

28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City

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Abstract—In this paper, we present reflection coefficients and penetration losses for common building materials at 28 GHz for the design and deployment of future millimeter wave mobile communication networks. Reflections from walls and buildings and penetration losses were measured for indoor and outdoor materials, such as tinted glass, clear glass, brick, concrete, and drywall at 28 GHz in New York City. A 400 Mega-chip-per-second sliding correlator channel sounder and 24.5 dBi steerable horn antennas were used to emulate future mobile devices with adaptive antennas that will likely be used in future millimeter wave cellular systems [1]. Measurements in and around buildings show that outdoor building materials are excellent reflectors with the largest measured reflection coefficient of 0.896 for tinted glass as compared to indoor building materials that are less reflective. We also found that penetration loss is dependent not only on the number of obstructions and distance between transmitter and receiver, but also on the surrounding environment. The greatest penetration loss containing three interior walls of an office building was found to be 45.1 dB, with 11.39 m separation between the transmitter and receiver.

Index Terms—28 GHz, mm-wave communication, indoor-to-outdoor penetration, reflection, in-building propagation, building penetration, 5G

I. INTRODUCTION

In recent years, the demand for high speed cellular data and the need for more spectrum have motivated the use of millimeter wave (mm-wave) carrier frequencies for future cellular networks, where high gain adaptive antennas, MIMO, and spatial beamforming can be implemented in very small form factors [1][2][3][4]. Unused or underutilized LMDS broadband spectrum exists at 28 GHz [4], and given the low atmospheric absorption as compared to 60 GHz, the spectrum at 28 GHz has very comparable free space path loss as today's 1-2 GHz cellular bands [2]. In addition, despite myths to the contrary, rain attenuation and oxygen loss does not significantly increase at 28 GHz, and, in fact, may offer better propagation conditions as compared to today's cellular networks when one considers the availability of high gain adaptive antennas and cell sizes on the order of 200 meters [4][5][6].

The design and optimization of future mm-wave mobile communication systems is highly influenced by the spatial

multipath characteristics of the wireless channel. A fundamental relationship was established between the angular distribution of power in a multipath channel and the narrowband fading in a local region [7]. In addition, the performance of Code Division Multiple Access (CDMA) cellular radio systems in multipath environments was shown to improve dramatically with proper spatial filtering provided by adaptive antenna arrays and switched beam systems [8]. These and other results from the 1990s offer promise for future beamforming methodologies that may use narrowband pilot signals to rapidly find, lock on, and combine the best spatial paths using highly directional adaptive antennas [6].

Besides the spatial parameters of the wireless channel, reflection and penetration characteristics of common building materials will also be required for the planning and design of future mm-wave wireless communication systems.

Previous research showed that 9.6 GHz, 28.8 GHz and 57.6 GHz waves propagate through a glass wall with virtually no loss, while the penetration loss increased by 25 dB to 50 dB when the glass surface was metal coated [9]. Today, external building glass is routinely infused or coated with metal to block ultraviolet rays while improving thermal insulating properties. In [9], no signal was detected through brick pillars throughout the mm-wave bands, yet signals through a hollow plasterboard wall resulted in a penetration loss ranging between 5.4 dB and 8.1 dB. In [10], researchers measured penetration losses of 2 dB, 9 dB, and 35.5 dB at 60 GHz through a glass door, a plasterboard wall with metallic studs, and a wall with a metal-backed blackboard, respectively [10].

The reflected multipath distribution was found to be highly correlated with the propagation environment at 60 GHz [11]. Multipath reflections from buildings and other objects in an urban environment at street level, as measured with narrow beam antennas, caused at least 15 dB additional path loss relative to line of sight (LOS) signals [9]. In addition, 15 to 20 dB of attenuation in single-bounce reflected paths, as compared to LOS paths, were measured in an office environment at 60 GHz [12].

