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Single-Pixel Compressive Direction of Arrival Estimation using Programmable Metasurface Apertures

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ABSTRACT

Radar systems for direction of arrival (DoA) estimation have been the subject of significant research with applications ranging from security to channel sounding and automotive radars. Conventional DoA retrieval techniques rely on an array based system architecture as the receiving unit, typically synthesized at the Nyquist limit. This classical array based approach makes it necessary to collect the received radar signals from multiple channels, and process it using DoA estimation algorithms to retrieve the DoA information of incoming far-field sources. A challenge with this multi-pixel approach is that, as the operating frequency is increased, the number of antennas (and hence the number of data acquisition channels) also increases. This can result in a rather complex system architecture at the receiver unit, especially at millimetre-wave and submillimetre-wave frequencies. As an enabling technology for the compressing sensing paradigm, a single-pixel based coded aperture can substantially simplify the physical hardware layer for DoA estimation. A significant advantage of this technique is that the received data from the source is compressed into a single channel, circumventing the necessity to have array-based multiple channels to retrieve the DoA information. In this work, we present a passive compressive sensing radar technique for DoA estimation using a single-frequency, dynamically reconfigurable wave-chaotic metasurface antenna as a receiver. We demonstrate that using spatio-temporally incoherent measurement modes generated by the coded programmable metasurface aperture to encode and compress source generated far-field incident waves into a single channel, we can retrieve high fidelity DoA patterns from compressed measurements.

Keywords: Direction of arrival, compressed sensing, coded aperture, programmable metasurface, radar, microwaves.

1. INTRODUCTION

Direction of arrival (DOA) estimation is a fundamental problem in array signal processing and plays a vital role in various applications such as automotive radar¹, sonar², channel sounding³, and wireless communications⁴. Conventional DoA retrieval techniques rely on a dense array-based system architecture as the receiving unit, typically synthesized at the Nyquist spatial sampling of half of the operational wavelength. These DOA estimations are based on beamforming techniques or numerical methods such as MUSIC⁵⁻⁷ and ESPRIT⁸⁻¹⁰. This classical array-based approach makes it necessary to collect the received radar signals from multiple channels, and process them using DoA estimation algorithms to retrieve the DoA information of incoming far-field sources. A challenge with this multi-pixel approach is that with a higher number of antenna elements in a dense array, the associated RF chains are also bound to increase, putting a load on the hardware requirements and deployment cost. As an enabling technology for the compressing sensing paradigm, a single-pixel based metasurface aperture can substantially simplify the physical hardware layer for DoA estimation. A significant advantage of this technique is that the received data from the source is compressed into a single channel, circumventing the necessity to have array-based multiple channels to retrieve the DoA information.

Recently, DOA estimation using single-pixel based frequency-diverse metasurface apertures has gained significant traction^{11,12}. In [11, 12], the authors proved, for the first time, that a frequency-diverse aperture can be used to retrieve the DoA information of incoming far-field sources. In this method, the characteristics of the aperture radiated fields are governed by a frequency sweep, with the aperture radiating a distinct radiation pattern at each frequency, which is ideally, orthogonal to the radiated field patterns at other frequencies. The radiation of random complex modes varying as a function of frequency can be achieved using mode-mixing cavities. However, this technique exhibits several disadvantages, such as the necessity to sweep a rather large bandwidth, complicated hardware design, and possible interference within the operating bandwidth due to the over-ly-congested microwave spectrum.

In this work, we present a passive compressive sensing radar technique for DoA estimation using a dynamically reconfigurable wave-chaotic metasurface antenna as a receiver. We demonstrate that using spatio-temporally incoherent measurement modes generated by the coded programmable metasurface aperture to encode and compress source generated far-field incident waves into a single channel, we can retrieve high fidelity DoA patterns from compressed measurements. Furthermore, the sparse array of radiator elements on the metasurface aperture can reduce hardware costs since fewer elements compared with a conventional dense array are needed.

