An Experimental Proof of Concept for Sensing Using Hybrid Reconfigurable Intelligent Surfaces

Idban Alamzadeh and Mohammadreza F. Imani
Arizona State University, Tempe, AZ 85287, USA, (Idban.Alamzadeh@asu.edu, Mohammadreza.Imani@asu.edu)

***Abstract*—This paper presents experimental proof-of-concept of a hybrid reconfigurable intelligent surface (HRIS) that can detect incident angles of arrivals (AoAs). Reconfigurable intelligent surfaces (RISs) can improve wireless communication by reflecting the incident signal in prescribed directions. This operation, however, requires knowledge about the intended transmitter and users (e.g., their AoAs) to be available at RISs. To achieve this operation without requiring extra feedback loops or complicated channel sensing algorithms, a sensing mechanism needs to be introduced into RISs. To address this challenge, we have designed HRISs that can couple a small portion of the incident signal on a few elements of the HRIS to be used for sensing purposes. We will outline and experimentally demonstrate a compressive sensing algorithm to utilize measurements at these few sparse sampling locations for detecting AoA. The proposed HRIS can be used to implement smart and autonomous wireless communication networks, wireless power transfer, and sensing systems.**

I. Introduction

Reconfigurable intelligent surfaces (RISs) are electrically large metasurfaces with many reconfigurable resonant reflectors. By changing their effective reflection phase profile, RISs can redirect signals to prescribed directions [1]. This capability can be used in wireless networks to mitigate signal blockage and interference issues or avoid jammers. In these transformative applications, the RIS needs to know the intended directions to enable the required adaptive beamforming operation.

Recently, several works have tried to address this need by proposing different sensing mechanisms for RISs. The most common is the joint channel estimation approach in which the channel encountered by the RIS are estimated at either the receiver or the transmitter before they are transferred to RIS [2], [3]. However, this approach results in complicated estimation processes. Alternatively, one can sense the incident signal by switching the RIS's elements to reception mode [4]. Switching between reflective and receptive modes requires costly and complex components. An intermediate solution was adopted in [5] to use compressive sensing. This method sparsely distributed a few dedicated receiving elements across the RIS. Nevertheless, elements used solely for sensing can cause discontinuity issues during beamforming.

To overcome the restrictive design space between sensing and reflection, an integrated compressive sensing mechanism for RIS was proposed in [6], [7]. Unlike conventional metasurfaces, these hybrid RIS (HRIS) contained sparsely distributed hybrid elements to sense a portion of the signal incident on the entire array while reflecting most of it. HRISs thus hold the promise to solve the issue stated above in a practical manner.

This paper presents an experimental proof of concept for an HRIS that can detect AoA. We will first measure the incident signal for a set of reference directions. Using these reference measurements, we form a computational estimation problem relating any incident AoA to the measured signal. We show that the proposed HRIS can detect AoA for a transmitter placed at different directions and distances from reference measurements, validating the proposed sensing operation.

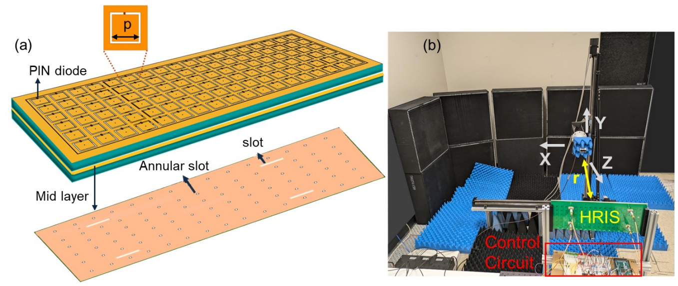

Fig. 1. a) The 2D HRIS configuration, and b) the experimental setup.

II. Measurement Setup and Results

The fabricated HRIS is comprised of two types of elements, namely conventional and hybrid [7]. Both elements are designed at 5.8 GHz based on the well-known mushroom structure [8]. The surface of the element is a square patch of side $p = 11.2$ mm surrounded by a conducting surface, as shown in Fig. 1a. The one-dimensional HRIS in [7] is extended to 2D with some noteworthy modifications. First, the element spacing is increased to a third of the wavelength to accommodate the necessary DC circuit chains without requiring another layer. Secondly, the number of elements along the longest dimension is reduced to 18 for the ease of PCB design and fabrication. On the shorter side, there are six elements resulting in an 18×6 array. The six elements in each column of the array are tuned simultaneously through the same DC trace to reduce the complexity of the control circuitry. Therefore, the array is reconfigurable only across its longer dimension and is thus expected to detect AoA along the horizon mainly. For simplicity of overall structure, only four hybrid elements are deployed on the entire array. It is worth noting that incident signals from all elements are multiplexed in the shared substrate before being coupled through four rectangular slots at four hybrid elements to a substrate-integrated waveguide (SIW) of length 18.3 mm and width 12.65 mm. To accommodate this complex sensing modality in a simple and compact structure, we designed the 2D prototype in three conducting layers. The top and the mid-layer are shown in Fig. 1a. The mid-layer acts as the ground plan. However, it also contains the slots of the hybrid elements to couple sensed signals. In addition, the grid of annular slots allows isolated passing of vias attached to all mushroom elements.

