Millimeter-Wave Channel Model Parameters for Various Office Environments

HIBIKI TSUKADA¹, KEIICHIRO KUMAKURA¹, SHUAIQIN TANG¹, MINSEOK KIM¹,(Senior, IEEE)
¹Graduate School of Science and Technology, Niigata University, Niigata, Japan
Corresponding author: Minseok Kim (e-mail: mskim@ieee.org).
This research has been conducted under the contract “R&D for the realization of high-precision radio wave emulator in cyberspace (JPJ000254)” made with the Ministry of Internal Affairs and Communications of Japan.

ABSTRACT In this paper, a 60-GHz millimeter-wave cluster channel model for various office environments was developed, and the impact of cluster characteristics on wireless data transmission was investigated. To develop the channel model, double-directional channel measurement campaigns were conducted in a university laboratory office environment. A custom-developed channel sounder with an angular resolution of 6° and a delay resolution of 2.5 ns at 58.32 GHz was used for the measurements. Using a super-resolution multipath parameter estimation algorithm, multipath components were extracted from the measured data with a delay resolution of 0.1 ns and an azimuth resolution of 0.1°, and clusters were identified using the K-PowerMeans algorithm. In this study, based on the conventional 3rd Generation Partnership Project (3GPP) model, which is a scenario-categorized site-general model, an attempt was made to develop a highly accurate cluster model that can more accurately reproduce small-scale fading fluctuations in site-specific environments. The large- and small-scale parameters obtained from the measured data were extracted and compared with those of the 3GPP map-based hybrid channel model, which is a quasi-deterministic channel model. The results revealed strong site dependency in the inter-cluster and intra-cluster properties. Moreover, the impact of different channel parameters on system evaluation was demonstrated using single-user and multi-user multiple-input–multiple-output channel capacities.

INDEX TERMS Millimeter-Wave, Channel sounding, Channel model, Cluster channel model

I. INTRODUCTION

In recent years, fifth-generation (5G) mobile communication systems have attracted much interest and have been launched already in many countries around the world. The 5G mobile communication systems have been developed under the recommendation ITU-R M.2083, which was formulated by the International Telecommunication Union Radio Communication Sector (ITU-R) in 2015, and the requirements for 5G include enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communications (uRLLC) [1]. In particular, it is necessary to secure a wide bandwidth of several hundred megahertz or greater to achieve eMBB. However, low-frequency bands, such as 700 MHz to 2.6 GHz are already occupied by various existing systems, and it is difficult to use the bandwidth necessary to achieve eMBB [2]. Therefore, the World Radio Conference (WRC-15) in 2015 approved the use of the previously unused 24.25–86 GHz millimeter-wave (mm-wave) bands for 5G, and the frequencies were specified at WRC-19 in 2019 [3], [4]. In addition to 5G, IEEE802.11ay, a wireless local-area network standard with a throughput of more than 20 Gbps at license-exempt 60-GHz mm-wave frequency bands was standardized in February 2021 and is attracting significant attention [5]. As described above, the demand for the design and evaluation of mm-wave communication systems is increasing because of the active use of mm-wave bands in the new wireless standards.

A radio propagation channel model that describes the radio propagation characteristics is needed for the design and evaluation of wireless systems. The geometry-based stochastic channel model (GSCM) has been widely used for various wireless systems in lower-frequency bands, such as fourth-
generation (4G) mobile communication systems. Radio propagation channels can be represented by the superposition of multiple plane waves, called “multipath components” (MPCs). In GSCM, the channels are generated based on a cluster that is defined by a group of MPCs with similar delays and angular characteristics. The characteristics of clusters and MPCs within a cluster are parameterized from statistical analysis using multiple propagation channel measurements.

Although the GSCM is a widely accepted channel model for conventional wireless systems, it is insufficient for evaluating new mm-wave radio systems because the mm-wave radios are quasi-optical and hence the characteristics are very different from those in the low-frequency bands. In particular, many studies [6]–[8] have shown that most of the transmitted power is conveyed to the receiver through line-of-sight (LoS) and up to double-bounce reflection paths because the propagation mechanisms such as diffraction and transmission are not significant. This is a major difference in the low-frequency band. This means that deterministic methods, such as ray tracing, can be a useful tool for obtaining the dominant propagation paths in the channel. However, because of the extremely short wavelength of the mm-wave, diffuse scattering by small objects in the propagation environment and the surface roughness of large objects cannot be ignored [7], [9]. From the viewpoint of computational complexity, it is not practical to obtain such microscopic interactions by ray tracing. Further, [8] revealed from high-resolution channel sounding at 60 GHz in an indoor environment that the diffuse scattering cannot be ignored in the design of millimeter-wave systems because it occupied almost 26 % of the total power.

