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Compressive Sensing as Applied to Channel Characterization and Beam Synthesis at Microwave Frequencies

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Abstract

This paper presents the application of compressive sensing to channel characterization at microwave frequencies. It is shown that, by leveraging spatio-temporally varying modes radiated by a single-channel compressive aperture, the DoA information can be retrieved without the need for an array-based receiver architecture. Building on the compressive DoA concept, it is then presented that a single aperture can be used to achieve a dual-mode operation. Such an aperture can operate in a compressive sensing mode to retireve the channel DoA information and can be dynamically reconfigured to synthesize a radiation pattern of interest to electronically scan the pattern. Presented results at 10 GHz frequency confirm high-fidelity DoA estimation and beam scanning capability from a single metasurface aperture.

1 Introduction

Recent advances in microwave systems and technology have resulted in a variety of applications, particularly in the context of innovative imaging modalities. Because the microwave window of the electromagnetic (EM) spectrum offers non-ionizing radiation and the capability to operate in all-weather conditions, radar systems and imaging technologies have found a primary usage in these applications. In this context, recently, the concept of computational imaging to facilitate physical layer compression has received significant attraction [1, 2, 3, 4, 5, 6, 7].

Channel characterization plays a crucial role in wireless communications. This demand has recently been further amplified by the introduction of software-defined intelligent reflecting surfaces (IRSs) [8, 9]. A major challenge in this implementation is the need for direction of arrival (DoA) estimation to identify the end user direction and reconfigure the IRS accordingly. DoA estimation conventionally requires a hardware-intense receiver layout, typically relying on a Nyquist-sampled raster scan to retrieve the DoA information in a wireless channel [10, 11, 12]. This places a significant burden on the system hardware layer at microwave frequencies caused by the dense sampling requirements. As a result, because the conventional DoA estimation techniques rely on array-based solutions, they require data acquisition from an excessive number of channels. Compressive sensing can play a significant role here to reduce the number of channels and to simplify the system physical hardware architecture. In particular, it has recently been shown that a single-pixel, frequency-diverse metasurface aperture can achieve DoA estimation using single-channel architecture by leveraging the physical layer compression concept [13, 14, 15, 16, 17, 18].

In this work, we present the concept of a dynamically modulated metasurface aperture to realize the compressive DoA estimation technique. We show that such an aperture can operate in multiple modes: Because the complex weights across the aperture can be dynamically modulated, the aperture can achieve compressive DoA estimation and beamforming as successive tasks.

2 Compressive DoA Estimation

The compressive DoA estimation technique is illustrated in Fig. 1.

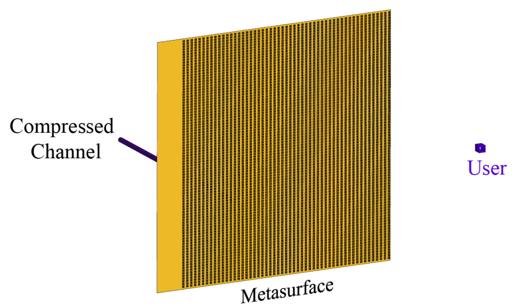


Figure 1. Compressive DoA estimation concept: A single-pixel metasurface aperture and an end user located in front of it. In this description, the end user is a far-field source that is incident on the aperture of the metasurface.

A critical component within the presented framework in Fig. 1 is the compressive metasurface aperture which exhibits a single-pixel data acquisition architecture. The metasurface consists of sub-wavelength sized meta-atoms distributed across the aperture. In this implementation, various feeding architectures can be used to connect the compressed channel to the meta-atoms and excite the metasurface, such as printed-circuit-board (PCB)-based structures

[6, 7] and electrically-large wave-chaotic cavities [19, 20]. The compressed channel is connected to the meta-atoms Different from the conventional multi-pixel system topologies relying on a raster-scan to measure the channel data, the single-pixel architecture leverages the physical layer compression concept. In other words, at a single frequency, the channel data captured by the single-pixel aperture is sampled by the wave-chaotic transfer function of the aperture and compressed into a single channel as follows:

$$g(m) = \int_r E(r,m)P(r)dr + n(m) \tag{1}$$

In (1), g denotes the compressed data measured at the single channel of the aperture, E is the transfer function of the compressive metasurface measured at its aperture and P denotes the projection of the incident far-field source on the metasurface aperture. In this description, the aperture coordinates are denoted by $r(x,y,z)$ whereas the variable m controls the measurement number and n represents the system noise.

