In-Building Wideband Multipath Characteristics at 2.5 & 60 GHz

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***Abstract*— This paper contains measured data for 2.5 & 60 GHz in-building partition loss. Path loss measurements were recorded using a broadband sliding correlator channel sounder which recorded over 39,000 Power Delay Profiles (PDPs) in 22 separate locations in a modern office building. Transmitters and receivers were separated by distances ranging from 3.5 to 27.4 meters, and were separated by a variety of obstructions, in order to emulate future single-cell-per-room wireless networks. These measurements may aid in the development of future in-building wireless networks in the unlicensed 2.4 GHz and 60 GHz bands.**

***Keywords*—** *In building propagation, path loss, partition loss, millimeter wavelength*

I. Introduction

Over the past decade, the market for wireless service has grown at an unprecedented rate. The industry has expanded from cellular phones and pagers to Personal Communication Systems (PCS), wireless local area networks (WLANs), and broadband wireless services that can provide voice, data, and full-motion video in real time [1]. In order for the visions of 3rd and 4th generation of wireless communication standards to be realized, system design engineers must have a thorough understanding of the wireless channels in which these devices operate.

In recent years, there has been an increasing interest in providing broadband communications in the 2.4 GHz ISM band and the 60 GHz unlicensed band for WLANs. In particular, the propagation characteristics of the 60 GHz band provides the promise of high spatial frequency reuse, with low-power transmitters operating in a single-cell-per-room configuration [2], [3], called "femtocellular" [2]. Such a system will provide high data-rate services for densely populated buildings, carrying many times more traffic than current wireless networks. While spectrum in the 2.4 and 60

Most of the available literature has so far concentrated on investigating penetration loss into buildings, rather than from obstructions inside buildings. Several propagation studies show that penetration loss of various building materials increases as the transmission frequency increases. Zhang and Hwang as well as Golding and Livine show how penetration loss in various building materials increases over the frequency range of 900 MHz—18 GHz and 20—50 GHz, respectively [14], [15]. Additionally, penetration losses for building materials at various frequencies between 5 and 60 GHz are reported in [4], [14], [16]—[23], and a general increase in penetration loss as frequency increases can be observed. These data compare favorably to the penetration losses reported in Section III of this paper.

II. Experimental Setup

A. Description of Measurement Procedure and Locations

Eight separate transmitter and 22 separate receiver locations were selected on the 4th floor of Durham Hall on the Virginia Tech campus. The measurement sites were chosen to be representative of a broad range of typical femtocellular propagation environments in a work setting, where a low power transmitter will serve a single room or portion of a floor. Durham Hall was completed in 1998, with a foundation and framework made from steel reinforced concrete, with interior sheetrock and concrete cinderblock walls, ceramic tile and carpeted floors, and suspended panel ceilings. Fig. 1 illustrates the building floor plan and identifies transmitter and receiver locations for this measurement campaign. Measurements were grouped into eight different segments, based on transmitter location, and numbered based on both transmitter and receiver location. These measurements look specifically at the wideband propagation effects that may be encountered in a typical office building, with transmitter and receiver locations chosen to provide line-of-sight (LOS), non line-of-sight (NLOS), and cluttered propagation environments.

A broadband vector sliding correlator channel sounder, developed in [24] was used to record wideband PDPs at all measurement locations. The channel sounder utilized an 11-bit pseudo-random noise code running at 400 MHz, with GPS disciplined oscillators generating a highly stable frequency reference at transmitter and receiver, providing the channel sounder with a multipath temporal resolution of 2.5 nanoseconds. Two different RF chains were utilized, one for the 60 GHz measurements and the other for the 2.5 GHz measurements.

