A Non-Stationary 3D Wideband Twin-Cluster Model for 5G Massive MIMO Channels

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Abstract—This paper proposes a novel theoretical non-stationary three dimensional (3D) wideband twin-cluster channel model for massive multiple-input multiple-output (MIMO) communication systems with carrier frequencies in the order of gigahertz (GHz). As the dimension of antenna arrays cannot be ignored for massive MIMO, nearfield effects instead of farfield effects are considered in the proposed model. These include the spherical wavefront assumption and a birth-death process to model non-stationary properties of clusters such as cluster appearance and disappearance on both the array and time axes. Their impacts on massive MIMO channels are investigated via statistical properties including correlation functions, condition number, and angular power spectrum. Additionally, the impact of elevation angles on correlation functions is discussed. A corresponding simulation model for the theoretical model is also proposed. Last, numerical analysis shows that the proposed channel models are able to serve as a design framework for massive MIMO channel modeling.

Index Terms—Massive MIMO, 3D twin-cluster channel model, spherical wavefront, non-stationarity, birth-death process.

I. INTRODUCTION

MULTIPLE-input multiple-output (MIMO) technologies are of great importance in modern wireless communication systems as they are able to substantially increase spectral efficiency [1]–[3]. Recently, massive MIMO systems [4]–[6], which are equipped with tens or even hundreds of antennas, emerge as an enhanced MIMO technique to meet the increasing traffic demand of the fifth generation (5G) wireless communication networks [7],[8]. It was stated in [4]–[6] that massive MIMO systems have a number of additional benefits as compared with conventional MIMO systems which only have a small number of antenna elements. First, energy efficiency can be significantly increased by massive MIMO systems as they concentrate power on a sharp direction. Second, system throughput can be boosted by utilizing multi-user MIMO (MU-MIMO). Interference between users is averaged out by introducing a massive number of antennas according to the large number theorem. Third, implementation cost can be reduced by including simplification of medium-access control layer and deploying low-cost antenna elements due to great MU-MIMO and beamforming gain. Lastly, massive MIMO systems are more robust than conventional MIMO systems as they offer excessive degrees of freedom. As a result, massive MIMO is expected as an essential candidate technology for 5G wireless communication networks.

For the sake of MIMO system design and performance evaluation, it is indispensable to develop accurate and efficient small-scale fading MIMO channel models. For conventional MIMO systems, there are many small-scale fading channel models reported in the literature. Regular shape geometry-based stochastic models (GBSMs) such as one-ring, two-ring, and ellipse models can be found in [9]–[16], where the authors assumed that scatterers are distributed on regular shapes. Thus, channel impulse responses of these channel models were purely determined by the geometrical relationships between the scatterer and receiver (transmitter). Standardized GBSMs such as the spatial channel model (SCM) [17], the WINNER II model [18], and the international mobile telecommunications-advanced (IMT-Advanced) model [19] focus on the geometry of the first and the last bounces of scatterers. In addition, correlation-based stochastic models (CBSMs) [20]–[23], such as the Kronecker model and Weichselberger model, are usually utilized to study the performance of MIMO systems due to their low complexity.

However, the above mentioned conventional MIMO channel models are not suitable to be directly applied to modeling massive MIMO channels. Measurements on massive MIMO channels in [24] and [25] indicated that there are two characteristics making massive MIMO channels different from conventional MIMO channels. First, since the number of antennas is huge in massive MIMO systems, the farfield assumption in conventional MIMO channels may no longer be appropriate. The distance between the receiver and transmitter (or a cluster) may not be beyond the Rayleigh distance defined by $\frac{2 \pi}{\lambda}$.
[26], where \( L \) and \( \lambda \) are the dimension of the antenna array and carrier wavelength, respectively. For uniform linear arrays (ULAs) with a fixed antenna separation \( \Delta \) (e.g., \( \Delta = \lambda / 2 \)), the dimension \( L = (M - 1) \Delta \) is linearly increasing with the number of antenna elements \( M \). Therefore, the wavefront should be assumed as spherical instead of plane when the number of antennas is large. Although the impact of spherical wavefront on short-range or constant distance communications was studied in [27] and [28], its impact on massive MIMO channels has not yet been reported in the literature. Second, non-stationary properties can be observed on large antenna arrays [24], i.e., appearance and disappearance of clusters can occur on the array axis. This leads to the fact that each antenna element on the array may observe different sets of clusters, which is not characterized in conventional MIMO channels. As a result, the wide-sense stationary (WSS) assumption on antenna arrays does not necessarily hold for massive MIMO channels. The authors in [29]–[32] modeled cluster evolution on the time axis with birth-death processes or Markov processes. However, to the best of our knowledge, non-stationary properties of clusters on the array axis have not been studied for massive MIMO channels in the literature.

Additionally, it was reported in [33] that scatterers would disperse in elevation (or the vertical plane) and the impact of elevation angles needs to be addressed in realistic channel models. Therefore, three dimensional (3D) channel models should be developed for massive MIMO systems. Extensive conventional 3D MIMO models can be found in the literature such as the twin-cluster MIMO model [34], the COST 2100 model [35], [36], 3D extension of the WINNER model [37], 3D double-directional radio model [38], and 3D MIMO vehicle-to-vehicle channel model [39]. In this paper, we will extend the twin-cluster MIMO model in [34], where a cluster is divided into two representations of itself (one at the transmitter and the other at the receiver), by incorporating the spherical wavefront assumption, cluster evolution on the time and array axes, and 3D cluster properties to capture massive MIMO channel characteristics.

The contributions of this paper are summarized as follows:

1) This paper first proposes a theoretical non-stationary 3D wideband twin-cluster channel model for massive MIMO systems with carrier frequencies in the order of gigahertz (GHz), i.e., they are not applicable to millimeter wave communication systems. To the best of the authors’ knowledge, this is the first 3D model for massive MIMO channels. An infinite number of scatterers is assumed in the proposed theoretical model (or reference model), which cannot be implemented in hardware or for simulation purposes. Therefore, we also propose a corresponding 3D simulation model with finite numbers of scatterers. Various statistical properties, such as the spatial-temporal correlation function, Doppler power spectral density (PSD), and condition number, are studied for both the theoretical and simulation models. Numerical results have demonstrated that the statistical properties of the simulation model can fit those of the theoretical model very well with reasonable complexity. Also, the impact of cluster elevation angles on correlation properties of the proposed massive MIMO channel models is investigated.

2) In the proposed theoretical and simulation massive MIMO channel models, nearfield effects caused by the increasing antenna elements are considered, including the spherical wavefront assumption and the variation of Doppler frequencies over the antenna array.

