Comparing Channel Emulation Algorithms by Using Plane Waves and Spherical Vector Waves in Multi-Probe Anechoic Chamber Setups

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Published in:
I E E E Transactions on Antennas and Propagation

DOI (link to publication from Publisher):
10.1109/TAP.2019.2902728

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Comparisons of Channel Emulation Methods for State-of-the-Art Multi-Probe Anechoic Chamber based Millimeter-Wave Over-the-Air Testing

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***Abstract*—The sectored multi-probe anechoic chamber (MPAC) is regarded as a promising millimeter-wave (mmWave) over-the-air (OTA) testing solution. However, there are still debates in the literature about which channel emulation method, i.e., pre-faded synthesis (PFS) or plane wave synthesis (PWS), should be used for the sectored MPAC testing system. In this paper, a thorough comparison between the two channel emulation methods is conducted. It is found that for sectored MPAC (where the active probes are unlikely to be uniformly distributed over the probe panel) the PWS is more accurate than the PFS in line-of-sight (LOS) scenarios and less accurate than the PFS in non-LOS (NLOS) scenarios. Explanations are given.**

***Index Terms*—millimeter-wave (mmWave), multi-probe anechoic chamber (MPAC), over-the-air (OTA), plane wave synthesis (PWS), pre-faded synthesis (PFS)**

I. Introduction

Over-the-air (OTA) testing is essential for research and development of wireless devices [1], [2]. It enables performance evaluation of the device under test (DUT) by emulating multipath fading channel in controllable (laboratory) environments. Compared with field tests, OTA tests are repeatable, cost-effective, and time-efficient. As multiple-input multiple-output (MIMO) techniques become ubiquitous in modern communication systems, e.g., long term evolution (LTE) and wireless local area network (WLAN), MIMO-OTA testing attracts considerable attentions from both academia and industry. Popular MIMO-OTA techniques include the multi-probe anechoic chamber (MPAC) method [3], radiated two-stage (RTS) method [4], and the reverberation chamber (RC) method [5]. Both MPAC and RTS methods have been standardized for MIMO-OTA testing in the 3rd generation partnership project (3GPP) and cellular telecommunication and internet association (CTIA). Even though considerable efforts have been exerted in emulating non-isotropic power angular spectrum (PAS) in the RC, e.g., [6], [7], there is still limited controllability of the RCs PAS. Instead, the standalone RC was standardized for (single-antenna) large-form-factor DUTs in CTIA thanks to its large test area and relatively low cost [8].

The fifth generation (5G) millimeter-wave (mmWave) communication systems not only bring new challenges to OTA testing, but also make it the only testing solution. The reasons are multi-fold: 1) due to space limitation and high insertion loss, the standard antenna port will probably be eliminated in 5G mmWave systems; 2) even if antenna ports are accessible, tens or hundreds of antenna ports make the conducted testing a formidable task; 3) in order to test the adaptive beamforming [9] performance of the 5G mmWave system, the array antenna must be tested together with the rest of the transceiver [10].

The RTS method necessities non-intrusive antenna pattern measurements prior to actual OTA testing, making it less suitable for adaptive (hybrid) beamforming mmWave systems. Moreover, the number of probes (i.e., OTA antennas) in the RTS system must be no smaller than the number of antennas in the DUT, which increases the cost significantly for large mmWave arrays.

As concluded in [10], the MPAC method can be a feasible solution to mmWave OTA testing. In order to reduce the cost and increase the test zone, the sectored MPAC-based OTA method was proposed in [10]-[13], all of which assume the pre-faded synthesis (PFS) technique for channel emulations [14]. The PFS technique synthesizes the second-order moments of the wave field (such as the spatial correlation) instead of the wave field itself. It has been adopted in almost all commercial channel emulators (CEs). Unlike the PFS technique, the plane wave synthesis (PWS) technique selects the field synthesis error as the cost function to optimize the (complex) probe weights [15]. Theoretically speaking, the PWS is more accurate than the PFS (at the cost of increased complexity) for conventional MPAC with uniformly distributed probes in a two-dimensional (2D) horizontal ring [16]. Furthermore, it was speculated that deterministic field components, such as the line-of-sight (LOS) component, cannot be well emulated by the PFS technique [17]. However, mmWave OTA testing is quite different from conventional MIMO-OTA testing. By studying the required number of probes heuristically, it was concluded that the PWS dictates a much larger number of probes (and CE resources) than the PFS does for large DUT [18]. Surprisingly, to the authors best knowledge, no experimental (simulation) comparisons of the two techniques for mmWave OTA testing have been conducted, despite the contradicting conclusions in the literature, e.g., [13], [17], [18]. In this work, we compare the channel emulation accuracies of the MPAC-based mmWave OTA solution with PFS and PWS techniques. It is found that, for mmWave OTA testing of large DUT, such as mmWave base station (BS) array antennas, the PWS is more accurate than the PFS in LOS scenarios and less accurate in non-LOS (NLOS) scenarios.

