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Fast communication

On the performance of the cross-correlation detector for passive radar applications

Q1 Jun Liu [a,1], Hongbin Li [a], Braham Himed [b]

[a] Department of Electrical and Computer Engineering, Stevens Institute of Technology, Hoboken, NJ 07030, USA

Q2 [b] AFRL/RYMD, 2241 Avionics Circle, Bldg 620, Dayton, OH 45433, USA

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ABSTRACT

For passive radar target detection, the cross-correlation (CC) based detector is a popular method, which cross-correlates the signal received in a reference channel (RC) and the signal in a surveillance channel (SC). The CC is simple to implement and resembles the clairvoyant matched filter (MF) in idealistic conditions. However, there is limited understanding on its performance in passive sensing environments with non-negligible noise in the RC and direct-path interference in the SC. This paper examines such effects on the detection performance of the CC detector. Closed-form expressions for the probabilities of false alarm and detection of the CC detector are derived, which are employed to quantify to what extent the noise in the RC and the direct-path interference in the SC should be suppressed in order to achieve a targeted performance loss of the CC detector relative to the MF. These results are useful in designing practical CC solutions for passive radar sensing.

1. Introduction

A passive radar system can detect and track a target of interest by exploiting non-cooperative illuminators of opportunity (IOs), which is of great interest in both civilian and military scenarios due to a number of advantages such as low cost, spatial diversity and availability of many existing IOs [1–8]. In passive radars, the locations and waveforms used by the IOs are no longer under control. As such, passive radar systems often require an additional separate channel, referred to as the reference channel (RC), to measure the transmitted signal from the IO to serve as a reference. One of the most popular detection strategies in passive radar is to conduct delay-Doppler cross-correlation (CC) between the data received in the RC and surveillance channel (SC) [1,9–11], which mimics matched-filter (MF) processing in conventional active sensing systems where the transmitted signal is cross-correlated with the received signal. The principal advantages of the CC lie in its simplicity of implementation, and requirement of no prior knowledge of the transmitted waveform.

It is worth noting that under some ideal assumptions, the CC attains the detection performance of the optimum MF which maximizes the output signal-to-noise ratio (SNR). Specifically, the assumptions are (1) the RC is noiseless; and (2) the direct-path from the IO is absent from the SC. In practice, there inevitably exists noise in the RC [12]. Moreover, commercial IOs such as radios and TV stations typically employ isotropic antennas to cover a wide area. Without any pre-processing, the direct-path signal seen in the SC is typically stronger than the target signal by several orders of magnitude [13]. It is therefore necessary to apply some direct-path signal cancellation techniques in the SC before target detection, e.g., by using an adaptive array with a spatial null formed in the IO source direction. Due to array size limitation, the null may not provide adequate direct-path cancellation. As a result,

E-mail addresses: jun_liu_math@hotmail.com (J. Liu), hongbin.li@stevens.edu (H. Li), braham.himed@wpafb.af.mil (B. Himed).

[1] Now with the National Laboratory of Radar Signal Processing, Xidian University, Xi'an 710071, China.

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the SC may still see significant direct-path signal residual relative to the target signal strength. Apparently, the existence of the noise in the RC and the direct-path interference in the SC will deteriorate the CC detection performance. However, their impact on the CC detector has not been systematically studied in the open literature. It is unclear to what extent the noise in the RC and the direct-path interference in the SC should be suppressed in order to ensure an acceptable performance loss of the CC with respect to the optimal MF.

The goal of this work is to analyze the CC detector for passive sensing. Let $\mathrm{SNR_r}$ denotes the SNR in the RC, while the $\mathrm{INR_s}$ denotes the direct-path interference-to-noise in the SC. Our main contribution here is to quantitatively analyze the effects of the $\mathrm{SNR_r}$ and $\mathrm{INR_s}$ on the detection performance of the CC detector. To this end, we first derive closed-form expressions for the probability of false alarm (PFA) and probability of detection (PD) of the CC detector by taking into consideration the noise in the RC and the direct-path interference in the SC. Based on these theoretical results, we obtain simple expressions for the $\mathrm{SNR_r}$ and $\mathrm{INR_s}$ required by the CC detector to achieve a targeted performance loss with respect to the MF detector. Interestingly, it is found that there exists an upper bound for the $\mathrm{INR_s}$ above which it is impossible for the CC detector to achieve the targeted performance loss, no matter how clean the reference signal is. In addition, there exists a lower bound for the $\mathrm{SNR_r}$, below which it is impossible to ensure the targeted performance of the CC detector. Monte Carlo (MC) simulations are provided to confirm the theoretical analysis.

