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Direct target localization with an active radar network ☆

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ABSTRACT

Target localization is commonly achieved by a decentralized two-step approach. Recently, studies proposed new promising centralized one-step algorithm. Using an active radar network, we study here the detection and estimation performances of a (one step, Direct Position Determination based) direct target position and velocity determination algorithm. Numerical results show the improvement of the proposed algorithm compared to a classical two-step method. The proposed method is also experimentally verified on real data.

1. Introduction

Target localization in distributed sensor networks has always received great attention by the signal processing community over the last decades. This problem arises in such applications as radar, sonar, communications, etc.

Traditionally, target localization relies on two steps. Intermediate parameters, often called measurements (for example, times-of-arrival (TOAs) or Doppler as considered in this article) are first estimated on each node separately. A vast literature exists on such techniques (see [1] and the references therein). In a second step, the position (or velocity) is deduced using a localization algorithm (some examples of such algorithms can be found in [2–4]) at a central processing unit (CPU) exploiting all transmitted intermediate parameters (measurements) such as the range extracted from the measured signals at each node. The nonlinear (possibly weighted) least squares estimator is often used for localization.

While both steps of the two-step approach might be optimal given their input, the association of the two might still be suboptimal. Indeed, the common decentralized strategy suffers from limitations and is clearly suboptimal [5–7]. First, solving the problem by means of a multiple steps strategy is often suboptimal [8] since the first step does not take into account the fact that the received signals at each node come from the same targets, it results in performance degradation and data association issues (one has to identify among all available measurements of all nodes, which subset of measurements characterizes each target). If the second step is a weighted least squares, the study [8] shows that with a proper choice of the weighting matrix, the two-step approach can be asymptotically equivalent to a one-step approach. But unfortunately, this optimal weighting matrix, which is the covariance of the estimator involved in the first step, sometimes depends on the true (and thus unknown) value of the sought parameters. These are the reasons why an approach based on a one-step strategy, gathering the received signals of all

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available stations, that directly provides the target location, appears to be of great interest.

Such direct “one step” procedure estimates the position directly from all the received raw signals collected by all sensor nodes. It has been recently used in a number of studies [5,6,9–19]. Studies [15,16] deal with a passive direction of arrival based localization scheme whereas [13] deals with GNSS signals. Studies [5,6] consider the case of moving arrays and fixed targets, assuming that the signals are Gaussian and that there are no complex gains between the arrays. Moving array with intermittent emission is also studied in [14]. In [18], Direct Position Determination (DPD) targets with angular spread is investigated. The study [9] considered the case of unknown deterministic signal (passive radar). Detection performances of the one-step approach have also been studied under a passive signal case in [20,17,21]. Recent studies in Multiple-Input-Multiple-Output (MIMO) radar focus either on position [11,12,19] or velocity [10] estimation for algorithms [12] as well as estimation performance evaluation [10–12] based on Cramér–Rao bound (CRB) evaluation. Study [19] interestingly solves the multiple target problem directly thanks to ℓ_1 norm minimization, but griding error and obtaining the analytic expressions of the probability of detection and false alarm in such context remain, to our best knowledge, challenges that have to be faced by such an approach.

To the best of our knowledge, the simultaneous estimation of position and velocity of moving targets using an active radar network, with any kind of waveforms, in a one-step approach, has not been yet studied. To this end, following the DPD [12] approach, we study an algorithm, called direct target localization (DTL), that allows the simultaneous estimation of the target position and velocity. Detection and estimation performances of this algorithm are studied and compared to a classical two-step method in the presence of the widespread Swerling 0, I and III target fluctuation models (see [22] for more details). As far as we know, detection performance of one-step approaches was only investigated in [20,17,21] for the passive signal case. The studied detector, part of the suggested algorithm, is a kind of energy detector (contrary to the passive detectors [20,21]). The detector in [17] is similar in structure but was only investigated for Swerling I (Gaussian) target fluctuation model. For this kind of detector, literature exists in MIMO radars that provide closed-form expression that can be used in our case to characterize the detection performances [23–25] (see [26] for the general result) under Swerling I model. Under Swerling III model, to the best of our knowledge, the closest state of the art [27,28] provides the detection performance of an energy detector under a particular case, that corresponds for us to targets with the same Signal-to-Noise Ratio on all nodes. Extending [26], a new result is provided that allows the characterization of the detection performances under Swerling III model for a more general case where the SNR can be different on each node. The estimation performance study is conducted via CRB evaluation.The provided CRB expression is more compact than [12] (when extended to joint position and velocity estimation), what is of computational interest when target fluctuations have to be taken into account, since Monte-Carlo based average of the CRB is then needed in order to compute the corresponding modified CRB [29]. Finally, we propose an implementation of the DTL onto experimental data acquired in a realistic scenario.