3) Also, appearance and disappearance of clusters (i.e., cluster evolution) on both the array and time axes are jointly modeled by birth-death processes, which make the proposed massive MIMO channel models essentially non-stationary.

The rest of this paper is organized as follows. Section II gives a general description of the proposed theoretical non-stationary 3D wideband twin-cluster channel model for massive MIMO systems. Statistical properties of the proposed theoretical model are studied in Section III. Section IV presents the corresponding simulation model for the theoretical model. Numerical results are presented in Section V and conclusions are finally drawn in Section VI.

II. A THEORETICAL NON-STATIONARY 3D WIDEBAND TWIN-CLUSTER MASSIVE MIMO CHANNEL MODEL

Let us consider a wideband massive MIMO system with multiple twin clusters in a 3D space to describe different taps of the channel, as illustrated in Fig. 1. For a twin-cluster channel model with \( N_{\text{total}} \) clusters, each cluster, say Cluster\(_T^n\) \((n = 1, \ldots, N_{\text{total}})\), is made of a representation Cluster\(_T^n\) at the transmitter side denoting the first bounce and a representation Cluster\(_R^n\) at the receiver side denoting the last bounce. The propagation environment between these two representations is abstracted as a virtual link [34].

Let us assume that the transmitter and receiver are equipped with ULAs with \( M_T \) and \( M_R \) antenna elements, respectively. The distances between antenna elements are \( \delta_T \) at the transmitter and \( \delta_R \) at the receiver. Let the transmitter be the origin of the 3D space, the distance vector between the transmitter and receiver is \( \mathbf{D} = (D, 0, 0) \). Furthermore, both azimuth and elevation angles in the 3D space are considered for clusters, antenna arrays, movement direction of clusters, and movement direction of antenna arrays as listed in Table I. It should be noticed that the farfield conditions \((D > \frac{2M_T\delta_T}{\lambda}, D > \frac{2M_R\delta_R}{\lambda})\) for conventional MIMO channels are not assumed in the proposed model. Thus, the wavefront of each wireless link is assumed to be spherical resulting in the fact that the AoAs and AoDs on the antenna arrays are no longer equal for each antenna element and the phase of each antenna element is determined by geometrical relationships.

Another important characteristic of massive MIMO channel models is the appearance and disappearance of clusters on the antenna array as reported in [24]. Contrary to conventional MIMO channel models assuming that a cluster is always observable to all the antennas on an antenna array, a cluster may only be observable to a subset of antennas on an antenna array for massive MIMO. To put it another way, each antenna has its own set of observable clusters. Examples are shown in Fig. 1. Cluster\(_{n+1} \) is observable to the \( k \)-th but not observable to the \( q \)-th \((1 \leq k, q \leq M_R)\) receive antenna. Similarly,
Fig. 1. A 3D wideband twin-cluster massive MIMO channel model.

Cluster\(_{n+2}\) is observable to the \(l\)-th but not observable to the \(p\)-th \((1 \leq l, p \leq M_T)\) transmit antenna. On the other hand, Cluster\(_n\) is observable to both the \(l\)-th transmit antenna and the \(k\)-th receive antenna. Denote \(C^I_l(t)\) and \(C^R_k(t)\) as the cluster set in which clusters are observable to the \(l\)-th transmit antenna (the \(k\)-th receive antenna) at time instant \(t\). Let \(N_{\text{total}}\) be the total number of clusters that are observable to at least one transmit antenna and one receive antenna. The value of \(N_{\text{total}}\) can be calculated as

\[
N_{\text{total}} = \text{card} \left( \bigcup_{l=1}^{M_T} \bigcup_{k=1}^{M_R} C^I_l(t) \cap C^R_k(t) \right),
\]

where the operator card() denotes the cardinality of a set. Then, a cluster is observable to the \(l\)-th transmit antenna and the \(k\)-th receive antenna if and only if this cluster is in the set \(\{C^I_l(t) \cap C^R_k(t)\}\). Sets \(C^I_l(t)\) and \(C^R_k(t)\) are generated based on the cluster evolution (birth-death process) on both the time and array axes as described in Section II-B.

### A. Channel Impulse Response

Next, let us denote the maximum Doppler frequency as \(f_{\text{max}}\), the line-of-sight (LOS) Rician factor as \(K\), and the initial phase of the signal at the transmitter as \(\phi_0\). Additionally, let us assume that the power of the \(n\)-th cluster is \(P_n\) and there are respectively \(S_1\) and \(S_2\) rays within the representation at the receiver side and the representation at the transmitter side. Based on geometrical parameters in Table I, as \(S_1, S_2 \to \infty\), the theoretical model of the wideband massive MIMO channel matrix can be represented as an \(M_R \times M_T\) complex matrix \(H(t, \tau) = [h_{kl}(t, \tau)]_{M_R \times M_T}\) where \(k = 1, 2, \ldots, M_R\) and \(l = 1, 2, \ldots, M_T\). The multipath complex gains between the \(l\)-th transmit antenna and the \(k\)-th receive antenna at time \(t\) and delay \(\tau\), \(h_{kl}(t, \tau)\), can be presented as

\[
h_{kl}(t, \tau) = \sum_{n=1}^{N_{\text{total}}} h_{kl,n}(t) \delta(\tau - \tau_n(t))
\]

-If \(C^I_l(t) \cap C^R_k(t) \neq \emptyset\),

\[
h_{kl,n}(t) = \frac{\sqrt{P_n}}{K + 1} \sqrt{S_1 S_2} e^{j(2\pi f_{\text{LOS}} t + \phi_{\text{LOS}})}
\]

\[
+ \sqrt{\frac{P_n}{K + 1}} \lim_{s_1, s_2 \to \infty} \sum_{i_1=1}^{s_1} \sum_{i_2=1}^{s_2} e^{j(2\pi f_{k,n,i_1} t + \phi_{kl,n,i_1,i_2})}
\]

\[

\text{(3)}
\]

-If \(C^I_l(t) \cap C^R_k(t) = \emptyset\),

\[
h_{kl,n}(t) = 0.
\]

The calculation of complex gains can be divided into non-line-of-sight (NLOS) components and LOS component.

