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Compressive Imaging and Direction of Arrival Estimation using Reconfigurable Metasurface Apertures

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Abstract

This paper presents the concept of reconfigurable metasurface apertures as an enabling technology to facilitate physical layer compression for imaging and direction of arrival (DoA) estimation at microwave frequencies. Two different techniques are presented to spatially control the radiated field patterns and generate spatio-temporally incoherent measurement bases to replace the conventional array based raster scanning techniques. Leveraging the physical layer compression, high quality radar imaging and DoA estimation have been achieved, using only two channels for imaging and a single channel for DoA estimation.

1 Introduction

Apertures with reconfigurable radiation characteristics have recently gained significant traction. In this context, a particularly interesting scheme can be given as reconfigurable metasurface apertures and their adoption in computational imaging and sensing with applications ranging from security-screening [1, 2] to direction of arrival estimation (DoA) [3, 4] and automotive radars [5]. Conventionally, a radar aperture for such applications is synthesized to facilitate the raster scanning of the scene information. Common techniques to achieve this pixel-by-pixel raster scanning approach include the synthetic aperture radar (SAR) concept and phased array based modalities. Both these techniques exhibit certain limitations, such as the limited data acquisition speed in the case of SAR and complicated physical layer architecture in the case of phased array based techniques. This is due to the fact that, conventionally, SAR modalities synthesize an effective radar aperture by means of mechanical scanning whereas, for phased arrays, it is necessary that each antenna element forming the array architecture has a dedicated phase shifting circuit to have a full phase control at the array aperture.

Recently, alternative aperture modalities to break the raster scanning requirement have been the subject of much research, constituting a dramatic shift from the conventional multi-pixel approach to a single-pixel based architecture. Among these, metasurface antennas with reconfigurable radiation characteristics have been shown to offer a significant potential, enabling a rather unusual paradigm, namely a compressive hardware architecture [6, 7, 8, 9]. A significant advantage of this technique is that by compressing the radar data at the antenna channel, a substantial simplification in the hardware layer can be realized, paving the way for all-electronic, real-time data acquisition for millimetre-wave radar systems without the need for dedicated phase shifting circuits and power amplifiers. These advantages also play a key role in reducing the total amount of power consumption and form-factor of the synthesized radar aperture.

In this paper, we investigate the concept of hardware layer compression achieved in the context of compressive computational imaging and DoA estimation facilitated by reconfigurable metasurface apertures as the enabling technology. We show that using the reconfiguration principle facilitated by these apertures, wave-chaotic, spatio-temporally incoherent modes can be synthesized and used to replace the conventional raster scanning requirement for imaging and DoA estimation. The outline of this paper is as follows: In Section 2 we introduce the concept of compressive imaging and DoA localization. In Section 3, we explore the compressive aperture layout and the reconfiguration techniques to modulate the radiated fields from the radar aperture. In Section 4, we present several imaging and DoA localization scenarios solved through the presented computational technique.

2 Compressive Imaging and DoA Localization

Both computational imaging and DoA localization problems require that the scene information is correlated with the measurements at the compressive channel. Mathematically, this process is known as the forward-model. Considering that the measured signal at the antenna port is denoted by **g**, and the scene information is **f**, they are correlated by the transfer function of the compressive antennas, **H**, as follows:

$$\mathbf{g}_{Mx1} = \mathbf{H}_{MxN}\mathbf{f}_{Nx1}. \tag{1}$$

In Eq. (1), the bold font is used to denote the vector-matrix notation. Although, in this paper, we limit our attention to the scalar approximation, it is entirely possible that the reconstruction problem can be considered on a polarimetric basis, involving solving Eq. (1) for different wave polarizations [10, 11]. In Eq. (1), M denotes the number of measurement modes and N denotes the number of voxels into which the scene is discretized.

In this work, we consider two different applications of reconfigurable metasurface apertures radiating spatio-temporally varying radiation patterns; (a) computational imaging and (b) localization in the case of DoA estimation. These two applications diverge from each other in the interaction between the antennas and the scene information. For the imaging case, we consider a computational imaging scenario operating on a two-way back-scatter basis (transmission and reception of the reflected signal) whereas for the DoA estimation scenario, we consider a one-way passive scenario, consisting of listening to an active source and retrieving its DoA information. In light of this, for imaging and DoA estimation concepts, the definition of the sensing matrix, $\mathbf{H}$, can be given as follows:

$$\mathbf{H}_{MxN} = \mathbf{E}^{Tx}_{MxN}\mathbf{E}^{Rx}_{MxN}. \tag{2}$$

$$\mathbf{H}_{MxN} = \mathbf{E}^{Rx}_{MxN}. \tag{3}$$

In other words, for imaging, the sensing matrix, $\mathbf{H}$ is a function of both the transmit and receive aperture fields, $\mathbf{E}^{Tx}$ and $\mathbf{E}^{Rx}$, whereas for the DoA estimation problem, the sensing matrix is governed by the transfer function of the receive aperture, $\mathbf{E}^{Rx}$. It should be noted here that, for this assumption, we consider the first Born approximation which suggests that the forward-model in Eq. (1) is in a linear form [12].

