On Over-the-Air Testing for Devices With Directional Antennas

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ABSTRACT This paper investigates the impact of devices under test (DUTs) with directional antennas on the recreated channel in the over-the-air (OTA) testing for massive multiple-input multiple-output (MIMO) devices using prefaded signal synthesis (PFS) technique. Assuming the uplink in real radio environments, the directional receiver (Rx) antenna patterns would affect the gains in different incoming directions, thereby affecting the spatial characteristics of the target channel. A typical multi-probe anechoic chamber (MPAC) setup for massive MIMO base stations (BSs) is studied, where a limited number of probe antennas are distributed over the probe wall to emulate the target channel by proper probe weighting. The directional antenna patterns would have nonnegligible effects on the emulated spatial characteristics which may become inaccurate for DUTs with directional antennas and thus need to be re-examined. Therefore, the reconstructed channel with the PFS technique will be investigated under the MPAC setup in this paper, with particular focus on the DUTs with directional antennas. The deviations between the covariance matrix of the Rx antennas under the target channel and the covariance matrix under the reconstructed channel are used as the metric to evaluate the performance of the reconstructed channel, and the optimal probe weights are also re-determined. Furthermore, given beamforming capability of massive MIMO BSs, the impact of the BS antenna patterns on angular spectrum is investigated as well. In addition, since the reconstructed channel needs to not only reflect the spatial characteristics of Rx antennas but also reflect the spatial characteristics of transmitter antennas and propagation environment, the end-to-end channel capacities are evaluated. Simulation results under various scenarios show that the accuracies of the reconstructed channel in terms of spatial correlation, angular spectrum and channel capacity can be improved by using the re-optimized probe weights when directional antenna patterns of the DUTs are taken into account.

INDEX TERMS Antenna pattern, angular spectrum, massive MIMO, OTA, spatial covariance matrix.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) is one of the key technologies of the fifth-generation (5G) mobile communication system [1], which relies on deploying a large number of antennas at base stations (BSs). Increasing the number of antennas is able to enhance antenna directivity by focusing radiated energy into smaller spatial regions, thereby increasing both energy efficiency and spectral efficiency of the massive MIMO system [2]. In order to accelerate 5G commercial deployment as quickly as possible, it would be an urgent task to conveniently and efficiently evaluate the performance of massive MIMO devices.

Over-the-air (OTA) testing has been employed as a viable technology for evaluating the performance of MIMO devices. In order to reconstruct the characteristics of the realistic MIMO channel in a controlled laboratory environment, many works in the literature have addressed channel emulation methods for radio performance evaluation of MIMO-capable terminals [3]–[7]. As the concept of cluster has been widely adopted to model the multipath phenomenon based on extensive measurements [4], the multi-probe anechoic
chamber (MPAC) method is used to synthesize each cluster which is composed of a large number of rays with the same delay and has a specific power angular spectrum (PAS). The methodologies of the OTA testing for multi-antenna devices mainly include the prefaded signal synthesis (PFS) technique and the plane wave synthesis (PWS) technique. Compared with the PWS technique, phase calibration is not required for the PFS technique [3]; therefore, the PFS technique is usually used to recreate the target channel in the MPAC setup. Since the PAS and the spatial correlation function are Fourier transform pairs, the spatial correlation between antennas, as a second-order statistical measurement, is usually used as the performance metric to evaluate the reconstructed channel [3]–[5], [7]–[9]. PAS shape parameters, such as angle spread and angle of arrival, are introduced as additional constraints to address the problem that different PASs may result in similar spatial correlations if the number of sampling points is finite in the test area [4]. The reconstruction method for the three-dimensional (3-D) geometry-based channels is presented in [5]. Furthermore, in order to control the cost of the MPAC setup, the required number of probes and the probe selection algorithms are discussed to decrease the number of required active probes as much as possible [6], [7]. More recently, with the development of 5G, the design of practical OTA testing setup for massive MIMO BSs has been proposed in [8] and [9], and several key technologies and challenges for the 5G OTA measurements have been identified in [10].

Unlike the above works which usually assume that the devices under test (DUTs) are equipped with omni-directional antennas, the DUTs may be equipped with directional antennas for practical radio devices [11]. Specifically, massive MIMO BSs are typically equipped with a large number of directional antenna elements, and the characteristics of antenna elements are specified in [8], [9], [12], which would produce different antenna gains in different impinging directions [12]. Compared with the OTA testing for omni-directional antenna devices, the spatial correlations of the reconstructed channel will be affected by the antenna directional gains of the DUT under the PFS method, regardless of the number of probes. Therefore, the power weighting strategy for OTA probes, which characterizes the spatial correlation of the emulated channel, should take the antenna patterns of the DUT into account, and the probe configurations for omni-directional antenna devices can not apply directly to the directional antenna devices. However, it is clear that the reconstructed spatial characteristics would become accurate without considering the antenna patterns of the DUT if the number of active probes is sufficient and every ray direction of the reference channel is represented by an individual probe instead of using the PFS method. As a consequence, the probe weights used to evaluate omni-directional antenna devices will be equal to the probe weights for testing directional antenna devices. Actually, the number of probe antennas is limited in realistic OTA testing. Using the PFS technique, the spatial characteristics of the target channel would not be reconstructed accurately when antenna patterns of directional antenna devices are ignored, which, however, has been neglected in the existing works [8]–[10], [13]–[18]. Therefore, in the OTA testing under a limited number of probes, analyzing the impact of antenna patterns on the probe weights will be one of the focuses in our work.

