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28 GHz and 73 GHz Signal Outage Study for Millimeter Wave Cellular and Backhaul Communications

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Abstract—**This paper presents millimeter wave propagation measurements in New York City and an analysis of signal outage at 28 and 73 GHz using similar spread spectrum sliding correlator channel sounders that employed high gain, directional steerable antennas (24.5 dBi gain antennas at 28 GHz and 27 dBi gain antennas at 73 GHz) at both the transmitter and receiver. Three identical transmitter locations were used for both the 28 and 73 GHz campaigns, while the 73 GHz campaign included two new TX locations. The 28 GHz campaign tested 25 receiver locations for each of the three transmitter locations, and the 73 GHz campaign tested 27 receiver locations in various combinations with the five transmitter sites. Overall, 75 TX-RX location combinations were tested at 28 GHz and 74 TX-RX combinations were tested at 73 GHz, with T-R (transmitter-receiver) separation distances up to 425 m. The maximum transmit power was 30 dBm at 28 GHz and 14.6 dBm at 73 GHz. Our analysis shows that the estimated outage probabilities at 28 and 73 GHz for the cellular communication scenario are 14% and 17%, respectively, and is 16% for the 73 GHz backhaul scenario.**

***Keywords*— 28 GHz; 73 GHz; Millimeter Wave Communications; E-Band; Channel Sounder; Outage Probability**

I. INTRODUCTION

In recent years, millimeter wave (mmWave) bands, due to their large unlicensed and lightly licensed bandwidths, have become a promising candidate for next generation wireless communications. To accommodate users who will demand multi-Gbps data rates, both industrial and academic researchers have been studying the characteristics of the mmWave channel [1][2][3]. A study on power consumption and energy efficiency shows that as the bandwidth increases, the relative power consumption will improve [4], which indicates future smart phones will have more efficient power usage and higher data rates at mmWave frequencies as compared to common UHF and microwave bands used today.

A long standing myth in wireless communications is that in dense urban environments it is not feasible to conduct mmWave mobile communications. Early studies for local multipoint distribution service (LMDS) at 28 GHz in a residential urban environment showed that only line-of-sight (LOS) paths could provide sufficiently strong received signal strength. Building blockages, which cause non-line-of-sight (NLOS) radio paths, are a major limitation to maintaining an acceptable link [5] [6]. However, as we show in this paper, NLOS links can be established via scattering and reflection for cell radii up to 200 m. At 28 GHz, the atmospheric attenuation is 0.012 dB/200 m, nearly identical to the cellular bands used today [1]. For 28 GHz LMDS systems, early research showed the need for highly directional antennas to reduce channel dispersion and to improve link budget at the receivers [7]. An evaluation of 28 GHz LMDS showed the coverage ranged from 60% using a 40 foot tall antenna, to 80% using an 80 foot tall antenna for a cell radius of two kilometers [8]. These studies suggest that future wireless communication networks may deploy highly directional antennas for much smaller cell sizes as compared to current systems.

An outage study at 38 GHz in Austin, Texas showed that using directional antennas at both the transmitter and receiver can substantially improve the coverage probability from 60.4% to 100% for a cell radius of 200 meters [9]. Two transmitters with heights of 36 and 18 meters were used, and 53 receiver locations were randomly chosen for T-R separation distances up to 500 meters. The measurement results showed that for inter-site distances less than 200 m, the outage probability is zero.

A recent measurement campaign was conducted at 73 GHz in the dense urban environment of New York City to study the channel propagation characteristics for both cellular and backhaul scenarios. 73 GHz is within the E-band frequency range (71~76 GHz and 81~86 GHz), a lightly licensed portion of the mmWave spectrum that is an auspicious solution to meet future capacity demands. The large contiguous bandwidths at E-band could provide a substantial leap in data rates to be multi-Gbps in the next few years. The atmospheric absorption of E-band is around 0.09 dB/200 m, which is only slightly worse than that of currently used cellular bands with cell sizes of several hundred meters [1]. The rain attenuation characteristics are also known to be similar to today’s cellular bands [13]. Studies must be conducted and analyzed to characterize and understand the E-band channel in order to explore its potential application for cellular and backhaul communications.

