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Target detection based on F-test in passive multistatic radar

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ABSTRACT

Passive multistatic radar is of great interest in both civilian and military applications due to its numerous advantages. We focus on the target detection problem in passive multistatic radar consisting of a non-cooperative illuminator of opportunity, and several spatially separated surveillance receivers. Two F-test based detectors are proposed for target detection in this passive multistatic radar. They both exhibit a constant false alarm rate with respect to noise power. We drive closed-form expressions for the probability of false alarm of the proposed detector for the case of equal noise power in each receivers. Simulation results illustrate that the proposed detectors achieve satisfactory detection performance without requirement of knowledge about noise power.

1. Introduction

Radar system makes a decision on the presence or absence of a target according to the echoes that are reflected back by the target of interest. The so-called active radar illuminates the target of interest by emitting a signal itself. There is another class of radars called passive radars which silently listen for transmissions from other active devices [1–8]. For the last several decades, passive radars using illuminators of opportunity (IOs) have attracted much attention in the international radar field [9–16]. Without transmitter, passive radar is smaller, more portable, and is of lower cost compared to conventional active radar. Particularly, it is virtually undiscoverable to the surveillance receivers and there is also no constraint on the frequency allocation [17]. Besides, it often does not suffer from range and velocity ambiguities [17]. In addition, many IOs are available for this system, such as television [18,19], cell phone base stations [20], digital audio broadcasting [21] and digital video broadcasting-terrestrial sources [22,23].

It is called passive multistatic radar when multiple IOs and/or multiple receivers are used. In [24,25], the passive multistatic radar is also referred to as passive multiple-input multiple-output (MIMO) radar, where multiple IOs and multiple spatially separated receivers are exploited. Generally, the multistatic system performs better than a monostatic passive radar system [26]. With its spatially separated receivers, it is able to collect more data samples over a given observation time, and it is possible for this system to obtain spatial diversity of a target's radar cross section, which leads to potential gains in detection capabilities [27].

Due to non-cooperative nature of IOs, the transmitted signal is generally unknown to a passive receiver. As a result, a conventional matched filter cannot be implemented for target detection. Without requiring knowledge of the signal from the IO, we can employ multiple receivers to collect target echoes in a passive radar system. Note that the transmitted signal from the IO is unknown. However, a correlation exists among the observations collected by spatially separated receivers, which can be used for passive detection. This issue can be seen as detection of a common signal in multiple channels. In [28], a magnitude-squared coherence (MSC) detector is developed for a two-channel signal detection. The MSC is expressed as the magnitude square of the normalized cross-spectral density function. The properties of the MSC is further discussed in [29,30]. In order to deal with the detection of the presence of a common but unknown signal with several channels, a generalized coherence (GC) detector is proposed in [31,32], which is an extension of the MSC. The simple expression of the probability of false alarm (PFA) for the GC detector is given in [33]. It is shown that the GC detector has a constant false alarm rate (CFAR) property against the noise power. In [34], the asymptotic performance of the GC detector is analyzed.

For the detection problem in the passive multistatic radar with multiple receivers, the generalized canonical correlation (GCC) detector is proposed for the case of known noise power in [6]. The test statistic of the GCC is the largest eigenvalue of the covariance matrix (Gram matrix) of the received signal samples. In [27], the authors provide performance analysis of the GCC detector, and at the same time a generalized likelihood ratio test (GLRT) detec-

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tor is developed for the case of unknown noise power. However, direct-path interference is not considered in multiple surveillance channels in [27]. The authors in [35–37] proposed several detection algorithms in the passive multistatic radar, for the case where the direct-path interference in the surveillance channels is non-negligible.

Note that the studies on passive multistatic radars mentioned above do not need reference channels (RCs). In many passive radars, an additional separate channel, referred to as the RC, is usually deployed to collect the emitted signal as a reference for passive detection. The reference signal can be employed to conduct cross-correlation (CC) operation with the signal in surveillance channel for target detection [4][38]. In [25, eq. (21)], the conventional CC detector is extended to deal with the detection problem for the passive MIMO radar with each receiver equipped with a surveillance channel and a RC. It is worth noting that *a priori* knowledge on noise power is required in the CC detector. In particular, the detector in [25, eq. (21)] is the summation of conventional CC detectors with equal weights. In [39], a linear fusion detection framework is proposed, where the global decision in the fusion center is based on a weighted linear combination of the individual test statistics from spatially separated receivers, and the CC detector is employed in individual receiver. A modified deflection coefficient (MDC) is adopted in this framework as the criterion to optimize the weighting coefficients. Recently, a singular value decomposition (SVD) detector is proposed for the passive bistatic radar with noisy reference signal in the case of digital IO [40].