Compared with using the spatial correlation as the performance metric to evaluate the accuracy of the reconstructed channel, the channel covariance matrix can not only reflect the spatial correlation between spatial channels, but also reflect the power imbalance of different channels due to near-field effect and inconsistent radiation patterns. Therefore, the channel covariance matrix is proposed as the metric to measure the accuracy of the reconstructed channel [13]–[15], [19]–[21]. Furthermore, the massive MIMO devices usually have the beamforming capability, which should be evaluated when massive MIMO devices are under test [16]. As a consequence, the angular spectrum should be used to emphasize the performance of beam-related procedures, e.g., beam acquisition, tracking, refinement, and recovery [17], [18].

The main contributions of this paper include:
- Given that the number of probe antennas is limited in OTA testing, the impact of the DUT antenna patterns on spatial correlation of the reconstructed channel is investigated, based on which, an improved probe power weighting strategy is proposed to increase the accuracy of the emulated channel under the PFS technique.
- The channel covariance matrix and the angular spectrum are used as the metrics to evaluate the reconstructed channel, respectively; the effect of anechoic chamber radius on the accuracy of channel reconstruction is analyzed as well.
- Furthermore, the channel capacity of the reconstructed channel is also investigated to examine the emulated channel in the case of directional antenna devices.

This paper is organized as follows. Section II overviews the geometry-based stochastic channel (GBSC) model, and presents the principles of the PFS method as well as the MPAC setup under consideration. Section III derives both the channel covariance matrices and the angular spectrums for the target channel and the reconstructed channel, respectively. By taking into account the effect of the directional antennas on the reconstructed channel, the probe weights are re-calculated for DUTs with directional antennas. In Section IV, the accuracies of the reconstructed channel are examined in terms of spatial correlation, angular spectrum and channel capacity, respectively. Finally, conclusions are drawn in Section V.

The notations used in this paper are as follows. Matrices are represented by boldface capital letters and vectors are denoted by boldface small letters. $(\cdot)^\sigma$, $(\cdot)^T$ and $(\cdot)^H$ are the conjugate, the transpose and the Hermitian operators, respectively. $\|\cdot\|_1$ and $\|\cdot\|_2$ represents the $\ell_1$-norm and the $\ell_2$-norm (i.e., Euclidean norm), respectively, and $\mathbb{E}\{\cdot\}$ represents the expectation operator.
II. SYSTEM MODEL
A. GEOMETRY-BASED CHANNEL MODELLING

The GBSC models are usually used to characterize MIMO channels in a realistic field environment, which consists of multiple clusters [12], [22]. Each cluster can be described by the specific power, delay, angle of arrival (AoA), angle of departure (AoD), and cross-polarization power ratio (XPR). Therefore, the real radio channel models can be characterized by a set of channel parameters as illustrated in Figure 1. The number of clusters and rays-per-cluster in the MIMO link are denoted by \( L \) and \( Q \), respectively. \( \sigma_{\text{AoD}}^l \), \( \sigma_{\text{AoA}}^l \), \( \phi_{\text{ESD}}^l \) and \( \phi_{\text{ASA}}^l \) denote the azimuth angle spread of arrival (ASD) and the elevation angle spread of arrival (ESA) for the \( l \)th cluster, respectively. Similarly, \( \sigma_{\text{AoA}}^l \) and \( \sigma_{\text{AoD}}^l \) denote the azimuth angle spread of departure (ASD) and the elevation angle spread of departure (ESA) for the \( l \)th cluster, respectively. Assuming the uplink with the user equipment (UE) on the transmitter (Tx) side and the BS on the receiver (Rx) side, the Tx antenna array is composed of omni-directional antennas whereas the Rx antenna array consists of directional antennas. Since the DUT with directional antennas would produce different directional gains for different impinging angles, the antenna patterns would affect the accuracy of the recreated channel in the OTA testing.

Assuming that the Rx antennas are located in the desired far-field of the Tx antenna radiation. In the uplink, a system model with \( U \) Rx antenna elements on the BS side and \( S \) Tx antenna elements on the UE side is under consideration, and the target MIMO channel \( \mathbf{H}_{\text{tar}}(t, \tau) \in \mathbb{C}^{U \times S} \) can be represented by

\[
\mathbf{H}_{\text{tar}}(t, \tau) = \begin{bmatrix}
    h_{1,1}(t, \tau) & \cdots & h_{1,S}(t, \tau) \\
    \vdots & \ddots & \vdots \\
    h_{U,1}(t, \tau) & \cdots & h_{U,S}(t, \tau)
\end{bmatrix},
\]

where the time-variant radio channel transfer function \( h_{u,s}(t, \tau) \) can be written as

\[
h_{u,s}(t, \tau) = \sum_{l=1}^{L} h_{u,s,l}(t, \tau),
\]

where the time is denoted by \( t \). The fading channel for the \( l \)th cluster can be decomposed into the Doppler characteristics, the Tx antenna characteristics and the Rx antenna characteristics, etc., which is expressed as

\[
\begin{align*}
    h_{u,s,l}(t, \tau) &= \sqrt{\frac{P_l}{Q}} \sum_{q=1}^{Q} \left[ F_{s,\text{UE}}(\Phi_{s,l,q}) \right]^T \left[ \begin{array}{cc}
    a_{l,q}^{VV} & a_{l,q}^{VH} \\
    a_{l,q}^{HV} & a_{l,q}^{HH}
    \end{array} \right] \\
    &\cdot \exp(j2\pi \nu_{l,q} t) \cdot \exp(j\frac{2\pi}{\lambda} \mathbf{r}_{l,q}^u \cdot \mathbf{d}_s^u) \\
    &\cdot \exp(j\frac{2\pi}{\lambda} \mathbf{r}_{l,q}^s \cdot \mathbf{d}_a^u) \cdot \delta(\tau - \tau_j),
\end{align*}
\]

