Calculation

- Received power is **first arriving multipath component (MPC)** of a single PDP; resolvable with not much additional MPC energy using **1 GHz RF BW**
- Average penetration loss at each location determined through **linear averaging** of 5 PDPs first MPC in milliwatts for both V-V and V-H
- Cross-polarization discrimination factor (**XPD**) was calculated and removed from V-H measurements:
  - Farfield XPD determined with V-V and V-H comparison measurements from 2.6 m to 3.0 m in 0.1 m increments
  - All five XPD values measured were within 1.5 dB with an overall average **XPD of 27.1 dB** (averaged in linear and standard deviation under 1 dB)
- Penetration loss L [dB] for each material is the average of the 5 measurements
- Normalized penetration loss calculated for the material width at each location:

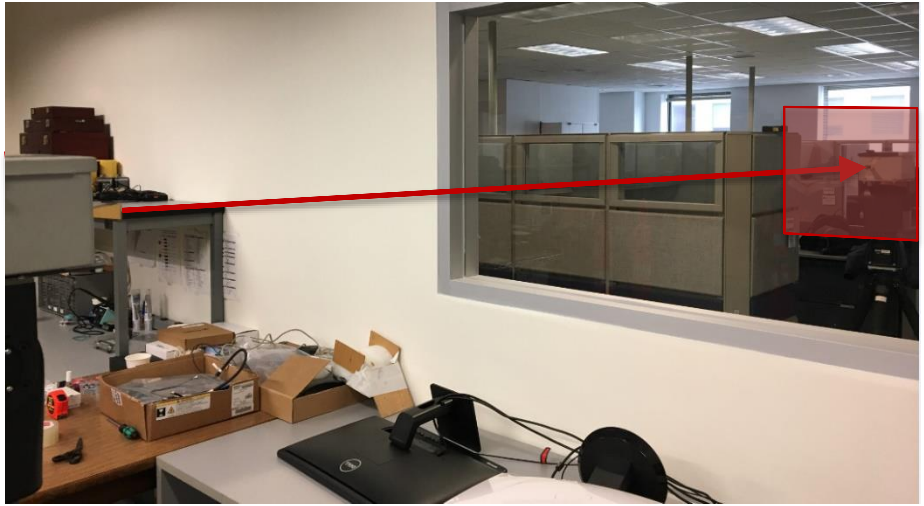
$$N\left[{}^{\mathrm{dB}}/_{\mathrm{cm}}\right] = \frac{L}{w}$$

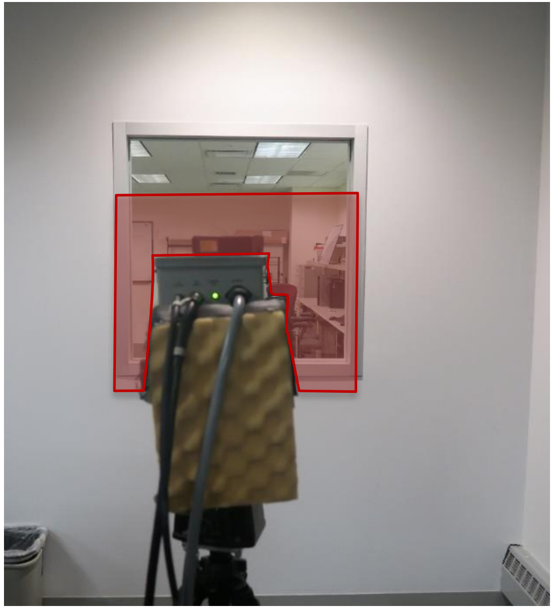
- Results are provided for common material types

Glass Door Results

- 5 glass door locations: 4 with steel frames; 1 entirely glass – 1 cm thick
  - 5.1 dB avg. penetration loss for all V-V measurements of glass doors
  - 23.4 dB avg. penetration loss for all V-H measurements of glass doors
  - 1.2 dB standard deviation across all V-V glass door measurements
  - 7.1 dB standard deviation across all V-H glass door measurements

