

# A Novel 3D Non-Stationary GBSM for 6G THz Ultra-Massive MIMO Wireless Systems

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## I. INTRODUCTION

**Abstract**—Terahertz (THz) communication is now being considered as one of possible technologies for the sixth generation (6G) wireless communication systems. In this paper, a novel three-dimensional (3D) space-time-frequency non-stationary theoretical channel model is first proposed for 6G THz wireless communication systems employing ultra-massive multiple-input multiple-output (MIMO) technologies with long traveling paths. Considering frequency-dependent diffuse scattering, which is a special property of THz channels different from millimeter wave (mmWave) channels, the relative angles and delays of rays within one cluster will evolve in the frequency domain. Then, a corresponding simulation model is proposed with discrete angles calculated using the method of equal area (MEA). The statistical properties of the proposed theoretical and simulation models are derived and compared, showing good agreements. The accuracy and flexibility of the proposed simulation model are demonstrated by comparing the simulation results of the relative angle spread and root mean square (RMS) delay spread with corresponding measurements.

**Index Terms**—6G, THz GBSM, ultra-massive MIMO, long traveling paths, space-time-frequency non-stationarity.

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THE peak data rate and connection density of the fifth generation (5G) wireless communication system are 20 gigabits per second (Gbps) and  $10^6$  devices/km<sup>2</sup>, respectively [1]. It is expected that the sixth generation (6G) wireless system will reach terabits per second (Tbps) level in terms of the peak data rate and  $10^7$ – $10^8$  devices/km<sup>2</sup> in terms of connection density [2]–[4]. To meet the massive data flow and massive connectivity requirements in 6G, increasing transmission bandwidth and improving spectrum efficiency are potential solutions. Terahertz (THz) communication has the ability to provide more than one hundred gigahertz (GHz) bandwidth [5] and can theoretically achieve ultra-high transmission rate of 100 Gbps or even higher [6]. By filling the gap between millimeter wave (mmWave) and optical wireless communication bands, THz communication has attracted great interests worldwide and been considered as one of the most promising 6G technologies. It has plenty of promising applications such as data center [7], [8] and kiosk downloading [9], [10], which support short-range (about 1 m) communications between fixed devices and terminal equipment such as smart phones. THz communications can also be applied to smart rail systems [11]–[13] by providing high data rate transmissions for passengers. In addition, the small size of THz devices makes nanoscale communications possible such as chip-to-chip [14], [15], computer motherboard links [16], and intra-body communications [17]–[20].

THz channel models that can accurately reflect THz channel characteristics are prerequisite for the design, optimization, and performance evaluation of THz wireless communication systems. The investigation of channel characteristics is very important for accurate channel modeling. Due to the high frequency and large bandwidth of THz communications, propagation mechanisms of THz bands are quite different from those of lower frequency bands such as mmWave bands. The THz propagation mechanisms were studied in [21]–[27]. In [21] and [22], THz measurements and modeling of multiple reflection effects in different materials were introduced. The reflection loss showed great dependence on frequency and materials and could be calculated by Kirchhoff theory. According to the measurement in [23], high-order paths were very hard to be detected due to high reflection loss which means that the number of multipaths is limited. The diffusely scattered propagation was investigated in [24]–[28]. In [24], the detected signal powers in all directions

for different materials were measured and simulated. Frequency-dependent scattering was also measured and simulated in [25] and [26]. The wavelength of THz waves is comparable to the roughness of some common materials. As a result, more power is diffusely scattered when frequency increases. Most of the diffusely scattered rays surround the specular reflected paths. In this case, scattered rays far away from the specular reflection points can be neglected [27].

Apart from investigations on THz channel characteristics, a number of THz channel models were proposed for THz communication systems. In [29], a multi-ray ray tracing channel model for THz indoor communication was presented and validated with experiments. In [30], a three-dimensional (3D) time-variant THz channel model based on ray tracing was investigated for dynamic environments. However, channel models based on ray tracing methods are not general and flexible. In [31], a stochastic THz indoor channel model considering the frequency dispersion was presented and verified by ray tracing. In [32], the authors investigated root mean square (RMS) delay spread and angular spread that were modeled by second order polynomial parameters for THz indoor communications. However, the existing stochastic THz channel models cannot show the unique propagation characteristics of THz bands such as frequency-dependent scattering.

In the existing THz channel models, massive multiple-input multiple-output (MIMO) were rarely mentioned. However, in THz communication systems, ultra-massive MIMO technologies employing hundreds or even thousands of antennas are considered as one of the solutions to compensate the high path loss [33] and are expected to be utilized in 6G [3], [4]. Massive MIMO channel models and measurements considering spatial non-stationarity were studied in [34]–[39]. In [34], massive MIMO channel measurements and models were summarized. In [40]–[42], channel measurements for massive MIMO channels in different scenarios at mmWave were presented. A novel 3D geometric-based stochastic model (GBSM) based on homogeneous Poisson point process was proposed for mmWave channels [42]. A GBSM for mobile-to-mobile scenarios for mmWave bands was presented in [43]. However, the existing massive MIMO channel models have only considered characteristics of sub-6GHz and mmWave bands, and are not suitable for THz communication systems because propagation mechanisms in THz bands are quite different from those of lower frequencies.

In addition, time variant channels caused by long traveling paths also need to be characterized in THz communication systems. It should be noted that for a realistic application of THz communications, the range of movement is not necessarily very long. For example, in some typical application scenarios such as movement of human body, even a short traveling path of several meters is quite long compared with the wavelength of THz signals. Unlike high mobility scenarios such as high-speed train and vehicle-to-vehicle communications in fifth generation (5G) systems, THz communications are usually applied in relatively static environments. The non-stationarity in the time domain is caused by the continuous moving of the transmitter or receiver over a long distance.

To the best of the authors knowledge, stochastic space-time-frequency non-stationary GBSMs for massive MIMO THz channels are still missing in the literature. We have done some early investigations in [44], [45]. However, the simulation models of THz channels were not studied in [45]. The major contributions and novelties of this paper are listed as follows.

- 1) A novel theoretical space-time-frequency non-stationary GBSM for ultra-massive MIMO THz channels considering long traveling paths is first proposed. The non-stationarity in space, time, and frequency domains caused by ultra-massive MIMO, long traveling paths, and large bandwidths, respectively, are considered.
- 2) The statistical properties of the theoretical model such as space-time-frequency correlation function (STFCF), time autocorrelation function (ACF), spatial cross-correlation function (CCF), and frequency correlation function (FCF) are derived.
- 3) The corresponding simulation model with discrete angles generated by the method of equal area (MEA) is then proposed. Its statistical properties are derived, verified by simulation results, and compared with those of the theoretical model, showing good agreements. Some simulated statistical properties are also compared with corresponding measurements, illustrating the validity and flexibility of the proposed THz simulation model.

The remainder of this paper is organized as follows. In Section II, the proposed theoretical THz GBSM is described in detail and the channel impulse response (CIR) is presented. In Section III, statistical properties of the theoretical THz channel model are derived. Then, the corresponding simulation model is proposed with discrete angles calculated using the MEA and its statistical properties are derived in Section IV. In Section V, statistical properties of the theoretical model and simulation model, simulation results, and measurements are compared and discussed. Finally, conclusions are drawn in Section VI.

## II. A 3D THZ NON-STATIONARY THEORETICAL MODEL

### A. Description of the Channel Model

In this sub-section, a 3D non-stationary THz massive MIMO channel model is proposed. The proposed model is illustrated in Fig. 1. Both transmitted antennas (Tx) and received antennas (Rx) are equipped with a massive number of antenna elements. To simplify the calculation, uniform linear arrays (ULAs) are assumed in this model. We assume that Tx has  $N_T$  antenna elements with the same distance  $\delta_T$ . It should be noted that only propagation model is studied so that each element in the array is assumed omni-directional. The direction of the Tx is represented by the elevation and azimuth angles  $\beta^T$  and  $\alpha^T$ , respectively. Rx is represented similarly. The  $p$ th transmit and  $q$ th receive antenna element are denoted by  $A_p^T$  and  $A_q^R$ , respectively. The position vector of the  $A_p^T$  from the center of the transmitted array  $\vec{\delta}_p$  and  $A_q^R$  from the center of the received array  $\vec{\delta}_q$  are expressed by

$$\vec{\delta}_p = \delta_p \cdot \begin{bmatrix} \cos \beta^T \cos \alpha^T \\ \cos \beta^T \sin \alpha^T \\ \sin \beta^T \end{bmatrix} \quad (1)$$