where \( \Phi_{s,l,q}, \Phi_{u,l,q} \) and \( \nu_{l,q} \) are AoD, AoA and Doppler frequency of the \( q \)th ray of the \( l \)th cluster, respectively. \( P_l \) and \( \tau_j \) denote the power and delay of the \( l \)th cluster. \( F_{s,\text{UE}}^V \) and \( F_{s,\text{UE}}^H \) are the field patterns of the UE antenna element \( s \) for the vertical and horizontal polarization, respectively. Similarly, \( F_{u,\text{BS}}^V \) and \( F_{u,\text{BS}}^H \) are the field patterns of the BS antenna element \( u \) for the vertical and horizontal polarization, respectively. In addition, the coefficient \( a_{l,q}^{\alpha \beta} \) is the complex amplitude to characterize the random initial phase of the \( q \)th ray of the \( l \)th cluster for transmitting polarization \( \alpha \) and receiving polarization \( \beta \). \( \mathbf{r}_{l,q}^u \) is the spherical unit vector with spatial angle of arrival \( \Phi_{u,l,q} \). Similarly, \( \mathbf{r}_{l,q}^s \) is the spherical unit vector with spatial angle of departure \( \Phi_{s,l,q} \). Moreover, \( \mathbf{d}_a^u \) is the location vector of the Rx antenna element \( u \) relative to the center of the BS, and \( \mathbf{d}_s^u \) is the location vector of the Tx antenna element \( s \) relative to the center of the UE.

B. MPAC SETUP

1) SYSTEM MODEL

As demonstrated in Figure 2, the MPAC setup designed for testing massive MIMO BSs is mainly composed of a fading emulator, an anechoic chamber, a limited number of OTA antennas located on the probe wall and an UE emulator. The DUT is placed in the anechoic chamber which can shield external interference signals. The probe antennas are...
distributed over the probe wall at proper locations, and each probe is connected to an output port of the fading emulator. The distance from each probe to the center of the test area is $R$. Specifically, in the uplink, the Tx signals are generated by the UE emulator and fed into the fading emulator. The fading emulator will create multipath environments including path delay, Doppler spread, and fast fading according to the specified channel models. Tx signals are convolved with channel impulse responses (CIRs) as described in Figure 2. The output fading sequences from the channel emulator are mapped to the OTA probes, and probe weights are properly assigned to reconstruct the spatial characteristics of the target channel in the test area as accurately as possible. By means of the above procedures, the target radio channels can be emulated to evaluate the performance of the DUT in the MPAC setup.

![Figure 2. An illustration of the MPAC setup for the massive MIMO BS performance evaluation.](image)

### 2) CHANNEL RECONSTRUCTION UNDER THE PFS TECHNIQUE

In OTA testing, the idea of the PFS technique is to emulate each cluster of the target channel through multiple probes which have independently and identically distributed (i.i.d.) fading sequences. By taking into account the PAS shape parameters of each cluster and the OTA probe locations, probe antennas are allocated with proper power weights to synthesize the discrete PAS. This method is to create specific sum characteristics of every cluster in the test area, such as spatial correlation, Doppler spectrum and power delay profile (PDP), etc., and the fading sequences are embodied in each probe. However, the DUT may be equipped with directional antennas, and there will be different directional gains to different probe antennas. The accuracy of the spatial channel reconstruction will be affected by the directional gains of the DUT antenna as well as the probe weights under a limited number of probe antennas. Therefore, there may be some errors in the spatial characteristics of the reconstructed channel if the antenna patterns of the DUT are ignored using the PFS technique. Analyzing the impact of antenna patterns on the probe weights will be one of the focuses in our work.

Suppose that the BS is placed in the center of the test area, and consists of $U$ directional antenna elements. For the MPAC setup equipped with $K$ OTA probes, the channel matrix $\mathbf{H}_{\text{ota}}(t, \tau) \in \mathbb{C}^{U \times S}$ is composed of the transfer matrix $\mathbf{V}$ from $K$ probes to $U$ DUT antennas and the fading components of the time-variant CIR $\mathbf{H}_{K,S}^{\text{ota}}(t, \tau)$, and is given by

$$\mathbf{H}_{\text{ota}} = \mathbf{V} \cdot \mathbf{H}_{K,S}^{\text{ota}}(t, \tau), \quad (4)$$

where, $\mathbf{V} = \{F_k,\text{BS}(\Phi_k) \cdot \exp(j2\pi\frac{\phi(t)}{\lambda} \cdot \mathbf{d}_k^a)\}$ $\in \mathbb{C}^{U \times K}$, and $\mathbf{H}_{K,S}^{\text{ota}}(t, \tau) = \{\sum_{l=1}^{L} h_{k,s}^{\text{ota}}(t, \tau)\} \in \mathbb{C}^{K \times S}$ where