Recovering an estimate of the scene information, $\mathbf{f}_{est}$, can be achieved by doing a phase compensation of the sensing matrix applied to the compressed measurements as follows:

$$\mathbf{f}_{est} = \mathbf{H}^{\dagger}\mathbf{g}. \tag{4}$$

In Eq. (4), the symbol † represents a conjugate transpose operation. The retrieval procedure outlined in Eq. (4) is known as matched-filtering [13, 14] and constitutes a single step reconstruction algorithm that can be applied in real-time.

3 Reconfiguration Techniques

Computational imaging and DoA estimation techniques rely on generating reconfigurable radiation patterns to facilitate quasi-random bases and probe the scene information using these bases. Leveraging this principle, it is possible to break the raster scanning requirement and compress the measurement data through the transfer function of the compressive antenna as outlined in Eqs. (1)-(3). Generating these wave-chaotic, spatio-temporally incoherent bases can be realized using several techniques. First of these techniques is known as frequency-diversity [15, 16, 17, 18], in which the antenna radiates spatially varying radiation patterns as a function of a frequency sweep. Using the frequency-diversity technique, the scene information can be encoded onto a set of quasi-random bases, each of which is generated at a separate frequency. The second technique is known as the active modulation scheme, in which the radiation pattern of the antenna is varied by actively modulating the antenna aperture with each mask generating a distinct radiation pattern [19, 20, 21]. Such a technique can be realized using a metasurface antenna consisting of unit-cells loaded with PIN diodes [20]. In this context, by activating a random subset of unit cells, for each measurement mask, the antenna radiates a distinct radiation pattern probing the scene information.

3.1 Frequency-Diversity

In frequency-diversity concept, the spatio-temporal variation of the radiation patterns probing the scene information is achieved as a result of a frequency-sweep. In this case, the main design criterion for the wave-chaotic metasurface antenna is to minimize the correlation between the radiated field patters at each frequency, reducing the redundancy of the information encoded onto the measurement modes. An example aperture generating spatio-temporally varying modes as a function of frequency is depicted in Figure 1.

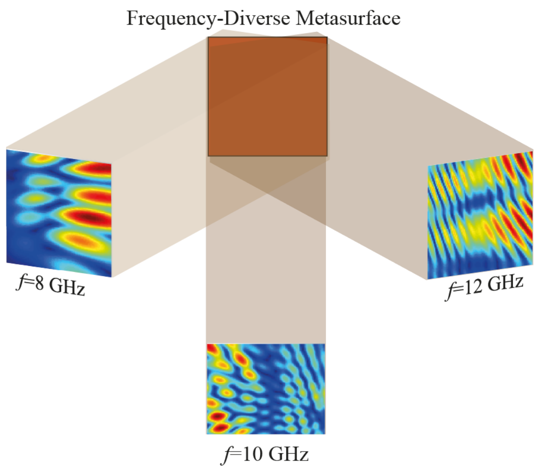

Figure 1. Depiction of the frequency-diverse reconfiguration mechanism to generate spatially varying radiation patterns from the same aperture as a function of frequency.

As can be seen in Figure 1, the radiation pattern of the frequency-diverse aperture undergoes a quasi-random variation as the frequency is swept from 8 GHz to 12 GHz. Due to the randomized nature of the radiated field patterns, the scene information is probed in an indirect manner, replacing the point-by-point raster scanning principle.

3.2 Dynamic Modulation

Leveraging the dynamic modulation principle, spatio-temporal variation of the radiation pattern can be realized on the aperture layer without the need for a frequency sweep. Metasurface type of apertures exhibit a great potential for this scheme in that by loading the unit-cells forming the aperture with semiconductor elements and varying the biasing patterns of these unit cells on a random basis, one can actively modulate the metasurface to radiate quasi-random radiation patterns. In this context, it is the case that each metasurface pattern constitutes a mask - effectively governing the radiation pattern generated by the metasurface. A depiction of the dynamic modulation scheme to radiate spatio-temporally incoherent modes is shown in Figure 2.

