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# On mm-Wave Multi-path Clustering and Channel Modeling

Carl Gustafson, Katsuyuki Haneda, *Member, IEEE*, Shurjeel Wyne, *Senior Member, IEEE*, and Fredrik Tufvesson, *Senior Member, IEEE*

**Abstract**—Efficient and realistic mm-wave channel models are of vital importance for the development of novel mm-wave wireless technologies. Though many of the current 60 GHz channel models are based on the useful concept of multi-path clusters, only a limited number of 60 GHz channel measurements have been reported in the literature for this purpose. Therefore, there is still a need for further measurement based analyses of multi-path clustering in the 60 GHz band.

This paper presents clustering results for a double-directional 60 GHz MIMO channel model. Based on these results, we derive a model which is validated with measured data. Statistical cluster parameters are evaluated and compared with existing channel models. It is shown that the cluster angular characteristics are closely related to the room geometry and environment, making it infeasible to model the delay and angular domains independently. We also show that when using ray tracing to model the channel, it is insufficient to only consider walls, ceiling, floor and tables; finer structures such as ceiling lamps, chairs and bookshelves need to be taken into account as well.

**Index Terms**—Millimeter wave propagation, channel modeling, 60 GHz WLAN, IEEE 802.11ad, IEEE 802.15.3c.

## I. INTRODUCTION

As the requirements for efficient and reliable wireless communications with high throughput are ever-increasing, novel wireless techniques have to be considered, and the available radio spectrum has to be used efficiently in order to overcome spectrum shortage. Due to the large bandwidth of at least 5 GHz available worldwide [1], the 60 GHz band is a promising candidate for short-range wireless systems that require very high data rates. Efforts have already been made regarding standardization by the IEEE 802.15.3c [2] and IEEE 802.11ad [3] working groups, and some commercial products are already available on the market.

The propagation characteristics in the 60 GHz band are quite different from those in the lower frequency bands commonly used today for cellular communication. Assuming identical transmit powers and antenna gains, the received power at 60 GHz is smaller than that at lower frequencies due to a smaller receive antenna aperture at 60 GHz. Furthermore, since the dimensions of typical shadowing objects are large in relation to the wavelength at 60 GHz, sharp shadow zones are formed, making diffraction an insignificant propagation mechanism [4]. Also, due to the high penetration loss of

most materials at 60 GHz, multi-path components propagating through walls or other objects typically have low power. Due to these propagation characteristics, highly directional antennas or adaptive beam-forming techniques are required in order to establish a reliable 60 GHz communication link [5].

As the potential benefits of systems operating in the 60 GHz band are directly related to the propagation environment characteristics, realistic and reliable channel models are of vital importance for the design and development of novel 60 GHz technologies. Furthermore, as beam forming techniques are vital for many types of mm-wave communications, the channel should ideally be modeled using a MIMO model that takes the angular characteristics of the channel into account.

The IEEE802.11ad channel model is a MIMO model based on a mixture of ray tracing and measurement-based statistical modeling techniques [6]. It is a cluster-based spatio-temporal channel model that supports several different environments. The measurements for the IEEE802.11ad model were conducted using highly directional antennas that were steered in different directions in order to evaluate and model the cluster parameters of 60 GHz channels.

Several recent studies are directly related to the IEEE802.11ad model and include theoretical investigations regarding capacity [7], spatial diversity techniques [8] and beamforming performance [9], as well as an extended model for human blockage in 60 GHz channels [10].

In this paper, we present measurement-based results for a double-directional 60 GHz MIMO channel model in a conference room environment. Statistical cluster parameters are evaluated and compared with existing 60 GHz channel models. The novel aspect of our proposed channel model is the method by which it models the spatio-temporal properties of the clusters. We provide two different ways of modeling the cluster spatio-temporal properties; one being stochastic and the other a semi-deterministic approach that is based on ray-tracing. Most of the current 60 GHz directional analyses rely on measurements using highly directional antennas that are mechanically steered [11] and sometimes also include ray tracing results [6]. The results in this paper are based on measurements using the virtual antenna array technique. The double-directional estimates for the multi-path components (MPCs) were obtained using the SAGE algorithm. This technique can potentially offer an improved resolution of the MPC parameters compared with techniques based on mechanically steered high-gain antennas [6]. The clustering results were then obtained using an automated clustering algorithm.

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## II. 60 GHz RADIO CHANNEL AND ANTENNA MEASUREMENTS

### A. Measurement Environment

This work is based on results from a 60 GHz radio channel measurement campaign performed in a conference room with a volume of  $6.8 \times 7.0 \times 2.5 \text{ m}^3$ . The IEEE802.11ad working group has performed measurements in smaller conference rooms with volumes of approximately  $3 \times 4.5 \times 3 \text{ m}^3$  [12] and in a slightly larger conference room with a width and length of 6.3 m and 4.3 m [13]. During our measurements, the Rx array was placed at a fixed position in one of the corners of the room whereas the Tx array was placed at one of 17 predefined positions on either of the two tables in the room. As indicated by Fig. 1, 17 different line-of-sight (LOS) measurements were performed at these positions as well as 15 additional obstructed-line-of-sight (OLOS) measurements. In the OLOS scenarios, a laptop computer screen was used to block the direct path between the Tx and the Rx. Further details about the measurements can be found in [14].

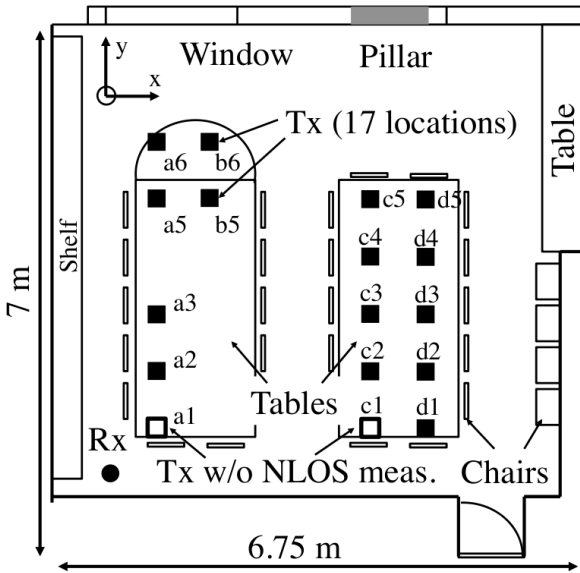


Fig. 1. Floorplan of the measured conference room.

### B. Measurement Equipment and Setup

The 60 GHz radio channel was measured using a vector network analyzer based system [15]. 2-D electromechanical positioners were used to move the Tx and Rx antennas in the horizontal and vertical planes, respectively. A commercial biconical antenna, Flann Microwave MD249, with an omnidirectional pattern in azimuth was used at the Tx side, and the Tx virtual array was a horizontal uniform rectangular array with  $7 \times 7$  elements. The Rx antenna was an open waveguide, vertically polarized and oriented such that the waveguide opening was directed towards the opposite corner of the room compared to where the Rx array was situated. The Rx virtual array was a vertical uniform rectangular array with  $7 \times 7$  elements. All measurements were performed with the antennas in a vertical-to-vertical (V-V) polarization orientation. The

inter-element spacing was 2 mm in both arrays. Back-to-back measurements were performed in order to remove the influence of the coaxial cables, mixers, and feeding waveguides.

