Scanning Aperture Antennas with Spherical Shells

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***Abstract*—We report on a prototyping platform for antenna design at millimeter wave frequencies with a steerable beam. The antenna beam is formed by a designed aperture in a hollow metallic half-sphere ("shell") on a circular ground plane which forms a cavity around the antenna feed. The aperture is rotatable around the fixed antenna feed which allows mechanical beam steering without the need for a millimeter wave rotary joint. The shell with the designed aperture is easily replaced by different designs to enable experiments with various beam shapes. Scanning is achieved by rotating the shell around a fixed monopole antenna feed at the center of the platform. Although our setup consists of several resonant parts, there are large enough regions of bandwidth with only a small variation in the antenna pattern.**

***Index Terms*—Millimeter wave communication, channel sounding, spatial channel information, scanning antenna**

I. Introduction

A current development in several vehicular communication standards is the incorporation of millimeter wave (mmwave) as additional short-range communication links for high throughput. Examples include the IEEE 802.11bd project, which operates in the 5.9 GHz frequency band, and plans an optional 60 GHz side-link, as well as investigations within 3GPP [1]. The system design will require models for the wireless propagation channel, and channel sounding measurements in different scenarios provide the foundation for modeling the vehicular wireless channel at mmwave frequencies. In order to characterize the wireless channel along a trajectory of the vehicle, it is important to keep track of the variation of the channel impulse response at sufficient rate. At the same time, mmwave communications need to employ beamforming to overcome the large free-space pathloss encountered with omni-directional antennas. Thus, channel measurements need to characterize the spatial characteristics of the channels. However, if spatial information, e.g. 360° angle in azimuth from a vehicle's perspective, is to be obtained, measurement time or complexity often explodes.

Several possibilities exist for performing directionally resolved measurements. The use of antenna arrays with multiple RF chains, antenna arrays with analog or digital phase-shifters, can be very effective, but is often complex and expensive. Virtual arrays are restricted to short distances and quasi-static environments. The most popular method, measurements with mechanically rotating horn antennas [3], suffers from a limited scanning rate. Additionally, mmwave communication hardware is sensitive to mechanical influences on the cabling. A lack of phase-stability between measurements degrades measurement results significantly. Phase-stable rotary joints offer a solution for this problem. However, they are expensive, in particular at frequencies above 40 GHz, and furthermore for long continuous operation they are fault-prone [2].

A method to avoid this problem is to effect the mechanical beamsteering not by the antenna itself, but rather a secondary device. An early work, targeted for automotive radar, utilized a spinning drum with a grating to allow scanning within a 30° range [4]. A paraboloid reflector rotating around a disc-cone antenna was shown in [5]. A parabolic offset reflector illuminated by a dielectric lens was presented in [6], where the reflector can be mechanically rotated for azimuth beam scanning. The parabolic shape makes it more difficult to design a system for high rotation speeds due to strong mechanical forces, which limits scanning speed. A virtual circular array approach was presented in [7], however, it is also sensitive to mechanical and electrical phase errors.

We propose in this paper a prototyping platform to design antennas for mmwave with a mechanically steerable beam. We create the beam by cutting an aperture on a hemispherical shell placed over an omnidirectional antenna feed. The shells are easy to replace and enable the design of different beams at low complexity. Scanning is achieved by rotating the shell around a fixed monopole antenna feed at the center of the platform. Although our setup consists of several resonant parts, there are large enough regions of the spectrum with only a small variation in the antenna pattern.

II. Prototype

The prototyping platform is shown in Fig. 1. It consists of a rotating disc as a base for an aperture antenna and a mechanically fixed mmwave RF chain. The disc has a center hole and is mounted on a spindle motor with a hollow shaft. A custom built omnidirectional monopole antenna is passed through the hollow shaft. A bearing keeps the antenna fixed at the center of the platform's axis of rotation. A shell is placed over the antenna and mounted on the rotating part only. We achieve spatial filtering of the omnidirectional pattern with an aperture on the shell. By rotating the shell we get

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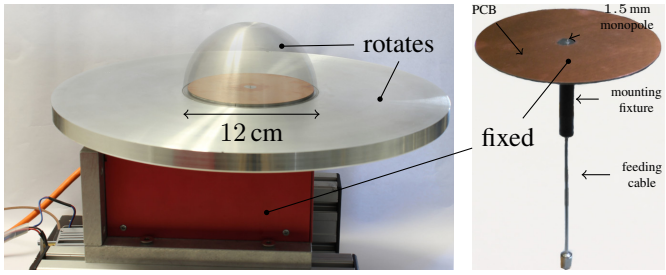

Fig. 1. (left) Prototype platform with a rotating disc and a fixed inserted antenna. A hemispherical shell with aperture is rotated together with the disc. (right) Monopole antenna with PCB groundplane.

