Clustering in 3D MIMO Channel: Measurement-based Results and Improvements

Pan Tang, Jianhua Zhang, Yanliang Sun, Ming Zeng, Zhenzi Liu, Yawei Yu
Key Laboratory of Universal Wireless Communications, Ministry of Education, China
Beijing University of Posts and Telecommunications, Mailbox NO.92, 100876
Email: tangpan27@bupt.edu.cn

***Abstract*—In this paper, we perform 3-Dimensional (3D) clustering based on the Outdoor-to-Indoor (O2I) wideband 3D multiple-input-multiple-output (MIMO) channel measurement at 3.5 GHz. Clusters are identified by KPowerMeans algorithm. Based on analysis on clustering results, we modified the definition of Multiple component distance (MCD) to split the bounding of azimuth and elevation, which can obtain larger number of clusters and the clusters are more intra-compact and inter-separated. Then, Calinski-Harabasz (CH) and Davies-Bouldin (DB) indices are used to further validate the proposed MCD. Finally, intra cluster and inter cluster statistics are both provided, which provides insights in 3D MIMO channel modeling.**

I. Introduction

Recently, the mobile traffic has remarkably increased. To balance the conflict between exploring data traffic and limited available bandwidth, ways like spatial multiplexing are adopted to improve spectrum efficiency. Meanwhile, to further exploit the potential of spatial multiplexing, the next step will be accounting for the 3 dimensional (3D) real world. [1] provides a state of the art review on 3D fading channel models, emphasizing research related to the elevation angle. It also reports some recent field measurements for 3D multiple-input-multiple-output (MIMO) and investigates the comprehensive propagation characteristics of the elevation angle. Besides, [2] discusses fundamentals and key technical issues in developing and realizing 3D MIMO technology for next generation mobile communications.

In 3D MIMO channels, a cluster is defined as a group of multipath components (MPCs) with similar parameters, e.g. azimuth angle of arrival (AoA), azimuth angle of departure (AoD), elevation angle of departure (EoD), elevation angle of arrival (EoA), and delay. The characteristics of clusters can reflect propagation mechanism of the channel more accurately. In addition, a global azimuth spread is not able to capture the detailed structure of direction dispersion in the radio propagation that is crucial for a number of MIMO transmission techniques, e.g. [3]. Furthermore, according to [4], capacity of unclustered models will be overestimated if the paths of the channel are truly clustered. Clustering can also help the antenna system to assign the power appropriately [5].

In the prior literatures, approach of clustering evolved from visual inspection of measurement data into automatic algorithm [6]. In MIMO channels, to identify clusters, many studies used the framework consisting of three parts - KPowerMeans algorithm, cluster validation and cluster shape pruning, e.g. [7], [8]. The task of KPowerMeans algorithm is to find the possible clustering results, then cluster validation indices help to point out the best result. To obtain consistent results, cluster pruning algorithm will be used in the last step. Specially, in KPowerMeans algorithm, the distance between MPCs was defined by the multipath component distance (MCD) [9]. Though 3D MIMO technology has been proposed for several years, traditional framerwork above is still utilized in 3D MIMO channel and does not have a big change.

In this paper, all the clustering results are based on the measurement on the Outdoor-to-Indoor (O2I) wideband 3D MIMO channels at 3.5 GHz. Clusters are identified by the aforementioned framework and statistical analysis of clusters in this scenario are also presented in this paper to provide concrete parameters about cluster propagation. But directly applying KPowerMeans algorithm in 3D channel will lead to several problems: No clustering performance can be exactly ideal and the number of clusters decreases comparing with the results in 2D channels. Based on a lot of simulation experiments, we propose a novel MCD and it consists of five parts– AoA, EoA, AoD, EoD and delay - rather than three parts - delay, arrival and departure. The proposed MCD separates the elevations from azimuths, which makes elevations and azimuths more contributive during clustering. Owing to this adjustment, better clustering results can be seen by the validity indices, Calinski-Harabasz (CH) and Davies-Bouldin (DB) [7]. Radical visualization is also adopted to display clustering results.