### C. Antenna measurements

The co- and cross-polarized antenna gains of the Tx- and Rx antenna were first measured using a setup based on a vector network analyzer (VNA) and electromechanical positioners. A standard gain horn antenna with known gain and high cross-polarization discrimination ratio was used as the reference antenna. Electromagnetic absorbers were used to cover equipment in the close vicinity of the antenna, such as the VNA, positioners and tables. Also, since the measurements were performed in a large open area in a room, the data will also include effects due to possible multi-path propagation within the room. A simple time-domain gating technique was employed to filter the measured data and remove parts of the impulse response with longer delays. The frequency range in the measurement was 60-64 GHz, yielding a time resolution of 0.25 ns. The gain transfer method [16] was then employed to calculate the antenna gain. Due to the small wavelength and considering the alignment accuracy of the measurement setup, it was not possible to extract the phase responses of the antennas precisely. Fig. 2 shows the co- and cross-polarized antenna gains of the Rx antenna at 62 GHz. The cross-polarized antenna gain of the biconical Tx antenna (not shown) is low in all directions, whereas the cross-polarized antenna gain of the open waveguide is fairly high in certain directions.

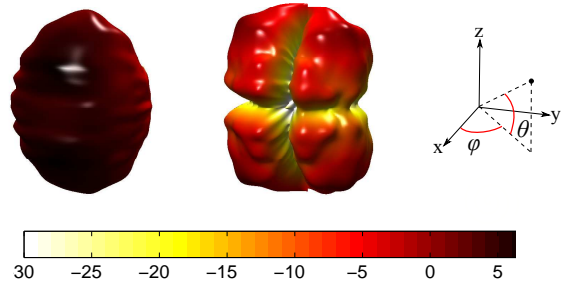


Fig. 2. Co-polarized (left) and cross-polarized (right) Rx antenna gain in dBi of the open waveguide at 62 GHz.

Using the measured co- and cross-polarized data, it was possible to estimate the cross-polarization discrimination ratio (XPD) of the antennas as

$$\text{XPD}(\phi, \theta)|_{\text{dB}} = G_{\text{co}}(\phi, \theta)|_{\text{dB}} - G_{\text{cross}}(\phi, \theta)|_{\text{dB}}. \quad (1)$$

In other words, we define the antenna XPD to be the difference between the co-polarized and cross-polarized antenna gain in a certain angular direction. This is of importance since the measurements were performed only with V-V polarization, which means that it is not possible to employ a full polarimetric estimation of the complex amplitudes in SAGE. Instead, only the complex gain of the V-V component is estimated. This means that the SAGE algorithm only produces accurate results for MPCs in directions where the XPDs of the Tx and

Rx antennas are large [17]. In total, less than 5% of the total number of MPCs in all scenarios were located in directions where the XPD was lower than 20 dB.

### III. MULTI-PATH ESTIMATION AND CLUSTERING

#### A. The SAGE algorithm

The measured transfer functions are assumed to be correctly described by a finite number of plane waves, i.e. multi-path components (MPCs). Each MPC is described by its complex amplitude, delay, direction of departure (DOD) and direction of arrival (DOA). In order to estimate these MPC parameters, the SAGE algorithm is used. A double-directional analysis using SAGE based on the same measurements was previously presented in [18], and the reader is referred to that paper for details regarding the signal model for the analysis. This work improves the SAGE estimates of [18] by employing a more detailed model for the gain patterns of the antennas used in the measurements. By taking the gain of the antennas into account, the estimated results describe the propagation channel.

The SAGE analysis was performed over an observation bandwidth of 200 MHz centered at 62 GHz with 26 equi-spaced frequency samples. The estimated MPCs can be used to model the 2 GHz band from 61–63 GHz because the multi-path parameters do not change drastically over this frequency band. This assertion is justified by the fact that neither the power angular profiles [19], nor the SAGE estimates change drastically when evaluated at center frequencies of 61, 62 and 63 GHz.

#### B. Clustering Method

In this paper, a cluster is defined as a group of multi-path components having similar delays and directions of departure and arrival. The estimated MPCs are grouped into clusters using the K-power-means algorithm wherein the multi-path component distance is used as a distance metric in parameter space [20]. For the validation of the number of clusters, the Kim-Parks index [21] was utilized. The Kim-Parks index,  $KP$ , can be considered as a normalized version of the Davies-Bouldin index. It is calculated using an over- and under-partition measure function,  $v_o$  and  $v_u$ , that are normalized with respect to the minimum and maximum number of clusters,  $C_{min}$  and  $C_{max}$ ,

$$KP(C) = v_o(C) + v_u(C). \quad (2)$$

The optimal number of clusters,  $C_{opt}$ , for a certain scenario is then given by

$$C_{opt} = \underset{C}{\operatorname{argmin}} \{KP(C)\}, C_{min} \leq C \leq C_{max}. \quad (3)$$

In practice, the largest number of clusters is set to be a number that is large enough to make sure that the correct number of

clusters is identified. For a more detailed description of the Kim-Parks index, the reader is referred to [21]. The Kim-Parks index was chosen over the combined validation scheme as it produced consistent results that agreed better with the number of clusters identified based on a visual inspection. When using the Kim-Parks index, the number of identified clusters ranged from 6 to 12 in the LOS scenario and 8 to 12 in the OLOS scenario. Fig. 3 shows typical clustering results for the direction of departure. Similar results were obtained for the direction of arrival. Each circle represents an MPC and the colors indicate identified clusters and the radius of each circle is proportional to the power of each MPC. In order to get more consistent results in the LOS and OLOS scenarios, the clustering in the LOS scenarios are performed without including the LOS component. That way, the power levels are similar in both scenarios. It is possible to exclude the LOS component from the clustering since this component can be treated deterministically. The clustering results for the LOS and OLOS scenarios are very similar. The main differences between the LOS and OLOS scenarios are

- 1) A strong LOS component present in the LOS scenario.
- 2) A number of components are present in the OLOS scenario that are diffracted around the computer screen.

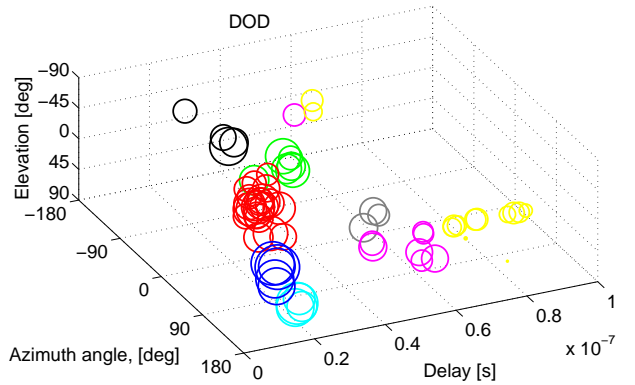


Fig. 3. Typical clustering result for the direction of departure.