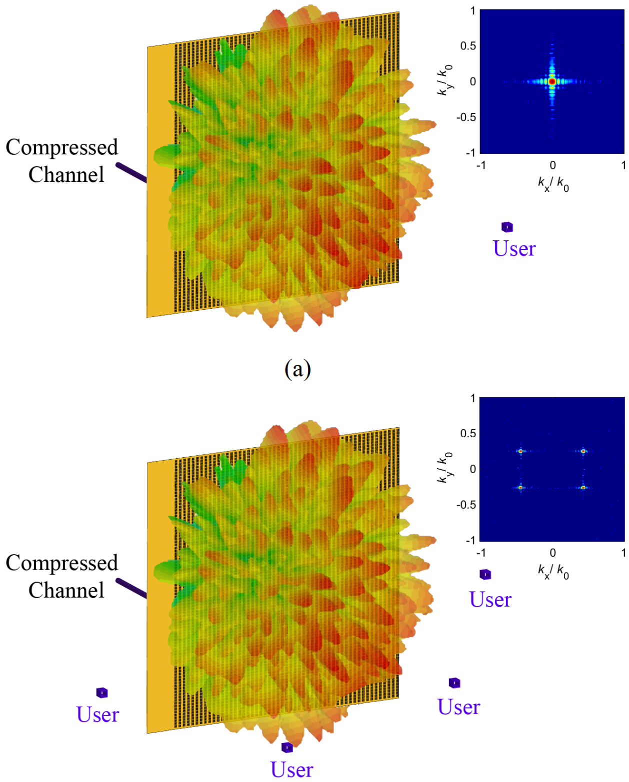
Whereas the compressive sensing paradigm can significantly simplify the physical hardware layer, in this technique, the sampling of the channel data is achieved in an indirect manner. As a result, recovering the DoA information from a compressed set of measurements requires an additional processing step. In this context, a simple solution can be found by correlating the compressed channel data with the phase conjugated transfer function of the compressive antenna as follows, which poses a matched-filter solution:

$$\mathbf{P}_{est} = \mathbf{E}^{\dagger}\mathbf{g} \tag{2}$$

In (2), $\mathbf{P}_{est}$ denotes the estimated projection of the far-field source at the metasurface aperture, and the symbol $.^{\dagger}$ is the Hermitian transpose. It should be noted here that, different from (1), (2) is expressed in a vector-matrix format, and hence, bold font is used to represent the vector-matrix notation of these terms. Finally, applying a simple Fourier transform to $\mathbf{P}_{est}$ recovers the channel DoA pattern [18].

3 Results and Discussion

The presented compressive DoA estimation concept is used to synthesize a dual-mode metasurface aperture. In the first mode, the aperture radiates spatio-temporally incoherent field patterns to encode the incident signal radiated from the end user and compress it into a single channel as presented in Fig. 2. The operating frequency for this scenario was selected to be 10 GHz. The aperture of the metaurface is modulated by randomly tuning the meta-atoms across the aperture *on* and *off*, with each aperture configuration state corresponding to an individual *mask* configuration [14]. In this implementation, the aperture of the metasurface is modulated to radiate $M = 100$ quasi-random field patterns, where M denotes the number of total masks. As an example, Fig. 2 shows the compressive sensing process for a single mask configuration.



(a)
(b)

Figure 2. Compressive metasurface aperture sampling (a) a single end user (far-field source) (b) multiple (four) end users using a wave-chaotic radiation pattern. The sampled data is then compressed into a single channel of the metasurface, i.e. physical layer compression. The reconstructed DoA patterns are shown as inset. For DoA estimation, the aperture works as a receiver.

