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Design and analysis of compressive antenna arrays for direction of arrival estimation☆

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ABSTRACT

In this paper we investigate the design of compressive antenna arrays for narrow-band direction of arrival (DOA) estimation that aim to provide a larger aperture with a reduced hardware complexity and allowing reconfigurability, by a linear combination of the antenna outputs to a lower number of receiver channels. We present a basic receiver architecture of such a compressive array and introduce a generic system model that includes different options for the hardware implementation. We then discuss the design of the analog combining network that performs the receiver channel reduction, and propose two design approaches. The first approach is based on the spatial correlation function which is a low-complexity scheme that in certain cases admits a closed-form solution. The second approach is based on minimizing the Cramér-Rao Bound (CRB) with the constraint to limit the probability of false detection of paths to a pre-specified level. Our numerical simulations demonstrate the superiority of the proposed optimized compressive arrays compared to the sparse arrays of the same complexity and to compressive arrays with randomly chosen combining kernels.

1. Introduction

Direction of arrival (DOA) estimation has been an active field of research for many decades [1]. In general, DOA estimation addresses the problem of locating sources which are radiating energy that is received by an array of sensors with known spatial positions [2]. Estimated DOAs are used in various applications like localization of transmitting sources, for direction finding [3,4], massive MIMO and 5G Networks [4,5], channel sounding and modeling [6–9], tracking and surveillance in radar [10], and many others. A major goal in research on DOA estimation is to develop approaches that allow to minimize hardware complexity in terms of receiver costs and power consumption, while providing a desired level of estimation accuracy and robustness in the presence of multiple sources and/or multiple paths. Furthermore, the developed methods shall be appropriate for realistic antenna arrays whose characteristics often significantly vary from commonly considered ideal models [11].

In the last few decades, research on narrow-band DOA estimation using array processing has largely focused on uniform arrays (e.g., linear and circular) [2] for which many efficient parameter estimation algorithms have been developed. Some well-known examples are ESPRIT [12], MUSIC [13] and Maximum Likelihood (ML)-based methods [8,14]. Note that ML-based methods are particularly suitable for realistic, non-ideal antenna arrays since they can easily account for the full set of parameters of the antenna array (e.g., antenna polarization, non-ideal antennas and array geometries, etc.). However, to perform well, the algorithms require to fulfill certain conditions on the sampling of the wavefront of the incident waves in the spatial domain. Namely, the distance between adjacent sensors should be less than or equal to half a wavelength of the impinging planar wavefronts, otherwise it leads to grating lobes (sidelobes) in the spatial correlation function which correspond to near ambiguities in the array manifold. At the same time, to achieve DOA estimation with a high resolution, the receiving arrays should have a relatively large aperture

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[2]. This implies that arrays with a large number of antennas are needed to obtain a high resolution, which is not always feasible.

This limitation has triggered the development of arrays with inter-element spacing larger than half the impinging wave's wavelength combined with specific constraints to control the ambiguity problem in DOA estimation. Such arrays are usually called sparse arrays. In [15], it was proposed to constitute a non-uniform sparse array with elements spaced at random positions. However, using such random arrays will often result in an unpredictable behavior of the sidelobes in the array's spatial correlation function. As a result, it is necessary to optimize the positions of the antenna elements in order to achieve a desired performance. An early approach towards that goal was the Minimum Redundancy Linear Array (MRLA) [16], where it is proposed to place the antenna elements such that the number of pairs of antennas which have the same spatial correlation properties are as small as possible. However, it is very difficult to construct an MRLA when the number of elements is relatively large [17]. Some non-linear optimization methods like genetic algorithms [18] and simulated annealing [19] have been regularly used to find optimum configurations for these sparse arrays. Moreover, it is shown in [20] that the optimization of the array aperture with respect to the Cramér-Rao Bound leads to V-shaped arrays. In more recent works, it has been shown that with co-prime arrays [21], and nested arrays [22] it is possible to resolve $\mathcal{O}(M^2)$ of uncorrelated sources with $\mathcal{O}(M)$ sensors, if they are observed over a large window in time.

Recently, compressed sensing (CS) [23–25] has been widely suggested for applications that exhibit sparsity in time, frequency or space to reduce the sampling efforts. The usage of sparse recovery in narrow-band DOA estimation has been considered for applications like localization of transmitting sources [26], channel modeling [27], tracking and surveillance in radar [28], and many others. It is highlighted in [29] that if the electromagnetic field is modeled as a superposition of a few plane waves, the DOA estimation problem can be expressed as a sparse recovery problem. The main focus is to use the sparse recovery algorithms that became popular in the CS field for the DOA estimation problem as an alternative to existing parameter estimation algorithms [30–33]. Compressed sensing has also been suggested to be applied in the spatial domain (e.g., array processing and radar) with the main goal to reduce the complexity of the measurement process by using fewer RF chains and storing less measured data without the loss of any significant information. Hence, the idea of sparse random arrays with increased aperture size has been revisited recently and proposed to perform spatial compressed sensing [34–37].