### IV. SURVEY OF 60 GHz CHANNEL MODELS

#### A. The Extended Saleh-Valenzuela Model

Based on the clustering results, a number of statistical 60 GHz channel model parameters can be derived. One of the most widely used channel models based on clusters is the extended Saleh-Valenzuela model, where the impulse response,  $h$ , is given by Eq. (4). Here,  $\beta_{k,l}$  is the complex amplitude of the  $k$ th ray (i.e. MPC) in the  $l$ th cluster and  $T_l$ ,  $\Omega_l$  and  $\Psi_l$  are the delay, DOA and DOD of the  $l$ th cluster, respectively. Similarly  $\tau_{k,l}$ ,  $\omega_{k,l}$  and  $\psi_{k,l}$  are the delay, DOA and DOD

$$h(t, \Theta_{rx}, \Theta_{tx}) = \sum_{l=0}^L \sum_{k=0}^{K_l} \beta_{k,l} e^{j\chi_{k,l}} \delta(t - T_l - \tau_{k,l}) \delta(\Theta_{rx} - \Omega_l - \omega_{k,l}) \delta(\Theta_{tx} - \Psi_l - \psi_{k,l}) \quad (4)$$

of the  $k$ th ray in the  $l$ th cluster, respectively. Finally,  $\delta(\cdot)$  is the Dirac delta function and the phase of each ray,  $\chi_{k,l}$ , is assumed to be described by statistically independent random variables uniformly distributed over  $[0, 2\pi)$ . The mean power of the  $k$ th ray in the  $l$ th cluster is given by

$$\overline{\beta_{k,l}^2} = \overline{\beta(0,0)^2} e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma}, \quad (5)$$

where  $\Gamma$  and  $\gamma$  are the cluster and ray decay constants, respectively, and  $\overline{\beta(0,0)^2}$  is the average power of the first ray in the first cluster [22].

If the delay and angular domains can be modeled independently, the cluster and ray arrival time distributions may be described by two Poisson processes. Under this assumption, the cluster and ray inter-arrival times are typically described by two independent exponential probability density functions. The cluster arrival time for each cluster is thus described by an exponentially distributed random variable that is conditioned on the arrival time of the previous cluster, i.e.

$$p(T_l|T_{l-1}) = \Lambda e^{-\Lambda(T_l - T_{l-1})}, l > 0. \quad (6)$$

Here,  $\Lambda$  is the cluster arrival rate. Similarly for the ray arrival times, we have

$$p(\tau_{k,l}|\tau_{k-1,l}) = \lambda e^{-\lambda(\tau_{k,l} - \tau_{k-1,l})}, l > 0, \quad (7)$$

where  $\lambda$  is the ray arrival rate.

The extended S-V model relies on the assumption that the delay and angular domains can be modeled independently. As will be shown later, this assumption might not be valid for 60 GHz channels. Instead, it is necessary to either jointly model the angular and delay domains using a joint angular-delay distribution [23], or to use a deterministic approach based on ray tracing, which is done in the IEEE 802.11ad channel model [6]. This will be discussed further in section VI.

### B. The IEEE 802.15.3c Channel Model

In the IEEE802.15.3c channel model, the extended S-V model of eq. (4) is used with the addition of a LOS component that is derived deterministically. It is a SIMO model that only models the DOA. The cluster DOA is modeled using a uniform distribution in the range  $[0, 2\pi)$ . Cluster arrival times are modeled using a certain cluster arrival rate as in eq. 6 [24].

### C. The IEEE 802.11ad Channel Model

The IEEE802.11ad channel model is similar to that of the extended S-V model. However, in contrast to the 802.15.3c model, the delay, DOD and DOA for clusters are derived from empirical distributions for different types of first and second order clusters stemming from, e.g., ceiling and wall-ceiling interactions. The gain of the clusters are determined based on propagation and reflection losses, where the reflection losses are modeled using truncated log-normal distributions. The rays within each cluster are modeled using a central ray and a number of pre- and post-cursor rays. The pre- and post-cursor rays are modeled using different arrival times,  $\lambda_{pre}$  and  $\lambda_{post}$ , decay rates,  $\gamma_{pre}$  and  $\gamma_{post}$ , and average ray amplitudes. The pre- and post-cursor rays also have K-factors,  $K_{pre}$  and  $K_{post}$ , related to the amplitude of the main ray [6].

## V. CLUSTERING RESULTS

Cluster-based channel models rely on two sets of parameters, namely inter- and intra-cluster parameters, describing the clusters and the rays in each cluster, respectively. In this section, results regarding the estimated inter- and intra-cluster parameters are presented and related to the channel models discussed above.

### A. LOS component

In our model, the Tx-Rx distance is assumed to be known and is used as an input to the model. For the LOS scenarios, the power of the direct wave (the LOS component) is modeled deterministically based on the free space path loss. The delay of the LOS component is determined by the Tx-Rx separation. Furthermore, the location of the Tx and Rx arrays are assumed to be known, so that the DOD and DOA of the LOS component can be determined.

### B. Inter-cluster Parameters

The cluster peak power is taken as the strongest MPC in each cluster. In this paper, we estimate the cluster decay using the cluster power and delay in absolute units, making it possible to estimate the cluster decay without normalizing the clusters with respect to delay and power of the first cluster. This also allows the noise floor to be kept at a constant level for all the different measurements. This way, the effect of clusters that might be located below the noise floor, and might thus have been missed, can be taken into account by modeling the clusters using a truncated normal distribution. Then, the cluster decay constant  $\Gamma$  was estimated based on a likelihood expression for this truncated model [25]. The cluster peak power and the result of the truncated regression is shown in Fig. 4.

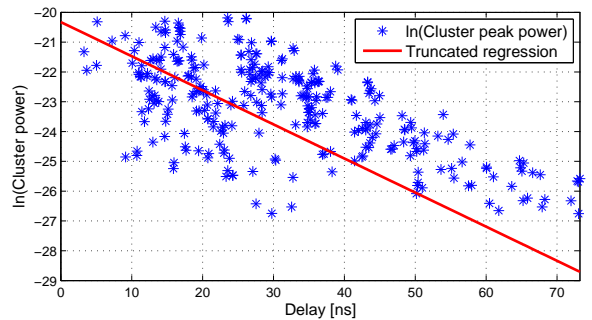


Fig. 4. Cluster peak power as a function of absolute delay and the estimated cluster decay based on a truncated model for the clusters.

As the LOS component already is being modeled deterministically, it was omitted when estimating the cluster decay for the LOS scenario. When estimating the decay constants for the LOS and OLOS scenarios separately, they were both estimated to be  $\Gamma = 8.7$  ns. Hence, the cluster decay can be modeled using the same value for both the LOS and OLOS scenarios. Fig. 4 shows the cluster peak power for the LOS and OLOS scenarios combined. The estimated data for the combined data also yielded a value of  $\Gamma = 8.7$  ns.