1) For NLOS components: The \(k\)-th receive antenna vector \(A^R_k(t)\) and the vector between the \(n\)-th cluster and the receive antenna array via the \(i_1\)-th ray \(D^R_{n,i_1}(t)\) can be presented as

\[
A^R_k(t) = \frac{M_R - 2k + 1}{2} \delta_R \left[ \frac{\cos \theta_{l,k}^R \cos \theta_{l,k}^A \sin \theta_{l,k}^A \sin \theta_{l,k}^E}{\sin \theta_{l,k}^E} \right]^T + \mathbf{D}
\]

\[
D^R_{n,i_1}(t) = D^T_n(t) \left[ \frac{\cos \theta_{l,k}^R \cos \theta_{l,k}^A \sin \theta_{l,k}^A \sin \theta_{l,k}^E}{\sin \theta_{l,k}^E} \right]^T + \mathbf{D}.
\]

Similarly, the \(l\)-th transmit antenna vector \(A^T_l\) and the vector between the \(n\)-th cluster and the transmit antenna array via the \(i_2\)-th ray \(D^T_{n,i_2}(t)\) can be given as

\[
A^T_l = \frac{M_T - 2l + 1}{2} \delta_T \left[ \frac{\cos \theta_{l,k}^T \cos \theta_{l,k}^A \sin \theta_{l,k}^A \sin \theta_{l,k}^E}{\sin \theta_{l,k}^E} \right]^T
\]

\[
D^T_{n,i_2}(t) = D^T_n(t) \left[ \frac{\cos \theta_{l,k}^T \cos \theta_{l,k}^A \sin \theta_{l,k}^A \sin \theta_{l,k}^E}{\sin \theta_{l,k}^E} \right]^T.
\]

Then, vectors \(D^R_{k,n,i_1}(t)\) and \(D^T_{l,n,i_2}(t)\) can be computed as

\[
D^R_{k,n,i_1}(t) = D^R_{n,i_1}(t) - A^R_k(t)
\]

\[
D^T_{l,n,i_2}(t) = D^T_{n,i_2}(t) - A^T_l.
\]

Next, the delay of the \(n\)-th cluster of the twin-cluster model is assumed to be the sum of two components. The first component is calculated according to the geometrical relationships between the antenna arrays and cluster locations. The second component abstracts the delay of the virtual link between the twin clusters. Then, the delay of the \(n\)-th cluster \(\tau_n(t)\) can be computed as

\[
\tau_n(t) = \left\| D^T_n(t) \right\| + \left\| D^R_n(t) \right\| + \delta_n(t)
\]

where the abstracted delay of the virtual link \(\delta_n(t)\) is randomly drawn according to the uniform distribution \(U(0, \tau_{\text{max}})\), and \(\tau_{\text{max}}\) is the maximum delay (\(\tau_{\text{max}} = 1845\) ns for NLOS [18]). The operator \(\| \cdot \|\) denotes the Euclidean norm, and \(c\) is the speed of light. Then, the phase between the \(k\)-th receive
antenna and the \(l\)-th transmit antenna via the \(i_1\)-th ray at the receiver, the \(i_2\)-th ray at the transmitter, and the \(n\)-th cluster, \(\varphi_{kl,n,i_1,i_2}(t)\), is derived as

\[
\varphi_{kl,n,i_1,i_2}(t) = \varphi_0 + \frac{2\pi}{\lambda} \left[ \|D_{kn,i_1}^R(t)\| + \|D_{ln,i_2}^T(t)\| + c\tilde{r}_n(t) \right].
\]

(12)

Accordingly, the Doppler frequency of the \(k\)-th receive antenna via the \(i_1\)-th ray of the \(n\)-th cluster \(f_{kn,i_1}(t)\) is presented as

\[
f_{kn,i_1}(t) = \frac{\max \langle D_{kn,i_1}^R(t), v \rangle}{\|D_{kn,i_1}^R(t)\| \|v\|}
\]

(13)

where \(\langle \cdot, \cdot \rangle\) represents the inner product.

2) For LOS component: In the same way, the Doppler frequency \(f_{kl}^{\text{LOS}}(t)\) and phase \(\varphi_{kl}^{\text{LOS}}(t)\) of the LOS components can also be calculated as

\[
D_{kl}^{\text{LOS}}(t) = A_k^R(t) - A_l^T(t)
\]

(14)

\[
f_{kl}^{\text{LOS}}(t) = \frac{\max \langle D_{kl}^{\text{LOS}}(t), v \rangle}{\|D_{kl}^{\text{LOS}}(t)\| \|v\|}
\]

(15)

\[
\varphi_{kl}^{\text{LOS}}(t) = \varphi_0 + \frac{2\pi}{\lambda} \|D_{kl}^{\text{LOS}}(t)\|.
\]

(16)

The generation procedure of the channel impulse response consists of the generation of the initial cluster set, generation of parameters (delays, cluster powers, AoAs, and AoDs) for the initial cluster set, array-time evolution of clusters, and the generation of channel impulse response, as presented in Fig. 2. This algorithm is a generalized version of the WINNER channel model [18] by adding an extra block of array-time evolution of clusters to capture massive MIMO channel characteristics. The block of array-time evolution of clusters will be discussed in the next section.

### Table I: Definitions of key geometry parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi_{R,i_1}^k, \psi_{T,i_1}^k)</td>
<td>elevation angles of the receive and transmit antenna arrays</td>
</tr>
<tr>
<td>(\theta_{R,i_1}^k, \theta_{T,i_1}^k)</td>
<td>azimuth angles of the receive and transmit antenna arrays</td>
</tr>
<tr>
<td>(\theta_{n,i_1}^k, \theta_{n,i_2}^k)</td>
<td>elevation and azimuth angles of the (n)-th ray of the (i_1)-th ray of the (i_2)-th ray</td>
</tr>
<tr>
<td>(D_{kn,i_1}^R(t), D_{ln,i_2}^T(t))</td>
<td>distance vectors between the (n)-th cluster and the (i_1)-th ray</td>
</tr>
<tr>
<td>(D_{kn,i_1}^R(t), D_{kn,i_2}^T(t))</td>
<td>distance vectors between the (n)-th cluster and the (i_1)-th ray and the (i_2)-th ray</td>
</tr>
<tr>
<td>(D_{kl}^{\text{LOS}}(t))</td>
<td>distance vector between the (k)-th receive antenna and the (l)-th transmit antenna</td>
</tr>
<tr>
<td>(v, v_n, v_{n,R})</td>
<td>velocity vectors of the (n)-th cluster at the receiver and transmitter side</td>
</tr>
</tbody>
</table>

Fig. 2. Algorithm flowchart of the generation of the channel impulse response.

Fig. 3. Algorithm flowchart of array-time evolution of the proposed 3D twin-cluster model.