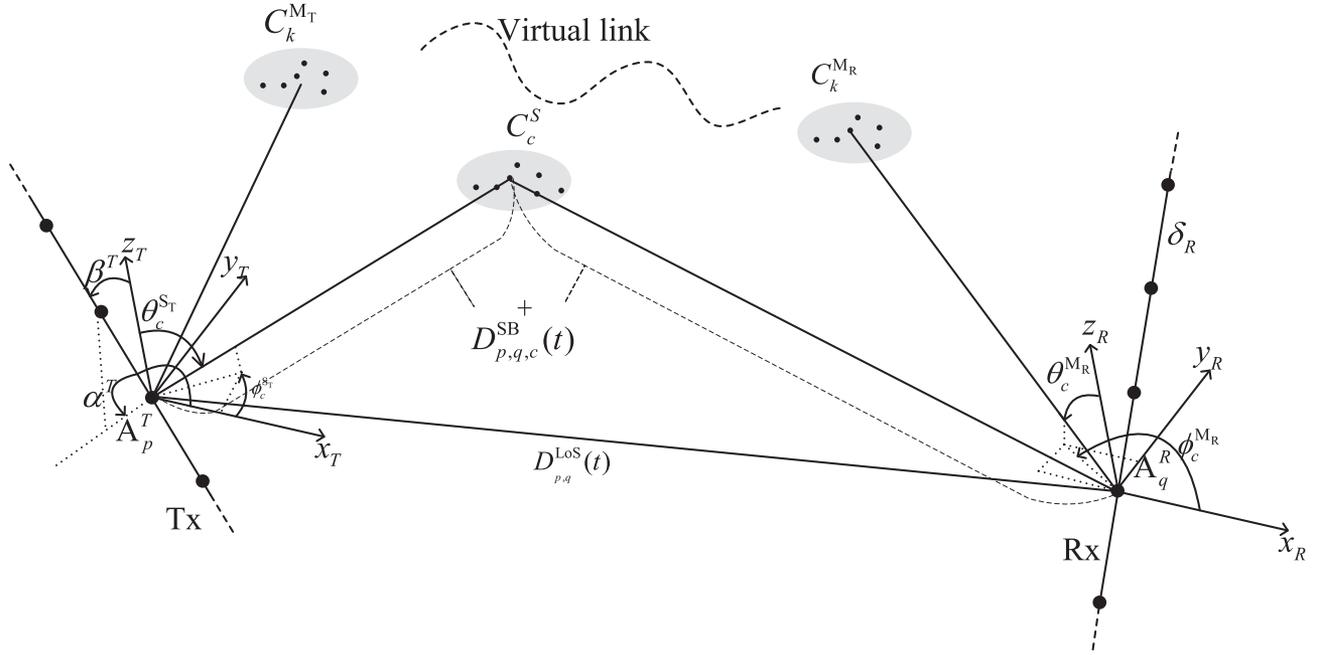


Fig. 1. A 3D THz GBSM for massive MIMO communication systems.

TABLE I  
DEFINITIONS OF MAIN PARAMETERS FOR THE PROPOSED THZ MASSIVE MIMO CHANNEL MODEL

Parameters	Definitions
$\delta_T, \delta_R$	Distances between consecutive elements in the Tx and Rx array, respectively
$D$	Distance between the center of Tx and Rx
$D_{p,q}^{\text{LoS}}(t)$	Distance from $A_p^T$ to $A_q^R$
$D_{p,q,c}^{\text{SB}}(t)$	Total distance of the path: $A_p^T - C_c^S - A_q^R$
$D_{p,q,c,l}^{\text{SB}}(t, f_i)$	Total distance of the path: $A_p^T - C_{c,l}^S - A_q^R$
$D_{p,q,k}^{\text{MB}}(t)$	Total distance of the path: $A_p^T - C_k^{\text{MT}} - C_k^{\text{MR}} - A_q^R$ +
$D_{p,q,k,m}^{\text{MB}}(t)$	Total distance of the path: $A_p^T - C_{k,m}^{\text{MT}} - C_{k,m}^{\text{MR}} - A_q^R$
$\beta^{\text{T(R)}}, \alpha^{\text{T(R)}}$	Elevation and azimuth angles of the Tx(Rx) array, respectively
$\theta^{\text{LoS}}, \phi^{\text{LoS}}$	Elevation and azimuth angles of the Rx with respect to the Tx, respectively
$\theta_{p(q),c}^{\text{ST(R)}}, \phi_{p(q),c}^{\text{ST(R)}}(t)$	Elevation and azimuth angles of $C_c^{\text{ST(R)}}$ , respectively
$\theta_{p(q),c,l}^{\text{ST(R)}}(t, f_i), \phi_{p(q),c,l}^{\text{ST(R)}}(t, f_i)$	Elevation and azimuth angles of the scatterer $C_{c,l}^{\text{ST(R)}}$ , respectively
$\theta_{p(q),k}^{\text{MT(R)}}, \phi_{p(q),k}^{\text{MT(R)}}(t)$	Elevation and azimuth angles of $C_k^{\text{MT(R)}}$ , respectively
$\theta_{p(q),k,m}^{\text{MT(R)}}(t, f_i), \phi_{p(q),k,m}^{\text{MT(R)}}(t, f_i)$	Elevation and azimuth angles of the scatterer $C_{k,m}^{\text{ST(R)}}$ , respectively
$\zeta^{\text{R}}, \xi^{\text{R}}$	Elevation and azimuth angles of the velocity of the Rx, respectively

$$\vec{\delta}_q = \delta_q \cdot \begin{bmatrix} \cos \beta^{\text{R}} \cos \alpha^{\text{R}} \\ \cos \beta^{\text{R}} \sin \alpha^{\text{R}} \\ \sin \beta^{\text{R}} \end{bmatrix} \quad (2)$$

with  $\delta_p = \frac{N_T - 2p + 1}{2} \delta_T$  and  $\delta_q = \frac{N_R - 2q + 1}{2} \delta_R$ . In addition, the speed of Rx is denoted by  $v^{\text{R}}$ . The elevation and azimuth angles of the speed are represented by  $\zeta^{\text{R}}$  and  $\xi^{\text{R}}$ , respectively.

The concept of cluster is proposed [46] to simplify the analysis of multipaths. In THz band, the wavelength of the carrier frequency is less than one millimeter and comparable to the surface roughness of some common objects such as furniture and walls. In this model, each cluster is comprised of diffusely scattering rays from the rough surface. The center of cluster is considered

as the specular reflected point. According to the study in [24], the power and angle of these clusters are frequency-dependent.

The received signal at the Rx is composed of the line of sight (LoS),  $C_S$  single-bounce clusters (SBCs), and  $C_M$  multi-bounce clusters (MBCs). In the picture, only the  $c$ th SBC and  $k$ th MBC are represented for clarity. Each MBC consists of two clusters at both Tx and Rx connected by a virtual link. For the  $k$ th MBC the transmit-side and receive-side MBC are denoted as  $C_k^{\text{MT}}$  and  $C_k^{\text{MR}}$ , respectively. The  $c$ th SBC is denoted by  $C_c^{\text{S}}$ . Both SBCs and MBCs are comprised of infinite scatterers. The main parameters are defined in Table I.

Considering the frequency domain non-stationarity in the propagation channel, the whole band is divided into  $N_F$  small sub-bands in which the channel is considered stationary in

frequency domain [29]. The CIR of sub-band  $h_{p,q}(t, \tau, f_i)$  is represented as

$$h_{p,q}(t, \tau, f_i) = h_{p,q}^{\text{LoS}}(t, \tau, f_i) + \sum_{c=1}^{C_{\text{SB}}} h_{p,q,c}^{\text{SB}}(t, \tau, f_i) + \sum_{k=1}^{C_{\text{MB}}} h_{p,q,k}^{\text{MB}}(t, \tau, f_i) \quad (3)$$

where LoS, SB, and MB refer to line of sight, single bounce, and multi bounce components, respectively. In (3), the LoS component is represented as

$$h_{p,q}^{\text{LoS}}(t, \tau, f_i) = \sqrt{\frac{K}{K+1}} \times e^{-j(2\pi f_i \tau_{p,q}^{\text{LoS}}(t))} \delta(\tau - \tau_{p,q}^{\text{LoS}}(t)) \quad (4)$$

where  $K$  is the Rician factor. The delay  $\tau_{p,q}^{\text{LoS}}(t)$  is given by  $D_{p,q}^{\text{LoS}}(t)/c_0$  where  $c_0$  refers to the speed of light. The distance between  $A_p^T$  and  $A_q^R$  is calculated by the vector  $\vec{D}_{p,q}^{\text{LoS}}(t) = \|\vec{D}_{p,q}^{\text{LoS}}(t)\|$  where  $\|\cdot\|$  calculates the Frobenius norm. The  $\vec{D}_{p,q}^{\text{LoS}}(t)$  is expressed as

$$\vec{D}_{p,q}^{\text{LoS}}(t) = \vec{D} + \vec{\delta}_q - \vec{\delta}_p + \vec{v}^R \cdot t \quad (5)$$

where

$$\vec{D} = D \cdot \begin{bmatrix} \cos \theta^{\text{LoS}} \cos \phi^{\text{LoS}} \\ \cos \theta^{\text{LoS}} \sin \phi^{\text{LoS}} \\ \sin \theta^{\text{LoS}} \end{bmatrix} \quad (6)$$

$$\vec{v}^R = v^R \begin{bmatrix} \cos \zeta^R \cos \xi^R \\ \cos \zeta^R \sin \xi^R \\ \sin \zeta^R \end{bmatrix}. \quad (7)$$

