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ABSTRACT

With the severe spectrum congestion of sub-6GHz cellular systems, large-scale antenna systems in the millimeter-wave (mmWave) bands can potentially meet the high data rate envisioned for fifth generation (5G) communications. Performance evaluation of antenna systems is an essential step in the product design and development stage. However, conventional cable conducted test methods are not applicable for mmWave devices. There is a strong need for over-the-air (OTA) radiated methods, where mmWave device performance can be evaluated in a reliable, repeatable, and feasible way in laboratory conditions. In this article, radiated testing methods are reviewed, with a focus on their principle and applicability for beam steerable mmWave devices. To explore the spatial sparsity of mmWave channel profiles, a cost-effective simplified 3D sectored multi-probe anechoic chamber (MPAC) system with an OTA antenna selection scheme is proposed. This setup is suitable for evaluation of beam-steerable devices, including both base station (BS) and user equipment (UE) devices. The requirements for the test system design are analyzed, including the measurement range, number of OTA antennas, number of active OTA antennas and amount of channel emulator resource. Finally, several metrics to validate system performance are described for evaluation of mmWave devices.

INTRODUCTION

MmWave communication is regarded as one of the enabling components for 5G cellular communication systems due to the large amount of available spectrum in mmWave frequency bands. However, compared to legacy cellular bands (i.e., sub-6 GHz), transmissions at mmWave bands suffer from high transmission loss and are highly susceptible to blockage [1, 2]. Furthermore, to achieve the high capacity offered by the large system bandwidth, the signal to interference and noise ratio (SINR) should remain high, indicating that the signal power needs to grow proportionally to bandwidth [1]. MmWave channels are also well-known to be highly sparse and specular, due to high penetration, diffraction, and reflection losses [1-3]. To overcome this radio propagation loss and achieve high signal power, mmWave systems should incorporate high gain antenna systems [1, 2, 4]. Thanks to the small wavelength at mmWave frequencies, mmWave antenna systems of practical size can contain an order of magnitude more elements than sub-6 GHz cellular antenna systems. Such antenna systems offer sufficient array gain to compensate for the propagation loss to ensure sufficient signal power. To maintain the link budget in both line-of-sight (LOS) and non-LOS (NLOS) environments, adaptive arrays should be employed both at the BS and UE to monitor, acquire and track the available dominant propagation paths in the radio environment [3]. To make mmWave cellular systems a reality, tremendous efforts have been exerted from academia, industry and government laboratories. Performance evaluation, including both radio and baseband parts, is a mandatory step and essential in product design and development. The mmWave beam-steerable antenna systems, however, have posed unprecedented challenges on testing methodologies.

For sub-6 GHz antenna systems, accessible antenna connectors are typically implemented for conducted testing. In this way, radio frequency (RF) test signals can be carried directly to the DUT antenna ports with RF cables, bypassing the antennas. Due to its simplicity and low-cost, this form of conducted testing has been dominantly used by the industry. However, it is predicted that the conducted testing will no longer be applicable for mmWave antenna systems [4-7]. The reasons are three-fold. First, mmWave antennas will be small and highly integrated units (e.g., antenna on chip or antenna in package), and the number of antenna elements will be tens or hundreds. Thus, antenna connectors will not be available for conducted testing due to cost, size and design challenges. Second, even if antenna connectors would be accessible, mmWave antenna systems equipped with many antennas would require many lossy mmWave cable connections and associated RF hardware, leading to impractical test setups. Finally, the features of mmWave antenna systems rely highly on their spatial discrimination capability for target and interfering signals in the far field region, which cannot be evaluated at each element port [4, 8]. Therefore, mmWave antenna testing will move exclusively to radiated modes (i.e., without RF cable connections), where only the device antennas are directly used as the interface to the test system [4, 6].

Radiated testing of mmWave antenna systems can be divided into four categories: RF requirements (testing of RF characteristics of the transceiver), antenna requirements (testing of antenna characteristics), demodulation requirements (testing the ability to demodulate received signals), and radio resource management (RRM) requirements (testing of initial system access, connection reconfiguration, mobility and handover, beam acquisition, refinement, and tracking, etc.) [1, 2]. To properly evaluate demodulation and RRM performance of mmWave systems, the propagation environment and adaptive antenna systems should be considered. Radiated testing of adaptive mmWave antenna arrays in realistic propagation channels is expected to be crucial in the development of 5G mmWave antenna systems [3, 5]. For example, in the link establishment process, the beam acquisition and beam tracking operations should be evaluated under realistic mmWave channels. Beam refinement and beam recovery testing also require realistic propagation environments with time-variant spatial profiles [3].