The rest of this paper is organized as follows. Section II shows measurement facilities and environment. Cluster identification and proposed MCD are described in Section III. Section IV shows a comparison of clustering results between traditional MCD and proposed MCD. Section V shows the statistical analysis of clusters. Finally, section VI concludes this paper.

II. MEASUREMENT FACILITIES AND SCENARIO

A. Measurement Facilities

In this measurement, we utilized the Elektrobit Propsound Sounder based on TDM-MIMO model, which estimates channel information using antenna arrays. Table I shows the basic sounder parameters. As shown in Fig. 1, to capture the basic parameters of the radio channel, we adopted a uniform patch array (UPA) with 32 elements at the transmitting side (TX).

(a) UPA (b) ODA

Fig. 1. Antenna arrays.

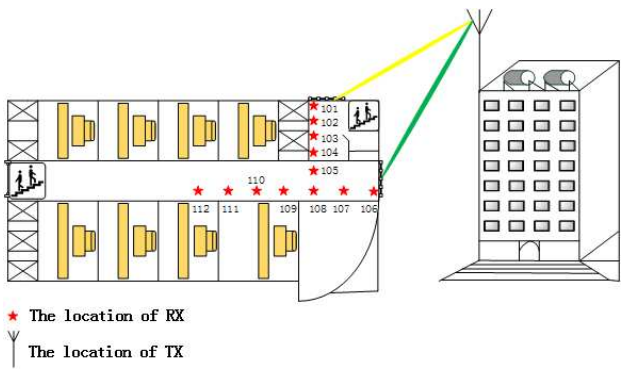

Fig. 2. Measurement spot and the relative location information between TX and RX.

Meanwhile, at the receiving side (RX), we employed an omnidirectional antenna (ODA) with 56 elements. Table II shows the basic parameters of antennas.

TABLE I
SOUNDER PARAMETERS

Parameters	Values
Carrier frequency [GHz]	3.5
Bandwidth [MHz]	50
Transmit power [dBm]	37
Chip frequency [MHz]	127
Code length [ns]	40
Cycle duration [ms]	9.28
Channel sampling rate [Hz]	26.983

TABLE II
ANTENNA PARAMETERS

	UPA	ODA
Number	32	56
Polarization	dual	dual
Space	0.5 wavelength	0.5 wavelength
Azimuth	$-70° \sim 70°$	$-180° \sim 180°$
Elevation	$-70° \sim 70°$	$-55° \sim 90°$

B. Measurement Scenario

The measurement was conducted on the campus of the Beijing University of Posts and Telecommunications (BUPT), China. As shown in Fig. 2, this was a typical O2I scenario and TX was fixed on the roof of a comparatively higher building while RX was placed on different spots across 7 floors of a lower teaching building, whose walls covered with plasterboard on the surface are made of bricks and doors are made of wood rather than glass . For each floor, about 9 receiver spots were measured with the RX antenna fixed on a trolley whose height was about 1.8 m. For the sake of calculation, the height of the TX was set to be zero. Consequently, the relative height of the RX was negative, which is shown in Table III.

TABLE III
HEIGHT DIFFERENCE BETWEEN RX AND TX.

Floor	1	2	3	4	5	6	7
Height difference(m)	-54.8	-52.4	-46.4	-40	-33.4	-29.6	-25

III. CLUSTER IDENTIFICATION AND THE PROPOSED MCD

In this paper, we adopt KpowerMeans algorithm with a novel intial step [8] to identify clusters. Besides, all measurement results are extracted from space-alternating generalized expectation maximization (SAGE) algorithm [10]. The KPowerMeans algorithm is showed as follow.

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1. Get K initial centroid positions $c_1^{(0)}, ..., c_K^{(0)}$ with the method proposed in [8].