II. CHANNEL EMULATION METHODS

A sectored MPAC based mmWave OTA testing system is illustrated in Fig. 1. As can be seen, it consists of an anechoic chamber (AC), the DUT (i.e., BS with a sectored array antenna) and probes located at two ends of the AC, a CE, a switch network selecting K active probes out of all the Q probes and connecting them to the CE, and user equipments (UEs) or UE emulators. In this work, we assume that the probes are equally spanned over a BS sector (yet the selected active probes are unlikely to be uniformly distributed, as shown in Section III). For simplicity, we assume vertical polarization throughout this work, which can be extended to dual-polarized channel in a straightforward manner. Without loss of generality, we assume the uplink mode, i.e., the BS DUT is the receiver and the UE is the transmitter.

Following the same procedure given in [13], we first apply mechanical rotation to the DUT based on a priori channel information in order to utilize the angular sector of the probe panel. Then we sort the powers of the channel clusters in descending order and select the probes with closest angles w.r.t. the clusters. Precaution is taken so that probes are not allocated to clusters outside the probe panel. The optimal weights at the active probes depend on the channel emulation methods (i.e., PFS and PWS). For the sake of completeness, we briefly present the two methods (after introducing the target channel) in the sequel.

A. Target Channel

The channel from the sth transmit (Tx) element to the uth receive (Rx) element via the lth cluster can be expressed as

$$\begin{aligned} h_{s,u,l}\left(f,t\right) =& \sqrt{\frac{P_l}{M}} \sum_{m=1}^{M} f_s^{\mathrm{Tx}}\left(\Omega_{l,m}^{\mathrm{Tx}}\right) f_u^{\mathrm{Rx}}\left(\Omega_{l,m}^{\mathrm{Rx}}\right) \\ & \times \exp\left(j2\pi v_{l,m} t + j\Phi_{l,m} - j2\pi f \tau_l\right). \end{aligned} \tag{1}$$

where M is the number of subpaths of each cluster; P_l and τ_l are the power and delay of the lth cluster, respectively; f_s^{Tx} and f_u^{Rx} are Tx and Rx (complex) antenna patterns, respectively; $\Omega_{l,m}^{\mathrm{Tx}}$ and $\Omega_{l,m}^{\mathrm{Rx}}$ are the solid angles of departure and arrival of the lth cluster and mth subpath, respectively; $v_{l,m}$ and $\Phi_{l,m}$ are Doppler frequency shift and random initial phase of the lth cluster and mth subpath, respectively.

B. PFS and PWS Methods

The emulated channel using the PFS or PWS method can be expressed in a unified form as

$$\begin{aligned} \hat{h}_{s,u,l}\left(f,t\right) =& \sqrt{\frac{P_l}{M}} \sum_{m=1}^{M} f_s^{\mathrm{Tx}}\left(\omega_{l,m}^{\mathrm{Tx}}\right) f_u^{\mathrm{Rx}}\left(\omega_{l,k}^{\mathrm{OTA}}\right) \omega_{l,m,k} \\ & \times \exp\left(j2\pi v_{l,m} t + j\Phi_{l,m,k} - j2\pi f \tau_l\right). \end{aligned} \tag{2}$$

where K is the number of active probes, $\Omega_{l,k}^{\mathrm{OTA}}$ is the solid angle of arrival from the lth cluster and kth probe. Note that the initial phases $\Phi_{l,m,k}$ from different probes in PFS are independent of each other, whereas in PWS the probe index k should be dropped as in (1) (i.e., $\Phi_{l,m}$) since different probes therein are coherent. Nevertheless, the difference between the PFS and PWS methods mainly resides in the weighting coefficient $\omega_{l,m,k}$.