The SB components and the MB components can be expressed as

$$h_{p,q,c}^{\text{SB}}(t, \tau, f_i) = \sqrt{\frac{1}{K+1}} \lim_{L_c \rightarrow \infty} \sum_{l=1}^{L_c} \sqrt{\frac{P_c^{\text{SB}}}{L_c}} e^{-j(2\pi f_i \tau_{p,q,c,l}^{\text{SB}}(t) - \Theta_{c,l}^{\text{SB}})} \delta(\tau - \tau_{p,q,c,l}^{\text{SB}}(t)) \quad (8)$$

$$h_{p,q,k}^{\text{MB}}(t, \tau, f_i) = \sqrt{\frac{1}{K+1}} \lim_{M_k \rightarrow \infty} \sum_{m=1}^{M_k} \sqrt{\frac{P_k^{\text{MB}}}{M_k}} e^{-j(2\pi f_i \tau_{p,q,k,m}^{\text{MB}}(t) - \Theta_{k,m}^{\text{MB}})} \delta(\tau - \tau_{p,q,k,m}^{\text{MB}}(t)) \quad (9)$$

where  $\Theta_{c,l}^{\text{SB}}$  and  $\Theta_{k,m}^{\text{MB}}$  are uniformly distributed over  $(0, 2\pi)$ . The  $L_c$  and  $M_k$  refer to the number of rays for the  $c$ th single-bounce cluster and the  $k$ th multi-bounce cluster, respectively. In addition,  $P_c^{\text{SB}}$  and  $P_k^{\text{MB}}$  are the frequency-dependent power of corresponding clusters. The symbols  $\tau_{p,q,c,l}^{\text{SB}}(t)$  and  $\tau_{p,q,k,m}^{\text{MB}}(t)$  are the delays of corresponding rays.

The delay  $\tau_{p,q,c,l}^{\text{SB}}(t)$  of the  $l$ th ray in the  $c$ th SBC is composed of two parts, i.e.,

$$\tau_{p,q,c,l}^{\text{SB}}(t) = \tau_{p,q,c}^{\text{SB}}(t) + \Delta\tau_{p,q,c,l}^{\text{SB}}(t) \quad (10)$$

where  $\tau_{p,q,c}^{\text{SB}}(t)$  is the delay of the path  $A_p^T - C_c^S - A_q^R$ . Here,  $C_c^S$  represents the center of the cluster so this path is the specular

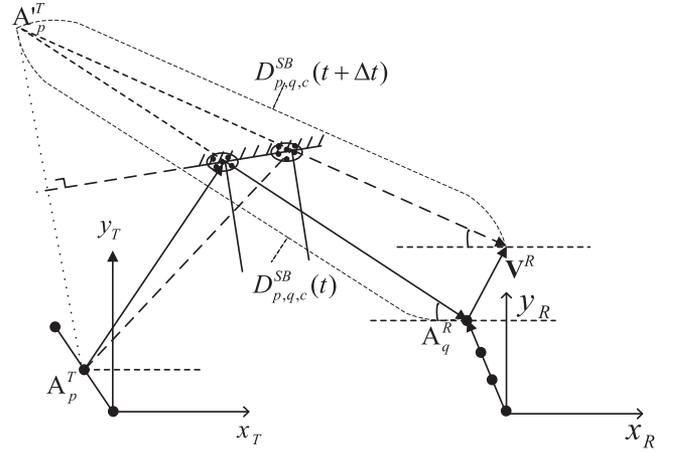


Fig. 2. Geometric relationship of the time-variant path via the SBC.

reflection path of this cluster. The relative delay with respect to this specular reflection path is denoted by  $\Delta\tau_{p,q,c,l}^{\text{SB}}(t)$ .

To obtain the  $\Delta\tau_{p,q,c,l}^{\text{SB}}(t)$ , we need to generate the initial delay between the center of Tx and Rx arrays via all the clusters at initial time  $\tau_c^{\text{SB}}$ . The initial cluster delay  $\tau_c^{\text{SB}}(t_0)$  is generated by random variables  $\Delta\tau_{c,\text{SB}}$ [31], where  $\Delta\tau_{c,\text{SB}}$  is defined as the time interval of arrival between two adjacent clusters for the first order cluster and the second order cluster, respectively. For the first cluster,  $\Delta\tau_{1,\text{SB}}$  is the time interval compared to the LoS path. So, we have

$$\tau_c^{\text{SB}}(t_0) = \begin{cases} D/c_0 + \Delta\tau_{c,\text{SB}}, & c = 1; \\ \tau_{c-1} + \Delta\tau_{c,\text{SB}}, & 2 \leq c \leq C_{\text{SB}}. \end{cases} \quad (11)$$

A similar method is used to generate MBCs expressed as

$$\tau_k^{\text{MB}}(t_0) = \begin{cases} D/c_0 + \Delta\tau_{k,\text{MB}}, & k = 1; \\ \tau_{k-1} + \Delta\tau_{k,\text{MB}}, & 2 \leq k \leq C_{\text{MB}}. \end{cases} \quad (12)$$

Here,  $\Delta\tau_{c,\text{SB}}$  and  $\Delta\tau_{k,\text{MB}}$  are exponential random variables with the mean values  $\mu_{\Delta\tau_{\text{SB}}}$  and  $\mu_{\Delta\tau_{\text{MB}}}$ , respectively.

Considering the long traveling paths, after we generate the initial delay for SBC at  $t$ , the total delay of the cluster at  $t + \Delta t$  can be calculated according to the geometric relationship in Fig. 2. When the Tx is fixed and the Rx moves, we extend the reflection surface closest to the Tx and obtain the mirror point of the Tx. When the Rx moves in a short period, the mirror point keeps static and the cluster slides for a short length at the surface. The solid line is the initial path and the dashed line represents the path after the Rx moves. Similarly, when the Rx is fixed and the Tx moves, we can also find the mirror point of the Rx for calculation. This method jointly considers the movement of the clusters and the Tx/Rx.

We denote  $A_p^T$  to represent the mirror point of  $A_p^T$ . It is clear that the distance from  $A_p^T$  to  $A_q^R$  at time  $t$  equals  $D_{p,q,c}^{\text{SB}}(t)$ . The vector  $\vec{D}_{p,q,c}^{\text{SB}}(t)$  from  $A_p^T$  to  $A_q^R$  is

$$\vec{D}_{p,q,c}^{\text{SB}}(t) = D_{p,q,c}^{\text{SB}}(t) \cdot \begin{bmatrix} \cos \theta_{q,c}^{\text{SR}} \cos \phi_{q,c}^{\text{SR}} \\ \cos \theta_{q,c}^{\text{SR}} \sin \phi_{q,c}^{\text{SR}} \\ \sin \theta_{q,c}^{\text{SR}} \end{bmatrix}. \quad (13)$$

The vector  $\vec{D}_{p,q,c}^{\text{SB}}(t + \Delta t)$  at time  $t + \Delta t$  is easily calculated as

$$\begin{aligned} \vec{D}_{p,q,c}^{\text{SB}}(t + \Delta t) &= \vec{D}_{p,q,c}^{\text{SB}}(t) + \vec{v}^{\text{R}} \Delta t \\ &= D_{p,q,c}^{\text{SB}}(t) \begin{bmatrix} \cos \theta_{q,c}^{\text{SR}} \cos \phi_{q,c}^{\text{SR}} \\ \cos \theta_{q,c}^{\text{SR}} \sin \phi_{q,c}^{\text{SR}} \\ \sin \theta_{q,c}^{\text{SR}} \end{bmatrix} \\ &\quad + v_{\text{R}} \Delta t \cdot \begin{bmatrix} \cos \zeta^{\text{R}} \cos \xi^{\text{R}} \\ \cos \zeta^{\text{R}} \sin \xi^{\text{R}} \\ \sin \zeta^{\text{R}} \end{bmatrix}. \end{aligned} \quad (14)$$