2. For $i = 1$ To $Iteration_{max}$
a. Assign MPCs according to cluster centroid and store the indices.
$I_l^{(i)} = \arg\min_k \{P_l \cdot MCD(x_l, c_k^{(i-1)})\}$
$I^{(i)} = [I_1^{(i)}, ..., I_L^{(i)}], IC_k^{(i)} = Indice(I_l^{(i)} = k)$
b. Recalculate cluster centroid $c_k^{(i)} = \frac{\Sigma_{m \in IC_k^{(i)}} (P_l \cdot x_l)}{\Sigma_{m \in IC_k^{(i)}} P_l}$
c. If $c_k^{(i)} = c_k^{(i-1)}$ for all $k = 1...K$, then go to 3th step, else next i.

3. Return $R_K = [I^{(i)}, c_k^{(i)}]$

In this algorithm, a range $[K_{min}, K_{max}]$ is set at first. P_l means the power of the lth subpath and x_l means its basic parameters including AoA, AoD, EoD, EoA and delay. L means the number of all subpaths. For each possible K, the algorithm will find the best cluster centroid and allocation plan. The key of this algorithm is the MCD, which is the distance measure for different paths, because it is the principle to determine which MPCs are similar and belong to the same cluster. The parameters used to calculate MCD are $X = [x_1, x_2, ..., x_L]$ and x_l is described in the form of $[\tau, \theta_{AoA}, \theta_{AoD}, \varphi_{EoD}, \varphi_{EoA}]$.

A. Traditional MCD

Since MCD was adopted in clustering algorithm, it has been in use without any change. Equation 1-3 show the traditional MCD.

For delay distance, the definition is given as

$$MCD_{\tau,ij} = \eta \cdot \frac{|\tau_i - \tau_j|}{\Delta\tau} \cdot \frac{\tau_{sd}}{\Delta\tau} \quad (1)$$

In this equation, η is a scaling factor to adjust the weight of delay in the distance function. $\Delta\tau$ means the range of delay and $\Delta\tau = \max_{i,j} |\tau_i - \tau_j|$. τ_{sd} is the standard deviation of delay.

For angle distance, the definition is given as

$$MCD_{T/R,ij} = \frac{1}{2} \left| \begin{pmatrix} \sin(\theta_i)\cos(\varphi_i) \\ \sin(\theta_i)\sin(\varphi_i) \\ \cos(\theta_i) \end{pmatrix} - \begin{pmatrix} \sin(\theta_j)\cos(\varphi_j) \\ \sin(\theta_j)\sin(\varphi_j) \\ \cos(\theta_j) \end{pmatrix} \right| \quad (2)$$

For TX or RX, the angle distance is obtained in the spherical coordinate system. θ means the elevation angle and φ means the azimuth angle.

The total distance is given by

$$MCD_{ij} = \sqrt{\|MCD_{T,ij}\|^2 + \|MCD_{R,ij}\|^2 + \|MCD_{\tau,ij}\|^2} \quad (3)$$

We can see from above equations that MCD consists of three parts, angle of arrival, angle of departure, delay. Besides, in each side, azimuths and elevations are integrated together.

B. Proposed MCD

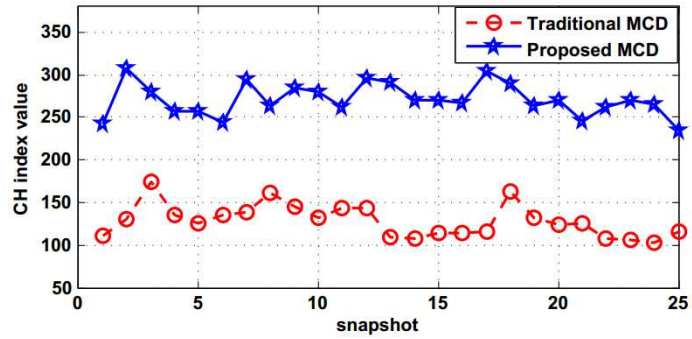
In this part, we propose a novel MCD with five parts, delay, AoA, AoD, EoD and EoA corresponding to the X. Equation 4-5 describe this MCD and $MCD_{\tau,ij}$ is defined as the same as equation 1.

