Millimeter-Wave Intra-Cluster Channel Model
for In-Room Access Scenarios

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This work was supported in part by the MIC/SCOPE under Grant 195004002, and in part by the KDDI foundation.

ABSTRACT To develop an millimeter-waves (mm-waves) channel model for in-room access scenarios, a double-directional channel measurement campaign conducted in a conference room environment is presented. In the measurements, a custom-developed channel sounder with a 12° angle and 2.5-ns delay resolutions at 58.5 GHz was used. From the measured data, the multi-path components were extracted using a high-resolution path parameter estimation algorithm; then, they were clustered based on the actual physical propagation paths to identify the scattering processes explicitly. The cluster analysis revealed that the signal paths by line-of-sight, single-bounce, and double-bounce reflections were power-dominant and well predicted by ray-tracing, but the contribution of random clusters was not significant. In this study, to express diffuse scattering on the rough surface of an ambient reflector, an intra-cluster model of plasterboard wall reflection was parameterized. Furthermore, the proposed intra-cluster model was experimentally validated by analyzing the small-scale fading captured along the wall in the time domain which is caused by the constructive and destructive interference of the specular reflection and diffuse scattering components.

INDEX TERMS Millimeter wave, indoor channel, intra-cluster, diffuse scattering, radio propagation measurement, ray-tracing, parameter estimation, direction-of-arrival.

I. INTRODUCTION

The resolution on new spectrum use at millimeter-wave (mm-wave) bands in the range from 24.25 to 86 GHz for ultra-high bit rate transmission in fifth-generation (5G) mobile communications was adopted in the World Radio Conference (WRC 15) in 2015 [1]. Since then, various research and standardization activities have been conducted [2]. Meanwhile, IEEE 802.11ay [3] was launched in May 2015 for development of a new standard to enhance the efficiency and performance of the IEEE 802.11ad specification [4]. It provides wireless local-area networks (WLANs) connectivity with up to 30-Gbps throughput at the license-exempt 60-GHz mm-wave frequencies, and it is now in the final phase of standardization.

At mm-wave frequencies, the free-space propagation loss is significantly large, and additional attenuation resulting from diffraction and penetration is also very high. Extensive measurement results [5]–[8] have revealed that the propagation processes with diffraction and penetration are not significant and are not practically viable. Therefore, the signal propagation pathways, apart from the line-of-sight (LoS), include only a few multi-paths, mainly generated by specular reflection. This means that ray-tracing (RT) tools can accurately predict the mm-wave radio channels, and such characteristics are quite different from those at conventional lower-frequency bands. This requires a highly directional communication through the possible propagation pathways by beamforming to extend the coverage area [9]. Such a transition from omni-directional to directional wireless medium usage can simplify the radio channel description with only the small-scale fading caused by some multi-paths within the narrow antenna beamwidth and the diffuse scattering on the rough surface of reflectors [10], [11].

To date the geometry-based stochastic channel model (GSCM) has been widely accepted in existing wireless systems [2], [12]. The recent GSCM channel models are parameterized based on a cluster that is a group of multi-path components (MPCs) having similar delay and angle domain properties. In channel modeling, the MPCs are usually
extracted from the measured channel by high-resolution path parameter estimation algorithms based on the assumption that the received signal should be the superposition of multiple plane waves; namely, specular components (SCs). Additionally, the diffuse scattering, which can be described by a continuous spectrum of dispersion over delay and angular domains, is often modeled by using the residual part after SC extraction from the measured channel [13]. In particular, the superposition of a large number of SCs, i.e., dense multi-path components (DMCs), has been introduced as another modeling approach for diffuse scattering for easy extension of the MPC cluster concept in the COST 2100 channel model [14]. Here, the DMCs are clustered around the SCs which are already clustered with similar delay and angle.

However, the specular reflection dominant mm-wave properties should be taken into careful consideration for a more accurate reproduction of channel responses [15]. To compensate for the weaknesses of stochastic modeling, hybrid channel models have also been developed with both the deterministic description for the signal paths associated with major environmental objects, such as ground and building walls, and the stochastic description for those associated with non-common less significant objects such as indoor furniture and outdoor random small objects. Then, the stochastic description of delay-angular dispersion caused by diffuse scattering is added to each signal path. This is the quasi-deterministic (Q-D) channel modeling methodology as shown in Fig.1 [3], [16]. As mentioned previously, in highly directional mm-wave communications, the delay-angular dispersion within the narrow antenna beamwidth can often be generated by diffuse scattering on the rough surface of a single reflector.