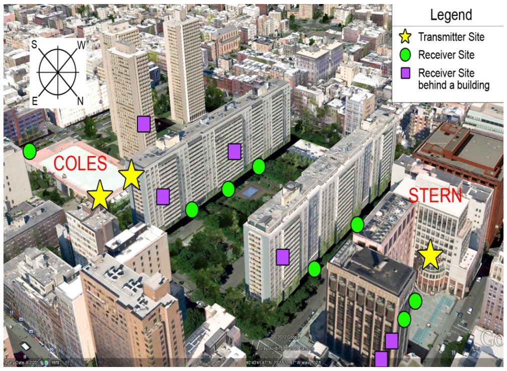

Fig. 1. A map showing 28 GHz measurement locations in New York City. Three transmitter locations are shown as yellow stars, and receiver locations are shown as green dots and purple squares. The purple squares indicate receiver locations that are blocked by buildings in this image [10].

The classification of LOS and NLOS physical environments is important for characterizing radio links, and we define them as follows:

1) LOS: no obstruction is between the transmitter and receiver.
2) Moderate NLOS: there are small obstructions such as foliage, building edges, vehicles, and/or pedestrians between the transmitter and receiver. These obstructions will partially block the optical link.
3) Heavily obstructed NLOS: there is no optical link between the transmitter and receiver. The path is entirely blocked by obstructions, including high rise buildings and extremely heavy foliage.

To study channel propagation characteristics, path loss as a function of distance is an important parameter to describe the coverage distance and the outage probability. Five meters is chosen to be the close-in reference distance at 28 GHz since it is in the far field of the antennas yet close enough for reliable free space propagation. The free space path loss with a close-in free space reference distance can be expressed as the following equation,

$$\overline{PL(d)} = PL_{free\ space}(d_0) + 10\bar{n}\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

where d_0 is five meters, d is the T-R separation distance in meters, $\bar{n}$ represents the path loss exponent, and X_σ is a zero mean Gaussian random variable with standard deviation of σ, also known as the shadow factor. In the 73 GHz measurements the close-in reference distance was chosen to be four meters for better accuracy during the system calibration.

This paper presents 28 GHz and 73 GHz measurement campaigns in New York City, with a focus on outage analysis, and gives the estimated outage probability based on the receiver locations and environments. The ultimate goal is to use the outage probability and coverage statistics to help design future wireless communication systems. The results show that low outage probability with respect to cell size is similar to the UHF and microwave cells used today, and supports the viability of millimeter wave communication systems in dense urban environments such as New York City.

II. Measurement Hardware

Measurements at 28 GHz and 73 GHz used similar channel sounding equipment. The channel sounder was designed based on the theory of sliding correlation, initially proposed by *D. Cox* [15][20]. Our baseband signal, a 400 Mega chip per second (Mcps) baseband spread spectrum pseudorandom noise (PN) sequence is generated using 11-bit shift registers with emitter-coupled logic (ECL) circuit on a PCB board. This baseband sequence is then mixed with a first stage intermediate frequency (IF) to form the spread spectrum IF signal. At 28 GHz, the IF is 5.4 GHz and at 73 GHz it is 5.625 GHz. The IF signal is then mixed with a local oscillator (LO) frequency of 22.6 GHz at the upconverter in order to achieve the 28 GHz RF signal. At 73 GHz, the 22.625 GHz signal is tripled to obtain a LO frequency of 67.875 GHz, that is then mixed with the spread spectrum IF signal at 5.625 GHz to generate the final 73.5 GHz RF signal. The channel sounder has a 2.5 ns multipath time resolution and an 800 MHz first null-to-null bandwidth. In the 28 GHz measurement campaign, a pair of vertically polarized antennas with 24.5 dBi gain and a 10.9^o half-power beamwidth was used. In the 73 GHz campaign a pair of vertically polarized antennas with 27 dBi antennas and a 7^o half-power beamwidth was used. The maximum transmit power before the antenna for the 28 GHz measurements was 30 dBm, and 14.6 dBm for the 73 GHz measurements. The maximum measurable path loss for the channel sounder system was 178 dB for 28 GHz and 181 dB for 73 GHz due to different detection techniques in the two systems. The 28 GHz system signal detection algorithm was less sensitive than the one used in the 73 GHz campaign. The key parameters of the two channel sounders are listed in Table I.

