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# System Level Analysis of Computational Channel Characterization using Compressive Surfaces

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***Abstract*—Direction of arrival (DoA) estimation plays a crucial role in channel characterization and is a critical step to execute the necessary beam-shaping operations needed from antennas present within a wireless environment. Conventional DoA estimation frameworks rely on array-based topologies, making use of the phase difference information between the individual channels to retrieve the DoA data. Recently, the idea of computational imaging has been shown to offer a promising solution to conventional raster-scan-based techniques. This is mainly due to the physical layer compression facilitated by special types of compressive apertures (or surfaces) that leverage the idea of synthesizing quasi-orthogonal radiation patterns (modes) to probe and encode the scene information in an indirect manner and compress it into a single channel (or a reduced number of channels). The application of computational imaging to the channel characterization problem is intriguing. Yet, a system level of knowledge of the design parameters, which are key to understanding the development of compressive surfaces for computational DoA estimation, is far from comprehensive. In this paper, we demonstrate different techniques to synthesize spatio-temporally incoherent field patterns, a key requirement for computational DoA estimation, and provide a study of the different system level parameters needed to design such antennas. We show that by increasing the orthogonality of the radiated modes (and thus reducing the information redundancy), a single-channel compressive antenna can retrieve the DoA pattern of multiple far-field sources even under a signal-to-noise ratio (SNR) level of as low as 0 dB, without the necessity to use a multi-channel physical architecture.**

***Index Terms*—direction-of-arrival estimation, computational imaging, antenna aperture, surface, microwave.**

## I. INTRODUCTION

Recent advances in microwave and millimetre-wave systems and technology have resulted in a plethora of innovative concepts covering a wide range of applications, from imaging to wireless communications. Among those, computational imaging has been the subject of much research recently [1]–[4]. Computational imaging offers an alternative to conventional raster-scan-based techniques by making use of a physical layer compression facilitated by a single-channel hardware architecture [5]. As a result, computational imaging-based system solutions can be considered compressive apertures (or surfaces) that can replace the conventional, densely populated (at the Nyquist limit) array-based system topologies.

The concept of physical layer compression can be achieved using a variety of antenna architectures. Frequency-diversity is one such technique that can be used to radiate spatio-temporally incoherent radiation patterns which can be controlled as a function of a frequency sweep [4], [6]. In other words, a frequency-diverse surface can radiate quasi-random radiation patterns that undergo a spatial variation at each frequency across a desired frequency-band of operation. Despite the easiness of modulating the radiation pattern of the antenna by means of a simple frequency sweep, this method also brings some system-level challenges. One such challenge is that the quality-factor (or Q-factor) of the antenna needs to be large enough to support the generation of a sufficient number of independent (or orthogonal) radiated field patterns within the frequency band of operation. Increasing the Q-factor of the antenna can be a limiting factor while considering the fact that the radiation efficiency of the antenna should also be sufficient to ensure that an adequate signal-to-noise ratio (SNR) is achieved. Another approach to synthesize the spatio-temporally incoherent modes is the active modulation of the antenna aperture, eliminating the need for a frequency sweep [4], [7]. The active modulation of the surface can be achieved using semiconductor elements, such as PIN diodes or by synthesizing tunable impedance surfaces that can change the boundary conditions within the antenna medium. Finally, a combination of these techniques can be used to leverage their respective advantages and increase the number of total measurement modes, and hence the degrees of freedom in the imaging process [8].

Channel characterization by means of a direction of arrival estimation (DoA) can be a significant challenge particularly in terms of the hardware layer complexity. The recent deployment of the 5G technology and the growing research efforts into 6G and beyond to address the increasing data rate/bandwidth requirements make it advantageous to use higher frequencies, from the millimetre-wave into the submillimetre-wave regime. Conventionally, DoA estimation relies on an array topology, aiming to detect the phase differences between the multiple channels and calculate the DoA information. However, with the reduced wavelength scale, such conventional approaches can exhibit a significant complexity on the hardware layer, potentially requiring the use of an unpractical number of array elements (and data acquisition channels). Thus, this type of array topology can consume a significant amount of power and can be costly. Recently, we have demonstrated that the physical layer compression concept originated from the idea of computational imaging can offer a promising solution to address these challenges [9]–[11]. In particular, we have shown that, the DoA estimation can be achieved using a single-channel hardware architecture, by leveraging the frequency-diversity approach [9], the active aperture approach [10], or a combination of both [11]. Despite these efforts, a systematic level of analysis into design level parameters remains an important study to be carried out to understand the design constraints of this approach and provide a comparison between the performance of different computational imaging techniques in the context of compressive computational DoA estimation. In this paper, we aim to provide a system level understanding of the computational DoA estimation concept realized with compressive surfaces.

