Millimeter-Wave Directional Path Loss Models in the 26 GHz, 32 GHz, and 39 GHz Bands for Small Cell 5G Cellular System

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Abstract—This paper presents empirically-based large-scale propagation path loss models for small cell fifth generation (5G) cellular system in the millimeter-wave bands, based on practical propagation channel measurements at 26 GHz, 32 GHz, and 39 GHz. To characterize path loss at these frequency bands for 5G small cell scenarios, extensive wideband and directional channel measurements have been performed on the campus of the University of Surrey. Close-in reference (CI), and 3GPP path loss models have been studied, and large-scale fading characteristics have been obtained and presented.

Index Terms — 26 GHz, 32 GHz, 39 GHz, Millimeter-wave, small cell, path loss, 5G.

I. INTRODUCTION

The deployment of 5G cellular systems in millimeter wave (mmWave) frequency bands offers the capability to deliver multi-Gigabits of data per second since the abundant amounts of a vacant spectrum can be utilized in mobile and backhaul applications [1]–[3]. However, at such high frequencies, radio propagation, within the first meter from the transmitter (TX) antenna, is deteriorated regarding free space path loss (FSPL). Recently, to characterize mmWave channel propagation parameters such as RMS delay spread, angular spread, and path loss in outdoor and indoor environments, several channel measurements have been performed, and a vast quantity of measured data was obtained.

As an example, several mmWave measurement campaigns for future 5G mobile communications have been conducted and mmWave channel models presented by Samsung [4], [5], and Nokia [6], [7].

The founding of the mobile and wireless communications enablers for the 2020 information society (METIS) project aspired to develop innovative approaches which facilitate the deployment of 5G systems [8]. The METIS model incorporates three methods which are a deterministic map-based model, a stochastic model and hybrid model. The latter incorporates scalability between the map-based and stochastic models whereby the shadowing and path loss are determined through the map-based model whilst other parameters are found using stochastic model. However, to the best of authors knowledge, validation of the METIS model at mmWave frequency

bands 26 GHz, 60 GHz, and 63 GHz has not been extensive [9].

The contributions of the millimeter wave evolution for backhaul and access (MiWEBA) project also include propagation channel modelling. In the MiWEBA model, the same principle as the IEEE 802.11ad model is applied whilst the model only accounts for deterministic rays. In other words, the MiWEBA model is a quasi-deterministic model which combines deterministic rays as well as rays from random objects. Based on this model, extensive channel measurements were carried out over the 800 MHz at 60 GHz band for indoor and outdoor for LoS and obstacle-line-of-sight (OLOs) scenarios [10].

The aim of the millimeter wave based mobile radio access network for fifth generation integrated communications (mm-MAGIC) project is to introduce novel approaches for mobile radio access technology (RAT) that can be adapted in the 6–100 GHz range. During the project, extensive radio channel measurements will be carried out in the aforementioned range at several locations within Europe. Moreover, based on the rich set of results obtained from the measurements, advanced channel models will be developed which will be employed for validation and examination of future systems. Such models can also be used in regulatory and standards documentation. The predominant aspiration of the project is to champion a European 5G standard and be regarded as an accelerator for the previously developed 5G systems operating above 6 GHz [11].

Currently, Ofcom proposed 26 GHz band as a pioneer band for 5G in Europe and also highlighted 32 GHz and 40 GHz as promising bands for 5G in the UK [12]. Additionally, 39 GHz is recommended by FCC for 5G deployment in the US [13].

To study the radio propagation at 26 GHz, 32 GHz, and 39 GHz, an extensive wideband and directional channel measurements in different scenarios and environments have been conducted on the campus of University of Surrey, UK. In this paper, close-in reference (CI) path loss model is studied, and the large-scale fading (LSF) characteristics of 26 GHz, 32 GHz, and 39 GHz, including path loss exponent, and standard deviation of shadow fading are obtained and presented. Also,

Fig. 1. Automatic channel measurement setup

3GPP path loss model has been studied based on our channel measurement setup and transmitter and receiver (RX) antenna height. Finally, the measured path loss is compared to the free space path loss (FSPL) and 3GPP path loss models.