$$MCD_{AOA/AOD/EOD/EOA,ij} = \frac{|\theta_i - \theta_j|}{\Delta\theta} \cdot \frac{\theta_{sd}}{\Delta\theta} \quad (4)$$

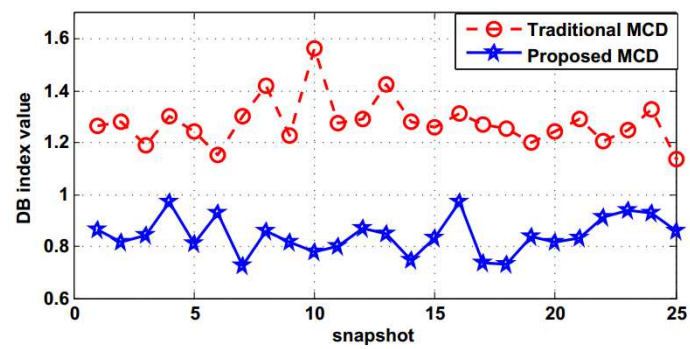
$\Delta\theta$ means the range of angles in each dimension and θ_{sd} is the standard deviation of angles. Comparing with the traditional MCD, the proposed MCD is completely defined in cartesian coordinate system, rather than spherical coordinates and it becomes easier to adjust the weight of each dimension. During our clustering, we make each dimension has the same weight. As shown in equation 5, the proposed MCD separates the elevations from azimuths and makes all five parts independent during clustering. Besides, it also makes it possible to visualize the clustering results, which is introduced in Section IV.

IV. COMPARISON OF CLUSTERING RESULTS

In order to validate the novel MCD, we compare the clustering results with traditional MCD and this proposed MCD based on the measurement data from section II. CH and DB indices are also utilized in this step. CH is the ratio between the traces of between cluster matrix and within scatter matrix and higher values indicate more separate clusters. DB index is a function of intra-cluster compactness and inter-cluster separation and lower values stand for more closely among the paths in cluster. Thus higher CH and lower DB index values mean more intra-compact and inter-separate clusters [8]. To get more reliable results, we also adopt visual inspection to validate the MCD.



(a) CH index values



(b) DB index values

Fig. 3. Validating index.

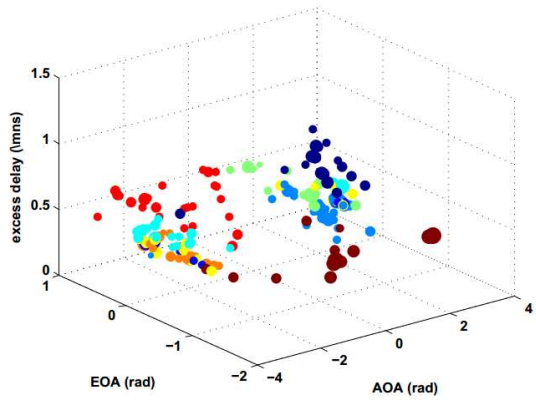
A. Comparing clustering results using CH and DB Indices

As shown in Fig. 3, the dotted line presents the results with traditional MCD while the solid line describes the results with proposed MCD. Fig. 3(a) shows that the dotted line is much lower than the solid line. On the contrary Fig. 3(b) shows the dotted line is much higher than the solid line. Hence, it is obvious that the clustering results with proposed MCD have lower DB indices and higher CH indices. Consequently, the proposed MCD can obtain better intra-compact and inter-separated clusters.