2. PROGRAMMABLE METASURFACE APERTURES

2.1 Programmable Metasurface Aperture for DoA Estimation

Figure 1. (a) Illustration of the proposed programmable aperture for DOA estimation concept. (b) Diagram of two-port programmable metasurface aperture using an array of sparsely sampled slot meta-element. (c) Design of the slot meta-element.

The frequency-diverse aperture concept for DoA estimation has been proposed in [11]. Following this concept, a similar principle can be applied to estimate a far-field source distribution from samples of the coherence function multiplexed according to a linear matrix equation defined in terms of complex-valued modulation patterns and single-pixel measurements using a dynamically tunable, programmable wave-chaotic metasurface aperture. The single-pixel DoA estimation technique facilitated by a passive compressive sensing concept is illustrated in Figure 1(a). In physical layer, DoA estimation using a single-pixel aperture is achieved by capturing the projection of a far-field source $P = e^{-jk_0(x \sin \theta \cos \varphi + y \sin \theta \sin \varphi)}$ onto a given modulation pattern across the aperture so that the far-field source can be formed as a linear superposition of the patterns weighted by the respective measurements ($g_m(\omega)$), where m is the m^{th} distinct sequence of random *on* and *off* states defined as a *tuning state* and ω is the operating frequency. For instance, the programmable aperture can multiplex spatial and spectral information onto a series of sequential single-port measurements by tuning the states of diodes randomly. Then, in the computational layer, advanced reconstruction techniques involving the pseudo-inversion of the linear matrix equation describing the system forward model, such as compressive single pixel¹³ and spectral imaging¹⁴, are used to retrieve the source information from the single-port compressed measurements. Defining a 2D plane capturing the radiated fields from the wave-chaotic aperture in the near-field (i.e. characterization plane), an estimate of

the source projection pattern on the characterization plane can be retrieved from the compressed measurement as follows:

$$P_{est} = E^\dagger g \quad (1)$$

where E is the projection of the radiating aperture on a characterization plane calculated as:

$$E_m(\bar{r}, \omega) = \int_{\bar{r}'} m_m(\bar{r}', \omega) G(\bar{r}, \bar{r}', \omega) \quad (2)$$

where $\bar{r}'$ is the coordinates of the characterization plane, $\bar{r}$ is the equivalent aperture plane, $m_m(\bar{r}', \omega)$ is the discrete dipole moments on the antenna aperture, ω denotes the angular frequency, while $G(\bar{r}, \bar{r}', \omega)$ is the Green's function defined as

$$G(\bar{r}_1, \bar{r}_2, \omega) = \frac{e^{-jk|\bar{r}_2 - \bar{r}_1|}}{|\bar{r}_2 - \bar{r}_1|} \quad (3)$$

Once an estimate of the far-field source on the characterization plane (P_{est}) is retrieved from the compressed measurements (g) in Eq. (1), taking the Fourier transform of P_{est} retrieves the DoA information.