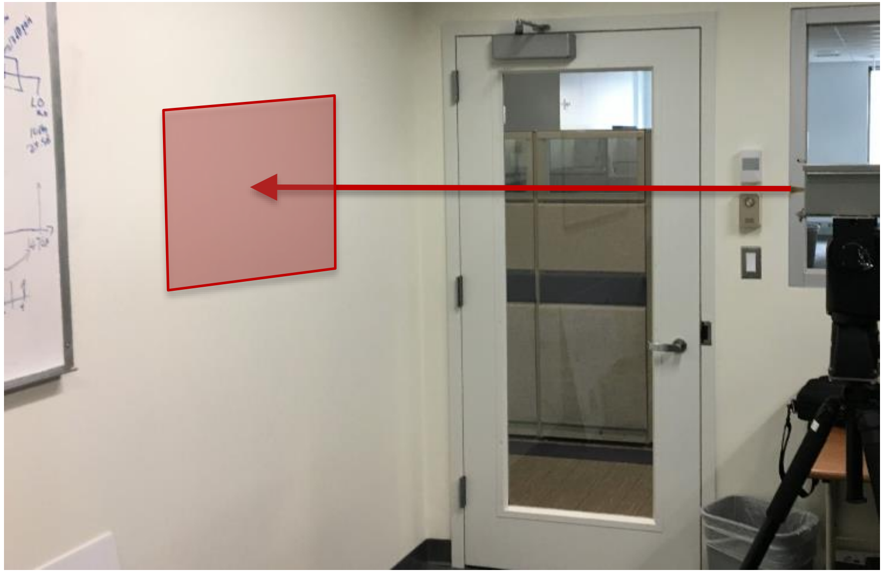
Clear Glass Results

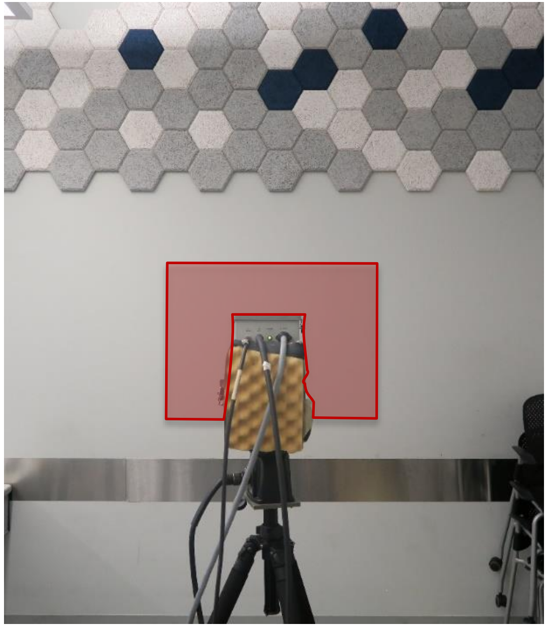




- 5 clear glass locations (internal windows) – 1 cm thick
  - 7.1 dB avg. penetration loss for all V-V measurements of glass doors
  - 18.3 dB avg. penetration loss for all V-H measurements of glass doors
  - 2.3 dB standard deviation across all V-V glass door measurements
  - 3.4 dB standard deviation across all V-H glass door measurements
  - For 1 window: At 1.5 m distance, antenna spread upon material was greater than width of window