The PFS method emulates the channel cluster-wise by optimizing the second order moment (i.e., spatial correlation), whereas the PWS emulate every subpath by optimizing the wave field directly. Therefore, for the PFS method, the weighting coefficient $\omega_{l,m,k}$ is independent of the subpath index m and only amplitude weights are needed. The PFS weights are obtained by minimizing the target and emulated (spatial) correlations using, e.g., the convex optimization with the constraint $\sum_{k=1}^{K} g_{l,k}^2 = 1$ [3], which is adopted in this work.

For the PWS method, $\omega_{l,m,k}$ is the optimal complex weight of the mth subpath of the lth cluster and kth probe obtained by minimizing the target and emulated wave field using either the least square (LS) method [14] or the spherical wave expansion [15]. (The former is used in this work in that it has slightly better performance [19].

Theoretically, the PWS should have better accuracy than the PFS does for small DUT in sub-6 GHz bands for the conventional MPAC with uniformly distributed probe in a 2D horizontal ring [16]. However, the PWS dictates not only power calibrations, as the PFS does, but also phase calibrations of the probes, which is a challenging task at mmWave frequencies. Moreover, it is expected that the PWS requires more (active) probes for large DUT [18]. As the cost of the mmWave OTA testing system increases drastically with increasing number of active probes (and corresponding CE resources), it is only fair to compare the mmWave OTA performances of the two methods under *the same number of active probes*. As a result, we address this question in the next section.

III. SIMULATION AND DISCUSSION

In this section, we assume that the Q = 561 probes are equally spanned over a sector of 120° in azimuth and 60° in elevation (with an angular resolution of 3.75°); K = 16 active probes are selected for NLOS scenario and K = 8 active probes are selected for the LOS scenario using the approaches mentioned in Section II (Fig. 2 illustrates the probe selection for both NLOS and LOS scenarios); the DUT is equipped with a 8 × 8 uniform rectangular array (with 64 elements in total); without specification, the center-to-center distance

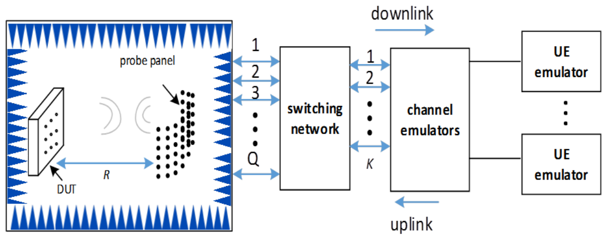


Fig. 1. Illustration of sectored MPAC based mmWave OTA testing system.

between the probe panel and the DUT is R = 2 m; and the operating frequency is 28 GHz.

In this work, the 3GPP clustered delay line (CDL) models [20] have been selected as the target channel models. (The 3GPP channel models support mmWave simulations up to 100 GHz and a bandwidth up to 2 GHz.) The 3GPP CDL models have been used in [10], [13]. It is worth noting that the 3GPP CDL models employ a simplified approach for the time evolution of the propagation channel, i.e., each subpath of a cluster is assigned a Doppler frequency shift based on the initial angle of arrival and these angles and delays remain unchanged regardless of the UE mobility. Due to this limitation of the 3GPP CDL models, the ray-tracing channel model [21] has been applied to the virtual drive testing in MPAC [22], even though the geometry based stochastic channel model (GSCM) is more preferable for MPAC-based OTA testing. Due to this reason, a GSCM channel model with better time evolution performance was used in [23] for testing the adaptive beamforming capability of the DUT. In that model, the UE trajectory is divided into segments. To take into account of the nonstationary channel in general [24], the technique of birth and death of clusters are applied to UE trajectories between segments. Nevertheless, in this work, we focus on the performances of PFS and PWS methods in emulating quasi-static mmWave spatial channels.

While the MIMO throughput [25] has been chosen as the standard performance metric for LTE MIMO-OTA testing [26], performance metrics for mmWave OTA testing have not been standardized yet. Since the channel properties in the frequency (delay) and time (Doppler frequency) domains are solely determined by the CE, the spatial domain statistical properties, i.e., spatial correlation and PAS, are usually regarded as suitable performance metrics for evaluating the accuracy of the mmWave OTA testing. Since the PAS is the Fourier transform of the spatial correlation, we focus on the PAS metric. For end-user experience, the capacity is used as another performance metric to compare the performances of the two channel emulation methods in this section.

