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Beam Probability Metric for OTA Testing of Adaptive Antenna Systems in Multi-Probe Anechoic Chamber Setups

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***Abstract*—With the utilization of massive multiple-input multiple-output (MIMO) and millimeter-wave (mmWave) technologies in 5G communications, over-the-air (OTA) testing for 5G antenna systems has become a strong need because conducted testing is no longer applicable. New OTA testing metrics are required to evaluate new performance of 5G antenna systems. This paper investigates whether the recently proposed metric, e.g. beam probability is suitable to evaluate channel emulation accuracy for adaptive antenna systems in multi-probe anechoic chamber (MPAC) OTA setups. Well-known 2D spatial channel models are selected as examples in simulation results to discuss the relationship between device under test (DUT) size and number of OTA antennas for beam probability metric.**

***Index Terms*—5G OTA testing, MPAC, adaptive antenna, beam probability.**

I. Introduction

The next generation (5G) wireless telecommunication system is currently in development stage. As two enabled technologies in 5G communications, massive multiple-input multiple-output (MIMO) and millimeter-wave (mmWave) have been utilized in base station (BS) and user equipment (UE) [1]. Since the radio channel is highly sparse and the severe free-space pathloss is suffered at mmWave frequencies, highly directive and high gain antenna systems are required at both BS and UE sides using beamforming to provide high signal power [2]. On the other hand, adaptive beam patterns of antenna systems are also enabled in the link establishment procedure and the time-variant radio channel conditions [3]. Therefore, the adaptive beamforming operation with beam selection process has become a key feature of 5G antenna systems due to the sparsity and the dynamics of channels. However, this feature introduces new challenges to the performance testing of 5G antenna systems compared with 4G antenna systems [4].

To evaluate the performance of antenna systems, over-the-air (OTA) testing for MIMO terminal has been developed for years [5]–[7]. Among three OTA testing methodologies, multi-probe anechoic chamber (MPAC) test system is more suitable for OTA testing of massive MIMO and adaptive antenna systems [8], [9], though the system design might be cost prohibitive. In MPAC setups, the target propagation channels experienced by device under test (DUT) are reproduced. Some OTA system performance metrics are developed to evaluate how well the target propagation channels are emulated [10]. For 4G antenna systems testing, power angular spectrum (PAS) based metrics are adopted. The direct one is PAS estimation and the indirect one is spatial correlation. The similarity of the estimated PAS by DUT and the error of spatial correlation under target and emulated channels are investigated to evaluate the channel emulation accuracy. However, compared with these PAS-based metrics, a new metric of beam probability becomes more important for 5G antenna systems testing because of the beam management and beam scheduling in 5G new radio [11], [12]. The beam selection performance of 5G antenna systems is evaluated by this metric. In this metric, the beam with the strongest power is selected by scanning beam power among all predefined beams per time snapshot of the fading channel. After all fading snapshot, predefined beam directions with their probabilities are determined [2]. Note that the DUT needs to have a predefined code book with fixed beams and only a single beam with the highest power is allocated for each time snapshot [3].

However, it is still interesting to investigate how to quantify the emulation accuracy in terms of beam probability under target channel and emulated channel. In this paper, the beam probability metric is investigated in MPAC OTA setups. Channel models, e.g. single cluster, SCME channels are selected, since they are well-known and well investigated for 4G OTA scenarios. Note that the work can be extended to 3D channel models, which are more suitable for 5G research.

The rest of the paper is organized as follows. The signal model of beam probability is presented in Section II. Simulation settings and results are discussed under several channel models in Section III. Conclusion is given in Section V.

II. Method

As a channel emulation technique in MPAC setups, the prefaded signal synthesis (PFS) method is adopted to transmit weighted independent identically distributed (i.i.d.) fading sequences from multiple probes to DUT. The received signals at the DUT array elements with noise neglected are written as [13]

$$\boldsymbol{x}[n] = \mathbf{F}\boldsymbol{s}[n] \tag{1}$$

where $\boldsymbol{x}[n] = \{x_m[n]\} \in \mathbb{C}^{M\times 1}$ is a vector containing M received signals at the nth snapshot. $\boldsymbol{s}[n] = \{s_k[n]\} \in \mathbb{C}^{K\times 1}$

is a vector containing K transmitted weighted i.i.d. OTA signals at the nth snapshot. $\mathbf{F} = \{\gamma_{mk}\} \in \mathbb{C}^{M\times K}$ is a transfer matrix of coefficients from the kth probe to the mth antenna element.