It was found that the cluster peak power variation around the mean could be appropriately modeled using a log-normal distribution, which corresponds to a normal distribution in the dB-domain. The estimated value for the standard deviation of this normal distribution was found to be the 6.4 dB in both the LOS and OLOS scenarios.

The cluster inter-arrival times can be described by an exponential distribution. Fig. 5 shows a CDF of the cluster inter-arrival times and an exponential distribution with an MLE of the parameter  $\Lambda$ . For both the LOS and OLOS scenarios, the estimated cluster arrival rate is  $1/\Lambda = 5$  ns.

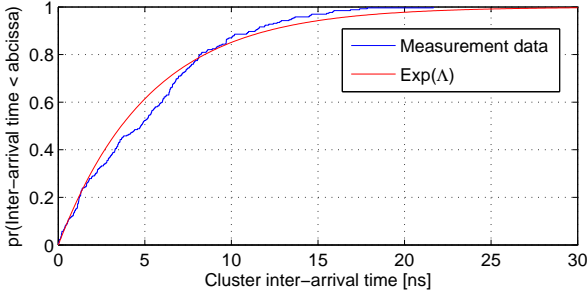


Fig. 5. CDF of the cluster inter-arrival times and an exponential distribution with a MLE of the parameter  $\Lambda$ .

### C. Modeling Cluster Angles and Delays

As shown in Fig. 6 and 7 below, it is not feasible to assume independence between the delay and angular properties of clusters. In the IEEE802.11ad model, this dependence is taken into account by modeling the cluster delays and angles deterministically, based on ray tracing results. In this paper, we consider two different ways of modeling the spatio-temporal properties of clusters; one being stochastic and one being deterministic (i.e. based on ray tracing). These two approaches both have their own strengths and weaknesses, depending on the intended use:

- Ray tracing is site-specific, which could be an advantage when assessing the performance at a specific site. However, when it comes to assessing the overall statistics of 60 GHz MIMO channels, it requires accurate ray tracing results for many different Tx- and Rx-positions, making it ineffective.
- Conversely, a stochastic model can not provide information about a specific room or site, but can effectively reproduce the stochastic properties of 60 GHz channels in a given type of environment.

From now on, these two models are referred to as the ray tracing model and the stochastic model and they are presented in detail below.

1) *Ray tracing model:* In the deterministic model, a ray tracing algorithm is used to determine the first and second order reflections, and the corresponding azimuth and elevation angles, as well as delays. In this paper, a simple three-dimensional image-based ray tracing algorithm is used, where the conference room is modeled as a parallelepiped with the same overall dimensions as the conference room and with

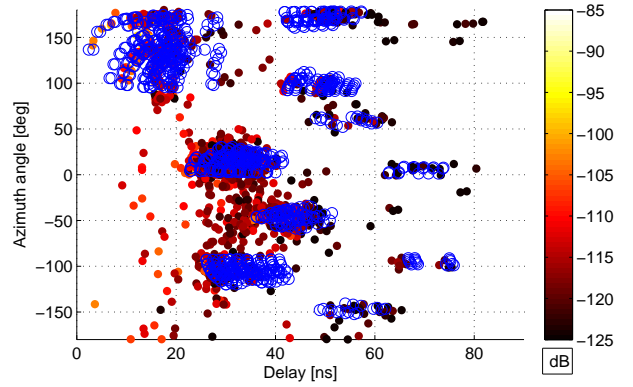


Fig. 6. Delay and azimuth angles of estimated multi-path components (dots) and ray-tracing results for first, second and third order reflections (circles).

tables as the only objects in the room. The conference room geometry is modeled in the same way in the IEEE802.11ad model [6] and has the advantage of being simple to use for modeling purposes. Fig. 6 compares the delay and azimuth angles of the estimated multi-path components with those of a ray-tracing simulations for all LOS scenarios. The elevation angles are not shown here for improved clarity. There is an overall agreement between the ray-tracing and measurement results, but at the same time, a large number of significant MPCs that have been estimated are *not* accurately captured by the ray tracing algorithm. The high resolution estimates of MPC delays and angles were matched with the furniture placement in the room such that it was confirmed that most of these MPCs were interacting with objects such as ceiling lamps, chairs and bookshelves, i.e. objects that are not included in the ray tracing model.

The results from the ray tracing algorithm can not be used directly with the parameters derived for the intra-cluster parameters, since the ray-tracing results are inconsistent with the cluster definition used in the clustering algorithm. When employing ray tracing, a number of possible reflections are identified, and all of these could be modeled as clusters. However, the intra-cluster parameters are all based on the results found using the clustering algorithm. In this algorithm, a cluster is defined as a group of MPCs that are close to each other in the spatio-temporal domain, whereas the clusters found using ray tracing are based on the physical interaction with the environment. As a result, the number of clusters found using ray tracing is significantly larger than those based on the clustering algorithm. Therefore, the multi-path component distance (MCD) metric [26] is used to group rays that are close to each other in the spatio-temporal domain. The MCD is calculated for a combination of two different reflections,  $i$  and  $j$ , as

$$\text{MCD}_{ij} = \sqrt{||\text{MCD}_{\text{DOD},ij}||^2 + ||\text{MCD}_{\text{DOA},ij}||^2 + \text{MCD}_{\tau,ij}^2}$$

where the delay distance is given by

$$\text{MCD}_{\tau,ij} = \xi \frac{|\tau_i - \tau_j|}{\Delta\tau_{\text{max}}} \frac{\tau_{\text{std}}}{\Delta\tau_{\text{max}}}. \quad (8)$$

Here,  $\Delta\tau_{max} = \max_{i,j} \{|\tau_i - \tau_j|\}$ , and  $\tau_{std}$  is the standard deviation of the delays. For our purposes,  $\xi = 3$  was found to be a suitable delay scaling factor. The MCD for angular data is given by  $MCD_{DOD/DOA,ij} = \frac{1}{2} |\mathbf{a}_i - \mathbf{a}_j|$ , where

$$\mathbf{a}_i = [\sin(\theta_i) \cos(\phi_i), \sin(\theta_i) \sin(\phi_i), \cos(\theta_i)]^T$$

Before calculating the MCD, all rays are sorted with respect to their delays. Then, the MCD between the ray with the shortest delay and all other rays are calculated, and all rays with a  $MCD < 0.25$  are grouped together with the ray with the shortest delay. Then, the same thing is done again for the remaining rays, until all rays have been assigned to a group. The cluster delays and angles are then determined as the delay and angles of the rays with the shortest delays in each group.

