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单频 MIMO PCL 中的数据关联改进

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摘　要：通过合并多输入多输出(MIMO)和无源相干定位(PCL)雷达的两种思想，可以同时获取近期开始研究的这两种雷达的优势。虽然在发射机和接收机中使用多个天线，即采用机会照射可提供目标的空间分集，但最重要的一点是雷达可对截击机进行隐蔽探测。但是，当单频网络(SFN)发射机用作非协作发射机时也会产生一些问题。这种情况下，在接收机中无法辨别出多发射机探测多目标返回的信号。因此，为了获取 MIMO 雷达的分集增益和定位目标，有必要开发一项技术将接收机中的每个回波分配至发射机和目标。在以前的工作中已经提出这一技术，该文通过智能化算法改进来提升这项技术。

关键词：多输入多输出(MIMO)；无源相干定位(PCL)；数据关联；无源雷达

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Improvement of Data Association in a Single Frequency MIMO PCL

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Abstract: By combining the two ideas of MIMO(Multiple Input Multiple Output) and PCL(Passive Coherent Location) in radar, one can achieve the advantages of both recently developed techniques simultaneously. While using multiple antennas in transmitter and receiver provides a spatial diversity of target, using the illuminators of opportunity, most importantly, makes the radar covert to the interceptors. But the problem arises when the transmitters of a single frequency network(SFN) are used as the noncooperative transmitters. In this case the signals of multiple transmitters from multiple targets cannot be distinguished in the receiver. Therefore, to obtain the diversity gain of the MIMO radar and localize the target, it is necessary to develop a technique to assign each echo in the receiver to a transmitter and a target. In previous works we have proposed such technique. Here, we improve it by a smart modification in the algorithm.

Key words: multiple input multiple output(MIMO); passive coherent location(PCL); data association; passive radar

1　Introduction

1.1　Passive Radar

Recently passive radar has attracted much attention due to its advantages over the active radar. Low-cost passive radar which requires no frequency allocation, is a good solution for increased surveillance at a lower cost[1]. In addition, its undetectability as a covert radar significantly increases its importance in military applications. The feasibility of different kinds of opportunistic signals for the passive radar application has been investigated before, such as FM[2], analogue TV[3-4], DTV (Digital TV)[5-7], satellite systems[8], and GSM[9-10]. New digital signals, like Digital Audio/Video Broadcast(DAB/DVB), are also excellent candidates[11-12], as they are widely available and can be easily decoded.

In traditional radar systems, the target's range is defined by comparing the time of the

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transmitted and received pulses. However such information is not directly available in the case of the passive radar receiver. Instead, two antennas are used: one for receiving directly the signal from its main source without the reflections from targets(reference antenna) and the other for collecting the reflections from targets in the environment(target antenna). Figure 1 depicts the overall structure of the passive radar.

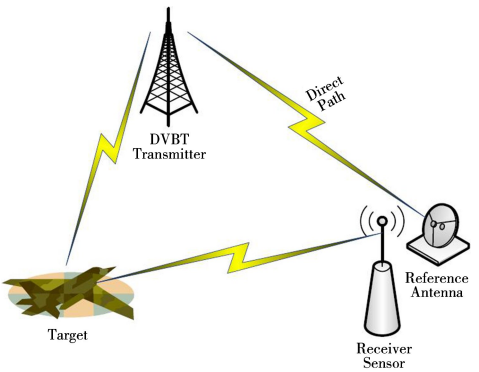

Fig. 1 Structure of the passive radar

Detection is done through computation of CAF(Cross Ambiguity Function) computed according to (1). It is a criterion of how much correlation exists between the reference and the target signal. A given CAF's peak in a range-Doppler cell is a representative of a target in that range and Doppler frequency.

$$|\chi(\tau,v)^2| = |\frac{1}{N}\sum_{n=1}^{N} x(n)r^*(n-\tau)e^{-j\frac{2\pi}{N}vn}|^2 \quad (1)$$

Where $x[n]$ is the signal at the target channel, $r[n]$ is the reference signal, v is the Doppler shift, τ is the sample shift and N is the number of samples collected.