$$h_{k,s}^{\text{ota}}(t, \tau) = \sqrt{\frac{P_l}{Q}} \sum_{q=1}^{Q} F_{s,\text{UE}}(\Phi_s, l, q) \left[ e^{j2\pi\frac{\phi(t)}{\lambda} \cdot \mathbf{d}_k^a} \cdot \mathbf{F}_{\text{OTA}} \cdot \sqrt{w_l k} \exp(j\pi \alpha_{l,q} t) \cdot \exp(j\frac{2\pi}{\lambda} \mathbf{r}_{l,q}^t) \cdot \delta(\tau - \tau_l),

where $w_l k$ represents the $k$th probe weight for the $l$th cluster, $\Phi_k$ denotes the spatial angle of the $k$th probe, and $\mathbf{F}_{\text{OTA}}$ is the ideal polarimetric antenna pattern matrix of the OTA probes. The coefficient $a_{l,q,k}$ is the complex amplitude to characterize the random initial phase of the $q$th ray of the $l$th cluster mapped to $k$th probe for transmitting polarization $a$ and receiving polarization $b$. In OTA testing, the transmit power of each OTA probe needs to be calibrated to the same level as the calibrated antenna at the center of the test area.

### III. POWER WEIGHTING

In a real propagation environment, the scatterers are usually far away from terminals. Therefore, the pathloss deviations are close to zero when the electromagnetic fields reach different antenna elements of the terminal. Similarly, in the MPAC setup, it is assumed that the distance $R$ is much larger than the radius of the test area $r$, and the pathloss deviations of the electromagnetic waves passing through the test area are also negligible [23]. Moreover, it is assumed that the antennas on the BS side have consistent radiation patterns. Due to the above arguments, the power imbalance of different channels can be ignored in both the real radio environment and the OTA testing, and the covariance matrices of spatial channels can be constructed as the metric to investigate the impact of the DUT antenna patterns on the spatial characteristics of the reconstructed channel, with particular focus on a limited number of probe antennas. In addition, the massive MIMO BS usually has the beamforming capability, and thus the impact of the DUT antenna patterns on the reconstructed channel needs to be investigated by analyzing the angular spectrum of the reconstructed channel. Therefore, two optimization metrics, namely, the covariance matrix and the angular spectrum of the spatial channels, will be discussed, respectively, to investigate the impact of the DUT antenna patterns on the test zone performance under a limited number of probe antennas in the massive MIMO OTA testing.

### A. SPATIAL COVARIANCE MATRIX

#### 1) SPATIAL COVARIANCE MATRIX OF THE TARGET CHANNEL WITH DIRECTIONAL ANTENNA PATTERNS

The correlation characteristics among Rx antennas are related to the channel covariance matrix directly which is employed as a statistical method to characterize the similarity of the
The target channel and the reconstructed channel are already

\[
R = \begin{bmatrix}
R_{u_1,u_1} & \cdots & R_{u_1,u_U} \\
\vdots & \ddots & \vdots \\
R_{u_U,u_1} & \cdots & R_{u_U,u_U}
\end{bmatrix}.
\]  

(5)

Due to the fact that the random initial phases of rays are statistically independent each other, the expectation for the product of any two rays is zero except when \(q = q'\). For the sake of simplicity and without loss of generality, the vertical polarization of the antenna and a single cluster are under consideration in this paper. By taking into account the antenna patterns of the DUT, the spatial correlation coefficient of the target channel at each sample time \(t\) can be written as

\[
R_{u_1,u_1} = \mathbb{E}\{h_{u_1,s,l} \cdot h_{u_1,s,l}^*\} = P_l \sum_{k=1}^{K} F_{u_1}^V(\Phi_k) \cdot F_{u_1}^V(\Phi_k)^* \cdot \exp\left(\frac{2\pi}{\lambda} r_{k,q}^r \cdot d_{q,u_1}^r\right) \\
\cdot \exp\left(\frac{2\pi}{\lambda} r_{k,q}^e \cdot d_{q,u_1}^e\right)^* \cdot p(\Phi) d\Phi;
\]

(6)

where \(p(\Phi)\) is the PAS density function of the \(l\)th cluster at spatial angular \(\Phi\), and spatial direction \(\Phi\) consists of the azimuth \(\phi\) and the elevation \(\theta\). Assuming \(P_l = 1\), note that the correlation coefficient between the spatial channels is related to the Rx antenna patterns as well as the parameter characteristics of the PAS. Therefore, the directional Rx antenna patterns should not be ignored when calculating correlation coefficients of the channels.

2) SPATIAL COVARIANCE MATRIX OF THE RECONSTRUCTED CHANNEL WITH DIRECTIONAL ANTENNA PATTERNS

Similar to the spatial correlation coefficient of the target channel, the spatial correlation coefficient of an arbitrary Rx antenna pair \((u_i, u_j)\) for the \(l\)th cluster can be derived from the reconstructed channel with directional antenna patterns at each sample time \(t\)

\[
\hat{R}_{ota}^{u_1,u_1} = \mathbb{E}\{h_{ota,u_1,s,l} \cdot h_{ota,u_1,s,l}^*\} = P_l \sum_{k=1}^{K} F_{u_1}^V(\Phi_k) \cdot F_{u_1}^V(\Phi_k)^* \cdot \exp\left(\frac{2\pi}{\lambda} r_{k,q}^r \cdot d_{q,u_1}^r\right) \\
\cdot \exp\left(\frac{2\pi}{\lambda} r_{k,q}^e \cdot d_{q,u_1}^e\right)^* \cdot w_{l,k}.
\]

(7)

