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IMPROVED BLIND SOURCE EXTRACTION FOR TIME DELAY ESTIMATE IN PASSIVE COHERENT LOCATION SYSTEM

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Abstract—Target localization is one challenge in passive coherent location (PCL) radar system, and the time delay is the most important parameter in the location. The difficulty of time delay estimate (TDE) in PCL system is that the target signal is completely buried in direct path signal, multipath and clutter (DMC). The conventional clutter cancellation algorithms in matched filter (MF) are time consuming. In this paper, we propose a time delay estimate method based on blind source extraction (BSE) which directly extract the target signal from the mixed signals, thus a new passive coherent location system is built. In this model, the reference antenna is not needed any more. For low signal to interference plus noise ratio (SINR) and frequency overlapped signals in passive coherent location, we introduce the cyclostationarity to enhance the target signal. The experiments on FM broadcast signals show that the computational burden of the proposed algorithm is extremely small and the improved SNR satisfies the location requirements of PCL system.

1. INTRODUCTION

Passive coherent location (PCL) radar has made attention 70 years ago since the experiment held at Daventry in February 1935 in which Watson-Watt and Wilkins were able to detect a Heyford bomber at about 8 miles by exploiting the radio waves of the BBC broadcasting signal [1]. In recent years, PCL radar system, with its military advantages of anti-jamming, anti-radiation missile and anti-stealth,

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is becoming the important branch in the radar system [2, 3]. On the other hand, the problems in PCL system mainly come from the following aspects: 1) the target echoed signal is a reflected echo from the target, its signal to noise and interference ratio (SINR) is lower than 0 dB (if the power ratio of the DMC to the target echoed signal is large in a matrix, the matrix is called ill-conditioned). Furthermore, the Doppler frequency caused by the velocity of the target is rather smaller than the carrier frequency of the direct path signal, the target echoed signal and DMC are time frequency masking. For maximizing output SNR, A typical passive radar system is based on matched filter (MF) configuration, which collocates two identical antennas at receivers, reference and surveillance antennas, with the reference antenna steer toward the transmitter and the surveillance antenna scan in the direction of interest. Due to the surveillance antenna is omnidirectional, the target echoed signal is inevitable polluted by DMC and the cancellation has been adopted to reject the DMC from the target echoed signal. However, this operation requires a high rate A/D converter at reception which produces a huge amount of data, especially true for those multistage cancellation which for the better DMC rejection.

Blind source separation (BSS), which can separate signals from linearly mixed signals using only the information of the observed signals, has been widely studied in denoising, direction finding and biomedical signal analysis [4]. To reduce the computational burden of BSS, blind source extraction (BSE) methods have been developed to only extract the signals of interest, especially in large number of signals. Recently, there is a trend to exploit signal characteristics such as non-gaussianity [5], bounded [6], finite alphabet [7] and cyclostationarity [8] to custom contrast function for better separation (or extraction) performance.

Time delay estimate (TDE) has been extensively applied in passive location, owing to its easy engineering implementation and high accuracy [9]. The conventional TDE methods include generalized cross correlation (GCC), generalized bispectrum estimate and adaptive TDE (ATDE), etc.. They almost assume that the target signal has been known and literature is few on how to obtain target signal from the mixed signals.

From the analysis above, we draw that the low SINR in the PCL radar receiver is lower than 0 dB, the conventional direction nulls against the DMC are invalid because of its high sidelobe which eventually buries the target signal [10, 11]. For these drawbacks of conventional methods in the PCL system, we consider whether BSS (or BSE) could be introduced in the PCL system to directly extract the target signal from the DMC and noise. Therefore, we build a new PCL configuration based on BSE. In this new configuration, the reference antenna is not needed any more. In our knowledge, this is the first one that applies BSS (or BSE) for specific problems in the PCL system (the low SINR and time and frequency overlap).

In the similar context of applying BSS in radar and sonar, joint approximate diagonaliztion of eigen-matrices (JADE) has been applied to the sonar system for target detection [12, 13], fast fixed point algorithm (FASTICA) has been utilized to feature extraction in radar [14, 15], gradient-based algorithm has been used in ground penetrating radar to remove ground bounce clutter [16] and canonical correlation analysis (CCA) has been used to passive location. But all of these are based on the simple assumptions that the received signals are statistically independent and SINR is high, not the case in the PCL system. In simulation, we analyze these the drawbacks of conventional BSS (or BSE) methods applied in the PCL system.