To address this problem, hybrid channel models such as the quasi-deterministic radio channel generator (QuaDRiGa) [10], map-based hybrid model [11], quasi-deterministic channel model (Q-D model) [12], [14], and so forth have been developed by various organizations. To compensate for the weaknesses of the GSCM, hybrid channel models describe the signal paths associated with major environmental objects, such as ground and building walls in a deterministic manner (deterministic components), and the signal paths associated with less common and less important objects, such as indoor furniture and random small outdoor objects, in a stochastic manner (random components).

As described above, the accuracy improvement in the hybrid channel model is highly convincing; however, it still uses stochastic channel model parameters extracted from the measurements in some typical scenarios to describe the random components [11]. Stochastic channel model parameters have been reported in several studies. For example, the parameters at 60 GHz in a lecture room environment were presented in [15]. In [16], high-resolution MPC extraction results at 60 GHz in a conference room environment were presented. Here, it was shown that the parameters largely depend on room geometry and surrounding environment comparing with the parameters of IEEE 802.15.3c model. However, in the existing works, the impact of the parameters on system performance has not been clearly investigated.

Therefore, in this study, the impact of stochastic channel model parameters on prediction accuracy was scrutinized. The original contributions of this study are summarized as follows.

1) The stochastic channel model parameters, including large-scale parameters (LSPs) and small-scale parameters (SSPs), for four different indoor scenarios obtained from the extensive double-directional (D-D) channel sounding measurement campaign in a university office environment are presented. Moreover, the site-specific nature of the channel model parameters was investigated by comparing the measured parameters with those of existing 3GPP models.

2) The impact of the differences between the measured and 3GPP parameters on the channel capacities in single-user (SU) multiple-input–multiple-output (MIMO) and multi-user (MU) MIMO were evaluated.

The remainder of this article is organized as follows. In Section II, the D-D channel sounder and measurement campaign are detailed. In Section III, the postprocessing procedures, such as MPC extraction and clustering, are described. Details of the implementation of the hybrid channel model are provided in Section IV, and the effects of different channel parameters on the MIMO channel capacity are described in Section V. Finally, Section VI concludes this paper.

II. MEASUREMENT CAMPAIGN

A. D-D CHANNEL SOUNDER

The D-D channel sounder consisted of a baseband processing unit and phased-array beamforming transceiver circuits (EVK06002, Sivers IMA) [17]. Each transceiver circuit used a 16-element uniform linear array (ULA) to synthesize a narrow beam pattern in the azimuth plane [18]. The transmit power was approximately 31 dBm, which is the equivalent isotropic radiated power (EIRP). The local oscillator of the transmitter and receiver circuits generated a carrier signal at 58.32 GHz (WiGig CH1). The half-power beamwidth (HPBW) of the boresight beam pattern was approximately 6° in the azimuth plane. A 90° azimuth scanning of the beamforming transceiver was achieved by selecting 12 beam patterns at 6° intervals. In addition, four phased-array antennas pointed at −135°, −45°, +45°, and +135° were combined to achieve azimuth angular scanning of 180° at the transmitter and 360° at the receiver. Simultaneous measurement of eight channels was achieved using the time-division multiplexing (TDM) method for 2 × 4 MIMO multiplexing. This enabled the angular characteristics of the entire azimuth range to be measured in approximately 5 minutes [19].

An unmodulated Newman phase multitone with 256 subcarriers (tones) with a bandwidth of 400 MHz was used as the sounding signal [20]. The delay resolution was 2.5 ns, and the maximum excess delay was 640 ns. The dynamic range in the channel impulse responses (CIRs) was 51 dB, which was determined by the signal-to-noise ratio (SNR) in the over-the-air (OTA) calibration. The maximum measurable path
More-detailed information on the channel sounder can be found elsewhere [19]–[21].