1.2 MIMO Radar, an Upcoming Technology

After a spark in communication in 1998[13] that resulted in MIMO communication, there has been a great attention towards MIMO in radar technology recently too. Researchers have studied this topic from several points of view. Generally MIMO radars are divided to two categories: MIMO radar with widely separated antennas and MIMO radar with collocated antennas[14-15]. Generally in a MIMO radar with widely separated antennas, we use multiple transmitters and multiple receivers that are widely separated in order to detect the targets. The difference with multistatic radar is in its jointly processing nature. As shown in [14] the concepts of spatial diversity and multiplexing gain emerge here in a dual manner to the MIMO communication. The main point in this radar is that, with looking to a target from different angles the probability of missed detection decreases, a concept called spatial diversity in MIMO communication.

On the other hand, in a MIMO radar with collocated antennas transmitters and receivers instead of being widely separated, are collocated. That is similar to phased array radar, but here the signals emitted by each antenna can be totally uncorrelated with each another.

The studies have shown that we can have enhanced detection performance (Diversity Gain)[16-17] and high resolution target localization(Spatial Multiplexing Gain)[18] with a MIMO radar with widely separated antennas; and significantly improved parameter identifiability[19], direct applicability of adaptive arrays for target detection and parameter estimation[20], and much enhanced flexibility for transmit beam pattern design[21-22] with MIMO radar with collocated antennas.

1.3 MIMO Passive Radar, a New Concept

By combining the subjects explained in sections 1.1 and 1.2, one can get the benefits of both MIMO radar and passive radar by using multiple receivers to detect targets illuminated by multiple noncooperative transmitters. Generally, even the illuminators can be sending different signals(e.g. a broadcasting FM radio station with a GSM base station).

1.4 Data Association Problem in the MIMO PCL

In a DVB-T SFN (Single Frequency Net-

work) all of the transmitters are broadcasting the same data on the same frequency. In the DVB-T - based passive radar, the target antenna at the receiver side collects the echoes of the DVB-T signal in the environment. These echoes may be due to clutters in the region or targets; and also it may be due to either of the transmitters. Some techniques have been developed for the signal processing part of the receiver to detect the targets according to the CW (continuous wave), OFDM(Orthogonal Frequency Division Multiplexing) DVB-T echoes each target produces[6-7]. In all of them the correlator outputs a peak in the range-Doppler board for each target (of course, with some probabilities, we have missed detections and false alarms). The problem arises here, that we do not know which peak is due to which target and oriented from which transmitter. This data association problem becomes important when we want to benefit the MIMO characteristics of the radar. As mentioned in section 1.2, the main contribution of a MIMO radar with widely separated antennas is its spatial diversity.

As each transmitter looks at the target from a different angle, when we combine the different illuminations of the target by different transmitters, it results in diversity at receiver. But, in the papers studied this feature of the MIMO radar, waveforms of the transmitters are chosen in a manner that can be separated in the receiver, e.g. each transmitter sends through a different frequency orthogonal to the others[23]. But here as a result of using noncooperative opportunistic illuminators we should develop some techniques to distinguish the echoes. So it is necessary to develope a method to resolve the origins of the echoes, so that each echo(measurements) detected at the receiver is associated to the transmitter it is transmitted from. In[24], we derived a method for this problem by a smart use of the algorithm that has been proposed in [25] for the multisensor multi-target tracking. Here, we will propose a method to improve the aforementioned data association algorithm. In fact we will show that there is some information laid in the data which was ignored before.

In section 2 we formulate the problem and suggest an algorithm to solve it. Section 3 is dedicated to the results of the simulations of the proposed method. Finally, the paper is concluded in section 4.