To characterize the cluster properties of mm-wave channels, various measurement-based models have been proposed. In [17], 70 – 77-GHz wideband channel characteristics for small office and entrance hall scenarios were presented. In that work, the MPCs extracted from the measured multi-dimensional power spectra were grouped into clusters by using various clustering algorithms, and the inter-cluster/intra-cluster properties were statistically parameterized. Similar measurement and analysis at 60 GHz were carried out for indoor office environments in other research [18], [19]. In prior studies [17]–[19], clusters were treated as a group of MPCs, which are determined by an information-theoretical criterion, and thus, cannot always relate the clusters to any physical interacting objects (IOs). However, clustering should be based on the actual physical propagation paths to model the clusters in more sophisticated manners for mm-wave communications, because highly directional communication by beamforming toward any possible propagation path is considered.

On the other hand, a stochastic map-based model for a data center at 60 GHz was presented in [20], where the intra-cluster properties of ambient reflectors were characterized by high-resolution MPC extraction with 0.5-ns delay resolution and 2° angle-resolution. In particular, the diffuse scattering effect on the rough surface of reflectors was modeled as the intra-cluster properties obtained from multiple small-scale channel acquisitions. However, because a further investigation of a microscopic diffuse scattering phenomenon by double-directional measurement is difficult because of limited resolution in the measurements, comprehensive validation of the intra-cluster effect is still needed.

In this paper, the inter-cluster/intra-cluster characteristics obtained from conference room mm-wave channel measurement assuming an in-room hot-spot access scenario are presented based on the Q-D channel model description. In the measurements, double-directional angular delay power spectra (DDADPSs) were captured using the developed channel sounder [5], [22], where double-directional angle scanning was performed using highly directive antennas having a 12° half power beamwidth (HPBW). The sounding signal has a 400-MHz bandwidth (2.5-ns delay resolution) centered at 58.5 GHz. Using the sub-grid CLEAN algorithm developed in previous work [23], the MPCs were extracted in high resolution. Then, clustering was performed based on the actual physical propagation paths. Thus, the scattering processes can be explicitly identified via comparison with the ray-paths retrieved with the aid of an in-house developed RT simulator [24]. To overcome the problem that channel acquisition is inevitably limited because of the long measurement time in directional scanning, the small-scale behavior generated by diffuse scattering was captured by using the multiple sets of clusters identified as first-order specular reflection on the same plasterboard walls. Plasterboard is a widely used interior wall material. The intra-cluster model was experimentally validated by analyzing the small-scale fading fluctuation in the specular component of the plasterboard wall reflection. The original contributions of this study are as follows.

1) The scattering processes in the conference room environment are comprehensively investigated by comparing the propagation paths identified by the measurements with those obtained from the RT simulation.

2) The intra-cluster model accounting for diffuse scattering on the rough surface of the plasterboard walls is parameterized.

3) The intra-cluster model is validated based on the fading distribution and angle dispersion obtained from the measured small-scale fading fluctuation.
The remainder of this paper is organized as follows. In Sect. II, the measurement scenarios and channel sounding methodology are described. The cluster identification results with a detailed procedure from MPC extraction to clustering are presented in Sect. III. Then, the channel model is presented in Sect. IV. In Sect. V, the validation of the proposed model by small-scale fading analysis is discussed. Finally, conclusions are given in Sect. VI.