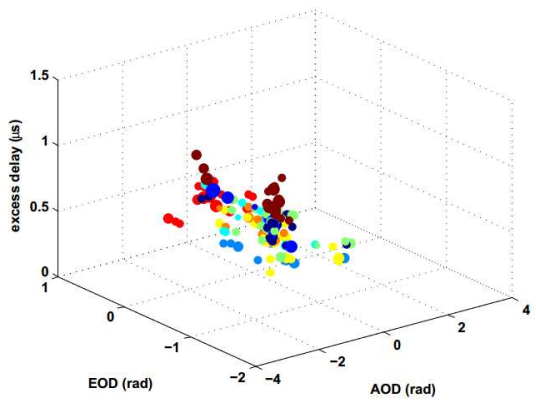
B. Comparing clustering results using visual inspect

As mentioned in Section III, proposed MCD makes all five parts independently. Hence, the five parts can be separately mapped into another plane for visualizing. Fig. 4 shows the clustering results without visualization. Because each path, x_l, has five dimensions, the clustering results have to be described in two 3D figures. The results looks like scattered and not compact. Hence, it can not help to validate the proposed MCD. After utilizing the RadVizs [11], visual inspection can be used to solve this problem because it can make these results displayed correctly in a 3D figure. The theory of the RadVizs is to utilize Hooke's law from the physics to map the parameters x_l into a plane presented by $U = [u_1, u_2]$, which is shown by Fig. 5. To solve the problem of overlapping between different

$$MCD_{ij} = \sqrt{\|MCD_{AOA,ij}\|^2 + \|MCD_{AOD,ij}\|^2 + \|MCD_{EOD,ij}\|^2 + \|MCD_{EOA,ij}\|^2 + \|MCD_{\tau,ij}\|^2} \quad (5)$$



(a) RX



(b) TX

Fig. 4. Clustering results without visualization. There are 10 clusters with different colors and the dot size represents the power of MPC. The clustering performance of RX is shown in (a) while (b) shows the clustering performance of TX.

MPCs, the distance of x_l from the coordinate origin as the vertical domain u_3. Finally, all the parameters x_l is mapped to $U = [u_1, u_2, u_3]$ in 3D space. Fig. 6(a) and Fig. 6(b) present the clustering results with the traditional MCD and the proposed MCD, respectively. In the cycle a of Fig. 6(b), there are 3 more clusters and in the cycle b, the cluster is better intra-compact compared with Fig. 6(a). Apparently, the clustering results with proposed MCD is better.

In conclusion, regardless of using CH and DB indexes or using visual inspection, they both demonstrate that the proposed MCD get better clustering performance in 3D MIMO channel. Specially, it can get more clusters and the clusters are more intra-compact and inter-separated.

V. STATISTICAL ANALYSIS OF CLUSTERS

Based on the novel MCD, we get intra-cluster parameters, including DS, ASA, ASD, ESA and ESD, and inter-cluster parameters of cluster number and path number distribution in the O2I MIMO measurement campaign.

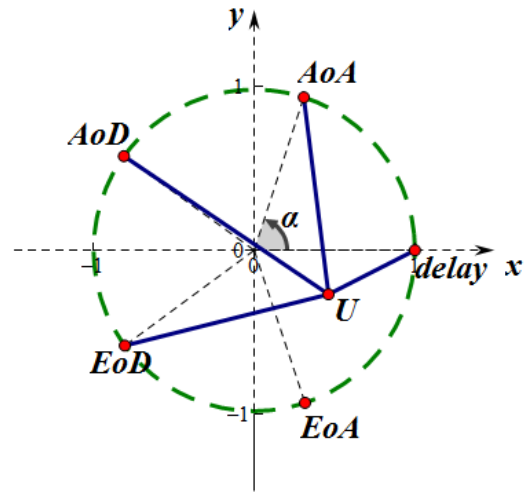
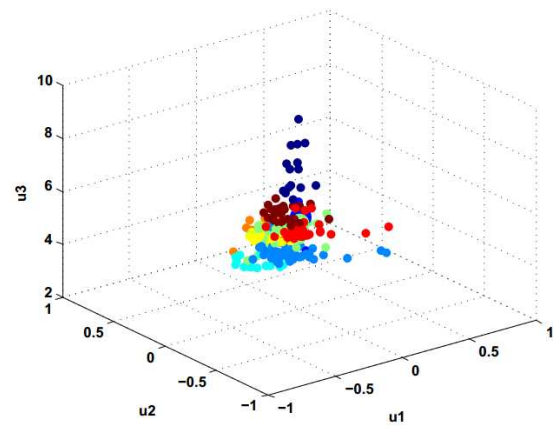
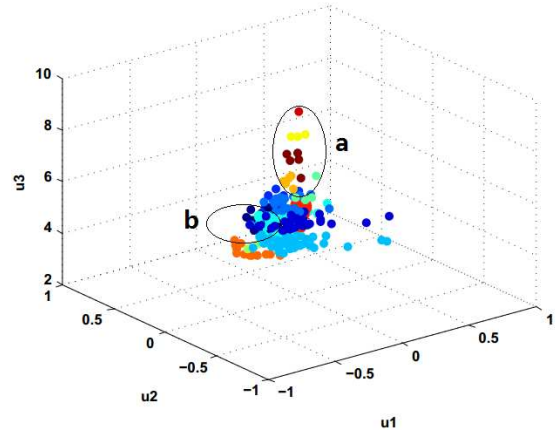


