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Technical Report

MmWave Omnidirectional Path Loss Data at 28 GHz and 73 GHz for 5G Channel Modeling

George R. MacCartney Jr., Mathew K. Samimi, Theodore S. Rappaport

gmac@nyu.edu, mks@nyu.edu, tsr@nyu.edu

NYU WIRELESS
NYU Polytechnic School of Engineering
2 MetroTech Center
Brooklyn, NY 11201

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{gmac,tsr,mks}@nyu.edu

***Abstract*—This technical report provides 28 GHz and 73 GHz urban omnidirectional propagation path loss data measured in Downtown New York City during the summers of 2012 and 2013. The data provided herein may be used by antenna, propagation, and communications researchers for emerging mobile and/or backhaul millimeter-wave path loss models. This report also presents measurement layout maps with TX and RX 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 millimeter-wave outage.**

***Index Terms*—mmWave; 5G; 28 GHz; 73 GHz; path loss; 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 applications, but without the advantage of real-world measurements. The NYU WIRELESS research center has built 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], [2]. Omnidirectional path loss values calculated from LOS and NLOS measurements are further tabulated in this report, in Tables II and III.

By providing measured data for both the 28 GHz and 73 GHz urban channels, we strive to assist others who may wish to create or validate their own empirical models and outage analyses from our data. Some of the more common path loss models that may be generated from the data include the close-in free space reference distance model [3], [4], the floating-intercept (*alpha-beta*) model [5], the Stanford University Interim (SUI) model [6], probabilistic models [7], and estimation models using the expectation maximum (EM) algorithm [8]. In the following sections of this technical report we describe the directional measurements from which the omnidirectional path loss data were calculated, we display map-based layouts of the 28 GHz and 73 GHz measurement campaigns for the use of site-specific modeling, and also provide tabulated omnidirectional path loss data in LOS and NLOS environments at 28 GHz and 73 GHz.

II. MmWave Measurement Descriptions

A. 28 GHz Measurement Descriptions

The 28 GHz omnidirectional path loss data were determined from summer 2012 narrowbeam-to-narrowbeam measurements that used 24.5 dBi, 10.9° half-power beamwidth (HPBW) antennas at the transmitter (TX) and receiver (RX) [1]. These measurements were conducted using three TX locations (KAU, COL1, and COL2) identified in Table I, 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].

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 [5]. 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 fixed TX antenna azimuth angles with a downtilt of -10°. A power delay profile (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 fixed at -10° downtilt in the elevation plane and sweeping in HPBW increments in the azimuth plane, while the RX antenna remained fixed at the unique azimuth and elevation pointing angle that yielded the strongest link (i.e., the strongest received power) determined from the initial RX sweeps. Additional information regarding the 28 GHz measurement campaign is given in [1], [5].

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]. The

TABLE I: TX locations, GPS coordinates in decimal degrees, and TX heights for the 28 GHz and 73 GHz measurements in New York City [2]. A ✓ 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	-	✓

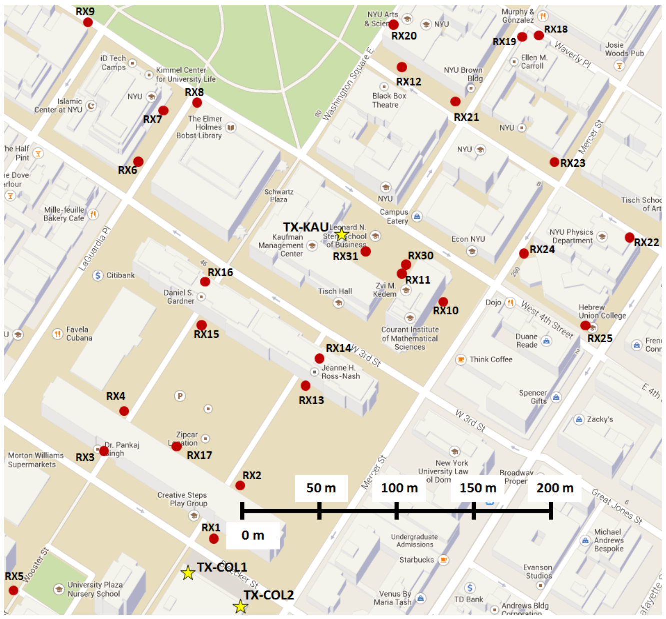

Fig. 1: Map of TX and RX locations around NYU's Manhattan campus for 28 GHz measurements during the summer of 2012. Yellow stars indicate TX locations and red dots indicate RX locations.