### B. MEASUREMENT SCENARIOS

The measurement campaign was conducted on the office floor of a university building, as shown in Fig. 1. The red and yellow markers indicate the locations of the transmitter (Tx) and receiver (Rx), respectively. The D-D angle resolved channel transfer functions (CTFs) at 41 points were measured, and the table in Fig. 1 shows four scenarios: in-room (InR), room-to-room (R2R), in-corridor (InC), and room-to-corridor (R2C). As shown in Fig. 2(a), the room was equipped with multiple office desks, PC monitors, chairs, bookshelves, and whiteboards.

Regarding concrete walls, the surfaces were covered with plasterboard and separated from the surface by an air gap, which is a typical structure of a wall between a room and the outside of the room (for example, between a room and a corridor). In addition, there were several hollow plasterboard walls, which are typically used as inner walls separating two rooms (between a room and another room). Glass windows and metallic doors were present in some parts of the walls. The heights of the Tx and Rx antennas were 1.4 m in all scenarios.

### III. CHANNEL MODEL PARAMETER EXTRACTION

#### A. POSTPROCESSING

The band-limited D-D CTFs obtained in the measurement are expressed as

\[ H(\tilde{f}, \tilde{\phi}_T, \tilde{\phi}_R). \]  

The azimuth pointing angles for Tx and Rx are shown as

\[ \tilde{\phi}_T \in \{ n_{\phi_T} \Delta_{\phi_T} | n_{\phi_T} = 0, \ldots, N_{\phi_T} - 1 \}, \]

\[ \tilde{\phi}_R \in \{ n_{\phi_R} \Delta_{\phi_R} | n_{\phi_R} = 0, \ldots, N_{\phi_R} - 1 \}, \]

and the subcarrier (tone) frequency is

\[ \tilde{f} \in \{ f_c + (n - N/2) \Delta_f | n = 0, \ldots, N - 1 \}. \]
In this system, $n_{\phi_T}$ and $n_{\phi_R}$ are the indices of the transmitting and receiving pointing angles, respectively, and $\Delta_{\phi_T}$ and $\Delta_{\phi_R}$ denote the angular scanning intervals, respectively (actually nonuniform). Furthermore, $\Delta_f = 400$ MHz, and $N = 256$. Then, the CIR for each combination of Tx and Rx pointing angles can be obtained using the inverse discrete Fourier transform of the CTF as

$$h(\hat{\tau}, \hat{\phi}_T, \hat{\phi}_R) = F^{-1} \{ H(\hat{f}, \hat{\phi}_T, \hat{\phi}_R) \}$$  \hspace{1cm} (5)

where the delay taps $\hat{\tau} \in \{n_{\tau}\Delta_{\tau} \mid n_{\tau} = 0, \ldots, N - 1\}$. The double-directional angular delay power spectra (DDADPSs)

$$P(\hat{\tau}, \hat{\phi}_T, \hat{\phi}_R) \triangleq \left| h(\hat{\tau}, \hat{\phi}_T, \hat{\phi}_R) \right|^2$$  \hspace{1cm} (6)

are obtained. After the DDADPSs are denoised, the MPC is extracted using the sub-grid CLEAN algorithm [22], which is a successive interference cancellation (SIC) method that treats the DDADPSs as a multidimensional image, creates an image (replica) of the MPC from the continuous function of the beam pattern and signal autocorrelation function, and estimates multipath parameters (clean maps) by repeatedly subtracting them from the dirty map in the order of power magnitude. The extraction resolution was set by $0.1^\circ$ for angular resolution and $0.1$ ns for delay resolution.

Clustering was applied to the extracted MPCs to classify them using similar angle and delay parameters. Because the physical meaning of a cluster is a group of scattered waves associated with a group of interacting objects, clustering has been widely accepted as a tool for more physically meaningful stochastic channel modeling. In this study, the $K$-PowerMeans algorithm was used for clustering [23]. The number of clusters, $K$, was determined manually rather than automatically so that clustering could be performed without loss of physical meaning [19].