Additionally, in the 73 GHz measurement campaign, the analog signal generators were replaced by QuickSyn digital frequency synthesizers provided by National Instruments. The frequency synthesizers greatly reduced the size and weight of the entire channel sounder system, and are easily controlled by a personal computer through USB connection [16].

III. Measurement Procedure

In the 28 GHz measurement campaign, three transmitters and 25 receiver locations were chosen on the campus of New York University, located in a densely populated neighborhood in downtown Manhattan with T-R separation distances ranging from 19 m to 425 m, as shown in Fig.2 [10][11][12]. Two of the transmitters were located on the rooftop of the Coles Sports Center (COL1 and COL2), seven meters above ground. The third transmitter was on the fifth floor balcony of the Kaufman Management Center (KAU), 17 meters above ground level. All 25 receiver locations shared each of the three transmitters, thus providing 75 distinct TX-RX location combinations [14]. Among the total 75 TX-RX combinations, only five were LOS, others were NLOS, either blocked by foliage or tall buildings.

In the 73 GHz measurements, five transmitter locations were chosen in the same area as in the 28 GHz measurements with consideration of two communication scenarios: cellular

TABLE I. CHANNEL SOUNDER CHARACTERISTICS AT 28 GHZ AND 73 GHZ

Frequency	28 GHz	73.5 GHz
TX/RX IF Frequency	5.4 GHZ	5.625 GHz
TX/RX LO Frequency	22.6 GHz	67.875 GHz
TX Antenna	24.5 dBi Horn Antenna	27 dBi Horn Antenna
RX Antenna	24.5 dBi Horn Antenna	27 dBi Horn Antenna
Antenna Half-power Beamwidth	10.9°	7°
Transmit Power	30 dBm	14.6 dBm
Pseudorandom Noise Code Chip Rate	400 Mcps	
Maximum Measurable Path Loss (5 dB SNR)	178 dB	181 dB
RF Bandwidth (Null-to-Null)	800 MHz	
Multipath Time Resolution	2.5 ns	
Antenna Polarization	Vertical Polarization	

TABLE II. NUMBERS OF CELLULAR AND BACKHAUL RECEIVER LOCATIONS FOR EACH TRANSMITTER LOCATION FOR THE 28 AND 73 GHZ MEASUREMENTS WITHIN 200 METERS

Transmitter Locations	Number of 73 GHz Cellular Receiver Locations	Number of 73 GHz Backhaul Receiver Locations	Number of 28 GHz Cellular Receiver Locations
COL1	11	7	10
COL2	9	14	10
KAU	11	11	15
KIM1	3	3	N/A
KIM2	2	3	N/A
Total	36	38	35

and backhaul. Three of the five transmitter locations were identical to the locations in the 28 GHz measurements, namely COL1, COL2, and KAU. The fourth and fifth transmitters were on the second floor balcony of the Kimmel Center (KIM1 and KIM2), seven meters above ground. 27 receiver locations were selected based on the 28 GHz measurement campaign with a smaller T-R separation range of 27 to 216 m [10][12]. Overall, there were 36 cellular TX-RX location combinations and 38 backhaul location combinations tested, for a total of 74 distinct TX-RX location combinations. Table II shows the numbers of both cellular and backhaul receivers that each transmitter had within 200 m. Nine of the 74 TX-RX combinations were in LOS environments, the other 65 were either in a moderate NLOS or a heavy NLOS environment. Among the 74 TX-RX combinations, 12 were heavily obstructed by Washington Square Village, a 48-meter-tall and 175-meter-wide apartment complex building.