OTA TEST METHODS

OTA test methods for sub-6 GHz MIMO UE have been developed for many years, where both reverberation chamber (RC) and anechoic chamber (AC) based methods have been studied [9]. Propagation channels and device antenna design should be reflected in the test method since they are both key to sub-6GHz MIMO performance evaluation. Various MIMO OTA test methods proposed in the literature differ concerning incorporation of UE antenna characteristics and spatial channel models. In this section, basic principles of OTA test methods and their applicability to beam-steerable mmWave antenna systems are discussed.

RC

An RC is an enclosed metallic cavity typically equipped with metallic paddles and turntables. RC is a well-proven method to characterize single antenna systems, e.g., Total Radiated Power (TRP) and Total Radiated Sensitivity (TRS). For sub-6 GHz MIMO OTA testing, the antennas are inherently included. However, the RC emulates rich multipath environments with statistically isotropic angular distribution and Rayleigh (or Rician) fading channels. There is limited control of the power delay profile (PDP) and Doppler spread [9]. The RC combined with a radio channel emulator (CE) can overcome some of these RC limitations, e.g. the desired PDP and Doppler spread. However, it is commonly understood that RC methods do not offer control over angular distribution and cross polarization discrimination (XPD) of the channel. Since mmWave channels are highly sparse, characterized by a few dominant propagation paths [1, 2], RC might be less suitable for OTA testing of adaptive mmWave antenna systems. Nevertheless, researchers are currently investigating the possibility of using highly anisotropic environments in RC for testing directional-channel technology [10].

Radiated Two-Stage (RTS)

RTS is an AC based method and its principles are outlined in [11]. It has been approved as an alternative MIMO OTA test method to MPAC (as discussed later) in 3GPP [9]. The first stage comprises measuring the DUT complex antenna pattern non-intrusively, which requires an antenna test function in the UE. In the second stage, measured radiation patterns are embedded in the reference spatial channel model in the CE. The objective is to generate signals that would have been received by the DUT had it been placed in the same physically generated spatial field as in the MPAC method. These spatially faded test signals incorporating measured DUT antenna patterns should be guided to the DUT antennas from OTA antennas, using one OTA antenna per DUT antenna. This is achieved by measuring the transmission matrix in the AC between the OTA antenna ports and DUT receivers so that by precoding the test signals with the inverse transmission matrix, the test signals intended for each receiver become orthogonal to a sufficient degree not to degrade the accuracy of throughput measurements [11].

It is noted that the second stage of the RTS method is also named wireless cable method in the literature [5, 12]. The wireless cable method is essentially an RF cable replacement technique, where one can achieve cable connection functionality, without actual RF cable connections. To achieve the wireless cable, one can directly measure and calibrate out the transmission matrix as discussed in the RTS method. An alternative way is that the transmission matrix can be determined via monitoring the average received power per DUT antenna port, without measuring the actual transfer matrix [12].

The RTS method is a promising candidate for static mmWave antenna testing, which is currently being actively discussed in 3GPP (i.e. UE in the beam-lock test mode). However, it is not suitable for testing in dynamic channel conditions when the DUT antenna is expected to adapt. With the RTS method, the number of OTA antennas must be equal to the number of receive antennas on the DUT. Therefore, the use of RTS for mmWave systems with a high antenna count is not practical. Nevertheless, strategies to reduce RTS system cost for large-scale mmWave antenna systems are under discussion in 3GPP.