The remainder of this paper is organized as follow: The new PCL system configuration and received signals model in the PCL system is described in Section 2; the method of cyclostationarity-whitening, oblique projector, and cyclostationarity-based TDE are discussed in Section 3; the simulations about whitening, extraction, TDE and computational complexity comparison are showed in Section 4; finally we end this paper with the overviews of the proposed algorithm.

2. SIGNAL MODEL

For huge computational burden of the cancellation processing in matched filtering. Especially in those network-based illuminators, (such as single frequency network (SFN)-based illuminators in digital video broadcast (DVB-T) system and and MIMO-based illumators in WIMAX system), the date is too huge for cancellation algorithm

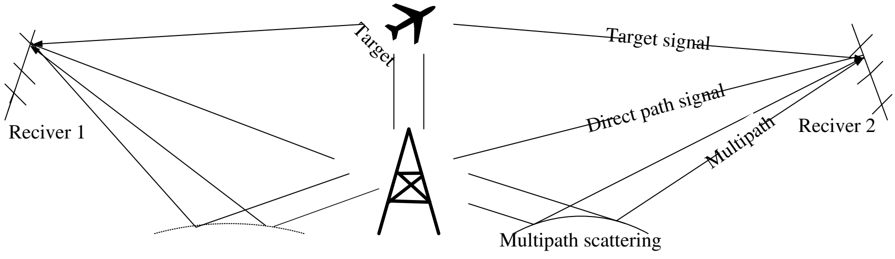

Figure 1. New passive coherent radar system employing multiple receiver antennas.

to handle. In this paper, we propose a new BSE-based processing model in the PCL system. In the proposed model, conventional DMC cancellation is not needed any more [17], reference antenna is not, neither. To improve the locating accuracy, two spatially separated receivers is built for estimating time difference between two target signals from two separated receivers, and we assume that the both receivers can receive the target signal. Owing to the strong time and frequency overlapped signals in the PCL system, multi-sensor array is necessary to achieve the extraction. Generally, we consider a uniform linear array (ULA) antennas and the mixture has to be overdetermined ($M > P+1$, where M is the number of antennas, $P+1$ is the number of signals). Therefore, the novel target detection model is presented in Figure 1. The received data $x(t)$ for each receiver can be expressed as:

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_M(t) \end{bmatrix} = a_m(\theta_m)As(t-\tau_m)e^{j2\pi f_{dm}(t)t} + [a_b(\theta_b), a_{c1}(\theta_{c1}), \ldots, a_{cP}(\theta_{cP})] \times \begin{bmatrix} bs(t) \\ c_1 s(t-\tau_{c1}) \\ \vdots \\ c_P s(t-\tau_{cP}) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \\ \vdots \\ n_M(t) \end{bmatrix} \quad 0 \le t < T_0 \quad (1)$$

where

$x_m(t)$, for $m = 1, \ldots, M$ is the received data from each array antenna;

T_0 is the global observation time;

$s(t)$, is the complex envelope of the direct path signal (a delayed replica of the transmitted signal);

$a_m(\theta_m)$, A, τ_m and $f_{dm}(t)$ are the array response vector (corresponding to the θ_m), the complex amplitude, the delay and the Doppler frequency of the target;

$a_b(\theta_b)$ and b are the array response vector (corresponding to the θ_b) and complex amplitude of the direct path signal;

$a_{cp}(\theta_{cp})$, c_p and τ_{cp} are the array response vector (corresponds to the θ_{cp}), complex amplitude and the delay of the pth stationary multipath ($p = 1, \ldots, P$);

$n_m(t)$, for $m = 1, \ldots, M$, is the Gaussian white noise process with mean zero and variance σ^2.