### B. Non-Stationary Properties

The non-stationary process of the proposed massive MIMO channel model is based on the array-time evolution of clusters which can be characterized by two parts. The first part is the generation of cluster sets \(C_{kl}^R(t)\) and \(C_{kl}^T(t)\) for each antenna based on birth-death process on both the time and array axes. This aims at modeling not only the phenomena of cluster appearance and disappearance on antenna arrays of massive MIMO, but also non-stationary behaviors of clusters on the time axis. The generation procedure is achieved by extending the concept of birth-death process on the time axis in previous literature [29], [30] to the array axis as well. The outcome
of the first part determines the cluster set of each antenna. The second part is the updates of geometrical relationships with respect to the movements of the receiver and clusters. The outcome of the second part determines all parameters for each cluster. The algorithm flowchart describing the array-time cluster evolution is depicted in Fig. 3.

**Part 1:** To describe the algorithm of the array-time cluster evolution, let us first denote $\lambda_G$ (per meter) and $\lambda_R$ (per meter) as the cluster generation rate and recombination rate. Assume the initial number of clusters $N$ and the initial cluster sets of the 1-st transmit and receive antennas $C_i^T = \{c_i^T : x = 1, 2, \ldots, N\}$ and $C_i^R = \{c_i^R : x = 1, 2, \ldots, N\}$ at the initial time instant $t$ are given, where $c_i^T$ and $c_i^R$ are two representations of Cluster $x$. Then, these clusters in cluster sets $C_i^T$ and $C_i^R$ evolve according to birth-death process on the array axis to recursively generate the cluster sets of the rest of antennas at the transmitter and receiver at the initial time instant $t$, which is expressed as

$$C_{i-1}^T(t) \xrightarrow{E} C_i^T(t) \quad (l = 2, 3, \ldots, M_T)$$

$$C_{k-1}^R(t) \xrightarrow{E} C_k^R(t) \quad (k = 2, 3, \ldots, M_R)$$

where the operator $\xrightarrow{E}$ denotes cluster evolution on either the array or time axis. The survival probabilities of the clusters inside the cluster set the on array axis to the transmitter $P_{T\text{survival}}^T$ and the receiver $P_{T\text{survival}}^R$ can be modeled as exponential functions [40]

$$P_{T\text{survival}}^T = e^{-\frac{\lambda_R}{\lambda_T} D_T}$$

$$P_{R\text{survival}}^T = e^{-\frac{\lambda_R}{\lambda_T} D_T}$$

where $D_T^n$ is the scenario-dependent correlation factor on the array axis. According to the birth-death process, the average number of newly generated clusters $N_{\text{new}}^T$ and $N_{\text{new}}^R$ on the array axis based on the birth-death process can be computed as [40]

$$E[N_{\text{new}}^T] = \frac{\lambda_G}{\lambda_T} \left(1 - e^{-\frac{\lambda_R}{\lambda_T} D_T}\right)$$

$$E[N_{\text{new}}^R] = \frac{\lambda_G}{\lambda_R} \left(1 - e^{-\frac{\lambda_R}{\lambda_T} D_T}\right)$$

where $E[\cdot]$ designates the expectation. After this process on the array axis, a number of initial clusters may not survive for certain antennas. Meanwhile, new clusters may appear on the array. Each cluster evolves gradually on the antenna array. It can be observed from (19) to (22) that, if two antenna elements are more separated, the probability that they share the same set of clusters is smaller. To imitate the complex propagation environment, cluster indices in set $\bigcup_{l=1}^{M_T} C_i^T$ and set $\bigcup_{k=1}^{M_R} C_k^R$ are randomly shuffled and paired to determine which transmit and receive antennas each cluster is observable. Then, the cluster indices are reassigned from 1 to $N_{\text{total}}$. Moreover, parameters of the initial clusters such as mean AoAs, mean AoDs, delays, and distances are randomly drawn according to distributions listed in Table II. The means and standard deviations for $\xi_n^T$, $\tilde{\theta}_n^T$, $\tilde{\theta}_n^R$, and $\tau_n$ in Table II are generated according to [18]. Also, the power of each cluster is calculated and normalized as in [18].

At the next time instant $t + \Delta t$, the time-axis evolution of clusters is operated as

$$P_{T\text{survival}}^T = e^{-\frac{\lambda_R}{\lambda_T} D_T}$$

$$P_{R\text{survival}}^T = e^{-\frac{\lambda_R}{\lambda_T} D_T}$$

To perform the evolution process of cluster on the time axis as (23) and (24) show, define the time-dependent channel fluctuation in the time axis at $t + \Delta t$ as $q(t + \Delta t)$. The channel fluctuation measures how much the scattering environment varies within a short period of time. The variation of scattering environment is due to the movements of the receiver and the clusters. Thus, the channel fluctuation is defined by [29]

$$q(t + \Delta t) = q_r(t + \Delta t) + q_c(t + \Delta t)$$

where $q_r(t + \Delta t)$ is the channel fluctuation caused by the movement of receiver defined by $q_r(t + \Delta t) = \|\xi\| |\Delta t|$ and $q_c(t + \Delta t)$ is the channel fluctuation caused by the movement of clusters defined by $q_c(t + \Delta t) = P_F(||\xi^R_t|| + ||\xi^R||) |\Delta t|$ ($P_F$ is the percentage of moving clusters). Given the scenario-dependent space correlation factor $D_T^n$, each cluster survives with probability $P_{\text{survival}}^T$ on the time axis which can be calculated as [29]

$$P_{\text{survival}}(q(t + \Delta t)) = e^{-\frac{\lambda_R}{\lambda_T} D_T}.$$ 

The mean number of newly generated clusters at instant $t + \Delta t$ on the time axis $E[N_{\text{new}}(t + \Delta t)]$ is computed according to the birth-death process [40]

$$E[N_{\text{new}}(t + \Delta t)] = \frac{\lambda_G}{\lambda_R} \left(1 - e^{-\frac{\lambda_R}{\lambda_T} D_T}\right).$$

After the time evolution process as (23)-(27) show, all clusters can be categorized as survived clusters or newly generated clusters. The next issue is to decide the set of transmit and receive antennas that are observable to each newly generated cluster. This is determined by the birth-death process on the array axis, which can be summarized into 4 steps:

**Step 1:** Randomly generate initial indices $\tilde{l}$ ($1 \leq \tilde{l} \leq M_T$) and $\tilde{k}$ ($1 \leq \tilde{k} \leq M_R$) for the transmit and receive antenna arrays. Then, let the newly generated cluster be observable to the $\tilde{l}$-th transmit antenna and the $\tilde{k}$-th receive antenna.

**Step 2:** Evolve the cluster on the transmit antenna array based on birth-death process from the $(\tilde{l} - 1)$-th to the 1-st and from $(\tilde{l} + 1)$-th to the $M_T$-th antennas.

