Hybrid Massive MIMO Channel Model Based on Edge Detection of Interacting Objects and Cluster Concept

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1. INTRODUCTION

In the fifth generation (5G) of wireless communication systems, significant improvement in energy and spectrum efficiency, as well as reliability, is considered in compare to the previous generation [1]. Millimeter wave technology is an innovation that allows benefiting from large bandwidths and very high data rates. However, this technology imposes the constraints of high attenuation and blockage to the system design. To achieve projected theoretically specifications, massive MIMO is regarded as a cornerstone and the most promising technology for meeting 5G wireless communication systems [2]. A large number of antenna elements in massive MIMO systems yield to increase the channel capacity, spatial resolution, energy, and spectral efficiency as well as linkage reliability [3, 4]. Massive MIMO systems also provide superior channel orthogonality and more channel stability than conventional MIMO systems [5]. Another essential objective behind the use of massive MIMO in 5G is to scan the overall pattern of the antenna for interference reduction and long distance communication [2]. Three dimensional (3D) channel modeling has an important role in accurate designing and a better understanding of the wireless communication systems [4, 6]. Also, massive MIMO benefits severely on accurate channel estimation. The parametric channel model is a way to regularize the channel estimation, which exploits the fact that a signal arrives at the receiver via a limited number of MPCs [7, 8]. The channel model should consider several emerging features of massive MIMO such as spherical waveform and appearance and disappearance of MPCs on both time and array axis. As the dimension of the antenna array becomes large, different kinds of non-stationary properties appear across the array and different array elements may observe different receiving paths [9, 10]. Likewise, the channel components such as Rx and IOs may have relative motion, the Doppler effect should be considered in the calculations. Furthermore, a comprehensive model should consider channel characteristics in the 3D space. Due to the complexity of many propagation environments, the simplicity and applicability of the

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channel model are very important. In recent years, the development of a comprehensive model that can take into account various aspects of the massive MIMO channel has attracted much interest from the researchers.

1. 1. Related Massive MIMO Channel Model
Many efforts have been prepared for MIMO channel modeling. Some examples of these models include European Cooperation in Science and Technology [11], Wireless World Initiative New Radio (WINNER) + [12], WINNER II [13], 3D Spatial Channel Model (SCM) [14], and IMT-A models. However, such models cannot be extended to the massive MIMO systems, because most of these models consider plane wave condition in their calculations. Also, the birth-death property of the clusters cannot be observed on the array axis of MIMO system, while this phenomenon may exist in the many massive MIMO systems. Recently, several channel models have been presented for massive MIMO systems, each of which incorporates some of the features of the corresponding channel.

Several channel models for massive MIMO technology are 3D twin cluster model [15], 3D 5G channel model [16], 3D ellipsoid model [17], and 2D KBSM-BD-AA [18], have been compared and evaluated by Bai et al. [19] The visibility region method with the birth-death process is utilized to model the non-stationary property of clusters in the massive MIMO channel [20]. This model assumes spherical wavefront to capture the characteristics of AoA shifts and Doppler frequency variations because of the near-field effects. We have also presented a channel model based on the cluster concept discussed by Tamaddondar and Noori [21].

Some other channel models are presented based on the channel measurements. Measurement results at 2.6 GHz by Gao et al. [22] show that some antennas in massive MIMO systems contribute more than the others, while in i.i.d. Rayleigh channels, all antennas have equal contributions. Hence, the CIR of the channel may vary significantly over the antenna array in massive MIMO systems. Some other measurement-based channel model with their overall output results are listed in Table 1.

1. 2. Our Contributions
To the best of the authors’ knowledge, a comprehensive and standardized channel model for massive MIMO systems is still missing in the literatures. This paper aims to cover the specifications of the massive MIMO channels and derives a hybrid channel model. This hybrid model includes two deterministic and stochastic modes. The deterministic mode uses numerical techniques for solving Maxwell’s equations by taking into account the geometry of the environment. Due to the complexity of the channel, those parts of the channel that cannot be model in the deterministic mode are considered in the stochastic mode. The edge detection technique is utilized to find scattering of MPCs. The major contributions and novelties of this paper can be summarized as follows:

1) A novel 3D hybrid channel model for massive MIMO systems is presented in this paper based on the edge detection of the IOs and cluster concepts. The central limit theorem (CLT) is utilized to simulate arrived signal to the receiver.