## II. COMPUTATIONAL IMAGING AND DOA ESTIMATION

The computational imaging technique relies on the idea of illuminating a scene to be imaged using quasi-random, spatio-temporally incoherent radiation patterns (or modes) radiated from chaotic apertures [4], [5]. The backscattered signals are then encoded and compressed into a single-channel by the transfer function of the aperture. Using the first Born approximation, this process can be mathematically described as follows:

$$\mathbf{g}_{M\times 1} = \mathbf{H}_{M\times N}\mathbf{f}_{N\times 1} + \mathbf{n}_{M\times 1}. \tag{1}$$

In (1), $\mathbf{H}$ denotes the sensing matrix, which is the dot product of the electric fields radiated by the transmit ($\mathbf{E}_{Tx}$) and receive ($\mathbf{E}_{Rx}$) apertures propagated to the imaged scene ($\mathbf{H} = \mathbf{E}_{Tx} \cdot \mathbf{E}_{Rx}$), while $\mathbf{f}$ denotes the scene reflectivity and $\mathbf{g}$ is the backscattered data collected at the receive channel. $M$ is the total number of modes (or measurements) produced by the surface and $N$ denotes the number of voxels into which the scene is discretized. The bold font in (1) refers to a vector-matrix notation. Once the backscattered data compressed at the receiver channel is captured, an estimate of the scene reflectivity can be recovered by means of a simple Hermitian transpose operation of the sensing matrix applied to the measured data [12].

A careful investigation of (1) reveals that the backscattered problem is linked to the DoA problem by means of a simple modification. In the DoA estimation scenario, the wavefronts radiated by far-field sources are captured by the transfer function of the antenna aperture. Most importantly, through this transformation, the relative phase information of the far-field sources is projected onto the aperture surface which is then sampled by the transfer function of the aperture. In this case, the imaging equation given in (1) can be simplified to the following form:

$$\hat{\mathbf{f}} = \mathbf{E}^{\dagger}\mathbf{g}. \tag{2}$$

In (2), $\mathbf{E}$ represents the transfer function of the receive aperture. Accordingly, to retrieve the DoA pattern, one can recover an estimate of the projection of the far-field sources on the antenna aperture, $\hat{\mathbf{f}}$ in (2). The DoA pattern can then be retrieved by means of a simple Fourier transform [9]–[11]. It is worth mentioning here that the absolute reference phases of the far-field sources do not need to be coherent. In fact, in this work, the far-field sources are given random phase references (non-cooperative) selected on an arbitrary basis. Fig. 1 shows a scheme of the computational DoA estimation using a compressive surface. The electrical size of the surface shown in Fig. 1 is $10\lambda \times 10\lambda$ (where $\lambda$ is the free space wavelength at 10 GHz). Whereas this surface has a single-channel output compressing the collected field at the aperture through the aperture transfer function, synthesizing the same aperture using the conventional array architecture would require 21 x 21 elements, each comprising a dedicated feeding network. This physical layer compression can substantially simplify the hardware architecture for DoA estimation.

## III. SYSTEM LEVEL ANALYSES

In this section, we present system level analyses of the design metrics of such compressive surfaces in computational DoA estimation. For these analyses, we study two different aperture scenarios: a frequency-diverse aperture and an active aperture.

### A. Frequency-Diversity

As mentioned earlier, the frequency-diverse concept relies on the radiation of spatio-temporally incoherent modes by means of a frequency sweep. In this concept, an important factor that directly affects the fidelity of the reconstructed DoA patterns is the correlation between the measurement modes radiated by the aperture at each frequency sampling point within the swept frequency bandwidth. The Q-factor of the antenna plays an important role in the governance of this parameter. A useful metric to analyze the orthogonality of the modes radiated by the frequency-diverse antenna can be extracted from the singular values of the sensing matrix, which in turn are obtained by means of the singular value decomposition (SVD). In Fig. 1, we consider a frequency-diverse aperture operating across 8-12 GHz in the presence of 3 far-field sources ($S_1$, $S_2$ and $S_3$). Please note that this selection is made on an arbitrary basis and the number of sources can be varied without loss of generality.

*1) Effect of Q-factor:* Using the above setup, in Fig. 2 we first investigate the effect of the antenna Q-factor on the SVD patterns. It is evident from Fig. 2 that as the Q-factor of the antenna is increased, the SVD pattern for the DoA estimation problem at hand becomes better conditioned. In other words, increasing the Q-factor of the antenna increases the orthogonality of the measurement modes, reducing the information redundancy.