This work presents 28 GHz propagation measurements in and around buildings in New York City. By comparing

transmitted power to reflected power measured from a material or obstruction under test, the magnitude of the reflection coefficient $|\Gamma_{||}|$ for a vertically polarized plane wave can be computed from (1) [13][14]:

$$|\Gamma_{||}| = \frac{\sqrt{\frac{|E_r|^2}{120\pi} A_e}}{\sqrt{\frac{|E_i|^2}{120\pi} A_e}} = \frac{\sqrt{|E_r|^2}}{\sqrt{|E_i|^2}} = \frac{|E_r|}{|E_i|} \quad (1)$$

where $|E_r|$ and $|E_i|$ are the magnitudes of the reflected and incident electric fields in V/m , respectively, and A_e is the antenna effective area measured in the far-field. In our case, a far field close-in reference distance was set at $d_o = 5m$ for 24.5 dBi antennas.

Penetration loss was calculated by comparing the difference in received power between unobstructed free space measurements versus the test material obstructing the transmitter (TX) and receiver (RX). Received power at $d \geq d_o$ with respect to a reference distance, d_o , can be calculated using (2) [15]:

$$P_R(d) = P_T + G_T + G_R - 20\log_{10}\left(\frac{4\pi d_o}{\lambda}\right) - ECL[dB] \quad (2)$$

where P_R and P_T are the received and transmitted powers in dBm, G_T and G_R are the transmitter and receiver antenna gains of 24.5 dBi each with 10° half power beamwidth, λ is the wavelength of the carrier wave (10.71 mm at 28 GHz), d_o is 5 m, the far-field close-in reference distance between the TX and RX, and ECL is excess channel loss in dB beyond d_o . In our measurements, the different P_T values used were -8.55 dBm, +11.63 dBm and +21.37 dBm. The corresponding EIRPs were +15.95 dBm, +36.13 dBm, and +45.87 dBm, respectively.

This paper is structured as follows: Section II describes the experimental procedure and the equipment setup for reflection and penetration measurements for common building materials. Section III presents the analysis for reflectivity and penetration loss for different environments in New York City. Section IV concludes with key results presented in this paper.

II. 28 GHZ PENETRATION AND REFLECTION MEASUREMENT PROCEDURE

Throughout the measurement campaign conducted during the summer of 2012, reflection and penetration measurements were recorded in and around many buildings on the NYU campuses in Manhattan and Brooklyn. These sites include the 10th floor of 2 MetroTech Center (MTC) at NYU-Poly in Brooklyn, Othmer Residence Hall (ORH) in Brooklyn, and Warren Weaver Hall (WWH) in Manhattan. Propagation characteristics in these urban environments were measured using the same broadband channel sounding hardware used in [4][5][6][14]. When transmitting with full power ($P_T = +30$ dBm before TX antenna), the largest path loss that our hardware could have recorded was 178 dB (103 dB relative to 5 meter free space). In this paper, all presented path losses are in excess of the 5 meter free space reference path loss of 75.3 dB at 28 GHz.

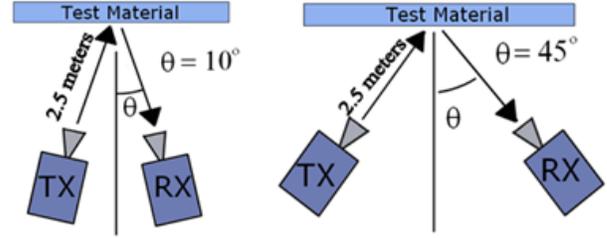


Fig. 1. Test setup at ORH and WWH for measuring reflected power from various building materials at 28 GHz. The TX and RX were placed 2.5 m away from the material, with the antennas at equal heights at 1.5 m, oriented at two different incident angles, $\theta = 10^\circ$ and 45° . Both the TX and RX horn antennas had 24.5 dBi gains with 10° half power beamwidth.

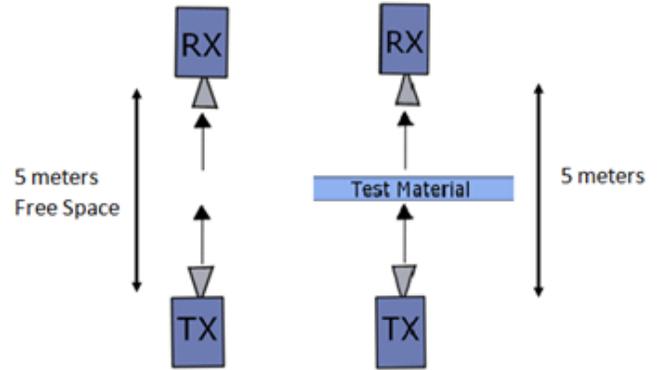


Fig. 2. Test setup at ORH and WWH for measuring penetration loss of various building materials at 28 GHz. To measure the penetration loss for a test material, first, the TX and RX were placed 5 m away from each other in free space (left). Then, they were moved and positioned at normal incidence on opposite sides of test materials at equal heights of 1.5 m, with antennas pointing at each other, and both 2.5 m away from the test material (right). Both of the horn antennas had 24.5 dBi gains with 10° half power beamwidth.