Common PAS estimators used in the previous OTA works are Bartlett beamformer and multiple signal classification (MUSIC) algorithm. Although the MUSIC algorithm has higher resolution, it is sensitive to channel model errors and, therefore, is not suitable for PAS estimation of the emulated channels. The Bartlett beamformer is robust to channel model errors and has good resolution for the considered DUT with large array aperture. Moreover, it is equivalent to the popular maximum ratio transmission precoding for massive MIMO system, making the estimated PAS a more relevant performance metric. Therefore, we use the Bartlett beamformer to estimate the PAS. The estimated PASs of the target channel, the emulated channel using PFS, and the emulated channel using PWS are shown in Figs. 3 and 4 for NLOS and LOS scenarios, respectively. As can be seen, the PAS of the emulated channel with the PFS method resembles that of the target channel more, as compared with that of the emulated channel with the PWS method for the NLOS scenario. For the LOS scenario, the PASs of the emulated channels using both methods agree well with that of the target channel. To

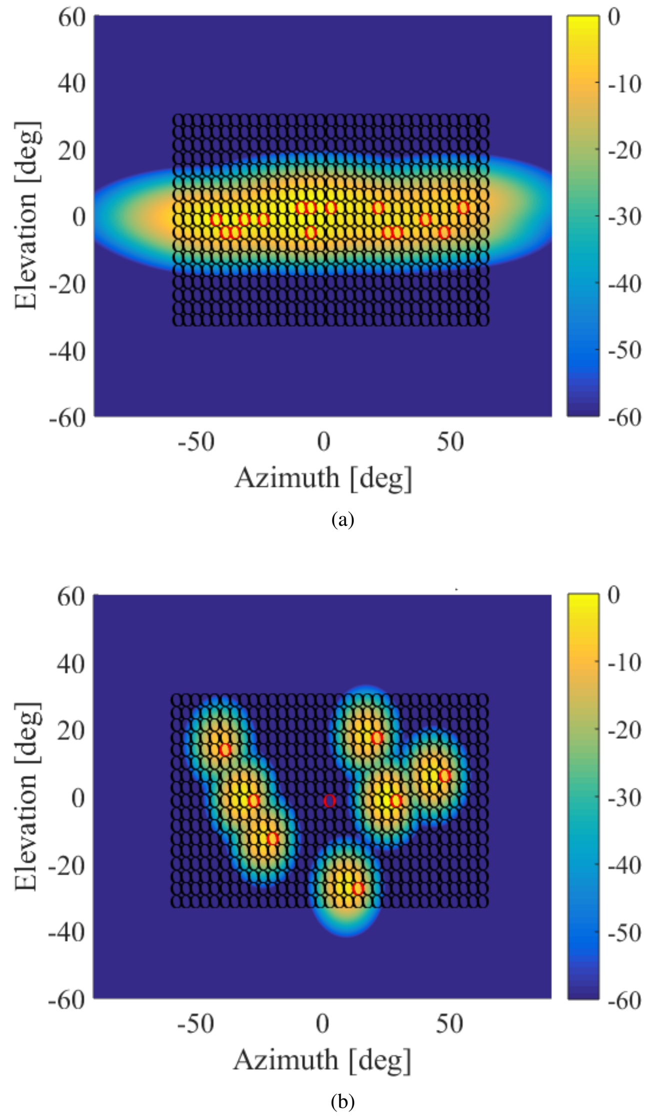


Fig. 2. Illustration of probe selection for a target PAS: (a) NLOS scenario; (b) LOS scenario. Black circles represent the available probes; red circles denote the selected active probes. The red circle in the center of (b) corresponds to the LOS path with no angular spread.