For the 60 GHz measurements, the transmitter and receiver utilized pyramidal horn antennas which had a gain of 25 dBi and first-null beamwidths of 50°. These high-gain horn antennas were used in order to overcome the considerable amount of path loss at 60 GHz, as well as to emulate sectored

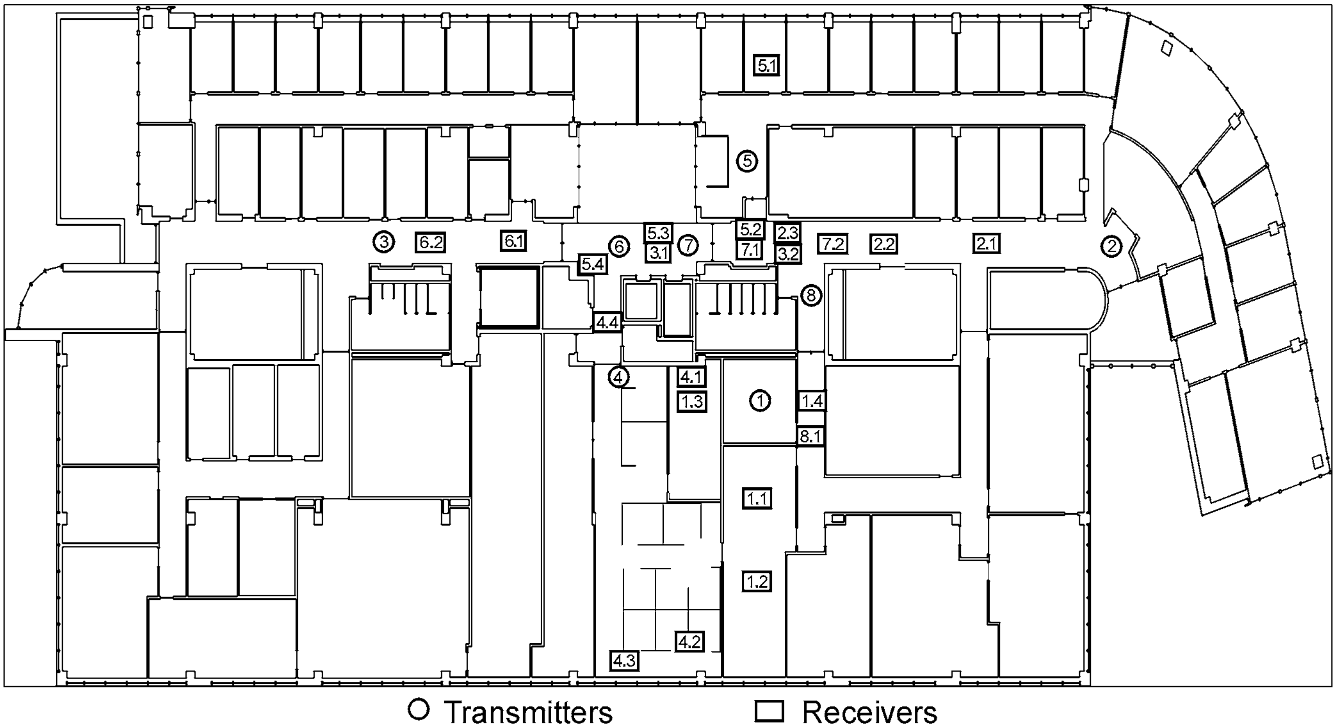

Fig. 1. Map of the 4th floor of Durham Hall at Virginia Tech, with transmitter and receiver locations identified

antenna systems proposed for millimeter-wavelength indoor applications. Transmitter output power (as measured at the base of the antenna) was set at -10 dBm. For the 2.5 GHz measurements, transmitter and receiver utilized omnidirectional biconical antennas with a 6 dBi gain. These lower gain omnidirectional antennas were used due to their compact physical size, as well as to emulate 2.4 GHz WLANs operating with omnidirectional antennas. Transmitter output power (as measured at the base of the antenna) was set at 0 dBm.

For both configurations, transmitter and receiver antennas were vertically polarized, and heights were nominally set at 1.2 meters, with the exception of transmitter location 4 where the antenna height was increased to 2.4 meters. A laptop computer was used to record inphase and quadrature delay profiles, and software post-processing generated the PDPs. Measured power delay profiles may be found in [24], [25].