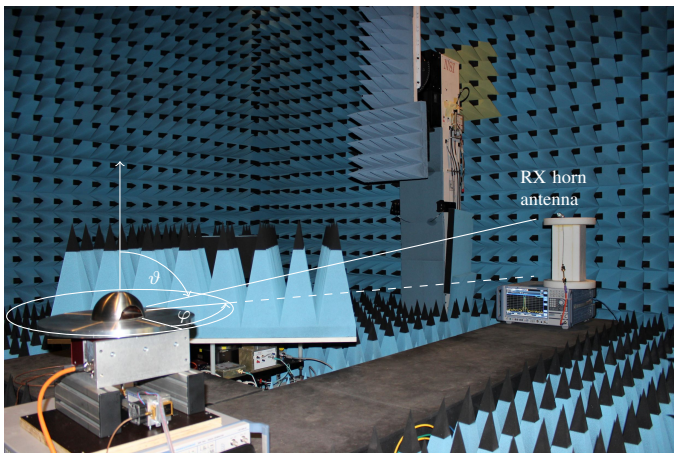

Fig. 2. Measurement setup for characterizing realized mechanically steerable beams with the prototyping platform. The anechoic chamber creates a static environment for the measurement.

a mechanically steerable beam without moving the feeding monopole.

The design of the shell faces several challenges such as achieving fine spatial resolution, side-lobe suppression, and the usable bandwidth. A high gain antenna is usually obtained with a parabolid reflector. However, for high speed rotation, the shell has to be as circular symmetric as possible.

We choose hemispherical steel bowls for their good availability and ease of creating apertures on them. The utilized shells are half-sphere steel bowls with 12 cm diameter. The rotating disc is made out of aluminum with 35 cm diameter. The omnidirectional monopole antenna feed is built out of an 1.85 mm coaxial cable and a circular groundplane PCB with a diameter of 11.73 cm. The radiating element is a 1.5 mm extension of the coaxial cable's inner conductor. The PCB's copper layer is facing up and connected to the outer conductor. The dielectric layer of the PCB does not influence the design as the field does not penetrate the dielectric part.

III. Measurement Setup

The measurement as shown in Fig. 2 took place in an anechoic chamber. Although the chamber is not able to measure antennas at mmwave frequencies with built-in equipment,

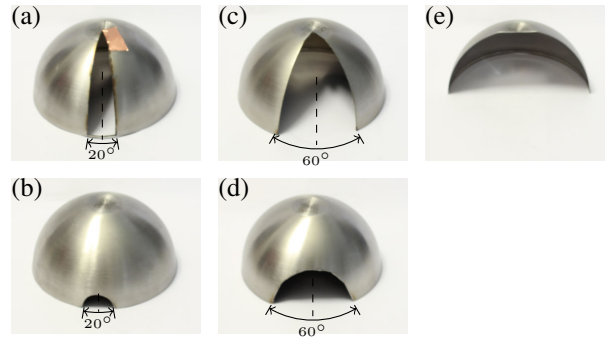

Fig. 3. Investigated shell cut-outs. (a) eye-slit 20°, (b) Igloo 20°, (c) eye-slit 60°, (d) Igloo 60°, (e) half-cut.

it still serves as an echo-minimizing, static environment for the measurement. The measurements were remote controlled from outside the chamber. A sine generator together with a frequency multiplier and an isolator for protection provided the source signal for the scanning antenna under test (AUT). A horn antenna was used as a sensing antenna at a distance of 2.56 m and co-polarized with the monopole. For each spatial sampling point, the received power of a frequency sweep from 50 GHz to 67 GHz was obtained with a spectrum analyzer. Generator and spectrum analyzer were synchronized in frequency with the spectrum analyzer's 10 MHz reference. An introduced frequency response due to the measurement equipment was corrected for by a back-to-back calibration. We measured the azimuthal patterns $\varphi \in [-180°, 180°]$ at an elevation angle $\vartheta = 83.7°$ of different antenna realizations with the antenna prototype.

IV. Results

Different types of shell cut-outs, as shown in Fig. 3, are measured: eye-slit with 20° opening angle (eye-slit 20°), eye-slit with 60° opening angle (eye-slit 60°), semi-circle aperture at 20° on the equator (Igloo 20°), semi-circle aperture at 60° on the equator (Igloo 60°), and half-cut. One full rotation of a hemispherical shell with aperture was done on a 2.5° grid. The center of the aperture was aligned with $\varphi = 0°$. The frequency of the source signal was swept at 10 MHz steps. The measured received power P_{AUT} is normalized to the maximum measured received power of the monopole antenna P_{MP} without a shell present.