The new distance from  $A_p^{\text{T}}$  to  $A_q^{\text{R}}$  at time  $(t + \Delta t)$  denoted by  $D_{p,q,c}^{\text{SB}}(t + \Delta t)$  can be calculated by

$$D_{p,q,c}^{\text{SB}}(t + \Delta t) = \left\| \vec{D}_{p,q,c}^{\text{SB}}(t + \Delta t) \right\|. \quad (15)$$

For the MBCs, when the Rx is moving, the mirror point of the Tx can be obtained by extending the line between Rx and last reflection point with the total path length. The virtual link is contained in the extended line so that this method can also be adopted in the MBCs. Considering the spatial non-stationarity of ultra-massive MIMO, the distance from  $A_p^{\text{T}}$  to  $A_q^{\text{R}}$  can be analogously obtained by using  $\vec{\delta}_q$  to replace  $\vec{v}^{\text{R}} \Delta t$  and can be calculated by

$$D_{p,q,c}^{\text{SB}}(t) = \left\| \vec{D}_c^{\text{SB}}(t) + \vec{\delta}_p \right\| \quad (16)$$

where

$$\vec{D}_c^{\text{SB}}(t) = D_c^{\text{SB}}(t) \begin{bmatrix} \cos \theta_c^{\text{SR}} \cos \phi_c^{\text{SR}} \\ \cos \theta_c^{\text{SR}} \sin \phi_c^{\text{SR}} \\ \sin \theta_c^{\text{SR}} \end{bmatrix}. \quad (17)$$

Here  $D_c^{\text{SB}}(t)$  represents the total distance from the center of Tx to Rx via  $C_c^{\text{S}}$ .

The power of the cluster  $P_c^{\text{SB}}$  and  $P_k^{\text{MB}}$  is generated according to the delay of the paths [31]. We use SBC as an example and they can be expressed as

$$P_c^{\text{SB}}(\text{dB}) = -n_\tau \cdot (\tau_c^{\text{SB}} - \tau^{\text{LoS}}) + \Delta a_i \quad (18)$$

where  $n_\tau$  is the temporal decay coefficient. Moreover,  $\Delta a_i$  is a Gaussian distributed random variable describing the random deviation of different clusters. After we generate the power of all clusters, we need to normalize these by the total power.

### B. Frequency-Dependent Parameters

In THz bands, wavelength is comparable to the roughness of the reflection surface. In addition, scattering rays are closely related to the frequency, which is quite different from lower frequencies. The distribution of reflected power from one incident wave can be measured by scattering coefficient which was investigated in [27]. For an incident wave, the path with the strongest reflection is the specular reflection. However, the scattering around the specular reflection path also need to be considered. In [27], the average scattering coefficient  $\langle \rho \rho^* \rangle_\infty$  is

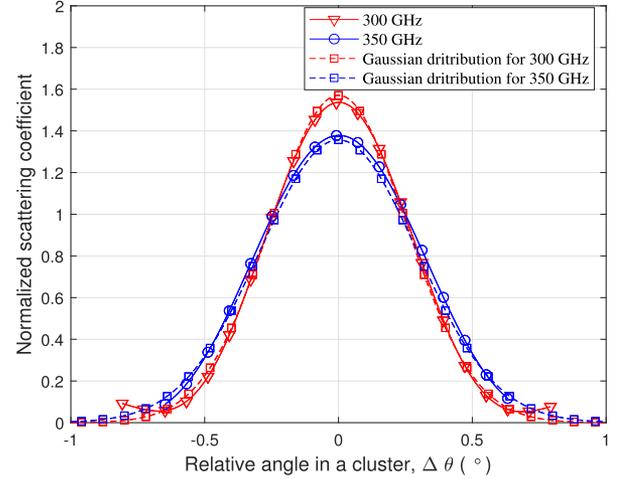


Fig. 3. The comparison of normalized scattering coefficients at different frequencies and fitting with Gaussian distribution ( $\sigma = 0.25$  at 300 GHz,  $\sigma = 0.29$  at 350 GHz,  $l_{\text{corr}} = 2.3$  mm,  $l_x = l_y = 10l_{\text{corr}}$ ,  $\sigma_h = 0.13$  mm).

given, and can be calculated as

$$\langle \rho \rho^* \rangle_\infty = e^{-g} \cdot \left( \rho_0^2 + \frac{\pi l_{\text{corr}}^2 F^2}{A} \sum_{m=1}^{\infty} \frac{g^m}{m! m} e^{-\frac{v_{xy}^2 l_{\text{corr}}^2}{4m}} \right) \quad (19)$$

with

$$\rho_0 = \text{sinc}(v_x l_x) \cdot \text{sinc}(v_y l_y) \quad (20)$$

$$v_x = k \cdot (\sin(\theta_1) - \sin(\theta_2) \cos(\theta_3)) \quad (21)$$

$$v_y = k \cdot (-\sin(\theta_2) \sin(\theta_3)) \quad (22)$$

$$v_{xy} = \sqrt{v_x^2 + v_y^2} \quad (23)$$

$$F = \frac{1 + \cos(\theta_1) \cos(\theta_2) - \sin(\theta_1) \sin(\theta_2) \cos(\theta_3)}{\cos(\theta_1) (\cos(\theta_1) + \cos(\theta_2))} \quad (24)$$

$$g = k^2 \sigma_h^2 (\cos(\theta_1) + \cos(\theta_2))^2. \quad (25)$$

Here,  $l_x \cdot l_y$  calculates the rectangular surface area. The parameters  $\sigma_h$  and  $l_{\text{corr}}$  represent the standard deviation of heights and the surface correlation length, respectively, given in [27].  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  represent the incident angle, exit angle, and the angle between incident plane and exit plane, respectively. Parameter  $k$  is the wave number decided by frequency. According to these equations, the normalized scattering coefficients at different frequencies are compared in Fig. 3. It should be noticed that only the main lobe of the scattering beam is taken into consideration. From Fig. 3, we find that Gaussian distribution fits well with the main lobe at different frequencies. The standard deviation  $\sigma$  of scattered wave at 300 GHz is 0.25 and is 0.29 at 350 GHz. This means that the relative angle in each cluster can be considered as zero mean Gaussian distributed random variables.

Here,  $\phi_{p,c,l}^{\text{ST}}$  is shown as an example. The azimuth angle of the  $l$ th ray in the  $c$ th cluster is

$$\phi_{p,c,l}^{\text{ST}} = \phi_{p,c}^{\text{ST}} + \Delta \phi_{p,c,l}^{\text{ST}} \quad (26)$$

where  $\Delta\phi_{p,c,l}^{\text{ST}}$  is the relative angle for the  $l$ th ray in the  $c$ th cluster with respect to  $\phi_{p,c}^{\text{ST}}$  and follows a Gaussian distribution with standard deviation of  $\sigma_{c,\phi}^{\text{ST}}(f_i)$ . The standard deviation  $\sigma_{c,\phi}^{\text{ST}}(f_i)$  is considered as an exponential distributed random variable according to [32]

$$f_\mu(x) = \frac{1}{\mu} e^{-\frac{x}{\mu}} \quad (27)$$

where  $\mu$  is the mean value of azimuth for the  $c$ th cluster described by parameter  $\mu_{c,\phi}^{\text{ST}}$ . Relative angles need to be regenerated at new frequencies and can be modeled as

$$\sigma_{c,\phi}^{\text{ST}}(f_i) = \sigma_{c,\phi}^{\text{ST}}(f_0) \times (f_i/f_0)^{\rho_\phi^{\text{ST}}} \quad (28)$$

where  $\rho_\phi^{\text{ST}}$  represents the frequency-dependent factor for relative angle. The relative elevation and azimuth angles of clusters are considered as independent.

According to the relative angle, the total time of arrival of different scattering paths can be calculated by the geometric relationship as

$$D_{p,q,c,l}^{\text{SB}} = \sqrt{D_{p,q,c,l}^{\text{SB,V}^2} + D_{p,q,c,l}^{\text{SB,H}^2}} \quad (29)$$

where  $D_{p,q,c,l}^{\text{SB,V}}$  and  $D_{p,q,c,l}^{\text{SB,H}}$  represent the vertical and horizontal distances of the path length, respectively. They can be calculated by

$$D_{p,q,c,l}^{\text{SB,V}} = D_{p,q,c}^{\text{SB}} \sin(\theta_{q,c}^{\text{SR}}) r_c^{\text{SR}} / \cos(\Delta\theta_{p,c,l}^{\text{SR}}) + D_{p,q,c}^{\text{SB}} \sin(\theta_{q,c}^{\text{SR}}) r_c^{\text{ST}} / \cos(\Delta\theta_{p,c,l}^{\text{ST}}) \quad (30)$$

$$D_{p,q,c,l}^{\text{SB,H}} = D_{p,q,c}^{\text{SB}} \cos(\theta_{q,c}^{\text{SR}}) r_c^{\text{SR}} / \cos(\Delta\phi_{p,c,l}^{\text{SR}}) + D_{p,q,c}^{\text{SB}} \cos(\theta_{q,c}^{\text{SR}}) r_c^{\text{ST}} / \cos(\Delta\phi_{p,c,l}^{\text{ST}}) \quad (31)$$

where  $r_c^{\text{ST(R)}}$  is the ratio of the distance between the cluster and the Tx(Rx) to the total distance. For SBCs, it is clear that  $r_c^{\text{ST}} + r_c^{\text{SR}} = 1$ . For MBCs,  $r_c^{\text{ST}} + r_c^{\text{SR}} < 1$ . When relative angles are updated in the frequency domain, corresponding total distances are also updated according to the geometric relationship in (29)–(31).

