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Sparse transmit array design for dual-function radar communications by antenna selection ☆

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ABSTRACT

Dual-function radar communications (DFRC) systems have recently been proposed to enable the coexistence of radar and wireless communications, which in turn alleviates the increased spectrum congestion crisis. In this paper, we consider the problem of sparse transmit array design for DFRC systems by antenna selection where same or different antennas are assigned to different functions. We consider three different types of DFRC systems which implement different simultaneous beamformers associated with single and different sparse arrays with shared aperture. We utilize the array configuration as an additional spatial degree of freedom (DoF) to suppress the cross-interference and facilitate the cohabitation of the two system functions. It is shown that the use of sparse arrays adds to improved angular resolution with well-controlled sidelobes on DFRC system paradigm. The utilization of sparse arrays in DFRC systems is validated using simulation examples.

1. Introduction

In recent years, radio frequency (RF) spectrum is becoming increasingly congested with an exponentially growing demand by end-consumers. Consequently, defense applications are losing spectrum to commercial communications, and have to operate in contested environments. Emerging research in multi-function platforms aims at using common or shared aperture and frequency spectrum between radar, electronic warfare, and military communications [1–5], whose coexistence benefits from common transmit platform, and in turn moving away from independent systems [6–8]. In order to enable usage or sharing of spectrum resources and platform hardware, a dual-function radar communications (DFRC) system utilizing waveform diversity in tandem with amplitude/phase control of the radar beam was introduced in [9–14], where radar is considered as the primary function and presents itself as a system of opportunity to secondary communication functions. In dual-function paradigm, identical signals, same carrier frequency and bandwidth, and common antenna array are deployed to fulfill the objectives of both radar and communication operations. In DFRC system, secondary communications strive to embed a sequence of binary data during each radar pulse which can be achieved through scaling or modulation of either the radar beam or the radar waveform or both. This signal embedding, however, should be accomplished with no, or minimum, alterations to primary radar function, whether it is detection, tracking, or estimation.

One signaling strategy for embedding information into the radar pulsed emissions uses sidelobe amplitude modulation (AM) and changes the sidelobe level (SLL), according to the information message, towards the intended communication user direction [15]. In lieu of AM, a coherent phase-modulation (PM)-based method was proposed in [16,17] to embed one symbol into the radar emission by controlling the phase of complex transmit array pattern. The benefits of decomposing the radar pulse into different waveforms were demonstrated in [17] where a communication symbol is embedded as a phase rotation between a pair of transmitted orthogonal waveforms. A multi-waveform amplitude shift keying (ASK) strategy was introduced in [18] to embed one binary bit with each orthogonal waveform through bilevel sidelobe control.

Similar to the offering of multi-waveforms, the dual functions of the radar communications system can be improved by properly utilizing the multi-sensor transmit/receive array configurations [19–21]. Although the nominal array configuration for existing

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DFRC systems is uniform and of fixed-structured, it is not necessarily optimum in every sense, and ignores the additional degrees of freedom (DoFs) provided by the flexibility in configuring the antenna array [22–26]. Non-uniform sparse arrays have attracted increased attention in multi-sensor transmit/receive systems as an effective solution to reduce the system's complexity and cost, yet retain desired performance [27–29]. Sparse array design is often cast as optimally placing a given number of antennas on a larger number of possible uniform grid points. In so doing, we are able to span large aperture without introducing unwanted high sidelobes, thus improving spatial resolution. Sparse array design becomes an "antenna selection" problem when the number of antennas is equal to the number of grid points, but with fewer RF units. In this case, antenna selection amounts, in essence, to assigning antennas to RF units. In transmit antenna selection, the number of expensive RF chains, which consist of digital-to-analog converter, up-converter, filters and power amplifiers, is smaller than the number of available transmit antenna elements [30,31]. Thus sparse arrays can, undoubtedly, alleviate pressures on the resource management and efficiency requirements on power amplifiers.

It had been clearly documented in recent papers [32–34] that the performance of optimum sparse array beamformer is dependent on both array configuration and beamforming weights. In this paper, we add to DFRC system paradigm by introducing a new co-existence approach based on antenna selection. Specifically, we examine the problem of sparse array beampattern synthesis with a fixed number of transmit antennas under the framework of dual functional system design. Three different types of DFRC systems are considered, namely, a system that implements (a) single sparse array with one set of weights, i.e., a single beamformer; (b) single sparse array but with different beamformers; (c) multiple sparse but complementary arrays with different beamformers. The latter case is referred to as "shared aperture", where the combined sparse arrays span the given system aperture. The main advantages of utilizing sparse arrays in DFRC systems are manifested by simulation results in the suppression of cross-interference between the two functions and improved hardware efficiency.

