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PHD filter based track-before-detect for MIMO radars

Biruk K. Habtemariam*, R. Tharmarasa, T. Kirubarajan

ECE Department, McMaster University, Hamilton, Ontario, Canada L8S 4K1

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ABSTRACT

In this paper a Probability Hypothesis Density (PHD) filter based track-before-detect (TBD) algorithm is proposed for Multiple-Input-Multiple-Output (MIMO) radars. The PHD filter, which propagates only the first-order statistical moment of the full target posterior, is a computationally efficient solution to multitarget tracking problems with varying number of targets. The proposed algorithm avoids any assumption on the maximum number of targets as a result of estimating the number of targets together with target states. With widely separated transmitter and receiver pairs, the algorithm utilizes the Radar Cross Section (RCS) diversity as a result of target illumination from ideally uncorrelated aspects. Furthermore, a multiple sensor TBD is proposed in order to process the received signals from different transmitter-receiver pairs in the MIMO radar system. In this model, the target observability to the sensor as a result of target RCS diversity is taken in to consideration in the likelihood calculation. In order to quantify the performance of the proposed algorithm, the Posterior Cramer–Rao Lower Bound (PCRLB) for widely separated MIMO radars is also derived. Simulation results show that the new algorithm meets the PCRLB and provides better results compared with standard Maximum Likelihood (ML) based localizations.

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1. Introduction

Track-Before-Detect (TBD) algorithms simultaneously detect and track targets without thresholding the measurement signals [2,29,34]. Standard association based tracking algorithms use a Detect-Before-Track (DBT) approach that performs clustering and filtering based on the detections [5,7]. Detections are formed by applying the thresholds on the output of the receiver using, for example, a Constant-false-alarm-ratio (CFAR). In terms of computational load and complexity, detection based tracking methods are better in scenarios where the target originated measurements are strong compared to the background clutter. However, in low Signal-to-Noise-Ratio (SNR) tracking scenarios the amplitudes of the signals reflected from the target might not be strong enough to be above the detection threshold. This problem may be more acute with widely separated sensor networks like Multiple-Input-Multiple-Output (MIMO) radars, where a target's visibility to a specific transmitter–receiver pair might be degraded due to its orientation with respect to that pair. In such cases, one possible solution is to decrease the level of the threshold in order to detect low SNR targets. But this will result in a high number of false alarms in the measurement space. The high density of false alarms caused by the clutter in the regions of interest leads to difficulties in measurement-to-track associations in standard tracking algorithms. A TBD approach, in contrast, uses the entire output of the raw signal processing stage as the input with the objective of retaining as much information as possible. Hence, the TBD approach provides tracks and detection results simultaneously in spite of excessive false alarms by exploiting the consistency of target originated measurements.

TBD is a well-studied tracking approach. For example, a TBD implementation using the Hough transform is presented in [11]. This approach integrates the data over

* Corresponding author.
E-mail address: habtembk@mcmaster.ca (B.K. Habtemariam).

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several time frames along all possible paths. TBD techniques such as dynamic programming algorithm [2,4] and maximum likelihood estimation [34] are computationally demanding due to the processing of several scans of received signal. A recursive TBD algorithm, which uses particle filtering was presented in [29] and a recursive TBD with target amplitude fluctuations, was derived in [28]. An extension of particle based TBD algorithms for multitarget tracking is given in [9]. In this approach a modeling setup is used for varying number of targets where a multiple model Sequential Monte Carlo based TBD approach is used to solve the problem conditioned on the model, which depends on the number of targets. The main limitation of this algorithm is that it can only deal with a limited number of targets and it was assumed that the maximum possible number of targets is a priori. Also, the algorithm does not consider the case of multiple sensors.