Assuming that OTA probes are located in the far field of DUT array, we have

$$\gamma_{mk} = \frac{\lambda}{4\pi||\overrightarrow{p_k}||} e^{-j\frac{2\pi}{\lambda}\frac{\overrightarrow{p_k}\cdot\overrightarrow{e_m}}{||\overrightarrow{p_k}||}} \quad (2)$$

where $\overrightarrow{p_k}$ and $\overrightarrow{e_m}$ denote the location vectors of the kth probe and the mth antenna element, respectively. $||\cdot||$ and $(\cdot)$ are the vector norm operator and the vector dot product operator, respectively.

The steering vector $\boldsymbol{a}(\Omega) = \{a_m(\Omega)\} \in \mathbb{C}^{M\times 1}$ of a DUT array to the space angle Ω of predefined beam direction is expressed as

$$a_m(\Omega) = e^{-j\frac{2\pi}{\lambda}\overrightarrow{e_m}\cdot\overrightarrow{\Omega}} \quad (3)$$

where $\overrightarrow{\Omega}$ is a unit vector corresponding to the space angle Ω.

The beam power from the space angle Ω at the nth snapshot is

$$P(\Omega)[n] = \left|\boldsymbol{a}^H(\Omega)\boldsymbol{x}[n]\right|^2 \quad (4)$$

where $\{\cdot\}^H$ denotes the Hermitian operator.

The highest power of the bth beam at the nth snapshot is

$$P[n] = \max_b P(\Omega_b)[n] \quad (5)$$

where Ω_b denotes space angle of bth beam direction.

Then the probability of detecting the maximum power in the bth beam is

$$p(\Omega_b) = \frac{n_b}{N} \quad (6)$$

where n_b is the time for bth beam satisfying (5) over N snapshots.

Two quantitative measures are adopted to evaluate the beam probability metric for 5G OTA testing [14].

1) Beam peak distance: the probability weighted angular distance (barycenter offset) between the reference and the OTA beam allocation distributions:

$$D_p = \left\| \sum_{b=1}^{B} \Omega_b p_r(\Omega_b) - \Omega_b p_o(\Omega_b) \right\| \quad (7)$$

2) Beam statistical distance: the total variation distance (similarity percentile) between the reference and the OTA beam allocation distributions:

$$D_s = \frac{1}{2}\sum_{b=1}^{B} |p_r(\Omega_b) - p_o(\Omega_b)| \quad (8)$$

where $p_r(\Omega_b)$ and $p_o(\Omega_b)$ are probabilities of the bth predefined beam in the reference case and the OTA case, respectively. B is the number of predefined beams.

The smaller the beam peak distance, the smaller the barycenter offset between the reference and the OTA beam allocation distributions. The smaller the beam statistical distance, the more similar the reference and the OTA beam allocation distributions.

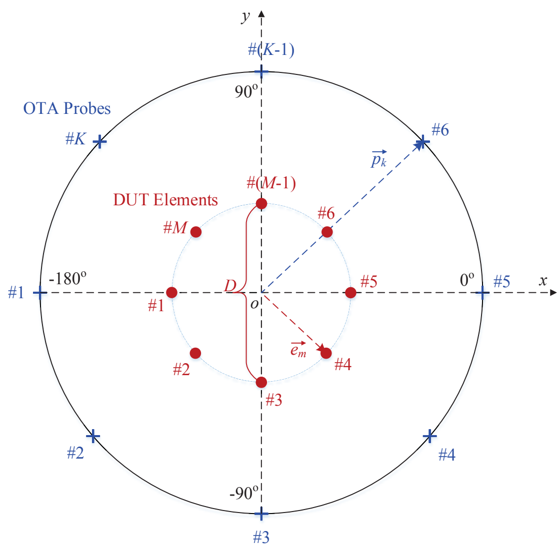

Fig. 1. A 2D MPAC setup.