2) The near-field effect caused by the massive number of the antennas is considered in the proposed channel model.

3) The Doppler effect is considered in this channel model due to the relative motion of different channel components such as transmitter, receiver and IOs.

4) Appearance and disappearance of the clusters due to the huge number of antenna in the massive MIMO systems are evaluated to observe the non-stationary property of the channel on the array axis.
The rest of the paper is organized as follows. Section II gives a general description of the proposed 3D hybrid channel model for massive MIMO systems. Theoretical mathematic relations are given in section III. Some simulation results are depicted in section IV. Conclusions are finally drawn in section V.

2. PROCESS OF CHANNEL MODELING

Different aspects of the channel can be extracted in the channel modeling. Here, we try to propose a novel channel model for a standard massive MIMO system with $M$ antenna element at the base station (BS) which serves $N$ mobile station (MS). The propagation channel usually produces MPCs that arrive with different time delays to the users. By finding these MPCs, the CIR of the channel can be calculated. However, theoretical methods may face a huge amount of computations due to the complexity of the channel. To overcome this challenge, a novel hybrid method including both deterministic and stochastic modes is utilized to model the channel. In the deterministic mode, the line of sight (LoS) and reflection components are calculated. The equivalent planes are defined and used instead of smooth surfaces of the environment such as walls, ramps, and the ground. Then, the image theory is applied to these planes to find if any reflection path exists. The LoS or reflection paths may cross other surfaces. In such cases, the transmission coefficients are also considered in the calculations. Figure 1 shows the propagation mechanism in the deterministic mode.

The mechanism of buildings simulation is shown in Figure 2. For buildings modeling, 3D coordinates of the building’s front plane quadrangle are defined clockwise. Then, by extruding the front surface along the vector of extrusion, three other surfaces of the building are completed. Finally, the ceiling and floor of the building are defined. If the ground effect is considered, then definition of the floor is neglected. Some parts of the channel that are too complex to be modeled in the deterministic mode are considered in the stochastic mode. Different kinds of propagation phenomena such as reflection, diffraction, and scattering occur at the edge of the IOs. These IOs are modeled with their equivalent structural geometry in the simulator as shown in Figure 3. Here, edge detection technique is utilized to distinguish the border of the IOs. Then, new MPCs are assigned to the edge of the IOs. We assume that the rays arriving at the MS follow the clustering behavior. Thus, the environment around the MS is divided into range cells (RCs). The edges of the IOs with the corresponding RCs are considered as active RCs. The MPCs may reach the MS from these active RCs. The mechanism of MPCs generation in the stochastic mode with the edge detection algorithm is shown in Figure 4. The number of MPCs in such RCs is modeled with Poisson random distribution. The MPCs may cross the other RCs which are filled with other part of IOs. The pathloss of these IOs are considered in the calculations. Different components of the channel such as BS, MS, and IOs may have relative velocity. This causes frequency shifts due to the Doppler effect. This effect is considered in both deterministic and stochastic modes.
Finally, both derived deterministic and stochastic CIRs are integrated. Then the channel characteristics such as total CIR, delay spread, AoA, and ToA are extracted.

The flowchart in Figure 5 shows the presented channel modeling algorithm. As can be seen in Figure 5, several blocks are considered for channel modeling. In general, the initial parameters such as operating frequency, antenna radiation pattern, location of the BS and MS antennas, and the number of the antenna array elements with their configurations, as well as velocity vector should be defined at the first step. In the deterministic part, the equivalent surfaces are defined and in the stochastic part, the edges of the objects are drawn and the propagation environment is clustered.

At any time instance, all time-variant variables are updated. All MPCs are found by applying ray tracing in the deterministic mode and the idea of detecting the edges of IOs in the stochastic mode. Then both deterministic and stochastic calculations are integrated. If the update time is finished, the required results will be extracted from the simulations.

Generally, deterministic channel models require geometrical information of the propagation environment, while, stochastic channel models are based on the channel statistics. In this paper, a hybrid channel model is proposed which includes two deterministic and stochastic modes. Such a channel model can be applied to a wide range of practical propagation channels. If the process of channel modeling is completely implemented in both deterministic and stochastic modes, the computational algorithm is shown in Figure 5 will extract different characteristics of a real channel. However, the deterministic mode needs geometrical information of the channel like other deterministic models.