Plasterboard Wall Results



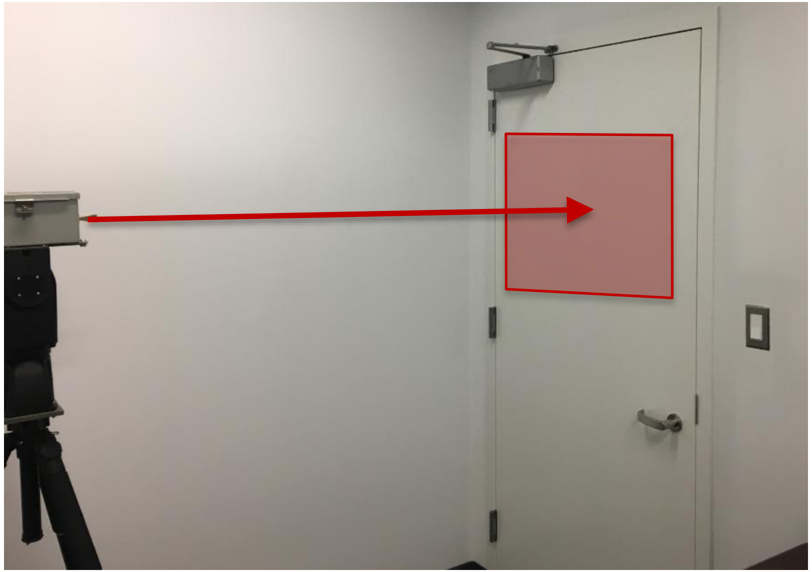


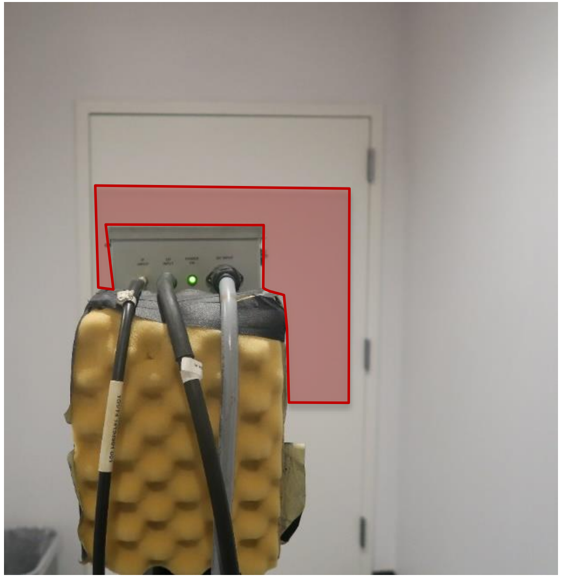
- 4 walls constructed with plasterboard: ~ 14 cm thick
  - 10.6 dB avg. penetration loss over all V-V measurements of walls
  - 11.7 dB avg. penetration loss over all V-H measurements of walls
  - 5.6 dB standard deviation across all V-V wall measurements
  - 6.2 dB standard deviation across all V-H wall measurements

MDF Closet Door Results

- 3 closet doors measured – MDF / plywood material: 7 cm thick
  - 32.3 dB avg. penetration loss over all V-V measurements of closet doors
  - 16.3 dB avg. penetration loss over all V-H measurements of closet doors
  - 8.2 dB standard deviation across all V-V closet door measurements
  - 4.2 dB standard deviation across all V-H closet door measurements

Steel Door Results





- 4 steel door locations: ~ 5 cm thick
  - 52.2 dB avg. penetration loss over all V-V measurements of steel doors
  - 48.3 dB avg. penetration loss over all V-H measurements of steel doors
  - 4.0 dB standard deviation across all V-V steel door measurements
  - 5.6 dB standard deviation across all V-H steel door measurements

Whiteboard w/ Wall Results

- 2 whiteboards with wall: ~ 21 cm thick
  - 73.8 dB avg. penetration loss over all V-V measurements of walls
  - 58.1 dB avg. penetration loss over all V-H measurements of walls
  - 9.8 dB standard deviation across all V-V wall measurements
  - 3.0 dB standard deviation across all V-H wall measurements