In this paper we consider the target detection problem in a passive multistatic radar consisting of one IO and several spatially separated receivers. The transmitted signal from the IO is collected by a separate channel as a reference. Nevertheless, noise may exist in the reference signal [17,25,38,41]. According to the two-step GLRT principle, we derive two F-test based detectors in the cases of equal and unequal noise powers. The statistical properties of the proposed detectors under null hypothesis are studied, which show that the proposed detectors have a CFAR with respect to noise powers in both surveillance channels and RC. Simulation results demonstrate that the proposed detectors perform much better than the GLRT detector in [27], which benefits from the use of the reference signal. Notably, the proposed detectors without knowledge on the noise power have detection performance close to the CC detector in [25, eq. (21)] which needs to know the noise power. In addition, the mismatch in the noise power significantly deteriorates the performance of the CC detector in [25, eq. (21)], but has no impact on the detection performance of the proposed detectors. This is a great superiority of our proposed detectors over the CC detector in [25, eq. (21)].

The paper is organized as follows. In Section 2, we formulate the detection problem. A detector is proposed for the case of unequal noise powers in Section 3. In Section 4, we design a detector for the case of equal noise powers. In Section 5, simulation results are provided. Section 6 concludes the paper.

Notation: $\|\cdot\|$ is the Frobenius norm, $|\cdot|$ represents the modulus of a complex number, the superscript $(\cdot)^\dagger$ means conjugate transpose, $(\cdot)^{\mathrm{T}}$ denotes transpose, $\mathbf{I}_N$ states the identity matrix of order N, and C_n^m represents the binomial coefficient. The notation $\sim$ means "is distributed as," and $\mathcal{CN}$ denotes a circularly symmetric, complex Gaussian distribution.

2. Problem formulation

We consider a passive multistatic radar system as shown in Fig. 1, which involves one IO, and K spatially separated receivers (called surveillance channels). The geographically dispersed receivers are deployed to collect the echoes of a target of interest due to the illumination of the IO.

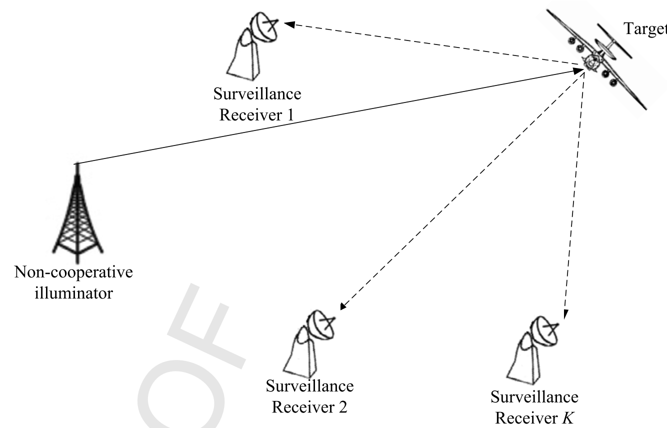

Fig. 1. Configuration of a multistatic passive radar system.

Denoted by $x_k(n)$ the signal received in the kth receiver, which can be expressed as the sum of target echo of interest and noise, i.e.,

$$x_k(n) = a_k s(n - \tau_k) \exp(j2\pi \Omega_k n) + w_k(n), \quad n = 1, 2, ..., N, \quad (1)$$

where $k = 1, 2, \ldots, K$, N is the sample number, a_k is an unknown scaling parameter accounting for the target reflectivity as well as the propagation attenuation in the kth receiver, $s(n)$ denotes the signal emitted by the non-cooperated IO in the discrete time domain, τ_k is the time delay of the target echoes, Ω_k is the normalized Doppler frequency in the kth receiver, and $w_k(n)$ is the circularly symmetric, complex Gaussian noise with zero mean and variance σ_k^2, i.e., $w_k(n) \sim \mathcal{CN}(0, \sigma_k^2)$. Here, σ_k^2 is assumed unknown, but is not necessarily the same for all k. It is supposed that $w_k(n)$ for $n = 1, 2, \ldots, N$ and $k = 1, 2, \ldots, K$ are independently distributed. For passive radar system, the waveforms used by the IOs are no longer under control, and hence the transmitted signal is unknown.

It is well known that the cancellation of direct signal and clutter/multipath echoes is a crucial issue for target detection in passive radar. Some cancellation algorithms have been proposed to deal with this issue [42–45]. Besides, if the IO is chosen in the expectation that the peak of its ambiguity is sufficiently narrow, then the clutter at time delays and frequency shifts other than those postulated can be treated as noise [6]. It is assumed that in each receiver the direct signal from the IO and clutter/multipath echoes have been removed by using a directional antenna or some signal processing techniques. Therefore, these unwanted signals are without of consideration in the signal model above.

It should be pointed out that the time delays and Doppler frequencies in different receivers may be different due to the geographical divergence of the receivers. Here, the signal collected in the first receiver is selected as a reference. The differences in the time delay and Doppler frequency between the kth receiver and this signal can be obtained by a cross-correlation operation between $x_k(n)$ and the signal in the first receiver. Thus, the time delays and Doppler frequencies of the received signals in all other receivers can be compensated. The similar compensation can also be found in [6,27,46].

With the valid hypothesis (H_1) be such that the received data in the receivers contain the target echoes and the alternative hypothesis (H_0) be such that the received data are free of the target echoes. After compensations in the time delay and Doppler frequency, the target detection problem becomes a binary hypothesis test of H_1 against H_0,

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