A Probability Hypothesis Density (PHD) filter [24–26,31] for recursive TBD algorithm is proposed in this paper. Amplitude detection information integration into the PHD filter and cardinalized PHD (CPHD) filter is presented in [12,38]. In a multitarget environment where both the states and the number of targets vary as a result of new born targets and disappearing ones, the PHD filter can effectively perform the state estimation together with estimating the number of targets in each time step. PHD filters propagate only the first-order statistical moment of the full target posterior, from which the number of targets in the surveillance region is estimated by the integral of the PHD or the total weight of the samples [25]. In this paper, the Sequential Monte Carlo (SMC) [35,36] approach is chosen for the implementation of the PHD filter. Alternatively, the Gaussian Mixture (GM) approach can be used as well [37]. The PHD filter proposed in this paper for TBD framework does not require a modeling setup to handle the varying number of targets and is computationally efficient when the number of targets is high. Instead, target birth, continuity and disappearance probabilities are used in the filtering process. Also, the proposed algorithm does not have a restriction on the maximum number of possible targets in the scenario.

Recently introduced MIMO radars [8,13,21,22] employ multiple transmit waveforms and jointly process signals received from multiple receive antennas. Inherited from MIMO communication systems, MIMO radars overcome the effect of fading in the wireless channel by transmitting redundant streams of data from several uncorrelated transmitters [14]. MIMO systems have more degrees of freedom due to multiple transmits. Furthermore, MIMO radar employs multiple independent (orthogonal) waveforms that can be chosen freely to illuminate the target from ideally uncorrelated aspects. In addition, waveform diversity enhances the separation between clutter and target returns. Two different configurations are possible for the MIMO radar: with antennas co-located or widely distributed over an area. With co-located antennas, MIMO radars improve parameter identifiability and enhance flexibility for transmit beam pattern design [22,23]. Flexibility in transmit beam pattern design makes it possible to apply waveform optimization for better performance. With widely separated antennas, MIMO radars have the ability to improve radar performance by exploiting Radar Cross Section (RCS) diversity, handle slow moving targets by exploiting Doppler estimates from multiple directions, and support high resolution for target localization [14,17,21]. For the localization of multiple targets, the estimation of arrival angles and the corresponding fading matrix can be performed using the Maximum Likelihood (ML) method [22]. The significance of transmit diversity on the error of direction finding techniques has been explored theoretically based on the average Cramer–Rao Lower Bound (CRLB) [16]. Most of the work done so far on MIMO radars focuses on waveform design, signal processing and target localization with MIMO radars while little attention has been paid to tracking algorithm development.

Tracking multiple targets with MIMO radars with widely separated sensors is a nonlinear problem. The information about target states that can be extracted from MIMO radar signal model in the given scenario is amplitude measurement of each range bin for each M to N transmitter-receiver combination. Thus the target state signatures will be mapped to the received amplitude measurement in each range bin by a nonlinear bi-static range only measurement. Depending on a target's orientation to the sensors, the received amplitude may vary from one transmitter-to-receiver path to another. In addition, because of low SNR, the received signal may be very weak. In such a scenario, classical tracking techniques based on the thresholding of the measurement data may result in poor performance.

In this paper all the raw signal measurements are processed together without applying thresholding, and a TBD approach that allows simultaneous detection and tracking is developed. The contribution of this paper is two-fold: (i) A PHD filter based TBD algorithm is proposed and applied to MIMO radars. Furthermore, in order to accommodate the multisensor architecture of a MIMO radar system a multisensor TBD, which computes the centralized likelihood of target existence for the possible transmitter to receiver path, is presented. As a result, the sensor with better observability to the target will gain more weight in the resulting likelihood calculations; (ii) The Posterior Cramer–Rao Lower Bound (PCRLB) for the estimation error is derived for the case of widely separated MIMO radars, to provide a benchmark for testing the proposed algorithm performance.

The remainder of the paper is structured as follows. In Section 2 the widely separated MIMO radar signal model, target dynamics and measurement models are discussed. Section 3 discusses the multitarget TBD with particle filter. Multisensor TBD is also proposed in this section. A track before detect PHD filter is presented in Section 4. In Section 5 the PCRLB for widely separated MIMO radar is derived. Simulation results are discussed in Section 6. Finally, the paper concludes with a summary and suggestions for further research.

2. MIMO radar signal model

A MIMO radar system with an array of M antennas at the transmitter and an array of N antennas at the receiver is assumed. In contrast to the commonly used point

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