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Single-platform passive emitter localization with bearing and Doppler-shift measurements using pseudolinear estimation techniques

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ABSTRACT

The maximum-likelihood (ML) estimator for single-platform Doppler-bearing emitter localization does not admit a closed-form solution and must be implemented using computationally demanding iterative numerical search algorithms. The iterative ML solution is vulnerable to convergence problems due to the nonconvex nature of the ML cost function and the threshold effect. To alleviate these problems, this paper presents new closed-form Doppler-bearing emitter localization algorithms in the 2D-plane based on pseudolinear estimation techniques; namely, the pseudolinear estimator (PLE), the bias-compensated PLE and the weighted instrumental variable (WIV) estimator. The bias-compensated PLE aims to remove the instantaneous estimation bias inherent in the PLE. The WIV estimator incorporates the bias-compensated PLE to achieve an asymptotically unbiased estimate of the emitter position. The proposed WIV estimator is proved to be asymptotically efficient for sufficiently small measurement noise. Through simulation examples its performance is shown to be almost identical to that of the ML estimator, exhibiting small bias and approaching the Cramer–Rao lower bound at moderate noise levels.

1. Introduction

Passive emitter localization has found a variety of applications in both civilian and military domains such as user and asset localization, satellite geolocation, search and rescue, radar and sonar [1–11]. The objective of passive emitter localization is to estimate the location of a stationary emitter by utilizing passive measurements collected by a moving sensor or a number of spatially distributed sensors at fixed locations. The passive sensor measurements usually include a combination of angle-of-arrival (bearing angle), time-difference-of-arrival (TDOA) and Doppler-frequency-shift data. In this paper, we focus our attention on the problem of passive Doppler-bearing emitter localization in the 2D-plane using a single moving sensor platform.

Stationary emitter localization using a single moving sensor with bearing-only measurements or Doppler-only measurements has been well investigated in the literature (see e.g., [5–9] and the references therein). It was shown in [7] that the bearing-only method significantly differs from the Doppler-only method and the substantial differences between those two methods lead to a significant improvement in

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localization performance if both bearing and Doppler measurements are utilized in the localization process. The maximum likelihood (ML) estimator for the Doppler-bearing emitter localization was presented in [7]. Despite the fact that the ML estimator is asymptotically unbiased and efficient, it does not have a closed-form solution and is often implemented as a computationally demanding iterative numerical search algorithm. The iterative ML solution is known to be vulnerable to convergence problems because of the non-convex nature of the ML cost function [1–3,12–17]. In particular, the iterative ML algorithms require the use of an initial guess that must be sufficiently close to the actual emitter position in order to avoid divergence. In addition, the ML algorithms suffer from the threshold effect leading to divergence problems in the presence of large measurement noise. An analysis of the convergence properties of iterative algorithms can be found in [18].

The pseudolinear estimator (PLE)—a linear least squares estimator with closed-form solution—is an attractive alternative to alleviate the computational complexity and convergence problems of the iterative ML estimator [1–3,12–17]. The PLE for bearing-only emitter localization was proposed in [8,19]. Despite its stability and low computational complexity, the PLE suffers from severe bias problems due to the correlation between the measurement matrix and the pseudolinear noise vector [8,14,19–21]. In [8], the asymptotic bias of the bearing-only PLE was characterized and a non-iterative weighted instrumental variable (WIV) estimator was proposed to overcome the PLE bias problem. The PLE approach was also applied to Doppler-only emitter localization in [9]. However, the linearization of the nonlinear Doppler equation in [9] requires the sensor to follow a particular trajectory with non-maneuvering segments. In addition, the bias problem associated with the PLE was not studied analytically. In the broader context of target localization and tracking using different sensor types, several closed-form pseudolinear algorithms have been proposed in the literature; see, e.g., [12] for TDOA localization, [13] for time-of-arrival (TOA) localization, [15] for multistatic TOA localization, [14,16] for bearing-only target motion analysis (bearing-only TMA), [3] for hybrid TDOA and bearing localization, and [17] for hybrid TDOA and frequency-difference-of-arrival localization.

In contrast to the bearing-only and Doppler-only emitter localization problems, to the best of our knowledge, no closed-form solution has been proposed to date for the Doppler-bearing emitter localization problem. In [21–24] closed-form solutions were presented for the Doppler-bearing target motion analysis (DB-TMA) problem, in which the kinematic parameters (position and velocity) of a *moving* target are estimated from bearing and Doppler measurements obtained by a single moving sensor. However, the linearization approach applied to the nonlinear Doppler frequency equation in the DB-TMA problem cannot be readily extended to the Doppler-bearing emitter localization problem. The predominant reason for this is that, while the linearization of the Doppler equation aims to transform the Doppler information into target velocity information in the DB-TMA problem, for a stationary emitter it should instead be transformed into emitter position information, which is not trivial. The closed-form DB-TMA algorithms can still be applied to the stationary emitter localization problem by letting them estimate the emitter velocity which is known to be zero. However, this not only increases the number of unknowns unnecessarily, but also degrades the localization performance as demonstrated in Section 8.

The main objective of the paper is to develop closed-form Doppler-bearing emitter localization estimators with low computational complexity and high performance advantages. The paper first presents a new Doppler-bearing PLE in which a new method of linearization for the nonlinear Doppler frequency shift equation is proposed. The proposed Doppler linearization, as different from [21–24], transforms the Doppler information into emitter position information. In addition, it does not require the sensor to follow non-maneuvering trajectory paths as in [9]. In common with the bearing-only PLE, a major disadvantage of the proposed Doppler-bearing PLE is its asymptotically nonvanishing bias caused by the correlation between the measurement matrix and the pseudolinear noise vector. To overcome this bias problem, the asymptotic bias of the proposed Doppler-bearing PLE is analysed and a bias-compensated Doppler-bearing PLE is developed based on instantaneous bias estimation for the PLE. The asymptotically unbiased Doppler-bearing WIV estimator is developed with the instrumental variable matrix and weighting matrix constructed from the bias-compensated PLE. The proposed Doppler-bearing WIV estimator is also analytically shown to be asymptotically efficient, i.e., achieving the Cramér–Rao lower bound (CRLB), at moderately low measurement noise levels.

The paper is organized as follows. Section 2 introduces the single-platform Doppler-bearing emitter localization problem. An overview of the ML estimator and the expression of CRLB are provided in Section 3. Section 4 presents the proposed Doppler-bearing PLE with the new linearization of Doppler frequency shift equation. In Section 5, an asymptotic bias analysis for the Doppler-bearing PLE is provided and the bias-compensated Doppler-bearing PLE is developed. Section 6 develops the asymptotically unbiased Doppler-bearing WIV estimator and presents an analysis for its asymptotic efficiency. The computational requirements of the estimators are analysed in Section 7. Comparative simulation studies are presented in Section 8 and conclusions are drawn in Section 9.

2. Problem statement and assumptions

The problem of two-dimensional (2-D) single-platform passive emitter localization using bearing (azimuth) angle and Doppler frequency shift measurements is depicted in Fig. 1, where $\mathbf{p}=[p_x, p_y]^T$ is the unknown position of a stationary emitter, $\mathbf{r}_k=[r_{x,k}, r_{y,k}]^T$ is the sensor position and $\mathbf{v}_k=[v_{x,k}, v_{y,k}]^T$ is the sensor velocity at time instant $k \in \{1, \ldots, N\}$. Here the superscript T denotes the matrix transpose operator. Note that the 2-D scenario is commonly used in the literature as an approximation of the actual three-dimensional geometry for low elevation-angle emitters. The objective of emitter localization is to