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Review

Multistatic moving target detection in unknown coloured Gaussian interference

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ABSTRACT

One of the main interferers for a Doppler radar has always been the radar's own signal being reflected off the surroundings. This creates the problem of searching for a target in a coloured noise and interference environment. Traditional space–time adaptive processing (STAP) deals with the problem by using target-free training data to study this environment and build its characteristic covariance matrix. The maximum likelihood estimation detector (MLED) and its generalised counterpart (GMLED) are two reduced-rank STAP algorithms that eliminate the need for training data when mapping the statistics of the background interference. In this work the MLED and GMLED solutions to a multistatic scenario are derived. A hybrid multiple-input multiple-output (MIMO) system where each receiver is a coherent STAP radar has been employed. The focus of the work is the spatial diversity provided by the wide separation of the individual transmitter and receiver platforms. It is proven that this configuration does not affect the constant false alarm rate (CFAR) property of the bistatic radar case. A Gaussian approximation to the statistics of the multistatic algorithms is derived in order to provide a more in-depth analysis. The viability of the theoretical models and their approximations are tested against a numerical simulation.

1. Introduction

Multiple-input multiple-output (MIMO) radar with widely separated antennas has gained an increasing popularity over the past decade. The advantages of using multiple transmitters and receivers are numerous: higher accuracy of target localisation, higher detection rate under a certain false alarm probability, increased spatial and angular diversity, increased resolution [1–8]. All the benefits come at the cost of the additional elements in the system and the higher processing power that is required to obtain and utilise their observations. Apart from deliberate jamming techniques, ground clutter reflections are usually the strongest interferers for Doppler radar. In the MIMO case this is likely to cause an even more significant problem due to the additional probing signals and their reflections present in the system. A well-known limitation of MIMO radar with fast-time orthogonal waveforms is the reduction of the region clear of sidelobes in the total ambiguity function [9,10]. This phenomenon has the potential to degrade the expected theoretical performance of a MIMO detector.

In this paper two single data set (SDS) [11–22,8] MIMO algorithms for target detection in coloured Gaussian clutter are presented. The strength of the algorithms is that they require neither prior knowledge of the spectral support or power of the background interference as in [18] nor access to secondary data as in [23–26] and thus can operate blindly in any environment. Moreover, in a heterogeneous environment there is no secondary data for

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covariance estimation, thus leaving SDS detection as the only viable option.

Each receiver platform in the proposed algorithms operates coherently using the space–time adaptive processing (STAP) technique which boosts radar performance when dealing with ground clutter returns [27]. However, the main focus of this work is not on the coherent processing at each unit but rather on the cooperation between multiple widely spaced transmitters and STAP receivers as in [5]. Thus the maximum likelihood (ML) estimation and detection of a single target in such a multistatic scenario is derived where the whole radar network reaches a joint detection decision.

The proposed algorithms draw multiple low-rank snapshots from the observations of each STAP range gate. This greatly reduces the computational load associated with estimating and inverting the full STAP interference correlation matrix. Further rank-reduction of the algorithm can be achieved through the subspace projection methods proposed in [21,22].

The main contribution of this paper is the derivation of an approximate model for the statistics of the proposed MIMO detection algorithms. Extensive statistical analysis of the bistatic case has been derived and presented in [14,12,15]. As discussed in [23–26], the challenges associated with the theoretical analysis of mono/bistatic target detectors are compounded in multistatic widely spaced MIMO. Even when the individual bistatic paths (or channels) are mutually independent, it is unlikely that the corresponding general multistatic solutions exist in closed form [23–26,20]. In [24,26] a specific closed-form expression is provided for the pdf of a multistatic detector when no target is present in the system, and thus the multistatic probability of false alarm is derived. However, the corresponding derivation for the pdf and detection probability in the presence of targets is a problem of higher complexity that has not been solved. In this paper a methodology is proposed for deriving approximate expressions for probability of false alarm and detection for widely spaced MIMO systems. The methodology is illustrated in detail for the proposed SDS algorithms and could easily Fbe extended to the theoretical analysis of other multistatic target detectors such as [23–26]. The key to obtaining the approximations is the application of the central limit theorem (CLT), or more precisely Lindeberg's condition [28, p. 307], to the summation of bistatic detectors. This approximation enables the link between the radar operational parameters and the probabilities of detection and false alarm to be made.

