System Level Modeling and Performance of an Outdoor mmWave Local Area Access System

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***Abstract*—Millimeter wave (mmWave) frequencies offer the potential for very large capacity increases from traditional cellular frequencies because of the incredible amount of available spectrum (e.g., 10 GHz in the E-band alone). Additionally the latest channel measurements and research have shown that mmWave frequencies are useable for a 5G-type local area access system. However, employing mmWave frequencies for outdoor local area access presents a challenge particularly from blockage of the signal from the mobile to the access point. Using the latest path loss equations from measured data, a newly developed mmWave channel environment, and a model for distance-dependence LOS blocking probability, system-level capacity results are presented for a dense urban environment. The results show that with adequate access point density that low outage probability can be obtained with cell-edge rates well in excess of 100 Mbps and cell-average user throughputs of up to 5.12 Gbps.**

Keywords—mmWave, system simulations, LOS probability.

I. INTRODUCTION

The use of millimeter (mmWave) frequencies instead of traditional frequencies of less than 6 GHz for local area access systems has recently been shown to be a possibility [1]-[4]. These mmWave systems exploit the large amount of spectrum available (e.g., the 10 GHz available in the E-band from 71-76 and 81-86 GHz) to significantly boost the system capacity relative to lower frequencies. Hence mmWave systems are well positioned to meet the proposed 5G requirements of over 10 Gbps peak rate, at least 100 Mbps everywhere, and latencies of less than 1 msec [3] by exploiting the large available bandwidths.

Of course to be able to operate at mmWave frequencies certain challenges need to be met such as overcoming the oxygen and rain absorption, overcoming the increased path loss, being able to operate with random signal blockage to an access point (AP), and access to practical RF technology. The oxygen and rain absorption is overcome by the use of mmWave in small cells with inter-site distances of no more than 200 m resulting in worst-case losses of around 3-6 dB for the heaviest downpours [3]. The increased path loss is overcome by using larger array sizes than at lower frequencies such as 4x4 or 8x8 arrays at the AP and 2x2 or 4x4 arrays at the mobile. These large antenna array sizes are very practical at mmWave given the small wavelengths. For example, at 73 GHz a 4x4 array with 0.5 wavelength spacing in each dimension can fit within a 1 cm^2 area. The random blockage can be handled through sufficient AP density, intelligent antenna placement and selection at the mobile, and by having an architecture which enables rapid re-routing between APs [3]. In the case of complete blockage of the mmWave signal, the mobile could also fall back to an LTE or WiFi overlay network [3] which will operate in conjunction with the mmWave network. Finally the efficient integration of large scale arrays at mmWave frequencies is becoming a reality [5]-[7].

In this paper we explore the use of mmWave frequencies in outdoor dense-urban local area access systems. In Section II we give a brief overview of the expected mmWave channel characteristics in small cells including some details of a newly developed mmWave urban-micro channel model [8]. In Section III we use a simple ray-tracing environment to produce a LOS blocking probability model which can be used in system-level simulations. In Section IV we discuss some mmWave outdoor urban scenarios for system simulations which are developed from METIS scenarios [9]. In Section V we present mmWave system-level results and Section VI concludes the paper.

II. MMWAVE CHANNEL OVERVIEW

Proper modeling of the mmWave channel will be extremely important to be able to accurately assess the system-level performance of a mmWave local area access outdoor system. To this end, New York University (NYU) has recently taken outdoor measurements at 73 GHz in the dense urban environment of Manhattan [2][10]. One of the first channel characteristics analyzed was path loss where it was shown that the following model holds for omni-directional antennas at both the AP and the mobile [3]:

$$PL[dB](d) = 20\log_{10}\left(\frac{4\pi d_o}{\lambda}\right) + 10n\log_{10}(d / d_o) + X \qquad (1)$$

where d_o is a reference distance (1 m as in [3]), λ is the wavelength, n is the path loss exponent, d is the distance between transmitter and receiver in m, and X is the shadow fading term which is a zero-mean Gaussian random variable with a specified standard deviation (i.e., the shadow fading). For the line of sight (LOS) AP to mobile channel, n=2.1 and the shadow fading is 4.9 dB and for the non-LOS (NLOS) AP to mobile channel, n=3.3 and the shadow fading is 7.6 dB [3].