Fig. 5. Definition of the mapping.

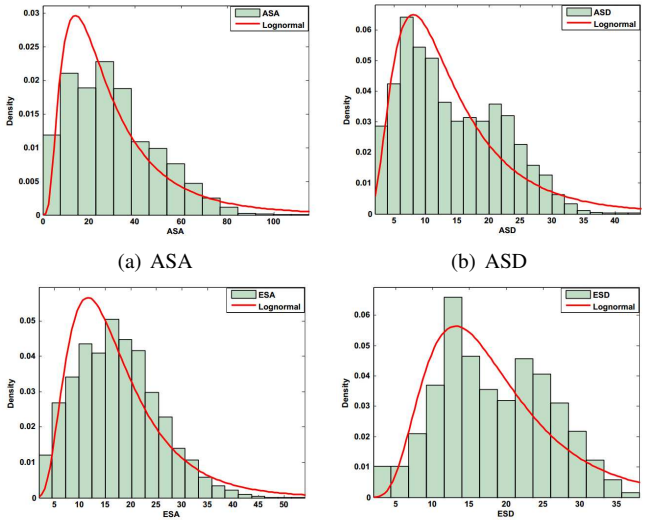


(a) Clustering results with traditional MCD.



(b) Clustering results with proposed MCD.

Fig. 6. Visualization of clustering results.



(a) ASA (b) ASD

(c) ESA (d) ESD

Fig. 7. Lognormal distribution of intra-cluster parameters spread within a cluster.

A. Delay Spread

In kth cluster, σ_k is calculated by equation 7

$$\mu_{\tau,k} = (\sum_{l=1}^{L_k} \tau_l \cdot P_l)/(\sum_{l=1}^{L_k} P_l) \tag{6}$$

$$\sigma_{\tau,k} = \sqrt{(\sum_{l=1}^{L_k} (\tau_l - \mu_{\tau,k})^2 \cdot P_l)/(\sum_{l=1}^{L_k} P_l)} \tag{7}$$

$\mu_{\tau,k}$ is the mean delay of the kth cluster. τ_l and P_l are respectively the delay and normalized power of the lth path. The L_k means the number of paths in the kth cluster.

B. Angular Spread

AS of kth cluster can be calculated by the same way referred above.

$$\mu_{\theta,k} = (\sum_{l=1}^{L_k} \theta_l \cdot P_l)/(\sum_{l=1}^{L_k} P_l) \tag{8}$$

$$\sigma_{AS,k} = \sqrt{(\sum_{l=1}^{L_k} (\theta_l - \mu_{\theta,k})^2 \cdot P_l)/(\sum_{l=1}^{L_k} P_l)} \tag{9}$$

To get ASA, ASD, ESA and ESD, just change the θ_l with the corresponding angle. Besides, to solve angular ambiguity, we use the method proposed in [12].