Similar proofs for (6) and (7) are formulated in [24], [25]. Furthermore, the channel covariance matrix \(\hat{R}_{ota}^{u_1,u_1}\) between the \(U\) Rx antennas is written as

\[
\hat{R}_{ota}^{u_1,u_1} = \begin{bmatrix}
\hat{R}_{ota,u_1,u_1} & \cdots & \hat{R}_{ota,u_1,u_U} \\
\vdots & \ddots & \vdots \\
\hat{R}_{ota,u_U,u_1} & \cdots & \hat{R}_{ota,u_U,u_U}
\end{bmatrix}.
\]

(8)

3) PROBLEM FORMULATION

The covariance matrices of the Rx antennas corresponding to the target channel and the reconstructed channel are already defined in (5) and (8), respectively. Unlike the existing works which usually assume that DUTs are equipped with omni-directional antennas [3], [4], [26], the massive MIMO BS equipped with a large number of directional antennas is considered to investigate the impact of the DUT antenna patterns on the channel reconstruction in the MPAC setup. Using the PFS technique, a limited number of probe antennas are allocated with proper power weights, and the spatial characteristics of the target channel should be reconstructed as closely as possible. Therefore, sampling the test area with a pair of directional antennas, the deviations between \(R\) and \(\hat{R}_{ota}^{u_1,u_1}\) can be described in the Frobenius norm, and then the Frobenius matrix norm is minimized for all antenna pairs \((u_i, u_j)\) to determine the proper probe weights accordingly. By means of the above procedures, the optimization function between the target channel covariance matrix and reconstructed one can be formulated as

\[
\min_w ||R - \hat{R}_{ota}^{u_1,u_1}(w)||_F^2 \\
\text{s.t.} ||w||_1 = 1, \quad 0 \leq w_k \leq 1.
\]

(9)

where \(k = 1, 2, \ldots, K\). It is clear that (9) is a convex programming problem with linear constraints, which can be solved by convex optimization techniques readily.

B. POWER ANGULAR SPECTRUM

1) TARGET POWER ANGULAR SPECTRUM WITH DIRECTIONAL ANTENNA PATTERNS

Compared with MIMO OTA testing which usually uses the spatial correlation as the metric, the massive MIMO antenna array usually has the beamforming capability which needs to be studied in OTA testing. As a consequence, angular spectrum is also used as the performance metric to evaluate the impact of the DUT antenna patterns on the reconstructed channel. Using the classical Bartlett beamformer under a given geometry antenna array, the angular spectrum can be obtained by scanning the signal power in each direction-of-arrival (DoA) through spatial filtering [27]. Therefore, the angular spectrum under the target channel can be calculated as [18]

\[
P(\Psi) = a^H(\Psi)Ra(\Psi),
\]

(10)

where \(a(\Psi)\) is the normalized steering vector for the spatial direction \(\Psi\) which consists of the azimuth \(\phi\) and the elevation \(\theta\). Assuming the ideal far-field, the expression of the steering vector is \(a(\Psi) = \left[\frac{1}{\sqrt{\phi} \exp(j2\pi \phi/\lambda) \cdot \delta \phi}{|\delta \phi|}, \frac{1}{\sqrt{\theta} \exp(j2\pi \theta/\lambda) \cdot \delta \theta}{|\delta \theta|}, \cdots, \frac{1}{\sqrt{\phi \theta} \exp(j2\pi \phi \cdot \theta/\lambda) \cdot |\delta \phi \delta \theta|}{|\delta \phi \delta \theta|}\right]^T\). \(\psi d\theta\) represents the direction vector of the angular direction \(\Psi\) to the center origin \(\phi\), and \(\delta \psi d\theta\) is the vector from the antenna element unit of the BS to the center origin \(\phi\), where \(u = 1, 2, \ldots, U\). \(R\) is the covariance matrix of the target channel, which has been given in (5).
2) RECONSTRUCTED POWER ANGULAR SPECTRUM WITH DIRECTIONAL ANTENNA PATTERNS

Using the PFS technique, the reconstructed angular spectrum can also be synthesized by a limited number of probes in the anechoic chamber when testing massive MIMO BSs. However, the antenna element patterns of the DUT may produce different directional gains to different spatial probes, and thus the accuracy of the reconstructed angular spectrum will be affected. Suppose that there are $K$ available probes in the OTA testing, the corresponding probe weight settings are $\{w_k\}$, $k = 1, 2, \ldots, K$. Similar to the expression of the target angular spectrum, the reconstructed angular spectrum can be given by [18]

$$
\hat{P}\text{ota}(\Psi) = a^H(\Psi)\hat{R}\text{ota}a(\Psi).
$$

\(\hat{R}\text{ota}\) is the Rx antenna covariance matrix under the reconstructed target channel, which has been obtained by (8).

3) OBJECTIVE FUNCTION

The angular spectrums under the target channel and under the reconstructed channel are given in (10) and (11), respectively. In order to minimize the deviation between the target angular spectrum and the reconstructed one, the following optimization function is constructed to determine the probe weights,

$$
\min_w ||P(\Psi) - \hat{P}\text{ota}(\Psi, w)||^2_f
$$

s.t. $||w||_1 = 1, \ 0 \leq w_k \leq 1$. \hspace{1cm} (12)