In the DoA mode of operation presented in Fig. 2, the DoA pattern is reconstructed by correlating the compressed channel data, $\mathbf{g}$, to the transfer function of the aperture, $\mathbf{E}$, and applying a simple Fourier transform to $\mathbf{P}_{est}$. The reconstructed DoA patterns are shown in Fig. 2 as an inset. For this study, two scenarios are investigated. For the first studied scenario in Fig. 2a, the end user is located along the optical axis ($\theta = 0°, \phi = 0°$), where θ and ϕ denote the original incident angles representing the source (ground truth). As can be seen in Fig. 2a, the retrieved DoA pattern is in good agreement with the ground truth and the incident angles are estimated as ($\theta_{est} = 0°, \phi_{est} = 0°$). For the second scenario, the number of end users is selected to be four, located at ($\theta_1 = -30°, \phi_1 = -30°$), ($\theta_2 = 30°, \phi_2 = 30°$), ($\theta_3 = -30°, \phi_3 = 30°$), and ($\theta_4 = 30°, \phi_4 = -30°$) respectively. As can be seen in Fig. 2b, for this multi-user scenario, the retrieved DoA pattern exhibits four peaks with the estimated DoA peak points calculated as ($\theta_{1,est} = -30.3°, \phi_{1,est} = -29.4°$), ($\theta_{2,est} = 29.2°, \phi_{2,est} = 30.4°$), ($\theta_{3,est} = -30.7°, \phi_{3,est} = 30.5°$), and ($\theta_{4,est} = 29.9°, \phi_{4,est} =$

−31.1°) respectively. The retrieved DoA data is in good agreement with the ground truth values. It should also be noted here that the number of far-field sources, four in this case, is selected on an arbitrary basis and a similar analysis can be performed for a different number of sources without loss of generality.

Following the retrieval of the channel DoA estimation, the metasurface aperture is switched to operate in the second mode. In this mode, the complex-weights of the meta-atoms across the metasurface aperture are engineered in such a way that the collective radiated fields from the metasurface aperture constructively add in the direction of the end user. This would imply that the metasurface can scan its radiation pattern to cover the user in an all-electronic manner as depicted in Fig. 3.

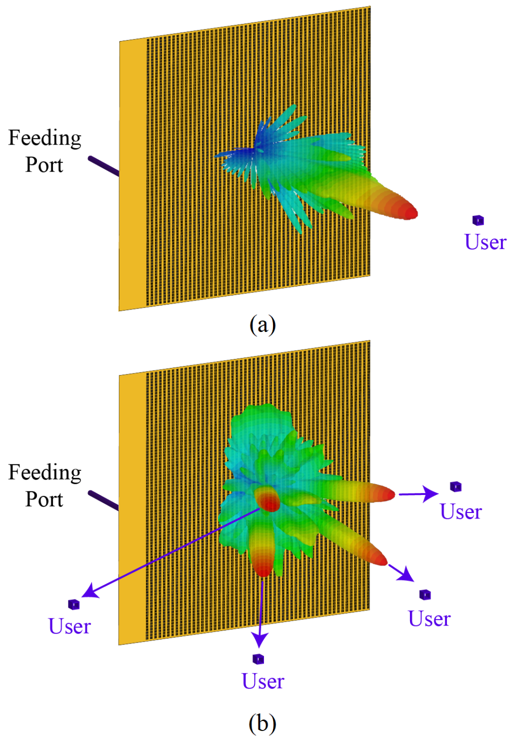


Figure 3. Metasurface operating in beam-scanning mode as a transmitter. In this example, the metasurface aperture is all-electronically reconfigured to radiate in the direction of the end user when (a) a single end user is present (b) the number of end users is four.

4 Conclusion

In this paper, we presented a single-pixel compressive aperture to achieve DoA estimation at 10 GHz. The presented aperture exhibits spatio-temporally incoherent field patterns, representing a wave-chaotic transfer function that can encode the incident signal onto a series of measurements. The communication channel information is compressed and passed on into a single radio hardware channel, making it a physical layer compression medium. It was shown that, by dynamically modulating the metasurface aperture, the channel information can be retrieved without the need for an array based receiver architecture, significantly simplifying the data acquisition process. Moreover, we also showed that the same aperture can be dynamically modulated to achieve beam-scanning. Such a metasurface aperture with dual-mode operation characteristics holds a significant potential for future wireless communication networks, particularly given the growing importance of IRSs, which can be considered a special type of metasurface. It should also be noted that although the presented technique was demonstrated for operation at 10 GHz, it can readily be scaled to higher frequencies, such as millimetre-waves and THz, with potential applications in 6G and beyond. Because Nyquist sampling the conventional array apertures at such high frequencies would require a rather complex hardware layout, the advantage of the presented single-pixel compressive DoA estimation framework can be further amplified at millimetre-wave and THz frequencies.

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