III. Simulation Results and Discussions

To illustrate the beam probability metric for OTA testing of adaptive DUT, a 2D MPAC setup emulating 2D channel models is considered for simplicity, as shown in Fig. 1. K OTA probes are distributed uniformly in an OTA ring. DUT is a uniform circular array (UCA) with diameter D, whose center is the same as that of OTA ring. It is assumed that the predefined main beams of DUT array are targeted to $B = 32$ directions. Both single cluster and multi-cluster channel models at the UE side are investigated for example.

A. Beamforming power pattern

The beamforming capability of adaptive DUT is presented first in this part. It is required that the main beam of DUT pattern is formed in the specified directions. Taking several directions for example, beamforming power patterns of DUT using Bartlett beamforming in these directions are shown in Fig. 2. Two values of DUT size D ($D = 0.7\lambda$ and $D = 1.4\lambda$) are considered. The beam patterns in different directions have the same shape with the main beam targeted to corresponding directions for each DUT size. Furthermore, narrower pattern is obtained with larger DUT size. It demonstrates that the beam resolution of beamforming pattern is enhanced by large DUT aperture. Therefore, larger DUT has stronger capability to distinguish spatial paths due to narrower beamwidth. More OTA antennas are needed to ensure that the DUT cannot distinguish between target and emulated spatial channels.

B. Beam probability under single cluster channel models

The single cluster channel models with any angle of arrival (AoA) and azimuth spread of 35° are investigated in this part. Considering the effect of the symmetry and asymmetry of probe locations with respect to AoA on beam probability under single cluster channel models, three AoAs (AoA $= 0°$, AoA $= 10°$, and AoA $= 22.5°$) are discussed as examples.

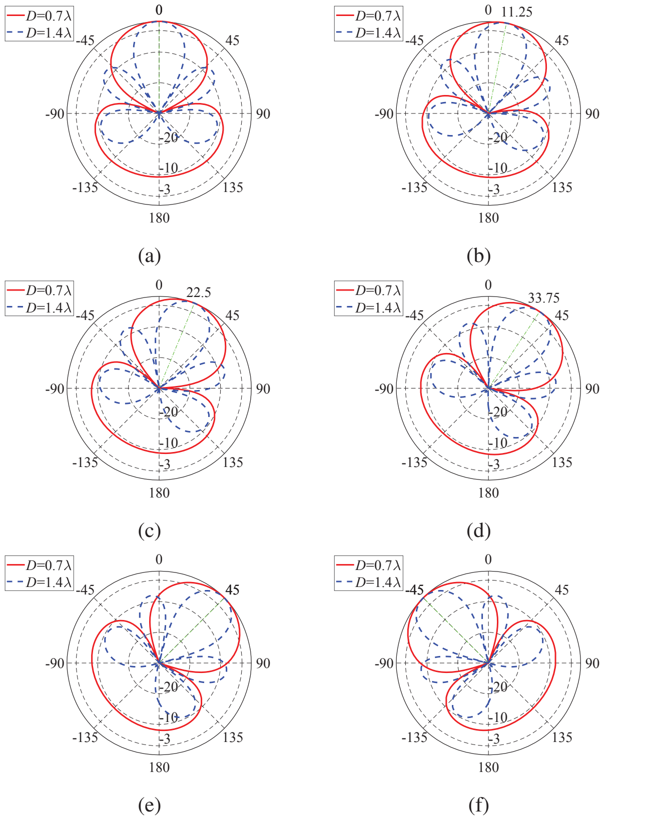

Fig. 2. Beamforming power patterns of DUT for $D = 0.7\lambda$ and $D = 1.4\lambda$ in the specified directions. (a) $0°$; (b) $11.25°$; (c) $22.5°$; (d) $33.75°$; (e) $45°$; (f) $-45°$.