The outline of the paper is as follows: we formalize the problem and introduce the signal model in Section 2. Section 3 provides the description of the proposed DTL algorithm. Section 4 provides the detection performance study and Section 5 the expression of the corresponding CRB. Finally, Section 6 provides a comparison of the proposed technique to a classical two-step approach and to the provided CRB. The proposed method is also tested on real data.

In the paper, we adopted the following notation: $(.)^T$ and $(.)^H$ denote transpose and Hermitian transpose, respectively; bold lower case letters denote vectors, whereas bold upper case letters denote matrices; $\mathrm{diag}(\mathbf{U}_1,..,\mathbf{U}_L)$ is a block-diagonal matrix whose diagonal elements are $\mathbf{U}_1,..,\mathbf{U}_L$; $\odot$ and $\otimes$ denote the Hadamard (element-wise) and Kronecker product, respectively; $Re(.)$ and $Im(.)$ denote real and imaginary parts of a complex element, respectively; “$\sim$” stands for “distributed as”; $\mathbf{x}\sim\mathcal{N}(\mathbf{m},\mathbf{C})$ means that the vector $\mathbf{x}$ is Gaussian distributed, with mean $\mathbf{m}$ and covariance $\mathbf{C}$; $\mathbf{x}\sim\mathcal{CN}(\mathbf{m},\mathbf{C})$ means that the vector $\mathbf{x}$ is complex circular Gaussian distributed, with mean $\mathbf{m}$ and covariance $\mathbf{C}$; $E[.]$ stands for the mathematical expectation.

2. Model of the signal and problem formulation

When cheap omni-directional radar sensors are used, azimuth and elevation are unknown. This is why several radar nodes are needed to achieve the localization. Let us assume that we have L omni-directional (or at least with a very wide beam) radars, each one emitting a known signal $s_l(t), l\in[1,L]$. All radar node signals are operating in non-overlapping frequency bandwidth so that there is no interference between them: the system consists of fully monostatic nodes, as illustrated by Fig. 1. The signal reflected on Q targets and received on node l is then under the classical narrowband approximation

$$r_l(t)=\sum_{q=1}^{Q}\rho_{l,q}s_l(t-\tau_l(\mathbf{p}_q))e^{j2\pi f_0\nu_l(\mathbf{p}_q,\mathbf{v}_q)t}+n_l(t), \tag{1}$$

where f_0 is the carrier frequency and where we denoted the round trip time delay for the l-th radar signal scattered by the q-th target

$$\tau_l\left(\mathbf{p}_q\right)=\frac{2\,\|\mathbf{p}_q-\mathbf{p}_l\|}{c}, \tag{2}$$

where $\mathbf{p}_l$ is the position of the node l and $\mathbf{p}_q$ is the $D\times 1$ position vector of the target q. The Doppler shift is

$$\nu_l\left(\mathbf{p}_q,\mathbf{v}_q\right)=-2\frac{\mathbf{v}_q^T}{c}\frac{(\mathbf{p}_q-\mathbf{p}_l)}{\|\mathbf{p}_q-\mathbf{p}_l\|}, \tag{3}$$

where $\mathbf{v}_q$ is the $D\times 1$ velocity vector of the target q. Since the radar is static and we consider slow moving targets (with respect to the speed of light c), then there is no effect of the target velocity (time compression) to the delayed

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