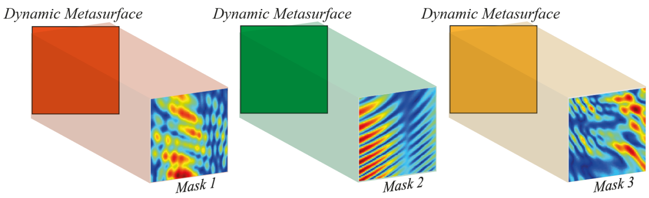

Figure 2. Depiction of the dynamic modulation mechanism to generate spatially varying radiation patterns from the same aperture as a function of different masks.

4 Results and Discussion

In this work, we demonstrate the application of the reconfigurable metasurface aperture concept to generate the spatio-temporally incoherent bases as an enabling principle for computational radar imaging and DoA estimation. In view of this, we choose the dynamic modulation principle highlighted in Section 3.2, and synthesize an aperture consisting of two compressive antennas, one acting as a transmitter and the other as a receiver. The size of the antennas is chosen to be D=50 cm and the imaged object is placed at a distance of d=50 cm, remaining within the Fresnel region of the synthesized radar aperture. The operating frequency is f=10 GHz. It is worth mentioning that the synthesized aperture consists of only two channels, transmit and receive. This is a substantial simplification in the hardware architecture facilitated by the compression in the physical layer in comparison to the conventional raster scanning principle, which would require 280 channels to synthesize the same aperture size at the Nyquist limit. For imaging, we use a target consisting of the letters "QUB". The reconstructed image of the imaged object is shown in Figure 3. In Figure 3, we also study the fidelity of the reconstructed image as a function of measurement masks. It is evident that as the number of masks is increased, the reconstruction quality becomes superior.

As a second application, we study the presented compression concept for DoA estimation. For this scenario, we consider two arbitrarily selected far-field sources incident on the synthesized aperture at (θ_1=-35°, ϕ_1=20°) and (θ_2=30°, ϕ_2=-45°) for source 1 and source 2, respectively. The reconstructed DoA estimation patterns are shown in Figure 4.

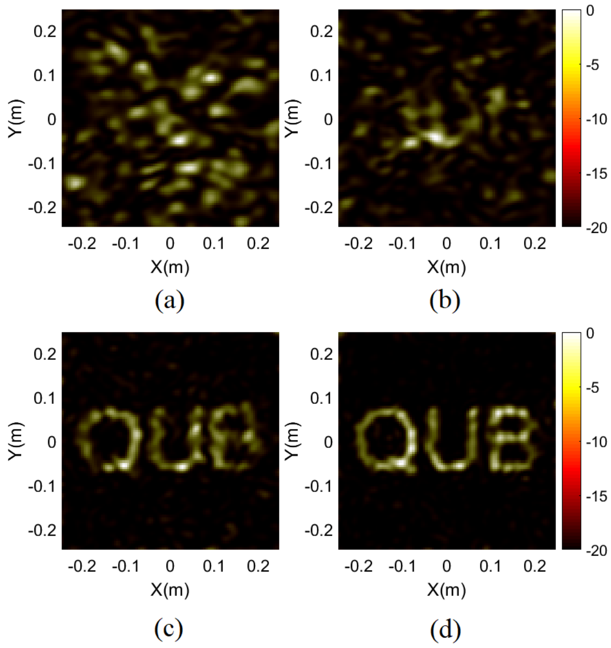

Figure 3. Reconstructed images of the word "QUB" as a function of number of masks. (a) 10 masks (b) 100 masks (c) 500 masks (d) 1000 masks. Colorbar is in dB scale.

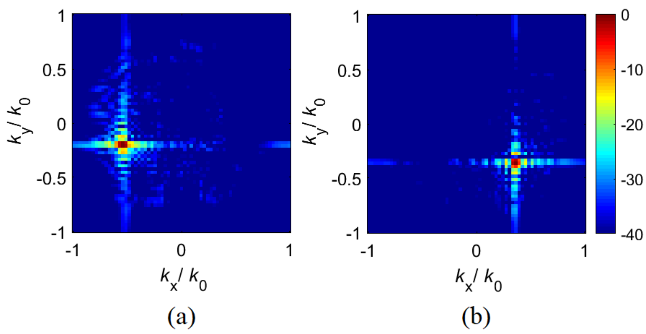

Figure 4. Reconstructed DoA estimation patterns. (a) incident source 1 (θ_1=-35°, ϕ_1=20°) (b) incident source 2 (θ_2=30°, ϕ_2=-45°). For these DoA retrievals, the number of masks is fixed at 1000. Colorbar is in dB scale.

As can be seen in Figure 4, the DoA estimation information for both far-field sources incident on the aperture are successfully retrieved using the compressed hardware layer. It is worth emphasizing here that the radar aperture for the presented DoA problem consists of only the receive aperture, and hence, a single channel. This eliminates the need for an array-based architecture of conventional DoA estimation techniques.

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