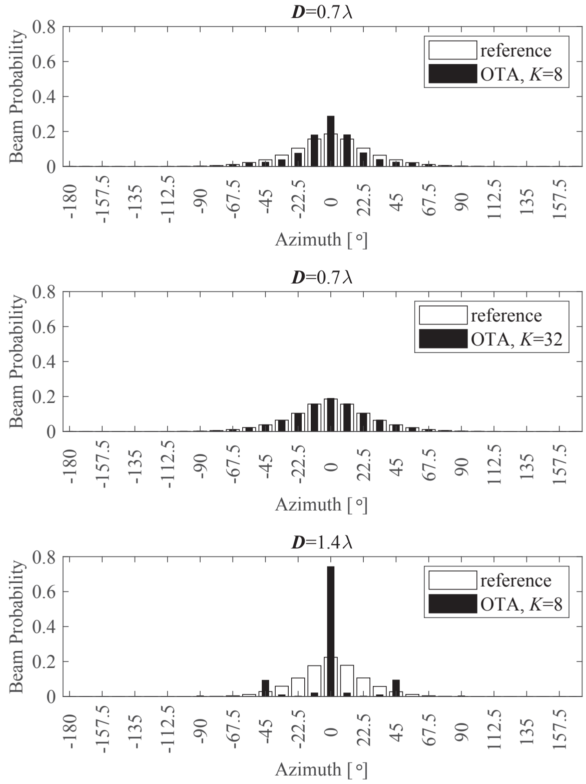

Fig. 3. Predefined beam directions and their probabilities under the single cluster channel model with AoA $= 0°$ in the reference and the OTA cases.

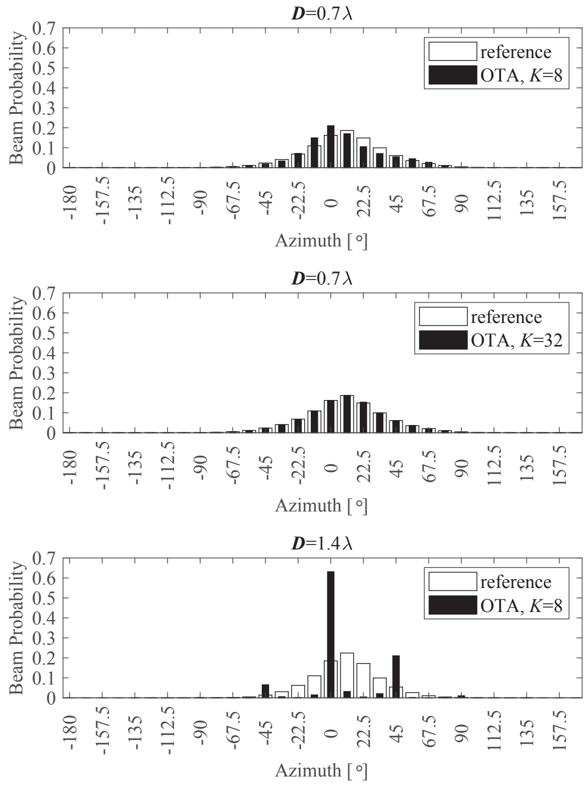

Fig. 4. Predefined beam directions and their probabilities under the single cluster channel model with AoA $= 10°$ in the reference and the OTA cases.

The results of beam probability emulation under single cluster channel models with AoA $= 0°$, AoA $= 10°$, and AoA $= 22.5°$ are presented for three sets of DUT size D and probe number K in Fig. 3, Fig. 4, and Fig. 5, respectively. The quantitative measures are detailed in Table I.

Since the beam peak distance D_p is close to $0°$ for three sets of D and K under the single cluster channel models with AoA $= 0°$ and AoA $= 22.5°$, the increase of DUT size and probe number basically has no impact on the beam peak distance. In these two cases, the probe locations are symmetrical with respect to AoA $= 0°$ and AoA $= 22.5°$ for both $K = 8$ and $K = 32$. However, under the single cluster channel models with AoA $= 10°$, D_p is close to $2°$ and $0°$ for $K = 8$ and $K = 32$, respectively. The increase of probe number results in slight decrease of beam peak distance for $D = 0.7\lambda$, whereas the increase of DUT size nearly does not affect the beam peak distance for $K = 8$. In this case, the probe locations are approximately symmetrical with respect to AoA $= 10°$ for $K = 32$, but not for $K = 8$. It indicates that beam peak distance is reduced slightly by more probes when limited probe locations are not symmetrical with respect to AoA under single cluster channel models, otherwise the beam peak distance is hardly affected by the increased OTA probes.