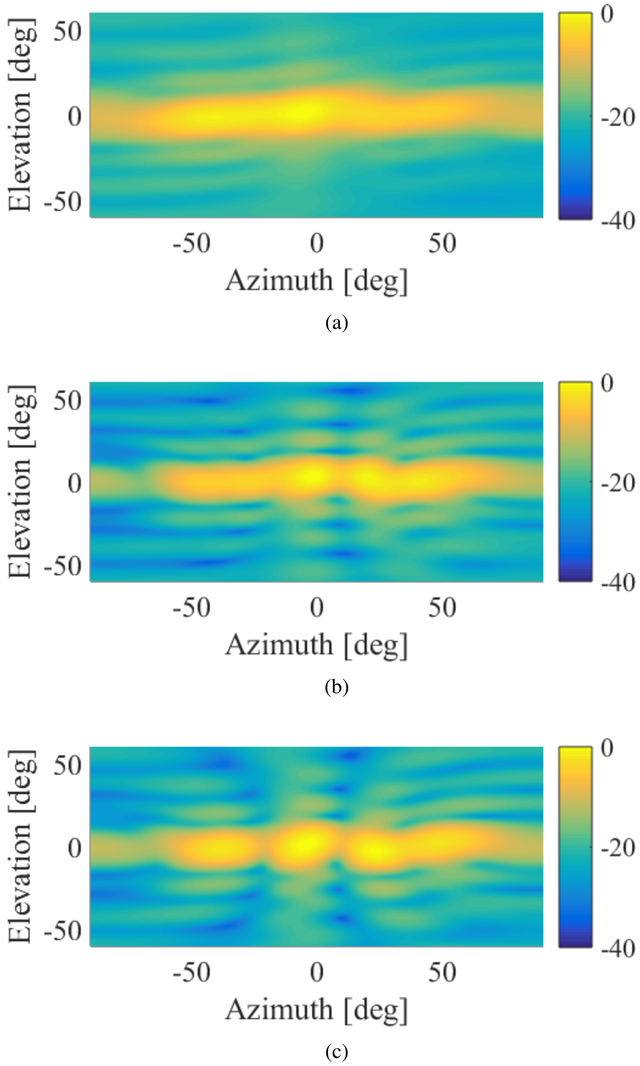


Fig. 3. PASs of (a) the target channel, (b) the emulated channel using PFS, and (c) the emulated channel using PWS in the NLOS scenario.

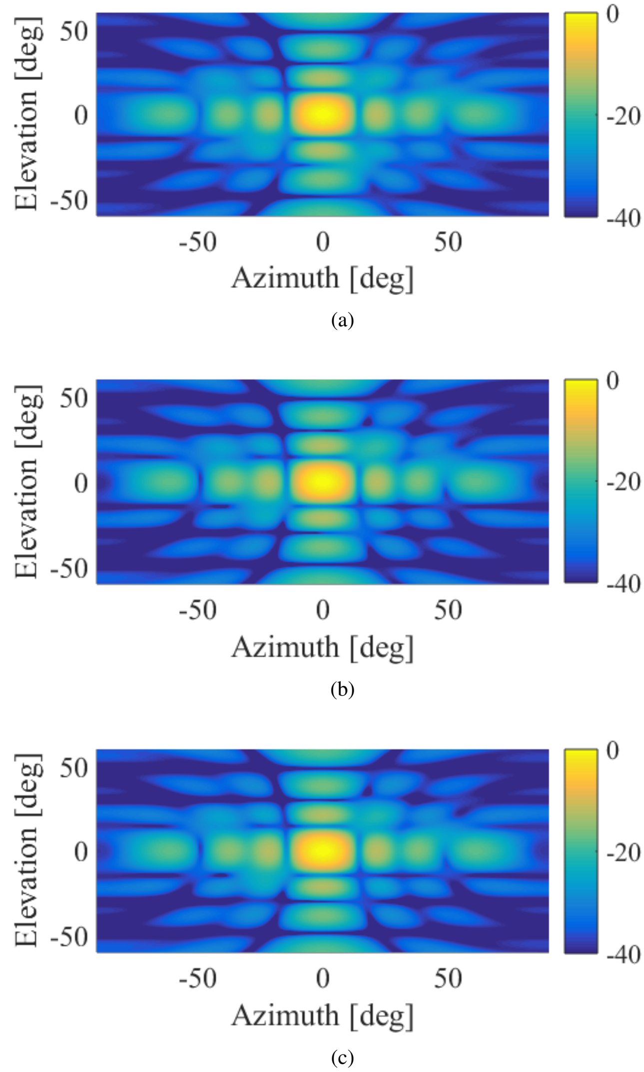


Fig. 4. PASs of (a) the target channel, (b) the emulated channel using PFS, and (c) the emulated channel using PWS, in LOS scenario.