To measure the reflected power from a test material, the TX and RX were separated by a distance of 2.5 m from the material with the antennas oriented at two different incident angles, $\theta = 10^\circ$ and 45° , for tinted glass, clear glass, concrete, and drywall, as shown in Fig. 1.

As illustrated in Fig. 2, in order to conduct the penetration loss measurement, the TX and RX were first separated by 5 meters in free space conditions to provide a far-field reference path loss, which was consistently measured to be 75.3 dB. Then, the TX and RX were moved to be on each side of a test material while still maintaining a 5 m separation distance. Both TX and RX were placed 2.5 m away from the test material with identical antenna heights of 1.5 m as seen in Fig. 2. In all tests, vertically polarized 28 GHz radio waves were transmitted with directional antennas pointing at each other, normal to the test material. Measurements of penetration loss for common building materials (tinted glass, clear glass, brick, and drywall) were conducted at all three locations (ORH, MTC, and WWH). Fig. 3 shows the TX and RX setup for outdoor reflection, and both indoor and outdoor penetration measurements. The images are representatives of

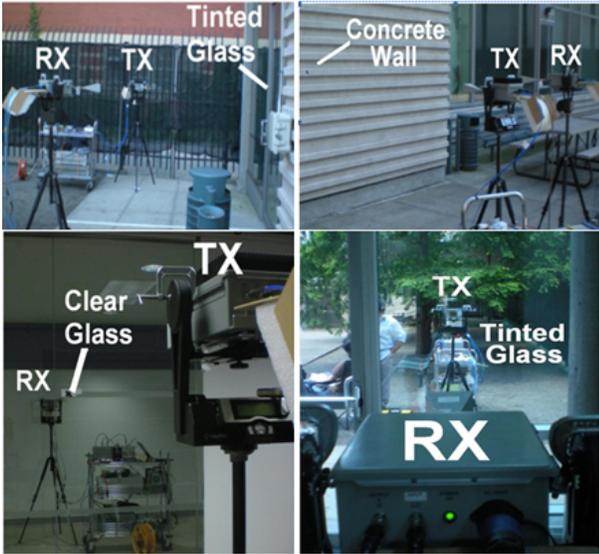


Fig. 3. Pictures of the 28 GHz reflection measurement for outdoor tinted glass at ORH (top left), outdoor concrete wall at ORH (top right), penetration loss measurement for indoor clear glass at MTC (bottom left) and tinted glass at ORH (bottom right).

the configuration used for all materials.

At MTC, indoor measurements of penetration losses for multiple walls and obstructions were conducted at eight different RX locations as illustrated in Fig. 4. For RX 1 and 2, the signal was transmitted through two and three walls, respectively. All of the walls measured here were made of gypsum drywall and had the same thickness of 13 cm. For RX 3 and 4, the signal was transmitted first through three walls and then one door, and through three walls followed by two doors, respectively. The doors mentioned above were made of wood with a thickness of 4.5 cm, and had a 60 cm × 10.2 cm glass window pane with a 2 mm-thick square-shaped metal grating contained in a metal frame. For RX 5 and RX 6, the signal propagated through two office cubicles and four walls successively. For RX 7, the signal went through two office cubicles, two walls, one wooden door, one wall, one metal door, and two other walls in succession. For RX 8, the signal was transmitted through two office cubicles, two walls, an elevator bank, and another three walls successively.