C. CHANNEL CAPACITY

The end-to-end channel capacity reflects the signal transmission rate ability, which can be improved effectively by using antenna array technology at both the Tx and the Rx sides. Specifically, in 5G communication system, massive antenna array at the BS side is utilized to improve transmission rate of the MIMO communications. Moreover, channel capacity not only reflects the spatial correlations on the Rx side antennas, but also embodies the spatial characteristics of the Tx antennas and the propagation environment. Considering the Rx array with a large number of directional antennas, the antenna patterns will affect the received power, thereby affecting the channel capacity results. For the achievable uplink rate of a massive MIMO system, the channel capacity can be expressed by the Shannon formula

$$
C(t) = \frac{1}{N_f} \sum_{n_f=1}^{N_f} \log_2 \det(1 + \frac{\gamma}{S} \cdot H(t, n_f) \cdot H(t, n_f)^H), \hspace{1cm} (13)
$$

where $\gamma$ is the signal-to-noise ratio, and $N_f$ is the number of subcarriers, which has to be large enough to ensure that each subchannel experiences flat fading, i.e., subchannel bandwidth is much smaller than channel coherence bandwidth. $H\text{tar}(t, n_f) \in \mathbb{C}^{U \times S}$ and $H\text{ota}(t, n_f) \in \mathbb{C}^{U \times S}$ are the target channel matrix and the reconstructed channel matrix in the frequency domain, respectively, which can be obtained by performing the Fourier transform of the channel impulse responses $[H\text{tar}(t, \tau)]$ and $[H\text{ota}(t, \tau)]$. According to (13), target channel capacity $C\text{tar}(t)$ and reconstructed channel capacity $C\text{ota}(t)$ can be simulated to analyze the impact of directional Rx antennas in the sequel.

IV. SIMULATION RESULTS

A. SIMULATION SCENARIOS

To understand the impact of the directional Rx antennas on the spatial correlation, angular spectrum and channel capacity of the reconstructed target channel in OTA testing, four simulation scenarios are discussed as detailed in Table 1. In simulations, uniform line array (ULA) on the Tx side consists of 4 ideal dipole antennas, and uniform rectangular array (URA) on the Rx side is composed of $8 \times 8$ directional antennas under four scenarios, where the 3dB beamwidths of the antenna elements are $10^\circ$, $30^\circ$ and $65^\circ$, respectively. However, there may be some deviations in radiation patterns of the actual antenna elements, and the complex patterns of each antenna element can be measured nonintrusively as in the first stage of the radiated two-stage method, but it’s unrealistic for testing massive antenna devices [8]. Therefore, how to conveniently and accurately measure nonintrusively the pattern of each antenna element for massive MIMO devices should be investigated in the future. For simplicity and without loss of generality, the radiation pattern of the BS antenna element specified by the 3GPP 38.901 standard is used as an example to investigate the influence of the DUTs with directional antennas on the recreated target channel using the PFS technique in simulations, which is identical for every antenna element. The maximal separation is $3.5 \times \sqrt{2} \lambda$ on the Rx side and $1.5 \lambda$ on the Rx side with antenna spacing of $0.5 \lambda$, and the mutual coupling effect between any Tx/Rx antennas is ignored. In addition, ignoring the bandwidth of the channel as well, it is assumed that the massive MIMO DUT operates over the fixed carrier frequency of 28 GHz, which corresponds to FR2. Moreover, for simplicity, we only discuss a single cluster $l$ of the spatial channel (the power $P_l = 1$) and the vertical polarization of the antenna hereafter.

| Scenarios | Mean DoA | Angular spread | Rx configuration |
|-----------|----------|----------------|------------------|
| A         | $\theta = 5^\circ$ | $\theta = 10^\circ$ | ASA = $10^\circ$ ESA = $3^\circ$ | 3dB beamwidth = $10^\circ$ |
| B         | $\theta = 15^\circ$ | $\theta = 10^\circ$ | ASA = $10^\circ$ ESA = $3^\circ$ | 3dB beamwidth = $30^\circ$ |
| C         | $\theta = 25^\circ$ | $\theta = 10^\circ$ | ASA = $10^\circ$ ESA = $3^\circ$ | 3dB beamwidth = $65^\circ$ |
| D         | $\theta = 15^\circ$ | $\theta = 10^\circ$ | ASA = $10^\circ$ ESA = $3^\circ$ | 3dB beamwidth = $65^\circ$ |

Figure 3 shows the antenna element patterns of both directional antennas and omni-directional antenna in the angular region of the probe wall. The 3dB beamwidths are defined as $10^\circ$, $30^\circ$ and $65^\circ$ to describe the directivity of the different Rx antenna elements, respectively. For each radiated direction, directional antennas will produce the significantly different...
The patterns for a single directional antenna and omni-directional antenna in the angle area of probe wall. The 3dB beamwidths are $10^\circ$, $30^\circ$ and $65^\circ$, respectively.

The target PAS and the probe distributions. The mean impinging directions of the clusters are $(5^\circ, 10^\circ)$, $(15^\circ, 10^\circ)$, and $(25^\circ, 10^\circ)$. ASA = $10^\circ$ and ESA = $3^\circ$.

The target correlations of directional Rx antennas under four different simulation scenarios.

The reconstructed correlations of directional Rx antennas with the probe weights of omni-directional antennas under different simulation scenarios.