2. Signal model

Consider a passive bistatic radar system as shown in Fig. 1. Denote by $x_s(n)$ the signal received in the SC, which involves noise, a direct-path signal (i.e., interference) from the IO, and the echo of a target of interest, i.e.,

$$x_s(n) = \gamma p(n) + \alpha p(n-\tau)\exp(j\Omega_d n) + w(n), \tag{1}$$

where $p(n)$ is the signal transmitted by the non-cooperative IO, γ is a scaling parameter accounting for the channel propagation effects of the direct path from the IO to the receive antenna in the SC, τ is the propagation delay of the target return relative to the direct path, α is a scaling parameter accounting for the target reflectivity as well as the channel propagation effects, Ω_d is a normalized Doppler frequency, and $w(n)$ denotes noise modeled as identically and independently distributed (i.i.d.) circular complex Gaussian with zero mean and variance σ_w^2, i.e., $w(n) \sim \mathcal{CN}(0, \sigma_w^2)$. Unlike [9,14], where the direct-path interference is assumed to be fully suppressed, we consider a more realistic scenario with direct-path residual due to imperfect interference mitigation.

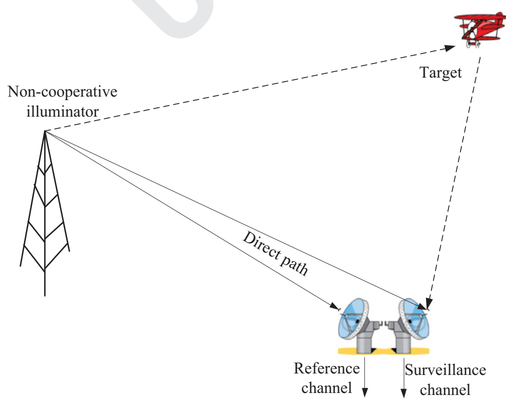

Fig. 1. Configuration of a passive radar system.

The RC usually employs a directional antenna pointing toward the IO, and its received signal can be written as

$$x_r(n) = \beta p(n) + v(n), \tag{2}$$

where β is a scaling parameter accounting for the channel propagation effects from the IO to the receive antenna in the RC, and $v(n)$ is i.i.d. circular complex Gaussian noise with zero mean and variance σ_v^2, i.e., $v(n) \sim \mathcal{CN}(0, \sigma_v^2)$. It is reasonable to assume that $v(n)$ and $w(n)$ are independent.

Let the null hypothesis (H_0) be such that the data in the SC is free of target echoes whereas the alternative hypothesis (H_1) be the opposite. Hence, the passive detection problem can be formulated in terms of the following binary hypothesis test:

$$\begin{cases} H_0: \begin{cases} x_r(n) = \beta p(n) + v(n), \\ x_s(n) = \gamma p(n) + w(n), \end{cases} \\ H_1: \begin{cases} x_r(n) = \beta p(n) + v(n), \\ x_s(n) = \gamma p(n) + \alpha p(n-\tau)\exp(j\Omega_d n) + w(n). \end{cases} \end{cases} \tag{3}$$

3. Analysis of the CC detector

A popular solution for the above passive detection problem is the CC detector given by

$$T_{\mathrm{CC}} = |\overline{T}|^2 = \left| \sum_{n=0}^{N-1} T_n \right|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda, \tag{4}$$

where $T_n = x_s^*(n) x_r(n-\tau)\exp(j\Omega_d n)$, N is integration time, λ is the detection threshold, $|\cdot|$ represents the modulus of a complex number, and the superscript $(\cdot)^*$ is the conjugate operation. In other words, the RC signal $x_r(n)$ is delay- and Doppler-compensated, before it is cross-correlated with the SC signal $x_s(n)$. This resembles the MF in active radar, except that the latter uses the noiseless waveform $p(n)$ instead of $x_r(n)$ for processing. The delay τ and Doppler Ω_d are generally unknown in practice. A standard approach for CC or MF implementation is to divide the uncertainty region of the target delay and Doppler frequency into small cells and the test is run on each cell with a given delay and Doppler frequency.

It is well-known that the MF is the optimum detector in active radar. The MF performance can be thought of as an upper bound for passive detection when the RC noise and SC direct-path interference vanish. An important question is, how far is the CC detector away from the MF bound in typical passive radar environments where the noise in the RC and the direct-path interference in the SC cannot be neglected? To the best of our knowledge, the problem has not be addressed in the open literature.

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