To see the effect of the Q-factor on the DoA retrieval problem, the reconstructed DoA patterns for the Q-factor values studied in Fig. 2 are presented in Fig. 3.

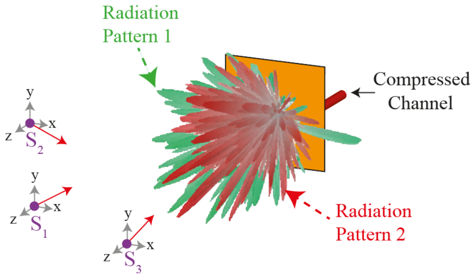


Fig. 1. Computational DoA estimation of multiple far-field sources using a compressive surface generating quasi-random radiation patterns.

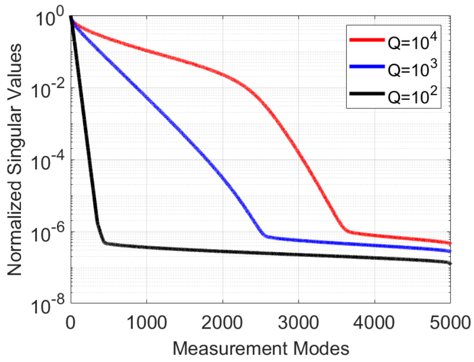


Fig. 2. SVD patterns as a function of antenna Q-factor.

In Fig. 3 it is clear that the reconstructed DoA pattern with $Q = 10^4$ is of significantly better quality than the DoA pattern retrieved with $Q = 10^2$. It should be noted that, for this study, no noise is considered and the effect of finite SNR will be studied in the next section.

*2) Effect of Noise:* For a practical DoA estimation scenario, the system SNR becomes a crucial factor. Reducing the system SNR level can result in the noise subspace dominating over the information captured by measurement modes exhibiting poor orthogonality, thus effectively reducing the number of "useful" measurement modes [12]. To study this effect, we choose two different Q-factors from the study presented in Fig. 2, $Q = 10^3$ and $Q = 10^4$, and we investigate the quality of the retrieved DoA patterns as a function of varying SNR levels, selected to be 0 dB, 10 dB and 20 dB, respectively. The retrieved DoA patterns are shown in Figs. 4 and 5.

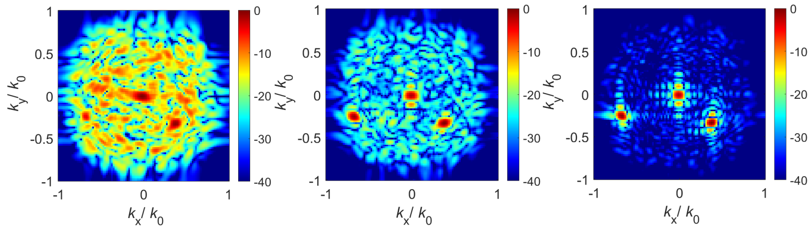
As can be seen in Figs. 4 and 5, the effect of SNR on the DoA estimation can be significant. This is particularly evident when the Q-factor of the antenna is low, further amplifying the effect of the noise on the DoA estimation. It is, thus, important that, for computational DoA estimation relying on frequency-diversity to achieve spatio-temporal incoherence, the Q-factor of the antenna is maximized while also ensuring that the antenna exhibits sufficient radiation efficiency to achieve a good SNR level.

*3) Number of Measurement Modes:* As a final design parameter for frequency-diversity, we study the effect of the number of total measurement modes on the DoA retrieval problem. Whereas it is desired that the number of measurement modes is increased to improve the fidelity of the retrieved DoA patterns, there are fundamental limits to this parameter. For a frequency-diverse surface with a defined Q-factor and imaging bandwidth, the theoretical upper bound limit on the statistically independent number of available measurement modes was analyzed in [13]. Whereas it might be assumed that increasing the number of measurement modes would be beneficial to improve the quality of the retrieved DoA patterns, in fact, this improvement has an upper bound limit. In other words, increasing the number of measurement modes beyond the theoretical limit on the number of independent modes generated by the aperture would bring redundant information. This would increase the data acquisition time and the complexity of solving the computational DoA equation in (1) without actually improving the quality of the retrieved DoA patterns. To demonstrate this point, in Fig. 6, we study the DoA estimation scenario originally presented in Fig. 1, as a function of varying the number of measurement modes. The reconstructed DoA patterns shown in Fig. 6 confirm this conclusion. It is evident in Fig. 6 that increasing the number of measurement modes to the upper bound limit significantly improves the fidelity of the retrieved DoA patterns. However, once the number of measurements is increased beyond the theoretical limit, which is calculated to be around 4000 using the theoretical analysis in [13] and also confirmed by the SVD analysis shown in Fig. 2, the improvement in the reconstructed DoA patterns saturates.