**TABLE II**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Distributions</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_n^T$</td>
<td>wrapped Gaussian</td>
<td>0.78rad</td>
<td>0.11rad</td>
</tr>
<tr>
<td>$\theta_n^T$</td>
<td>wrapped Gaussian</td>
<td>1.06rad</td>
<td>0.53rad</td>
</tr>
<tr>
<td>$\xi_n^R$</td>
<td>wrapped Gaussian</td>
<td>0.78rad</td>
<td>0.18rad</td>
</tr>
<tr>
<td>$\theta_n^R$</td>
<td>wrapped Gaussian</td>
<td>0.78rad</td>
<td>0.91rad</td>
</tr>
<tr>
<td>$D_{11}^T(t)$</td>
<td>exponential</td>
<td>25m</td>
<td>0.07m</td>
</tr>
<tr>
<td>$D_{11}^R(t)$</td>
<td>exponential</td>
<td>30m</td>
<td>0.05m</td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>exponential</td>
<td>930ns</td>
<td>930ns</td>
</tr>
</tbody>
</table>
Step 3: Evolve the cluster on the receive antenna array based on birth-death process from the $(\tilde{k} - 1)$-th to the 1-st and from $(\tilde{k} + 1)$-th to the $M_T$-th antennas. 
Step 4: Add the cluster to cluster sets whose corresponding antennas can observe the cluster. 

**Part 2:** The remaining issue is the updates of geometry relationships of clusters from $t$ to $t + \Delta t$. The updates of geometry relationships are different for survived clusters and newly generated clusters. Thus, they are described separately.

1) Survived clusters: Regarding survived clusters, their properties such as delays, Doppler frequencies, AoAs and AoDs should be recalculated based on the updates of geometrical relationships from $t$ to $t + \Delta t$. First, the distance vectors are updated due to movements of the receiver and clusters according to 

$$D_{n}^{R}(t + \Delta t) = D_{n}^{R}(t) + v_{n}^{R} \Delta t \quad \text{(28)}$$

$$D_{n}^{T}(t + \Delta t) = D_{n}^{T}(t) + v_{n}^{T} \Delta t \quad \text{(29)}$$

$$D_{kn,i_{1}}^{R}(t + \Delta t) = D_{n}^{R}(t) - A_{k}^{R}(t) + (v_{n}^{R} - v) \Delta t \quad \text{(30)}$$

$$D_{kn,i_{2}}^{T}(t + \Delta t) = D_{n}^{T}(t) + v_{n}^{T} \Delta t - A_{T}^{T}. \quad \text{(31)}$$

Second, the delay of the $n$-th cluster at $t + \Delta t$ is expressed as the sum of the updated geometrical delay and the delay of the evolved virtual link, 

$$\tau_{n}(t + \Delta t) = \frac{||D_{n}^{T}(t + \Delta t)|| + ||D_{k}^{R}(t + \Delta t)||}{c} + \tilde{\tau}_{n}(t + \Delta t). \quad \text{(32)}$$

To describe the evolution of the virtual link, its delay $\tilde{\tau}_{n}(t + \Delta t)$ is based on a first-order filtering algorithm as 

$$\tilde{\tau}_{n}(t + \Delta t) = e^{-\frac{\Delta t}{\tau_{\max}}} \tilde{\tau}_{n}(t) + (1 - e^{-\frac{\Delta t}{\tau_{\max}}}) X$$

where $X$ is randomly drawn according to the uniform distribution $U(D/c, \tau_{\max})$. $\varsigma$ is a parameter that depends on the coherence of a virtual link and scenarios. Third, the time-variant phase and Doppler frequency are accordingly computed as 

$$\varphi_{kl,n,i_{1},i_{2}}(t + \Delta t) = \varphi_{0} + \frac{2\pi}{\lambda} c \tilde{\tau}_{n}(t + \Delta t) + \frac{2\pi}{\lambda} [||D_{kn,i_{1}}^{R}(t + \Delta t)|| + ||D_{kn,i_{2}}^{T}(t + \Delta t)||]$$

$$f_{kn,i_{1}}(t + \Delta t) = \frac{f_{\max} \langle D_{kn,i_{1}}^{R}(t + \Delta t), v \rangle}{||D_{kn,i_{1}}^{R}(t + \Delta t)|| ||v||}. \quad \text{(33)}$$

Last, geometrical relationships of LOS components need to be refreshed as well 

$$D_{kl}^{LOS}(t + \Delta t) = A_{k}^{R}(t) + v \Delta t - A_{T}^{T} \quad \text{(35)}$$

$$f_{kl}^{LOS}(t + \Delta t) = \frac{f_{\max} \langle D_{kl}^{LOS}(t + \Delta t), v \rangle}{||D_{kl}^{LOS}(t + \Delta t)|| ||v||} \quad \text{(36)}$$

$$\varphi_{kl}^{LOS}(t + \Delta t) = \varphi_{0} + \frac{2\pi}{\lambda} ||D_{kl}^{LOS}(t + \Delta t)|| \quad \text{(37)}$$

2) Newly generated clusters: On the other hand, for newly generated clusters, their AoAs, AoDs, delays, and distances are initialized according to distributions in Table II. The power of each cluster is calculated and normalized as in [18]. Denote the set of all survived clusters as $C_{\text{Survived}}$ and the set of all newly generated clusters as $C_{\text{New}}$ after the time-axis evolution. The average total power of survived and newly generated clusters should be normalized as 

$$\sum_{\text{Cluster}_{e} \in C_{\text{Survived}}} P_{e} + \sum_{\text{Cluster}_{e} \in C_{\text{New}}} P_{e} = 1. \quad \text{(38)}$$

Thus far, the array-time evolution of clusters from $t$ to $t + \Delta t$ is finished. This evolution process can be operated recursively with respect to time.