II. CHANNEL MEASUREMENT CAMPAIGN

Fig. 1, shows the automatic channel measurement setup. R&S®SMW200A wideband signal generator transmits the sounding signal, where at the receiver, signal analyzer R&SFSW67 captures I/Q data to be processed by the Matlab based sounding software tool (R&S TS-SGC). The sounding signal is transmitted with the power of 17 dBm over 2 GHz bandwidth. R&SRTO1044 is used at the receiver side (RX) to support 2 GHz sounding bandwidth. Semi-directional horn antennas are used at the transmitter side (TX) while very directive antennas have been used at RX. A rotator table is used to scan the azimuth with rotation steps of 8° and 5° to emulate steerable antenna at RX. Before the channel measurement, the SMW is directly connected to the FSW to determine mmWave cable loss. Also, the triggered calibration is done, and the calibration data is stored. Table I presents the wideband channel sounding setup along with antennas parameters.

Two different environments have been examined. From Fig. 3a, the location of the base station (TX) which was fixed during the channel measurement as well as user-equipment (RX) can be observed at each route. Fig. 3b illustrates the first route of channel measurements in the pavement close to the 5GIC building at University of Surrey (Route 1). Fig. 3c indicates the environment of the second route as well as TX and RX locations. In the second location, measurements have been performed with the base station height of 5 m ($h_T = 5$ m) and 8 m ($h_T = 8$ m) while the horizontal distance between the transmitter and the receiver antennas varies from 5 to 50 m (Route 2).

III. MEASUREMENT RESULTS

Measured channel impulse responses (CIRs) for three frequencies are derived with a delay resolution of 0.5 ns and

TABLE I
WIDEBAND CHANNEL SOUNDING SETUP SPECIFICATIONS FOR THE 26 GHz, 32 GHz, AND 39 GHz

Carrier Frequency	26 GHz	32 GHz	39 GHz
Sounding Waveform	Frank-Zadoff-Chu 65535		
RF Bandwidth	2 GHz		
Transmit Power	17 dBm		
Delay Resolution	0.5 ns		
TX Polarization	Vertical		
RX Polarization	Vertical		
TX E-Plane HPBW	78°	54°	
TX H-Plane HPBW	61°	54°	
RX E-Plane HPBW	5°	8°	
RX H-Plane HPBW	5°	8°	
Height of TX Antenna (h_T)	5 m, 8 m		
Height of RX Antenna	1.7 m		
TX Antenna Gain	6.8 dBi	10 dBi	
RX Antenna Gain	24 dBi	23 dBi	25 dBi

Fig. 2. Directional delay profile at 32 GHz, for TX-RX = 25 m on Route 1.

azimuth angular resolution of 8° (for 32 GHz and 39 GHz) and 5° (for 26 GHz). At each azimuth angle-of-arrival, 200 snapshots of the CIR are captured and averaged. An example of directional delay power profile at 32 GHz, for the Route 1, when separation is 25 m is displayed in Fig. 2. Path loss (PL) models are imperative to the design of wireless communication systems since they enable the determination of attention over distance using the following formula.

$$L(d) = P_t + G_t + G_r - P_r(d) - L_0 [\text{dB}] \quad (1)$$

In (1), G_t and G_r respectively denote TX and RX antenna gains in dBi, and P_t and P_r respectively represent transmitted power and received power in dBm, and L_0 is mmWave cable loss in dB.

A. CI Path Loss Model

One of the most popular path loss models, discussed in this paper, is single frequency path loss model (CI model), defined as [14]

$$\text{PL}^{\text{CI}}(f, d) [\text{dB}] = \text{FSPL}(f, d_0) + 10n \log_{10}(d/d_0) + X_\sigma^{\text{CI}} \quad (2)$$

where $\text{PL}^{\text{CI}}(f, d)$ represents the path loss at a given frequency of f with different TX-RX separation distance of d , whilst $\text{FSPL}(f, d_0)$ is the path loss in dB at a close-in (CI) distance d_0 . Moreover, X_σ is a zero mean Gaussian random variable

Fig. 3. (a) Measurement routes on campus, University of Surrey, (b) Environment of the route 1, (c) Environment of the route 2.

