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Millimeter Wave Communications for Path Loss Data for Small Cell Fifth-Generation (5G) Wireless Networks Channel Modeling

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ABSTRACT

This paper provides 28- and 73-GHz urban omnidirectional propagation large-scale path loss data measured in downtown New York City during the summers of 2012 and 2013, and 38 GHz data measured in downtown Austin in the summer of 2011. The data provided herein may be used by antenna, propagation, and communications researchers for emerging mobile and/or backhaul millimeter-wave (mmWave) system analyses. This paper also presents measurement layout maps with transmitter and receiver locations and GPS coordinates, so that anyone may create similar or new measurements and models, or may perform further processing, such as with ray-tracers and modeling tools, in addition to studying mmWave system performance. Using the data provided herein, large-scale path loss models using a standard close-in 1 meter free-space reference distance are provided for each of the three frequency bands.

Keywords: mmWave, 5G, 28 GHz, 38 GHz, 73 GHz, Propagation, Path Loss, And Outage, Omnidirectional Models

I. INTRODUCTION

Millimeter-wave (mmWave) propagation measurements in an urban environment such as New York City are very expensive and time intensive. These resource limitations lead many researchers to perform mmWave simulations and analyses with readily available software tools and applica-tions, but without the advantage of real-world measurements. The NYU WIRELESS research center has built customized mmWave measurement equipment and has conducted extensive mmWave propagation measurements in the dense urban environment around New York University's (NYU) Manhattan campus at both 28 GHz and 73 GHz [1] [3], and around the campus of The University of Texas at Austin (UTA) at 38 GHz [3], [4]. Omni directional large-scale path loss values calculated from line-of-sight (LOS) and non-line-of-sight (NLOS) directional measurements are provided in Tables 3, 4, 5, and 6.

By providing measured data for the 28 GHz, 38 GHz, and 73 GHz urban channels, we strive to assist others who may wish to create or validate their own propagation models and system or outage analyses from the data. Some of the more common large-scale path loss models that may be generated from the data include the close-in free space reference distance (CI) model [3], [5], [6], the oating-intercept (FI) model [7], the Stanford University Interim (SUI) model [8], probabilistic models [9], ray-tracing.

Table 1. TX locations, GPS coordinates in decimal degrees, and TX heights for the 28 GHz and 73 GHz measurements in New York City [2]. A X indicates that the TX location was used for measurements

TX ID	Latitude (°)	Longitude (°)	Height (m)	28 GHz	73 GHz
COL1	40.7270944	-73.9974972	7	✓	✓
COL2	40.7268833	-73.9970556	7	✓	✓
KAU	40.7290611	-73.9962500	17	✓	✓
KIM1	40.7300472	-73.9978333	7	-	✓
KIM2	40.7297444	-73.9977222	7	-	✓

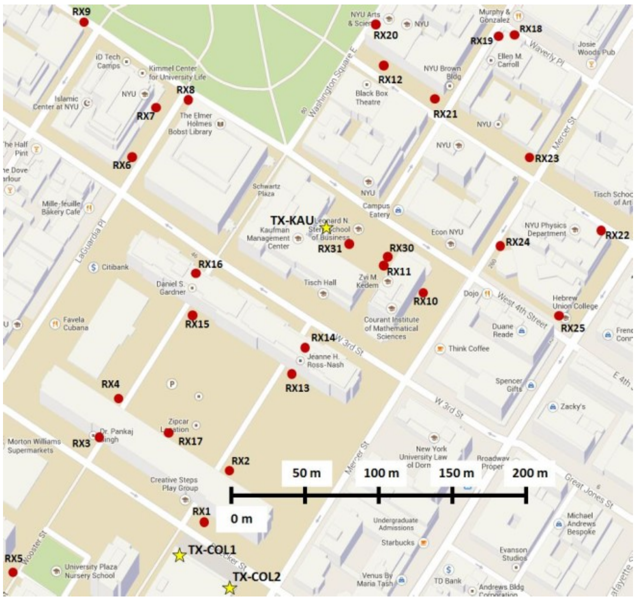

Figure 1. Map of TX and RX locations around NYU's Manhattan campus for 28 GHz measurements during the summer of 2012. Yellow stars indicate TX locations and red dots indicate RX locations.

models [5], [6], [10], [11], and estimation models using the expectation maximum (EM) algorithm [12]. In the following sections of this article, descriptions of the directional measurements from which the omnidirectional large-scale path loss data were calculated are given, map-based layouts of the 28 GHz and 73 GHz measurement campaigns are provided for use in site-speci c modeling, and tabulated omnidirectional large-scale path loss data in LOS and NLOS environments at 28 GHz, 38 GHz, and 73 GHz are presented. A standardized 1 meter (m) close-in free space reference distance large-scale path loss model is computed using the measured and synthesized path loss data provided at each mmWave band in this article [3].