Besides the path loss, the system simulations will need a reasonable channel model for both the LOS and NLOS conditions. To meet this goal, a ray-based channel model was proposed in [8] which is based on results from a detailed commercial ray tracer [11] which used the same measurement area as the NYU measurements [10]. The ray tracer was tuned to

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match the large-scale path loss of the NYU measurements at the same transmit and receive locations. The ray tracer was used to generate the channel model because it provided significantly more data than was available with the NYU measurements and was particularly helpful in modeling the elevation dimension. In fact it was seen that the elevation (zenith) angle spread at mmWave had a similar distance-dependence as was seen at lower frequencies [12]. This distance-dependent elevation angle spread is shown in Fig. 1 for the elevation (zenith) angle of departure from the AP. As can be seen, the mean of the log (base ten) of the elevation angle spread of departure decreases with distance as a linear function and the standard deviation of the log of the elevation spread is relatively constant. A similar observation is seen for the elevation angle spread of arrival.

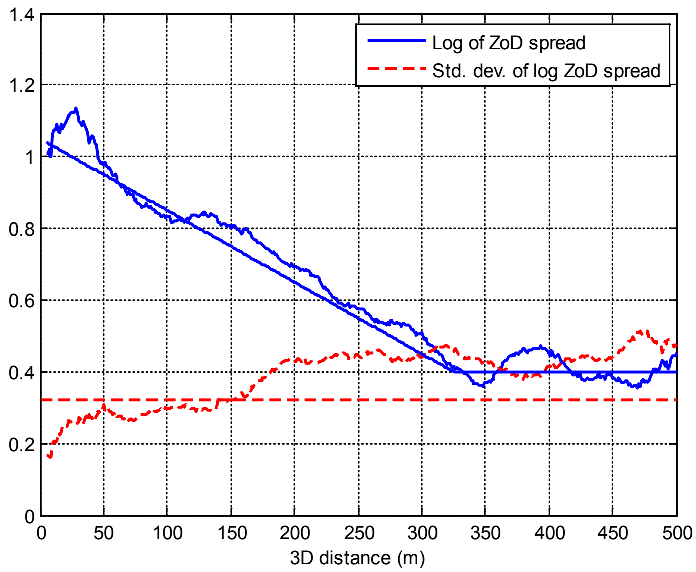

Fig. 1. Distance dependence of the mean and standard deviation of the log (base ten) of the elevation (zenith) spread of departure (ZoD) for the mmWave NLOS urban-micro channel.

Similar to the elevation spread of departure, the elevation angle bias was also seen as having a distance dependence [8]. The elevation angle bias is defined as the average deviation of the elevation angles from the LOS elevation angle. In fact it was seen that in NLOS channels that the elevation angle bias was virtually always above the LOS angles at both the AP and mobile. The reason for this is that in urban canyons that when the LOS was blocked that it was better to reflect off upper stories of buildings than endure the penetration loss through blockers (usually foliage).

The full details of the channel can be found in [8], and some of the highlights are shown in Table 1 for omni-directional antennas at both the AP and mobile. Note that only the NLOS elevation spread equations are shown as the LOS channel is generated as a NLOS channel with a LOS ray added in with an average Ricean factor of 12 dB with a standard deviation of 3 dB. Hence the LOS channel has a distance-dependent elevation spread which is related to the NLOS elevation spread.