B. *Definition of Path Loss*

To measure path loss, the channel sounder records wideband power delay profiles at 2.5 GHz and 60 GHz. Narrowband received power fluctuates over a small area due to multipath-induced fading, however, averaging power over a local area yields a reliable estimate for the local average received power independent of signal bandwidth [16]. Additionally, narrowband power can be calculated from a wideband PDP using the following relationship [26]

$$P_R\,(dBm) = P_{cal}\,(dBm) + 10\log_{10}\left(\frac{\sum_r G_r \Delta\tau_r}{\sum_r G_{cal}\Delta\tau_{cal}}\right) \quad (1)$$

where $\sum_r G_r \Delta\tau_r$ is the integrated power in a given PDP (area under the PDP). The term $\sum_r G_{cal}\Delta\tau_{cal}$ is the integrated power in a PDP from a calibration run and is assigned the known input power P_{cal}.

III. SITE-SPECIFIC MEASUREMENT RESULTS

A. *Large Scale Path Loss*

Figures 4a and 4b are scatter plots of all measured path loss values versus distance for the 2.5 GHz and 60 GHz measurements. A Minimum Mean Square Error analysis was applied to the measured data to determine the path loss exponent [16]. The resulting path loss exponent for 2.5 GHz was $n = 2.4$, with a standard deviation of $\sigma = 5.8$dB and for 60 GHz the path loss exponent was $n = 2.1$ with $\sigma = 7.9$dB, which are within the ranges for in-building same-floor propagation reported in [6], [16], [22], [26], [27].

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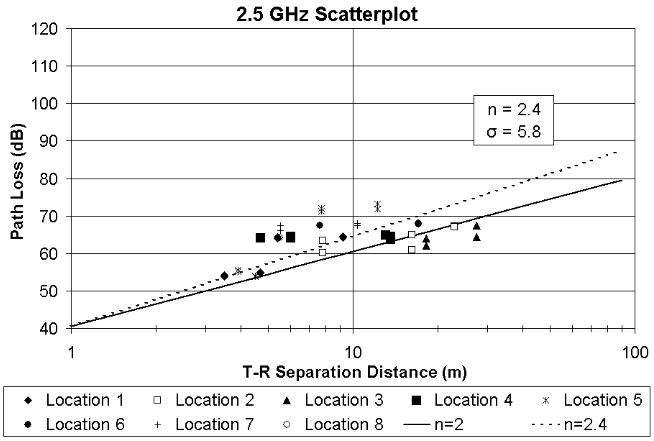
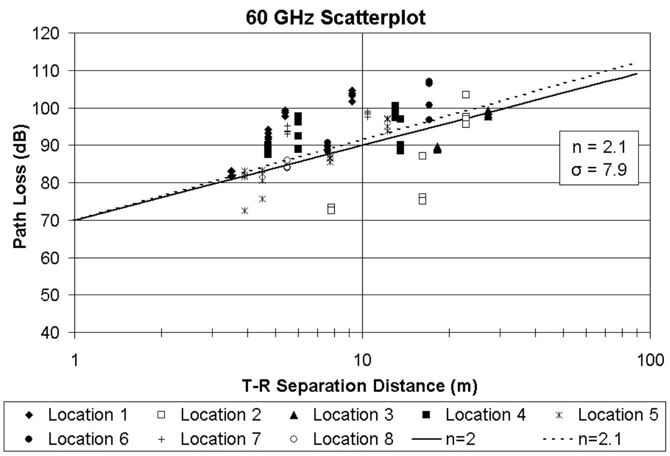


(a)



(b)

Fig. 4. Scatterplot of all Measured Path Loss Values (Excluding Antenna Gains) on a Single Floor of a Modern Office Building for (a) 2.5 GHz with Transmitter and Receiver using Omnidirectional Biconical Antennas with 6dBi Gain, and (b) 60 GHz with Transmitter and Receiver using Pyramidal Horn Antennas with 25dBi Gain and 50° First-Null Beamwidth

B. Partition Based Path Loss Analysis

Using measured penetration losses, Durgin, et. al., Nobles, et. al., and Karlsson, et. al., have developed indoor propagation models at 5.8 GHz, 17 & 60 GHz, and 5.0 GHz, respectively, to predict path loss based on the number and types of obstructions encountered between transmitter and receiver [4], [22], [23]. These models can also be used to characterize the site-specific nature of emerging femtocellular systems, and may be used in ray-tracing algorithms to predict network coverage and throughput.