MPAC for Sub-6 GHz MIMO OTA Testing

In the MPAC test method, multiple OTA antennas are placed around the DUT in an AC [13]. The signals emitted from the OTA antennas are controlled in the CE such that the emulated channels experienced by the DUT will mimic the target channel models. A two dimensional (2D) OTA antenna configuration is typically adopted, since 2D spatial channel models are sufficient
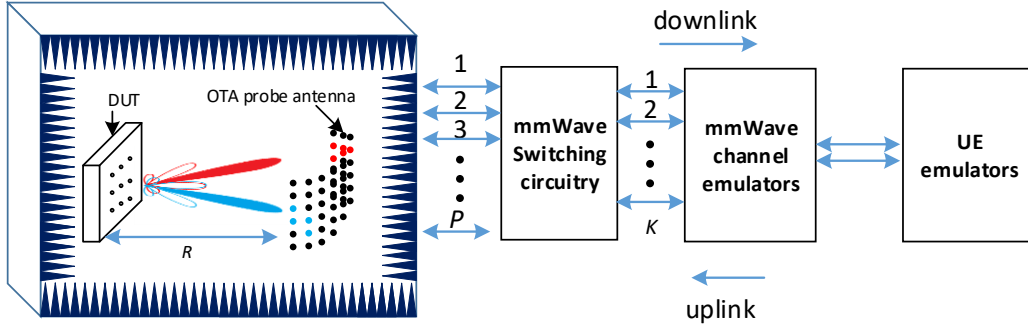
Figure 1 An illustration of the 3D sectored MPAC setup implemented with switching circuitry. OTA antennas and selected active OTA antennas are denoted with black and coloured dots, respectively.

for MIMO handset performance evaluation [9]. A uniform probe configuration can offer the flexibility of emulating arbitrary spatial channel profiles due to random nearby scatterers and placement of UEs in real world scenarios. Typically, the focus is on emulating realistic downlink spatial channel models (i.e., communication from the BS to the UE), while the uplink is realized simply by a communication antenna connected directly to the BS emulator, bypassing the CE [9, 13]. With the MPAC test method, the challenging part is to reconstruct the polarimetric and especially the spatial channel profiles, while other channel parameters can be accurately reproduced using a CE [13].

The MPAC test method is attractive due to its ability to test off-the-shelf DUTs, where all critical parts of the DUT design (e.g. antennas, RF front-end, baseband processing) are tested at once. Any adaptive antenna technologies that utilize or adapt to the characteristics of the RF environment can therefore be reliably evaluated in the MPAC method, since it offers a realistic test condition for the device to operate normally [6, 8]. However, the existing MPAC configuration, i.e., with a 2D uniform OTA antenna configuration where each OTA antenna is connected to an RF interface port of the CE, though technically sound for beam steerable antenna systems, is challenging for mmWave antenna systems. 3D spatial channel modeling is essential to enable beam steering both over elevation and azimuth dimensions for mmWave antenna systems. Bi-directional channel emulation (i.e. radio channel emulation both for the downlink communication and uplink communication in the system), though not considered in 3GPP for UE or BS testing, is needed for overall system validation. To generate a test zone large enough for mmWave antenna systems, a massive number of OTA antennas and associated CE resources are needed, which would lead to a complicated and cost-prohibitive design [5, 6]. Therefore, there is a strong need to develop a new MPAC configuration that is sufficient and cost-effective for mmWave antenna systems.

3D SECTORED MPAC CONFIGURATION

A cost-effective 3D sectored MPAC configuration equipped with switching circuitry has been recently discussed for mmWave antenna systems [6]. An example of the system for a BS test configuration is shown in Figure 1. It consists of an AC, a large set of OTA antennas covering the sector of interest, a controller which selects the active OTA antennas from available OTA antennas, a switch circuitry which connects the active OTA antennas to the RF interface ports of the CE, a mmWave CE, a mmWave BS system as the DUT, and mmWave UE emulators (or UEs) to mimic UE behaviour [6]. To illustrate its principle, the uplink communication is taken as an example. The UE emulators create the testing signal, which is fed to the mmWave CE. The CE creates the multipath environment including path delays, Doppler spread and fast fading. A CE performs convolution of testing signals with channel impulse responses (CIRs). To mimic the spatial characteristic of the target channel at the DUT side, the active OTA antennas are properly selected and radiated signals are properly designed in the CE. The DUT would operate as it would in the intended propagation environment, but in a repeatable and controllable way. Note that the system is applicable for both mmWave BS and UE radiated testing.

Anechoic Chamber (AC)

The AC is utilized to shield external unintended noise and interference and eliminate unwanted reflections. Radio absorber is an important component of the AC. Compared to absorbers at sub-6 GHz bands, mmWave absorbers are smaller and cheaper.