For the eye-slit 20° aperture (Fig. 3a), Fig. 4 shows a good confinement of the beam in azimuth. For the Igloo 20° aperture (Fig. 3b), Fig. 5 shows a narrow beam in azimuth, however the interference pattern is strongly dominated by frequent and deep notches in frequency. In this case the elevation angle is already very close to the upper edge of the cut-out. Additional diffraction is the possible cause for this interference pattern.

For the eye-slit 60° and the Igloo 60° aperture (Fig. 3c, Fig. 3d), Fig. 6 show patterns which are confined similar to geometry of the 60° cut-out. The frequency dependence is mainly dominated by notches 2.5 GHz apart.

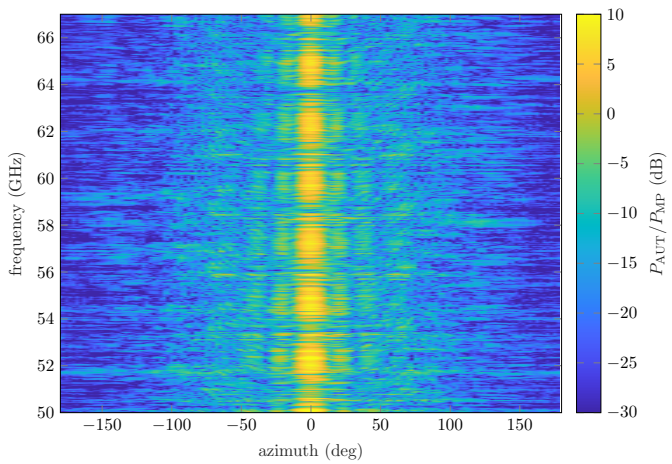

Fig. 4. Normalized received power of the eye-slit 20° aperture depending on frequency and azimuth φ as measured elevation.

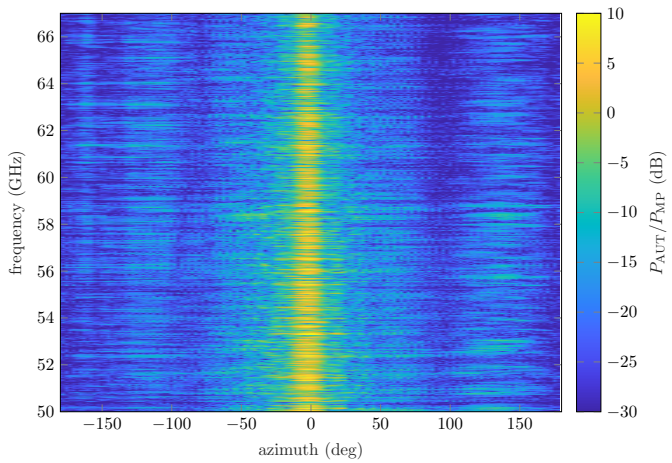

Fig. 5. Normalized received power of the 20° aperture depending on frequency and azimuth φ as measured elevation.

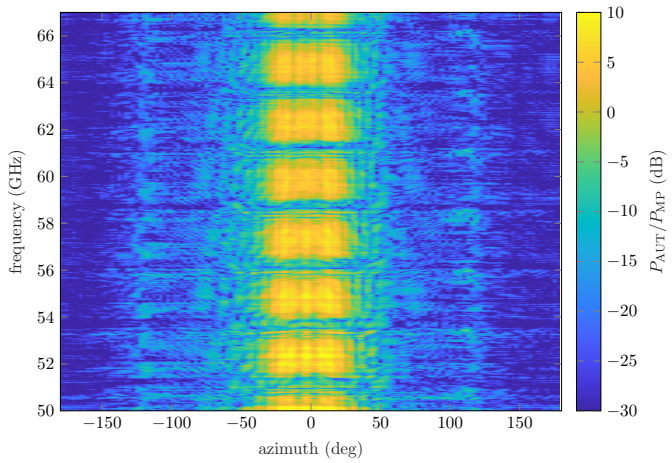

Fig. 6. Normalized received power of the eye-slit 60° aperture depending on frequency and azimuth φ as measured elevation.