In propagation analysis the path loss exponent, n, is useful for predicting large-scale propagation effects. However, the path loss exponent model is inadequate at predicting site-specific propagation effects, such as reflection, diffraction, or penetration losses caused by a particular building layout, construction materials, furniture, etc. A more refined model uses *partition-dependant attenuation factors* [4], [28], which assumes free space propagation ($n=2$) with additional path loss incurred based on the number and type of objects (such as walls or doors) intersected by a single ray drawn from transmitter to receiver. Then, the path loss is given by the following [4]

$$PL(d) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + aX_a + bX_b + \ldots \qquad (2)$$

where $PL(d)$ is the path loss in dB at a particular distance d in meters from the transmitter, $X_a, X_b, \ldots$ are the attenuation values in dB for the partitions between transmitter and receiver, and $a, b, \ldots$ are the number of times the ray intersects each type of partition (i.e. a intersections with partition X_a, b intersections with partition X_b, and so forth).

For measurement data at a particular site, the only unknowns in (2) are the individual partition attenuation factors, $X_a, X_b, \ldots$, which may be found by applying a Minimum Mean Square Error analysis of measured versus predicted path loss using the procedure described in [4].

By looking at the building floor plan (Fig. 1), partitions that existed between each transmitter and receiver link were placed in five separate categories:

1. *Drywall*: 2 sheets of standard ½ inch thick sheetrock wallboard.
2. *Office Whiteboard*: Standard office dry-erase melamine whiteboard, attached to ½ inch thick plywood backing.
3. *Clear Glass*: 3mm thick clear glass which is untextured and unreinforced.
4. *Mesh Glass*: 3 mm thick clear glass which has been reinforced with interlacing 24 gauge wires configured in a rectangular grid with openings of ½ inch × ½ inch.
5. *Clutter*: Objects that encroached into the first Fresnel zone but did not directly block the LOS signal from transmitter to receiver. Clutter includes office furniture such as chairs, desks, bookcases, and filing cabinets, in addition to soft partitions that did not extend to the ceiling.

A summary of all partition attenuation factors at 2.5 GHz and 60 GHz is shown in Table I, with the attenuation values representing loss in excess of free space, i.e., loss induced by the partition in addition to the ideal free space path loss (n = 2). Additionally, to ensure that partition attenuation values could be compared in a meaningful way, all attenuation values were normalized to dB per centimeter of material thickness.

IV. CONCLUSIONS

This paper presented the results of a measurement campaign and detailed analysis of in-building 2.5 GHz and 60 GHz wireless channels. Measurements were analyzed in context with site-specific information, and results include partition loss values for a variety of materials encountered in an office or laboratory building, and are comparable to values published in the literature.

TABLE I.
PARTITION LOSSES (LOSS IN EXCESS OF FREE SPACE) AT 2.5 & 60 GHZ ON THE 4TH FLOOR OF DURHAM HALL, VIRGINIA TECH

		Drywall	Office Whiteboard	Clear Glass	Mesh Glass	Clutter
Number of Measurements at Each Frequency		7	4	4	4	4
Material Thickness (cm)		2.5	1.9	0.3	0.3	--
2.5 GHz	Average Measured Attenuation (dB)	5.4	0.5	6.4	7.7	2.5
	Measurement Standard Deviation (dB)	2.1	2.3	1.9	1.4	2.2
	Normalized Average Attenuation (dB/cm)	2.1	0.3	20.0	24.1	--
60 GHz	Average Measured Attenuation (dB)	6.0	9.6	3.6	10.2	1.2
	Measurement Standard Deviation (dB)	3.4	1.3	2.2	2.1	1.8
	Normalized Average Attenuation (dB/cm)	2.4	5.0	11.3	31.9	--

A pseudo deterministic method for determining the received power in an environment where transmitter and receiver are separated by various obstructions is given by [4]

$$P_R(d)=P_T+G_T+G_R-20\log_{10}\left(\frac{4\pi d}{\lambda}\right)-\sum_{i=1}^{N}a_i X_i \quad (3)$$

where $P_R(d)$ is the received power in dBm at a particular distance d in meters from the transmitter, P_T is the transmitter power in dBm, and a_i & X_i are the number and attenuation value (chosen from Tables IV or V) for the i^{th} obstruction intersected by a line drawn from the transmitter to the receiver.