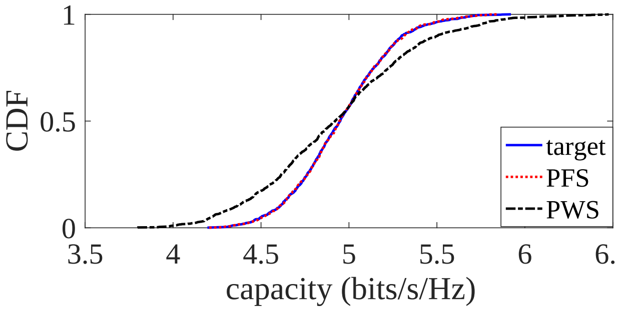
quantify the PAS similarity, we resort to the total variation distance between normalized PASs [13],

$$D = \frac{1}{2}\oint_{4\pi}\left|\frac{\hat{S}\left(\Omega\right)}{\oint_{4\pi}\hat{S}\left(\Omega'\right)d\Omega'} - \frac{S\left(\Omega\right)}{\oint_{4\pi}S\left(\Omega'\right)d\Omega'}\right|d\Omega. \tag{3}$$

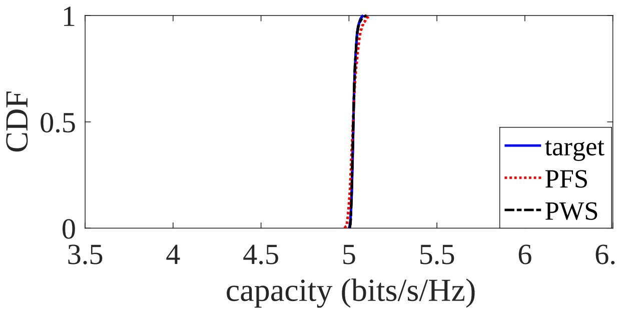
where S and $\hat{S}$ denote the estimated PAS of the target channel and the emulated channel (using either the PFS or PWS method), respectively. The total variation distance of the emulated channel using PFS (w.r.t. the target channel) is 0.0209 and 0.2026 for LOS and NLOS scenarios, respectively, whereas that of the emulated channel using PWS is 0.0199 and 0.2344 for LOS and NLOS scenarios, respectively. As can be seen, the PFS is more accurate than the PWS in the NLOS scenario and less accurate than the PWS in the LOS scenario. Nevertheless, it is worth noting that the PAS errors of both methods are rather small in the LOS scenario and there is only insignificant improvement of using the PWS.

The cumulative distribution functions (CDFs) of the capacities of the target channel and the emulated channels are shown in Fig. 5. As expected, the PFS is more accurate than the PWS in the NLOS scenario and less accurate than the PWS in the LOS scenario. As can be seen from Fig. 5b, the capacity emulated using the PWS is almost identical to that of the target channel in the LOS scenario. Yet the discrepancy of the capacity emulated using the PFS w.r.t. that of the target channel is almost negligible. On the other hand, for the NLOS scenario, the capacity emulated using the PFS agrees well with that of the target channel, whereas noticeable error of the capacity emulated using the PWS (cf. Fig. 5a).

It can be seen from the simulation results that, given a fixed number of active probes and large DUT, it is more difficult to accurately emulate the mmWave channel using the PWS for the NLOS scenario where there is no deterministic dominant path. On the other hand, when there is a strong LOS path, it is relatively easier for the PWS to accurately emulate the



(a)



(b)

Fig. 5. Capacity CDFs of target and emulated channels: (a) NLOS scenario, (b) LOS scenario.

mmWave channel. Since the PFS outperforms the PWS in the NLOS scenario and is almost as good as the PWS in the LOS scenario and given the fact that only power calibration is needed for the PFS (as opposed to the power and phase calibrations for the PWS), it is safe to conclude that the PFS is more suitable for mmWave OTA testing of large DUT (e.g. BS array) using the sectored MPAC configuration.

IV. Conclusion

In this paper, two channel emulation methods for the sectored MPAC setup are studied and compared in terms of PAS and capacity for the mmWave channel. It is found that the PFS outperforms the PWS in the NLOS scenario and is almost as good as the PWS in the LOS scenario for large DUT (with 64 array elements). Explanations are given. Based on the results, it is concluded that the PFS is more suitable for mmWave OTA testing of large DUT.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China under Grant 61801366 and in part by the Open Project Program of the State Key Laboratory of Millimeter Waves under Grant K201933.

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