Conclusions and Tabulated Results

- Measurements conducted with **1 GHz RF BW**
- Glass doors and clear glass are **sensitive to polarization** and exhibit similar loss
- Loss from walls is not polarization dependent: 0.8 dB/cm
- Normalized MDF closet doors VV loss similar to glass: 4.6 dB/cm
- Highest penetration loss of **73.8 dB** for whiteboard writing walls (much **lower** normalized loss)
- Thickness of doors (many cm) creates large overall penetration losses compared to thin glass layers ~ 1cm
- Normalized average attenuations can be used to represent common building materials in **ray-tracing** or **site-planning simulations**
- Large penetration losses can promote **interference isolation**
- **Future work:** Validate these values for use in primary-ray based simulations and indoors site-planning tools

Penetration Loss of Common Building Materials for 73 GHz V-V and V-H

Material	No. of Loc.	Pol.	Loss (dB)	σ_L (dB)	Norm. Avg. Atten. (dB/cm)	σ_N (dB/cm)
Glass Door	5	V-V	5.1	1.2	5.1	1.2
		V-H	23.4	7.1	23.4	7.1
Clear Glass	3	V-V	7.1	2.3	7.1	2.3
		V-H	18.3	3.4	18.3	3.4
Wall	4	V-V	10.6	5.6	0.8	0.3
		V-H	11.7	6.2	0.8	0.4
Closet Door	3	V-V	32.3	8.2	4.6	1.2
		V-H	16.3	4.2	2.3	0.6
Steel Door	4	V-V	52.2	4.0	9.9	0.9
		V-H	48.3	5.6	9.2	0.5
Whiteboard W. Wall	2	V-V	73.8	9.8	3.5	0.5
		V-H	58.1	3.0	2.7	0.2

NYU WIRELESS Industrial Affiliates

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF:

NSF

at&t
CableLabs
CROWN CASTLE
ERICSSON
HUAWEI
intel
INTERDIGITAL
KEYSIGHT TECHNOLOGIES
L3 communications
NATIONAL INSTRUMENTS
nextlink
NOKIA
oppo
QUALCOMM
SiBEAM
Sprint
UMC
verizon

References

[1] R. R. Skidmore, T. S. Rappaport, and A. L. Abbott, “Interactive coverage region and system design simulation for wireless communication systems in multifloored indoor environments: SMT PLUS,” in Proceedings of the 5th IEEE International Conference on Universal Personal Communications, vol. 2, Sept. 1996, pp. 646–650.
[2] T. T. Tran and T. S. Rappaport, “Site specific propagation prediction models for PCS design and installation,” in MILCOM 92 Conference Record, vol. 3, Oct. 1992, pp. 1062–1065.
[3] G. R. MacCartney, Jr. et al., “Indoor office wideband millimeter-wave propagation measurements and models at 28 GHz and 73 GHz for ultradense 5G wireless networks (Invited Paper),” IEEE Access, pp. 2388– 2424, Oct. 2015.
[4] T. S. Rappaport et al., “Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (Invited Paper),” IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029–3056, Sept. 2015.
[5] S. Y. Seidel and T. S. Rappaport, “900 MHz path loss measurements and prediction techniques for in-building communication system design,” in 1991 Proceedings of the 41st IEEE Vehicular Technology Conference, May 1991, pp. 613–618.
[6] S. Y. Seidel and T. S. Rappaport, “Path loss prediction in multifloored buildings at 914 MHz,” Electronics Letters, vol. 27, no. 15, pp. 1384–1387, July 1991.
[7] Path loss prediction in multifloored buildings at 914 MHz, “914 MHz path loss prediction models for indoor wireless communications in multifloored buildings,” IEEE Transactions on Antennas and Propagation, vol. 40, no. 2, pp. 207–217, Feb. 1992.
[8] C. M. P. Ho and T. S. Rappaport, “Wireless channel prediction in a modern office building using an image-based ray tracing method,” in 1993 IEEE Global Telecommunications Conference (GLOBECOM ’93), including a Communications Theory Mini-Conference, vol. 2, Nov. 1993, pp. 1247–1251.
[9] C. R. Anderson et al., “In-building wideband multipath characteristics at 2.5 and 60 GHz,” in Proceedings IEEE 56th Vehicular Technology Conference, vol. 1, Sept. 2002, pp. 97–101.
[10] C. R. Anderson and T. S. Rappaport, “In-building wideband partition loss measurements at 2.5 and 60 GHz,” IEEE Transactions on Wireless Communications, vol. 3, no. 3, pp. 922–928, May 2004.
[11] G. D. Durgin, T. S. Rappaport, and H. Xu, “Measurements and models for radio path loss and penetration loss in and around homes and trees at 5.85 GHz,” IEEE Transactions on Communications, vol. 46, no. 11, pp. 1484–1496, Nov. 1998.
[12] M. A. Panjwani, A. L. Abbott, and T. S. Rappaport, “Interactive computation of coverage regions for wireless communication in multifloored indoor environments,” IEEE Journal on Selected Areas in Communications, vol. 14, no. 3, pp. 420–430, Apr. 1996.
[13] D. A. Hawbaker and T. S. Rappaport, “Indoor wideband radiowave propagation measurements at 1.3 GHz and 4.0 GHz,” Electronics Letters, vol. 26, no. 21, pp. 1800–1802, Oct. 1990.