Based on this work, the partition based channel model works well for short transmitter-receiver separations, provided there are a small number of multipath scatterers in the environment. If a significant amount of the received power comes from multipath, then the partition based model loses its physical significance. One drawback to the partition based model is the need for site-specific information, consisting of a floor plan that identifies the composition of all walls, doors, and other obstructions; however, future generations of wireless networks may warrant such detail and accuracy [29].

REFERENCES

[1] T. S. Rappaport, A. Annamalai, R. M. Buehrer, and W. H. Tranter, "Wireless communications: past events and future perspectives," *IEEE Communications Magazine 50th Anniversary Issue,* pp. 148-161, May 2002.

[2] G. Vannucci and R. S. Roman, "Measurement results on indoor radio frequency reuse at 900 MHz and 18 GHz," *IEEE 3rd International Conference on Personal, Indoor, and Mobile Radio Communications*, pp. 308-314, October 1992.

[3] D. Molkdar, "Review on radio propagation into and within buildings," *IEE Proceedings—Microwaves, Antennas, and Propagation*, Vol. 138, No. 1, pp. 61-73, February 1991.

[4] G. 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, November 1998.

[5] H. Xu, "Terrestrial radio wave propagation at millimeter-wave frequencies," Ph. D. Dissertation, Virginia Polytechnic Institute and State University, http://scholar.lib.vt.edu/theses/index.html, May 2000.

[6] H. Xu, V. Kukshya, and T. S. Rappaport, "Spatial and temporal characteristics of 60-GHz indoor channels," *IEEE Journal on Selected Areas in Communications*, vol. 20, No. 3, pp. 620-630, April 2002.

[7] W. J. Tanis, II, and G. J. Pilato, "Building penetration characteristics of 880 MHz and 1922 MHz radio waves," *Proceedings IEEE 43rd Vehicular Technology Conference*, Secanus, NJ, May 1993, pp. 2006-209.

[8] A. F. de Toledo, and A. M. D. Turkmani, "Propagation into and within buildings at 900, 1800, and 2300 MHz," *Proceedings IEEE 42nd Vehicular Technology Conference,* Denver, CO, May 1992, vol. 2, pp. 633-655.

[9] E. H. Walker, "Penetration of radio signals into buildings in the cellular radio environment," *Bell System Technical Journal*, vol. 62, no. 9, pp. 2719-2734, Nov. 1983.

[10] Y. P. Zhang, and Y. Hwang, "Time delay characteristics of 2.4 GHz band radio propagation channels in room environments," *Proceedings IEEE 5th Personal, Indoor and Mobile Radio Communications*, The Hague, Netherlands, September 1994, vol. 1, pp. 28-32.

[11] R. Davies, M. Bensebti, M. A. Beach, and J. P. McGeehan, "Wireless propagation measurements in indoor multipath environments at 1.7 GHz and 60 GHz for small cell systems," in *Proceedings IEEE 41st Vehicular Technology Conference*, St. Louis, MO, 1991, pp. 589-593.

[12] T. Manabe, Y. Miura, and T. Ihara, "Effects of antenna directivity and polarization on indoor multipath propagation characteristics at 60 GHz," *IEEE Journal on Selected Areas in Communications*, vol. 14, No. 3, pp. 441-447, April 1996.

[13] S. E. Alexander and G. Pugliese, "Cordless communication within buildings: results of measurements at 900 MHz and 60 GHz," *British Telecom Technology Journal*, vol. 44, No. 10, pp. 99-105, October 1996.