At the beginning of each measurement day, a free space system calibration was performed, since the equipment characteristics vary day-to-day due to temperature, humidity

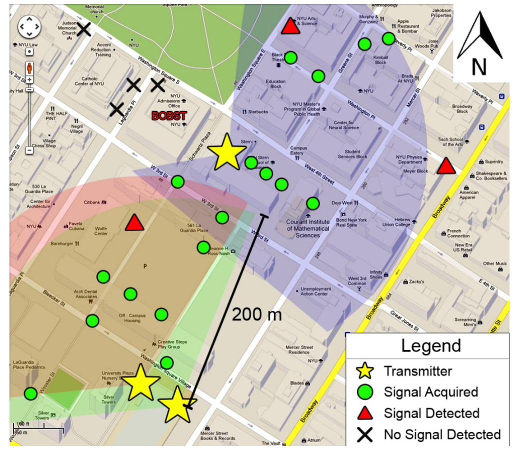

Fig. 2 A map for 28 GHz measurement results. All receiver locations are within 425 meters of transmitter locations. The transmitters are shown as yellow stars, and receiver locations which could acquire signal are shown as green dots. Receiver locations which only could detect signal are shown as red triangles, and signal outages are shown as black crosses [10].

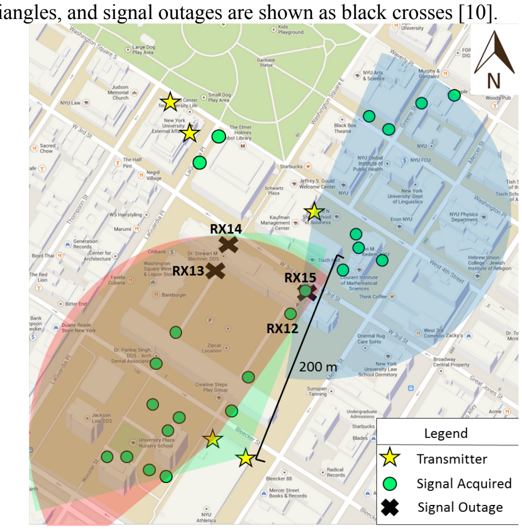

Fig.3 Sectorized map of 73 GHz measurement results. The receiver locations are within 216 meters of the five transmitters. Transmitters are shown as yellow stars, receiver locations with acquirable signal are shown as green dots, and signal outage locations are shown as black crosses.

and equipment conditions. The purpose of calibration is to establish the gain of the system in order to recover the true received power from the measured data.

In the 28 GHz measurement campaign, both the TX and RX antennas were initially rotated exhaustively in azimuth and elevation to find the strongest received power and this angle was specified as the zero reference angle. The TX antenna elevation remained fixed at -10° for all measurements. The TX antenna also had three azimuth angles of -5°, 0°, and +5°, where 0° represented the strongest reference angle. Each specific RX had three elevation angles, -20°, 0°, and +20° with the RX 0° representing the strongest azimuth reference angle. Thus each TX-RX location combination had nine angle combinations to measure angles of arrivals. For each of the nine TX-RX angle configurations, the RX antenna was swept 360° in the azimuth plane in steps of 10° while the TX antenna was fixed. A PDP was recorded at each step when there was observable energy above the noise floor [10]. TX antenna sweeps were also conducted for a tenth configuration with the

RX antenna fixed to the strongest azimuth and elevation angle while the TX antenna was swept in 10^o increments in the azimuth plane. At each increment a PDP was recorded at the receiver when there was observable energy above the noise floor.

In the 73 GHz measurement campaign, both the TX and RX antennas were exhaustively swept in the azimuth and elevation planes to determine the strongest received power angle combination. Unlike the 28 GHz measurements, the TX antenna elevation was maneuvered for the strongest power rather than remaining fixed at -10^o. After the strongest received power angle combination was determined, the RX antenna was swept in steps of 8^o (10^o for LOS conditions) in the azimuth plane for NLOS conditions. PDPs were acquired at each step when the received power was sufficiently strong and observable above the system noise floor. After the initial sweep, the RX antenna was uptilted and downtilted by 8^0 in the elevation plane for two azimuth sweeps, then RX elevation was reset back to its strongest power elevation and then swept two additional times for the TX antenna uptilted and downtilted 8^o from its 0^o strongest elevation angle, resulting in five initial RX sweeps. Then the RX antenna was fixed at the two strongest azimuth and elevation angle combinations determined during the initial five RX sweeps, while the TX antenna was swept in the entire azimuth plane. Another angle of departure in the elevation and azimuth plane was determined from TX sweeps, and the RX antenna was then swept an additional five times in a similar manner to the first five RX sweeps. Therefore a total of 12 antenna sweeps for each TX-RX location combination were performed for both cellular and backhaul communication scenarios.