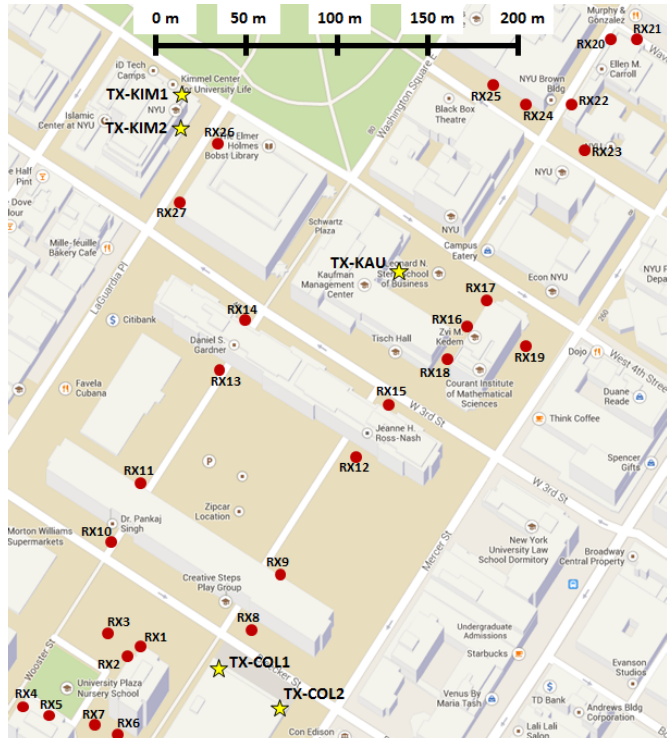

Fig. 2: Map of TX and RX locations around NYU's Manhattan campus for 73 GHz measurements during the summer of 2013. Yellow stars indicate TX locations and red dots indicate RX locations [2].

measurements consisted of five 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 I. 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 [5]. 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 fixed 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 angles were adjacent (orthogonal) to each other for each sweep [2]. We then summed the received powers from every unique azimuth and elevation antenna pointing angle combination between the TX and RX after removing the antenna gains to recover received power, and then calculated the omnidirectional path loss data [5].

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 we only include five LOS data points 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, we tested 68 NLOS TX-RX location combinations, but could only measure signal at 20 of the locations. In Table II we provide the corresponding TX IDs, RX IDs, GPS coordinates in decimal degrees, environment types, transmitter-receiver (T-R) separation distances 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 [9].

TABLE II: 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 I.

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	-
COL2	22	40.7290528	-73.9940278	N	351	-
COL2	23	40.7295556	-73.9946806	N	358	-
COL2	24	40.7289722	-73.9948361	N	298	-
COL2	25	40.7285361	-73.9943917	N	290	-
KAU	1	40.7273222	-73.9973000	N	213	-
KAU	2	40.7275417	-73.9970833	N	184	-
KAU	3	40.7279056	-73.9980556	N	200	-
KAU	4	40.7280750	-73.9980167	N	186	149.2
KAU	5	40.7269861	-73.9988417	N	318	-
KAU	6	40.7295000	-73.9978889	N	147	-
KAU	7	40.7298361	-73.9976167	N	145	-
KAU	8	40.7297444	-73.9971278	N	107	-
KAU	9	40.7303444	-73.9983000	N	225	-
KAU	10	40.7286694	-73.9955139	N	77	124.2
KAU	11	40.7287806	-73.9957667	L	54	102.1
KAU	12	40.7300500	-73.9957083	N	120	140
KAU	13	40.7281139	-73.9966750	N	112	-
KAU	14	40.7283472	-73.9964389	N	82	127
KAU	15	40.7285139	-73.9973250	N	110	-
KAU	16	40.7287500	-73.9973000	N	96	140
KAU	17	40.7278333	-73.9975000	N	173	-
KAU	18	40.7301222	-73.9945389	N	187	-
KAU	19	40.7302361	-73.9948806	N	175	137
KAU	20	40.7302833	-73.9958972	N	140	-
KAU	21	40.7299306	-73.9954500	N	119	118
KAU	22	40.7290528	-73.9940278	N	188	-
KAU	30	40.7287806	-73.9957667	L	53	94.6
KAU	31	40.7288778	-73.9960028	L	33	88.4

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 measurement campaign, we found the strongest received power azimuth and elevation antenna pointing angle combinations between the TX and RX by systematically searching before conducting measurements for each TX-RX location combination, thereby yielding more elevation diverse measurements and results compared to the 28 GHz measurements. Table III 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 [9].