[14] Y. P. Zhang, Y. Hwang, "Measurements of the characteristics of indoor penetration loss," *IEEE 44th Vehicular Technology Conference*, Stockholm, Sweeden, June 1994, vol. 3, pp. 1741-1744.

[15] L. Golding and A. Livine, "RLAN-A radio local area network for voice and data communications," *Proceedings IEEE GLOBECOM* vol. 3, pp 1900-1904, November 1987.

[16] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd Edition. New Jersey: Prentice-Hall, 2002.

[17] B. Langen, G. Lober, W. Herzig, "Reflection and transmission behaviour of building materials at 60 GHz," *IEEE 4th International Conference on Personal, Indoor, and Mobile Radio Communications*, The Hague, Netherlands, September 1994, vol. 4, pp. 505-509.

[18] L. M. Correia and P. O. Françês, "Estimation of materials characteristics from power measurements at 60 GHz," *IEEE 7th International Conference on Personal, Indoor, and Mobile Radio Communications*, The Hague, Netherlands, September 1994, vol. 1, pp. 510-513.

[19] K. Sato, T. Manabe, T. Ihara, H. Saito, S. Ito, T. Tanaka, K. Sugai, N. Ohmi, Y. Murakami, M. Shibayama, Y. Konishi, and T. Kimura, "Measurements of reflection and transmission characteristics of interior structures of office building in the 60-GHz band," *IEEE Transactions on Antennas and Propagation*, vol. 45, No. 2, pp. 1783-1792, December 1997.

[20] M. Lott and I. Forkel, "A multi-wall-and-floor model for indoor radio propagation," *IEEE 53rd Vehicular Technology Conference*, Rhodes, Greece, May 2001, vol. 1, pp. 464-468.

[21] K. Sato, T. Manabe, J. Polivka, T. Ihara, Y. Kasashima, and K. Yamaki, "Measurement of the complex refractive index of concrete at 57.5 GHz," *IEEE Transactions on Antennas and Propagation,* vol. 44, No. 1, pp. 35-40, January 1996.

[22] P. Nobles and F. Halsall, "Indoor propagation at 17 GHz and 60 GHz – measurements and modeling," *IEE National Conference on Antennas and Propagation*, pp. 93 – 96, 1999.

[23] P. Karlsson, C. Bergljung, E. Thomsen, and H. Börjeson, "Wideband measurement and analysis of penetration loss in the 5 GHz band," *Proceedings IEEE 50th Vehicular Technology Conference,* Amsterdam, Netherlands, September 1999, vol. 4, pp. 2323-2328.

[24] C. R. Anderson, "Design and implementation of an ultrabroadband millimeter-wavelength vector sliding correlator channel sounder and in-building measurements at 2.5 & 60 GHz," Masters Thesis, Virginia Polytechnic Institute and State University, http://scholar.lib.vt.edu/theses/index.html, May 2002.

[25] Site-specific system simulator for wireless system design [Online]. Available: http://gnida.cs.vt.edu/~s4w/

[26] M. J. Feuerstein, K. L. Blackard, T. S. Rappaport, S. Y. Seidel, H. H. Xia, "Path loss, delay spread, and outage models as functions of antenna height for microcellular system design," *IEEE Transactions on Vehicular Technology*, vol. 44, No. 3, pp. 487-497, August 1994.

[27] D. M. Matic, H. Harada, R. Prasad, "Indoor and outdoor frequency measurements for MM-waves in the range of 60 GHz," *Proceedings IEEE 48th Vehicular Technology Conference*, Ottawa, Canada, May 1998, vol. 1, pp. 567-571.

[28] R. R. Skidmore, T. S. Rappaport, A. L. Abbott, "Interactive coverage region and system design simulation for wireless communication systems in multifloored indoor environments: SMT Plus," *IEEE 5th International Conference on Universal Personal Communications*, Cambridge, Mass. USA, October 1996, vol. 2, pp. 646-650.

[29] T. S. Rappaport and S. Sandhu, "Radio-wave propagation for emerging wireless personal-communication systems," *IEEE Antennas and Propagation Magazine*, vol. 36, pp. 14-24, Oct. 1994.