II. MEASUREMENT CAMPAIGN

A. SCENARIO

The measurements were conducted in a typical conference room environment, as shown in Fig. 2(a), with dimensions of $7.8 \times 6.0 \times 2.8$ m. The room contained several conference tables, chairs, a television, a whiteboard, a podium, and light-emitting diode (LED) lamps. The surrounding walls were plasterboard, and two air conditioners and circuit breakers were attached on the walls. There were some glass windows and two metal doors in some parts of the walls. The environment was modeled by a simplified 3-D structure, as shown in Fig. 2(b), where it includes only relatively large objects, such as the tables, TV, whiteboard and air conditioners ignoring relatively small and complicated-shaped objects, such as chairs, circuit breakers, and the LED lamps on the ceiling. As illustrated in Fig. 2, the transmitter (Tx) as an access point (AP) was mounted on top of the television, and the channel responses, two horn antennas (Pasternack, PE9881-24) having a 12° HPBW (24-dBi gain) were orthogonally polarized ($\theta$ and $\phi$) and used at both Tx and Rx [23]. Fig. 3(a) shows the channel sounding system [5], [22]. Because the antennas could not be co-located, they were directed toward the opposite side ($180^\circ$) on the same plane, as shown in Fig. 3(b) [23]. As illustrated in Fig. 3(c), the Tx was mounted on top of the television, and the channel responses were measured at the five Rx positions (denoted by Rx1–Rx5). All Rx positions had the LoS link between Tx and Rx.

In the measurement, the band-limited angle-resolved CTFs for the “pq” polarization combination expressed as

$$H_{qp}(\tilde{\theta}_T, \tilde{\phi}_T, \tilde{\theta}_R, \tilde{\phi}_R) \quad (1)$$

were obtained, where the subscripts $p$ and $q \in \{\theta, \phi\}$ denote Tx and Rx antenna polarization, respectively. The pointing angles of the co-elevation and azimuth angles at Tx and those at Rx, respectively, are denoted by

$$\tilde{\theta}_T = \{n_{\theta_T}\Delta_{\theta_T} | n_{\theta_T} = 0, \ldots, N_{\theta_T} - 1\},$$
$$\tilde{\phi}_T = \{n_{\phi_T}\Delta_{\phi_T} | n_{\phi_T} = 0, \ldots, N_{\phi_T} - 1\},$$
$$\tilde{\theta}_R = \{n_{\theta_R}\Delta_{\theta_R} | n_{\theta_R} = 0, \ldots, N_{\theta_R} - 1\},$$
$$\tilde{\phi}_R = \{n_{\phi_R}\Delta_{\phi_R} | n_{\phi_R} = 0, \ldots, N_{\phi_R} - 1\},$$

and the sub-carrier (multitone) frequency is denoted by

$$\tilde{\gamma} \in \{f_c + (n - N/2) \Delta \gamma | n = 0, \ldots, N - 1\}.$$

Here, $n$, $N$, and $\Delta$ denote the sample indices, the total numbers of samples, and the sampling intervals of the sub-scripted domain, respectively. Then, the angle-resolved
channel impulse response (CIR) is obtained by discrete inverse Fourier transform of the CTFs as

\[ h_{\text{ip}}(\tilde{\tau}, \tilde{\theta}_T, \tilde{\phi}_T, \tilde{\theta}_R, \tilde{\phi}_R) = \mathcal{F}^{-1}(H_{\text{ip}}(\tilde{\tau}, \tilde{\theta}_T, \tilde{\phi}_T, \tilde{\theta}_R, \tilde{\phi}_R)). \]  

(2)

where the delay taps \( \tilde{\tau} \in \{ n_\tau | n_\tau = 0, \ldots, N - 1 \} \). The DDADPS is defined by

\[ P_{\text{ip}}(\tilde{\tau}, \tilde{\theta}_T, \tilde{\phi}_T, \tilde{\theta}_R, \tilde{\phi}_R) \triangleq |h_{\text{ip}}(\tilde{\tau}, \tilde{\theta}_T, \tilde{\phi}_T, \tilde{\theta}_R, \tilde{\phi}_R)|^2. \]  

(3)

In this measurement, the Tx and Rx antennas were rotated over 180° and 360° azimuth angles, respectively, at every \( \Delta \phi_T = \Delta \phi_R = 12^\circ \) as illustrated in Fig. 3(c). Thus, \( N_{\phi_T} = 16 \) and \( N_{\phi_R} = 30 \) angular samples were obtained. At the same time, the Tx and Rx antennas were tilted over 60° and 48° co-elevation angles, respectively, at every \( \Delta \theta_T = \Delta \theta_R = 12^\circ \), as illustrated in Fig. 3(d). Thus, \( N_{\theta_T} = 4 \) and \( N_{\theta_R} = 5 \) angular samples were obtained. Consequently, 9,600 samples in the angle domain were acquired by directional scanning, which took approximately 12 hours. In the delay domain, the resolution was \( \Delta \tau = 2.5 \) ns, and the maximum measurable delay was 640 ns (\( N = 256 \)).