Table 1. Select mmWave channel parameters (*d* is in m)

Parameter	LOS?	value
Delay spread, nsec	LOS	43 nsec
	NLOS	131 nsec
Azimuth angle spread of arrival at mobile, degrees	LOS	3°
	NLOS	20°
Azimuth angle spread of departure from AP, degrees	LOS	3.5°
	NLOS	12°
Elevation angle spread of arrival at mobile, $\log_{10}$(degrees)	NLOS	Mean: min(-0.0025*d*+1.1,0.3)
	NLOS	Std. dev: 0.26
Elevation angle spread of departure from AP, $\log_{10}$(degrees)	NLOS	Mean: min(-0.002*d*+1.05,0.4)
	NLOS	Std. dev: 0.32

III. mmWave LOS Probability

At mmWave frequencies objects such as vehicles, trees, and people, will block the LOS signal from the AP to the mobile if they are between the AP and mobile. Modeling this blockage will be important for reasonably assessing the capacity gains as well as outage probabilities. In this section we use a simple ray tracer implemented in Matlab™ to determine a distance-dependent LOS blocking probability which can be used by system simulators. The idea is similar to the one in [13] except that other blocking objects such as cars, trucks, and trees are included in addition to the human blockage.

The ray tracer models five blocks of an urban street environment where APs are located 5 m high on lampposts 5 m north and 5 m west from the southeast building adjacent to a street intersection. Fig. 2 shows one block of the simulated environment which includes cars, trucks, sport-utility vehicles (SUVs), trees, people, and APs. One hundred users are dropped along 3 m wide sidewalks which are on both the north and south sides of the street and the users are assumed to be walking east or west (randomly determined). The users hold the mobile 0.4 m in front of them and 1.5 m above the ground at shoulder height. The user is modeled as a 1.5 m high and 0.5 m wide cylinder topped with a head which is a 0.3 m high and 0.3 m wide cylinder.

There are 50 vehicles randomly placed along the 5 block street in one of four lanes where there is a 15% chance of the vehicle being a truck, a 17% chance of the vehicle being a SUV, and a 68% chance of the vehicle being a car. A car is modeled as a 5x2x1.5 m rectangle, a SUV is modeled as a 5.3x2.1x2 m rectangle, and a truck as a 14x2x3.7 m rectangle. The trees are modeled as having a 3.5 m high trunk with the foliage being a 4 m high and 4 m wide cylinder on top of the trunk. The trees are placed every 20 m along the 3 m wide sidewalks (except in intersections) where the trees are 2 m from a building.

The distance-dependent LOS blocking probability using this ray-tracing model is given in Fig. 3. The blocking probability is broken up into three cases, all users, users on the south side of the street, and users on the north side of the street. Interestingly the users on the same side of the street as the APs (i.e., the users on the south side of the street) have a higher blocking probability than the users on the opposite side of the street. The reason is twofold: 1) there is an increased chance of being blocked by a tree when the user is on the same side of the street as the AP and 2) there is an increased chance of selfblockage by the user when the user is on the same side of the street as the AP. For all mobiles a reasonable linear fit to the LOS blocking probability with foliage is given as

$$P_{block} = \min(0.0078d + 0.1,\, 0.8)\,, \tag{2}$$

where d is in m.

A model for the blocking probability without foliage on the trees for 5 m high APs is given by

$$P_{block} = \min(0.0078d + 0.08,\, 0.59)\,. \tag{3}$$

A model for the blocking probability for 3 m high APs with and without foliage on the trees (there is no difference since the APs are below the start of the foliage on the trees) is given by:

$$P_{block} = \min(0.0092d + 0.1,\, 0.0005d + 0.58,\, 0.9)\,. \tag{4}$$

Fig. 4 shows the LOS probability models for AP heights of 3 and 5 m both with and without foliage. With foliage, the lower AP height produces a higher blocking probability for distances less than 66 m and distances greater than 440 m (off scale). What is seen is that at some distances that being below the foliage seems to improve the chances of having a LOS link. Although not shown, it turns out that when the AP height is lowered to 3 m from 5 m then there is very little difference between the blocking probabilities between the users on each side of the street. Additionally without foliage for an AP height of 5 m there also is only a slight difference between the blocking probabilities for users on each side of the street.