References

[14] T. K. Blankenship, D. M. Kriztman, and T. S. Rappaport, “Measurements and simulation of radio frequency impulsive noise in hospitals and clinics,” in 1997 IEEE 47th Vehicular Technology Conference. Technology in Motion, vol. 3, May 1997, pp. 1942–1946.
[15] T. S. Rappaport, “Wireless personal communications: trends and challenges,” IEEE Antennas and Propagation Magazine, vol. 33, no. 5, pp. 19–29, Oct. 1991.
[16] Y. P. Zhang and Y. Hwang, “Measurements of the characteristics of indoor penetration loss,” in 1994 IEEE 44th Vehicular Technology Conference (VTC), vol. 3, June 1994, pp. 1741–1744.
[17] G. D. Durgin, T. S. Rappaport, and H. Xu, “Partition-based path loss analysis for in-home and residential areas at 5.85 GHz,” in 1998 IEEE Global Communications Conference (GLOBECOM), vol. 2, Nov. 1998, pp. 904–909.
[18] G. Durgin, T. S. Rappaport, and H. Xu, “5.85-GHz radio path loss and penetration loss measurements in and around homes and trees,” IEEE Communications Letters, vol. 2, no. 3, pp. 70–72, Mar. 1998.
[19] T. S. Rappaport et al., “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol. 1, pp. 335–349, May 2013.
[20] H. Zhao et al., “28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city,” in 2013 IEEE International Conference on Communications (ICC), June 2013, pp. 5163–5167.
[21] A. K. M. Isa, A. Nix, and G. Hilton, “Impact of diffraction and attenuation for material characterisation in millimetre wave bands,” in 2015 Loughborough Antennas and Propagation Conference (LAPC), Nov. 2015, pp. 1–4.
[22] T. S. Rappaport and S. Sandhu, “Radio-wave propagation for emerging wireless personal-communication systems,” IEEE Antennas and Propagation Magazine, vol. 36, no. 5, pp. 14–24, Oct. 1994.
[23] T. S. Rappaport and R. Skidmore, “System and method for ray tracing using reception surfaces,” Dec. 2004, US Patent 10/830,445. [Online]. Available: https://www.google.com/patents/US20040259554
[24] Austin Business Journal, “Motorola buys wireless valley,” Dec. 2005. [Online]. Available: http://www.bizjournals.com/austin/stories/2005/12/19/daily46.html
[25] S. Y. Seidel and T. S. Rappaport, “A ray tracing technique to predict path loss and delay spread inside buildings,” in 1992 IEEE Global Communications Conference (GLOBECOM): Communication for Global Users, vol. 2, Dec. 1992, pp. 649–653.
[26] S. Y. Seidel and T. S. Rappaport, “Site-specific propagation prediction for wireless in-building personal communication system design,” IEEE Transactions on Vehicular Technology, vol. 43, no. 4, pp. 879–891, Nov. 1994.
[27] M. Lott and I. Forkel, “A multi-wall-and-floor model for indoor radio propagation,” in IEEE VTS 53rd Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No.01CH37202), vol. 1, May 2001, pp. 464–468.

