Over-The-Air Test Method for Evaluation of 5G Millimeter Wave Devices under 3D Spatially Dynamic Environment from Single Feeder

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Abstract— **This paper presents a novel Over-the-Air test method that facilitates the excitation of 5G New Radio mobile devices from multiple Angles-of-Arrival in 3D-space to perform Radio Resource Management (RRM) testing, required to evaluate the beamforming capabilities when operating at millimeter wave frequencies. The aim of this test system is to recreate realistic operating propagation conditions in both spatial and temporal domains. The advantage of this method is that up to four simultaneous signals can be generated by a single 2D feeder antenna array with multiple independent radio frequency ports from a unique location, minimizing the use of mechanical positioners. This is achieved by the implementation of multiple plane reflectors tangentially placed to the surface of a semi-ellipsoid. The Device Under Test and Feeder antennas are centered at the foci, respectively. Simulations and measurements performed show the ability of this method to create the required test environment to test RRM requirements**

Keywords— **Over-The-Air, OTA, 5G, millimeter waves, New Radio, ellipsoidal reflectors, discrete reflectors.**

I. Introduction

The fifth-generation (5G) of mobile technologies is being developed for supporting the ever-increasing demand for mobile data traffic and step-change in the number of interconnected devices [1]. 5G will enable multiple gigahertz of new spectrum in the millimeter frequency range to become available for operational deployments by the network operators. This will significantly improve the capacity, performance, and efficiency of wireless mobile networks to the end user [2].

However, communicating at mmWave frequencies results in additional propagation impairments such as additional path loss [3], higher penetration losses as well as greater susceptibility to blockages (e.g., foliage, vehicles, people, etc.) [4]. To mitigate these effects, the Base Station (BS) and the User Equipment (UE) will employ Active Antennas Systems (AAS) incorporating phased array antennas. The AAS' provide dynamic and adaptive electronic beam steering functions and high-gain directional beams needed to mitigate the losses [5].

To maintain a reliable connection, the UE must offer dynamic three-dimensional (3D) (azimuth and elevation) antenna pattern control and rapid reconfiguration [5]. This functionality presents new challenges when compared with legacy sub-6 GHz mobile devices regarding product conformance testing [6]. The small size of the AAS makes the provision of antenna connectors for conductive testing unlikely; thus, testing of 5G mmWave frequency devices has to be performed with OTA methodologies [6], [7]. Currently, there exist some standardized testing methods for evaluating the UE RRM (Radio Resource Management) requirements described in [7]. The Direct Far Field (DFF) method assumes that there is a large enough separation between the probe antenna and the DUT. This separation is calculated by the Fraunhofer formula $R > \frac{2D^2}{\lambda}$ where D is the radiating aperture of the DUT, and λ is the wavelength. The Indirect Far Field (IFF) refers to Compact Antenna Test Ranges (CATR), that create a far field environment using a transformation with a parabolic reflector[7]. In [8] a method using multiple combined CATR to perform RRM measurements is described. To measure RRM requirements the system shall be capable of establishing an OTA link between the device under test (DUT) and a number of emulated 5G-NR base station gNodeB sources. Currently, Far Field conditions are required for RRM and DFF is considered as the baseline. In Release 16 the maximum number of simultaneously active (emulating signal) angles of arrival AoAs required is two [8].

In [9], [10] the authors have described an early plausible solution considering the use of elliptical cylinder reflectors. Theoretical analysis of the realizable Angles-of-Arrival (AoA) that this system can achieve and test results validating the curvature of the prototype were included. However, after further analysis, it was concluded that the Test Zone (TZ) area was not sufficiently large to test devices bigger that 6 cm by 20 cm. Here, the TZ can be defined as a geometrical zone (volume) where the target channels can be accurately reproduced [11].

This paper describes further and important developments of the method described in [9], [10], addressing the limitation of the TZ area. This new OTA test method is shown to be capable of emulating 3D spatially dynamic channels using discrete plane reflectors distributed along a part-ellipsoid surface through both simulations and practical measurements. The emulated signals have fixed angular spread at discretely variable angles of azimuth and elevation. The primary advantage is that the new method requires only one probe transceiver which uses phase array technology to generate up to four simultaneous AoAs. It requires minimal use of the mechanical positioners during test, and reduces the hardware required to implement a similar solution. Additionally, offers

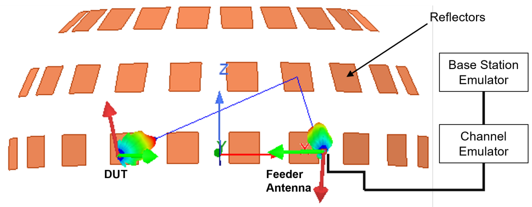


Fig. 1. Pictorial view of the proposed mmWAVE OTA test method. The orange squares represent the reflectors, the two antenna patterns represent the DUT and Feeder antenna placed at the focal points.

a cost-effective means of emulating a sparse spatially dynamic mmWave propagation channel, with the DUT experiencing real-life propagation conditions.