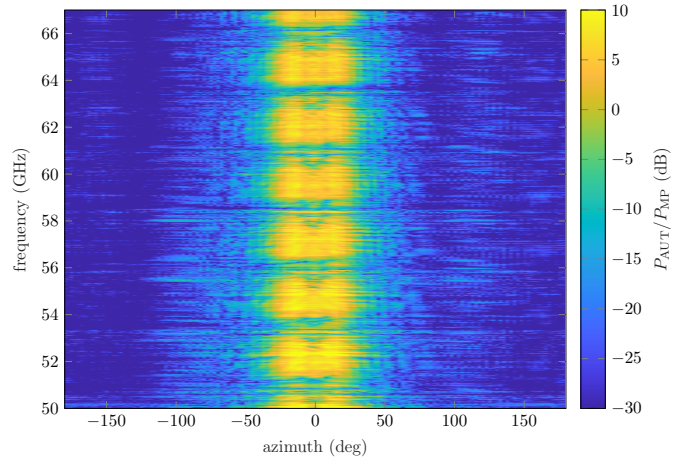

Fig. 7. Normalized received power of the Igloo 60° aperture depending on frequency and azimuth φ as measured elevation.

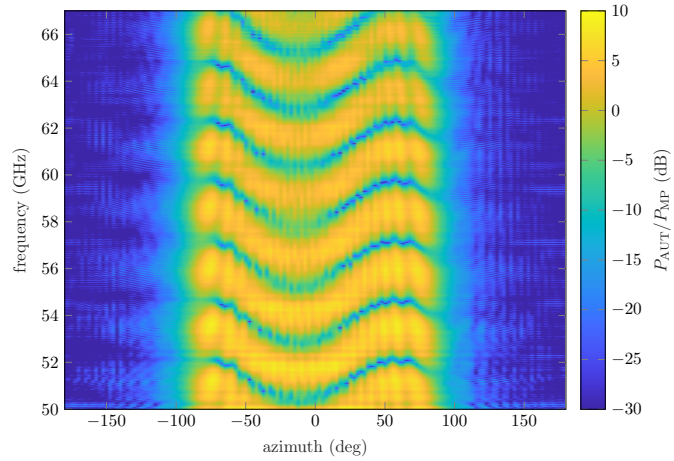

Fig. 8. Normalized received power of the half-cut shell depending on frequency and azimuth φ as measured elevation.

The pattern in Fig. 8 is from a half-cut hemispherical shell (Fig. 3e) and shows angle dependent frequency notches. The reason for this effect is unknown, although a possible explanation is the deviation of the shell's equator from a perfect circle.

In all measurements, we see notches in the frequency spectrum at distance of 2.5 GHz or 400 ps when interpreted as difference in propagation delay between two dominating paths. This corresponds nicely with two times the radius of the hemispherical shell as propagation distance, which is 12 cm. Those notches are not visible when the monopole is measured without a shell acting as a reflector.

Given the received power dependence on frequency and azimuth, we search for regions of angle and bandwidth $(\varphi_{6\,\mathrm{dB}}, B_{6\,\mathrm{dB}})$ where the variation in received power is within 6 dB to yield a usable antenna pattern for operation. Due to calibration, the frequency variation will not pose a problem for operation as long as the characteristic of the beam pattern does not change. The results for the greatest region in terms of

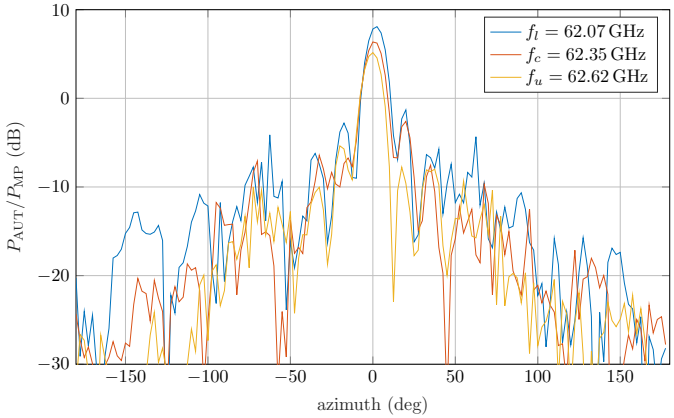

Fig. 9. Frequency dependence of the eye-slit 20° azimuthal antenna pattern within the region $\varphi_{6\,\mathrm{dB}} = 10°$ and $B_{6\,\mathrm{dB}} = 550\,\mathrm{MHz}$.