### C. Channel Transfer Function

In this model, we divide the whole band into many small sub-bands with different CIR. As a result, we need to calculate the CTF of each sub-band and then combine them together. Fig. 4 is an example of adding up two sub-band channels. Similarly, we can add up more sub-band channels in the same manner.

The CTF of sub-band channel  $H_{p,q}(t, f, f_i)$  is calculated as the Fourier transformation of the sub-band CIR, i.e.,

$$H_{p,q}(t, f, f_i) = \int_{-\infty}^{\infty} h_{p,q}(t, \tau, f_i) e^{-j2\pi f\tau} d\tau, f \in f_i. \quad (32)$$

The CTF of the whole band is given by

$$H_{p,q}(t, f) = \sum_{i=1}^{N_F} H_{p,q}(t, f, f_i). \quad (33)$$

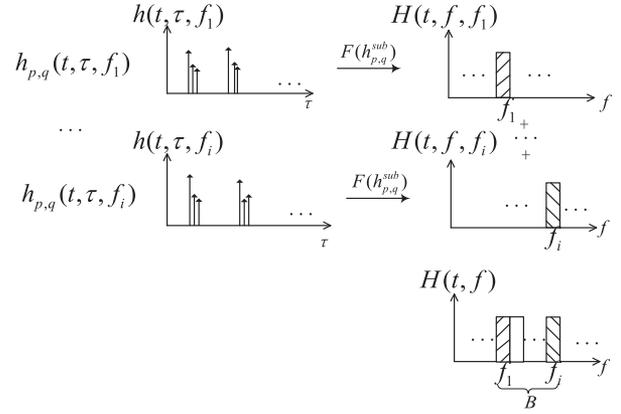


Fig. 4. An example of adding up two sub-band channels.

## III. STATISTICAL PROPERTIES OF THE THEORETICAL MODEL

### A. STFCF

The correlation between two arbitrary CIRs,  $h_{p,q}(t, \tau, f_i)$  and  $h_{p,q'}(t + \Delta t, \tau, f_i + \Delta f)$  at different times, spaces, and frequencies can be calculated by superimposing the correlation of all the clusters with the assumption of uncorrelated scattering. The correlation function of two arbitrary channels can be calculated as follows

$$R_h(p, q, p', q', t, \Delta t, f_i, \Delta f) = E [h_{p,q}(t, \tau, f_i) h_{p',q'}^*(t + \Delta t, \tau, f_i + \Delta f)] \quad (34)$$

where  $(\cdot)^*$  is the complex conjugate operation, and  $E[\cdot]$  calculates the expectation value by taking all 3D directions at both Tx and Rx sides into consideration. With the assumption of uncorrelated scatterers, the STFCF can be also written as

$$R_h(p, q, p', q', t, \Delta t, f_i, \Delta f) = R_h^{\text{LoS}}(p, q, p', q', t, \Delta t, f_i, \Delta f) + \sum_{c=1}^{C_{\text{SB}}} R_{h,c}^{\text{SB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) + \sum_{k=1}^{C_{\text{MB}}} R_{h,k}^{\text{MB}}(p, q, p', q', t, \Delta t, f_i, \Delta f). \quad (35)$$

– In the LoS case,

$$R_h^{\text{LoS}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{K}{K+1} e^{j2\pi(f_i\tau_{p,q}(t) - (f_i + \Delta f)\tau_{p',q'}(t + \Delta t))}. \quad (36)$$

– In the SB case,

$$R_{h,c}^{\text{SB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{P_c^{\text{SB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi(f_i\tau_{p,q}(t) - (f_i + \Delta f)\tau_{p',q'}(t + \Delta t))} f(\theta_{p,c}^{\text{ST}}) f(\phi_{p,c}^{\text{ST}}) f(\theta_{q,c}^{\text{SR}}) f(\phi_{q,c}^{\text{SR}}) d\theta_{p,c}^{\text{ST}} d\phi_{p,c}^{\text{ST}} d\theta_{q,c}^{\text{SR}} d\phi_{q,c}^{\text{SR}}. \quad (37)$$

– In the MB case,

$$R_{h,k}^{\text{MB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{P_k^{\text{MB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi(f_i\tau_{p,q}(t) - (f_i + \Delta f)\tau_{p',q'}(t + \Delta t))} f(\theta_{p,k}^{\text{MT}}) f(\phi_{p,k}^{\text{MT}}) f(\theta_{q,k}^{\text{MR}}) f(\phi_{q,k}^{\text{MR}}) d\theta_{p,k}^{\text{MT}} d\phi_{p,k}^{\text{MT}} d\theta_{q,k}^{\text{MR}} d\phi_{q,k}^{\text{MR}}. \quad (38)$$

### B. Time Variant ACF

The time-variant ACF reflects the correlation between two channels at different instants. It can be calculated by setting  $p' = p$ ,  $q' = q$  and  $\Delta f = 0$  in (34) and can be expressed as

$$r_h(p, q, t, \Delta t, f_i) = R_h(p, q, t, \Delta t, f_i) = r_h^{\text{LoS}}(p, q, t, \Delta t, f_i) + \sum_{c=1}^{C_{\text{SB}}} r_{h,c}^{\text{SB}}(p, q, t, \Delta t, f_i) + \sum_{k=1}^{C_{\text{MB}}} r_{h,k}^{\text{MB}}(p, q, t, \Delta t, f_i). \quad (39)$$

– In the LoS case,

$$r_h^{\text{LoS}}(p, q, t, \Delta t, f_i) = \frac{K}{K+1} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p,q}(t + \Delta t))}. \quad (40)$$

– In the SB case,

$$r_{h,c}^{\text{SB}}(p, q, t, \Delta t, f_i) = \frac{P_c^{\text{SB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p,q}(t + \Delta t))} f(\theta_{p,c}^{\text{ST}}) f(\phi_{p,c}^{\text{ST}}) f(\theta_{q,c}^{\text{SR}}) f(\phi_{q,c}^{\text{SR}}) d\theta_{p,c}^{\text{ST}} d\phi_{p,c}^{\text{ST}} d\theta_{q,c}^{\text{SR}} d\phi_{q,c}^{\text{SR}}. \quad (41)$$

– In the MB case,

$$r_{h,k}^{\text{MB}}(p, q, t, \Delta t, f_i) = \frac{P_k^{\text{MB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p,q}(t + \Delta t))} f(\theta_{p,k}^{\text{MT}}) f(\phi_{p,k}^{\text{MT}}) f(\theta_{q,k}^{\text{MR}}) f(\phi_{q,k}^{\text{MR}}) d\theta_{p,k}^{\text{MT}} d\phi_{p,k}^{\text{MT}} d\theta_{q,k}^{\text{MR}} d\phi_{q,k}^{\text{MR}}. \quad (42)$$

### C. Spatial CCF

From (34), the spatial CCF can be derived by imposing  $\Delta t = 0$  and  $\Delta f = 0$  and can be written as

$$\begin{aligned} \rho_h(p, q, p', q', t, f_i) &= R_h(p, q, p', q', t, f_i) \\ &= \rho_h^{\text{LoS}}(p, q, p', q', t, f_i) \\ &\quad + \sum_{c=1}^{C_{\text{SB}}} \rho_{h,c}^{\text{SB}}(p, q, p', q', t, f_i) \\ &\quad + \sum_{k=1}^{C_{\text{MB}}} \rho_{h,k}^{\text{MB}}(p, q, p', q', t, f_i). \end{aligned} \quad (43)$$

– In the LoS case,

$$\rho_h^{\text{LoS}}(p, q, p', q', t, f_i) = \frac{K}{K+1} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p',q'}(t))}. \quad (44)$$