2　Problem Formulation and Solution

First, we introduce briefly the data association algorithm for the MIMO PCL suggested in [24] and then explain the improvement.

Assume there are an unknown number of targets(N) with M illuminators of opportunity (e.g. broadcasting DVB-T signal in a SFN) and one receiver (including a reference and a target antenna). The target antenna is omnidirectional and collects the signal in all directions. Each transmitter will illuminate each target in the receiver with the probability P_d, also we will have false alarms with the probability P_{fa}. In the receiver after DPI cancellation, the signal is passed through a CAF processor to obtain the delays and Dopplers of different echoes collected from the targets. We use the term measurement for the information we get from each echo. Usually each measurement consists of a delay and a Doppler. After constructing these measurements there are two stages to solve the association problem: first measurement-to-target association and second measurement-to-transmitter association. It should be noticed that the two stages are not completely distinct. But for more clarity, we choose this structure for the rest of the paper.

2.1　Measurement -to- Target Association

To describe the algorithm more clearly, first we assume that the measurements are assigned to the transmitters by some criteria. By this assumption we have M groups of measurements,

each from a different transmitter. The number of measurements in the m'th group is denoted by n_m, with $i_m = 1, \cdots, n_m$, the index of each measurement.

We want to associate the observations from M groups of n_m, $m = 1, \cdots, M$, measurements. Let the position of the transmitter related to the m' th group be TX_m, then a target, x_q will result in a measurement of $T(TX_m, x_q)$ plus some additive white Gaussian noise $n(t) \sim N(0, \sigma_r)$.

In the algorithm we consider only the TDOAs for the measurements:

$$w_{m,i_m} = T(TX_m, x_q) + n(t)$$

$$T(TX_m, x_q) = \frac{\| TX_m - x_q \| + \| RX - x_q \|}{c}$$

Here we want to estimate the number and location of the targets. For each M-tuple of measurements (each element from a different group) we assign a cost by using a generalized likelihood ratio.

To obtain the likelihood ratios we have

$$p(w_{mi_m} | x_q) = \frac{1}{\sqrt{2\pi}\sigma_r} \exp \frac{[w_{mi_m} - T(TX_m, x_q)]^2}{2\sigma_r^2} \tag{2}$$

and

$$\Lambda(W_{i_1 \cdots i_M} | x_q) = \prod_{m=1}^{M} [1 - P_d]^{1-u(i_m)} \times [P_d p(w_{mi_m} | x_q)]^{u(i_m)} \tag{3}$$

where

$$u(i_m) = \begin{cases} 0, & \text{if } i_m = 0 \\ 1, & \text{else} \end{cases}$$

The likelihood that all measurements are spurious (i. e. $x_q = \varnothing$) is

$$\Lambda(W_{i_1 \cdots i_M} | x_q = \varnothing) = \prod_{m=1}^{M} \left(\frac{1}{\Psi}\right)^{u(i_m)}$$

where Ψ is the number of distinct TDOAs the receiver can sense, for a detailed discussion of see[26].

The cost of assigning a M-tuple to the target x_q is given by

$$c_{i_1 \cdots i_M} = -\ln \frac{\Lambda(W_{i_1 \cdots i_M} | x_q)}{\Lambda(W_{i_1 \cdots i_M} | x_q = \varnothing)} \tag{4}$$

But as we do not know x_q, we use

$$\hat{x}_q = \arg \max_{x_q} \Lambda(W_{i_1 \cdots i_M} | x_q) \tag{5}$$

If we put all these possible costs in a matrix, it will have M dimensions with $n_1 \times n_2 \times \cdots \times n_M$ elements, each related to the cost of an individual M-tuple.