III. 28 GHz REFLECTION AND PENETRATION ANALYSIS

Table I summarizes the reflection coefficients for common building materials at 28 GHz. The table compares results of indoor materials to outdoor materials. Note that the outdoor materials have larger reflection coefficients of 0.896 for tinted glass and 0.815 for concrete at a 10° incident angle, as compared to clear non-tinted glass and drywall, which have lower reflection coefficients of 0.740 and 0.704, respectively. This result follows theory [15], and is most likely due to outdoor building materials containing thick and dense metal layers. Reflective surfaces at 28 GHz allow radio frequency (RF) energy to be contained within the building, which reduces co-channel intercell interference that could leak outside of

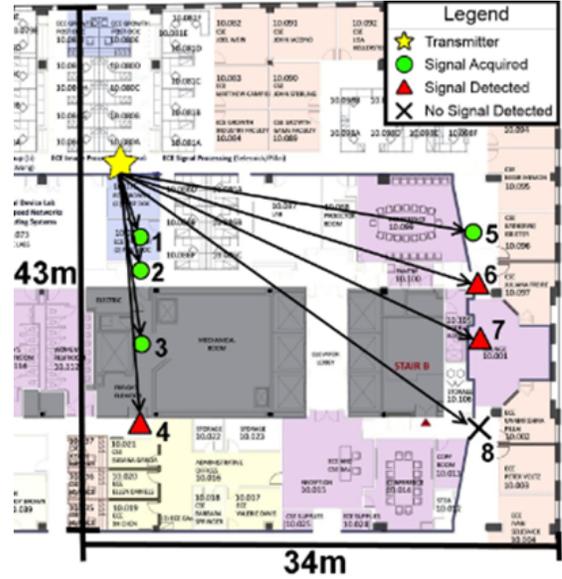


Fig. 4. Indoor office wall penetration measurement plan at MTC 10th floor. The TX location is marked by a yellow star, the RX locations where signals can be acquired are marked by green circles, and locations where weak signals can be detected are red triangles. An outage (penetration loss is greater than 74 dB) is shown as a black cross. The paths for wave penetration are shown in black arrows.

TABLE I

COMPARISON OF REFLECTIVITY FOR DIFFERENT MATERIALS AT 28 GHz. CONCRETE AND DRYWALL MEASUREMENTS WERE CONDUCTED WITH 10° AND 45° INCIDENT ANGLES, WHILE TINTED AND CLEAR GLASS REFLECTIVITY WERE MEASURED AT 10°. BOTH OF THE HORN ANTENNAS HAVE 24.5 DBI GAINS WITH 10° HALF POWER BEAMWIDTH.

Environment	Location	Material	Angle (°)	Reflection Coefficient ($ \Gamma_{ }$)
Outdoor	ORH	Tinted Glass	10	0.896
		Concrete	10	0.815
			45	0.623
Indoor	MTC	Clear Glass	10	0.740
		Drywall	10	0.704
			45	0.628

the building, and thus suggests high frequency reuse between indoor and outdoor networks. This also illuminates difficulties in achieving indoor coverage with outdoor infrastructure, as the buildings appear very difficult to penetrate from the outside at 28 GHz. Relays and ultrawideband repeaters will likely be required to achieve indoor-to-outdoor coverage, or else outdoor mobile users will need to handoff into the indoor network (perhaps unlicensed spectrum or reused mm-wave spectrum) as a user enters a building.

Table II contains the penetration losses of building materials at a 5 m TX-RX separation distance. The results for outdoor tinted glass in ORH consistently show that a large portion of the signal power ($|\Gamma| = 0.896$) is reflected and could not penetrate through the glass. Brick also shows a high penetration loss of 28.3 dB at 1.83 m thickness through a brick pillar. Indoor drywall has moderate attenuation of 6.84 dB and clear, non-tinted glass had the least attenuation of 3.6-3.9 dB. High penetration loss through brick and tinted glass, and low

TABLE II

COMPARISON OF PENETRATION LOSSES FOR DIFFERENT ENVIRONMENTS AT 28 GHZ. THICKNESSES OF DIFFERENT COMMON BUILDING MATERIALS ARE LISTED. BOTH OF THE HORN ANTENNAS HAVE 24.5 DBI GAINS WITH 10° HALF POWER BEAMWIDTH.

Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
	WWH	Brick	185.4	-34.7	-63.1	28.3
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
		Tinted Glass	<1.3	-34.7	-59.2	24.5
	WWH	Clear Glass	<1.3	-34.7	-38.3	3.6
		Wall	38.1	-34.0	-40.9	6.8

attenuation through clear glass and drywall suggest that RF energy can be contained in intended areas within buildings, also reducing interference, but making building penetration more difficult.