OTA Antenna

MmWave OTA antennas, e.g. patch antennas, can be fabricated on a printed circuit board (PCB), and are cheap to manufacture. Therefore, the massive installation of such OTA antennas is possible. Note that each OTA antenna might need to support controlled polarization states for transmission/reception. A straightforward scheme is to utilize co-located orthogonally polarized probe elements with separate feeds for both transmission and reception, like the OTA antennas for sub-6 GHz MPAC systems. To reduce cost, a simple scheme can be utilized as shown in Figure 2, where four closely-spaced OTA antennas can be employed to support two orthogonal polarizations for reception/transmission. The polarization control is essential for measuring 5G antenna systems utilizing

orthogonal polarizations. OTA antenna panels (which houses several OTA antennas) can be then stacked to cover the sector of interest. Note that OTA antennas should be properly designed and mounted to minimize antenna coupling effects, which could effectively alter the emulated radio channels in the AC.
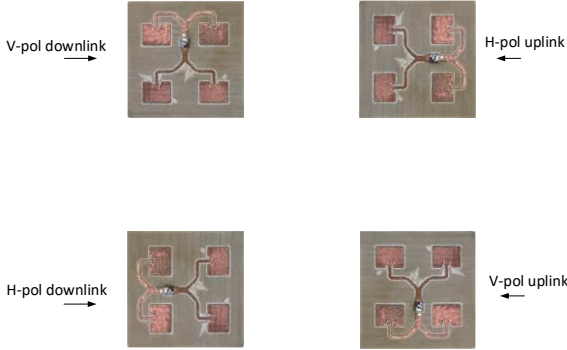

Figure 2 A photo of preliminary OTA antenna design. Patch antenna arrays can be used as a single OTA antenna element to improve directivity and gain.

Probe Allocation Scheme with Switching Circuitry

An OTA antenna selection mechanism implemented with switching circuitry is a logical choice to significantly reduce system cost in mmWave bands, with little degradation on the system performance. There are several reasons:

- While mmWave OTA antennas are cheap, the associated RF chains (e.g., RF interface of the CE, up- and-down frequency converters, RF cables, etc.) connected to the OTA antennas are expensive. Therefore, a massive installation of low-cost OTA antennas allows for channel model flexibility, while the number of active RF chains is limited to save cost.

- Unlike rich multipath in sub-6GHz bands, mmWave communications will rely heavily on dominant paths, where a major portion of the received power will come through line-of-sight or first-reflected signal components [1, 2]. Therefore, the impinging power angular spectra of mmWave channels would be highly

specular and sparse in the angular domain. Thus, most of the OTA antennas are inactive if a uniform OTA antenna configuration is used.

The purpose of adopting an OTA antenna allocation mechanism is that the number of active OTA antennas and the associated RF chains can be minimized, while still retaining the flexibility of emulating the desired spatial channels with minimal loss of fidelity.

Sectored OTA Antenna Configuration

Another strategy to reduce system cost is to adopt a sectored OTA antenna configuration. This works well for a BS antenna which is normally restricted to receive and transmit power in a limited angular zone. This also works well for the single link UE test cases where the expected angular spread of the channel after filtering by typical BS antenna patterns is limited. For UE testing involving multiple BSs, the expected angular range is wider, which makes selecting appropriate sectors more challenging. A good trade-off between system cost and performance should be made to determine the size of the sector of interest and the number of sectors.

Wideband mmWave CE Design

The CE is an essential component for air interface testing in wireless communications. Radio environments can be mathematically modeled and physically implemented in the CE. Current commercial CEs are generally designed for sub-6 GHz applications, with a limited system bandwidth. It is not yet clear how much contiguous frequency spectrum and frequency bands will be required for 5G mmWave communications. For Release 15 new radio (NR), 3GPP has chosen 400 MHz maximum channel bandwidth with many carrier aggregation combinations. Therefore, the mmWave CE should support flexible carrier frequency setting ranging from sub-6GHz to mmWave bands, and a flexible bandwidth enhancement scheme. An example scheme to extend current sub-6 GHz CE to mmWave is shown in Figure 3 (a), where frequency mixers and local oscillators (LO) shift signals from one frequency range to another. To
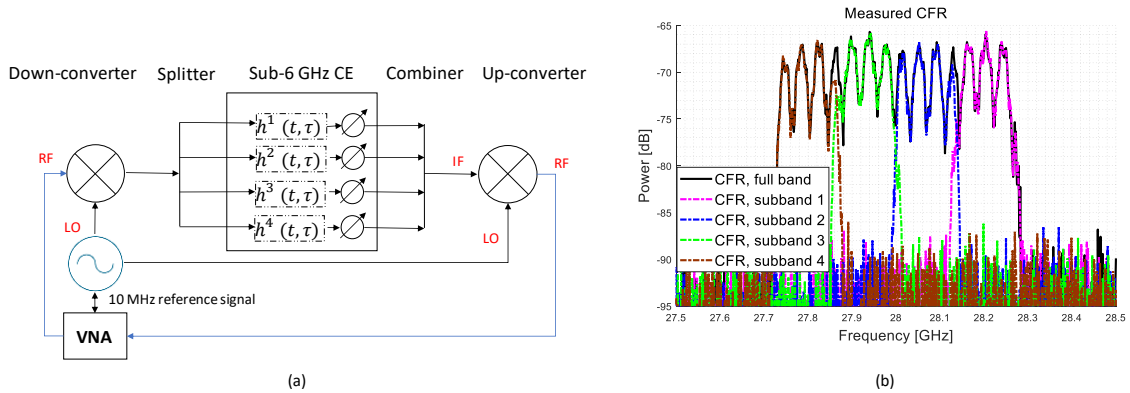