The azimuth delay power spectra (ADPS) of $\text{InR}$ and $\text{InC}$ are shown in Fig. 3 as an example of MPC extraction and clustering results. The horizontal axis represents the azimuth angles of Tx and Rx, and the vertical axis represents the propagation delay. The extracted MPCs are indicated by markers whose size is proportional to the MPC power, and the markers are colored differently for each cluster. The font size of the cluster number is proportional to the cluster gain. See [19] for more detail on the validation and propagation mechanism analysis.
B. CHANNEL MODEL PARAMETERS

The azimuth spread of departure (ASD), azimuth spread of arrival (ASA) and delay spread (DS), which represent the spread between clusters (inter-cluster), are LSPs, whereas the cluster delay spread (CDS), cluster azimuth spread of departure (CASD) and cluster azimuth spread of arrival (CAS), which represent the spread within clusters (intra-cluster), are SSPs. These parameters are generally expressed as root-mean-square spreads, which are the standard deviations of power-weighted delays and angles. The DS and azimuth spread (AS) are calculated as

\[
\sigma_{DS} = \sqrt{\frac{\int (\tau - \mu_{\tau})^2 P(\tau) d\tau}{\int P(\tau) d\tau}} \tag{7}
\]

\[
\mu_{\tau} = \frac{\int \tau P(\tau) d\tau}{\int P(\tau) d\tau} \tag{8}
\]

\[
\sigma_{AS} = \sqrt{-2 \ln \left( \frac{\int \exp(j\phi) P(\phi) d\phi}{\int P(\phi) d\phi} \right)} \tag{9}
\]

where \( P(\tau) \) denotes the delay profile, \( \mu_{\tau} \) denotes the delay mean, and \( P(\phi) \) denotes the angle profile [11]. Table 1 lists the channel parameters obtained in this study for each scenario and the parameter values provided by the 3GPP model for the indoor office scenario as reference values [13]. The parameters for LSPs and SSPs were extracted for the four scenarios measured. The parameters were also presented by classifying the scenarios into LoS and NLoS and merging them. Even if the number of measurement data points was still small, the mean and standard deviation based on a lognormal distribution model in each scenario were obtained. In addition, each cumulative distribution function (CDF) classified and merged into LoS and NLoS is shown in Fig. 4. The extracted LSPs and SSPs are described in detail below.

1) LSPs

Comparing the merged LoS and NLoS DSs in Table 1 and Fig. 4(a) with the DSs in the 3GPP model, one can see that the 3GPP parameters are approximately 10 ns larger in the LoS scenario and about 17 ns larger in the NLoS scenario. This is because the InR environment defined in the 3GPP model differs significantly from the environment in which the measurements were conducted. Specifically, in this measurement, the Tx and Rx were placed within the same room (InR) of maximum of 8.0 × 14.3 m and the same corridor (InC) of a maximum 20.0 × 2.3 m for LoS, and between multiple rooms on the same floor of a maximum Tx–Rx distance of 17 m for the NLoS environment. However, the
3GPP reference model was developed in a large open office of $120 \times 50$ m. For NLoS condition, it should be noted that the Tx and Rx were located in physically separated areas in this measurement while those were located in the same open office in the 3GPP model. The DS is greatly affected not only by the difference between the LoS and NLoS, but also by the difference in room size. As can be expected, this is because the larger the room, the larger the propagation delay of the reflected wave. Therefore, it can be inferred that the DS of the 3GPP reference model was larger.

On the other hand, the CDF of the ASD in Fig. 4(b) shows that the values of the measured parameters are smaller than those of the 3GPP reference model for both LoS and NLoS, and the variance is also smaller. This is probably because the azimuth angle scanning range of the Tx array used in the measurement is $180^\circ$ towards the RX direction, and thus the multipath components from the opposite side were not received. The CDF of the ASA in Fig. 4(c) shows that the variance is smaller in the measured data, but the average is larger in the measured data. As mentioned in the discussion on the DS, this may be owing to the room size in the LoS case and the difference in the definition of NLoS in the NLoS case. Specifically, in the LoS case, the environment assumed in 3GPP is wider than the measurement environment, thus the attenuation of the reflected scattered wave is larger with a longer path length, and thus the LoS component becomes more prominent.

2) SSPs
Although the cluster DS is not considered in the 3GPP reference model ($0\,\text{ns}$), it is also seen that the measured value is also very small (less than $1\,\text{ns}$) and can be considered negligible, as in the 3GPP reference model. In contrast, the measured cluster ASA and ASD are smaller than those of 3GPP by a few degrees. It is difficult to conclude clearly the reason for the difference in cluster AS because it is affected by various factors, such as the roughness of the wall surface and small objects in the environment. As described above, evidently, the parameters used in the mm-wave channel model vary significantly depending on the specific conditions of the environment.

In the next section, the impact on the channel characteristics of the difference in parameters between the reference model and measurement is discussed.