IV. OUTAGE RESULTS AND ANALYSIS

Wavelengths at mmWave frequencies are much smaller compared to lower microwave frequencies used for current cellular systems. Thus, small obstructions, edges, and rough surface will have a greater influence on mmWave signal transmission than UHF and microwaves. In legacy cellular networks, the major limit for system capacity is the intercell interference, so in previous studies, the outage probability is mainly based on how to achieve satisfactory signal-to-interference ratio (SIR). On the other hand, mmWave systems will not be as concerned with interference because of the highly directional narrowbeam antennas that will be used, compared to current widebeam sectored cells. Obstructions and shadowing however will have a major impact, because as the T-R separation distance increases, the transmitted signal gets weaker along the transmission paths. This is a concern because with such large bandwidths proposed for mmWave systems, we will become power-limited instead of interference-limited [17][18]. The outage probability therefore can be defined as the likelihood that the received signal strength falls below the minimum measurable signal power level, as shown below,

$$P_{out} = Pr\{P_{receive} < P_{transmit} - PL_{max}\} \quad (2)$$

where P_{out} is the outage probability, $P_{receive}$ is the received signal strength, $P_{transmit}$ is the transmit power output from the TX antenna, and PL_{max} is the system's maximum measurable path loss.

For our channel sounder the maximum measurable path loss is 178 dB at 28 GHz and 181 dB at 73 GHz, representing the channel sounder's sensitivity. The criterion for signal outage is path loss greater than the maximum measurable path loss within 200 meters, which showed either pure noise or no detectable signal at any TX-RX angle combination measured. The 200 meters distance suggests the maximum radius for future wireless networks. In the 28 GHz measurements, some receiver locations could detect signal but the power level of received signal was too weak to acquire, but with beam combining techniques presented in [19], the received power can be greatly increased.

In the 28 GHz measurements, the majority of all the 75 TX-RX location combinations were blocked by tall buildings, heavy foliage and other urban constructions. 30 TX-RX location combinations were able to detect signal. Among the total 75 TX-RX location combinations, 35 were located within a 200 m T-R separation distance range. The outage probability was found to be 60% for all receiver locations, but only 14% for receiver locations within 200 m. There were four receiver locations which could not detect any signal at any angle. The reason is that the Bobst Library blocked all paths between the transmitter and receivers, and the signal could not penetrate through the building. The outage probability is a little different from [10] because more data has been processed after the paper was published.

In the 73 GHz campaign, there were nine TX-RX location combinations with LOS paths from the transmitters. For urban environments, high rise buildings are most commonly known to be blockages in cellular communications. Among all 74 TX-RX location combinations, six cellular level receivers and six backhaul level receivers had signal outage due to building blockage, which are shown as black crosses in Fig. 3. These outage locations were blocked by Washington Square Village, a large apartment complex with height of 48 meters. The resulting outage probability for 73 GHz measurements for the cellular communication scenario is 17% while the backhaul scenario is 16%. The estimated outage probability comparison for 28 and 73 GHz cellular and backhaul communication scenarios are shown in Table III. The results indicate comparable low outage probabilities at both 28 and 73 GHz for 200 m cell sizes.

There are two notable measurement results at 73 GHz as shown in Fig. 4 and 5. One of the receiver locations, RX 15, was measured for both KAU and COL1. The distance between this receiver and KAU was 73 meters and from COL1 was 183 meters. An outage occured at this receiver location for the COL1 transmitter, but it received enough strength signal from KAU, even though it was completely blocked by a tall concrete building. A primary ray tracing for RX 15 from KAU is shown in Fig. 4, where the yellow marker represents the KAU transmitter and the green marker represents RX 15. The reason that RX 15 could receive strong enough signal from KAU

TABLE III. COMPARISON OF THE OUTAGE PROBABILITY FOR 28 GHZ CELLULAR SCENARIOS AND 73 GHZ CELLULAR AND BACKHAUL SCENARIOS TRANSMITTER LOCATIONS WITHIN 200 METERS.