To further examine the wave propagation during the penetration measurements at ORH, Fig. 5 shows a Power Delay Profile (PDP) measuring the penetration loss through the tinted glass. After initial penetration and reception (excess delay of 0 ns) through the glass, the transmitted wave reflected within the building and was received with excess delays of 35 ns, 50 ns, and 75 ns. We computed a penetration loss of 40.1 dB through the tinted glass at ORH with Equation 2, where received power was -75 dBm and 5 m free space received power was -34.9 dBm, using a transmitted power of -8.55 dBm and high gain 24.5 dBi horn antennas. Despite 40.1 dB penetration loss through the tinted glass, the radiated signal

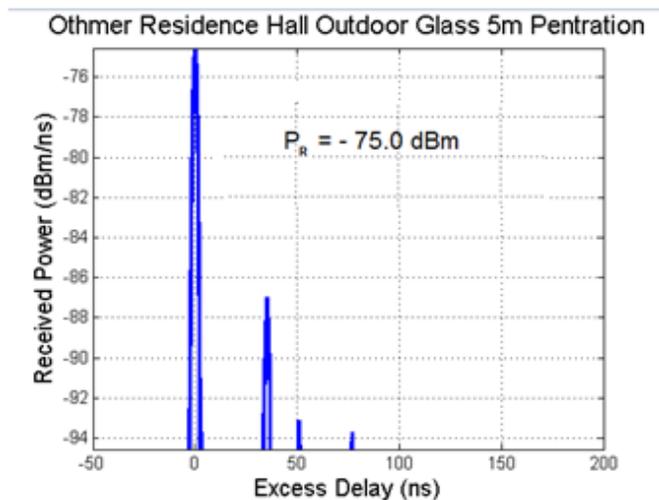


Fig. 5. Multipath delay spread observed in the 5 m tinted glass penetration test at ORH at 28 GHz. P_R is the received power of the first arriving peak. It is also the multipath observed with the largest excess delay (75 ns) among all the data collected for penetration measurements. The TX is positioned in an outdoor environment, and the RX is positioned indoors in a residential environment. Both of the horn antennas have 24.5 dBi gains with 10° half power beamwidth.

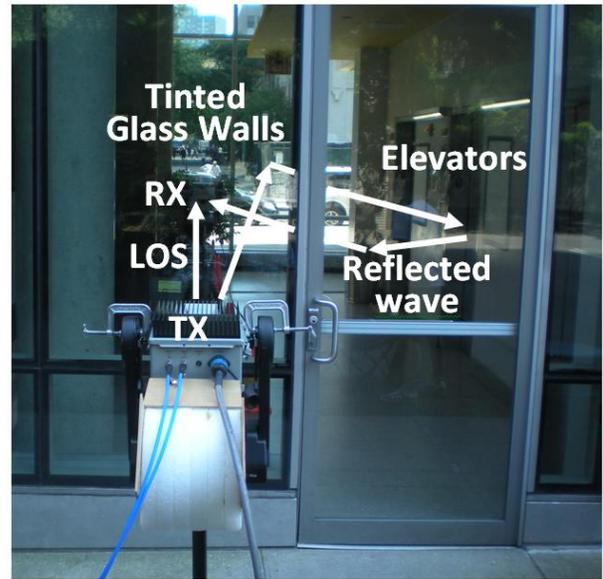


Fig. 6. Potential reflectors that created multipath propagation observed after initial penetration through tinted glass at ORH at 28 GHz. The reflections measured in Fig. 5, travelled 75 feet (e.g. 75 ns) after the first incoming wave (LOS component) was received.

still had enough power to be received up to 75 ns, which indicates there are many reflective materials in the building that will propagate well at 28 GHz, as shown in Fig. 6.

Table III presents the values for penetration losses through multiple interior rooms and walls in an office environment, with variations in TX-RX separation distance and the number of penetration obstructions as seen in Fig. 4. Data is grouped into three subsections: signal acquired, signal detected, and no signal detected, as shown in Fig. 4. Signal acquired is defined as a location where the SNR is sufficiently high for accurate acquisition, i.e. penetration loss (relative to a 5 meter free space test) is less than 64 dB beyond the 5 m free space loss. Signal detected is a location where the SNR is high enough to distinguish signal from noise; however, SNR is not large enough to be accurately acquired, i.e. penetration loss between 64 dB and 74 dB. No signal detected denotes an outage, where penetration loss is greater than 74 dB beyond the 5 m free space loss.