III. CLUSTER ANALYSIS

A. MPC EXTRACTION

The noise components were removed by applying a certain threshold as a pre-processing before the MPC extraction. The noise threshold was determined based on measuring the actual noise statistics [23]. From the noisy filtered DDADPSs, a specified number of MPCs were extracted by the sub-grid CLEAN algorithm in high resolution [23], assuming that the measured full polarimetric angle-resolved CIR is expressed by superposition of \( L \) MPCs as

\[ h_n = \begin{bmatrix} h_{\theta \theta, n} & h_{\theta \phi, n} & h_{\phi \theta, n} & h_{\phi \phi, n} \end{bmatrix} = \sum_{l=1}^{L} \text{diag} \left( \begin{bmatrix} A_{n}(\theta, \phi)_{l}^{(0)} \ A_{n}(\theta, \phi)_{l}^{(1)} \ A_{n}(\theta, \phi)_{l}^{(2)} \ A_{n}(\theta, \phi)_{l}^{(3)} \end{bmatrix} \right) \cdot y_{l}, \]  

(4)

where the multi-dimensional array indices in vector form, \( n \triangleq [n_\theta_T, n_\phi_T, n_\theta_R, n_\phi_R]^T \). The combined response function is defined by

\[ A_{n}(\theta, \phi)_{l}^{(p)} \Delta \equiv a_T(\tilde{\tau} - \tau_l) \cdot a_R(\tilde{\theta}_R - \theta_{R,l}, \tilde{\phi}_R - \phi_{R,l}) \]  

\[ a_T(\tilde{\tau} - \tau_l) \cdot a_R(\tilde{\theta}_R - \theta_{R,l}, \tilde{\phi}_R - \phi_{R,l}) \]  

(5)

where \( a_T(\tilde{\tau}) \) denotes the auto-correlation function of the sounding signal which is a periodic Sinc function, and \( a_R^{(p)} \) and \( a_R^{(q)} \) denote the Tx and Rx antenna radiation patterns having \( p \) and \( q \) polarizations, respectively. Here, \( \tilde{\Omega}_l \triangleq [\tilde{\tau}_l, \tilde{\theta}_{T,l}, \tilde{\phi}_{T,l}, \tilde{\theta}_{R,l}, \tilde{\phi}_{R,l}]^T \) where \( \tau_l \) denotes the delay time, and \( \theta_{T,l} \) and \( \phi_{T,l} \), and \( \theta_{R,l} \) and \( \phi_{R,l} \) indicate the co-elevation and azimuth angles of departure (AoDs) and arrival (AoAs) of the \( l \)th MPC, respectively. The polarimetric complex amplitude is expressed as \( y_l = [y_{\gamma_1, \phi_1} y_{\gamma_1, \phi_2} y_{\gamma_1, \phi_3} y_{\gamma_1, \phi_4}]^T \).

Here, 60 MPCs were extracted with the angle and delay resolutions of 0.1° and 0.01 ns, respectively. Figs. 4 and 5 show the angular power spectra (APSs) and azimuth delay power spectra (ADPSs) seen from Tx and Rx obtained at Rx1, respectively. The APS and ADPS were synthesized by summing the DDADPSs along all the other dimensions except for the AoD or AoA and the delay and azimuth AoD or AoA, respectively. In Figs. 4 and 5, the results for the measured spectra, the ones reconstructed by the extracted MPCs, and the ones reconstructed by the RT are compared. The reconstructed spectra were obtained by embedding the antenna directivity and the bandwidth effect into the MPCs extracted by parameter estimation and into the ray paths calculated by RT simulation with three reflections and a single diffraction, respectively. All those spectra were scaled by the Tx/Rx antenna gains. The comparison shows that the reconstructed APS and ADPS, shown in Figs. 4(b) and 5(b), respectively, matched up well with the measured ones, as shown in Figs. 4(a) and 5(a), respectively. Figs. 4(c) and 5(c) show the APS and ADPS reconstructed by RT simulation, respectively. It can be observed that the RT predicts the channel well because the spectra are also very similar to the measured ones. At the other Rx positions, a similar trend to the results obtained at Rx1 was confirmed [8].

