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Accurate Angle-of-Arrival Sensing for Receiving and Scattering Array Antennas

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***Abstract*—Incorporating sensing capabilities into reconfigurable intelligent surfaces coupled with signal rerouting functionalities provides a promising route to integrating sensing and communication functionalities. In this paper, we propose and numerically demonstrate the feasibility of accurate angle-of-arrival detection in reconfigurable reflectarrays. A theoretical model has been formulated to articulate the sensing ability, drawing upon principles rooted in the receiving antenna theory.**

I. Introduction

Nowadays, multi-functional reconfigurable intelligent surfaces (RISs) have attained interest in executing multiple functions simultaneously within a single platform, avoiding redesign and refabrication of antennas. Numerous research works explore RISs composed of sub-wavelength-sized passive meta-atoms for rerouting incoming electromagnetic (EM) waves, e.g. [1], [2]. For proper operation, an RIS needs information about the propagation environment, in particular, the directions of arrival of the incident waves. Known hybrid sensing and reflecting RISs [3], [4] exhibit inefficiencies in reflecting the incident impinging wave energy because the sensing function uses the portion of it. Beyond these losses, the energy consumption and cost increase gradually due to the additional power needed for locally processing the sensed signals associated with auxiliary RF chain(s) utilization.

In [5], an alternative approach to realize the angle of arrival (AoA) sensing capability for arbitrary illuminations was proposed. In that method, the AoAs are found from the same measured data as used for optimizing the power reflected towards the receiver. That is, the reflectarray antenna itself is used as a network sensor. In this paper, we consider an RIS realized as arrays of small loaded patch antennas and show how the AoAs can be found at any time by temporarily setting all the controllable loads to the same value. Similarly to [5], this method is based on measuring the structural scattering voltages or currents, but it does not require pre-optimization of the RIS response.

II. AoA Extraction

As a possible hardware platform for dual-functionality RIS we contemplate a finite planar array of perfect electric conductor (PEC) patches positioned on a lossless dielectric substrate on a common finite PEC ground plane, as illustrated in Fig. 1(a). Each sub-wavelength-spaced radiating patch element incorporates lumped loads for tuning the array response.

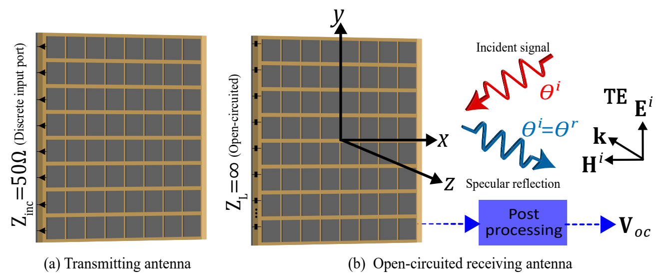

Fig. 1. Schematic representation of a finite planar array of patch elements. (a) The transmitting case for preliminary parameter calculation and (b) the receiving case under plane- wave illumination at θ^i with all controllable loads open-circuited.

Within a planar array consisting of N loaded elements, the n-th element is terminated by a tunable reactive load Z_{Ln} ($n = 1, \ldots, N$). Here we use the receiving and scattering antenna theory to show that AoA extraction is feasible based on the knowledge of currents or voltages induced in the loads. As a specific example, we consider a planar array excited by a transverse electric (TE) polarized incident plane wave with an E-field

$$\mathbf{E}^i = \hat{y}E_0^i e^{+jk(x\sin\theta^i + z\cos\theta^i)}, \quad (1)$$

where θ^i signifies the incidence angle, and k represents the free-space wavenumber. While we will show that the AoA can be approximately found based only on measured load voltages in the receiving regime, for more accurate determination we will use also the pre-computed effective heights of the array elements in the transmission regime [Fig. 1(a)]. To determine the AoA, we temporarily set all loads of N meta-atoms to the open-circuit state, as shown in Fig. 1(b), and measure the voltage distribution at the terminals. Since the load impedances of the planar array are uniform and all the patches are identical, the reflected beam will have the maximum amplitude in the specular direction. Thus, the phase distribution of the load voltages over the antenna array will mimic that of the incident field, allowing us to find the AoA of the illuminating wave.