IV. IMPACT OF CHANNEL MODEL PARAMETER DIFFERENCE
In this section, based on the 3GPP map-based hybrid channel model, the impact of channel parameter difference on system evaluation is demonstrated using SU-MIMO and MU-MIMO channel capacities.

A. CHANNEL MATRIX GENERATION USING HYBRID CHANNEL MODEL
The map-based hybrid channel model is a Q-D model developed in 3GPP [11]. Here, the channel coefficients are generated in three steps: 1) deterministic cluster allocation, 2) random cluster allocation, and 3) intra-cluster spread addition. Here, “cluster allocation” refers to determining the power and spatiotemporal center of the clusters. In other words, regarding the placement of clusters by ray tracing as an example, the power of each MPC generated by ray tracing is treated as the cluster power, and the delay and angle of the MPC are taken as the spatiotemporal center of the cluster. Each procedure is explained in detail in 1)–3) below, and the method of calculating the channel matrix is explained in 4).

1) Deterministic cluster allocation
Deterministic clusters are placed using simplified ray tracing. Because ray tracing always generates deterministic rays (MPCs) that exist in the environment, it is not necessary to include random small objects in the 3D model, but only simplified ones. The 3GPP document does not specify the extent of the deterministic clusters. In this study, however, considering the quasioptical nature of the 60-GHz band, up to triple bounce reflections, including LoS, are considered as the center of the deterministic clusters.

2) Random cluster allocation
First, random clusters are determined based on their delays. Cluster delay is determined as an exponential random variable that satisfies the DS defined in 3GPP, where the delay of each cluster is a Poisson process with an exponential distribution of arrival intervals. The next step is to determine the power of each cluster. The cluster power is determined as an exponential function of the delay. Finally, the azimuth-of-departure (AoD) and azimuth-of-arrival (AoA) are determined for each cluster. Following a wrapped Gaussian distribution with the AS defined by 3GPP, both the AoD and AoA are determined as a function of the power calculated earlier.

3) Intra-cluster spread addition
The intra-cluster spread is obtained by decomposing the deterministic and random clusters arranged in the above procedure into $M$ MPCs. The power $P_{n,m}$ of the $m$-th MPC of the $n$-th cluster can be obtained by simple division as $P_{n,m} = P_n/M$, where $P_n$ is the $n$-th cluster power. The

FIGURE 5: (Left) Laplace distribution with an azimuth spread of $1^\circ$. (Right) Representation by equal power MPCs and non-uniform offset angles
departure angle $\phi_{n,m}$ of the $m$-th MPC of the $n$-th cluster is calculated using the departure angle $\phi_n$ of the $n$-th cluster and the $c_{\text{ASD}}$, as follows.

$$\phi_{n,m} = \phi_n + c_{\text{ASD}} \cdot \alpha_m$$  \hspace{1cm} (10)

where $\alpha_m$ denotes the offset angle when the $c_{\text{ASD}}$ is $1^\circ$. By multiplying $\alpha_m$ by the $c_{\text{ASD}}$, the angle of MPCs with the desired AS can be generated. This offset angle is given in the 3GPP model, which is designed to obtain a Laplacian angular power distribution by assigning a nonuniform offset angle to an equal-power elementary wave, as shown in Fig. 5 [24]. The arrival angles $\phi_{n,m}$ in the cluster are determined in the same manner.

4) MIMO channel matrix calculation

When the transmit and receive antennas are linear arrays, each element of the propagation channel matrix $H(f,t)$ between the $s$-th transmit antenna element and $u$-th receive antenna is calculated as

$$H_{u,s}(f,t) = \sqrt{P_{n,m}} \cdot e^{i(2\pi(v_{n,m} t - f \tau_n) + k_0(d_s \sin \phi_{n,m} + d_u \sin \varphi_{n,m}) + \Phi_{n,m})}$$  \hspace{1cm} (11)

where $N$ and $M$ denote the numbers of clusters and MPCs in the cluster, respectively. $P_{n,m}$ and $\tau_n$ denote the cluster power and delay, respectively. $\Phi_{n,m} \sim \text{Uniform}(-\pi, \pi)$, $\phi_{n,m}$ and $\varphi_{n,m}$ denote the initial phase, departure/arrival angles of MPCs, respectively. $\lambda_0$ is the wavelength of the carrier signal, and $d_s$ and $d_u$ are the distances from the reference point to the transmit antenna element $s$ and the receiver antenna element $u$, respectively. In addition, $v_{n,m}$ represents the phase rotation accompanying the movement of the mobile station, which is given by

$$v_{n,m} = \frac{||v|| \cos (\varphi_{n,m} - \theta_v)}{\lambda_0}$$  \hspace{1cm} (12)

where $v$ and $\theta_v$ denote the moving speed and direction of the mobile station, respectively.