TABLE III: 73 GHz TX-RX location combinations with corresponding TX IDs, RX IDs, Latitude (Lat) and Longitude (Long) coordinates in decimal degrees, the RX height h_{RX} where *M* corresponds to a mobile height of 2 m and *B* corresponds to a backhaul height of 4.06 m, 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). TX heights are given in Table I.

TX	RX	Lat (°)	Long (°)	h_{RX}	Env	T-R(m)	PL(dB)
COL1	1	40.7270861	-73.9980611	M	N	48	123.7
COL1	2	40.7270361	-73.9981167	M	N	53	136.5
COL1	3	40.7271917	-73.9982417	M	N	64	128.2
COL1	4	40.7269000	-73.9987000	M	N	104	131.8
COL1	5	40.7268472	-73.9985722	M	N	95	132.3
COL1	6	40.7267694	-73.9982250	M	N	71	136.2
COL1	7	40.7268111	-73.9983194	M	N	76	136.7
COL1	8	40.7272972	-73.9972694	M	L	30	108.4
COL1	9	40.7275139	-73.9970806	B	N	58	137.4
COL1	10	40.7277861	-73.9981556	B	N	95	137.3
COL1	11	40.7279917	-73.9980242	B	N	109	150.9
COL1	12	40.7281306	-73.9965472	B	N	140	138.3
COL1	13	40.7286333	-73.9975111	M	N	171	-
COL1	13	40.7286333	-73.9975111	B	N	171	-
COL1	14	40.7288139	-73.9973361	M	N	192	-
COL1	14	40.7288139	-73.9973361	B	N	192	-
COL1	15	40.7283639	-73.9964111	M	N	168	-
COL1	15	40.7283639	-73.9964111	B	N	168	-
COL2	1	40.7270861	-73.9980611	B	N	88	132.2
COL2	2	40.7270361	-73.9981167	M	N	91	140.7
COL2	2	40.7270361	-73.9981167	B	N	91	143
COL2	3	40.7271917	-73.9982417	M	N	106	137.6
COL2	3	40.7271917	-73.9982417	B	N	106	137.3
COL2	4	40.7269000	-73.9987000	M	N	139	148.1
COL2	4	40.7269000	-73.9987000	B	N	139	154.6
COL2	5	40.7268472	-73.9985722	M	N	128	148.2
COL2	5	40.7268472	-73.9985722	B	N	128	147.9
COL2	6	40.7267694	-73.9982250	M	N	99	158
COL2	6	40.7267694	-73.9982250	B	N	99	144.3
COL2	7	40.7268111	-73.9983194	B	N	107	148.6
COL2	8	40.7272972	-73.9972694	M	L	50	108.1
COL2	9	40.7275139	-73.9970806	B	N	70	142.1
COL2	10	40.7277861	-73.9981556	B	N	137	136
COL2	11	40.7279917	-73.9980242	B	N	148	159.7
COL2	12	40.7281306	-73.9965472	B	N	145	139.8
COL2	13	40.7286333	-73.9975111	M	N	198	-
COL2	13	40.7286333	-73.9975111	B	N	198	-
COL2	14	40.7288139	-73.9973361	M	N	216	-
COL2	14	40.7288139	-73.9973361	B	N	216	-
COL2	15	40.7283639	-73.9964111	M	N	173	-
COL2	15	40.7283639	-73.9964111	B	N	173	-
KAU	15	40.7283639	-73.9964111	M	N	80	134.6
KAU	15	40.7283639	-73.9964111	B	N	80	139.5
KAU	16	40.7287639	-73.9957806	M	L	54	99.5
KAU	16	40.7287639	-73.9957806	B	L	54	99.4
KAU	17	40.7289361	-73.9957167	M	L	49	103.3
KAU	17	40.7289361	-73.9957167	B	L	49	106.1
KAU	18	40.7285917	-73.9959694	M	N	59	117.4
KAU	18	40.7285917	-73.9959694	B	N	59	122.9
KAU	19	40.7287472	-73.9954278	M	N	79	128
KAU	19	40.7287472	-73.9954278	B	N	79	135.5
KAU	20	40.7301583	-73.9948972	M	N	168	136.1
KAU	20	40.7301583	-73.9948972	B	N	168	145.9
KAU	21	40.7301833	-73.9947111	M	N	181	133.5
KAU	21	40.7301833	-73.9947111	B	N	181	137.4
KAU	22	40.7298583	-73.9951444	M	N	129	129.2
KAU	22	40.7298583	-73.9951444	B	N	129	139.6
KAU	23	40.7296889	-73.9950056	M	N	127	135.1
KAU	23	40.7296889	-73.9950056	B	N	127	140.4
KAU	24	40.7299028	-73.9954194	M	N	118	133.6
KAU	24	40.7299028	-73.9954194	B	N	118	118.6
KAU	25	40.7299694	-73.9955833	M	N	117	138.3
KAU	25	40.7299694	-73.9955833	B	N	117	133.3
KIM1	25	40.7299694	-73.9955833	M	N	190	146
KIM1	25	40.7299694	-73.9955833	B	N	190	149.3
KIM1	26	40.7297389	-73.9974000	M	N	50	132
KIM1	26	40.7297389	-73.9974000	B	N	50	133.3
KIM1	27	40.7293861	-73.9976972	M	N	74	135
KIM1	27	40.7293861	-73.9976972	B	N	74	137.3
KIM2	25	40.7299694	-73.9955833	M	N	182	154.5
KIM2	25	40.7299694	-73.9955833	B	N	182	156.2
KIM2	26	40.7297389	-73.9974000	B	L	27	103.3
KIM2	27	40.7293861	-73.9976972	M	L	40	98
KIM2	27	40.7293861	-73.9976972	B	L	40	97.8