For the spatial correlations of the Rx antennas are discussed under various scenarios. The target correlations of directional Rx antennas are simulated in Figure 5. Given the antenna element patterns as illustrated in Figure 3, the target correlation between any pair of antennas is less than 1. It can be seen that the narrower 3dB beamwidth of the DUT antenna patterns, the greater impact of antenna patterns on the spatial correlations between antennas. Figure 6 presents the reconstructed spatial correlations with the probe weights which are obtained under omni-directional antennas. The differences between Figure 6 and Figure 5 are obvious under different simulation scenarios, especially when the BS antenna patterns are narrower. The third and fourth subfigures in Figure 6 show different phenomena under the same antenna element patterns, which are mainly caused by the relative positions between the probe antennas and 3dB beamwidth of the directional Rx antenna. The 3dB beamwidth is $65^\circ$ under simulation scenario C and D, and the weights allocated to different probes are affected by the antenna element patterns. There are similar phenomena between the second and fourth subfigures in Figure 6. Therefore, the probe power weights obtained under omni-directional antennas can not...
apply directly to evaluate the directional antenna devices, and the probe weights need to be re-optimized to improve the reconstructed spatial characteristics according to the antenna patterns of the DUT. The reconstructed spatial correlations by solving (9) are given in Figure 7. Obviously, Figure 7 can reconstruct the spatial correlations of the target channel more accurately than Figure 6 under various scenarios.

**FIGURE 7.** The reconstructed correlations of directional Rx antennas with the equation (9) under different simulation scenarios.

Furthermore, the probe weights are presented in Figure 8 where the weights of probes are calculated with or without considering the antenna patterns of the DUT, which can directly compare the impact of the antenna patterns on the channel reconstruction. It is clear that the greater differences the direction gains between the probes, and the greater effect of antenna patterns on the channel reconstruction. In addition, according to the numerical analysis, the maximum value deviation between the target spatial correlation and the reconstructed one is insignificant in Figure 7, which is 0.0041 under scenario A, and the deviation is 0.0121 corresponding to the reconstructed spatial correlation in Figure 6. Moreover, the root-mean-square (r.m.s.) error can be used to describe the average variance distance between the target spatial correlation (Figure 5) and the reconstructed spatial correlations (Figure 6 and Figure 7), and the r.m.s. errors are 0.0285 and 0.0134, respectively. Numerical results under the four simulation scenarios are given in Table 2, which show that the antenna element patterns of the DUT need to be taken into account in the process of the channel reconstruction, especially in the cases of narrow 3dB beamwidths or clusters with a high angular spread.

**C. ANTENNA_GAIN AND NEAR-FAR FIELD ANALYSIS**

1) **ANTENNA_GAINS**

Suppose that each antenna has the same physical structure, and the patterns of each antenna element are completely identical. However, the massive MIMO BS is equipped with a large number of directional antennas, based on which, the antennas which locates at different physical positions may produce different antenna gains for same probe. Therefore, the impact of the DUT antennas with different physical positions on the probes are discussed in Figure 9, where 64 antennas are arranged on the DUT panel uniformly, and the antenna spacing is 0.5λ. Specifically, the 27th antenna and the 53th antenna may produce different antenna gains for probe 1 or probe 2. Reasonably, the antenna gain deviations of different directional antennas for the same probe can be ignored under ideal far-field conditions (R is infinity), but should be taken into account under near-field conditions. Due to the above arguments, the impact of the antenna gain deviations on the accuracies of the reconstructed spatial correlations are simulated in the sequel.

2) **NEAR-FAR FIELD**

By taking into account the various radius R, the r.m.s. errors of spatial correlations are shown in Figure 10. Under different

| Scenarios | Figure 5 max | Figure 5 mean | Figure 6 max | Figure 6 r.m.s. | Figure 7 max | Figure 7 r.m.s. |
|-----------|--------------|---------------|--------------|----------------|--------------|----------------|
| A         | 0.0501       | 0.0365        | 0.0622       | 0.0285         | 0.0542       | 0.0134         |
| B         | 0.3600       | 0.2043        | 0.3688       | 0.0388         | 0.3584       | 0.0278         |
| C         | 0.5860       | 0.3314        | 0.6001       | 0.0439         | 0.5804       | 0.0388         |
| D         | 0.7539       | 0.4129        | 0.7701       | 0.0621         | 0.7548       | 0.0587         |

**TABLE 2.** Numerical analysis under different simulation scenarios.
Simulation scenarios, the r.m.s. errors become smaller gradually with increasing radius $R$. Due to the fact that the Fraunhofer distance needs to be required to specify the far-field plan, a larger anechoic chamber is required for testing massive MIMO devices [9], [28]. The distance $R$ is at least 0.5 meter when the radius of the test area is $3.5 \times \sqrt{2} \lambda$ and the working frequency is 28 GHz. Consistent with the previous conclusions, re-determining the probe weights in terms of the DUT antenna patterns is able to improve the accuracy of the reconstructed radio channel. In addition, directional gain deviations of the different directional antennas for the same probe are simulated under different simulation scenarios. When the Rx antenna has high directivity, such as in scenario A, it is necessary to consider the gain effect of different location antennas on the spatial correlation. However, for other simulation scenarios, the effect could be ignored.

### D. Angular Spectrum Analysis

Angular spectrums observed by the DUT through Bartlett beamforming are also simulated under four simulation scenarios. According to (10) and (11), the target angular spectrum and the reconstructed angular spectrum can be calculated conveniently. Figure 11 depicts the simulation results of the target angular spectrum for a single cluster.
the deviations between the reconstructed angular spectrums and the target angular spectrums over the whole sector of interest are defined in Figure 14 and Figure 15, respectively, given by $10 \log |P(\Psi) - \hat{P}(\Psi, w)|$.