Also we add a dummy measurement, w_{m0} to each group, representing the targets that were not detected by the corresponding transmitter. The goal is to find the most likely set of M-tuples such that each measurement is assigned to one and only one target, or declared false, and each target receives at most one measurement from each group. This can be reformulated as the following

$$J = \min_{\mu_{i_1 i_2 \cdots i_M}} \sum_{i_1=0}^{n_1} \cdots \sum_{i_M=0}^{n_M} c_{i_1 \cdots i_M} \mu_{i_1 \cdots i_M} \tag{6}$$

subject to

$$\begin{aligned} &\textstyle\sum_{i_2=0}^{n_2} \cdots \sum_{i_M=0}^{n_M} \mu_{i_1 \cdots i_M} = 1; \ i_1 = 1, \cdots, n_1 \\ &\textstyle\sum_{i_1=0}^{n_1} \cdots \sum_{i_M=0}^{n_M} \mu_{i_1 \cdots i_M} = 1; \ i_2 = 1, \cdots, n_2 \\ &\qquad \vdots \\ &\textstyle\sum_{i_1=0}^{n_1} \cdots \sum_{i_{M-1}=0}^{n_{M-1}} = 0 \ \mu_{i_1 \cdots i_M} = 1; \ i_M = 1, \cdots, n_M \end{aligned} \tag{7}$$

where, $\mu_{i_1 \cdots i_M}$s are binary association variables such that $\mu_{i_1 \cdots i_M} = 1$ if the M-tuple $W_{i_1 \cdots i_M} = \{w_{1i_1}, w_{2i_2}, \cdots, w_{Mi_M}\}$ is associated with a candidate target. Otherwise, it is set to zero.

Although this generalized assignment algorithm is NP-hard for $M \geqslant 3$, Deb et al. have developed a suboptimal polynomial-time algorithm in [25] (S-D algorithm) for it. By using this algorithm, the targets will be defined and the measurements will be assigned to the targets in an efficient way.

2.2 Measurement -to- Transmitter Association

For each transmitter assignment (or group configuration) in the previous section, the algorithm will minimize the cost function and give the M-tuples corresponding to that minimum. If we compare the minimized function, J, for all group configurations, we can choose the minimum J, so that the group configuration corresponding to this minimum J will be the solution to the Measurement-to-Transmitter association problem.

The block diagram of the algorithm is depicted in Figure 2.

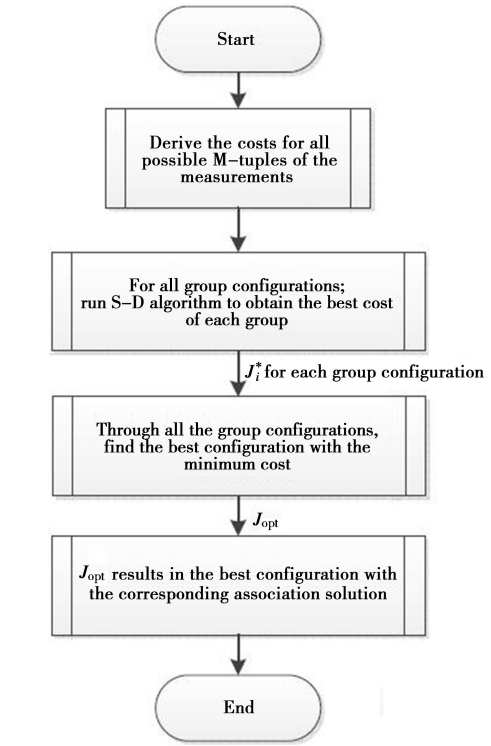

Fig. 2　Block diagram of the proposed algorithm

2.3　Improving the Data Association Algorithm

In (3), in order to compute $p(w_{mi_m}|x_q)$, the maximum R_T and R_R are used, i. e. in the mathematical computation of the cost function for the true targets, we assume the worst case for the bistatic range measurement, which is independent of the R_R, R_T and is the same for all measurements. Here, we modify the noise model (of the measurements) to reduce the cost function for the true targets and consequently the number of false targets.