IV. Conclusion

This technical report freely provides omnidirectional path loss data in LOS and NLOS environments at both 28 GHz and 73 GHz in the dense urban environment of New York City, obtained from time intensive measurements and very expensive mmWave equipment. The data is openly given for academicians and researchers to replicate or create mmWave path loss models for future 5G system simulation and design, since such data are not readily available 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. We also suggest additional references for further information regarding our work: [10]–[12]

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References

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

[2] 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.

[3] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

[4] T. S. Rappaport, R. W. Heath, Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*. Pearson/Prentice Hall, 2015.

[5] G. R. MacCartney, Jr., M. K. Samimi, and T. S. Rappaport, “Omnidirectional path loss models in New York City at 28 GHz and 73 GHz,” in *2014 IEEE 25th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2014.

[6] A. I. Sulyman, A. T. Nassar, M. K. Samimi, G. R. MacCartney, Jr., T. S. Rappaport, and A. Alsanie, “Radio propagation path loss models for 5G cellular networks in the 28 GHz and 38 GHz millimeter-wave bands,” *IEEE Communications Magazine*, vol. 52, no. 9, pp. 78–86, Sept. 2014.

[7] M. K. Samimi, T. S. Rappaport, and G. R. MacCartney, Jr., “Probabilistic omnidirectional path loss models for millimeter-wave outdoor communications,” *IEEE Wireless Communications Letters*, Mar. 2015.

[8] T. Abbas, C. Gustafson, and F. Tufvesson, “Pathloss estimation techniques for incomplete channel measurement data,” in *COST IC1004 10th Management Committee and Scientific Meeting*, 2014, pp. 1–5.

[9] T. S. Rappaport, G. R. MacCartney, Jr., M. K. Samimi, and S. Sun, “Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (invited),” *IEEE Transactions on Communications*, 2015.

[10] S. Sun, T. S. Rappaport, R. W. Heath, A. Nix, and S. Rangan, “Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both?” *IEEE Communications Magazine*, vol. 52, no. 12, pp. 110–121, Dec. 2014.

[11] G. R. MacCartney, Jr., M. K. Samimi, and T. S. Rappaport, “Exploiting directionality for millimeter-wave wireless system improvement,” in *2015 IEEE International Conference on Communications (ICC)*, June 2015.

[12] M. K. Samimi and T. S. Rappaport, “3-D statistical channel model for millimeter-wave outdoor mobile broadband communications,” in *2015 IEEE International Conference on Communications (ICC)*, June 2015.