– In the SB case,

$$\rho_{h,c}^{\text{SB}}(p, q, p', q', t, f_i) = \frac{P_c^{\text{SB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p',q'}(t))} f(\theta_{p,c}^{\text{ST}}) f(\phi_{p,c}^{\text{ST}}) f(\theta_{q,c}^{\text{SR}}) f(\phi_{q,c}^{\text{SR}}) d\theta_{p,c}^{\text{ST}} d\phi_{p,c}^{\text{ST}} d\theta_{q,c}^{\text{SR}} d\phi_{q,c}^{\text{SR}}. \quad (45)$$

– In the MB case,

$$\rho_{h,k}^{\text{MB}}(p, q, p', q', t, f_i) = \frac{P_k^{\text{MB}}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} e^{j2\pi f_i(\tau_{p,q}(t) - \tau_{p',q'}(t))} f(\theta_{p,k}^{\text{MT}}) f(\phi_{p,k}^{\text{MT}}) f(\theta_{q,k}^{\text{MR}}) f(\phi_{q,k}^{\text{MR}}) d\theta_{p,k}^{\text{MT}} d\phi_{p,k}^{\text{MT}} d\theta_{q,k}^{\text{MR}} d\phi_{q,k}^{\text{MR}}. \quad (46)$$

### D. FCF

The FCF is another important channel statistical property reflecting the correlation of the channels at different frequencies. It can be calculated by

$$\begin{aligned} T_h(p, q, t, f, \Delta f) &= E [H_{p,q}(t, f) \cdot H_{p,q}^*(t, f + \Delta f)] \\ &= E \left[ \int_{-\infty}^{\infty} h_{p,q}(t, \tau, f) e^{-j2\pi f \tau} d\tau \int_{-\infty}^{\infty} h_{p,q}(t, \tau, f + \Delta f) e^{-j2\pi f \tau} d\tau \right]. \end{aligned} \quad (47)$$

## IV. THE SIMULATION MODEL AND STATISTICAL PROPERTIES

### A. Description of the Simulation Model

In the aforementioned theoretical channel model, each cluster is composed of an infinite number of rays, which can not be implemented in hardware or software. According to the theoretical model, the simulation model comprises finite rays in each cluster expressed as

$$\begin{aligned} \tilde{h}_{p,q}(t, \tau, f_i) &= \tilde{h}_{p,q}^{\text{LoS}}(t, \tau, f_i) + \sum_{c=1}^{C_{\text{SB}}} \tilde{h}_{p,q,c}^{\text{SB}}(t, \tau, f_i) \\ &\quad + \sum_{k=1}^{C_{\text{MB}}} \tilde{h}_{p,q,k}^{\text{MB}}(t, \tau, f_i) \end{aligned} \quad (48)$$

where the LoS part is expressed as

$$\tilde{h}_{p,q}^{\text{LoS}}(t, \tau, f_i) = \sqrt{\frac{K}{K+1}} \times e^{-j(2\pi f_i \tau_{p,q}^{\text{LoS}}(t))} \delta(\tau - \tau_{p,q}^{\text{LoS}}(t)). \quad (49)$$

The SB and MB components of the simulation model are

$$\tilde{h}_{p,q,c}^{\text{SB}}(t, \tau, f_i) = \sqrt{\frac{P_c^{\text{SB}}}{K+1}} \sum_{l=1}^{L_c} \sqrt{\frac{1}{L_c}} e^{-j(2\pi f_i \tau_{p,q,c,l}^{\text{SB}}(t) - \Theta_{c,l}^{\text{SB}})} \delta(\tau - \tau_{p,q,c,l}^{\text{SB}}(t)) \quad (50)$$

$$\tilde{h}_{p,q,k}^{\text{MB}}(t, \tau, f_i) = \sqrt{\frac{P_k^{\text{MB}}}{K+1}} \sum_{m=1}^{M_k} \sqrt{\frac{1}{M_k}} e^{-j(2\pi f_i \tau_{p,q,c,m}^{\text{MB}}(t) - \Theta_{c,m}^{\text{MB}})} \delta(\tau - \tau_{p,q,c,m}^{\text{MB}}(t)). \quad (51)$$

In this simulation model, relative angles are discrete for simulation. In each cluster, maximum relative angle corresponds to maximum relative delay so that the discrete relative delay can be generated by relative angles. Hence, an appropriate parameter calculation method is necessary to approximate the properties of the theoretical channel model. In this simulation model, we apply the MEA [47] method to generate the discrete angles. In this simulation model, the MEA method is used to calculate limited discrete angles according to principle that the integral of the probability between two adjacent angles are equal.

Here, we use  $\theta_{p,c,l}^{\text{ST}}$  as an example to generate  $\sqrt{L_c}$  discrete values with the MEA method. The whole probability are divided into  $\sqrt{L_c}$  parts with the same area  $1/\sqrt{L_c}$ . According to the equation  $\int_{l-1}^l dF(x) = 1/\sqrt{L_c}$  where  $F(x)$  is the cumulative distribution function (CDF) of  $\theta_{p,c,l}^{\text{ST}}$ , then  $\sqrt{L_c}$  discrete angle can be obtained. Similarly, the  $\phi_{p,c,l}^{\text{ST}}$  can also generate  $\sqrt{L_c}$  discrete values. So there are  $L_c$  discrete values in this cluster. Meanwhile, the discrete  $\theta_{q,c,l}^{\text{SR}}$  and  $\phi_{q,c,l}^{\text{SR}}$  can also be obtained.

### B. Statistical Properties of the Simulation Model

In this sub-section, the statistical properties of the non-stationary THz simulated model are derived.

1) *STFCF*: The STFCF of the simulation model  $\tilde{R}_h(p, q, p', q', t, \Delta t, f, \Delta f)$  can be represented as

$$\begin{aligned} & \tilde{R}_h(p, q, p', q', t, \Delta t, f, \Delta f) \\ &= E \left[ \tilde{h}_{p,q}(t, f_i) \cdot \tilde{h}_{p',q'}^*(t + \Delta t, f + \Delta f) \right] \\ &= \tilde{R}_h^{\text{LoS}}(p, q, p', q', t, \Delta t, f_i, \Delta f) \\ &+ \sum_{c=1}^{C_{\text{SB}}} \tilde{R}_{n,c}^{\text{SB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) \\ &+ \sum_{k=1}^{C_{\text{MB}}} \tilde{R}_{h,k}^{\text{MB}}(p, q, p', q', t, \Delta t, f_i, \Delta f). \quad (52) \end{aligned}$$

The correlation function of the channel also consists of the LoS, SBCs, and MBCs. –In the LoS case,

$$\tilde{R}_h^{\text{LoS}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{K}{K+1} e^{j2\pi(f_i \tau_{p,q}(t) - (f_i + \Delta f) \tau_{p',q'}(t + \Delta t))}. \quad (53)$$

–In the SB case,

$$\tilde{R}_{h,c}^{\text{SB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{P_c^{\text{SB}}}{K+1} \sum_{l=1}^{L_c} e^{j2\pi(f_i \tau_{p,q}(t) - (f_i + \Delta f) \tau_{p',q'}(t + \Delta t))}. \quad (54)$$

–In the MB case,

$$\tilde{R}_{h,k}^{\text{MB}}(p, q, p', q', t, \Delta t, f_i, \Delta f) = \frac{P_k^{\text{MB}}}{K+1} \sum_{m=1}^{M_k} e^{j2\pi(f_i \tau_{p,q}(t) - (f_i + \Delta f) \tau_{p',q'}(t + \Delta t))}. \quad (55)$$

By setting partial parameters of  $(\Delta p, \Delta q, \Delta t, \Delta f)$  as 0, the STFCF can easily be simplified to time-variant ACF, spatial CCF, and FCF.

2) *The Delay PSD*: The delay PSD of the simulation model  $\Upsilon_{p,q}(t, \tau, f_i)$  is calculated as

$$\begin{aligned} \Upsilon_{p,q}(t, \tau, f_i) &= \left| \tilde{h}_{p,q}(t, \tau, f_i) \right|^2 \\ &= \left| \tilde{h}_{p,q}^{\text{LoS}}(t, \tau, f_i) \right|^2 + \sum_{c=1}^{C_{\text{SB}}} \left| \tilde{h}_{p,q,c}^{\text{SB}}(t, \tau, f_i) \right|^2 \\ &+ \sum_{k=1}^{C_{\text{MB}}} \left| \tilde{h}_{p,q,k}^{\text{MB}}(t, \tau, f_i) \right|^2. \quad (56) \end{aligned}$$

It should be noted that the time-space-frequency variant properties of delay PSD is caused by the time-space-frequency variant powers and delays.