Due to the variable and unpredictable characteristics of the transmitted waveform, the sidelobes of the ambiguity function is usually time-varying. Therefore,we divide the data into blocks and

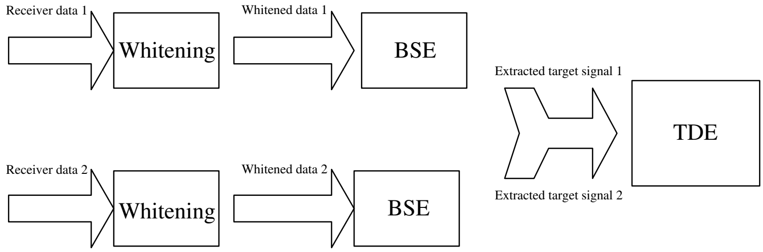

Figure 2. Configuration of the proposed method.

assume it is time invariant for each block. This means the Doppler f_{dm}, array response matrix a and complex amplitudes A, b, c don't change for each block.

3. THE PROPOSED ALGORITHM

In this section, we exhibit improved BSE-based TDE for PCL radar system in details. For the characteristics of PCL system, we propose the processing including four steps, which is shown in Figure 2. Step 1, cyclostationarity based-whitening to eliminate the ill-conditioned from one receiver; Step 2, extract the target signal by using the whitened data obtained from the step 1; Step 3, repeat the step 1 and the step 2 to extract the second target signals from the other receiver; Step 4, the TDE between two target signals extracted from the step 1, 2 and 3. Following we separately show each part in details.

3.1. Cyclostationarity Based-whitening

Normally, the BSE includes two steps: the first step is to white the data to reduce the dimension of the data by transforming the general mixing matrix into an orthogonal one; the second step is to apply the specific contrast function to extract signals from the whitened data. However, conventional whitening methods take time delay correlation at time delay 0 that is no help for the ill-conditioned [22] in the PCL system. On the other hand, the ill-conditioned under noisy environment must be detected and conducted in the whitening, otherwise, the ill-conditioned will expand to the extraction procedure.

There are some literatures [18, 19] have addressed the ill-conditioned mixing, but these algorithms are rather complex to operate. Considering most man-made signals encountered in communication, telemetry, radar, and sonar systems are quasi-cyclostationary signals [20]. A random process $s(t)$ can be widesense cyclostationary satisfying $m_s(t) = E\{s(t)\}$ and autocorrelation $R_{ss}(t,u) = E\{s(t)s^*(u)\}$ is periodic with some delay, say $1/\alpha$:

$$\begin{cases} m_s\left(t + k/\alpha\right) = m_s(t) \\ R_{ss}\left(t + k/\alpha, u + k/\alpha\right) = R_{ss}(t,u) \end{cases} \tag{2}$$

where α is the cyclic frequency; k is any integer; $\langle\cdot\rangle^*$ denotes complex conjugate of a vector.

Time delay correlation at the fundamental period T of $x_i(t)$ has the following properties:

$$\begin{cases} R_{x_i x_i}(T) = E\left\{x_i(t)x_i^*(t+T)\right\} > 0 \\ R_{x_i x_j}(T) = E\left\{x_i(t)x_j^*(t+T)\right\} = 0 \quad \forall i \neq j \end{cases} \tag{3}$$

where $T = 1/\alpha$. From (3) one can see that, assuming that the fundamental period of one signal is different from the others, one can takes time delay correlation at the fundamental period of the signal, consequently the signal is enhanced with other signals are suppressed, and this process is called signal selectivity [21]. Therefore, in our problem, we propose cyclostationarity-based whitening to enhance the target signal. The only requirement is that the fundamental period has been estimated, which is reasonable for weak signal extraction [23]. The method to estimate the Doppler in low SNR is out of the scope of this paper, for details one can see [24]. Thus in the received data, take time delay correlation $R(\tau)$ at the K periods of the target signal:

$$R_{xx}(kT^*) = E\left\{x(t)x^H(t + kT^*)\right\} \quad \text{for} \quad k = 1, \dots, k \tag{4}$$

where T^* is the fundamental period of the target signal. Compared with the method in [18, 19], our method is simple and efficient.

Furthermore, we consider one realistic issue. The samples length is finite, the cross correlation values among signals are non-zeros. The theorem in (3) doesn't completely hold any more. In this case, the conventional BSE based on cyclostationarity is invalid [25]. In this paper, we propose a robust whitening which modify $R_{xx}(kT^*)$ as:

$$R_{xx}^k = 1/2\left(R_{xx}(kT^*) + R_{xx}(kT^*)^H\right) \quad k = 1, \dots, K. \tag{5}$$

where $\langle\cdot\rangle^H$, complex conjugate transpose of a matrix.