The novelty of this paper is summarized as follows:

- We utilize array configurations as additional spatial DoFs to facilitate the co-existence of dual-function radar communications and improve the communication performance without sacrificing radar functions.
- We solve the new problem of sparse array beampattern synthesis under the framework of dual function system design and propose a method to enhance the robustness of proposed antenna selection algorithm against initial search point.
- We consider dual-functional system platforms equipped with different beamformers associated with shared aperture sparse arrays.

The rest of the paper is organized as follows. We provide the system configuration and signal model of the DFRC system with antenna selection network in section 2. The sparse transmit array design under the framework of common array and single beamformer for two functions is investigated in section 3. We examine the common sparse array design associated with different beamformers for two functions in section 4. The design of sparse arrays for radar and communications under the framework of shared aperture is delineated in section 5. Simulation results are provided in section 6. Section 7 summarizes the work of this paper.

2. System configuration and signal model

We consider a joint radar communications platform equipped with a reconfigurable transmit antenna array through an antenna selection network, as shown in Fig. 1. There are K transmit antennas uniformly spaced with an inter-element spacing of d and M front-ends available for waveform transmitting. The antenna selection network comprises K RF switches which connect/disconnect antennas with front-ends. Suppose a transmit array is configured with M selected antennas located at $p_m d, m = 1, \ldots, M$ with $p_m \in \mathbb{N}$ being non-negative integers. The radar receiver, on the other hand, employs an array of N receive antennas with an arbitrary linear configuration. Without loss of generality, a single-element communication receiver is assumed to be located in the far field at direction θ_c, which is known to the transmitter. Let $\Psi_l(t), l = 1, \ldots, L$ be a set of L orthogonal waveforms, each occupying the same bandwidth. In other words, the spectral contents of all waveforms fully overlap in the frequency domain. Each waveform is normalized to have unit power, i.e., $\int_T |\Psi_l(t)|^2 dt = 1$, with T and t denoting the radar pulse duration and the fast time index, respectively. It is further assumed that the orthogonality condition $\int_T \Psi_l(t)\Psi_{l'}^*(t)dt = 0$ is satisfied for $l \neq l'$, where $()^*$ stands for the complex conjugate.

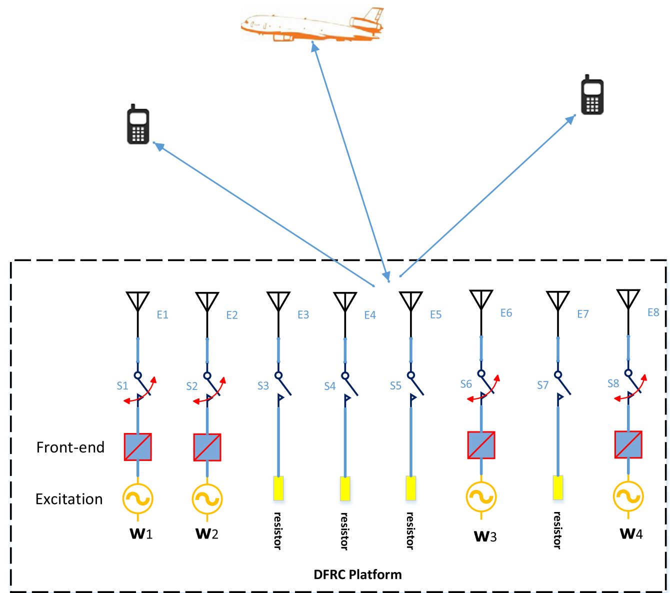

Fig. 1. Joint platform of dual function radar communications with antenna selection network.

Let $\mathbf{s}(t; \tau)$ be the $M \times 1$ baseband transmit signal vector during the τth radar pulse. Assume that Q far-field targets at directions $\theta_q, q = 1, \ldots, Q$, located within the radar main beam, are observed in the background of strong clutter and interference. The $N \times 1$ baseband representation of the signals at the output of the radar receive antenna array is given by,

$$\mathbf{x}(t; \tau) = \sum_{q=1}^{Q} \beta_q(\tau)\mathbf{s}^H(t; \tau)\mathbf{a}(\theta_q)\mathbf{b}(\theta_q) + \mathbf{n}(t; \tau), \tag{1}$$

where $\beta_q(\tau)$ is the qth target reflection coefficient which obeys the Swerling-II target model [15], i.e., they remain constant during the entire pulse duration, but vary independently from pulse to pulse. The vector $\mathbf{a}(\theta)$ is the steering vector of the transmitting array, defined as,

$$\mathbf{a}(\theta) = [e^{jk_0 p_1 d \sin\theta}, \ldots, e^{jk_0 p_M d \sin\theta}]^T, \tag{2}$$

where $k_0 = 2\pi/\lambda$ is the wavenumber. The steering vector of the receiving array, $\mathbf{b}(\theta)$, can be defined in a similar way as $\mathbf{a}(\theta)$. The vector $\mathbf{n}(t; \tau)$ is of $N \times 1$ dimension, representing the unwanted clutter, interference and white noise in the τth radar pulse.