On the other hand, the increase of probe number reduces the beam statistical distance D_s and strengthens the similarity

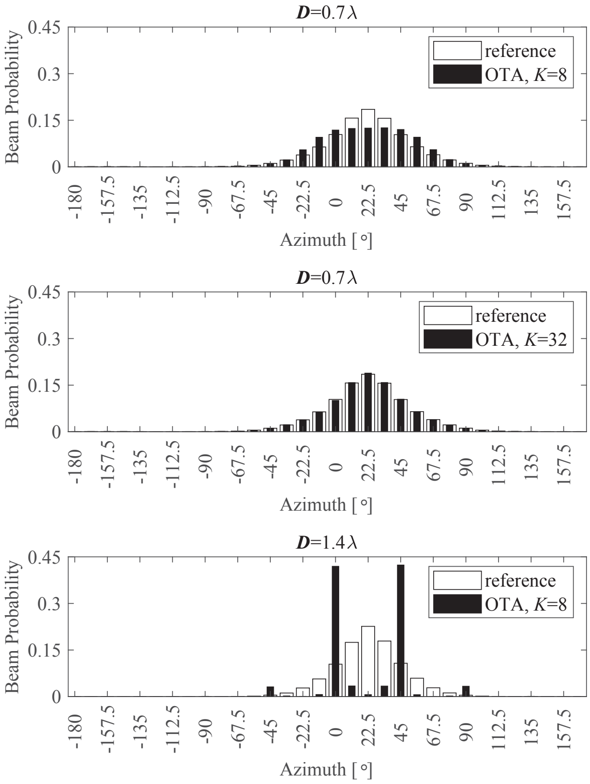

Fig. 5. Predefined beam directions and their probabilities under the single cluster channel model with AoA $= 22.5°$ in the reference and the OTA cases.

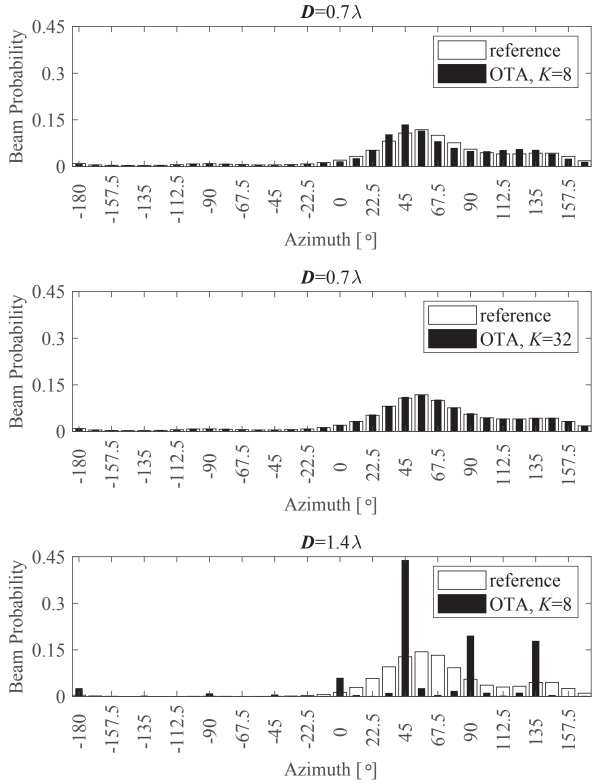

Fig. 6. A predefined set of fixed beam directions and their probabilities under the SCME UMa channel model in the reference case and the OTA case.

TABLE I
RESULTS OF BEAM PROBABILITY EMULATION UNDER THREE SINGLE CLUSTER CHANNEL MODELS FOR THREE SETS OF D AND K

Parameter Setting	AoA $= 0°$		AoA $= 10°$		AoA $= 22.5°$	
	D_p (°)	D_s	D_p (°)	D_s	D_p (°)	D_s
$D = 0.7\lambda$, $K = 8$	0.24	0.15	1.69	0.11	0.01	0.13
$D = 0.7\lambda$, $K = 32$	0.14	0.01	0.13	0.01	0.19	0.01
$D = 1.4\lambda$, $K = 8$	0.02	0.66	1.95	0.67	0.04	0.69

percentile between the reference and the OTA beam probability distributions for $D = 0.7\lambda$, whereas the increase of DUT size reduces the similarity percentile for $K = 8$.