II. mmWAVE MEASUREMENT DESCRIPTIONS A. 28 GHz MEASUREMENT DESCRIPTIONS

The 28 GHz omnidirectional path loss data were calculated from summer 2012 narrowbeam-to-narrowbeam measurements that used 24.5 dBi, 10.9 half-power beamwidth (HPBW) steerable horn antennas at the trans-mitter (TX) and receiver (RX) [1], [3]. These measurements were conducted using three TX locations (KAU, COL1, and COL2) identi ed in Table 1, with antenna heights set to 7 m and 17 m above ground level (AGL). The RX antennas were set 1.5 m AGL around typical sidewalks on the NYU campus. Fig. 1 shows the TX and RX locations used for measurements at 28 GHz during the summer of 2012, where 74 total outdoor-to-outdoor (O2O) TX-RX location combinations were measured [1], [3].

The total received power at the RX for each TX-RX location combination was obtained by summing the received powers at each and every unique azimuth and elevation pointing angle, after removing the antenna gains, which was then used to recover the omnidirectional path loss, as presented in [7]. For each TX-RX location combination, nine RX antenna azimuth measurement sweeps were performed at three distinct RX antenna elevation planes of 0 and 20 , and for three distinct xed TX antenna azimuth angles with a downtilt of 10 . A power delay pro le (PDP) was recorded at approximate HPBW increments in the azimuth plane for each sweep. A tenth measurement (antenna) sweep was conducted with the TX antenna xed at 10 downtilt in the elevation plane and sweeping in HPBW increments in the azimuth plane, while the RX antenna remained xed at the unique azimuth and elevation pointing angle that yielded the strongest link (i.e., the strongest received power) deter-mined from the initial RX sweeps. Additional information regarding the 28 GHz measurement campaign is given in [1], [3], and [7].

B. 73 GHz MEASUREMENT DESCRIPTIONS

The 73 GHz measurements during the summer of 2013 used 27 dBi, 7 HPBW antennas at the TX and RX [2], [3]. The measurements consisted of ve TX locations (COL1, COL2, KAU, KIM1, and KIM2), with the KAU TX at a height of 17 m AGL and the other four TX heights at 7 m AGL, as given in Table 1. There were 27 distinct RX locations used for measurements that included two RX antenna height scenarios, with the mobile scenario RX antennas at 2 m AGL and the backhaul scenario RX antennas at 4.06 m AGL. Overall, 36 and 38 TX-RX location combinations were measured for the mobile and backhaul scenarios, respectively. A hybrid model was also considered, where we bundled together the mobile and backhaul scenario measurement data, resulting in 74 TX-RX location combinations for the hybrid model [7]. Fig. 2 shows the TX and RX locations measured during the summer 2013 campaign at 73 GHz.

The 73 GHz omnidirectional path loss data were synthesized from directional antenna measurements, where for each TX-RX location combination, up to 10 antenna sweeps in the azimuth plane were conducted at the RX and up to two antenna sweeps in the azimuth plane were conducted at the TX, all for different xed elevation planes (separated by approximately one HPBW in elevation). Antenna azimuth sweeps were performed by stepping the RX antenna in HPBW increments in the azimuth plane, such that all measured beam patterns were adjacent (orthogonal) to each other for each sweep [2], [3]. The received powers from every unique azimuth and elevation antenna pointing angle combination between the TX and RX were then summed after removing the antenna gains to recover omnidirectional received power, and subsequently omnidirectional path loss was calculated [7].

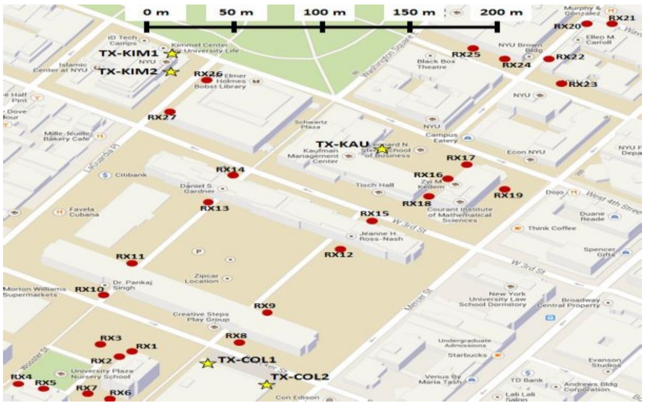

Figure 2. Map of TX and RX locations around NYU's Manhattan campus for 73 GHz measurements during the summer of 2013. Yellow stars indicate TX locations and red dots indicate RX locations [2].