3) *The Stationary Intervals*: The stationary interval is the time, distance, and frequency bandwidth during which the propagation channel can be considered as unchanged in time, space, and frequency domains, respectively. The stationary interval is defined as the maximum length within which the ACF of the time-space-frequency variant delay PSD exceeds the threshold [48]. Here we calculate the stationary interval in time and frequency domains expressed as  $I(\Delta t, \Delta f) = \inf\{\Delta t, \Delta f \mid R_{\Upsilon}(t, f, \Delta t, \Delta f) < c_{th}\}$  where  $\inf\{\cdot\}$  calculates the infimum of a function. The normalized ACF of the delay PSD  $R_{\Lambda}(t, f, \Delta t, \Delta f)$  is defined by

$$\begin{aligned} R_{\Lambda}(t, f_i, \Delta t, \Delta f) &= \\ & \frac{\int \Upsilon_{p,q}(t, \tau, f_i) \Upsilon_{p,q}(t_i + \Delta t, \tau, f_i + \Delta f) d\tau}{\max\left\{ \int \Upsilon_{p,q}^2(t, \tau, f_i) d\tau, \int \Upsilon_{p,q}^2(t_i + \Delta t, \tau, f_i + \Delta f) d\tau \right\}}. \quad (57) \end{aligned}$$

## V. RESULTS AND ANALYSIS

In this section, the statistical properties of the THz channel models are simulated and discussed. The frequency band is chosen from 300 GHz to 350 GHz. The numbers of antenna elements at the Tx and Rx are 256 at both Tx and Rx. Both  $\delta_T$  and  $\delta_R$  equal to half of wavelength at 325 GHz. The moving speed of Rx is  $v^R = 0.1$  m/s with the direction angle  $\zeta^R = 0$  and  $\xi^R = \frac{\pi}{3}$  while the Tx is fixed. The bandwidth of sub-band is

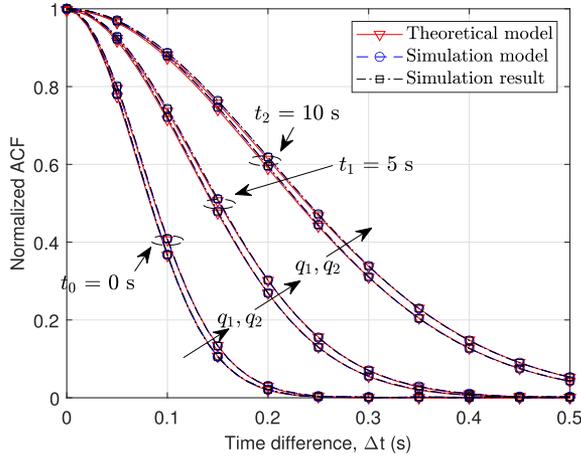


Fig. 5. The comparison of time-variant ACFs of theoretical model, simulation model, and simulation results for cluster  $C_1^S$  at  $t_0 = 0$  s,  $t_1 = 5$  s and  $t_2 = 10$  s with  $q_1 = 1$  and  $q_2 = 200$  ( $D = 3$  m,  $p = 1$ ,  $f_0 = 325$  GHz,  $v^R = 0.1$  m/s,  $\zeta^R = 0$ ,  $\xi^R = \frac{\pi}{3}$ ,  $\mu_{c,\theta}^{SR} = 1.4^\circ$ ,  $\mu_{c,\phi}^{SR} = 2.8^\circ$ ,  $r_c^{ST} = 0.4$ ).

0.1 GHz. It should be noted that it is less than the real stationary bandwidth to make sure that each sub-band in the simulation is frequency stationary. The number of rays in each cluster is  $L_c = M_c = 400$ .

#### A. ACF

The time ACF of the model can be calculated by setting  $\Delta p, \Delta q, \Delta f$  as 0. The comparison of theoretical model, simulation model, and simulation result at  $t_0 = 0$  s,  $t_1 = 5$  s, and  $t_2 = 10$  s of Cluster<sub>1</sub> at different antennas is shown in Fig. 5. From the results, we can observe that the simulation models fit well with the theoretical model and the simulation results. We can also observe different time ACFs at different time instants, showing the non-stationarity in time domain. The difference between different receive antennas can also be observed clearly showing the non-stationarity of ultra-massive MIMO.

#### B. Spatial CCF

The spatial CCFs of the theoretical model, simulation model, and simulation result for Cluster<sub>1</sub> at different time and different frequencies are shown in Fig. 6. We can see that the theoretical model, simulation model, and simulation result match very well. We can also observe significant differences at different time instants. Due to the traveling of the Rx, the channel shows non-stationarity in the time domain. In addition, we present the results in different frequencies showing unnegligible frequency non-stationarity. For higher frequencies, the spatial CCFs tend to be smaller.

#### C. FCF

The absolute values of FCFs for NLoS paths at different  $f_0 = 300$  GHz,  $f_1 = 325$  GHz, and  $f_2 = 350$  GHz for THz massive MIMO channel model are shown in Fig. 7. We can notice that differences among FCFs at different frequencies are

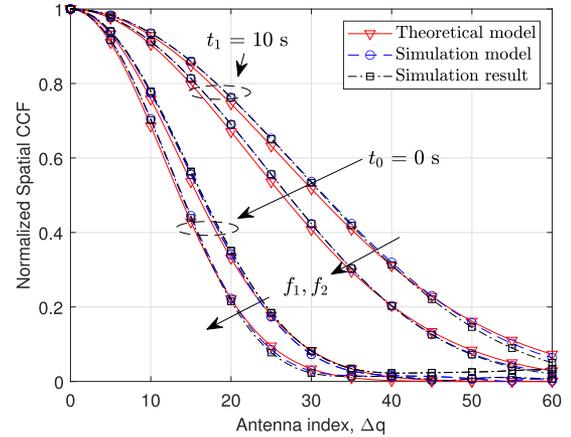


Fig. 6. The comparison of spatial CCFs of theoretical model, simulation model, and simulation results for cluster  $C_1^S$  ( $D = 3$  m,  $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $t_1 = 10$  s,  $f_1 = 300$  GHz,  $f_2 = 350$  GHz,  $v^R = 0.1$  m/s,  $\zeta^R = 0$ ,  $\xi^R = \frac{\pi}{3}$ ,  $\alpha^R = \frac{\pi}{3}$ ,  $\beta^R = \frac{\pi}{4}$ ,  $\mu_{c,\theta}^{SR} = 1.4^\circ$ ,  $\mu_{c,\phi}^{SR} = 2.8^\circ$ ,  $r_c^{ST} = 0.4$ ).

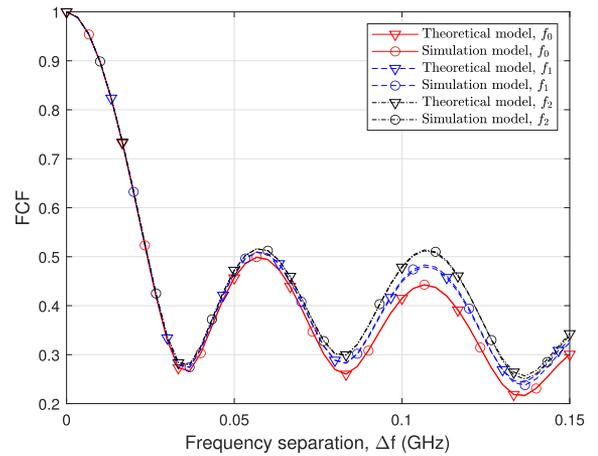


Fig. 7. The comparison of FCFs of theoretical model and simulation model at  $f_0 = 300$  GHz,  $f_1 = 325$  GHz and  $f_2 = 350$  GHz ( $D = 3$  m,  $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $v^R = 0$  m/s,  $\mu_{c,\theta}^{ST} = 1.2^\circ$ ,  $\mu_{c,\phi}^{ST} = 1.7^\circ$ ,  $\mu_{c,\theta}^{SR} = 1.4^\circ$ ,  $\mu_{c,\phi}^{SR} = 2.8^\circ$ ,  $\mu_c^{ToA} = 0.3$  ns,  $\rho_\phi^{ST} = \rho_\phi^{ST} = \rho_\phi^{SR} = \rho_\phi^{SR} = 1.2$ ).

small but still observable which means that the non-stationarity in the frequency domain needs to be considered. When frequency difference increases, the gaps between different frequencies will also increase because the change rate of frequency correlation is related to the center frequency.