In our multistatic PCL configuration, each target is illuminated by the signal transmitted by the noncooperative transmitter, reflected from the target and received at the receiver. Therefore, the SNR of this received signal will be proportional to the inverse square of the R_T and R_R (i. e. $SNR \sim \frac{1}{R_T^2 R_R^2}$). If we define $\sigma_{r,\max}$ as the maximum noise power for the largest range ($r_{\max}$), we will have:

$$\sigma_r = \sigma_{r,\max} \frac{R_R^* R_T^*}{r_{r,\max}^2} \tag{8}$$

Where σ_r^2 is the variance of the bistatic range detected at the receiver from the target (x_q) located at a distance R_R^* from the receiver and R_T^* from the transmitter.

By substituting (8) in (9) we will conclude that:

$$p(w_{mi_m}|x_q) = \frac{1}{\sqrt{2\pi}}\left[\sigma_{r,\max}\frac{R_R^* R_T^*}{r_{r,\max}^2}\right] \times \exp\frac{\left[w_{mi_m} - T(TX_m, x_q)\right]^2}{2\left[\sigma_{r,\max}\frac{R_R^* R_T^*}{r_{r,\max}^2}\right]^2} \tag{9}$$

By using this value in the likelihood ratio of (3) and subsequently in the cost function of (4), we expect to get better results as we have used the information laid in the bistatic ranges.

3　Numerical Simulation

3.1　Radar Parameters

In our simulations, we assume a square region of 30 km sides and DVB-T stations as noncooperative illuminators. In our passive platform, we use a different form of range cells called bistatic range cells instead of typical range cells defined for monostatic cases. Such cells represent the resolution of the passive scheme's object position estimation, approximated by [27] as:

$$\Delta R_B \approx \frac{c}{2\beta\cos\frac{\psi}{2}} \tag{10}$$

where β is the DVB-T transmitter bandwidth which is about 6 MHz, and ψ is the bistatic angle:

$$\psi = \cos^{-1}\left[\frac{R_R^2 + R_T^2 - L^2}{2R_R R_T}\right] \tag{11}$$

where L is the transmitter-receiver distance. The parameters R_R, R_T denote the distances between the object and receiving and transmitting antennas, respectively. Accordingly, spatial resolution will be approximately in the range of 25～47 m. For the range-likelihood function $p(w_{mi_m}|x_q)$, we use the Gaussian distribution with parameters $N(T(TX_m, RX_m, x_q), \sigma_r^2)$. The variance of the

bistatic range is then as follows:

$$\sigma_r^2 = c^2 \cdot \sigma_t^2 \tag{12}$$

where for σ_t^2 we have[28]:

$$\sigma_t^2 = \frac{1}{2\beta \mathrm{SNR}(x_q)} \tag{13}$$

and the $\mathrm{SNR}(x_q)$ is defined as

$$\mathrm{SNR}(x_q) = \frac{K}{R_\mathrm{R}^2 R_\mathrm{T}^2} \tag{14}$$

The parameter K is derived as follows

$$K = \frac{P_\mathrm{T} G_\mathrm{T} G_\mathrm{R} \lambda_f^2 \sigma_\mathrm{rcs} F_\mathrm{T}^2 F_\mathrm{R}^2}{(4\pi)^3 k T_0 (\frac{1}{T_\mathrm{int}})(NF)} \tag{15}$$

The receiver and transmitter parameters used in the above expression are all denoted in Table 1. These parameters are the transmitter power P_T, gains for transmitter and receiver antennas G_T and G_R, and the DVB-T signal wavelength $\lambda_f = c/f$, where f is the DVB-T signal carrier frequency. The object's bistatic cross section is denoted by σ_rcs, where k is the Boltzmann's constant, and F_T and F_R are the signal propagation factors. T_int denotes the integration interval for the DVB-T signal in our passive scheme and parameter NF denotes the receiver noise figure. Based on the aforementioned parameter values, σ_r will be derived as a function of R_T (the distance between the transmitter and the object) and R_R (the distance between the receiver and the object).