Since the knowledge of induced voltages is in any case necessary to tune the RIS to reflect towards the receiver, we do not need any additional circuitry to detect the AoA. The choice of the measurement technique depends on the operational frequency range, and other practical considerations. Basically, an array of amplitude and phase detectors can be used.

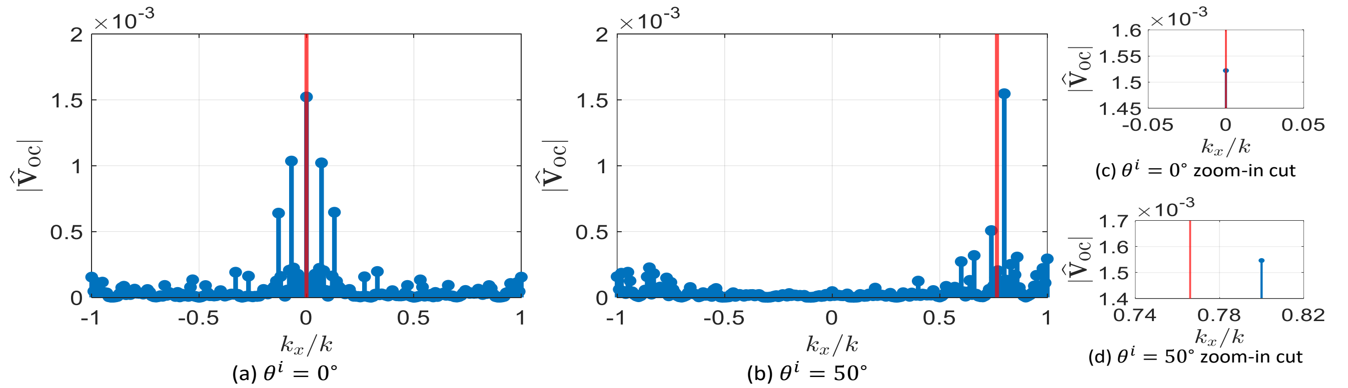

Fig. 2. The spatial frequency spectrum computed for (a) $\theta^i = 0°$, and (b) $\theta^i = 50°$. The blue stem lines conform to the computed $\widehat{\mathbf{V}}_{\rm oc}(k_\parallel)$ harmonics, and the red line represents the incident wave harmonic. The zoom-in cuts for (c) $\theta^i = 0°$, and (d) $\theta^i = 50°$ show that the detected angle is very accurate for $\theta^i = 0°$, but a 3.13° deviation for $\theta^i = 50°$ is shown. We normalize k_x by k so that the maximum value 1 corresponds to grazing incidence.

Subsequently, the AoA is estimated by computing the Fourier Transform (FT) of the $\mathbf{V}_{\rm oc}$ vector, denoted as $\widehat{\mathbf{V}}_{\rm oc}(k_\parallel) = \mathscr{F}\{\mathbf{V}_{\rm oc}\}$, where $k_\parallel$ represents the tangential wavevector. The resulting spectrum $\widehat{\mathbf{V}}_{\rm oc}(k_\parallel)$ features a distinct peak at the spatial frequency corresponding to the incident angle, expressed as $\widehat{\mathbf{V}}_{\rm oc}(k\sin\theta^i)$. Due to the finite size of the array, the spatial frequency's peak is not a delta function and it is not precisely aligned with the incident angle harmonic, especially for very large incident angles. Accurate AoA detection is possible using the measured $\mathbf{V}_{\rm oc}$ and pre-computed effective heights $\mathbf{h}(\theta,\phi)$ using the relation

$$\angle(\mathbf{E}^i(O)) = \angle(\mathbf{h}(\theta^i,\phi^i)^{-1}\cdot\mathbf{V}_{\rm oc}). \quad (2)$$

With the pre-computed impedance matrix $\mathbf{Z}_A$ and the effective heights, AoA extraction is rapid, involving a matrix multiplication, even for a large N, taking just a few milliseconds for the sensing function in real-time applications. We can accurately detect the phase front of the impinging wave, with a high accuracy for various element size, type, and spacing.