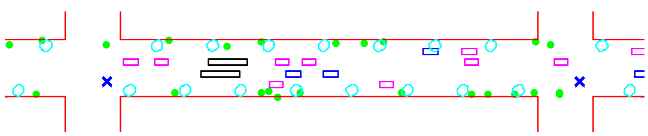

Fig. 2. Example ray-tracing environment for determining LOS probability. Green dots are users, cyan circles are trees, blue x's are APs, magenta rectangles are cars, blue rectangles are SUVs, and black rectangles are trucks.

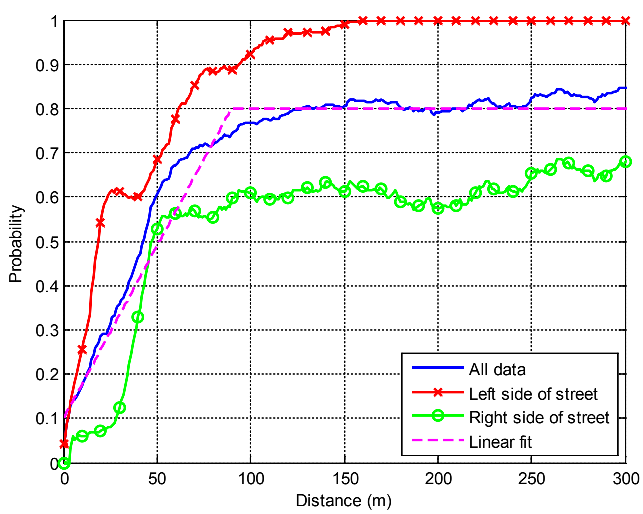

Fig. 3. LOS probability as a function of distance (m) for AP heights of 5 m and with foliage on the trees.

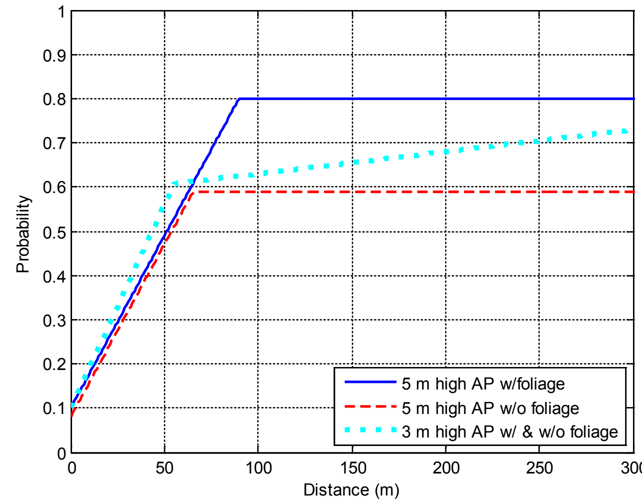

Fig. 4. LOS probability models as a function of distance (m) for AP heights of 3 and 5 m both with and without foliage.

IV. MMWAVE SCENARIOS

A European Union project, METIS [9], has recently been looking at 5G-type systems, and mmWave applications are a subset of this project. In this project all aspects of the mmWave local access system design will be considered, for example, channel modeling, system modeling, physical layer definitions, system architecture, etc. In this paper we will adapt their outdoor urban simulation model for use in our system simulations at mmWave. In particular we use the Madrid-grid layout from METIS TC-2 as shown in Fig. 5. The map is a 1161 by 1656 m grid which a 3x3 repetition of a single Madrid grid where the repetition is used to create interference for users in the data collection area which is just the center Madrid grid. Within a grid, various surface types are modeled including roads, parkways, sidewalks (which are 3 m wide), square buildings (120x120 m), rectangular buildings (120x30 m), and a grass park (120x120 m). Users at density of 437 users/km^2 (the green dots in Fig. 5) are uniformly dropped along sidewalks and within the park, and no users are dropped on roads or within buildings. If a building is between a user and an AP then the link is declared a NLOS link, otherwise the blocking model of the previous section is used to determine whether the link should be declared a LOS or NLOS link. The appropriate path loss and channel model from Section II will then be used.