Figure 3 (a) mmWave CE design with band-combining scheme and (b) measured CFR for each sub-band and full band. Four sub-bands, each with 125 MHz bandwidth, are utilized in the sub-6 GHz CE to achieve 500 MHz bandwidth. IF and LO frequencies are set to 5.1 GHz and 33.1 GHz to generate RF signals at 28 GHz.

extend the system bandwidth, signal processing is parallelized within the CE. A band combining scheme can be realized with the help of a power splitter, multiple fading units in the CE (each with a unique sub-band frequency and frequency shifted version of original CIR), and a power combiner. Tradeoffs of CE resources must be made (e.g., RF interface ports and fading units) for more system bandwidth with the band combining scheme.

A measurement setup to validate the mmWave CE implemented with band combining scheme is shown in Figure 3 (a). Phase and gain calibration at each CE output port is required to ensure that the same frequency response for each RF chain is achieved for each sub-band. To validate the mmWave CE design, a time snapshot of the METIS map-based model is utilized as an example [14]. The measured channel frequency responses (CFRs) for each sub-band and the full band are shown in Fig. 3 (b). The achieved dynamic range is around 30 dB. The target CFR (i.e. over a 500MHz band) can be accurately achieved with four sub-bands.

MmWave Switching Circuitry

MmWave switching circuitry is another important component of the system. Due to channel sparseness in mmWave bands, it might be sufficient to select only a few active OTA antennas from the available antennas.

Absorptive mmWave switches, where unselected OTA antennas are terminated with a 50Ω load, should be utilized to minimize reflections in the test system. Critical switching parameters, e.g., switching speed, insertion loss, isolation, cost, size, linearity, etc., highly depend on the switching technologies. For example, the mechanical relay switches, though slow (ms switching speed), offer less than 1 dB insertion loss and support bi-directional communication. The required switching speed is determined by how often the channel spatial profile should be updated. Though highly dynamic, the update rate of the mmWave spatial channels is slow compared to test system switching speeds. The power weight of the OTA antenna might be effectively modified if the switch isolation level is too low. Efforts should be taken to trade-off switching parameters for designing the flexible mmWave switching circuitry. Furthermore, switching architectures with limited connectivity might be promising as a means for reducing the complexity and cost of the fully-flexible switching while still achieving the desired switching functionality.

It is noted that to implement mmWave channel sparsity, OTA antennas can be placed at the desired optimal angular locations to avoid a massive installation of OTA antennas and switching circuitry. This alternative solution, though cheaper, is unable to emulate dynamic scenarios (e.g. time-variant channel spatial profiles and active beamforming at the UE end). The more generic setup proposed in the paper is beneficial in many cases.