2) *Stochastic model*: In the stochastic model, the cluster angles are modeled using conditional probabilities. The cluster delays,  $T_k$ , are modeled based on exponentially distributed cluster inter-arrival times. Then, the cluster elevation angles,  $\Theta_k$  are determined using a joint pdf for the elevation angles conditioned on the cluster delay, i.e.,

$$f(T_k, \Theta_k) = f(\Theta_k|T_k)f(T_k), \quad (9)$$

where  $f(\Theta_k|T_k)$  is the conditional cluster elevation pdf and  $f(T_k)$  is the marginal pdf for the cluster delay. This conditional pdf is determined empirically by considering the possible elevation angles for first and second order reflections in a room with certain dimensions. The idea is that this conditional pdf should reflect upon the possible elevation angles for several different scenarios, with the Tx and Rx placed at different height. Here, we note that this paper only includes measured results for a single height of the Tx and Rx arrays. However, for the conditional pdf, we consider hypothetical scenarios where the Tx is located at a table at different heights,  $h_1$ , varying from 5-40 cm above the table, emulating a laptop or a similar device. The Rx is located at heights,  $h_2$ , varying from 5 cm above the table height up to 5 cm from the ceiling, thereby emulating a device such as a DVD-player, projector or internet access point.

Then, three different curves are used to put bounds on the possible elevation angles for the clusters. The first two curves, the upper and lower bounds, are determined by the maximum and minimum elevation angles for the second order reflections as a function of delay. The third bound, the shortest delay bound, is given by the curve for the shortest possible delay at a given elevation angle for a specific Tx-Rx separation, and is thus different for different scenarios. These three curves are shown in Fig. 7, together with the estimated Tx elevation angles of the MPCs as a function of delay.

Based on the measured data and ray tracing simulations, approximately 40% of the clusters are located within  $\pm 5^\circ$  of the horizontal plane. Therefore, we assign a 40% probability for the clusters to be located in the horizontal plane and a 60% probability of being located within the area bounded by the dashed curves in fig. 7. The clusters that are not assigned to the horizontal plane are randomly placed at a certain elevation angle using a uniform distribution over the supported elevation

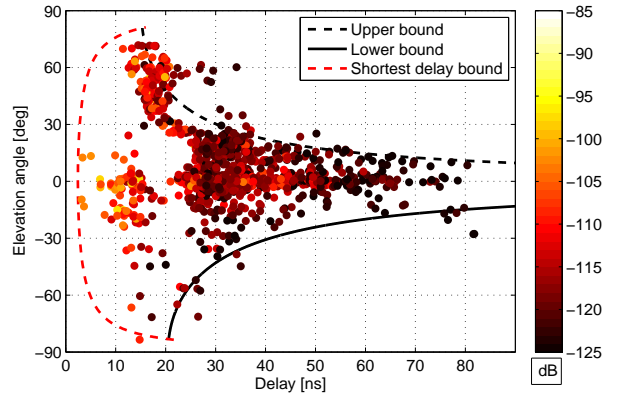


Fig. 7. Elevation-delay dependence model for the stochastic channel model.

angles for the given delay, i.e.,

$$f(\Theta_l|T_l) = \frac{1}{\Theta_{max}(T_l) - \Theta_{min}(T_l)}. \quad (10)$$

The values  $\Theta_{min}(T_l)$  and  $\Theta_{max}(T_l)$  are the smallest and largest possible elevation angles at a given delay, respectively. The azimuth cluster angles are, for simplicity, modeled using a uniform distribution over the interval  $[0, 2\pi)$ .

#### D. Intra-cluster Parameters

Our clustering results confirm that the clusters generally consist of a main peak surrounded by weaker components with longer *and* shorter delays. Hence, we adopt the same basic intra-cluster delay model as in [6], where each cluster consist of a number of pre- and post-cursor rays. The ray inter-arrival times were calculated by taking the delay of each pre- and post-cursor ray and subtracting it with the previous one, thereby creating a set of conditional arrival times.

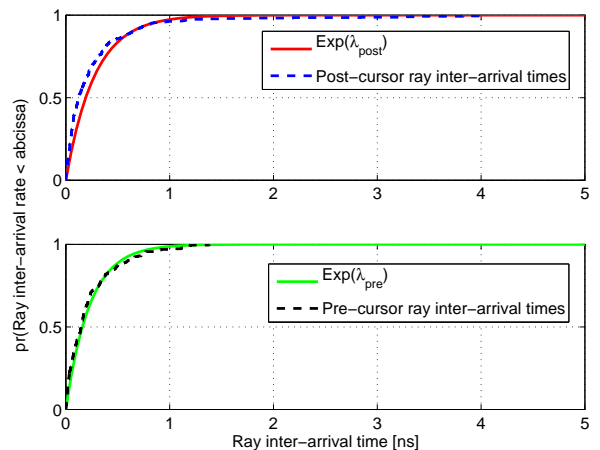


Fig. 8. CDF of the ray inter-arrival times for the pre- and post-cursor rays in the LOS scenario, and exponential distributions with MLEs of the parameters  $\lambda_{pre}$  and  $\lambda_{post}$ .

Fig. 8 shows CDFs for the ray inter-arrival times for the pre- and post-cursor rays in the LOS scenario and CDFs for

exponential distributions with MLEs of the rate parameters  $\lambda_{pre}$  and  $\lambda_{post}$ .

Next, the mean ray decay rates and K-factors for the pre- and post-cursor rays,  $\gamma_{pre}$ ,  $\gamma_{post}$ ,  $K_{pre}$  and  $K_{post}$ , were calculated by normalizing each ray with respect to the delay and mean amplitude of each associated cluster and performing a linear regression.

Then, the normalized path amplitude gain distribution of the pre- and post-cursor rays could be calculated by normalizing each ray with respect to the mean ray amplitudes at a certain delay. The power of the pre- and post-cursor rays are appropriately modeled using a log-normal distribution, or a normal distribution in the dB-domain. In Fig. 9, CDFs of the post-cursor ray power distributions for the LOS and OLOS scenarios are shown. The standard deviation of the normal distributions are very similar for both the pre- and post-cursor rays as well as for the LOS and OLOS scenarios, with values in the range of 5.6 to 7.1 dB. These values are similar to the standard deviation for the cluster peak power (i.e. the power of the main ray in each cluster), where the standard deviation is 6.4 dB.

The intra-cluster angles were calculated by taking the difference of the ray angles and the associated cluster centroid angles. Our results show that a good fit to the measured inter-cluster angles,  $\omega_{k,l}$ , is achieved by a zero-mean Laplace distribution with standard deviation  $\sigma$ , with probability density

function

$$p(\omega_{k,l}) = \frac{1}{\sqrt{2}\sigma} e^{-|\sqrt{2}\omega_{k,l}/\sigma|}. \quad (11)$$

Fig. 10 shows the CDF of the intra-cluster azimuth angles of arrival in the LOS scenario, and a Laplacian distribution. Similar curves were obtained for both the LOS and OLOS scenarios in both the azimuth and elevation domains. We also note that the intra-cluster angles for the azimuth and elevation domains showed very small correlation coefficients, indicating that they can be modeled independently. The estimated values of the variance  $\sigma$  for the azimuth intra-cluster angles for the DOD and DOA were 0.7 and 0.3 radians, respectively. This difference is most likely attributed to the difference in placement of the Tx and Rx arrays. The Rx array is located close to one of the corners of the room. For the elevation intra-cluster angles, the values of  $\sigma$  for DOD and DOA were estimated to be 0.2 and 0.3 radians, respectively.