Here we should discuss the relationship between beamforming and whitening. Although in our model, beamforming and whitening have similar structure and goals [26], this paper assumes array manifold is unknown. This implies that the proposed method is robust since it is efficient when array manifold calibration exists. In fact, even the array manifold is available, once one direction of arrival (DOA) error happens (e.g., 0.001 degree deviation), it is very probable to greatly degrade the performance in the extraction. Therefore we will continue to discuss the extraction method in the next section.

3.2. BSE

The BSS has been proposed for about 20 years, and the early BSS (or BSE) methods are under the assumptions of high SNR and the received signals are statistically independent (e.g., FASTICA [27], second-order blind identification (SOBI) [8]). However, the two requirements are unrealistic for the mixed signals in radar, sonar, biomedicine and telecommunication system, and this is one reason why the BSS and BSE are hard for realistic applications. Laterally, some researchers discuss robust BSE such as high-order statistics (HOS)-based BSS [29] and FIR-filter-based BSS [7, 25] to separately solve the two problems. But the problem in the PCL system seems more troublesome. Since the Doppler term is added to the transmitted signal when one target is illuminated by the signal, this Doppler frequency is much smaller than carrier frequency, therefore, the target signal is strong time-frequency overlapped with DMC and hard to separate. The traditional band-pass filtering has a large cut off frequency. Especially for those band-pass signals, the target signal and DMC are almost time-frequency overlapped.

Those conventional BSE algorithms based on time delay correlation at time delay 0, assume that The whitened data is a Hermitian positive definite matrix, where exist a Hermitian matrix B satisfying that:

$$BB = R_{yy}(0) - \sigma^2 I_N = U_s^H [R_{zz}(0) - \sigma^2 I_{(P+1)}] U_s \tag{6}$$

However, Equation (6) is not Hermitian any more at time delay non-zero. In this case, oblique projector [28, 29] has been introduced. Contrary to the orthogonal projection is idempotent and Hermitian, the oblique one is idempotent and not Hermitian. Therefore, the orthogonal projector is a special example of the oblique projector. In this paper, considering the mixing matrix is possible non-orthogonal and the existence of noise, we introduce oblique projector, which has been proposed by Peng and Zhang in [30] to consider noise in extraction process. In oblique projector, the vector of target signal can be obtained by minimizing the contrast function:

$$\min: \ J(t, w, d_1, \ldots, d_K) = \sum_{k=1}^{K} ||R_{yy}^k w - d_k t||^2 \tag{7}$$

where R_{yy}^k, for $k = 1, \ldots, K$, is time delay correlation matrix (at any time delay τ) of whitened data; $d_1, \ldots, d_K$ are unknown scalars, and $|| \cdot ||$ denotes Euclidean norm.

Since that the method is based on second-order statistics (SOS), one can replace these time delay correlation matrices at any time delay τ by the periods of the target signal to extract the target signal.

Here, the technicality of minimizing the contrast function (7) is the sequential approximate digitalization algorithm (SDA) proposed in [31]. Since R_{yy}^k is whitened data, d_k can be constant ($d_k = 1$). The extraction algorithm can be simplified as:

- Stage 1: Freeze t and adjust w to yield the optimal w:

$$w \leftarrow H\left(\sum_{k=1}^{K} R_{yy}^k\right) \times t \tag{8}$$

where $H = [\sum_{k=1}^{K}(R_{yy}^k)^2]^{-1}$ and $e \leftarrow f$ denotes replacing e by f.

- Stage 2: Freeze w and adjust t and consider the Lagrange function

$$J_{\lambda_t} = J + \lambda_t(t^T t) - 1 \tag{9}$$

To obtain the adjustment for t

$$t \leftarrow \frac{v}{||v||}, \quad v = \sum\nolimits_{k=1}^{K} r_k \tag{10}$$

where $r_k = R_{yy}^k w$. These stages are repeated until the contrast function converges.