For intra-cluster parameters, DS ASA, ASD, ESA, ESD are fitted by Lognormal distribution with mean values 7.29 ns, $14.99°, 11.61°, 12.46°, 12.69°$ respectively. That is shown in Fig. 7 and Fig. 8.

Fig. 9 presents the distribution of cluster number, which is modeled by Normal distribution with the mean value of 13. Fig. 10 shows the distribution of the path number and its mean value is 12.64.

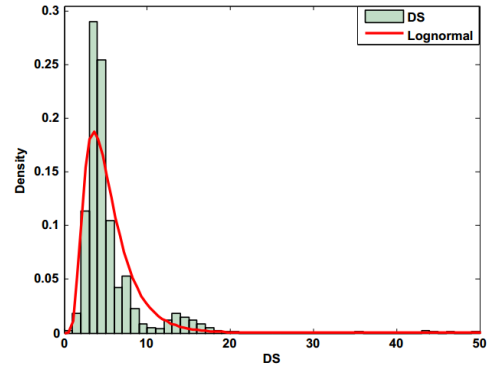


Fig. 8. Distribution of delay spread within a cluster

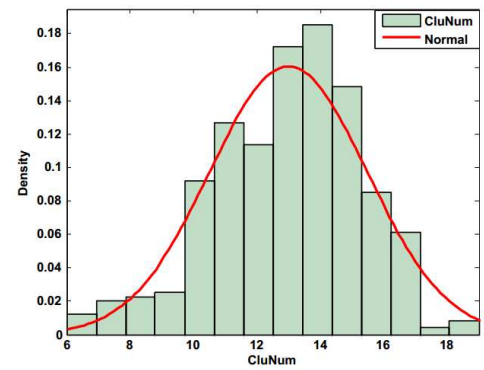


Fig. 9. Normal distribution of the cluster number.

VI. CONCLUSION

In this paper, intra cluster and inter cluster parameters are presented based on the O2I wideband 3D MIMO channel measurement at 3.5 GHz. Clusters are identified with KPower-Means algorithm. Specially, to make KPowerMeans algorithm work better in 3D MIMO channels, we propose a novel MCD, which significantly improves the clustering performance with more intra-compact and inter-separated clusters. The proposed MCD, distance function, is redefined as five parts, delay, AoA, AoD, EoD and EoA. Hence, elevation angle is separated from azimuth angle as an independent part, which makes elevations and azimuths more contributive during clustering. Besides,

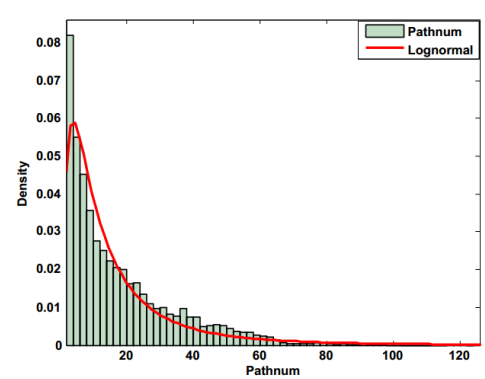


Fig. 10. Lognormal distribution of the path number within one cluster.

we perform a comparison of the clustering results between traditional MCD and proposed MCD with two methods and they both demonstrate proposed MCD is better than traditional MCD. Then, the intra cluster parameters DS, ASA, ASD, ESA and ESD are obtained and they are all fitted well by Lognormal distribution. The inter cluster parameters of path number and cluster number distribution are also put forward. Specially, Lognormal fits well the path number in one cluster, while Normal fits well the cluster number distribution. Mean values are 7.29 ns, $14.99°, 11.61°, 12.46°, 12.69°$, 13, 12.69 for DS ASA, ASD, ESA, ESD, cluster number, path number within cluster respectively. These results will be very useful for 3D MIMO channel modeling.

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