## VI. CHANNEL MODEL COMPARISON

In this section, the extracted channel model parameters are compared with those of the IEEE802.11ad and IEEE802.15.3c channel models. Also, the number of clusters and number of rays inside each cluster is also discussed.

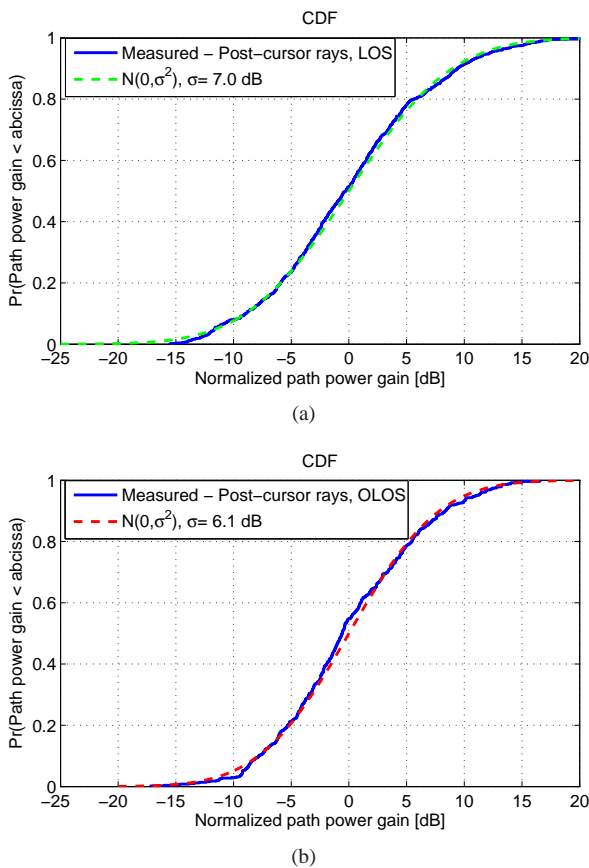


Fig. 9. CDFs of the normalized path power gains of the post-cursor rays and a normal distribution with a MLE of the variance  $\sigma^2$ , for the (a) LOS and (b) OLOS scenarios.

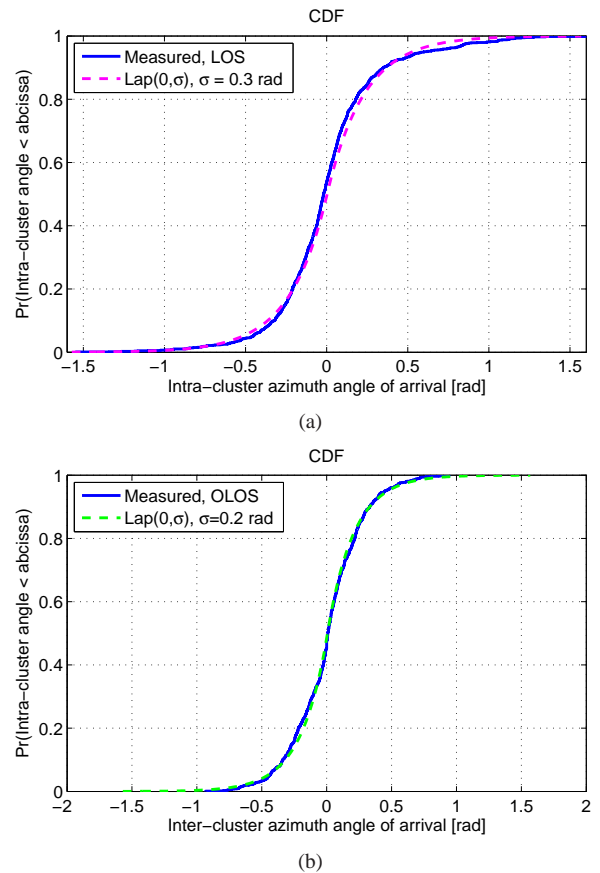


Fig. 10. CDFs of the intra-cluster azimuth angles of arrival and normal and Laplace distributions with MLEs for the standard deviation  $\sigma$ , for the (a) LOS and (b) OLOS scenarios.



### A. The IEEE 802.11ad Channel Model

In the IEEE802.11ad conference room channel model, the inter-cluster parameters are largely based on ray tracing results and empirical distributions [6]. For instance, the time and angle of arrival for clusters, as well as attenuation due to reflections, are all modeled using empirical distributions. Hence, it is not possible to compare the inter-cluster parameters of our proposed model with the IEEE802.11ad model.

However, our proposed model adopts the same basic intra-cluster model used in [6], making it possible to compare the two models. In Table I, the estimated intra-cluster time-domain parameters for the LOS and OLOS scenarios are presented and compared with the values from the IEEE802.11ad channel model for the conference room environment.

TABLE I  
INTRA-CLUSTER TIME-DOMAIN PARAMETERS; COMPARISON WITH THE IEEE802.11AD CONFERENCE ROOM MODEL

Parameter	Notation	LOS	OLOS	802.11ad
Ray decay time	$\gamma_{pre}$ [ns]	4.6	4.8	3.7
	$\gamma_{post}$ [ns]	4.7	4.5	4.5
Ray K-factor	$K_{pre}$ [dB]	8.6	10.3	10
	$K_{post}$ [dB]	9.0	11.0	14.2
Ray arrival rate	$\lambda_{pre}$ [1/ns]	0.90	1.1	0.37
	$\lambda_{post}$ [1/ns]	0.90	1.0	0.31

Our results show larger values for the ray arrival rates and somewhat larger ray decay times. These differences might be explained in part by differences in the measurement environment but also due to differences in how the data analysis is performed. Since the rays in our analysis are estimated using a high-resolution algorithm in a real furnished environment, a larger number of rays might be detected, resulting in a different ray arrival rate. The ray K-factors are however similar.

### B. The IEEE802.15.3c Channel Model

The 802.15.3c channel model uses a Laplacian or Gaussian distribution, with standard deviation  $\sigma_\phi$ , to model the intra-cluster azimuth angular distribution of the rays inside each cluster. The cluster and ray powers are modeled using lognormal distributions with standard deviations  $\sigma_c$  and  $\sigma_r$ , respectively. This is in agreement with the findings in this paper, and our proposed model also employs a Laplacian distribution for the intra-cluster angular distribution and log-normal distributions for the cluster and ray powers.

The IEEE802.15.3c channel model supports several different scenarios and channel model parameters have been presented for desktop, office, residential, kiosk and library scenarios [24]. Among these, the library scenario is most similar to the conference room scenario considered in this paper. In Table II, channel model parameters (both inter- and intra-cluster parameters) for the IEEE802.15.3c library LOS scenario are compared with the parameters of our model.