B. CLUSTERING AND SCATTERING PROCESS IDENTIFICATION

In this study, the \( K \)-powerMeans (KPM) automatic clustering algorithm [25] was applied to the extracted MPCs. It iteratively minimizes the total sum of the power-weighted distance of MPCs to a given number of cluster centroids, thereby minimizing global spreads of the clusters. As usual, the KPM result is not very robust and often subject to various conditions, because it treats a cluster as a group of MPCs from the information-theoretical viewpoints without explicit relation to any physical IOs. As mentioned above, clustering should be based on the actual physical propagation paths, and the clusters should be modeled in a more sophisticated manner for mm-wave communications. Therefore, in this study, the number of clusters was manually judged by visual inspection of the MPC distribution on the APS. After pruning and merging some clusters manually, the numbers of clusters were finally determined to be 10, 12, 9, 8, and 10 for Rx1, Rx2, Rx3, Rx4, and Rx5, respectively. Fig. 6 illustrates the result of Rx1 as an example.

Comparing the measured clusters with the RT results, the dominant scattering processes, such as LoS, single-bounce (SB) reflection, and double-bounce (DB) reflection were identified, as shown in Fig. 7, where Figs. 7(a) and (b) illustrate the measurement and RT results, respectively. The LoS, SB reflection and DB reflection can be well reproduced by the RT simulation. In the case of Rx1, the power of the LoS, SB reflection, DB reflection and unidentified scattering occupied 38.7%, 36.3%, 8.9% and 16.1% of the total power, respectively. This result indicates that the LoS and SB/DB reflection are dominant scattering processes occupying almost 90% of the total power [26].
IV. CHANNEL MODEL

In the Q-D channel model, several dominant propagation paths in a cluster are deterministically expressed by the Tx and Rx locations and environment geometry. However, weak high-order reflections and scattering from occasional small and random objects, are stochastically treated as random clusters. In IEEE 802.11ay, the random clusters are statistically generated based on the Saleh-Valenzuela (S-V) model by inter-cluster parameters, i.e., exponentially distributed in arrival time, exponentially decaying in power, and uniformly distributed in angle [3], [16]. Then, for each cluster the dispersions in delay and angle domains are added by the intra-cluster stochastic model in the same methodology as the inter-cluster case.

A. INTER-CLUSTER MODEL

The cluster analysis described in the previous section demonstrated that the LoS and SB/DB reflection can be well
reproduced by the RT simulation and those components are dominant scattering processes constituting almost 90% of the total power. The contribution of random clusters was not as significant [26]. Therefore, it is expected that, in the channel model, it is sufficient to include only the LoS and SB/DB reflection calculated by RT as deterministic components, the so-called D-rays.

B. INTRA-CLUSTER MODEL FOR ROUGH SURFACE OF WALLS

At mm-wave frequencies, the irregularity and roughness on the reflecting surfaces can create diffuse scattering as well as specular reflection. Here, the diffuse scattering is modeled by a cluster that is a group of the specular reflection ray and additional diffuse scattering rays with close delays and angles. From the viewpoint of geometrical optics, each segment of the ray has facets that meet the condition of equal angles of incidence and reflection. The diffuse scattering is considered to arise out of a multitude of specular reflection rays from various facets on the rough surface mainly contained within the first Fresnel zone [27], [28]. As described above, in this study, the MPCs obtained by parameter estimation were clustered based on the actual physical propagation paths to model the intra-cluster characteristics of the wall reflection. To overcome the problem that channel acquisition is inevitably limited because of the long measurement time in directional scanning, the small-scale behavior was captured by using the multiple sets of the clusters identified as first-order specular reflection on the same plasterboard walls from the data obtained at all Rx positions.

The intra-cluster characteristics were statistically modeled in the delay and angle domains by delay time and by azimuth and co-elevation AoA and AoD. The delay domain characteristics were modeled by the cursors, i.e., the MPC with the largest power within a cluster, the pre-cursor and post-cursor components arriving before and after the cursor, respectively. They were parameterized by the number of rays (\(N_{\text{pre/post}}\)), ray arrival rate (\(\lambda_{\text{pre/post}}\)), ray power-decay constant (\(\gamma_{\text{pre/post}}\)), and ray K-factor (\(K_{\text{pre/post}}\)). Because the cluster arrival was modeled by a Poisson process, the inter-arrival times followed an exponential distribution as

\[
f_{\text{pre/post}}(\tau_i|\tau_{i-1}) \sim \lambda_{\text{pre/post}} \exp\left(-\lambda_{\text{pre/post}}(\tau_i - \tau_{i-1})\right) \quad (6)
\]