MPAC DESIGN PARAMETERS

A major question to be addressed for radiated OTA testing in MPAC test systems is what are the requirements on the MPAC design parameters, i.e., the measurement range (distance) R between the DUT and the OTA antennas, the number of OTA antennas, the amount of required active OTA antennas, and the amount of required mmWave CE resources. The accuracy of reconstruction of the target spatial-polarimetric profiles and the system cost are mainly determined by the design parameters. The channel emulation framework to determine MPAC design parameters is shown in Figure 4 and explained below [6]. As illustrated in Figure 4, MPAC parameters are selected via evaluating how well the OTA system performance metrics under emulated propagation scenarios approximate those under target propagation scenarios. The OTA system performance metrics are determined by MPAC parameters, DUT antenna specifications, and target channel spatial profiles.
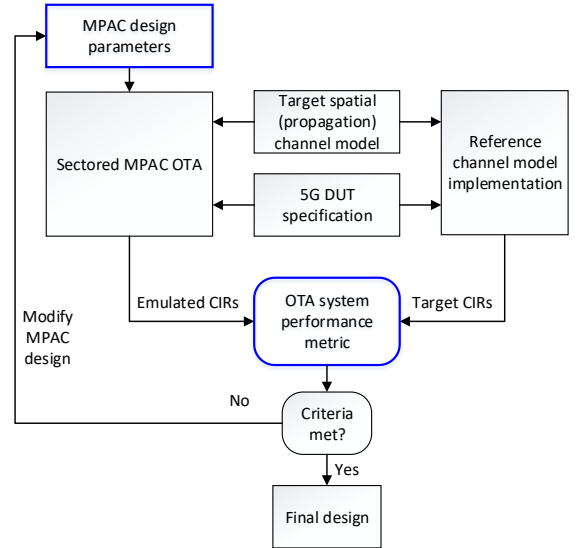

Figure 4 An illustration of the channel emulation framework to determine the MPAC design parameters. The blocks marked in blue are detailed below.

Measurement Range

Measurement range is an important aspect for system design, as it is directly proportional to chamber size, which is a major cost-determining factor of the setup. The requirement on the measurement range for mmWave antenna array is extensively discussed in [6] and referenced therein, where the objective is to determine whether the conventional far field criteria (i.e. $2D^2/\lambda$ with D the maximal DUT dimension and λ the wavelength) must be followed when determining R or if R can be reduced. It was concluded that the far field distance based on the maximum device dimension is not supported by the system link budget [7]. Results have indicated that shorter distances can still yield reasonable measurement accuracy for antenna array and MIMO related metrics for testing purposes [6, 7] (e.g., fixed beam

power loss as discussed later). A measurement range of 1 m was assessed and recommended for a 16×16 planar array with half wavelength element spacing at 28 GHz [6, 7]. The range length is an active discussion item within 3GPP.

OTA Antenna Configuration Design

The OTA antenna configuration (i.e., number and locations of OTA antennas, and number and locations of active OTA antennas) are mainly determined by the required radio channel emulation accuracy in the test zone.

The radio channel emulation algorithm in MPAC test systems (i.e. mapping radio channel models to multiple OTA antennas) has been extensively investigated for sub-6GHz MIMO OTA testing. Two algorithms have been discussed, i.e. plane wave synthesis (PWS) and prefaded signal synthesis (PFS) [13]. The former can reconstruct the exact spatial channel models and in principle can emulate dynamic channels with arbitrary spatial profiles. However, it requires coherent phase control of the OTA antenna weights. It was concluded in [5, 6] that PWS would require a high number of OTA antennas for electrically large devices. Furthermore, coherent phase control of the mmWave switching circuitry and active OTA antennas, unstable phase performance due to long-term phase drift, and ambient temperature changes, are concrete challenges in mmWave bands and potentially obstructive to the use of the PWS method. Therefore, the channel emulation algorithm based on coherent wave field synthesis is expected to be less suitable. The PFS technique only requires power control of signals radiated from OTA antennas and only targets reconstructing statistically similar spatial channel models. Using a CE, the PDP, Doppler spectrum, Ricean K-factor, amplitude distribution, and cross polarization power ratio can be accurately reproduced for the target channel model. The challenging part is to reconstruct the spatial characteristics of the channel using a limited number of active OTA antennas. Note that reconstruction of the specular path with wavefronts from arbitrary directions is not feasible with the PFS technique. As a limitation, the LOS (specular) path is restricted to the directions where OTA antennas are located. The PFS is widely adopted in commercial CEs due to its simplicity and capability to emulate geometry-based stochastic channel (GBSC) models (e.g., SCME [9] and 3GPP 38.901 channel models [15]). A simple and low-complexity probe allocation scheme based on the spatial profile of the multi-cluster channel models is described to determine locations and power weights of the active OTA antennas in [6]. There is a strong need to develop low-computational optimization algorithms to further improve the probe allocation performance.

The required CE resources are determined by two factors: the required interface ports at the BS and UE side, and the logical fading resources inside the CE. The number of logical fading resources is determined by the interface ports, whether bi-directional support is needed, and if multi-UE and multi-BS are needed. The proposed MPAC setup is cost-effective. As an example, assuming we have a test system supporting for bi-directional channel emulation, equipped with 64 dual polarized OTA antennas (where eight antennas are active), a single UE with two antenna ports, we would need CEs with 512 logical fading units and 128 active RF chains from OTA antenna ports to CE input interface ports for the existing MPAC configuration; As a comparison, CEs with only 64 logical fading units and 16 active RF chains are needed for the proposed MPAC configuration, with an additional switching circuitry supporting inter-connection of 128 OTA antenna ports to 16 active OTA antenna ports.