Table 1 System parameters

Parameter	Value
P_T	10 kW
$G_\mathrm{T} = G_\mathrm{R}$	0 dB
λ_f	0.6 m
σ_rcs	10 dBsm
$F_\mathrm{T} = F_\mathrm{R}$	0 dB
NF	30 dB
Ψ	1708

For Ψ we have:

$$\Psi \cong \frac{\text{range extent}}{\Delta R_B} = \frac{1.5 \times \sqrt{2} \times 30\ \mathrm{km}}{37.5} = 1708 \tag{16}$$

(1) Scenario configuration: The scenario is shown in figure 3. Also Table 2 shows the corresponding positions of the receiver, transmitters and targets.

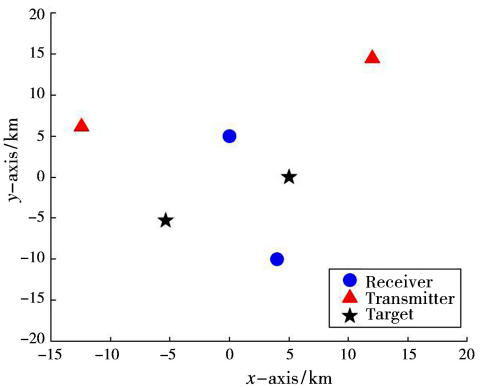

Fig. 3 Scenario configuration

Table 2 Position of transmitters, receiver and targets

	x/km	y/km
Rx1	0	5
Rx2	4	−10
Tx1	−12.45	6.15
Tx2	12.01	14.46
Target1	−5.37	−5.28
Target2	5.01	0.01

The positions of the targets detected without employing the modification discussed in section 2.3 is shown in figure4. As can be observed, one target is missed and instead, a false target has appeared.

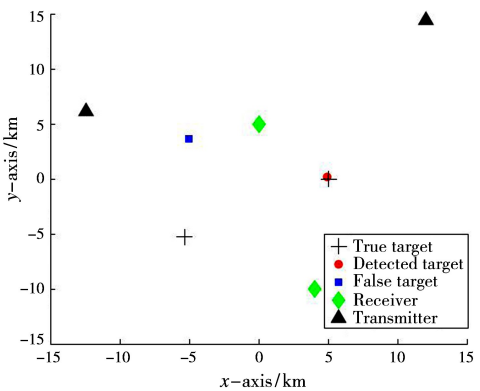

Fig. 4 Target localization without employing the modification

The results for the same configuration, this time with employing the aforementioned modification is shown in figure 5. It can be seen that the number of targets and their positions are truly detected. This verifies the improvement of our modification for the target localization in MIMO passive radar.

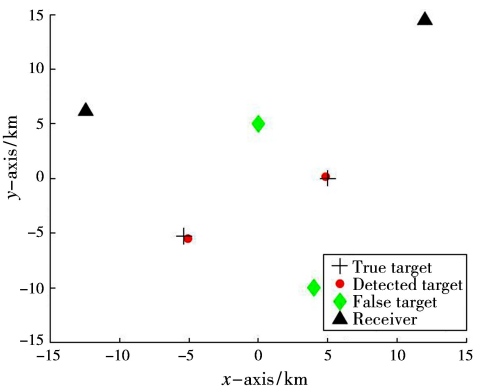

Fig. 5 Target localization after employing the modification in the detection part

4 Conclusion

In this paper, we described the new concept of MIMO passive radar, which seems to get much more attention during the coming years after the passive radar did. To make this concept practical, there are a number of problems that should be solved efficiently. An important one is the data association, which aims to associate the measurements(or echoes) in the receiver to the targets and transmitters(their sources). We stated that this is essential in order to get the benefit of MIMO radar. Having proposed a technique to solve this problem in the previous works, here, we developed a technique to improve the localization. The simulations gave satisfying results for this method.

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