Four different AP layouts are considered as shown in Fig. 6 and Fig. 7 where all APs are 5 m above the ground. In all cases the APs have four sectors pointing north, east, south, and west. In layout A there are APs located 5 m west and 5 m north of the southeast building corner in every intersection. Layout B has the same AP locations as layout A but with an additional AP in each intersection located 5 m east and 5 m south of the northwest building corner in an intersection. The additional APs give a second chance for a user to have a LOS link if the user is blocked to one of the APs (in our simulations we assume that the blocking probability is independent between APs regardless of the proximity of the APs to each other). In layout C an additional set of APs over layout A are added in the middle of the blocks (5 m from the west building) of the north-south running streets. In layout D an additional set of APs over layout C are added in the middle of the blocks (5 m from the north building) of the east-west running streets. The AP density is 75/km^2 for layout A, 150/km^2 for layouts B and C, and 187/km^2 for layout D.

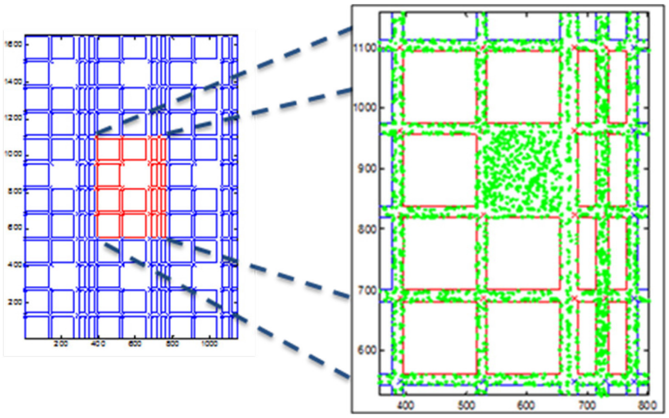

Fig. 5. Madrid-grid layout from METIS TC-2.

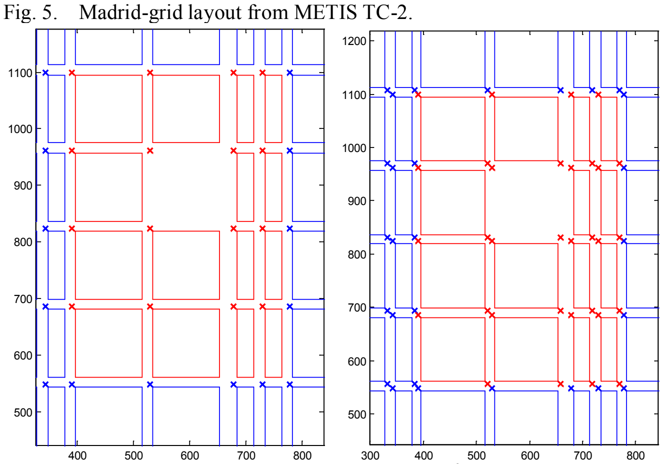

Fig. 6. AP layouts A with an AP density of 75/km^2 (left) and B with an AP density of 150/km^2 (right). AP locations are marked with an x and the red area demarcates the data collection area.

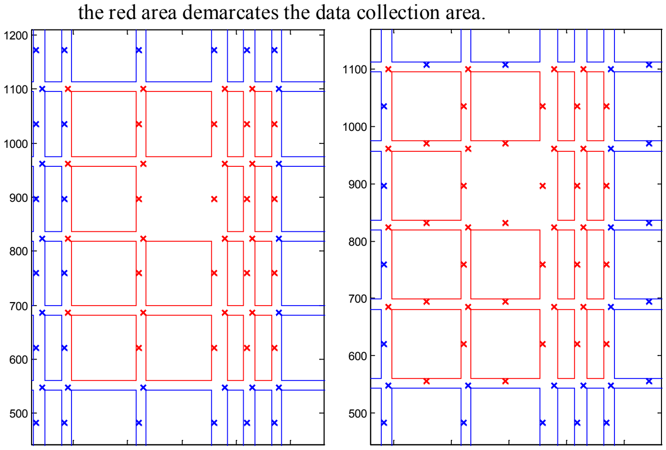

Fig. 7. AP layouts C with an AP density of 150/km^2 (left) and D with an AP density of 187/km^2 (right). AP locations are marked with an x and the red area demarcates the data collection area.