Table 3. 28 GHz TX-RX location combinations with corresponding TX IDs, RX IDs, Latitude (Lat) and Longitude (Long) coordinates in decimal degrees, environment (Env) type, T-R separation distances in meters, and omnidirectional path loss (PL) values. A ``-'' in the path loss value column indicates no signal (e.g. an outage), whereas a `` '' indicates that the location was not considered for omnidirectional path loss. All RX heights were set to 1.5 m AGL, and TX heights are given in Table 1.

TX	RX	Lat (°)	Long (°)	Env	T-R(m)	PL(dB)
COL1	1	40.7273222	-73.9973000	L	31	92.3
COL1	2	40.7275417	-73.9970833	N	61	123.8
COL1	3	40.7279056	-73.9980556	L	102	*
COL1	4	40.7280750	-73.9980167	N	118	136.4
COL1	5	40.7269861	-73.9988417	N	114	115.6
COL1	6	40.7295000	-73.9978889	N	270	-
COL1	7	40.7298361	-73.9976167	N	305	-
COL1	8	40.7297444	-73.9971278	N	296	-
COL1	9	40.7303444	-73.9983000	N	368	-
COL1	10	40.7286694	-73.9955139	N	242	-
COL1	11	40.7287806	-73.9957667	N	238	-
COL1	12	40.7300500	-73.9957083	N	362	-
COL1	13	40.7281139	-73.9966750	N	133	132.9
COL1	14	40.7283472	-73.9964389	N	165	137.1
COL1	15	40.7285139	-73.9973250	N	159	-
COL1	16	40.7287500	-73.9973000	N	185	-
COL1	17	40.7278333	-73.9975000	N	82	148.1
COL1	18	40.7301222	-73.9945389	N	419	-
COL1	19	40.7302361	-73.9948806	N	413	-
COL1	20	40.7302833	-73.9958972	N	379	-
COL1	21	40.7299306	-73.9954500	N	360	-
COL1	22	40.7290528	-73.9940278	N	365	-
COL1	23	40.7295556	-73.9946806	N	362	-
COL1	24	40.7289722	-73.9948361	N	306	-
COL1	25	40.7285361	-73.9943917	N	307	-
COL2	1	40.7273222	-73.9973000	L	53	100.8
COL2	2	40.7275417	-73.9970833	N	73	121.4
COL2	3	40.7279056	-73.9980556	N	142	119
COL2	4	40.7280750	-73.9980167	N	155	141.4
COL2	5	40.7269861	-73.9988417	N	151	124.9
COL2	6	40.7295000	-73.9978889	N	299	-
COL2	7	40.7298361	-73.9976167	N	332	-
COL2	8	40.7297444	-73.9971278	N	318	-
COL2	9	40.7303444	-73.9983000	N	399	-
COL2	10	40.7286694	-73.9955139	N	237	-
COL2	11	40.7287806	-73.9957667	N	237	-
COL2	12	40.7300500	-73.9957083	N	370	-
COL2	13	40.7281139	-73.9966750	N	141	124.8
COL2	14	40.7283472	-73.9964389	N	171	144.5
COL2	15	40.7285139	-73.9973250	N	183	-
COL2	16	40.7287500	-73.9973000	N	209	-
COL2	17	40.7278333	-73.9975000	N	112	142.2
COL2	18	40.7301222	-73.9945389	N	418	-
COL2	19	40.7302361	-73.9948806	N	415	-
COL2	20	40.7302833	-73.9958972	N	390	-
COL2	21	40.7299306	-73.9954500	N	365	-

III. mmWAVE OMNIDIRECTIONAL PATH LOSS DATA

A. 28 GHz OMNIDIRECTIONAL PATH LOSS DATA

The 28 GHz measurement campaign included six LOS TX-RX location combinations, but only ve LOS data points are included here because the sixth LOS data point at 102 m had a much larger path loss than free space, resulting from TX and RX antenna misalignment off boresight for that location (due to pre-determined angles for the measurement campaign, and not systematically searching for the strongest received power). In addition, 68 NLOS TX-RX location combinations were tested, but signal could only be measured at 20 of the locations. Table 3 provides the corresponding TX IDs, RX IDs, GPS coordinates in decimal degrees, environment types, transmitter-receiver (T-R) separation dis-tances in meters, and path loss values in dB for the 28 GHz omnidirectional path loss data. Additional details regarding 28 GHz outage can be found in [3].