OTA SYSTEM EVALUATION METRIC

For any OTA test system, there is a need for metrics to evaluate how well the desired propagation channels are reconstructed. Direct comparison of a continuous target power angular spectrum (PAS) to a discrete emulated PAS implementation using a limited number of active OTA antennas is problematic [13]. For sub-6 GHz systems, the PAS deviation is indirectly evaluated via the spatial correlation function [13]. However, the spatial correlation function might be less relevant to determine OTA system performance at mmWave frequencies because antenna systems are more directive and mmWave channels are highly sparse and specular.

The OTA system performance metric that is key to mmWave antenna beamforming performance should be selected. The expected antenna control at mmWave will use hybrid beamforming [1, 3], where the antenna system is divided into a few subarrays, each connected to an RF port. Subarray antenna patterns can be controlled by an analog weighting matrix, which enables a predefined set of fixed antenna beams covering the sector of interest. The mmWave array is expected to be well calibrated and the fixed main beams are targeted to a grid of directions, i.e., for transmitting/receiving paths. The UE will have less beam steering capability due to its smaller array aperture and a more limited set of codebooks. The selected metrics should emphasize the performance evaluation of beamforming procedures, e.g., beam acquisition, tracking, refinement, and recovery.

Several OTA system performance evaluation metrics can be selected:

- **Beam probability**. This metric is adopted to characterize the beam selection performance of the mmWave antenna system under spatial fading channels. In the target spatial fading channel, the beam with the highest power per time snapshot of the fading channels among all the fixed beams can be selected. The strongest beam is found by sequentially scanning all fixed beam powers for each snapshot. This procedure can be repeated for all fading snapshots and a histogram over all the pre-defined beam directions can be obtained to characterize the beam probability under the reference channel. The beam probability under the OTA emulated channels can be calculated in
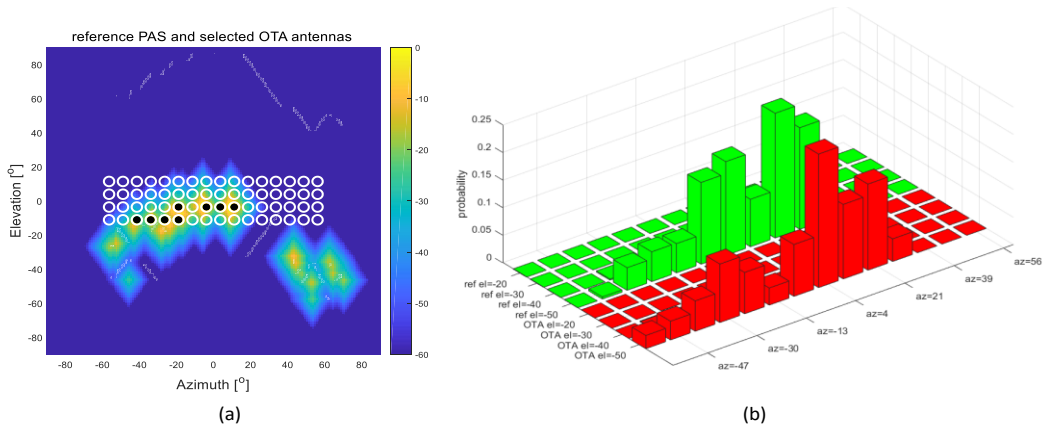
Figure 5 (a) PAS of the reference channel and an illustration of available OTA antennas (white circles) and active OTA antennas (black dots). (b) Simulated beam probability of the reference channel (green) and emulated channel (red). 64 OTA antennas (4×16) with 7.5^o azimuth and elevation angular spacing, R = 1m, and eight active OTA antennas are set for the OTA antenna configuration. DUT is a 8×8 planar array with 0.5λ element spacing at 28 GHz. The predefined beam directions are shown in Figure 6 (b). It is noted that the DUT antenna coordinate (b) is rotated compared to the OTA antenna coordinate (a) with 3° and -45° for the azimuth and elevation, respectively.

a similar way. In Figure 5, a 3GPP 38.901 NLOS channel (cluster delay line (CDL) C) is selected as the reference channel. As shown in Figure 5 (a), eight active OTA antennas (black dots) that are dominant in synthesizing the channels are selected from 64 available OTA antennas (white circles). A portion of the PAS of the reference channel is not covered by the probe sector, which would result in deviations in the channel emulation. The beam probability distributions under emulated channel (green) and reference channel (red) over predefined beam directions are shown in Figure 5 (b), where a similar pattern can be observed, even though only a few active OTA antennas are selected. The deviation in the beam probability distributions between reference and OTA beam probability can be quantified in terms of, e.g., beam peak distance or similarity percentile as detailed in [6].