The performance of the proposed detectors and the validity of the approximate statistical analysis are tested. It has been shown that the proposed detectors exhibit the highly desirable constant false alarm rate (CFAR) property. The two target detection algorithms have been simulated in a scenario involving a mixture of multiple transmit antennas and multiple receive phased arrays. A number of numerical tests have been performed that validate the approximate statistical analysis of the algorithms proposed in this paper. The advantages of the MIMO system with the increasing number of antennas in terms of detection probabilities are shown in the results.

Section 2 of this paper states the problem and assumptions of this work and provides a brief background on the most widely used target detection schemes currently available. Sections 3 and 4 provide the derivations of the two multistatic SDS radar detection algorithms proposed in this paper. Section 5 contains the statistical analysis of the detectors, the proposed Gaussian approximations. Section 6 contains the results of the numerical simulations and a discussion of these results. Section 7 presents the conclusions drawn from the work.

2. Problem formulation and background

This work focuses on widely separated (multistatic) radar detection, sometimes referred to as statistical MIMO radar. Consider a setup consisting of M transmit antennas and N receive arrays that probe an area for the presence of a moving target. Each array consists of P_T closely spaced elements that can perform coherent processing and STAP detection. However, as coherent processing is not the main focus of this work, each array is considered as a single unit, and the aim is to combine the detection capabilities of multiple widely separated such units. For simplicity and without loss of generality the receivers are assumed to be uniform linear arrays (ULA). Therefore each transmit–receive pair here forms a standard bistatic STAP system; this setup is often referred to as a single-input multiple-output (SIMO) coherent radar [29,30]. The term MIMO here is reserved for a multistatic setup (Fig. 1) and refers to non-coherent processing of a number of widely spaced STAP phased array receivers. Each of the ULA units collects K_T slow-time pulses per STAP range gate. A sliding window over the observation samples is used to produce K snapshots containing independent clutter observations, each one consisting of a total of P spatio-temporal samples (Fig. 2 top). The values of K and P can be arbitrary and chosen to suit a specific radar setup and clutter conditions, e.g. in clutter with heavy correlation, the sliding window can skip over samples and trade available data for estimation accuracy, the window can contain more than once slow-time pulse or only a part of a slow time pulse, etc.

Once obtained from the sliding window, the snapshots are vectorised by stacking their columns on top of each other and labelled as $\boldsymbol{x}_{m,n,k},\ k=1\ldots K$. The index $\{m,n\}$ signifies the path between the mth transmitter and the nth receiver. Throughout this work these different bistatic paths will be referred to as "channels." Let the observation vectors be arranged as the columns of the observation matrix $\boldsymbol{X}_{m,n}$ (Fig. 2 bottom). If the complex amplitude of the returned signal in a channel is $\alpha_{m,n}$, the signal model for the observations in each individual bistatic STAP channel is the following:

$$\boldsymbol{X}_{m,n} = \alpha_{m,n}\boldsymbol{s}_{m,n}\boldsymbol{t}_{m,n}^{T} + \boldsymbol{N}_{m,n} \qquad (1)$$

The superscript T indicates the transpose operator. The vectors $\boldsymbol{s}_{m,n}$ and $\boldsymbol{t}_{m,n}$ will be referred to as the spatial steering and the temporal steering vector respectively, and the matrix $\boldsymbol{N}_{m,n}$ is a combined term for the noise and interference in each channel. The spatial steering vector $\boldsymbol{s}_{m,n} \in \mathbb{C}^{P\times 1}$ is the template that the returned signal produces in each observation snapshot. It depends on the Doppler frequency of the