3.3. TDE

Target location is one of the most important goals of radar signal processing. As the DOA information is often unreliable, the localization has to be accomplished by TDE. The conventional method used in the PCL system is MF-based TDE, which make correlation between reference signal and received data. But in weak signal scenario, and the long integration time is needed to gain the high output SNR. On the contrary, the BSE-based TDE can obtain high SNR with short samples length, which indicates our method is robust to time varying environment.

To improve locating reliability, two spatially separated receivers are built to receive the target signals. Here, we assume the both receivers have received the target signals and take TDE by the time difference between the two target signals. Furthermore, it is impossible to completely eliminate noise by extraction since the noise is uniformly distributed in the whole bandwidth. To further eliminate the noise effect in TDE, we can employ the cyclostationarity again. In TDE, we use its cyclic cross correlation (CCC) property. The CCC function $R_x^\alpha(\tau)$ of $x(t)$ is defined as:

$$R_{xx}^\alpha(\tau) = \left\langle x(t+\tau/2)x^H(t-\tau/2)e^{-j2\pi\alpha t}\right\rangle \tag{11}$$

$\langle\cdot\rangle$, stands for time averaging operator. If $x(t)$ is a vector of N signals with different cyclic frequencies, CCC function has the following properties [8]:

$$\begin{cases} r^{\alpha_i}_{x_i x_j}(\tau) = \left\langle x_i(t+\tau/2)x^*_j(t-\tau/2)e^{-j2\pi\alpha_i t}\right\rangle = 0 & \text{if } i \neq j \\ r^{\alpha_j}_{x_i x_i}(\tau) = \left\langle x_i(t+\tau/2)x^*_i(t-\tau/2)e^{-j2\pi\alpha_j t}\right\rangle = 0 & \text{if } \alpha_i \neq \alpha_j \\ r^{\alpha_i}_{x_i x_i}(\tau) = \left\langle x_i(t+\tau/2)x^*_i(t-\tau/2)e^{-j2\pi\alpha_i t}\right\rangle > 0 & \forall i. \end{cases} \tag{12}$$

where α_i is the cyclic frequency of the $x_i(t)$. Thus we can estimate the TDE by minimizing the minimum mean square error (MMSE) ξ between CCC function R_{zz_1} (desired output) and $R_{z_2 z_1}$ (actual output):

$$\varepsilon = \sum_{\tau} \left(R^a_{zz_1}(\tau) - R^a_{z_2 z_1}(\tau)\right)^2 \tag{13}$$

The system block is shown in Figure 3. The TDE τ is not derived in these papers, whose steps can be seen in [32] for details.

Note that the synchronization among receivers is one crucial technology in multistatic locating, but discussion the synchronization is out of the scope of this paper. We simply realize the synchronization by utilizing the global positioning system (GPS) for a highly accurate synchronization in this paper.

4. SIMULATION ANALYSIS

The effectiveness of the proposed approach is evaluated by simulation experiments. Three representative examples are conducted to analyze

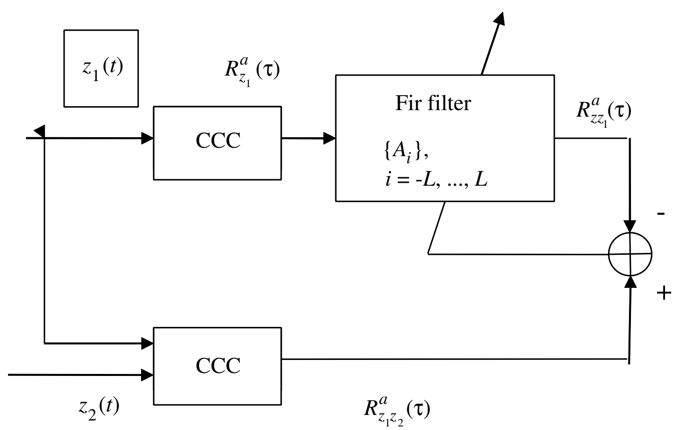

Figure 3. System block of ATDE.

