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Millimeter-wave Channel Sounding Technique Using Oversized Lens-loaded Cavity

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Abstract—This paper briefly summarizes an ongoing investigation on millimetre-wave (mmWave) channel sounding using a low complexity single RF chain mode mixing lens-loaded cavity. The main advantage of using the mode-mixing technique is to be able to process the information required to estimate the direction-of-arrival (DoA) of the incoming signal just by reading the signal at the single RF-chain output. This massively reduces the system complexity compared to a standard N -element array antenna that requires around N times RF chains. Specifically, this paper presents a way by which signal directivity towards the coverage area can be enhanced by placing a lens in-front of an oversized cavity. This provides an extra channel gain to the incoming wave, consequently enhancing the DoA estimation resolution. This ongoing investigation can substantially simplify the physical hardware layer of the mmWave channel sounder, offering a great potential for the forthcoming mmWave 5G.

Index Terms—5G, mmWave, sounding, channel, beamformer, lens, antenna.

I. INTRODUCTION AND MOTIVATION

The ability for a beamformer to collect the radio environment information, also called channel sounding, is vital for mmWave 5G communication to work. Fast, accurate, and reliable DoA estimations of incoming electromagnetic signals striking a beamformer are vital for high-resolution channel sounding. Classical channel sounders use antenna arrays connected to base-band processing units, leveraging a DoA estimation algorithm for an accurate channel sounding. This technique is well known, was common in earlier wireless communication generations, and now is used in sub-6 GHz bands of 5G [1, 2]. However, if we use the same fully-connected antenna array model for millimetre-wave (mmWave) channel sounding, the cost will be very high due to mmWave radio hardware limitations.

We propose a completely different approach in which frequency-diverse antenna apertures are preferred instead of cumbersome fully connected antenna arrays [3]. Our approach makes use of mode-mixing mmWave cavity to generate frequency-diverse conditions. This approach has been tested multiple times in computational microwave imaging domain where scene information is received and encoded by a mode-mixing cavity, compressed, and is delivered as a single output signal of a finite bandwidth [4, 6].

Here, we present a restructured mode-mixing cavity model. Our discussion follows previously presented studies in [5, 7] where we established that a mode-mixing cavity can be used

Fig. 1: (a) Frequency-diverse multimode mmWave lens-loaded chaotic cavity developed using metallic cavity and Rexolite lens. (b) Fabricated prototype for measurements in the NSI near-field anechoic chamber.

for DoA estimation. We present a unique antenna architecture in this paper which enhances the mode-mixing cavity's channel information capturing capabilities.

II. LENS LOADED MODE-MIXING CAVITY

A set of compressive measurements in a frequency-diverse cavity can be used to computationally evaluate the DoA of an incoming wave [5]. This is true for a radiating wall backed by an over-sized cavity with sub-wavelength holes, also referred to as metasurface in computational imaging literature [6]. When excited from the input of the cavity, the metasurface radiates spatially orthogonal fields that can illuminate a coverage area, while quasi-randomness of the cavity provides bases for encoding the back-scattered data [8, 9]. Fig. 1 shows one such example of an over-sized cavity with a unique feature that allows it to enhance the mode orthogonality.

The cavity is built using metallic sheets in 5 sides and a strategically designed curved surface with sub-wavelength holes. The curved surface hosts a portion of a spherical constant- ϵ_r lens [10, 11], designed to provide focal point outside the lens body at 28 GHz central frequency of operation.

Fig. 2: (a) Simulated reflection coefficient at the RF in of the lens-loaded cavity with and without the presence of lens, (b) simulated far-field gain plot against 0 dB input signal at the RF in, (c) 2-D cut of 3-D gain plots along azimuth axis (xz -plane) when each contour represents radiated fields along each mode, and (d) correlation coefficient between 11 mode patterns along azimuth angle from 27.75 – 28.25 GHz (number limited for brevity).

The curvature of the surface follows the principle that each sub-wavelength hole is at the focal point of the constant- ϵ_r lens at Petzval curvature [12], whereby, creating a gap between the lens and the curved surface. The cavity also hosts a randomly oriented metallic sheet, acting as a scatterer. A mmWave channel WR28 is placed at the rear metallic wall of the cavity for RF input/output. Physical dimensions of the lens and the constant- ϵ_r lens are presented in Fig. 1(a). Lens-loaded cavity hardware is built using single sided copper coated substrate sheets, while a copper sheet is used to create the scatterer. WR28 to K -type coveter is used at the RF input/output, connecting the frequency-diverse system to a subsequent processing system via single RF-chain. Lens is developed by machining out a sphere from Rexolite material, having a low dielectric constant ϵ_r of 2.53 and loss tangent ($\tan \delta$) of 0.00066. Rational behind the selection of this material for lens development is summarized in [10]. The cavity and the lens are assembled in the form shown in Fig. 1 to built the lens loaded mode-mixing cavity. Further details on the cavity structure can be found from [9].

III. LENS-LOADED CAVITY PERFORMANCE

When a band-limited signal is excited from the RF-input of the lens-loaded cavity, frequency-diverse operation is observed. First, looking at the return loss from Fig. 2(a), it can be observed that the cavity is rich with the resonance modes. One important observation is that the cavity resonance modes are almost the same when we compare the results of with and without the presence of lens. This is because the resonance modes relies more on the scatterer (see Fig. 1(a)) and not the lens, that is placed outside the cavity. Note that the

Fig. 3: (a) DoA estimation using NSI near-field measurements when a plane wave at and angle of (a) $\theta = 0^\circ$, $\phi = 0^\circ$ and (b) $\theta = -30^\circ$, $\phi = -30^\circ$ strikes the lens-loaded cavity.

orientation of the scatterer enhances the quasi-randomness of the cavity. Secondly, looking at the radiation patterns in Fig. 2(b) and (c) show that the fields are radiated randomly, leading to spatial orthogonality. The presence of lens enhances, on principal, this orthogonality [7], while it limits the coverage area. Comparing multiple radiation modes from Fig. 2(b), it can be observed that the fields show spatial orthogonality and all the radiation modes cover the same coverage area of almost 120° . It means that depending upon the requirements, almost 3 to 5 of lens-loaded cavities can be enough for 360° mmWave channel sounding. Out of around 77 simulated resonant modes, the correlation between gain plots against 11 modes is given in Fig. 2(d), where generally correlation is low, providing the required conditionality for DoA estimation following the methods in [5].

Finally, Fig. 3 show DoA estimation using the measured near-field data from setup in Fig. 1(b). Near-field is captured against 41 measurements modes from 27 to 29 GHz, and computational methods [5] are used for DoA estimation when a plane wave at 28 GHz frequency strikes the lens-loaded cavity. In both the cases, the DoA in θ and ϕ is accurately estimated, verifying the proposed approach.

IV. CONCLUSION AND FUTURE OBJECTIVES

We envision a fully connected mmWave channel sounder that utilizes the lens-loaded cavity and the DoA estimation introduced in this work. The presence of lens has shown that the radiation field's focusing capability can be enhanced. Our investigation is in line with the cost/complexity reduction objective of the telecom industry, which will lead to successful mmWave-5G deployment in the next 5 years.

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