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Radar mutual information and communication channel capacity of integrated radar-communication system using MIMO☆

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Abstract

Integrated radar-communication system based on multiple input and multiple output (MIMO) shares the hardware resource and spectrum to fulfill radar and communication functions, simultaneously. The baseband signal models of the MIMO radar and the integrated radar-communication system are set up. Then, the radar mutual information and the communication channel capacity are derived accordingly. Radar mutual information is used to evaluate the radar performance; communication channel capacity is one of the methods used to measure the communication capability. The influences of signal-to-noise ratio and the number of antennas, on the mutual information and channel capacity are presented through simulations.

Keywords: Radar-based communication; MIMO; Mutual information; Channel capacity

1. Introduction

The concept of radar-based communication was devised because of the necessity for networking radars [1–3] and the thorough exploration and utilization of the radar spectrum owing to spectrum scarcity. To improve the detection and tracking capabilities, it is effective to fuse data from several spatially distributed radars. Therefore, the communication between radars should be reliable and real-time. Meanwhile, it has been observed that the radio spectrum has become a diminishing commodity. It is difficult to integrate a new wireless application with significant bandwidth requirement into the excessively crowded radio spectrum, especially below 3 GHz; spectrum sharing and coexistence among multiple systems would be an appropriate solution.

In the past decades, considerable research has been done on integrated radar-communication systems. Without being equipped with a dedicated communication system, the radar shares the hardware (including the antenna, the RF module etc.) with the communication function. This integration is plausible because of the similarity between the two self-contained radio functionalities. The integrated radar-communication system not only alleviates the problem of 'spectrum scarcity', but also reduces the volume and weight of the loader by reusing the hardware.

Of late, MIMO-radars that have parallels with multiple-input multiple-output (MIMO) systems in wireless communication have generated considerable interest. As Donnet and Longstaff have proposed [4], orthogonal frequency division multiplexing (OFDM) can be applied to the MIMO-radar to achieve both radar and communication capabilities. In the candidate system, the whole band is divided into several groups of subcarriers with each group corresponding to an antenna element. In each subcarrier group, one subcarrier is used for the pilot while the others are used for data symbols. To ensure a robust operation in both the radar and communication functions, each data symbol is spread by a pulse compression code.

In this paper, we do not discuss the details of the integrated radar-communication system based on MIMO because studying what extent of the mutual information and capacity this novel system can achieve is of great interest.

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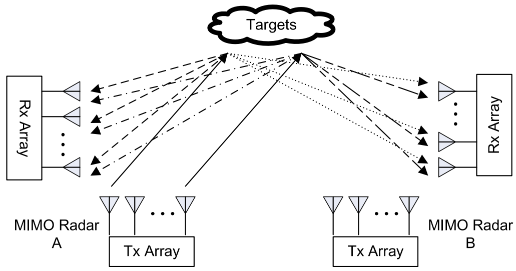

Fig. 1. Application scenario of MIMO-radar based communication.

The outline of the paper is as follows: Section 2 introduces the baseband signal model of the MIMO-radar and the MIMO-radar-based communication. The radar mutual information is derived in Section 3. In Section 4, the channel capacity of the MIMO-radar-based communication is discussed. Simulations are preseted in Section 5, followed by the concluding remarks in Section 6.

2. System model

The application scenario we study in this paper is shown in Fig. 1. Two MIMO-radars cooperate to work. MIMO radar A uses multiple antennas to transmit uncorrelated signals that are modulated by the data symbols. The dual-use signals are reflected by the scatters. Then, the receiving antennas of MIMO-radar A collect the echoes. At the same time, the signals of MIMO radar A arrive at the receiving ends of MIMO radar B and the information carried is extracted by the communication module. If two or more radars transmit simultaneously, their signal can be differentiated by a multi-access technique like the frequency division multi-access (FDMA).

Assume that a far-field target is presented in the illuminating area; there are N_T transmitting antennas and N_R receiving antennas of the MIMO-radar. The discrete-time baseband signal model of the MIMO radar system is considered. Fig. 2 presents the block diagram of the joint MIMO radar and communication system. The baseband data are mapped on to a symbol constellation, for example, phase shift key and the symbols are assigned to the antennas. After radar pulse shaping and D/A conversion, the symbols are converted into analog signals and are sent to an up-converter and a power amplifier before transmission.