V. SIMULATION RESULTS

We now present downlink simulation results for the different layouts presented in the previous section. A null cyclic prefix single carrier system is assumed similar to [4] and the general system-level parameters are given in Table 2. Users are dropped in the same locations for each layout and at each location a LOS blocking probability is drawn for each mobile-AP link for the case with foliage as given in (2) and without foliage as in (3) for the AP height of 5 m. A user will be in non-LOS conditions if a building is between it and an AP or if the blocking probability draw indicates a NLOS link. For LOS links the path loss exponent used is 2.0 with a shadow fading of 5.0 dB instead of the values reported in Section II since the measured LOS path loss parameters reported in that section were subsequently refined after the simulations were run. However the slight differences should not affect the simulation results. When more LOS data is available the LOS path loss parameters can be expected to be further refined. The NLOS links used the path loss parameters reported in Section II.

Table 2. System simulation parameters

Parameter	Value
Carrier frequency	72 GHz
Bandwidth	2.0 GHz
Traffic type	Full buffer
AP array	4 sectors, each sector has two 4x4 RF arrays (one vertically polarized, one horizontally polarized) with 0.5 λ spacing in both dimensions
Mobile antennas	2 omni-directional antennas, one with vertical polarization, one with horizontal polarization
AP Tx power	30.8 dBm/sector (split between the two arrays in each sector)
Maximum rank	2 (single-user MIMO only)
Beamforming	Eigen beamforming using the uplink signal to point AP RF beams
Modulation levels	LTE MCS levels
Channel estimation	Ideal
Scheduler	Proportional fair
HARQ	None, but retransmissions are allowed

A CDF of the user throughputs are shown in Fig. 8 when there is foliage on the trees and in Fig. 9 when there is no foliage on the trees. The overall system-level results including average user throughput, cell-edge throughput (i.e., the 5% throughput point), and outage probability (as determined as the percent of users which do not obtain 100 Mbps) is shown in Table 3. As can be seen, amazing average user throughputs of between 2.07 Gbps to 5.12 Gbps are obtained in all layouts. The cell-edge throughput of layout A is a disappointing 0 Mbps (with foliage) and 18.3 Mbps (without foliage) due to the inadequate AP density, but when the AP density is increased as in layouts B-D then the cell-edge throughputs are an impressive 173 to 707 Mbps. Also seen is that the outage probability greatly improves with AP density from 16.4% and 6.6% for layout A with and without foliage respectively to 1.0% and 0.33% for layout D with and without foliage respectively.

Foliage plays an interesting role in the results where it tends to help average user throughput but degrades cell edge throughput and outage probability. The reason appears to be that when there is no foliage that the interference is increased which decreases the capacity of the strongest links which play the biggest role in average user throughput. For longer links the lack of foliage results in more LOS links which improves both coverage and cell-edge data rates.

Note that intelligent layout of the APs plays an important role in system-level performance. For example just placing additional APs in the middle of some blocks as in layout C helps users in the north-south streets but not the east-west ones and hence it has a higher outage than just adding additional APs in the same intersection as in layout B. Hence that despite an average user throughput advantage of layout C over layout B, the cell edge throughput of layout B is indeed better. Note, however, these conclusions are for the case where the blocking probability is independent between APs despite their proximity to each other (as mentioned in Section IV).