An alternative approach that attempts to apply CS to the acquisition of the RF signals that are used for DOA estimation has recently been proposed in [38,39]. In particular, the CS paradigm can be applied in the spatial domain by employing N antenna elements that are combined using an analog combining network to obtain a smaller number of $M < N$ receiver channels. Since only M channels need to be sampled and digitized, the hardware complexity[1] remains comparably low (e.g., consuming less energy and storing less data) while a larger aperture is covered which yields a better selectivity than a traditional, Nyquist ($\lambda/2$) spaced M-channel antenna array. Note that equipping every antenna with an RF chain may imply a prohibitive hardware complexity (in terms of cost as well as power consumption) in certain applications where reconfigurable arrays with a high gain call for hundreds [40] or even several thousands of antenna elements [41]. Moreover, using a tunable analog combining network, CS-arrays allow to reconfigure the array on the fly without any change in receiver hardware. This advantage in flexibility can be crucial in many applications. A recent example is millimeter wave radio, where one of the major challenges is to solve the gain-resolution dilemma. In order to account for the high pass loss, a high gain is needed while at the same time the full angular domain needs to be scanned [42]. A similar problem occurs during the target acquisition and high resolution target tracking phases in radar [43]. Because of its flexibility, the compressive hardware architecture is particularly suitable for these applications (see for example [44] for more precise details on the practical implementation of such architectures).

In baseband, the operation of the combining network can be described by complex weights applied to the antenna outputs with a subsequent combination of the received signals from the antennas. The combining (measurement) matrix that contains the complex weights and the antenna array form an effective "compressive" array whose properties define the DOA estimation performance. In the field of "CS-DOA" it is usually advocated to draw the coefficients of the measurement matrix from a random distribution (e.g., Gaussian, Bernoulli) [38,39]. Random matrices have certain guarantees for signal recovery in the noise-free case and provide some stability guarantees in the noisy case [45–47]. However, since no criterion is used to design them, it is likely that they provide sub-optimal performance [48].

In this paper, we discuss the design and the performance of *compressive* arrays employing linear combinations in the analog domain by means of a network of power splitters, phase shifters, and power combiners. We present a basic receiver architecture of such a compressive array and introduce a generic system model that includes different options for the hardware implementation. Importantly, the model reflects the implications for the noise sources. Particularly, a well-known source of the receiver noise is the low noise amplifier (LNA) that is usually placed at the antenna outputs to account for the power losses of the following distribution/combining network. Depending on the frequency range, the components of the analog combining network (power combiners, power splitters, phase shifters[2]) will induce additional losses which also have to be compensated by the LNAs. To name an example, some typical commercially available phase shifters for phased array radar applications can induce insertion losses between 5 to 10 dB depending on the frequency range [50] while architectures based on waveguides promise a loss as low as 3 dB [41]. This motivates the need for the signal amplification prior the combining network.

Based on the generic system model we then discuss the design of the combining matrix, with the goal to obtain an array that is suitable for DOA estimation (i.e., minimum variance of DoA estimates and robustness in terms of low side lobe levels or low probability of false detections). We consider two design approaches. The first is based on the spatial correlation function which is a low-complexity scheme that in certain cases even admits a closed-form solution. The second is based on the minimization of the Cramér-Rao Bound (CRB). CRB-minimizing array designs tend to result in high sidelobes in the spatial correlation function which likely leads to false estimates. In order to be able to constrain this effect, we analytically derive the probability to detect a false peak (sidelobe) for a given array manifold. We then use this expression

[1] The hardware complexity (as well as the power consumption) depends on the frequency range, sampling rate/bandwidth, array application, exact realization of the antenna array and its elements, realization of the phase-shifter network, used RF amplifiers and ADC/DAC components, TX/RX switches, filters, etc. As an exact quantization of the hardware cost savings depends on so many factors and our approach is applicable to a wide range of scenarios, we avoid to give concrete numbers in the manuscript

[2] Note, that even though it is possible to adjust the amplitudes in addition to the phases in the combining network, we do not consider this option here. Adjusting amplitudes requires additional analog components that increase the hardware complexity as well as the losses in the combining network while the expected gain in flexibility and performance is low [44,49].