III. Numerical Results

In this conceptual study, we model a finite planar array depicted in Fig. 1. The overall size is $5\lambda \times 5\lambda$ (λ = free-space wavelength) with a $\lambda/4$ element spacing. The array comprises 400 patches. Using CST Microwave Studio, we design a linearly polarized PEC square patch antenna at 28 GHz tuned for impedance matching to 50 Ω. We use Rogers RO4350B (no loss) substrate having a 0.338-mm thickness and a relative permittivity $\epsilon_r = 3.66$. The square patch side is 2.347 mm, and the optimized feed position is $(x_p, y_p) = (0, 1.068)$ mm. Finally, we perform full-wave EM simulations using CST to determine $\mathbf{Z}_A$ and $\mathbf{h}(\theta,\phi)$.

To emulate the actual measurements, we perform two open-circuited RX antenna simulations for the incident angles 0° and 50° to capture $\mathbf{V}_{\rm oc}$ and enable the AoA sensing procedure. Next, we perform the Fourier transform and find $\widehat{\mathbf{V}}_{\rm oc}(k_\parallel)$. Figure 2 shows the amplitudes of different harmonics of the $\widehat{\mathbf{V}}_{\rm oc}(k_\parallel)$. The results show a peak corresponding to the spatial harmonic at the incident angle, and the estimated AoA are 0° and 53.13°, respectively [Figs. 2(a) and 2(b)]. Comparing the AoA result with simulations, the angle detection method at this stage is very accurate for the normal incidence, but we observe a 3.13° deviation for the 50° incidence, as seen in Figs. 2(c) and 2(d), respectively. This harmonic deviation is mostly due to distortions of the induced voltages near the edges of the finite array. In the conference presentation, we will show that this inaccuracy can be rectified using the pre-computed effective heights.

IV. Conclusions

In this study, we have numerically demonstrated the feasibility of detecting directions of arrival of arbitrary incoming waves in the context of a reconfigurble antenna array. Without the need of additional RF chains, we ensure accurate angle-of-arrival detection for planar rectangular arrays, employing plain passive meta-atoms.

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This work received funding from the European Union's Horizon 2020 MSCA-ITN-METAWIRELESS project, under the Marie Skłodowska-Curie grant agreement No 956256, and the US Army Research Office under grant W911NF-19-2-0244.

References

[1] S. K. R. Vuyyuru, R. Valkonen, D.-H. Kwon, and S. A. Tretyakov, "Efficient anomalous reflector design using array antenna scattering synthesis," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 7, pp. 1711–1715, Jul. 2023.

[2] S. K. R. Vuyyuru, R. Valkonen, S. A. Tretyakov, and D.-H. Kwon, "Efficient synthesis of passively loaded finite arrays for tunable anomalous reflection," *arXiv preprint arXiv:2312.04441*, 2023.

[3] I. Alamzadeh, G. C. Alexandropoulos, N. Shlezinger, and M. F. Imani, "A reconfigurable intelligent surface with integrated sensing capability," *Sci. Rep.*, vol. 11, p. 20737, Oct. 2021.

[4] G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang, and Y. C. Eldar, "Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6g wireless communications," *IEEE Veh. Technol. Mag.*, pp. 2–11, 2023.

[5] M. Movahediqomi, Y. Li, G. Ptitcyn, V. Asadchy, and S. A. Tretyakov, "Simultaneous high-efficiency anomalous reflection and angle of arrival sensing in reconfigurable intelligent surfaces," *arXiv preprint arXiv:2401.09864*, 2024.