The paper is organized as follows. Section II briefly describes the proposed OTA test method, introduces the characteristics and design criteria and the realizable AoA. Section III describes the implementation of a prototype and the results obtained regarding the AoA. Concluding remarks regarding the use of this new approach to mmWave OTA testing are given in Section IV.

II. Description of the OTA test method

The proposed OTA test method described here is based on a set of discrete plane reflectors distributed along a part-ellipsoid surface. A multi-port RF phased array probe antenna is employed as the feeding device (referred to as the feeder). The feeder is connected to a base station emulator to generate the test signals to stimulate the DUT's operation under real link conditions. Furthermore, if required, an optional channel emulator can create temporal, and frequency fading (path delays, Doppler spread, and fast fading). The feeder and the DUT are placed at the focal points of the ellipsoid. The feeder if realized through a 2D antenna array facet, allows to electronically steer the signals in both azimuth and elevation from the focal point. These signals are redirected towards the DUT arriving with different angles of arrival at the other focal point by means of the discretely distributed reflectors, thereby creating a 3D spatially addressable space. This will support the real-time emulation of the spatial dynamic mmWave channel and testing the RRM requirements of the DUT. A schematic of the proposed mmWave OTA test method is given in Fig. 1.

A. System design considerations

The system is intended for testing devices in the frequency bands from 20 to 30 GHz. Also, the test of the system can accommodate devices of 20 cm x 20 cm. It is also tolerant to the positioning of the array panels within the DUT, as it is expected that the devices will include multiple arrays panels to achieve sufficient spherical coverage. The number of independent simultaneous transmitting signals is given by the specifications of the feeder array antenna and number of available RF ports.

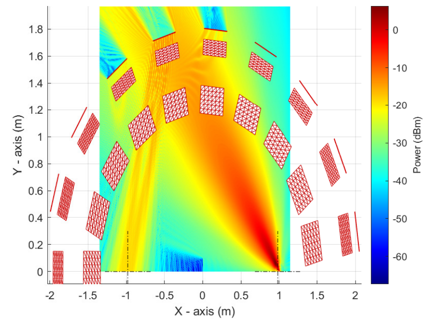


Fig. 2. Simulation of the electromagnetic field distribution when the feeder is illuminating one of the reflectors in the azimuth plane (Top view of the OTA test setup).

B. Design and distribution of the reflectors

The half ellipsoid under consideration can be mathematically described by (1)

$$x = a\sin\theta\cos\phi, \quad y = b\sin\theta\sin\phi, \quad z = b\cos\theta \quad (1)$$

Where, $x, y,$ and z are the coordinates in the space of the center points $P(x,y,z)$ of the reflectors where they are place tangentially to the ellipsoid surface, a is the length of the semi-major axis, b is the length the semi-minor axis, and $\theta = \{\pi/4, 3\pi/8\pi/2\}$ radians, and $\phi = \{0.1653k|k \in \{1,3,..,19\}\}$ radians. It is assumed that the ellipse is centred at the origin $O(0,0,0)$ of the Cartesian coordinate system. The distance dF of the focal points from the origin is defined as $dF = \sqrt{a^2 - b^2}$. The coordinate of the focal points are $F_1 = (-dF, 0, 0)$ and $F_2 = (dF, 0, 0)$.

To determine the dimension of the base ellipse two considerations were taken: Firstly, the TZ must have similar dimension as recommended by 3GPP in [12] where states that the quiet zone for smartphones shall be considered a sphere with radius of R = 10 cm. Secondly, the system was designed to operate in the far field region. Considering an average DUT diagonal dimension of 15 cm, then at 28 GHz the far-field region would be at approximately 4 m. Therefore, to achieve this distance the dimensions of the base ellipse is 205 cm x 180 cm (semi-major axis x semi-minor axis). Each reflector is a square of edge length 30 cm such that the beamwidth of the reflected signal is large enough to cover the target TZ and approximate a quasi-far field signal at the focal point.

Plane square reflectors used in this method produce signals that continuously diverge while propagating. The reflected signals suffer no magnification. Figure 2 illustrates the distribution of the electromagnetic fields inside the system from one of the reflectors simulated with HFSS. It can be seen that the reflected signal covers the test zone area depicted by the purple circle centered at the focal point on the left. The quality of the test zone will be analysed in a different paper.