the results of our method, performance comparison between our method and other existing methods, and the effects of realistic issues. In these experiments, we use the four FM signals:

$$\begin{aligned} s_1 &= \cos\left(2\pi f_c t + M \sin \Omega t\right) \\ s_2 &= \cos\left(2\pi f_c (t-\tau_1) + M \sin \Omega (t-\tau_1)\right) \\ s_3 &= \cos\left(2\pi f_c (t-\tau_2) + M \sin \Omega (t-\tau_2)\right) \\ s_4 &= \cos\left(2\pi \left(f_c + f_{dm}(t)\right)(t - r/c) + M \sin \Omega (t - r/c)\right) \end{aligned} \tag{14}$$

where the s_1 is the direct path signal with carrier frequency $f_c = 100\,\text{MHz}$; $\Omega = 20\,\text{kHz}$; M is the FM index. s_2 and s_3 is the multipath reflection of the direct path signal; τ_1 and τ_2 is the delay of the s_1 and s_2 with response to the direct path signal. s_4, the target signal; the distance difference between the direct path signal and the target signal $r = 100\,\text{km}$; c, the velocity of the light; $f_{dm} = 100\,\text{Hz}$, the Doppler shift of the target signal. The DOAs of the four signals [s_1, s_2, s_3, s_4] are [-60, -40, 20, 40]; The SNR of the four signals are separately [92.1034, 81.8869, 78.2405, -13.8629] dB. For simplicity, we assume that two receivers have the same the distances from the transmitter and, the time that two signals arrive the two receivers separately is the same. Thus the real time delay between two receivers is 0.

4.1. Result Analysis of The Proposed Method

In this section, we separately show the results of each step. One can exploits the cyclostationarity by dividing the data into small blocks and assumes each block is stationary, the proposed data can be used to extract the instanous time delay parameter from every block. In whitening step, beamforming is the same as whitening in essence,

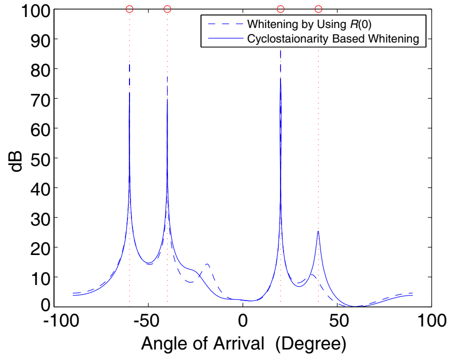

Figure 4. The conventional whitening and cyclostationarity-based whitening.

Table 1. Improved SNR under different input SNR.

Input SNR (dB)	-32.2	-13.9	-4.5	0
Output SNR (dB)	9	15.9	17.5	17.7

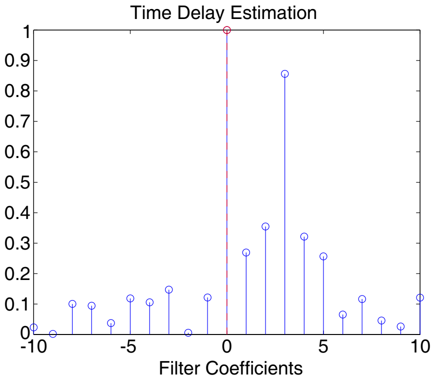

Figure 5. CCA-based TDE, this is the result after 3000 iterations.

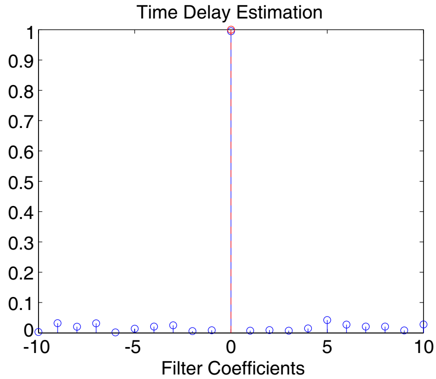

Figure 6. Robust oblique projector-based TDE, this is the result after 3000 iterations.

whose result can be investigated by beamforming [33]. Assume that the antennas are spaced by half a wavelength, the beamforming is shown in Figure 4. One can see that, cyclostationarity-based whitening could enhance weak target signal with higher accuracy than that of conventional whitening. In Table 1 shows the output SNR under different input SNR. From this table, one can see that the lower the SNR, the higher the improved SNR. In the case of input SNR -32.2 dB, the output SNR by our algorithm is 9 dB, which satisfies for the requirements of ATDE (it requires the SNR -3 dB before the estimate). In Figures 5 and 6, CCA-based TDE and robust oblique projector-based TDE are compared (since the assumption of CCA-based TDE is not equal to that of robust oblique projector-based TDE, they aren't compared directly). In this simulation, the initial time delay is 8, and the real time delay is 0. These results indicate that our method has better performance than that of CCA-based TDE.