B. MIMO CAPACITY EVALUATION

The MIMO performance evaluation was performed by simulation in an office room where Tx1 was installed in the measurement. Fig. 6(a) shows the 3D model, which is simplified by excluding furniture, such as PC monitors and office desks. First, deterministic clusters obtained by ray tracing in this 3D model were allocated. Then, the random components were obtained from the measurement parameters (LoS, InR & InC) and 3GPP parameters (LoS) in Table 1, and the results were compared. Here, the method of generating random clusters and intra-cluster rays follows the 3GPP model described in the subsection IV where the 3GPP model parameters were used for the other parameters which were not derived in this work. In addition, the cluster DS was neglected as in the 3GPP model because it was very small. The detailed evaluation procedure and results are described below.

1) SU-MIMO

For the SU-MIMO evaluation, to investigate the impact of the cluster AS on the channel characteristics, random clusters were not generated; instead, the channels were generated by only the deterministic components generated by ray tracing, which means that the total number of clusters is equal to the number of rays generated by ray tracing. The intra-cluster property was expressed by 20 MPCs generated using the cluster AS. The SU-MIMO was evaluated by assuming the wireless link shown in Fig. 6(b). The red and blue markers in the figures represent the centers of the transmit and receive arrays, respectively, and the ray tracing is performed at these points. The simulation parameters are as follows. The carrier frequency was set to $58.32$ MHz, the bandwidth to $400$ MHz, and the number of subcarriers to $64$. The MIMO configuration was $4 \times 4$, $8 \times 8$, and $16 \times 16$ MIMO with a ULA for transmitting and receiving antennas.

The channel coefficients shown in Eq. (11) were calculated
from the simulation parameters, ray tracing results, and the cluster spread, as shown in Table 1. Ray tracing was performed in the SISO (single-input-single-output) configuration at the center of each array, assuming that the plane wave approximation holds for both the transmitter and receiver, i.e., the ray amplitude and angle of departure/arrival are the same for all antenna elements. The number of clusters is seven. From the channel matrix $H(t, f)$, the Ergodic capacity $C_{\text{MIMO}}$ is obtained by averaging the channel capacity over $t$ and $f$ as

$$C_{\text{MIMO}} = \mathbb{E} \left[ \log_2 \left( \det \left( I_{NR} + \frac{\rho}{N_T} H^H(t, f) H(t, f) \right) \right) \right],$$

(13)

where $\rho$ is the SISO SNR, and $N_T$ and $N_R$ denote the number of elements in the transmit and receive antennas, respectively [25]. $C_{\text{MIMO}}$ was calculated with $\rho = 30$ dB because low SNR values do not provide adequate identification results. In addition, $H(t, f)$ is the channel matrix normalized to

$$E \left[ \left\| H(t, f) \right\|_F^2 \right] = N_R N_T.$$

(14)

Fig. 7 shows the channel capacity when the number of antenna elements was changed to four, eight, and sixteen in the InR environment. The blue and orange lines indicate the channel capacities calculated using the $c_{\text{AS}}$ of the 3GPP reference model and the measurement, respectively. This shows that the impact of the difference in cluster AS is negligible for small MIMO configurations, such as $4 \times 4$ MIMO, but increases with increasing number of antennas. However, comparing only the values of the cluster AS, the difference is only a few degrees, but this difference results in a difference of approximately 5 bits/s/Hz for a $16 \times 16$ MIMO channel capacity. In other words, one can conclude that more precise model of the cluster AS, a parameter that differs depending on environment, is required for a more accurate evaluation of the mm-wave radio systems.

2) MU-MIMO

The evaluation of SU-MIMO revealed that, when the MIMO configuration is relatively large, such as $16 \times 16$ MIMO, the cluster AS leads to a significant difference in the channel capacity. However, it is not feasible to use $16 \times 16$ SU-MIMO systems in small office room environments. Therefore, the impact of the LSP and SSP on the channel capacity in MU-MIMO systems was evaluated to investigate the impact more practically.