2.2 Programmable Metasurface Aperture Design

The programmable metasurface aperture used in this work is a printed cavity formed by a double-sided copper cladding dielectric substrate bounded by a metallic via fence as depicted in Figure 1(b). The metal walls (facilitated by the via fence) and the top and bottom copper layers form the boundaries of the cavity volume composed of a 1.52-mm thick Rogers 403C dielectric substrate. An RF coaxial connector is connected in the centre of the cavity, launching a cylindrical wave-front inside the cavity structure. The upper conductive layer is fashioned with a 2D array of sparse slot radiator metamaterial elements with the resonant frequencies distributed between 20–22 GHz. The complex fields formed within the cavity projects into the region to be imaged by superposing the contributions from each of the radiating metamaterial elements. A tunable metamaterial element in the form of a simple slot radiator integrated with a PIN diode is designed to form the reconfigurable metasurface aperture as depicted in Figure 1(c). Here, the PIN diode is conductive in the forward bias state and capacitive in the reverse bias state. When the diode is *on*, it exhibits a low impedance, effectively short-circuiting the slot-shaped metamaterial element in the centre. This results in a weak radiation from the metamaterial element. In contrast, when the diode is *off*, it exhibits a high impedance (ideally open circuit), ensuring that the resonant electrical length of the slot radiator is preserved. This results in a strong radiation from the metamaterial element¹⁵. By dynamically switching the states of the diodes, programmable manipulation of the radiation patterns is achieved. In this context, each metasurface aperture configuration with a specific pattern of *on* and *off* diodes is called a *mask*, producing a radiation pattern that changes as the mask is varied, i.e. spatio-temporal variation. These masks allow the projection of the incoming far-field source patterns to be probed using a number of spatio-temporally incoherent field patterns radiated from the programmable metasurface as a function of varying mask configurations. The size of the electrically large cavity is $8\lambda_0 \times 8\lambda_0$, where λ_0 is the free-space wavelength, allowing the metasurface to replace a large number of antennas. To put this statement into context, synthesizing the same aperture, $8\lambda_0 \times 8\lambda_0$, at the Nyquist limit ($\lambda_0/2$) would require 17 x 17 individual antennas, and hence data acquisition channels, whereas the 2D programmable metasurface has only one channel.

The dimensions of the slot-shaped metamaterial elements are chosen to resonate within the operating frequency band of 20–22 GHz, covering the lower portion of the K band. The PIN diode is modeled in the full-wave simulation as a series inductor-resistor circuit in its conducting state and as an inductor in series with a parallel capacitor-resistor in its non-conducting state. Here, the MACOM MADP000907-14020W PIN diode is used in this work^{16,17}. The dimensions of the proposed metamaterial element are shown in Figure 1(b), $a = \lambda_g/3.57 = 2.8$ mm x $b = \lambda_g/8.33 = 1.2$ mm. The simulated total radiated power pattern in Figure 2(a) clearly shows that the radiated power peaks within the 20–22 GHz spectrum whereas the reflection coefficient patterns in Figure 2(b) reveal that the resonant frequencies fall within the 20–22 GHz spectrum, covering the lower portion of the K band, when the metamaterial radiating element is *on*.

The simulated reflection coefficient patterns of the 2D programmable metasurface antenna without a target are shown in Figure 3(a). Analyzing Figure 3(a), the reflection coefficients of the metasurface remain below -10 dB. The -10 dB

magnitudes of the reflection coefficient patterns ensure that the cylindrical wave-front launched into the cavity structure is effectively radiated into free-space through the metamaterial elements and the signal reflected back to the feeding port is not significant. As expected, we also observe significant variation in the reflection coefficient as a function of tuning states (or varying masks) within the frequency band of 20–22 GHz. A multitude of resonances represented by the dips in the reflection coefficient pattern corresponding to the variation of the cavity modes can be observed for all four masks. Because the modes are reconfigured, the elements are excited by new fields for each of these masks.

In order to evaluate the orthogonality of the measurement modes and analyze the correlation among the fields radiated from the metasurface, in Figure 3(b), the singular value decomposition (SVD) technique is used to calculate the singular value spectrum. For this analysis, we consider two scenarios producing a similar number of total measurement modes, M . In the first case, we sample the operating frequency band, 20–22 GHz at $N_f=51$ frequency points and use a total number of $N_m=9$ masks to reconfigure the metasurface aperture, producing $M=510$ modes (blue curve). In the second scenario, we reduce the number of frequency sampling points to $N_f=26$ and increase the number of masks to $N_m=18$, producing $M=468$ modes (black curve). Analyzing this spectrum, it is observed the scenario with higher number of masks has a superior singular value pattern, suggesting that the number of masks has a dominant role in governing the orthogonality of the measurement modes in comparison to the number of frequency points.

In Figure 4, the diversity of the near-field patterns as a function of varying masks, a key component for the wave-chaotic operation to encode the radar measurements using programmable metasurface apertures, can be appreciated.

Figure 2. Total radiated power and reflection coefficient of the meta-element.