### *B. Active Aperture*

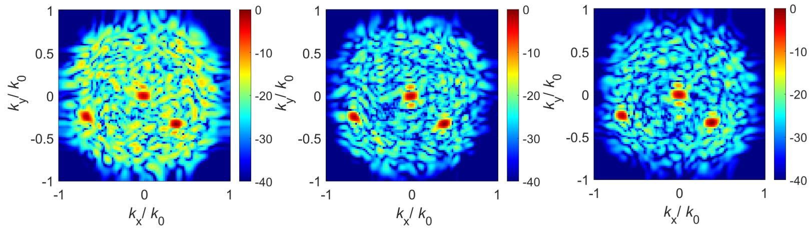
Following the investigation of the system parameters for frequency-diverse-based surfaces for computational DoA estimation, we present a similar study for the active-aperture-based technique.

*1) Number of Measurement Modes:* Different from the frequency-diversity approach, the active aperture technique does not need to rely on a frequency sweep to synthesize the diverse modes. Instead, the surface aperture is modulated to synthesize different "mask" configurations. In other words, by changing the coupling response of the elements across the surface in a random manner, the boundary condition at the antenna aperture can be changed dynamically, even at a single frequency. To achieve this, semiconductor elements with low power consumption and fast switching time can be used, such as PIN diodes and varactors [4], [7], [14]. As a result, evaluating the upper bound limit for an active surface does not necessarily need to follow the discussion provided in Section III.A. Instead, a more useful metric can be extracted from the SVD analysis of the aperture fields capturing the projection of the far-field sources on the antenna aperture. To demonstrate this point, we study the DoA estimation scenario originally presented in Fig. 1, and replace the frequency-diverse surface with an active surface operating at 10 GHz. For the studied scenario, doing an SVD analysis on the aperture field results in around 1000 measurement modes after which we observe a sharp decay in the singular values. As a result, increasing the number of measurements above this limit brings highly redundant information while increasing the computational size of the DoA estimation problem. To confirm this conclusion,



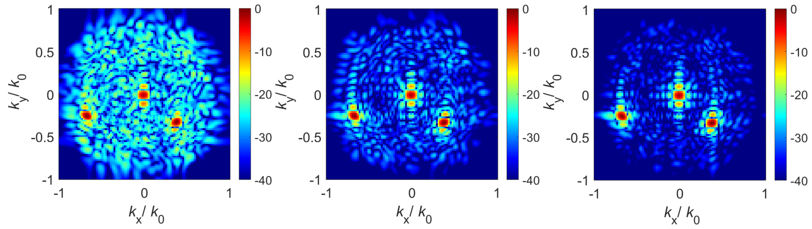
(a) (b) (c)

Fig. 3. Reconstructed DoA patterns as a function of the antenna Q-factor: (a) $Q = 10^2$, (b) $Q = 10^3$ and (c) $Q = 10^4$.



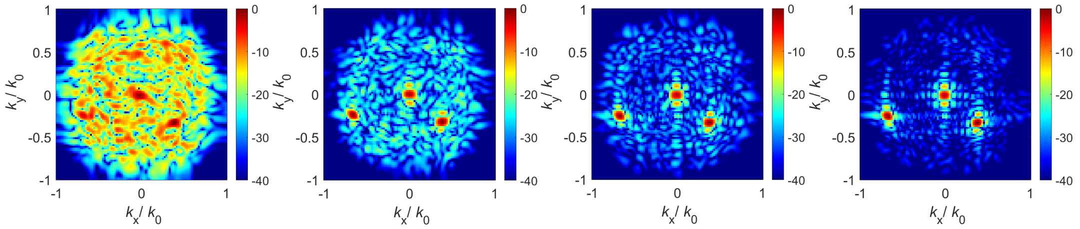
(a) (b) (c)

Fig. 4. Reconstructed DoA patterns as a function of SNR when the antenna Q-factor is $10^3$: (a) SNR = 0 dB, (b) SNR = 10 dB and (c) SNR = 20 dB.



(a) (b) (c)

Fig. 5. Reconstructed DoA patterns as a function of SNR when the antenna Q-factor is $10^4$: (a) SNR = 0 dB, (b) SNR = 10 dB and (c) SNR = 20 dB.