Fig. 6(c) plots the location of one Tx (base station), indicated by the red marker, and the location of 21 Rx (user terminals) spaced 1 m apart. The Tx and Rx are assumed to have a 16-element linear array for the Tx and a two-element linear array for the Rx around their respective markers. The channel generation was performed in the SISO configuration at the center of each array, assuming that the plane wave
approximation holds for both the transmitter and receiver sides. Using the 3GPP model described in section IV, the 2 × 16 MIMO propagation channel matrix \( H(f, t) \) was calculated for all 21 Tx–Rx links. Following the 3GPP model, the number of clusters was set to less than 15 and the number of rays within a cluster was set to 20.

In addition, for all Rx, the average values of LSP and SSP (\( \mu \) in Table 1) were used for channel generation. The time \( t \) and frequency \( f \) in \( H(f, t) \) have discrete values of \( T \) and \( F \), respectively. Here, the number of subcarriers to \( F = 100 \). The receiver moved at a speed of 3.6 km/h (1 m/s) and was sampled every 2.57 mm (half wavelength). The number of samples was \( T = 111 \). The array shape for the transmitter and receiver was a ULA, the array spacing was set by the half wavelength, and each element was omnidirectional.

In a MU-MIMO system, a base station provides services to multiple user terminals by using the same time and frequency resources [26]. In this study, for simplicity, user scheduling was not performed to select user terminals. Instead, \( N_U \) terminals were randomly selected from 21 Rx terminals. First, the Rx subset \( S \) of \( N_U \) terminals was extracted. The propagation channel matrix \( H_S(f, t) \) of subset \( S \) was a \( 2 \times N_U \times 16 \) matrix consisting of the propagation channel matrices calculated for each link stacked in the row direction. Next, to obtain the total channel capacity from the obtained propagation channel matrix, the block diagonalization (BD) method, a well-known MU-MIMO directivity control technique, was applied at the transmitter side. The BD method is a linear control technique that is used to perform MU-MIMO transmission without interfering with other users by determining the weights that create nulls for each user [27]. When the BD method is applied, the Ergodic channel capacity of the entire user is expressed as

\[
C_{BD} = E \left[ \sum_{k=1}^{N_U} \sum_{i=1}^{N_k} \log_2 \left( 1 + \frac{\rho \lambda^{(k)}(t, f) T F}{N_T} \right) \right],
\]

where \( \lambda^{(k)}(t, f) \) is the \( i \)-th eigenvalue for the \( k \)-th user. The SNR was set to \( \rho = 30 \) dB as in SU-MIMO. In addition, \( H_S(f, t) \) is the channel matrix normalized to

\[
\frac{1}{T \cdot F \cdot N_T \cdot N_R \cdot N_U} \sum_{f} \left\| H(t, f) \right\|_F^2 = 1.
\]

Fig. 8 shows the average sum rate capacity. The average sum rate capacity is shown in three ways: using the reference model parameters, using the measured parameters, and using only the rays obtained from ray tracing. The total channel capacity is larger when both parameters are used than when only the ray tracing result is used, and the difference in the channel capacity is especially noticeable around \( N_U = 7 \), where the total channel capacity is the largest. It is seen that the channel capacity calculated using the parameters of the 3GPP reference model is larger than that calculated by the parameters obtained from the measurements. This is because the ASD of the 3GPP model at the transmitter which has a larger number of antenna elements, is larger than that of the measurement, and hence the array inter-element correlation becomes smaller.

As mentioned above, the results in Fig. 8 are strongly influenced by LSPs (especially the ASD). Therefore, to confirm the effect of SSPs, the channel capacity was calculated with respect to the number of users without generating random clusters (namely, removing the influence of LSPs). The results are shown in Fig. 9, where the results in both cases are smaller than those in Fig. 8. This is because the array inter-element correlation increased due to the absence of random clusters.

Comparing with Fig. 8, the channel capacity obtained by the measurements is much more degraded than that calculated using the 3GPP parameters. Notably, the RT results are almost same especially with decreasing number of users even if the intra-cluster spread addition was applied using SSPs. On the other hand, regarding the channel capacity calculated using the 3GPP parameters, the values in Fig. 9 are smaller than those in Fig. 8. However, it is a smaller decrease than that obtained by the measurements. Since both LSPs and SSPs strongly affect the channel capacity, it can be inferred that a more sophisticated parameterization should be necessary to obtain more accurate channels in a specific environment or application (site-specific uses), especially for MIMO with large antenna array configurations.