- **Fixed beam power loss**. In an MPAC test system with a limited measurement range R, the DUT array does experience spherical wavefronts instead of planar wavefronts. Compared to coherent summation in case of planar wavefronts, the summation of signals from DUT array elements in target beam directions is incoherent, which would result in a loss of received power in practice. This metric is important when evaluating power-related metrics, e.g., the coverage and SNR of the mmWave system. This metric is determined by the measurement range, beam directions and DUT antenna array [6].

- **Beamforming power spectra similarity**. The last metric is the similarity of the target PAS and the discrete PAS reproduced in the OTA test system as seen by the DUT. The PAS of the received channel is filtered by the limited aperture of the DUT array. For

example, Bartlett beamforming can be implemented by the DUT by sweeping the angle over the sector of interest to obtain the beamforming power patterns of the reference and OTA cases, respectively. An example of beamforming power spectra for the reference channel and emulated channel is shown in Figure 6. Even though only a few active OTA antennas are utilized, the beamforming power spectra are similar due to limited DUT antenna aperture. The beamforming power spectra similarity can also be quantitatively analyzed, as explained in [6].

CONCLUSION

MmWave communication is an enabling technology for the upcoming 5G communication systems. The radiated over-the-air testing methodology is essential for performance evaluation of mmWave antennas. This article gives an overview of radiated testing methodologies for multiple antenna systems and discusses their principles and applicability for adaptive mmWave antenna systems. The MPAC system is technically sound for radiated testing of adaptive antenna systems. However, a major concern is its system cost when scaled to mmWave channels. By exploring the sparsity of mmWave channels, a sectored MPAC setup implemented with switching circuitry (that can significantly reduce the system cost) is presented. Its principle, feasibility of each test system component, and performance evaluation metrics are discussed. The presented system has great potential for performance testing of 5G mmWave active antenna systems.
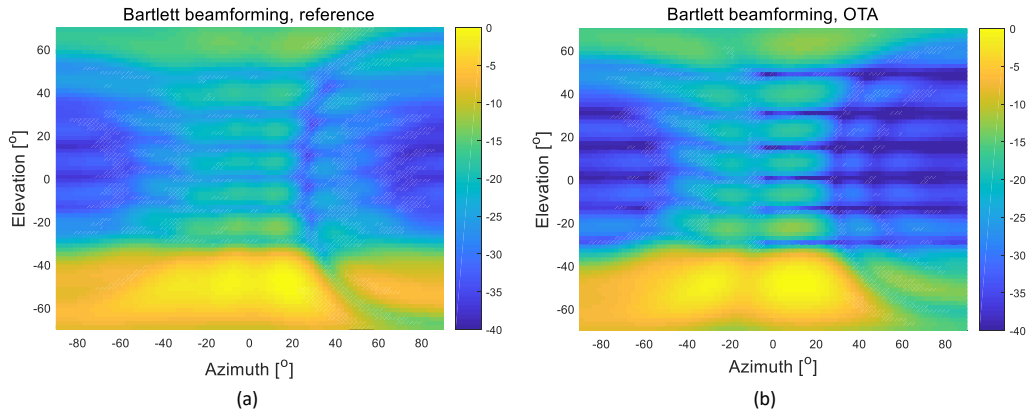
Figure 6 Beamforming power pattern of the reference (a) and OTA channel model (b). The simulation settings are the same as in Figure 5.

In this article, sectored OTA antenna configuration and probe allocation scheme implemented with switching circuitry are discussed for cost reduction purposes. Future work may include more cost-saving strategies. Low computational algorithms to determine active probe locations and weights in the probe allocation scheme should be developed. Calibration procedures for practical test systems might be challenging at mmWave frequencies and necessitate further investigation. Moreover, an acceptable error threshold for the defined evaluation metric should be set to design the final acceptable testing system.

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