Assuming that there are N_S symbols during a pulse with $N_S > N_T$ and $N_S > N_R$, the mth baseband symbol on the ith transmitting antenna is $S_i[m]$. Denoting the baseband signal of the antenna array on the mth snapshot as a $N_T \times 1$ vector, $\mathbf{s}[m] = \left[s_1[m] \cdots s_i[m] \cdots s_{N_T}[m]\right]^T$, $i = 1, \ldots, N_T$ with $[\cdot]^T$ being a matrix transpose.

2.1. Signal model at the MIMO-radar receiver

At the receiver of the MIMO-radar A, the received signal vector of the jth antenna can be written as

$$\mathbf{r}_j = \left[r_j[0] \quad r_j[1] \quad \cdots \quad r_j[N_S-1]\right]^T \tag{1}$$

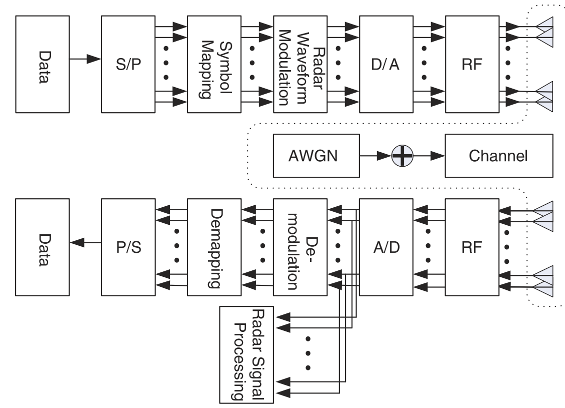

Fig. 2. The block diagram of MIMO radar with communication capability.

and the mth sample is

$$r_j[m] = \sum_{i=1}^{N_T} g_{i,j} s_i[m] + z_j[m] \tag{2}$$

where $g_{i,j}$ is the pulse response between the ith transmitting antenna and the jth receiving antenna; $z_j[m]$ is the clutter received by the jth receiving antenna, including the noise and interference [5]. Assume that the clutter is subject to complex Gaussian distribution with zero mean and variance σ_n^2.

The echo signal can also be written in matrix–vector form

$$\mathbf{r}_j = \mathbf{S}^T \mathbf{g}_j + \mathbf{z}_j \tag{3}$$

where $\mathbf{g}_j = \left[g_{1,j} \cdots g_{N_T,j}\right]^T$, $\mathbf{z}_j = \left[z_j[0] \cdots z_j[N_S-1]\right]^T$, and $\mathbf{S} = [\mathbf{s}[0] \cdots \mathbf{s}[N_S-1]]$.

Collect the receiving echo from all the receiving antennas during a pulse; and construct the received echo matrix Υ with $\{\Upsilon\}_{m,j} = r_j[m]$; define the pulse response matrix as $\mathbf{G}$ with $\{\mathbf{G}\}_{i,j} = g_{i,j}$ and the clutter matrix $\mathbf{Z}$ with $\{\mathbf{Z}\}_{m,j} = z_j[m]$; then the received echo is given by

$$\Upsilon = \mathbf{S}^T \mathbf{G} + \mathbf{Z}. \tag{4}$$

Assume that the clutter matrix $\mathbf{Z}$ is uncorrelated with the transmitted baseband signal $\mathbf{S}$ and the impulse response matrix $\mathbf{G}$. We also assume that the spatial correlation matrix

$$\Sigma_G = E\left\{\mathbf{G}\mathbf{G}^H\right\}$$

is with full rank, where $E\{\cdot\}$ represents the expectation and $[\cdot]^H$ is the conjugate transpose of the matrix.

2.2. Signal of the MIMO-radar-based communication system

As far as the MIMO-radar communication is concerned, the MIMO radar B extracts the communication information from the received signal. The communication signal from A to B experiences the different paths from the echo signal arriving at the receiving end of MIMO radar A. The received signal of MIMO radar B is modeled as

$$\mathbf{Y} = \mathbf{H}\mathbf{S} + \mathbf{N} \tag{5}$$