### III. Statistical Properties of the Theoretical Massive MIMO Channel Model

#### A. Spatial-Temporal Correlation Function

The spatial-temporal correlation function between the channel gains $h_{kl,n}(t)$ and $h_{k'l'v',n}(t)$ is defined as [10]

$$\rho_{kl,k'l',v',n}(\delta_{T}, \delta_{R}, \Delta t; t) = E \left[ \frac{h_{kl,n}(t) h_{k'l've',n}(t + \Delta t)}{|h_{kl,n}(t)||h_{k'l've',n}(t + \Delta t)|} \right]. \quad \text{(39)}$$

As the LOS component and NLOS components are independent, (39) can be rewritten as the sum of the spatial-temporal correlation functions of the LOS component and the NLOS components

$$\rho_{kl,k'l',v',n}(\delta_{T}, \delta_{R}, \Delta t; t) = \rho_{kl,k'l',v',n}^{LOS}(\delta_{T}, \delta_{R}, \Delta t; t) + \rho_{kl,k'l',v',n}^{NLOS}(\delta_{T}, \delta_{R}, \Delta t; t) \quad \text{(40)}$$

where

$$\rho_{kl,k'l',v',n}^{LOS}(\delta_{T}, \delta_{R}, \Delta t; t) = \frac{K \delta(n - 1)}{K + 1} \times e^{j[2\pi f_{k'l',v',n}^{LOS}(t + \Delta t) - 2\pi f_{kl,n}^{LOS}(t) + \varphi_{k'l',v',n}(t + \Delta t) - \varphi_{kl,n}(t)]} \quad \text{(41)}$$

$$\rho_{kl,k'l',v',n}^{NLOS}(\delta_{T}, \delta_{R}, \Delta t; t) = \frac{1}{K \delta(n - 1) + 1} \times E \left[ \frac{1}{S_{1} S_{2}} \sum_{i=1}^{S_{1}} \sum_{j=1}^{S_{2}} e^{j\Phi_{i}} \right] \quad \text{(42)}$$

with

$$\Phi_{0} = 2\pi f_{k',v',n,i}(t + \Delta t)(t + \Delta t) - 2\pi f_{kn,i}(t) t + \varphi_{k'l',v',n,i_{1}i_{2}}(t + \Delta t) - \varphi_{kl,n,i_{1}i_{2}}(t). \quad \text{(43)}$$

#### B. Spatial Cross-Correlation Function

By setting $\Delta t = 0$, the spatial-temporal correlation function reduces to the spatial cross-correlation (CCF) function $\rho_{kl,k'l',v',n}(\delta_{T}, \delta_{R}; t)$.

$$\rho_{kl,k'l',v',n}(\delta_{T}, \delta_{R}; t) = E \left[ \frac{h_{kl,n}(t) h_{k'l've',n}(t)}{|h_{kl,n}(t)||h_{k'l've',n}(t)|} \right] = \rho_{kl,k'l',v',n}^{LOS}(\delta_{T}, \delta_{R}; t) + \rho_{kl,k'l',v',n}^{NLOS}(\delta_{T}, \delta_{R}; t) \quad \text{(44)}$$
where
\[
\rho_{KL,K',L'}^{\text{LOS}}(\delta \tau, \delta R; t) = \frac{K \delta(n - 1)}{K + 1} e^{j[2\pi f_{K}^{\text{LOS}}(t)-2\pi f_{K'}^{\text{LOS}}(t)+\phi_{K}^{\text{LOS}}(t)-\phi_{K'}^{\text{LOS}}(t)]},
\]
(45)

Regarding the correlation of the NLOS components, as a cluster has a probability of \( e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \) to survive when evolving from \( h_{k,n}(t) \) to \( h_{k',n}(t) \), the spatial CCF of the NLOS components is scaled by \( e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \).

\[
\rho_{KL,K',L'}^{\text{NLOS}}(\delta \tau, \delta R; t) = \frac{1}{K \delta(n - 1)} e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \times
\]
\[
\int_{-\pi - \frac{\pi}{2}}^{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{j\Phi_1} p_R(\xi_1^R, \theta_1^R) p_T(\xi_1^T, \theta_1^T) d\xi_1^R d\theta_1^R d\xi_1^T d\theta_1^T
\]
(46)

with
\[
\Phi_1 = 2\pi f_{K'}(t) - 2\pi f_{K}(t) + \varphi_{k'}(n, t) - \varphi_{k,n}(t).
\]
(47)

As the spatial CCF \( \rho_{KL,K',L'}(\delta \tau, \delta R; t) \) depends on the values of \( k, k', l', l'' \), and can not be reduced to solely be with respect to \( |k - k'| \) and \( |l - l'| \), the WSS assumption on the array axis for massive MIMO is not valid.

C. Temporal Autocorrelation Function

On the other hand, by setting \( l = l' \), \( k = k' \), the temporal autocorrelation function (ACF) \( \rho_{k,n}(\Delta t; t) \) is obtained.

\[
\rho_{k,n}(\Delta t; t) = E \left[ h_{k,n}(t) h_{k,n}(t+\Delta t) \right] = \rho_{k,n}^{\text{LOS}}(\Delta t; t) + \rho_{k,n}^{\text{NLOS}}(\Delta t; t).
\]
(48)

Since the LOS component is uncorrelated to NLOS components, their temporal ACFs, \( \rho_{k,n}^{\text{LOS}}(\Delta t; t) \) and \( \rho_{k,n}^{\text{NLOS}}(\Delta t; t) \), are calculated separately as

\[
\rho_{k,n}^{\text{LOS}}(\Delta t; t) = \frac{K \delta(n - 1)}{K + 1} e^{j[2\pi f_{k}^{\text{LOS}}(t+\Delta t)+(k-k')R] - 2\pi f_{k}^{\text{LOS}}(t)+\varphi_{k,n}(t)-\varphi_{k,n}(t+\Delta t)}
\]
(49)

Regarding the correlation of the NLOS components, the survival probability of a cluster is \( e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \) when evolving from \( h_{k,n}(t) \) to \( h_{k,n}(t+\Delta t) \), the temporal ACF of the NLOS components is scaled by \( e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \).

\[
\rho_{k,n}^{\text{NLOS}}(\Delta t; t) = \frac{1}{K \delta(n - 1)} e^{-\lambda_R |\Delta| + P_R ||\xi_1^R|| + ||\xi_2^R||} \times
\]
\[
\int_{-\pi - \frac{\pi}{2}}^{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{j\Phi_2} p_R(\xi_1^R, \theta_1^R) p_T(\xi_1^T, \theta_1^T) d\xi_1^R d\theta_1^R d\xi_1^T d\theta_1^T
\]
(50)

with
\[
\Phi_2 = 2\pi f_{k,n}(t+\Delta t)(t+\Delta t) - 2\pi f_{k,n}(t) t + \varphi_{k,n}(t+\Delta t) - \varphi_{k,n}(t).
\]
(51)

As the temporal ACF \( \rho_{k,n}(\Delta t; t) \) depends on the values of \( t \), and can not be reduced to solely be with respect to \( \Delta t \), the WSS assumption on the time axis for the proposed massive MIMO channel model is not valid.