#### D. Stationary Bandwidth

The stationary bandwidth is simulated with parameters of a typical indoor scenario according to [31], [49]. The initial distance between the first elements of Tx and Rx is 3 m,  $\mu_{\Delta\tau_{c,SB}}$  and  $\mu_{\Delta\tau_{k,MB}}$  are set as 2.73 ns and 2.33 ns. The initial intra-cluster parameters  $\mu_{c,\theta}^{ST}$ ,  $\mu_{c,\phi}^{ST}$ ,  $\mu_{c,\theta}^{SR}$ , and  $\mu_{c,\phi}^{SR}$  are set as  $1.2^\circ$ ,  $1.7^\circ$ ,  $1.4^\circ$ , and  $2.8^\circ$ , respectively. The mean value of relative time of arrival  $\mu_c^{ToA}$  is set as 0.3 ns. The CDFs of the stationary bandwidth of the simulation channel model at different frequencies are shown

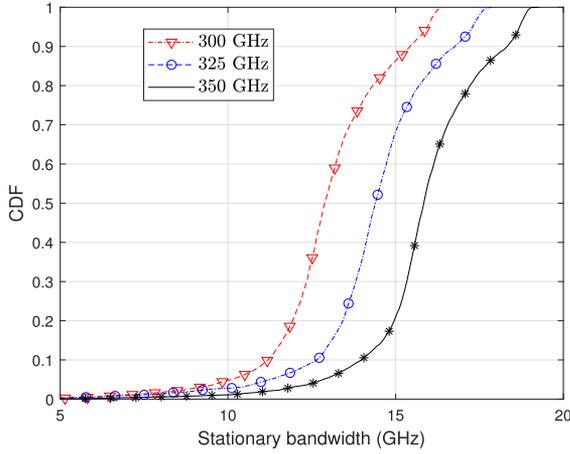


Fig. 8. The CDFs of stationary interval of the simulation model in frequency domain at  $f_0 = 300$  GHz,  $f_1 = 325$  GHz and  $f_2 = 350$  GHz ( $D = 3$  m,  $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $v^R = 0.1$  m/s,  $\mu_{c,\theta}^{S_T} = 1.2^\circ$ ,  $\mu_{c,\phi}^{S_T} = 1.7^\circ$ ,  $\mu_{c,\theta}^{S_R} = 1.4^\circ$ ,  $\mu_{c,\phi}^{S_R} = 2.8^\circ$ ,  $\mu_c^{ToA} = 0.3$  ns,  $\rho_\phi^{S_T} = \rho_\phi^{S_R} = \rho_\phi^{S_R} = \rho_\phi^{S_R} = 1.2$ ,  $c_{th} = 0.9$ ).

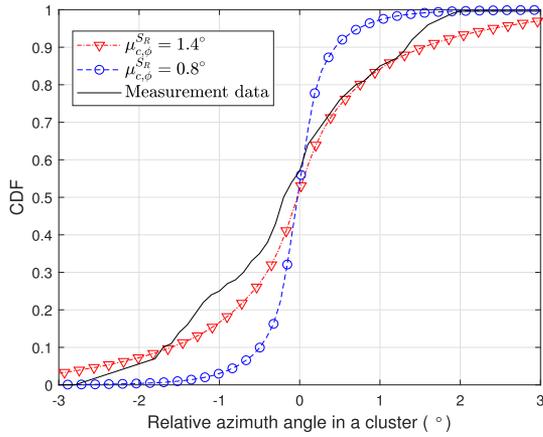


Fig. 9. The CDFs of relative angle in a cluster with different  $\mu_{c,\phi}^{S_R}$  and the measurement in [23] ( $D = 2.7$  m,  $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $f_0 = 300$  GHz,  $v^R = 0$  m/s).

in Fig. 8. The threshold is chosen as 0.9. The median of the stationary bandwidth at 300 GHz is approximately 12.5 GHz. Higher frequency band has larger frequency stationary bandwidth. If the bandwidth in THz communication is large than the stationary bandwidth, non-stationarity in frequency domain is unneglectable.

### E. Cluster Level Angle Spread

Cluster level angle spread reflect the degree of diffusely scattering in a cluster. In this simulation, the parameter  $\mu_{c,\phi}^{S_R}$  are estimated by using an optimization algorithm in order to fit the statistical properties of the channel model to those of the data from measurement [23] or ray tracing [32]. In the curve fitting (optimization) process, random initial values of those parameters were initialized. Then, the average mean square error of the simulation and measurement results is minimized by optimizing the values of those parameters in an iterative procedure. After

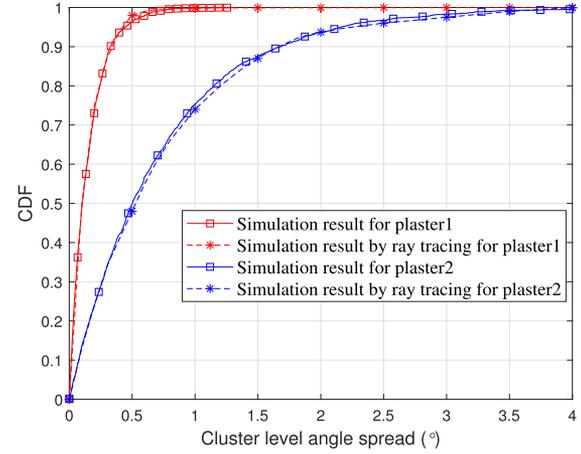


Fig. 10. The comparison of cluster level angular spread with different materials ( $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $f_0 = 300$  GHz,  $v^R = 0$  m/s,  $r_c^{S_T} = 0.4$ ,  $\mu_{c,\phi}^{S_R} = 0.15^\circ$  for plaster1,  $\mu_{c,\phi}^{S_R} = 0.75^\circ$  for plaster2).

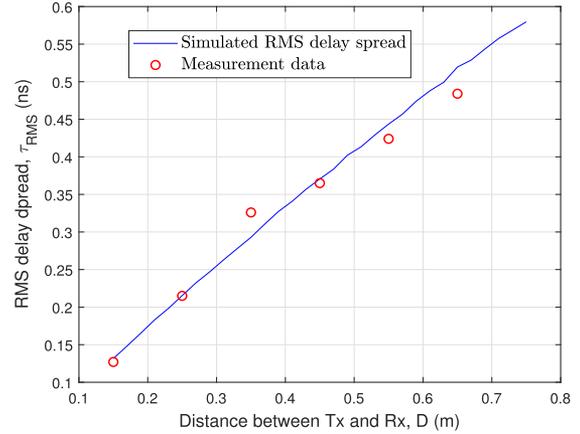


Fig. 11. The comparison of simulated RMS delay spread and measurement in [50] ( $p = 1$ ,  $q = 1$ ,  $t_0 = 0$  s,  $f_0 = 300$  GHz,  $v^R = 0$  m/s,  $\mu_{\Delta\tau_{SB}} = 0.08$ ,  $\mu_{\Delta\tau_{MB}} = 0.07$  for  $D = 0.15$  m).

the sufficient numbers of iterations, the optimal values of those parameters with the minimum mean square error can be found, which allows the desirable good fitting between the statistical property of the simulation model and measurement data. Firstly, the CDFs of relative azimuth angles of arrival with different  $\mu_{c,\phi}^{S_R}$  are simulated and compared with the measurement data [23] in Fig. 9. When the parameter  $\mu_{c,\phi}^{S_R}$  increases, the CDF of relative angles will be more gentle. We can observe the good agreement when  $\mu_{c,\phi}^{S_R} = 1.4^\circ$  indicating that the modeling methods can be applied to simulate realistic environments. Then we simulate the scattering in two materials with different roughness. The cluster level angle spread is greatly affected by the roughness of the material. The height standard deviation of plaster1 is  $\sigma_{\text{plaster1}} = 0.5$  mm and  $\sigma_{\text{plaster2}} = 1.5$  mm in [32]. Fig. 10 demonstrates the comparison of cluster level angle spread with different materials in this model and simulation by ray tracing in [32]. The results indicate that the proposed model can correctly approximate the results from ray tracing for different materials.

## F. RMS Delay Spread

The RMS delay spread is simulated and fitted with the measurement data [50] by minimum mean square error criterion in Fig. 11 for short range communication where the transmission distance is less than 1 m. In the simulation, the parameters  $\mu_{\Delta\tau_{c,SB}}$  and  $\mu_{\Delta\tau_{k,MB}}$  are linearly increase with the LoS distance and the parameters at  $D = 0.15$  m are estimated. We can observe good agreement between the simulation results and the measurement data. It means that the proposed model is suitable for this scenario.

## VI. CONCLUSION

Novel 3D space-time-frequency non-stationary ultra-massive MIMO THz channel models have been proposed for 6G wireless communication systems with long traveling paths. Considering the unique propagation characteristics of THz bands, i.e., frequency-dependent diffusely scattering, relative angles and delays of rays within one cluster have been assumed to be frequency variant parameters. The statistical properties such as ACF, spatial CCF, and FCF have been derived for the proposed theoretical model and corresponding simulation model based on the MEA. Numerical results have shown that the statistical properties of the simulation model, verified by simulation results, can match well with those of the theoretical model. The good agreements between simulated results and corresponding measurements in different scenarios have further demonstrated the accuracy and good flexibility of the proposed model.

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