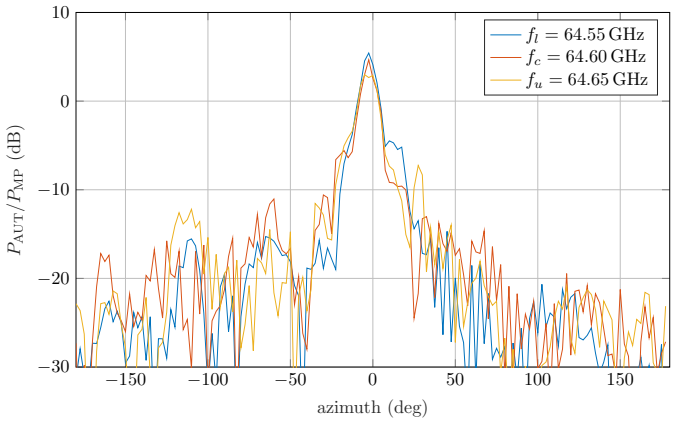

Fig. 10. Frequency dependence of the Igloo 20° azimuthal antenna pattern within the region $\varphi_{6\,\mathrm{dB}} = 7.5°$ and $B_{6\,\mathrm{dB}} = 100\,\mathrm{MHz}$.

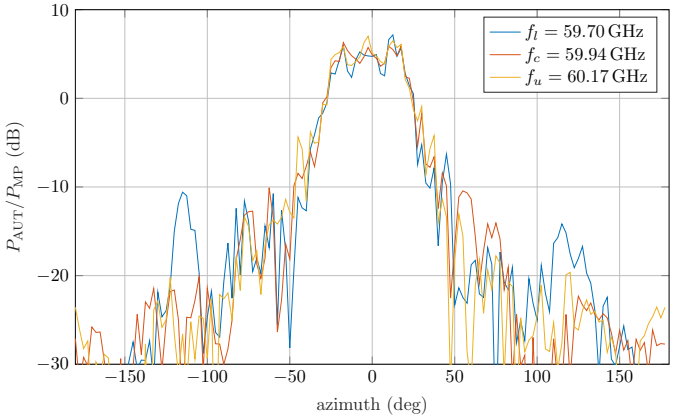

Fig. 11. Frequency dependence of the eye-slit 60° azimuthal antenna pattern within the region $\varphi_{6\,\mathrm{dB}} = 40°$ and $B_{6\,\mathrm{dB}} = 470\,\mathrm{MHz}$.

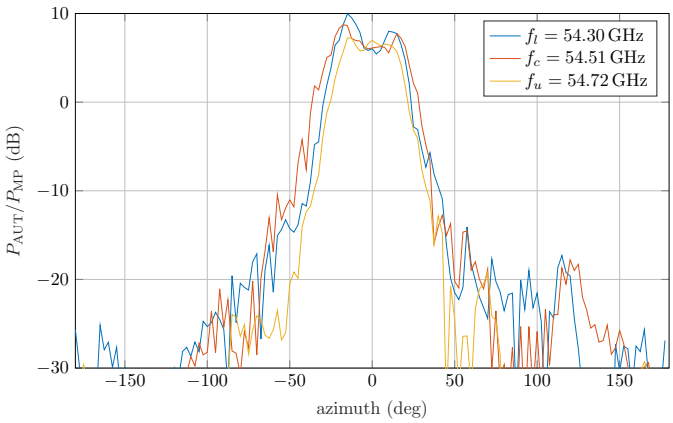

Fig. 12. Frequency dependence of the Igloo 60° azimuthal antenna pattern within the region $\varphi_{6\,\mathrm{dB}} = 35°$ and $B_{6\,\mathrm{dB}} = 420\,\mathrm{MHz}$.

maximum area $\varphi_{6\,\mathrm{dB}} \cdot B_{6\,\mathrm{dB}}$ are shown in Figs. 9 to 12 for each realized shell aperture, except the half-cut shell. Within those regions, side-lobe suppression is also very high especially in the Igloo 60° aperture case as shown Fig. 12.

Conclusion and Future Work

The prototyping platform enables scanning of full 360° range in azimuth and even continuous operation. Shells with designed aperture are easily replaced by different designs to enable experiments with various beam shapes. Among the investigated apertures, regions of several hundred megahertz are usable for scanning operation. Instead of apertures realized as cut-outs, selectively metallized radomes can be used to e.g. improve the implications of turbulences when rotating at high speeds. Furthermore, for this platform, shells are not limited to metallic materials. E.g. radomes coated with absorptive material, or dielectric lenses are possible shells for realizing a steerable beam and consequently, decrease the resonant behavior of the cavity-like hemispherical shell. To cover higher bandwidths further modifications are worth investigating, such as replacing the monopole antenna with a broadband antenna, e.g. a disc-cone antenna.

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