Figure 3. Simulated (a) reflection coefficient at each waveguide port and (b) singular value decomposition.

Figure 4. Simulated near-field patterns of the proposed 2D-PMA of (a) mask 1, (b) mask 2, (c) mask 3, and (d) mask 4 at 20 GHz. Unit of color bar: dB.

3. RESULTS AND DISCUSSION

For this work, the size of the programmable metasurface aperture is $D = 80$ mm. We first extract the radiated fields from the metasurface aperture in CST Microwave Studio. Once the radiated fields from the metasurface are obtained, we can calculate the field distribution at any other given distance using Green's functions. The number of frequency points is selected to be $N_f = 51$ in the frequency range of 20–22 GHz, and the number of masks is selected to be $N_m = 18$.

First, starting with the DoA estimation scenario consisting of a single source placed in the far-field of the radar aperture following the programmable metasurface aperture synthesized in Figure 1(b), an incident angle of the source is selected to be $\theta = 0^\circ$ and $\phi = 0^\circ$. The original (or ground truth) plane-wave projection on the characterization plane is shown in Figure 5(a) while the retrieved source projection pattern on the characterization plane, P_{est} , is shown in Figure 5(b). Taking the 2D Fourier transform of the original and retrieved source projections, we obtain the DoA patterns shown in Figures 5(c) and (d). It is observed that the retrieved source projection pattern is in good agreement with the original pattern. Similarly, when the incident angle of the source is selected to be $\theta = 20^\circ$ and $\phi = -20^\circ$, the retrieved source projection and DoA patterns are also in good agreement with the original plane-wave projection and DoA patterns, as shown in Figure 6.

Next, two sources with incident angles of $\theta_1 = 30^\circ$, $\phi_1 = -30^\circ$, and $\theta_2 = -30^\circ$, $\phi_2 = -30^\circ$ are chosen. The DoA estimation for sources 1 and 2 is presented in Figure 7. From Figure 7, it is evident that the estimated results exhibit good agreement with the actual DoA data. The result shows that the proposed dynamically programable DoA technique can achieve direction finding for multiple sources. More enhanced reconstructions and resolutions can be achieved by increasing the number of modes and using a larger aperture at the expense of increased computational complexity.

Figure 5. DoA estimation (a) source projection on the characterization plane (original) (phase in radians) (b) retrieved source projection on the characterization plane (phase in radians), (c) actual DoA pattern (original), (d) reconstructed DoA pattern at an incident angle of $\theta = 0^\circ$ and $\phi = 0^\circ$ with normalized magnitudes.

Figure 6. DoA estimation (a) source projection on the characterization plane (original) (phase in radians) (b) retrieved source projection on the characterization plane (phase in radians), (c) actual DoA pattern (original), (d) reconstructed DoA pattern at an incident angle of $\theta = 20^\circ$ and $\phi = -20^\circ$ with normalized magnitudes.

Figure 7. DoA estimation (a) source projection on the characterization plane (original) (phase in radians) (b) retrieved source projection on the characterization plane (phase in radians), (c) actual DoA pattern (original), (d) reconstructed DoA pattern at an incident angles of $\theta_1 = 30^\circ$, $\phi_1 = -30^\circ$, and $\theta_2 = -30^\circ$, $\phi_2 = -30^\circ$ with normalized magnitudes.

4. CONCLUSION

In this paper, a passive compressive sensing radar technique for DoA estimation using a reconfigurable wave-chaotic metasurface antenna as a receiver has been presented. We have demonstrated that using spatio-temporally incoherent measurement modes generated by the coded programmable metasurface aperture, high fidelity DoA patterns for multiple sources from compressed measurements can be retrieved. Using this technique, the DoA retrieval of far-field sources requires only a single data acquisition channel. This single-pixel compression of the incident source information on the metasurface antenna has been achieved through the wave-chaotic transfer function of the programmable metasurface, significantly simplifying the hardware layer in comparison to conventional multi-pixel array based DoA schemes.

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