Omnidirectional Path Loss Models (d_0 = 1 m)							
Frequency (City)	TX/RX scenario	TX Ht. (m)	RX Ht. (m)	LOS		NLOS	
				PLE	σ [dB]	PLE	σ [dB]
28 GHz (Man.)	Narrow/Narrow	7; 17	1.5	2.1	3.6	3.4	9.7
38 GHz (Austin)	Narrow/Narrow	23	1.5	2.0	2.4	2.8	9.1
		36		1.9	3.6	2.6	10.8
		23; 36		1.9	3.4	2.7	10.5
		8; 23; 36		1.9	4.4	2.7	10.1
	Narrow/Wide	23		1.8	2.4	2.6	-
		36		1.8	1.8	2.2	4.1
		23; 36		1.8	2.1	2.3	4.9
		8; 23; 36		1.8	3.2	2.3	7.4
73 GHz (Man.)	Mobile	7; 17	2	2.0	5.2	3.3	7.6
	Backhaul		4.06	2.0	4.2	3.5	7.9
	Hybrid		2; 4.06	2.0	4.8	3.4	7.9

TABLE . Omnidirectional close-in free space reference distance (**d_0** D 1 m) path loss models for all measured data for base station-to-mobile (access) and base station-to-base station (backhaul) scenarios. PLE is the path loss exponent (**n**N), is the standard deviation of the zero-mean Gaussian random variable (shadow factor) about the MMSE best fit line for the range of distances specified for each frequency band, and Man. stands for Manhattan [3].

B. 73 GHz OMNIDIRECTIONAL PATH LOSS DATA

At 73 GHz, nine LOS and 65 NLOS TX-RX location combinations were tested, with signal measured for all LOS combinations, but with signal only measurable for 53 NLOS combinations. During the 73 GHz measure-ment campaign, the strongest received power azimuth and elevation antenna pointing angle combinations between the TX and RX were found by systematically searching before conducting measurements for each TX-RX location com-bination, thereby yielding more elevation diverse measure-ments and results compared to the 28 GHz measurements. Table 4 provides the corresponding TX IDs, RX IDs, GPS coordinates in decimal degrees, scenario types, environment types, T-R separation distances in meters, and path loss values in dB, for the 73 GHz omnidirectional path loss data. Additional details regarding 73 GHz outage can be found in [3].

C. 38 GHz OMNIDIRECTIONAL PATH LOSS DATA

In the 38 GHz measurement campaign, four TX locations and 36 RX locations were tested for the narrowbeam mea-surements, whereas four TX locations and 19 RX locations were visited for the widebeam measurements, yielding a total of 43 and 22 TX-RX location combinations for the narrowbeam and widebeam measurements, respectively. Tables 5 and 6 provide the corresponding TX IDs, RX IDs, environment types, T-R separation distances in meters, and path loss values in dB, for the 38 GHz omnidirectional path loss data obtained from the narrowbeam and widebeam measurements, respectively.

It is worth noting that for a given TX-RX location combination, the omnidirectional path loss values syn-thesized from narrowbeam and widebeam measurements are identical or very close to each other, as shown by Tables 5 and 6. For instance, considering the combination of TX WRW and RX 22, the omnidirectional path loss is 108.4 dB for both narrowbeam and widebeam measurements. The larger (a few dB) omnidirectional path loss differences in other cases may be due to the fact that the antennas were not systematically rotated in the azimuth and elevation planes at 38 GHz, such that some spatial angles may not have been measured and the corresponding powers were missed for inclusion in omnidirectional received power. The comparable omnidirectional path loss values obtained from narrowbeam and widebeam measurements implicitly validate the method of synthesizing omnidirectional received power and path loss from directional measurements used here [14].

IV. CLOSE-IN REFERENCE DISTANCE PATH LOSS MODEL

The large-scale path loss values presented for the three bands in this article were used to generate a large-scale propagation path loss model that uses a close-in free space reference distance with d_0 D 1 m:

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0) + 10\bar{n}\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad \text{for } d \geq d_0 \tag{1}$$

a particular frequency band or environment [3], [5], [6], and X is a zero mean Gaussian random variable with standard deviation in dB (large-scale shadow factor [5],

[6]). The CI model uses a physically-based close-in free space reference scale path loss model is found by determining the best PLE *n*N via the minimum mean-square error (MMSE) method that estimates the measured data with smallest error using a phys-ical anchor point at d_0. For mmWave CI models we use d_0 D 1 m, proposed as a standard in [3]. The exact center frequen-cies of the wideband measurement data presented here are 28.0 GHz, 37.625 GHz, and 73.5 GHz. Table 7 provides the omndirectional CI path loss model parameters for the path loss data given in this article.

V. CONCLUSION

This article provides omnidirectional large-scale path loss data in LOS and NLOS environments at 28 GHz and 73 GHz in the dense urban environment of New York City, and at 38 GHz in the urban environment of Austin. The data is given for academicians and researchers to replicate or create mmWave large-scale path loss models for future 5G system simulation and design, since such data are not readily avail-able to many researchers. The omnidirectional data may also be utilized in more advanced ways through the use of 3-D ray-tracers and network capacity simulators. Two of the industry leaders in mmWave wireless channel modeling, Nokia and Samsung, have already developed channel models using the large-scale path loss data provided in this article in [15] [18]. Additional information regarding this work may be found in [3] and [16] [19].

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