Fig. 4. Measured directional path loss, FSPL, LS fitting and 3GPP path loss model (a) 26 GHz (Route 1, ($h_T = 5$ m)), (b) 32 GHz (Route 1, ($h_T = 5$ m)), (c) 39 GHz (Route 1, ($h_{Tm} = 5$)), (d) 26 GHz (Route 2, ($h_T = 8$ m)), (e) 32 GHz (Route 2, ($h_T = 8$ m)), (f) 39 GHz (Route 2, ($h_T = 8$ m)), (g) 32 GHz (Route 2, ($h_T = 5$ m)), and (h) 39 GHz (Route 2, ($h_T = 5$ m)).

TABLE II
PATH LOSS EXPONENTS AND STANDARD DEVIATIONS FOR LOS SCENARIOS AT 26 GHz, 32 GHz, AND 39 GHz AS A FUNCTION OF ENVIRONMENT AND TX ANTENNA HEIGHT

Carrier Frequency	26 GHz		32 GHz			39 GHz		
Route No.	Route 1 ($h_T = 5$ m)	Route 2 ($h_T = 8$ m)	Route 1 ($h_T = 5$ m)	Route 2 ($h_T = 5$ m)	Route 3 ($h_T = 8$ m)	Route 1 ($h_T = 5$ m)	Route 2 ($h_T = 5$ m)	Route 3 ($h_T = 8$ m)
Path Loss Exponent	1.8	2.04	2.1	1.81	1.94	1.95	1.8	1.91
σ (dB)	2.03	2.2	2.85	3.77	3.38	2.24	3.61	3.16

with standard deviation of σ in dB. The CI model is based on determining the path loss exponent (PLE) n using the minimum mean square error (MMSE) method in order to fit the measured data with smallest error through minimizing σ and using a true physically-based reference distance of d_0 .

The CI path loss model is therefore employed by considering $d_0 = 1$ m as a reference point. LSF characteristics including the PLE and standard deviation of the resulting shadow fading from the channel measurement data, provided in Table II for 3 frequencies and both routes for different TX antenna height.

B. 3GPP Path Loss Model

3GPP defined the path loss model for LoS scenarios in the Urban Micro Street Canyon as [15]

$$PL_{\text{Los}} = \begin{cases} PL_1, & 10\text{m} \leq d_{2D} \leq d'_{\text{BP}} \\ PL_2, & d'_{\text{BP}} \leq d_{2D} \leq 5\text{km} \end{cases} \quad (3)$$

with

$$\begin{aligned} PL_1 &= 32.4 + 211 \log_{10}(d_{3D}) + 20 \log_{10}(f_c), \\ PL_2 &= 32.4 + 40 \log_{10}(d_{3D}) + 20 \log_{10}(f_c) - \\ &\quad 9.5 \log_{10}((d'_{\text{BP}})^2 + (h_{\text{BS}} - h_{\text{UE}})^2), \\ d'_{\text{BP}} &= \frac{4(h_{\text{BS}} - 1)(h_{\text{UE}} - 1)f_c \times 10^9}{C}. \end{aligned} \quad (4)$$

In (4), f_c is the center frequency in GHz, C is the speed of light, d_{2D} and d_{3D} are the 2-dimensional and 3-dimensional distances between TX and RX in meter, respectively.

The 3GPP path loss model has been also studied based on our measurement setup and the measured directional path loss data for LoS are plotted in the log-log scale chart for different frequency and environment with different TX antenna height and compared with the FSPL and 3GPP path loss model as shown in Fig. 4. From Fig. 4, it is observed that when $h_T = 5$ m the least-squares (LS) fitting graphs are very close to the 3GPP model, while when $h_T = 8$ m, the 3GPP model has lower values than LS fitting graphs.

IV. CONCLUSION

Extensive mmWave outdoor channel measurements for small cell scenario have been conducted at three different mmWave frequency bands. CI path loss model has been studied to obtain large scale fading characteristics including the path loss component and shadow fading at 26 GHz, 32 GHz and 39 GHz. LS fitting curves were compared with FSPL and 3GPP path loss models and it is found that LS fitting

Fig. 5. (a) 32 GHz transmitter equipment, (b) 32 GHz receiver equipment, (c) Route 2 environment, (d) 26 GHz receiver equipment.

graphs are in a good agreement with 3GPP path loss model when base station antenna is 5 m.

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