References

[28] H. C. Nguyen et al., “A simple statistical signal loss model for deep underground garage,” in 2016 IEEE 84th Vehicular Technology Conference (VTC2016-Fall), Sept. 2016, pp. 1–5.
[29] M. Chamchoy, P. Jaturatussanai, and S. Promwong, “Empirically based path loss and penetration loss models for UWB communication in residential environment,” in 2005 Fifth International Conference on Information, Communications and Signal Processing, Dec. 2005, pp. 278–281.
[30] K. Haneda et al., “5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments,” in 2016 IEEE 83rd Vehicular Technology Conference (VTC2016-Spring), May 2016, pp. 1–7.
[31] G. Durgin, N. Patwari, and T. S. Rappaport, “Improved 3D ray launching method for wireless propagation prediction,” Electronics Letters, vol. 33, no. 16, pp. 1412–1413, July 1997.
[32] J. Kokkoniemi, J. Lehtomki, and M. Juntti, “Measurements on penetration loss in terahertz band,” in 2016 10th European Conference on Antennas and Propagation (EuCAP), Apr. 2016, pp. 1–5.
[33] G. R. MacCartney, Jr. and T. S. Rappaport, “A flexible millimeter-wave channel sounder with absolute timing,” IEEE Journal on Selected Areas in Communications, June 2017.
[34] G. R. MacCartney, Jr. et al., “A flexible wideband millimeter-wave channel sounder with local area and NLOS to LOS transition measurements,” in 2017 IEEE International Conference on Communications (ICC), May 2017, pp. 1–7.
[35] G. R. MacCartney, Jr. and T. S. Rappaport, “73 GHz millimeter wave propagation measurements for outdoor urban mobile and backhaul communications in New York City,” in 2014 IEEE International Conference on Communications (ICC), June 2014, pp. 4862–4867.
[36] G. Durgin and T. S. Rappaport, “Basic relationship between multipath angular spread and narrowband fading in wireless channels,” Electronics Letters, vol. 34, no. 25, pp. 2431–2432, Dec. 1998.
[37] W. G. Newhall and T. S. Rappaport, “An antenna pattern measurement technique using wideband channel profiles to resolve multipath signal components,” in Antenna Measurement Techniques Association 19th Annual Meeting & Symposium, Nov. 1997, pp. 17–21.
[38] Aalto University, AT&T, BUPT, CMCC, Ericsson, Huawei, Intel, KT Corporation, Nokia, NTT DOCOMO, New York University, Qualcomm, Samsung, University of Bristol, and University of Southern California, “5G channel model for bands up to 100 GHz,” 2016, Oct. 21. [Online]. Available: http://www.5gworkshops.com/5GCM.html
[39] G. G. Joshi et al., “Near-ground channel measurements over line-ofsight and forested paths,” IEEE Proceedings - Microwaves, Antennas and Propagation, vol. 152, no. 6, pp. 589–596, Dec. 2005.
[40] K. R. Schaubach, N. J. Davis, and T. S. Rappaport, “A ray tracing method for predicting path loss and delay spread in microcellular environments,” in 1992 Proceedings of the Vehicular Technology Society 42nd VTS Conference - Frontiers of Technology, vol. 2, May 1992, pp. 932–935.
[41] H. T. Friis, “A note on a simple transmission formula,” Proceedings of the IRE, vol. 34, no. 5, pp. 254–256, May 1946.

Thank You!

Questions