Intuitively, numerical results for the reconstructed angular spectrums under different scenarios are given in Table 3. Obviously, the errors of Figure 13 are smaller than Figure 12. Therefore, the antenna element patterns of the DUT need to be considered in the process of reconstructing the target channel. However, it is clear that the probe weights are re-optimized in the OTA testing, and the improvement of the reconstructed angular spectrum is limited. The reasons for this possibility are many, but in some sense they can be summarized as follows. Firstly, in order to control the cost of the OTA testing system, the number of probes is less, and thus the influence of the DUT antenna patterns on the reconstructed target channel is limited. Secondly, the angular spread of the cluster is narrow, and thus the distributions of probes are concentrated. Therefore, directional Rx antenna will produce the similar directional gains for different probes. Thirdly, probe positions obtained by the multi-shot algorithm under omni-directional antennas are not the optimal for evaluating directional antenna devices. It can be seen that some probe weights are zeros as illustrated in Figure 16. In other words, the probes do not perform as expected, and proper probe positions and more probes will improve the simulation results. Due to the above descriptions, the improvement of the reconstructed angular spectrum will be more obvious for testing directional antenna devices if the probe positions are determined by considering the DUT antenna patterns. Compared with Figure 8, the above explanations also apply to the spatial correlation analysis.

### E. CHANNEL CAPACITY ANALYSIS

The simulation results for the spatial correlation and the angular spectrum show that the accuracy of the reconstructed target channel will be affected, regardless of the DUT antenna element patterns. Figure 17 shows the patterns of directional Rx antennas in area of the probe wall, and 3dB beamwidths are 90°, 120° and 180°, respectively. Figure 18 investigates...
the impact of the antenna patterns on the target channel capacity. The cumulative distribution functions (CDFs) of the target channel are conducted for the spatial direction (15°, 10°) under different directional Rx antennas. By analyzing Figure 3 and Figure 17, omni-directional Rx antenna can capture all the incoming signals from the probes in the anechoic chamber, and the antenna gains are identical for each incoming direction. However, for the DUT with directional antennas, the directional gains are different for impinging angles, which would affect the total receiving power as well as the target channel capacity. As shown in Figure 18, the stronger the antenna directivity, the more significant the influence of antenna patterns on channel capacity.

The reconstructed channel capacities with directional Rx antennas are discussed under various scenarios in Figure 19. For scenario A, the average capacity of the target channel is 5.21 bits/s/Hz, and the average capacities of the reconstructed channel are 5.84 bits/s/Hz and 5.70 bits/s/Hz under the weights obtained by the omni-directional Rx antennas and the directional Rx antennas, respectively. The probe weights are re-optimized in the OTA testing system, but the increase of the channel capacity is limited. The reasons have been analyzed as mentioned above. The same phenomena and explanations apply to the scenario B and C as well. When the DUT antenna patterns become wider, the reconstructed channel capacities approach the target channel capacity gradually. Particularly, under the scenario D, the directional gain deviations are small for different probes, and thus the channel capacity will not be affected by the DUT antenna patterns. The average capacity of the target channel is 9.47 bits/s/Hz, and the average capacities of the reconstructed channel are 9.49 bits/s/Hz and 9.46 bits/s/Hz under the weights which are obtained by the omni-directional Rx antennas and the directional Rx antennas, respectively. In general, for reconstructing target channel in the MPAC setup, the DUT antenna element patterns need to be under consideration in the cases of narrower 3dB beamwidths or clusters with a high angular spread.

Due to the above simulations for both the spatial correlation, the angular spectrum and the channel capacity of the reconstructed channel, the results show that the DUT antenna element patterns will affect the probe weights, thereby affecting the accuracy of the target channel reconstruction when the number of active probe antennas is limited. The accuracy of the reconstructed channel can be improved significantly by using the re-optimized probe weights when antenna element patterns of DUTs are under consideration. Moreover, the probe configurations for multiclusters should be taken into account in the real OTA testing, and the performance of the reconstructed channel will be more prominent than that of the single cluster. In addition, it is clear that the reconstructed spatial characteristics would not be affected by the antenna patterns of the DUT if a sufficient number of probes is used and every ray of the target channel is emulated by an individual probe in the OTA testing. Therefore, the probe weights used to evaluate omni-directional antenna devices can directly apply to the directional antenna devices. This situation needs to be explained, but it is not contradictory to the researches of this paper due to using a limited number of probes in the real OTA testing.

V. CONCLUSIONS

Given that the DUTs may be equipped with directional antennas and the number of active probes is limited in the OTA testing, the influence of the DUT antenna patterns on the target channel reconstruction is discussed in the MPAC setup using the PFS technique. In this paper, the spatial channel covariance matrix and the angular spectrum are used as the metrics to re-determine the probe weights, respectively, which take the impact of the DUT antenna patterns into account. Furthermore, the channel capacity of the reconstructed channel is also investigated to examine the emulated channel in the case of directional antenna devices.

Extensive simulations are conducted, confirming that the DUT antenna patterns will affect the probe weights and should be under consideration when testing directional antenna devices in the MPAC setup using the PFS technique, especially for narrower 3dB beamwidths or clusters with a high angular spread. In addition, simulation results of the r.m.s. correlation errors for various anechoic chamber radii are analyzed as well, and the effect of anechoic chamber radius less than the Fraunhofer distance on channel reconstruction is obvious. In order to eliminate the influence of near-field effect on channel simulation, the radius of anechoic chamber is at least 0.5 meter when the radius of the test area is \(3.5 \times \frac{\lambda^2}{\Delta} \) and the working frequency is 28 GHz. Moreover, the antenna gain deviations could be ignored when the same incoming signal reaches the different Rx antennas, especially when the 3dB beamwidth of the directional antenna element is wider.

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