Table 3. Summary of system-level results (w/F indicates with foliage and w/o F indicates without foliage)

Layout	AP density	Ave. user TP	Cell edge TP	Outage Prob.
A w/F	75/km^2	2.07 Gbps	0 Mbps	16.4%
B w/F	150/km^2	4.06 Gbps	222 Mbps	3.2%
C w/F	150/km^2	4.15 Gbps	173 Mbps	4.4%
D w/F	187/km^2	5.12 Gbps	552 Mbps	1.0%
A w/o F	75/km^2	2.10 Gbps	18.3 Mbps	6.6%
B w/o F	150/km^2	3.80 Gbps	456 Mbps	1.0%
C w/o F	150/km^2	3.93 Gbps	375 Mbps	1.75%
D w/o F	187/km^2	4.82 Gbps	707 Mbps	0.33%

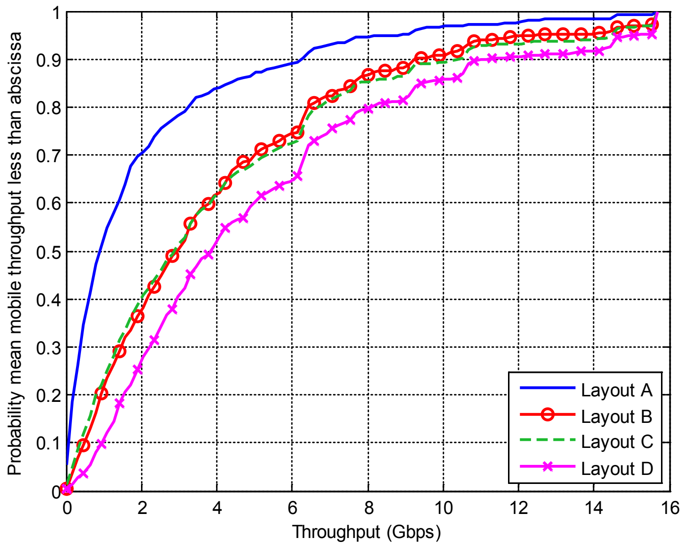

Fig. 8. CDF of user throughput for each layout with foliage on the trees.

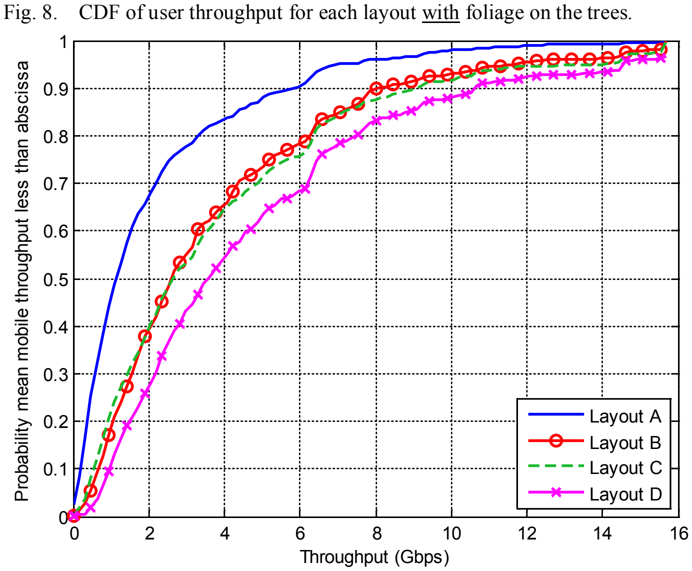

Fig. 9. CDF of user throughput for each layout without foliage on the trees.

VI. Conclusion

This paper presented details of system-level simulations for outdoor local area access systems employing mmWave frequencies. LOS blocking probability models were developed from a ray-tracing environment which can be used to add more realism to system-level simulations. System-level simulation results were presented using a newly developed mmWave channel model plus some scenarios derived from METIS simulation environments. The system simulation results showed that low outage probability is possible with a high enough AP density and that average mobile throughputs of up to 5.12 Gbps and cell edge rates of up to 707 Mbps are possible. Also the results showed the impact of foliage on the system capacity where foliage helps average user throughput by decreasing the interference seen by strong links but hurts cell-edge throughput and coverage by creating more non-LOS links.

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