D. Doppler Power Spectral Density

The Doppler PSD \( S_n(f; t) \) with respect to the Doppler frequency \( f \) is the Fourier transform of the temporal ACF, which can be presented as

\[
S_n(f; t) := \int_{-\infty}^{\infty} \rho_{k,n}(\Delta t; t) e^{-j2\pi f \Delta t} d(\Delta t).
\]
(52)

It should be also noticed that the Doppler PSD is time dependent.

E. Doppler Frequency Standard Deviation on the Antenna Array

As spherical wavefronts are assumed in the proposed channel model, different antennas on the same array will experience different Doppler shifts. Namely, Doppler frequencies may vary on the antenna array. To study the variations of Doppler frequency of the receiver on the array axis, the average Doppler frequency on the \( k \)-th receive antenna, \( \bar{f}_{kn} \), is calculated as

\[
\bar{f}_{kn} = \int_{-\pi}^{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} f_n(\xi_n^R, \theta_n^R) p_R(\xi_n^R, \theta_n^R) d\xi_n^R d\theta_n^R.
\]
(53)

Next, the average Doppler frequency on the array axis \( \mu_{f_n} \) is presented as

\[
\mu_{f_n} = E[\bar{f}_{kn}] = \sum_{k=1}^{M_k} \bar{f}_{kn}.
\]
Finally, the standard deviation of Doppler frequency \( \sigma_{f_n} \) on the array axis can be obtained as

\[
\sigma_{f_n} = \sqrt{\frac{\sum_{k=1}^{M_k} \left( \bar{f}_{kn} - \mu_{f_n} \right)^2}{M_k}}.
\]
(54)

For conventional MIMO channel models, the Doppler frequency on the whole antenna array is assumed to be the same which is equivalent to \( \sigma_{f_n} = 0 \). Conversely, for massive MIMO channel models, \( \sigma_{f_n} \) may not be 0 and a larger \( \sigma_{f_n} \) means that the Doppler frequency varies more significantly on the antenna array.

F. Condition Number

Condition number is used to measure the correlation of the channel matrix \([4] \). A larger condition number implies higher dependence. The condition number is defined by the quotient of maximum eigenvalue and the minimum eigenvalue of the channel matrix

\[
\gamma(\text{dB}) = 20 \log_{10} \frac{\lambda_{\text{max}}(H)}{\lambda_{\text{min}}(H)}
\]
(55)

where the operators \( \lambda_{\text{max}}(\cdot) \) and \( \lambda_{\text{min}}(\cdot) \) represent the maximum eigenvalue and the minimum eigenvalue, respectively.
IV. A NON-STATIONARY 3D WIDEBAND SIMULATION MODEL FOR MASSIVE MIMO CHANNELS

Previously, in the proposed channel theoretical model, the number of scatterers is assumed to be infinity \((S_1, S_2 \rightarrow \infty)\) which is capable of providing accurate analytic channel characteristic results. However, with respect to a channel simulator, infinite scatterers are not practical as the complexity of implementation is enormous. Therefore, a compromise between accuracy and complexity should be addressed. The target of this section is to develop a channel simulator with a finite and proper scatterer number while capturing channel characteristics as accurate as possible. The corresponding simulation model of the proposed massive MIMO channel model is obtained by reducing (3) as

\[
h_{k,l,n}(t) = \delta(n-1)\sqrt{\frac{K}{K+1}} e^{i\left(2\pi f_0 t + \varphi_{k,l,n}\right)} + \sqrt{\frac{P_n}{K+1} \sum_{i=1}^{S_1} \sum_{j=1}^{S_2} \delta_{i,j} e^{i\left(2\pi f_{s,n,i,j} t + \varphi_{k,l,n,i,j}\right)}}. \tag{56}
\]

Let \(x\) be the vector of AoAs and AoDs defined by \(x = (\theta^R, \xi^R, \theta^T, \xi^T)\). In the theoretical model, define \(g(x) = \frac{h_{k,l,n}(t)\delta_{\epsilon,k',l',n}(t+\Delta t)}{|h_{k,l,n}(t)||h_{k',l',n}(t+\Delta t)|}\) with \(x\) distributed according to the cumulative distribution function (CDF) \(F(x)\) of AoAs and AoDs. The spatial-temporal correlation function \(\rho_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t)\) for the theoretical model in (39) is calculated as the expectation of \(g(x)\).

\[
\rho_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t) = E[g(x)] = \int g(x) dF(x). \tag{57}
\]

On the other hand, a simulation model aims at approximating \(\rho_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t)\) with \(S_1S_2\) discrete vectors \(\{x_i\}_{i=1}^{S_1S_2}\), where each \(x_i\) follows the CDF \(F(x)\) and \(x_i = (\theta^R_i, \xi^R_i, \theta^T_i, \xi^T_i)\). Then, the approximated value \(\hat{\rho}_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t)\) can be expressed as

\[
\hat{\rho}_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t) = E[g(x)] = \frac{1}{S_1S_2} \sum_{i=1}^{S_1S_2} g(x_i). \tag{58}
\]

The remaining issue is to determine the vector sequence \(\{x_i\}_{i=1}^{S_1S_2}\) with reasonable computational complexity to approximate \(\rho_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t)\) with \(\hat{\rho}_{k,l,k',l',n}(\delta_T, \delta_R, \Delta t; t)\). A number of algorithms to calculate \(\{x_i\}_{i=1}^{S_1S_2}\) such as the method of equal distances (MED), method of equal areas (MEA), extended method of exact Doppler spread (MEDS), and the Monte Carlo Method (MCM) have been introduced in [10]. Here, the MEA is applied to calculating the discrete vectors \(\{x_i\}_{i=1}^{S_1S_2}\) of the simulation model according to \(\frac{1}{S_1S_2} dF(a) = \frac{1}{S_1S_2} dF(\cdot)\) [10]. Since \(x\) is four dimensional in this model, the “area” in MEA in this case is generalized as the probability measure of a set. As a result, \(F(x)\) is divided into \(S_1S_2\) sets with the same probability of \(\frac{1}{S_1S_2}\); then \(x_i\) can be computed as \(x_i = F^{-1}\left(\frac{i}{S_1S_2}\right)\) where \(F^{-1}(\cdot)\) is the inverse function of \(F(\cdot)\).