The ray power is usually modeled by exponentially decaying power delay profile as

\[
p_{\text{post}}(\tau) = \frac{p_{\text{cur}}}{K_{\text{post}}} \exp\left(\frac{\tau - \tau_{\text{cur}}}{\gamma_{\text{post}}}\right), \quad (7)
\]

\[
p_{\text{pre}}(\tau) = \frac{p_{\text{cur}}}{K_{\text{pre}}} \exp\left(-\frac{(\tau - \tau_{\text{cur}})}{\gamma_{\text{pre}}}\right) \quad (8)
\]

where \(p_{\text{cur}}\) denote the power of the cursor. The K-factor is determined by the y-intercept as

\[
K_{\text{pre/post}} = \frac{p_{\text{cur}}}{\sum_{i \in S_{\text{pre/post}}} p_i}, \quad (9)
\]

where \(S_{\text{pre/post}}\) denotes the set of pre-cursor/post-cursor MPCs. Here, \(p_i\) denotes the polarization combined power of the \(i\)th MPC, which is obtained by \(\frac{1}{2}(p_{i,\theta\theta} + p_{i,\phi\phi} + p_{i,\phi\theta} + p_{i,\theta\phi})\). The angle domain characteristics are parameterized by the RMS angle spread of the MPCs within a cluster as

\[
\sigma_\Psi = \sqrt{\frac{\sum_i (\Psi_i - \mu_\Psi)^2 p_i}{\sum p_i}}, \quad (10)
\]

for \(\Psi \in \{\theta_T, \phi_T, \theta_R, \phi_R\}\) where

\[
\mu_\Psi = \frac{\sum_i \Psi_i p_i}{\sum p_i}. \quad (11)
\]

The intra-cluster delay domain characteristics were obtained using the normalized reflection coefficients of the MPCs belonging to the clusters generated by the first-order plasterboard wall reflection, which are shown in Fig. 8. Table 1 presents the complete intra-cluster parameters, and Table 2 shows the polarimetric properties of the SB plasterboard wall reflection, such as the reflection loss, co-polarization power ratio (CPR) and cross-polarization power ratio (XPR) for downlink.

To verify the proposed model, the channels were generated by the IEEE 802.11ay channel model framework [29]
by replacing the parameters with those in Table 1 where the intra-cluster spread effect is added to the D-ray components calculated by RT. Fig. 9(a) shows the synthesized omni-directional power delay profiles (PDPs). The average PDP obtained by applying the intra-cluster characteristics to the specular components predicted by RT (yellow line in the figure) matches better with the measurement result (blue dashed line) than that synthesized by RT only (red line). Note that the proposed model and RT reconstructions have

**FIGURE 6.** Clustering result of Rx1.

**FIGURE 7.** Comparison between the scattering processes identified by (a) measurement and (b) ray-tracing (RT) simulation.

**FIGURE 8.** Intra-cluster delay domain characteristics.

| Parameters | Pre/Post Cursor | This work | $802.11$ad [4] |
|------------|-----------------|-----------|----------------|
| $K$ [dB]   | Pre             | 4.0       | 10.0           |
|            | Post            | 7.5       | 14.2           |
| $\gamma$ [ns] | Pre           | 2.8       | 3.7            |
|            | Post            | 5.2       | 4.5            |
| $\lambda$ [1/ns] | Pre          | 2.6       | 6.3            |
|            | Post            | 1.4       | 0.31           |
| $N$        | Pre             | 2         | 6              |
|            | Post            | 2         | 8              |
| $\sigma_{\theta_T}$ |            | 6.8       | 5.0            |
| $\sigma_{\phi_T}$  |               | 3.9       | 5.0            |
| $\sigma_{\theta_R}$ |            | 7.9       | 5.0            |
| $\sigma_{\phi_R}$  |               | 8.1       | 5.0            |
higher power at 0 to 20 ns than the measured values. It is because the measured CTFs have roll-off characteristics at high frequency, thus that works a window function to reduce the sidelobe level in delay domain. Furthermore, Fig. 9(b) shows an example APS synthesized by a single realization (Fig. 4 shows those obtained by the measurement and RT). These results show that the power dispersion in delay and angle domains is described well by the proposed intra-cluster model.