3. MATHEMATICAL DESCRIPTION OF THE CHANNEL MODEL

The mathematical description of the channel is required for theoretical channel modeling. When an impulse is sent from a BS antenna element to the propagation environment, different MPCs may be produced and received at the MS. These MPCs pass through different propagation paths with different delay times. Regarding Figure 6, the time-variant CIR between the nth antenna at the BS and the nth user is dependent on time and delay axes.

Since the channel modeling mechanism is divided into two separate modes, the CIR can be expressed in terms of two separate channel response of deterministic and stochastic modes as follows:

\[ h_{m,n}(t, \tau) = h_{m,n}^d(t, \tau) + h_{m,n}^s(t, \tau) \]  

(1)
where \( h_{m,n}^d \) and \( h_{m,n}^s \) are the multipath CIRs of the deterministic and stochastic modes, respectively. Here, the LoS and reflection components are calculated in the deterministic mode. Reflections up to second-order are considered in calculations. Thus the impulse response in the deterministic mode, \( h_{m,n}^d \), can be rewritten as a combination of LoS and other reflection components:

\[
h_{m,n}^d(t, \tau) = \sum_{i=1}^{N_i} \sum_{l=1}^{l_{c,i}} \alpha_{l,i}^d \exp(-j \beta_{l,i}^d) \delta(t-t_l) \delta(\tau-\tau_l)
\]

where \( i = \{1, 2, \ldots, T\} \) is the total number of time instances, \( \tau = [\tau_{i,1}, \tau_{i,2}, \ldots, \tau_{i,N_i}] \) is the delay series of the \( i \)th time instance. The number of MPCs in \( i \)th time instance is \( N_i \). The propagation constant is \( \beta \) and the length of the \( l \)th MPC in \( i \)th time instance in the deterministic mode is denoted by \( l_{c,i} \). The operator \( \delta(\cdot) \) is the delta Dirac function. The amplitude of the MPCs in the deterministic mode is equal to:

\[
\alpha_{l,i} = \frac{\lambda L_{c,i}^d}{4 \pi r_{l,i}^d}
\]

where \( L_{c,i}^d \) is the attenuation factor related to the LoS or the first or second order reflection components and is defined by:

\[
L_{c,i}^d = \begin{cases} 1 & \text{Line of sight} \\ I_{l,i}^{(1)} & \text{Reflection of the first order} \\ I_{l,i}^{(2)} & \text{Reflection of the second order} \end{cases}
\]

The attenuation factors of \( i \)th time instance and \( l \)th MPC for the first and second order reflections are denoted by \( I_{l,i}^{(1)} \) and \( I_{l,i}^{(2)} \), respectively.

As mentioned before, due to the complexity of many objects, they cannot be modeled in the deterministic mode. The stochastic mode is utilized here to overcome this problem. Here, we use this fact that different propagation phenomena such as reflection, diffraction and scattering typically occur at the boundaries of the medium discontinuities. Thus, an edge detection algorithm is proposed to diagnose the boundaries of the IOs. Accordingly, the boundaries and inner areas of the IOs are meshed separately for detecting boundaries and inner area of the IOs. The MPCs are attributed to the outer boundaries of the IOs. Simultaneously, as the propagation of MPCs has clustering behavior, the clustering technique is applied in the MS side to categorize the MPCs. Some characteristics of these MPCs are extracted by using random distributions. With such explanations, the CIR in the stochastic mode can be defined in the following form:

\[
h_{m,n}^s(t, \tau) = \sum_{i=1}^{C} \sum_{l=1}^{l_{c,i}} \alpha_{l,i}^s \exp(-j \phi_{l,i}^s) \times \delta(t-t_l) \delta(\tau-\tau_l)
\]

where \( c = \{1, 2, \ldots, C\} \) is the number of clusters, \( \alpha_{l,i}^s \) and \( \phi_{l,i}^s \) are the amplitude and phase shift of \( l \)th MPCs in the stochastic mode at the \( i \)th time instance in the \( c \)th cluster, respectively. The amplitude can be given by:

\[
\alpha_{l,i}^s = \frac{\lambda D_{l,i}^s}{4 \pi r_{l,i}^s}
\]