V. CONCLUSION

The development of new mm-wave radio systems requires a channel model that accurately represents the unique propagation characteristics of mm-waves. In this study, a hybrid channel model that can simulate the radio propagation in individual environments with high accuracy was considered. In particular, the 3GPP map-based hybrid channel model was described step by step in the channel coefficient generation procedure. To obtain the channel model parameters for the 3GPP model framework, a measurement campaign was conducted in various office environments using the mm-wave D-D channel sounder developed in a previous study. Comparing the parameters provided by the 3GPP model with the measured parameters revealed significant differences in all parameters except the \( c_{DS} \), indicating the high environmental dependence. The impact of the parameter difference on the SU-MIMO and MU-MIMO channel capacities was also evaluated. The results show that both SU-MIMO and MU-MIMO are strongly affected by the channel model parameters, especially in large-scale MIMO configurations.

REFERENCES

[1] Recommendation ITU-R: “IMT Vision - Framework and overall objectives for the future development of IMT for 2020 and beyond,” Sep. 2015.

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

[3] Provisional Final Acts World Radio Communication Conference (WRC-15), document RESOLUTION COM6/20 (WRC-15), pp. 424–428, 2016.
[4] P. Kyösti, J. Lehtomäki, J. Medbo, and M. Latva-aho, “Map-Based Channel Model for In-Room Access Scenarios,” IEEE Access, vol. 8, pp. 82042–82053, 2020.

[5] C. Gentile, P. B. Papazian, R. Sun, J. Senic, and J. Wang, “Quasi-Deterministic Channel Model Parameters for a Data Center at 60 GHz,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 808–812, May 2018.

[6] W. Yang, J. Huang, J. Zhang, Y. Gao, S. Salous and J. Zhang, “Verification of an Intelligent Ray Launching Algorithm in Indoor Environments in the Ka-Band,” Radio Science, vol. 56, iss. 9, pp. 1–11, Sep. 2021.

[7] S. Jaeckel, L. Raschkowski, K. Börner, and L. Thiele, “QuadDRiGa: A 3-D Multi-Cell Channel Model With Time Evolution for Enabling Virtual Field Trials,” IEEE Trans. Antennas Propag., vol. 62, no. 6, pp. 808–812, Jun. 2014.

[8] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[9] Channel Models for IEEE 802.11ay, document RESOLUTION COM4/7–10 (WRC-19), pp. 389–399, Mar. 2020.

[10] 3GPP TR 38.901 version 16.1.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[11] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[12] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[13] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[14] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[15] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[16] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[17] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[18] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[19] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[20] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[21] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[22] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[23] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[24] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[25] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[26] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

[27] 3GPP TR 38.901 version 16.0.0 Release 16, “Study on channel model for frequencies from 0.5 to 100 GHz”, ETSI TR 138 901 V16.1.0 Nov. 2020.

KEIICHIRO KUMAKURA received the B.E. degree in electrical and electronic engineering from Niigata University, Japan, in 2019. He is currently working toward M.E degree in the same university.

His research interests include millimeter-wave radio channel sounding and modeling. He is a student member of the IEICE.

HIBIKI TSUKADA received the B.E. degree in electrical and electronic engineering from Niigata University, Japan, in 2020. He is currently working toward M.E degree in the same university.

His research interests include millimeter-wave radio channel sounding and modeling. He is a student member of the IEICE.

SHUAIQIN TANG received the B.E. degree in City College of Science and Technology, Chongqing University, China, the M.E. degree in electrical and electronic engineering from Niigata University, Japan, in 2018 and 2021, respectively.

MINSEOK KIM (S’02-M’05-SM’18) was born in Seoul, Korea. He received the B.S. degree in Electrical Engineering from Hanyang University, Seoul, Korea, the M.E. and D.E. degrees in Division of Electrical and Computer Engineering, Yokohama National University (YNU), Japan in 1999, 2002 and 2005, respectively. In 2007, he was an Assistant Professor with the Tokyo Institute of Technology, Tokyo, Japan, and a Visiting Scholar with the Georgia Institute of Technology, Atlanta, GA, USA, in 2010. In 2014, he joined the Graduate School of Engineering, Niigata University, Niigata, Japan, as an Associate Professor.

His current research interests include radio propagation channel measurement and modeling, millimeter-wave radar, radio tomographic imaging techniques, and MIMO/antenna array signal processing. Dr. Kim is a senior member of the IEEE and IEICE.

***