Transmitter Locations	Transmitter Height (m)	Percentage of Outage for >Max. Measurable Path Loss		
		28 GHz	73 GHz	
		Cellular	Cellular	Backhaul
COL1	7	20%	27%	42%
COL2	7	11%	33%	15%
KAU	17	50%	0%	0%
KIM1	7	N/A	0%	0%
KIM2	7	N/A	0%	0%
Overall		14%	17%	16%

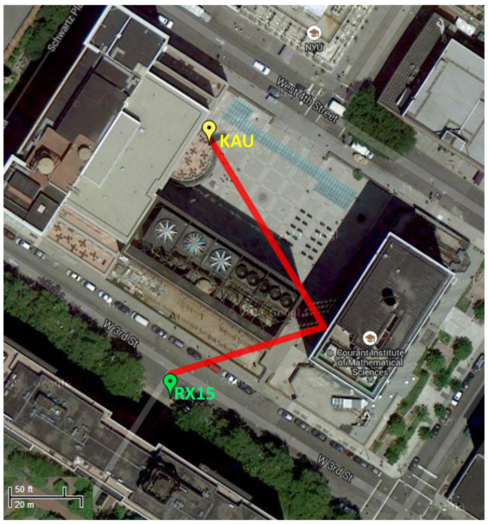

Fig. 4. A possible reflection path from the KAU transmitter to RX 15, creating a NLOS link for the 73 GHz measurement campaign.

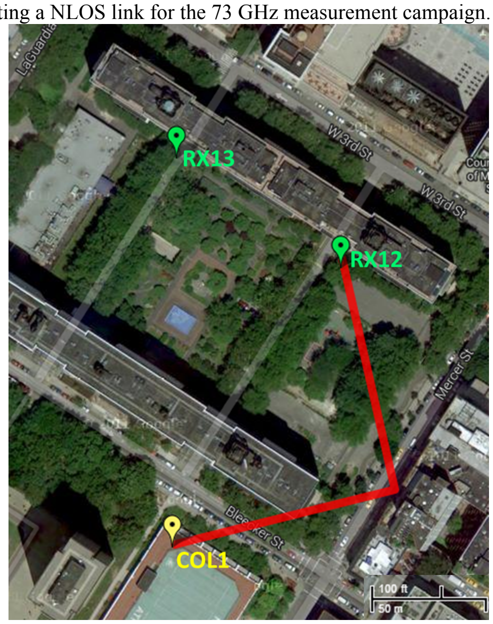

Fig. 5 A possible reflection path creating a NLOS link from COL1 to RX12 at 73 GHz. RX 13 is an outage location.

is a possible reflection path from the transmitter, as shown in the red lines in Fig. 4. Another result is that the receiver locations RX 12 and RX 13 had similar environment and separation distances from the COL1 transmitter, but RX 12 received strong signal, while RX 13 experienced an outage. The reason is that although both the receiver locations were blocked by Washington Square Village, there was a reflection path that could establish a sufficiently strong link from COL1 to RX 12. The other receiver location, however, has no reflection path from the transmitter, therefore resulting in an outage. Fig. 5 shows the possible reflection path from COL1 to RX 12.

V. CONCLUSION

Measurement campaigns were conducted at both 28 and 73 GHz in the dense urban environment in New York City with the consideration of cellular and backhaul communication scenarios. Three identical transmitter locations were used, and more than 25 receiver locations were randomly selected. The receiver locations cover both line-of-sight and non-line-of-sight links from transmitters. The majority of the links are non-line-of-sight, being partly and heavily blocked by high rise buildings, foliage, and vehicular traffic. Measurement results and outage probability calculations show that at 28 GHz the estimated outage probability is 14% for all RX locations within 200 meters. At 73 GHz the outage probabilities for T-R separation distances within 200 a meter cell size for cellular and backhaul scenarios are 17% and 16%, respectively. Heavy obstruction will cause outages within a 200 meter cell radius, but stable reflections and ground bounces can create non-line-of-sight paths and further extend the coverage range. The outage statistics demonstrate the viability of millimeter wave cellular and backhaul communication systems in dense urban environments, and prove the 200 m coverage potential for future small cell base stations at 28 and 73 GHz.

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