The diffraction or scattering coefficient in the stochastic mode is denoted by \( D_{l,i}^s \) and \( r_{l,i}^s \) is the path length of the \( l \)th MPC at the \( i \)th time instance in the \( c \)th cluster. The phase shift of each MPC is obtained from a uniform distribution between \([0, 2\pi)\). Also, Poisson distribution is used to compute the number of MPCs of the \( c \)th cluster, \( L_{c}^s \). Regarding the density of the propagation environment (sparse, medium or dense environments), and based on the various simulations such as what has been presented in [21], the proper average number of MPCs has been obtained between zero and five. In other words, as the diffraction parts of an IO are increased, the average number of MPCs used in Poisson distribution is also increased and vice versa.

The MPCs that arrive to the MS in each delay bin are summed with each other. It means that:

\[
h_{m,n}(t, \tau_k) = \sum_{p=1}^{K} h_{m,n}(t, \tau_p)
\]

\[
\tau_k = k \Delta \tau, \quad k = 0, 1, 2, \ldots, K
\]

where \( K \) is total number of successive delay bins and \( \Delta \tau \) is the number of MPCs in the \( k \)th delay bin. The width of each delay bin is \( \Delta \tau \). Both slow and fast fading are obtained during the channel simulations since the amplitude and phase of all received MPCs are calculated.

The average power delay profile (APDP) is generally used to calculate delay spread and remove impacts of the noise in time-invariant channel. It can be obtained from the PDF samples of the \( i \)th time instance which is defined as follows:

\[
APDP_{m,n}(\tau_i) = \frac{1}{N_{\text{cyc}}} \sum_{i=1}^{N_{\text{cyc}}} PDP_{m,n}(\tau_i)
\]
where $N_{\text{cycle}}$ is the number of PDP samples between the $m$th antenna of the BS and the $n$th user and $t_i$ is the $i$th time instance. It should be emphasized that Equation (7) is considered for such a channel that is stationary on time axis. For time-variant channels, the samples should be taken in the duration of coherence time. Then, the root mean square (RMS) delay spread can be calculated using APDP as follows:

$$
\tau_{\text{rms}} = \frac{\sum_q \text{APDP}(\tau_q) \tau_q^2}{\sum_q \text{APDP}(\tau_q)} \left( \frac{\sum_q \text{APDP}(\tau_q) r_q^2}{\sum_q \text{APDP}(\tau_q)} \right) \quad (9)
$$

The AoA is another useful parameter which shows the angle of MPCs arrived to the MS. This parameter is used in the clustering of MPCs. The AoAs in elevation and azimuth planes are shown by $\theta_{\text{AoA}}$ and $\varphi_{\text{AoA}}$, respectively and defined as:

$$
\theta_{\text{AoA}} = \cos^{-1} \left( \frac{a_z \cdot \text{IR}}{||\text{IR}||} \right) \quad (10)
$$

$$
\varphi_{\text{AoA}} = \cos^{-1} \left( \frac{a_z \cdot \text{IR}}{||\text{IR}||} \right) \quad (11)
$$

where, the vector point from the IO to the MS is $\text{IR}$ and $a_x$ and $a_z$ are the unit vectors on the $x$ and $z$ axes, respectively. Both AoA and time delay are used to separate arrival rays of different clusters. In fact, rays with similar AoAs and delays make one cluster. The MPCs are categorized by considering their time delay and AoAs using the K-mean algorithm. The paths of some MPCs go through clusters which are filled with IOs. Thus, the phase shifts and the pathloss due to these clusters are also added to total calculations.