C. Angles of Arrival and Departure

Theoretically the range of angles of arrival and departure of the signals in the azimuth plane can be chosen from 0

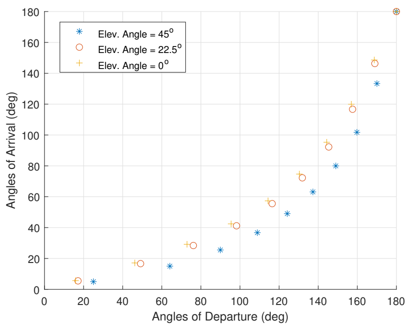
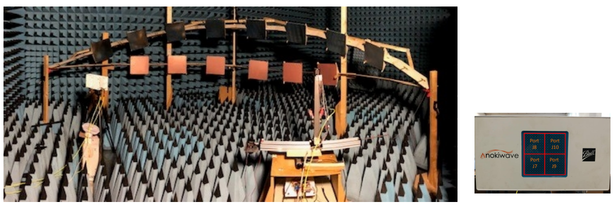


Fig. 3. Mapping of AoD with AoA for each set of reflectors at different elevations.



(a) (b)

Fig. 4. a)Discrete OTA test apparatus in Bristol's anechoic chamber, b) Anokiwave AWA-0142-IK phase array

degrees to 180 degrees. In the elevation plane could be from 0 to 90 degrees. In this case the separation between reflector is approximately 19 degrees in the azimuth plane, and every 22.5 degrees in the elevation plane as described above. With this distribution of the reflectors the angles of departure and arrival are calculated with respect to the local coordinate system at each focal point. The theoretical angular mappings between angles of departure and arrival in azimuth and elevation for the reflectors are summarized in Fig. 3. It can be seen that the range of azimuth AoA of the signals illuminating the DUT in the azimuth plane is between 5 and 180 degrees

III. PROTOTYPE CHARACTERIZATION

A prototype was built to evaluate the characteristics of this method. The test setup consists of two sets of discrete reflectors. Each set has eight reflectors. One is located in the horizontal plane and the second one was elevated 22.5 degrees. The feeder is located at one focal point and employed an Anokiwave AWA-0142-IK phase array antenna [13] (Fig. 4b). This can operate as 4 x 64-element independent sub-arrays, with each sub-array having an independent RF feed. Each sub-array antenna can independently steer the beam in a $\pm 60^o$ conical scan volume centered at boresight. The nominal half power beamwidth (HPBW) was 14 degrees. Deployed at the other focal point was a Flann horn antenna (DP241-AB) as a receiver (Rx) on top of a rotating motor. This had a HPBW of 17 degrees. To emulate two independent spatially separated signal sources stimulating the DUT, the forward S-parameters S12 and S13 were measured with a 4-ports Vector Network Analyzer. The Rx antenna was connected to port 1, whereas in ports 2 and 3 two diagonal sub-arrays were simultaneously

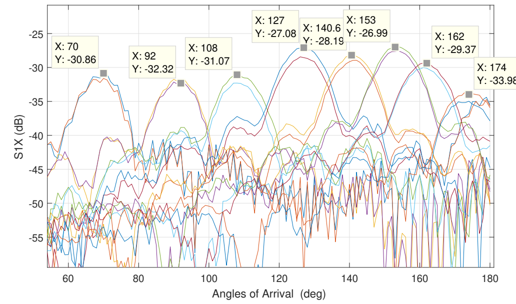


Fig. 5. Angular measurements: S12 and S13 parameters of two simultaneous transmitted signals, Antenna patterns, Peak pointing angles, and Gains.

connected as transmitters. The experiments were conducted at 26 GHz.

At the Tx end the beam was steered according to the theoretical AoD shown in Fig. 3, and the receiving antenna was rotated from 50 to 180 degrees in order to capture the AoA of the reflectors. For simplicity only measurements of the reflectors located in elevation 0 degrees are shown here. Figure 5 shows the measurement of the S12 and S13 parameters simultaneously. When compared with the theoretical AoA, it is possible to observe that the peak beam points measured differ by no more than 2 degrees. Interestingly, it is also possible to observe that although physically the sub-arrays are offset from the focal point the measured gains between them are very close. The greatest difference is in reflector 6 of about 1.36 dB. The differences in the gain may be due to several factors. Firstly, the further the beam is steered away from the boresight the gain is reduced impacting the received power. Secondly, surface imperfection of the reflectors produce unwanted scattered signal. Thirdly, the positioning of the Tx and Rx antennas could be offset by few millimeters from the focal points. Finally, construction imperfections of the holding structure.

IV. CONCLUSION

Given the significant interest in the use of millimeter wave spectrum for 5G NR, there is a pressing need for low cost testing methodologies to facilitate the design and appraisal of key system components such as the antenna array and beamformer alongside beam acquisition, tracking and handover algorithms. In this paper a novel and low cost mmWave OTA apparatus was proposed which exploits the reflective properties of an ellipse to generate 3D spatially dynamic environments representative of the operational environments associated with NR. Furthermore, through the use of state-of-the-art mmWave antenna array technology at the feed point, emulation of 3D spatially dynamic environments and multiple independent signal sources can be readily implemented, avoiding the need for mechanical actuation. Further, the approach requires less hardware components and offers inherent emulation of dynamic environments including both UE motion and handover.

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