The HRIS is fabricated using two 1.52 mm thick Rogers 4003 substrates. The bottom substrate accommodates the DC signal routing and the SIWs connected to SMA connectors to capture sensed data, as shown in Fig. 1b. Each element on the top layer, as noted in Fig. 1a, is loaded with a PIN diode to alter the reflection and reception pattern through different surface configurations. We denote each of these PIN-diodes-enabled surface configurations with a mask for brevity. The measurement setup is also depicted in Fig. 1b where the HRIS, control circuitry, and measurement probe are visible. The radial distance between the HRIS and the probe is denoted along the z axis. The open-ended waveguide probe is mounted on a linear stage and is connected to one port of a network analyzer. The other port is connected to the 4 hybrid meta-atoms via a mechanical switch. To realize signal incidence from different directions, the probe illuminates the HRIS at various locations along a horizontal line along the x axis that is distance z away from the HRIS. Thus, the angular position of the probe moving along the x axis is $\theta = cos^{-1}(\frac{x}{r})$, where r is the distance between the center of HRIS and the probe at a given location. Sensed signals from each location of the probe are measured for 40 masks.

The AoA detection consists of two steps. In the first step, we scan the HRIS at 33 discrete locations spaced at 30 mm along a line parallel to the HRIS at $z = 0.5$ m. We then take the differences between signals measured at the two top and the two bottom coaxial connectors, resulting in two sensed data for each mask. They are then used to populate a sensing matrix $\mathbf{H}$ for all the masks and locations. Thus, $\mathbf{H}$ becomes a 80×33 complex-valued matrix. To test AoA detection capability, we placed the probe at a distance of $z = 1$ m, resulting in incident signals that differ in amplitude, phase, and directions from the reference measurements. We denote the sensed data captured from each test location with $\mathbf{g}$. Thus, the estimation problem can be formulated as:

$$\mathbf{g}_{80\times 1} = \mathbf{H}_{80\times 33}\mathbf{f}_{33\times 1} \quad (1)$$

The $\mathbf{H}$ matrix is not square and has no inverse. We thus solve the problem above using computational techniques. Here, we used conjugate gradient squared (CGS) to estimate $\mathbf{f}$. Ideally, $\mathbf{f_est}$ would have peaks only at the locations where the measured data and the corresponding column of $\mathbf{H}$ are correlated. In practice, however, the measured data is inevitably perturbed by noise. As a result, we can see some redundant peaks in the estimated $\mathbf{f_{est}}$. To estimate the AoA, we thus looked for the maximum peak of $\mathbf{f_{est}}$. As illustrated in Fig 2a, the dominant peaks of $\mathbf{f_{est}}$ are close to actual incident AoAs and are easily distinguishable. However, due to the discretization of the possible AoA, we may have an error in estimating the actual AoA. We set the tolerance limit based on the half-power-beamwidth (HPBW) of the HRIS, which is 8.6°. Therefore, we consider an acceptable estimation within ±4.3° of the actual AoA. The estimated AoA versus the actual AoA are shown in Fig. 2b. Evidently, we can detect AoA within the device's accuracy.

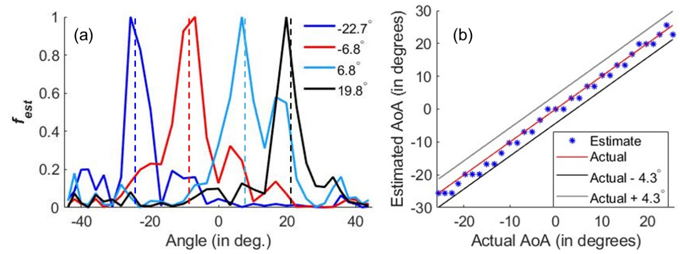

Fig. 2. a) A few illustrations of estimated $\mathbf{f}$ and b) estimated vs. actual AoAs from a source at 1m distance. The results are reported at 5.79 GHz.

III. Conclusion

In conclusion, we presented an experimental proof-of-concept of a novel integrated sensing mechanism for RIS using sparse data. In essence, we showed that using an HRIS with a few hybrid meta-atoms can provide a compact and simple solution to the sensing problem of RISs. An important future research direction would be to increase the aperture size to illustrate the desired beamforming from the proposed HRIS. The proposed HRIS paves the way for implementing smart and truly autonomous wireless networks.

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