V. VALIDATION
A. SMALL-SCALE FADING MEASUREMENT
In the previous section, the diffuse scattering effect on the rough surface of the plasterboard wall reflection was parameterized based on the intra-cluster model. However, validation of such a microscopic diffuse scattering phenomenon is still not practically viable because of limited resolution in double-directional measurement. Therefore, the intra-cluster model was validated by measuring the temporal fluctuation of the small-scale fading by the multi-path components reflected by the plasterboard wall. For this measurement, the trolley was configured by tying up the Tx and Rx of the channel sounder with two metallic poles as illustrated in Fig. 10. The Tx and Rx antennas with a 12° HPBW were orientated toward the same specular reflecting point on the wall maintaining the incident angle equal to the reflected angle. The gain of the wall reflected component was extracted from the measured PDP by taking the maximum power value as

\[ G(t) = \max_{\tau} PDP(\tau, t), \]

and that is approximately modeled by

\[ G(t) \approx G_{fs} \left| r_{sp} + \sum_{l} r_{sc,l}(t) \right|^2. \]  

where \( r_{sp}(t) \) and \( r_{sc} \) denote the specular reflection and scattering coefficients, respectively. \( G_{fs} \) denotes the free space path gain (FSPG), which is a unit-less value. Then, the combined reflection coefficients were obtained by
removing $G_{fs}$ as
\begin{equation}
    r(t) = \sqrt{G(t) / G_{fs}}.
\end{equation}

$G_{fs}$ was measured by the metal plate reflection at the same condition. The channel sounder acquired 1,000 channel impulse responses every 1 mm (the wavelength was approximately 5 mm) while moving the trolley approximately 1 m along the homogeneous wall at a constant speed ($v \approx 0.17 \approx 1 \text{ m/s}$) where the incident angles ranged from $25^\circ$ to $60^\circ$ in $5^\circ$ steps. Fig. 11 shows the temporal fluctuation of the reflection coefficient, $r(t)$ ($\theta = 25^\circ$, as an example), where it can be seen that $r(t)$ largely fluctuates in a 15 dB range, and a similar trend is observed at a different polarization.

**B. FADING DISTRIBUTION**

Regarding the surface roughness as a spatially stationary random process, the small-scale fading can be characterized through a certain statistical distribution. Fig. 12 shows the cumulative distribution functions (CDFs) of the normalized envelope, $x(t) = \sqrt{X(t)}$ where $X(t) = G(t)/E[G(t)]$ denotes the normalized power. In this figure, “Proposed” means the CDF obtained by using the channel responses realized by applying the proposed intra-cluster model to (4), and “Empirical” means the CDF obtained by all measurement results with respect to all incident angles and polarizations. The fading distribution of the reconstructed channel matches the measurement result very well; therefore, the proposed intra-cluster model is statistically valid. The statistical models fit by the measurement results are Nakagami-$m$ ($m = 2.65, \omega = 1.14$) and Rician ($s = 0.96, \sigma = 0.33$) distributions. In addition, regarding the result obtained by the IEEE 802.11ad model, the fading effect decreases, because the multi-paths with a small arrival rate are resolved in the delay domain. This demonstrates the intra-cluster in the IEEE 802.11ad model does not exactly express the diffuse scattering effect.
C. ANGLE DISPERSION

In the measurements described above, the reflection coefficient can be simply modeled by the superposition of several non-resolvable MPCs within the antenna beamwidth and delay bin as

$$r(t) = \sum_{m=0}^{M-1} \gamma_m \exp \left( -j \frac{2\pi}{\lambda} m \cdot v \cdot t \right)$$

where the complex amplitude $\gamma_m = r_m \exp(j\xi_m)$, $\mathbf{k}_m$ and $\mathbf{v}$ denote the wave vector of the $m$th MPC ($k_m = \frac{2\pi}{\lambda}$), and the velocity vector of the trolley, respectively. By moving the trolley along the wall, the small-scale fading fluctuation can be observed because of the constructive and destructive interference of the several MPCs including specular reflection and diffuse scattering components, which impinge on the Rx antenna. Because of the unpredictable nature, the small-scale fading is generally treated as a stochastic process. The Doppler power spectrum is a useful measure of second-order statistics of a stochastic process, and that depends on the AoA distribution of the received MPCs. In this study, it was assumed that the intra-cluster MPCs are generated by diffuse scattering on the rough surface of a wall and the angular dispersion is usually small, as presented in Table 1. Therefore, the angle dispersion is difficult to validate by only angle domain analysis because of the limited measurement resolution.