V. NUMERICAL RESULTS AND ANALYSIS

The distributions of azimuth and elevation angles at the transmitter side and the receiver side are assumed to obey the two dimensional von Mises distribution [41], where azimuth angles and elevation angles are assumed to be mutually independent. Therefore, the probability density function (PDF) of angles of the \(n\)-th cluster \(p_Z(\xi^R_n, \theta^T_n)\) with \(Z = \{T, R\}\) can be expressed as

\[
p_Z(\xi^R_n, \theta^T_n) = \exp\left[\kappa(\cos(\xi^R_n - \bar{\xi}^R_n) + \cos(\theta^T_n - \bar{\theta}^T_n))\right] \frac{1}{\pi I_0(k)} \tag{59}
\]

where \(\bar{\xi}^R_n\) and \(\bar{\theta}^T_n\) are the mean elevation and azimuth AoA/AoD, and \(I_0(\cdot)\) is the zero-th order modified Bessel function. Moreover, \(\kappa \geq 0\) controls the width of the distribution functions.

By setting \(\Delta t = 0\), the absolute values of the spatial CCF \(|\rho_{11,22,1}(\delta_T, \delta_R; t)|\) of the three dimensional twin cluster model are illustrated in Fig. 4. A decreasing trend can be observed as the normalized antenna spacings increase at both the transmitter and receiver sides. The absolute values of spatial CCF drop smoothly when antenna spacing at the transmitter side enlarges. Meanwhile, fluctuations can be seen as antenna spacing at the receiver side increases. These fluctuations are caused by non-stationary properties due to the movements of the receiver.

Next, by setting \(\delta_T\) and \(\Delta t = 0\), the impact of cluster elevation angles at the receiver side on the absolute spatial correlation function \(|\rho_{11,12,1}(0, \delta_R; t)|\) of the receiver is depicted in Fig. 5. The increase in cluster elevation angles at the receiver side results in high receive antenna correlations. Besides, the spatial correlation function of the simulation model is compared with the theoretical model, showing that the simulation model is able to capture the channel spatial correlation characteristic at the cost of slightly less accuracy.

The absolute values of the temporal ACF in terms of cluster elevation angles at the receiver side are analyzed in Fig. 6.
The figure shows that the temporal ACF decreases slower as the elevation angles become larger. The philosophy is that the Doppler frequency equals the product of $f_{\text{max}}$, cosine of the azimuth angle, and cosine of the elevation angle. For fixed $f_{\text{max}}$ and azimuth angle, the absolute Doppler frequency is decreasing as the elevation angle increases from 0 to $\pi/2$. Consequently, when the elevation angle reaches $\pi/2$, the absolute Doppler frequency is minimum which results in the slowest decrease of the temporal ACF. Meanwhile, the normalized Fourier transform of the temporal ACF, i.e., the PDF of Doppler frequency of the proposed model is illustrated in Fig. 7. The PDF of Doppler frequency of the conventional MIMO channel model is symmetrical with respect to 0. However, this may not be necessary for the proposed non-stationary massive MIMO channel model. There are two observations that should be noticed in Fig. 7. First, the PDFs of Doppler frequency at different time instants vary because of the non-stationary properties on the time axis. Namely, the WSS condition on the time domain is not available as a consequence of time-variant properties on the time axis. Consequently, when the elevation angle reaches $\pi$, the absolute Doppler frequency on the entire antenna array is minimum which results in the slowest decrease of the temporal ACF.

In addition, Fig. 8 shows the standard deviation of Doppler frequencies on the antenna array. Conventional MIMO channel models assume farfield condition which results in a constant Doppler frequency on the entire antenna array. Conversely, the nearfield condition is assumed in the proposed massive MIMO channel model. As a result, the Doppler frequencies for different antennas are different. Since the nearfield effect is more significant as the number of antennas grows, the standard deviation increases accordingly.

Furthermore, a comparison of condition numbers between the 2D and 3D models is shown in Fig. 9. Stronger correlations are observed in the 2D model than the 3D model due to the fact that clusters have higher probabilities to be correlated in a 2D space than a 3D space. However, this difference is relatively less significant because the random distribution of cluster locations partially averages out the impact.

Fig. 10 illustrates the non-stationary properties on the array axis in the form of the receiver angle power spectrum (APS). It should be noticed that the estimated angle here means the angle between the cluster and the receive antenna array. Here, the multiple signal classification (MUSIC) algorithm [42] is applied to AoA estimation. A sliding window formed by 3 consecutive receive antennas is shifted by 1 antenna at a time from the first to the last antenna. Consequently, for a 32-element antenna array, there are in total 30 window
positions as Fig. 10 shows. Clusters appear and disappear on
the array axis, which results in that different antennas may
observe different sets of clusters. Additionally, angles of a
number of clusters shift on the array axis due to the nearfield
effect. Finally, receive power variations can be observed on
the antenna array. Similar conclusions on these mentioned features
of the proposed model were also observed in measurements in
massive MIMO channels in [24].

Regarding cluster evolution on the time axis, an example
of cluster sets in different time instants is shown in Fig. 11.
Clusters evolve according to the birth-death process. Thus,
by can be seen that there are clusters disappearing and new
clusters appearing. In this case, the transmit and receive
antenna arrays observe a time-variant set of clusters.

It is important to note that in the numerical analysis,
parameters such as mean and standard deviation of azimuth
AoAs/AoDs of the transmitter and receiver, mean and stan-
dard deviation of delays, maximum delay, spatial correlation
distance, and cluster powers were generated according to
the WINNER II channel model in [18]. The generation and
recombination rates of clusters and percentage of moving
clusters were adapted from [29] and [30]. However, certain
parameters such as cluster distances to the transmitter or
receiver were given based on reasonable assumptions, since
we have not found any relevant measurement data so far.
These parameters of the model can be further validated by
measurements whenever available in the future.

VI. CONCLUSIONS

Key characteristics of massive MIMO channels have not
been captured by conventional MIMO channel models. In this
paper, we have proposed a novel theoretical non-stationary
3D wideband twin-cluster channel model along with the cor-
responding simulation model for massive MIMO systems with
carrier frequencies in the order of GHz. Spherical wavefronts have been assumed to characterize nearfield effects resulting in AoA shifts, received power variations, and Doppler frequency variations on the antenna array. The impact of elevation angles of clusters on the correlation properties of the massive MIMO channel model has been studied. Most importantly, non-stationary properties on both the time and array axes have been modeled by birth-death processes. The proposed massive MIMO channel model is able to describe not only the appearance and disappearance of clusters on the time axis, but also the cluster evolution on the array axis, which is normally not included in conventional MIMO channels. Moreover, it has been shown that the channel characteristics of the simulation model are consistent with those of the theoretical model. In addition, important channel features of massive MIMO channels are characterized by the proposed models, which may serve as a design framework to model massive MIMO channels. Finally, certain parameters of the proposed channel model need to be further validated by relevant channel measurements, which will be our future work when such channel measurements become available in the literature.

REFERENCES

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