It can be observed that our results show smaller values for the ray arrival rate compared to the 15.3c model. On the other hand, our results for the ray arrival rate is also larger compared to that of the IEEE802.11ad model. Furthermore, our results

TABLE II  
INTER- AND INTRA-CLUSTER TIME-DOMAIN PARAMETERS; COMPARISON WITH THE IEEE802.15.3C LIBRARY MODEL

Parameter	Notation	LOS	OLOS	802.15.3c
Cluster arrival rate	$\Lambda$ [1/ns]	0.2	0.2	0.25
Ray arrival rate	$\lambda$ [1/ns]	0.9	1.0-1.1	4.0
Cluster decay rate	$\Gamma$ [ns]	8.7	8.7	12
Ray decay rate	$\gamma$ [ns]	4.6-4.7	4.5-4.8	7.0
Cluster log-normal st. d.	$\sigma_c$ [dB]	6.4	6.4	5.0
Ray log-normal st. d.	$\sigma_r$ [dB]	7.0-7.1	5.6-6.1	6.0
Ray DOD azimuth st. d.	$\sigma_\phi$ [deg]	40	23	10
Ray DOA azimuth st. d.	$\sigma_\phi$ [deg]	17.2	17.3	N/A
Ray DOD elevation st. d.	$\sigma_\theta$ [deg]	11.4	12.1	N/A
Ray DOA elevation st. d.	$\sigma_\theta$ [deg]	17.2	17.5	N/A

show larger values for the standard deviations of the intra-cluster angular Laplacian distribution, especially for the DOD in the LOS scenario. The reason for this could be related to differences in how the rays and clusters are identified.

### C. Number of clusters and rays

In our results, we observed 6-12 and 8-12 clusters in the LOS and OLOS scenarios, respectively, with an average of 10 clusters for both scenarios. The average number of clusters in the 15.3c model is 9, whereas the IEEE802.11ad model has a fixed value of 18 clusters. This difference is due to the fact that the clusters in the IEEE802.11ad model are identified using ray tracing, and several of those clusters would be grouped into one cluster when using a clustering algorithm.

The observed number of rays inside each cluster ranged from 1 up to 38 in one extreme case. The mean observed number of rays in each cluster was 7 for LOS and 9 for OLOS. It was found that the number of rays in each cluster could be modeled using an exponential distribution. However, we have found that due to the ray decay and the large K-factor for the rays, only the first 2-10 rays make a significant contribution to the overall statistics of the simulated channel. Hence, the number of rays in each cluster is set to a fixed number in our model; 6 pre-cursors and 8 post cursor rays for each cluster. The same values are used in the IEEE802.11ad model.

## VII. CHANNEL MODEL VALIDATION

In order to assess the performance of the developed channel model, it needs to be validated. In this section, in order to verify the performance of the model, the following metrics are used to compare the outputs from the channel models with the results from the measurements: the relative eigenvalues of the MIMO channel matrices, the RMS delay spread and the direction spread. A large number of MIMO channel matrices were generated using the ray tracing and stochastic models, using the same array geometry, antenna patterns and array positions as in the measurements. For each array position, frequency transfer functions,  $\mathbf{H}(f) \in \mathbb{C}^{N_t \times N_r}$ , were generated for the same  $49 \times 49$  MIMO configuration as in the measurement, using a bandwidth of 2 GHz in the frequency range of 61-63 GHz, with 1001 frequency points. This frequency

range was chosen since 60 GHz wireless systems typically use bandwidths as large as 2 GHz [2], [3]. Based on these results, we compare the statistical results from the model with the measurements for the three chosen metrics.

1) *Eigenvalues*: The relative eigenvalues were calculated for a large number of  $9 \times 9$  MIMO channel matrices. These  $9 \times 9$  channel matrices are formed using rectangular subarrays based on the larger  $49 \times 49$  channel matrices at each Tx/Rx array position. We define the  $n$ th relative eigenvalue to be

$$\lambda_{n,rel.} = \frac{\lambda_n}{\sum_{i=1}^I \lambda_i}. \quad (12)$$

The relative eigenvalues are normalized with respect to the sum of all eigenvalues, which means each relative eigenvalue can be interpreted as a fraction of the total instantaneous channel power. Fig. 11 shows CDFs of the four strongest eigenvalues for the stochastic and ray tracing models as well as the measurements, for both the LOS and OLOS scenarios, using all Tx array positions. Both the stochastic and ray tracing models agree well with the measurement data, with a slightly better agreement for the stochastic model.

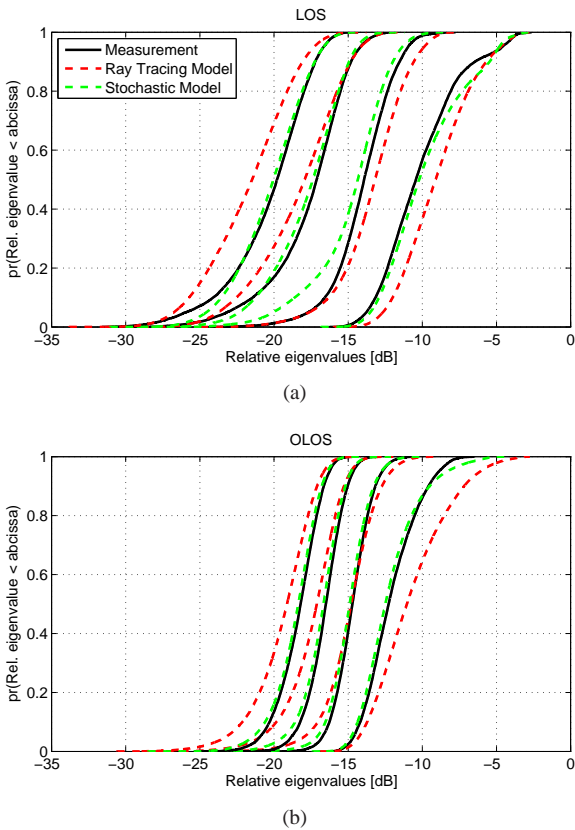


Fig. 11. CDFs of the four strongest relative eigenvalues for the measurement data and for a large number of realizations using the ray tracing and stochastic models in the LOS (a) and OLOS (b) scenarios.

2) *RMS Delay Spread*: The RMS delay spread (RMS DS) was calculated based on the power-delay profiles (PDPs) from the measurements and for the realized PDPs generated by the two models. The PDPs are calculated based on the channel impulse responses (CIRs). Each CIR,  $h(\tau)$ , is derived by applying a Hann window to  $\mathbf{H}(f)$  in order to suppress side

lobes, and then taking the inverse Fourier transform. The PDP,  $P_h(\tau)$  is then obtained as

$$P_h(\tau) = \frac{1}{N_t N_r} \sum_{n_t=1}^{N_t} \sum_{n_r=1}^{N_r} |h(\mathbf{s}_{n_r}, \mathbf{s}_{n_t}, \tau)|^2, \quad (13)$$

where  $\mathbf{s}_{n_t}$  and  $\mathbf{s}_{n_r}$  denote the spatial position relative to the array origin for the  $n_t$ th Tx and  $n_r$ th Rx antenna, respectively.