### 3.1. Antenna

The channel response depends on the antenna characteristics such as radiation pattern and gain. Since in massive MIMO systems, the radiation pattern can be affected by adjacent antenna elements, the radiation pattern of the antenna element in the array is imported into the calculations. As the near-field effect may influence on the response of the channel, the radiation pattern of the antenna is calculated in the required distance from the antenna element. Therefore, the CIR in both deterministic and stochastic modes can be rewritten as follows:

$$
\begin{align*}
R_m^h(t, \tau) &= \sum_{i=1}^{N} \alpha_{i,j}^h \exp(-j\beta_{i,j}^h) \\
F_m^h(R_{tx,j}^h, \theta_{tx,j}^h, \phi_{tx,j}^h) \cdot F_n^h(R_{rx,n}^h, \theta_{rx,n}^h, \phi_{rx,n}^h) \times \delta(\tau - t_i) \\
R_m^h(t, \tau) &= \sum_{i=1}^{C} \sum_{c=1}^{I} \alpha_{i,c,j}^h \exp(-j\phi_{i,c,j}^h) \\
F_m^h(R_{tx,c,j}^h, \theta_{tx,c,j}^h, \phi_{tx,c,j}^h) \cdot F_n^h(R_{rx,c,j}^h, \theta_{rx,c,j}^h, \phi_{rx,c,j}^h) \times \delta(\tau - t_i)
\end{align*}
$$

where $F_{tx}^h$ and $F_{rx}^h$ are the radiation pattern of the $m$th antenna element at the BS and the $n$th MS, respectively. The observation distances from BS and MS in spherical coordinates are $(r_{tx,c,j}^h, \theta_{tx,c,j}^h, \phi_{tx,c,j}^h)$ and $(r_{rx,c,j}^h, \theta_{rx,c,j}^h, \phi_{rx,c,j}^h)$, respectively.

### 3.1. Doppler Effect

Since the channel components typically have relative velocity, there is a Doppler effect in the channel. Accordingly, the Doppler frequency is calculated and considered in the CIR. Regarding Figure 7, the Doppler frequency can be expressed as follows:

$$
\begin{align*}
\hat{f}_D &= f_{\text{obs}} \left( 1 + \frac{v_{tx} \cos \theta_{tx,tx}}{c_0} \right) \left( 1 + \frac{v_{io} \cos \theta_{io,io}}{c_0} \right) \\
\hat{f}_D &= f_{\text{obs}} \left( 1 + \frac{v_{tx} \cos \theta_{tx,tx}}{c_0} \right) \left( 1 + \frac{v_{rx} \cos \theta_{rx,rx}}{c_0} \right)
\end{align*}
$$

where $f_c$ is the carrier frequency and $c_0$ is the velocity of the transmitted signal. The $v_{tx}$, $v_{io}$ and $v_{rx}$ are the velocity vectors of the Tx, IO and Rx, respectively. The angles $\theta_{tx,tx}$, $\theta_{io,io}$, $\theta_{tx,rx}$ and $\theta_{rx,io}$ are shown in Figure 7.

The locations of the BS and MS with their corresponding velocity vectors as well as the location and velocity vector of IOs are imported into the simulator. The simulator computes the required angles.
for the Doppler frequency calculation based on the departure and arrival angles of each observation point. This information is used to implement in Equations (14) and (15) to model and calculate Doppler effect of each path.

4. SIMULATION AND RESULTS

In this section, simulations are carried out to extract channel characteristics. An outdoor propagation environment is defined to implement the proposed channel model. This channel includes several buildings, ground effect, car parking and garages. These obstacles are defined in our simulations based on the procedure of deterministic and stochastic modes presented in previous sections. Accordingly, the buildings and ground are modeled with their equivalent surfaces. However, the other parts of the channel including garages and car parking are modeled by stochastic mode as IOs with their edge boundaries (as depicted in Figure 3). The geometrical schematic of this channel is shown in Figure 8. The buildings and the ground as well as three IOs are depicted in this figure. The ray tracing algorithm is utilized to find all paths between the BS and MS which is shown in Figure 8. The LoS, as well as the first and second order reflection components is calculated in the deterministic mode. The edge detection algorithm is used to distinguish the MPCs in the stochastic mode.

At first, the received power at the MS is obtained versus the distances between transmitter and receiver where BS and MS antennas have omni-directional radiation pattern. The obtained results of the proposed channel model are compared with those obtained by classic ray tracing method. This comparison is shown in Figure 9. In the ray tracing model, only the LoS and reflections are considered in the calculations, while in the proposed model, in addition to the deterministic mode components, the cluster behavior of the channel is also included in the calculations. Thus, the proposed model considers more details of the channel in comparison with the ray tracing model.