As shown in Fig. 4 and Table III, the results obtained at each RX site show that the penetration loss does not greatly depend on the TX-RX separation distance. Although RX 5 has a separation distance of 25.6 m (two cubicles and four walls of obstructions), which is 14.2 m greater than that of RX 3 (three walls and a door of obstructions), both locations have virtually identical measured penetration loss. Note that among the measured indoor RX sites, one outage was found at RX 8 with the TX-RX separation distance of 35.8 m. One possible cause for this outage is that the separation distance was too large and unable to penetrate the metal elevators in the elevator bank.

TABLE III

RESULTS FOR INDOOR WALL PENETRATION LOSS MEASUREMENTS IN AN OFFICE ENVIRONMENT AT 28 GHz. THE RX ID NUMBERS CORRESPOND TO THE LOCATIONS LABELED IN FIG. 4. RX LOCATIONS ARE ORDERED IN INCREASING TX-RX SEPARATION DISTANCES. MULTIPLE OBSTRUCTIONS EXISTED BETWEEN THE TX AND RX. "SIGNAL DETECTED" ARE DENOTED BY LOCATIONS WHERE THE SNR WAS HIGH ENOUGH TO DISTINGUISH SIGNAL FROM NOISE; HOWEVER, SNR WAS NOT LARGE ENOUGH FOR THE PDP TO BE ACQUIRED. "NO SIGNAL DETECTED" DENOTES AN OUTAGE WHERE MATERIAL PENETRATION LOSS IS GREATER THAN 74 dB.

RX ID	TX-RX Separation (m)	# of Partitions				Transmitted Power (dBm)	Received Power - Free Space (dBm)	Received Power - Test Material (dBm)	Penetration Loss (dB)
		Wall	Door	Cubicle	Elevator				
1	4.7	2	0	0	0	-8.6	-34.4	-58.8	24.4
2	7.8	3	0	0	0	-8.6	-38.7	-79.8	41.1
3	11.4	3	1	0	0	11.6	-21.9	-67.0	45.1
5	25.6	4	0	2	0	21.4	-19.0	-64.1	45.1
4	30.1	3	2	0	0	21.4	-30.4		
6	30.7	4	0	2	0	21.4	-30.5		Signal Detected
7	32.2	5	2	2	0	21.4	-30.9		
8	35.8	5	0	2	1	21.4	-31.9		No Signal Detected

IV. CONCLUSION

This paper presents measurements of reflection and penetration of common building materials at 28 GHz, using vertically polarized antennas in New York City. Utilizing a broadband sliding correlator channel sounder, received power was measured for various building materials, such as brick, concrete, drywall, tinted glass, and clear glass. Reflection coefficients for outdoor materials such as tinted glass and concrete were as large as 0.896, showing high reflectivity and very small transmittivity. Outdoor tinted glass had a penetration loss of 40.1 dB, indicating that such material is highly attenuative and very reflective. In contrast, indoor clear non-tinted glass had a penetration loss of 3.9 dB. In addition, indoor walls had a penetration loss of 6.84 dB at 28 GHz. In a densely urban environment, brick penetration through a pillar caused a 28.3 dB penetration loss. From the measurements presented here, it is clear that indoor-to-outdoor penetration will be quite difficult at 28 GHz, whereas indoor-to-indoor and outdoor-to-outdoor propagation is easily supported by the strong reflectivity of external building materials and low attenuation of indoor materials. The highly reflective external building materials can enhance outdoor signal coverage, and allow a wide range of possible angles of arrival to create TX-RX links in outdoor environments. Further, it was found that the penetration loss through indoor walls is dependent on the number of obstructions and the characteristics of the obstructions and the TX-RX separation distance. In addition, the lower penetration loss of indoor materials coupled with reflective outdoor materials and highly lossy external glass and walls helps reduce interference between indoor and outdoor mm-wave networks, thus allowing high frequency reuse. These measurement results of common building materials provide practical values for designing future mm-wave broadband cellular communication systems operating at 28 GHz.

V. ACKNOWLEDGMENT

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