C. Beam probability under multi-cluster channel models

The SCME UMa and SCME UMi channel models are investigated in this part. The results of beam probability emulation under these two channel models are presented for three sets of DUT size D and probe number K in Fig. 6 and Fig. 7, respectively. The quantitative measures are detailed in Table II.

It can be seen that the impact of DUT size and probe number on beam statistical distance is the same as that under the single cluster channel models. The beam peak distance under these two multi-cluster channel models is hardly affected by the increased OTA probes for $D = 0.7\lambda$. Larger DUT size greatly increases the beam peak distance under SCME UMa channel model, whereas it slightly increases the beam peak distance under SCME UMi channel model for $K = 8$.

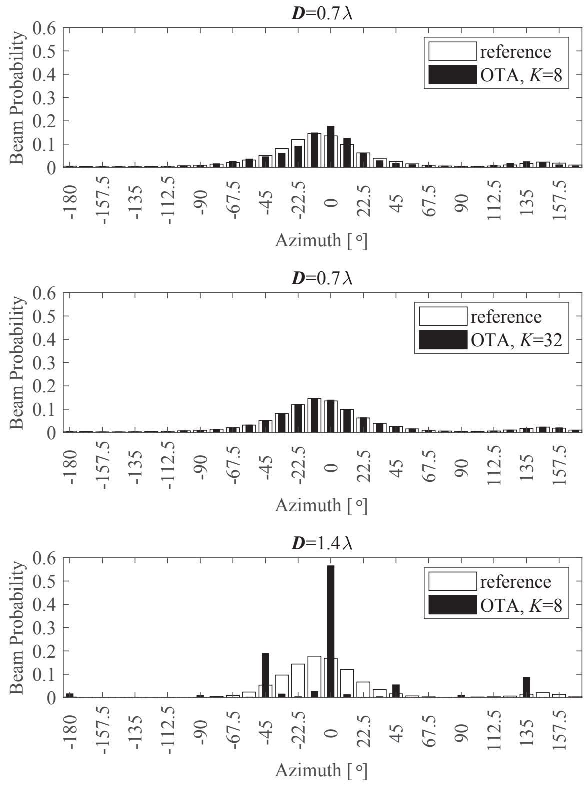

Fig. 7. A predefined set of fixed beam directions and their probabilities under the SCME UMi channel model in the reference case and the OTA case.

TABLE II
RESULTS OF BEAM PROBABILITY EMULATION UNDER TWO MULTI-CLUSTER CHANNEL MODELS FOR THREE SETS OF D AND K

Parameter Setting	SCME UMa		SCME UMi	
	D_p (°)	D_s	D_p (°)	D_s
$D = 0.7\lambda$, $K = 8$	0.62	0.09	0.37	0.10
$D = 0.7\lambda$, $K = 32$	0.16	0.01	0.49	0.01
$D = 1.4\lambda$, $K = 8$	5.98	0.66	1.15	0.67

D. Discussions

For any OTA metric, the emulation accuracy should be improved by more OTA probes when DUT size is fixed because the channel emulated by more OTA probes gets closer to the target channel. On the other hand, the emulation accuracy should be decreased by larger DUT size when probe number is fixed because the target and the emulated channels are distinguished more easily by DUT with higher beam resolution. However, the beam peak distance does not follow this principle. Therefore, beam peak distance is not a good metric to investigate the relationship between OTA probe number and the test zone size.

IV. CONCLUSION

A beam probability metric for 5G OTA test system is discussed in this paper. This metric is adopted to evaluate the beam selection performance of 5G antenna systems. In the paper, the beam probability emulation under single cluster and multi-cluster channel models is performed in MPAC OTA setups. First, beamforming power patterns of adaptive DUT are presented. Then the histograms of beam probability distributions under reference and OTA channel models are demonstrated. The emulation accuracy is quantified by the beam peak distance and the beam statistical distance. Simulation results imply that the beam statistical distance might be an more instructive quantitative measure for beam probability metric of 5G OTA testing compared with the beam peak distance.

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