Then, the simulations are done for a massive MIMO system including a 256-element antenna at the BS. The number of 256 elements represents a massive MIMO system, in which we want to show the non-stationary property of the channel along the array. The antenna element is placed in a linear configuration with half of the wavelength distance between successive elements. The frequency of simulation is set to 28 GHz since this frequency is a candidate for realizing millimeter-wave massive MIMO systems. All parameters of the considered system are listed in Table 2.

![Figure 8. The propagation environment in the simulator](image)

![Figure 9. Received power versus the distance between the first antenna at BS and MS](image)

| TABLE 2. Preliminary Definitions in the simulations |
|-----------------------------------------------|
| **Carrier Frequency** : 28 GHz |
| **BS Antenna:** | 256–Open-Ended Element, Linear Array, Vertical Polarization, Directive Pattern |
| **MS Antenna:** | Single Dipole, Vertical Polarization, Omnidirectional Pattern |
| **Transmit Power** : 1W |
| **BS Center Position:** | [120, 120, 18] |
| **MS Position** : | [13, -130, 1.5] |
| **MS Velocity Vector** : | $\left(\frac{17\sqrt{2}}{2}, \frac{17\sqrt{2}}{2}, 0\right)$ |
| **Building Characteristics** : $\varepsilon_r = 4.1, \mu_r = 1, \sigma = 0.001$ |
| **IO Characteristics** : $\varepsilon_r = 1, \mu_r = 1, \sigma = 1.45e6$ |

*The coordinates of the points are in meter.*
The PDP with respect to the delay of the MPCs are depicted in Figure 10. This PDP can be considered as the CIR of the first antenna element at the BS and the MS. Different kinds of MPCs are separated in the simulation as shown in Figure 10. These MPCs include LoS, reflections of the first-order from one wall, reflection of the second-order from two walls, and single bounce components due to diffraction or scattering from IOs. Hence, these different MPCs are originated from different paths and propagation phenomena. The LoS component has the highest strength among all MPCs, while the MPCs from IOs have lower strengths in overall look of Figure 10. The threshold level is considered to be -160 dBm in the simulations. The AoAs in both elevation and azimuth planes are derived in the simulations. Thus, the PAP between the first BS antenna element and the MS with respect to the AoAs is shown in Figure 11. The cluster behavior of the MPCs can be viewed in both Figures 10 and 11. Since the distance between the array elements at the BS is low at 28 GHz, the sub-arrays in the massive MIMO system almost experience a stationary channel. However, the non-stationary property between these sub-arrays is significant.

Figure 10 shows the non-stationary property of the channel along the array axis for 256-element antenna at the BS. The main reason of this phenomenon is that due to the huge number of the antenna elements and large size of the array against operating frequency wavelength, different channels are experienced along the massive MIMO array by distinct elements.

Here, the Doppler effect is considered in the simulations. As mentioned in Table 2, the MS has a relative velocity which causes a Doppler shift. The Doppler shift of the frequency for each MPC is shown in Figure 13. This shows that the Doppler shift of the frequency is about 3 kHz in this scenario.
5. SUMMARY AND CONCLUSION

In this paper, we have proposed a novel channel model for massive MIMO systems. This hybrid channel model includes deterministic and stochastic modes. The smooth surfaces are defined in the deterministic mode. Then the ray tracing algorithm is utilized to find the LoS component along with the first and second order reflections. Other parts of the channel are defined in the stochastic mode. In this mode, the edge detection algorithm is used to find the boundaries of the IOs. This is because of the fact that different propagation phenomenon such as reflection, diffraction and scattering often occurred at the boundaries of the objects. Thus the MPCs are assigned to the outer edges of the IOs. The relative motion of the channel components cause Doppler shifts in the frequency. This Doppler effect is considered in this channel model to have a better overview of the received signals at the MS. Finally, the MPCs from both deterministic and stochastic modes are integrated to extract the desired characteristics of the channel such as CIR, delay spread, AoAs and Doppler shifts. The non-stationary property of the massive MIMO channel is observed in the simulation. This channel model can be considered as a time-variant channel model due to the capability of updating all channel specifications such as antenna positions and velocity vectors of the BS and MS in each snapshot.

6. REFERENCES

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