Fortunately, an analytic measure for second-order statistics of small-scale fading under nonomnidirectional multi-path condition has been developed [30]. Here, the distribution of multi-path power is conveniently described by the function $S(\phi)$, where $\phi$ denotes the azimuth angle. In [30], an intuitive measure was proposed for quantifying the angular dispersion of multi-path power defined by

$$\Lambda = \sqrt{1 - \frac{|C_n|^2}{|C_0|^2}}$$

ranging from 0 to 1, where $C_n$ is the $n$th complex Fourier coefficient of $S(\phi)$ obtained as $C_n = \int_0^{2\pi} S(\phi) e^{jn\phi} d\phi$. In particular, the angle spread $\Delta \phi$ is defined by

$$\Delta \phi = \sqrt{1 - \frac{2}{\Delta \phi} \sin^2 \left( \frac{\Delta \phi}{2} \right)}$$

if a simple uniform distribution model of multi-path power with the sector width $\Delta \phi$ is applied. Fig. 13 shows the relationship between the angle spread $\Delta \phi$ and the sector width of the multi-path power, $\Delta \phi$. In addition, by defining the fading rate by $F(t) = \frac{dX(t)}{dt}$ where $X(t) = |r(t)|^2 / E[|r(t)|^2]$ denotes the normalized power, the variance is analytically approximated by

$$\sigma_F^2 = \text{Var} \{ F(t) \} \approx k^2 v^2 \Lambda^2.$$
Fig. 14 shows that the small-scale fading can be well approximated by (14), because the measured and calculated fluctuation patterns are quite similar, even though the measured functions are corrupted by noise.

Furthermore, an attempt was made to verify the intra-cluster angle parameters using the fading rate variance in (17). The angle spread, \( \Lambda \), defined in (15) can be obtained by substituting the fading rate variance into (17) where \( \nu = 0.17 \text{ m/s} \). As a more comprehensive measure, the sector width, \( \Delta \phi \) can be used. Fig. 15 shows the relationship between the sector width \( \Delta \phi \) and the incident angle \( \phi \), where \( \Delta \phi \) is numerically obtained from the measured \( \Lambda \) using the relation of (16). As expected, the sector width decreases with increasing incident angle, as is also illustrated in Fig. 15. From the fact that the sector width ranged between 2.24\(^{\circ}\) and 8.78\(^{\circ}\), it can be seen that the angle parameters of the proposed intra-cluster model in Table 1 have reasonable values, even though Fig. 15 assumes a simple uniformly distributed multi-path power.

VI. CONCLUSION

The measurement campaigns in a conference room environment conducted to develop a Q-D channel model for indoor access scenarios were presented. The MPCs were extracted from the measurement data in high resolution. Then, they were clustered based on the actual physical propagation paths for explicit identification of the scattering processes. The cluster analysis revealed that the signal paths by LoS, SB, and DB reflections are power-dominant, occupying almost 90\% of the total power, and accurately predicted by RT. Therefore, it is expected that, in the channel model, it is sufficient to include only the LoS, SB and DB reflection calculated by RT as deterministic components (D-rays).

To express diffuse scattering on the rough surface in mm-wave channels, the intra-cluster model of the commonly used plasterboard wall reflection was parameterized. The synthesized PDP and APS showed that the power dispersion in the delay and angle domains is described well by the proposed intra-cluster model. Finally, the proposed intra-cluster model was experimentally validated by analyzing the small-scale fading caused by the diffuse scattering. Regarding the fading distribution, because the reconstructed channel matched the measurement result well, the proposed intra-cluster model is statistically valid. In addition, the measured and simulated small-scale fluctuation patterns are surprisingly similar, and the intra-cluster angle parameters were successfully verified by using the fading rate variance.

ACKNOWLEDGMENT

The authors would like to thank the appreciation to Mr. K. Akasaka and Mr. T. Iwata for their measurement support.

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