The RMS DS is often calculated by only including values in the PDP that are within a certain range from the peak value. In this paper, we apply a 30 dB dynamic range when calculating the RMS DS. The RMS DS is then calculated as

$$S_\tau = \sqrt{\frac{\sum_{\tau} P_h(\tau) \tau^2}{\sum_{\tau} P_h(\tau)} - \left( \frac{\sum_{\tau} P_h(\tau) \tau}{\sum_{\tau} P_h(\tau)} \right)^2}. \quad (14)$$

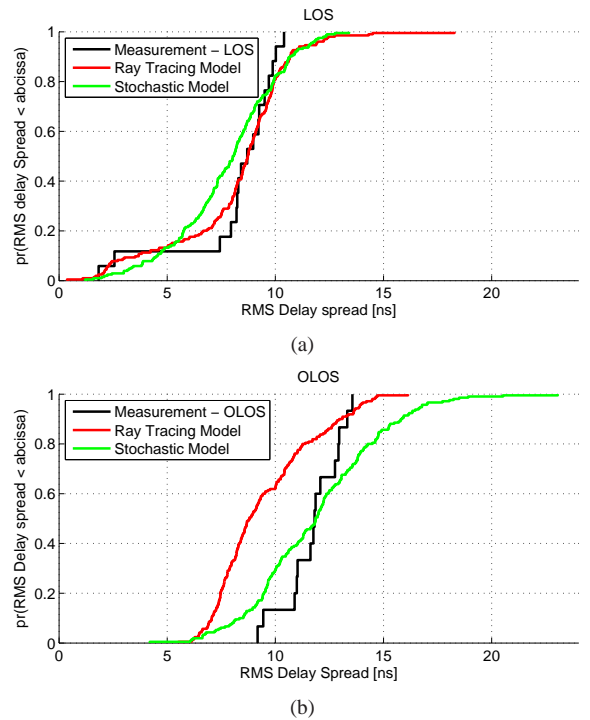


Fig. 12. CDFs of the RMS delay spreads for the measurement data and for a number of realizations using the ray tracing and stochastic models, for the LOS (a) and OLOS (b) scenarios.

Fig. 12 shows CDFs of the calculated RMS DS for the LOS and OLOS scenarios. It can be noted that both models agree well with the measured RMS DS for the LOS scenario, as seen in Fig. 12 (a). For the RMS DS in the OLOS scenarios seen in Fig. 12 (b), the ray tracing model seems to underestimate the RMS DS. The reason for this is not known, but might be related to the fact the ray tracing model does not model all the details present in the room and also always places clusters at the same delays and angles for a given Tx-Rx setup.

The stochastic model on the other hand, has a median value that agrees well with the measured values in the OLOS scenario, but exhibits a much larger variation compared to the measured results. Given that only 15 measured values of the

RMS DS is available for this comparison, it is difficult to tell whether this variation is reasonable or not. Based on reported values of the RMS DS in the literature for similar scenarios [27], we argue that the values of the RMS DS modeled by the stochastic modeled is reasonable.

3) *Direction Spread*: Lastly, the direction spread was chosen as a metric to evaluate and compare the statistical angular properties of the models and the measurements. For this comparison, the MPC estimates from SAGE for the measurements are used in the evaluation. The direction spread,  $\sigma_\Omega$ , is calculated for each scenario, using  $L$  MPCs, as [28]

$$\sigma_\Omega = \sqrt{\sum_{l=1}^L |e(\phi_l, \theta_l) - \mu_\Omega|^2 P(\phi_l, \theta_l)}, \quad (15)$$

where  $P(\phi_l, \theta_l)$  is the normalized power spectrum, whereas  $\phi_l$  and  $\theta_l$  denote the azimuth and polar angles of the  $l$ th MPC, respectively. The mean direction,  $\mu_\Omega$ , and the unit vector for the direction of the  $l$ th MPC,  $e(\phi_l, \theta_l)$ , are each given by

$$\mu_\Omega = \sum_{l=1}^L e(\phi_l, \theta_l) P(\phi_l, \theta_l), \quad (16)$$

$$e(\phi_l, \theta_l) = [\cos(\phi_l) \sin(\theta_l), \sin(\phi_l) \sin(\theta_l), \cos(\theta_l)]^T.$$

Fig. 13 shows CDFs of the direction spread at the Tx side for the models and measurements. The stochastic model tends to agree quite well with the measurement results, whereas the ray tracing model tend to underestimate the direction spread, especially for LOS scenarios. This is likely explained by the fact that an oversimplified geometry was used in the ray tracing model. In the measurements, there are several strong reflections from objects in the environment such as ceiling lamps and bookshelves [18], and these effects are not taken into account if the room is modeled as rectangular box with tables as the only objects in the ray tracing routine. This shows that it is of importance to include finer details in the environment when using a ray tracing-based approach. As a result, this makes it even more challenging to develop a simple ray tracing-based model that effectively models the statistical behavior of 60 GHz radio channels.

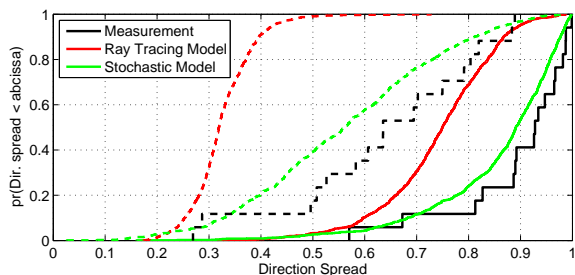


Fig. 13. CDFs of the Tx direction spread in the LOS (dashed curves) and OLOS scenarios (solid curves).

## VIII. CONCLUSIONS

In this paper, we have presented measurement-based results for a 60 GHz double-directional MIMO channel model. The measurements were performed in a conference room using a VNA-based measurement system with  $7 \times 7$  planar virtual arrays at both the Tx and Rx sides. The measurements included results from 17 LOS and 15 OLOS scenarios. A large number of MPCs were estimated using the SAGE algorithm and then clustered using the K-power-means algorithm. As the antenna patterns were de-embedded in the SAGE algorithm, the proposed channel model supports different antenna types and array geometries.

The intra-cluster properties describing the rays in each cluster are modeled stochastically. Estimated parameters for the ray decay time, K-factor and arrival rate have been presented. It has also been shown that the intra-cluster angles are appropriately modeled using a zero-mean Laplacian distribution and that the ray power distribution around the mean can be modeled using a log-normal distribution. Furthermore, we have shown that the angular characteristics of the MPCs and clusters exhibit a clear delay dependence related to overall geometry of the room as well as the objects in the room. Our proposed channel model includes two novel methods of modeling the cluster angular and delay properties; one semi-deterministic model using ray tracing and one stochastic model using joint angular-delay pdfs. Both of these models have been validated against the measurement data using three different metrics; the relative eigenvalues, the RMS delay spread and the direction spread. Both models agree reasonably well with the measured data. We have also provided a detailed comparison of the channel model parameters with those of the IEEE802.11ad and 802.15.3c channel models.

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