(a) (b) (c) (d)

Fig. 6. Reconstructed DoA patterns as a function of measurement modes when the antenna Q-factor is $10^4$: (a) 50, (b) 500, (c) 1000 and (d) 5000 modes.

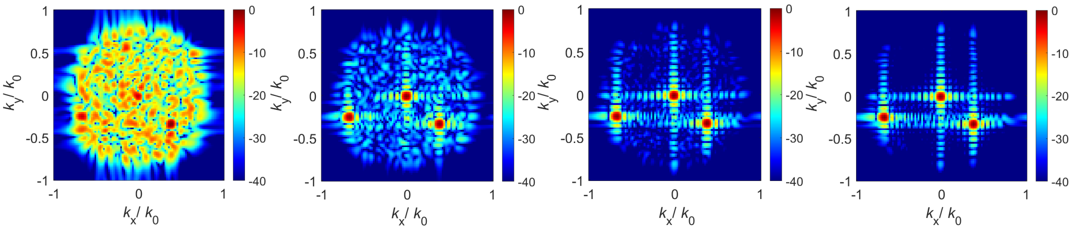
in Fig. 7, we demonstrate the DoA patterns reconstructed using the active surface as a function of varying number of measurements.

As can be seen in Fig. 7, the reconstructed DoA patterns improve consistently as the number of measurement modes is increased towards the upper bound limit determined by the SVD analysis. Beyond this limit, the captured information by the aperture is increasingly redundant, thus, the reconstructed DoA patterns do not exhibit a substantial improvement beyond this limit.

*2) Effect of Noise:* Similar to the frequency-diversity case, the effect of noise is an important parameter to study to assess the practicality of the active aperture concept for computational DoA estimation applications. In this context, we vary the SNR level from 0 dB to 20 dB, and study the retrieved DoA patterns as a function of SNR. The reconstructed DoA patterns are shown in Fig. 8. As can be seen in Fig. 8, reducing the system SNR level also reduces the quality of the reconstructed DoA patterns. Whereas this pattern is similar to the noise study presented for the frequency-diverse case in Section III.A, from a qualitative inspection of the of the reconstructed DoA images in Figs. 4, 5 and Fig. 8, it is evident that the effect of noise on the DoA patterns for the active aperture case follows a similar pattern to the frequency-diverse case when the Q-factor is high. In other words, in order for the frequency-diverse aperture to exhibit on par mode orthogonality performance to the active aperture case, the Q-factor of the frequency-diverse antenna needs to be sufficiently large.

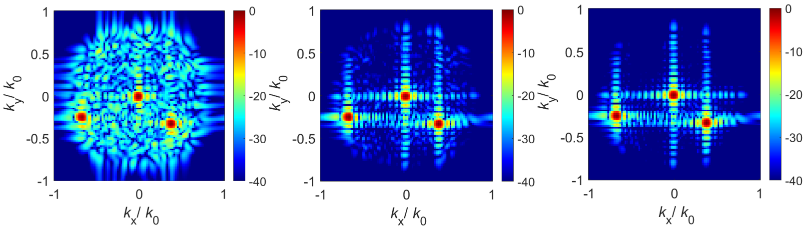
## IV. CONCLUSION

We presented a system level study for the concept of compressive antennas for computational DoA estimation. As



(a) (b) (c) (d)

Fig. 7. Reconstructed DoA patterns as a function of measurement modes when an active aperture is used: (a) 50, (b) 500, (c) 1000 and (d) 5000 modes.



(a) (b) (c)

Fig. 8. Reconstructed DoA patterns as a function of SNR when an active aperture is used: (a) SNR $= 0\,\mathrm{dB}$ (b) SNR $= 10\,\mathrm{dB}$ and (c) SNR $= 20\,\mathrm{dB}$.

a building block of the computational DoA estimation technique, in contrast to the conventional, array-based raster-scan solutions that exhibit densely populated number of antennas (and channels), we presented that compressive surfaces can simplify the hardware layer due to their single-channel architecture. At the same time, to achieve optimum performance from such computational DoA estimation schemes, a careful design process is needed, which in turn requires a system-level understanding of the design parameters. We presented a set of critical system parameters, such as SNR, number of measurement modes and Q-factor, with the aim of providing a system-level understanding into the design process of these antennas for DoA estimation. Although the presented diversity schemes (frequency-diversity and active aperture) were shown at microwave frequencies, without loss of generality, these results can be scaled, and thus are applicable, to other frequency bands where the channel characterization problem can be developed for next generation 5G and beyond wireless networks, extending into millimetre-wave and even submillimetre-wave frequencies.

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