4.2. Performance Analysis

In Figure 7, the conventional whitening, the proposed whitening and the cyclostationary Cramer-Rao lower bound (CRLB) [36] are

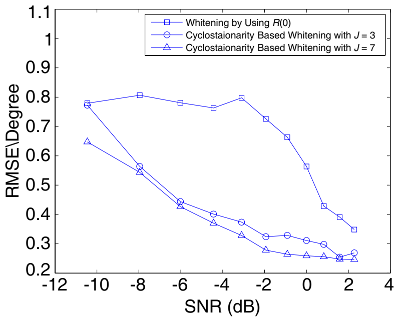

Figure 7. The whitening comparison, this result is 3000 independent trials.

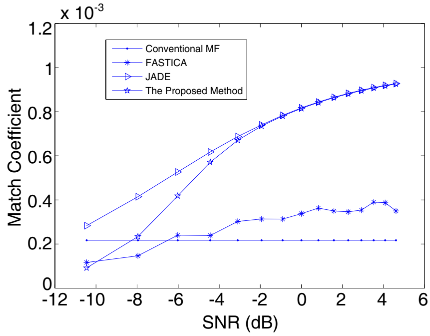

Figure 8. Separation comparison under different SNR, this is the result after 80 iterations.

compared in term of root mean squared error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{LMK}} \sum_{l=1}^{L} ||\hat{A}(l) - A||_F^2} \tag{15}$$

where L is the number of independent simulation runs. $\hat{A}(l)$ is the estimate of A obtained from the l-th run. The result indicates the RMSE errors decrease by improving input SNR; the proposed whitening is great prior to the conventional whitening in low SINR. It also shows that the more time delay correlation matrices are used, the better the whitening. One point we should know is that our method doesn't reach the CRLB, the reason is that in noisy environment, the estimated optimal mixing matrices by BSE is not to recover the array matrix but to maximize the output SNR.

We employ the block normalized matched filter (BNMF) [35] to compare our extraction method with other existing methods, the test is written as:

$$L = \frac{\left| \sum_{n=0}^{N-1} s(t)^* x(t) \right|^2}{(1/2N) \sum_{n=0}^{N-1} |s(t)|^2 \sum_{n=0}^{N-1} |x(t)|^2} \tag{16}$$

where $s(t)$ is the real target signal, $x(t)$ is the estimated signal. The larger the match coefficient, the better the extraction. Firstly we assume that the signals number has been correctly estimated. From the simulation in Figure 8, one can see that the match coefficient estimated by both JADE and the proposed algorithms increase with

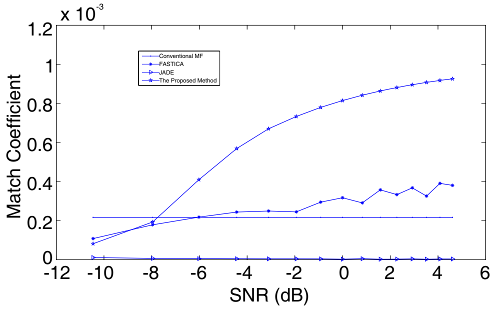

Figure 9. Robust oblique projector-based TDE, this is the result after 3000 iterations.

the increasing SNR with JADE little prior to the proposed. FASTICA algorithm, because of its decorrelation constraint, which prevents its extraction, as shown in [34], the optimal and the least square (LS) separators become strongly correlated for weak signals. At last, the direct matched filtering between the real signal and received data shows is the worst. In the other case, assuming the signals number is unknown, the JADE algorithm shows invalid in Figure 9, while our proposed method still works well with a little performance degradation. By comparing the Figures 8 and 9, one can see that JADE algorithm can only work in the case of signals number has been correctly estimated, but it is still a problem that estimating the signals number in multipath environment.

4.3. The Effect of Cyclic Frequency Estimate Errors

One important issue should be attended is that estimate error of periods. Although this paper assumes the period of the target signal has been estimated, the estimate error is inevitable. Our proposed method is robust to the errors of periods, as long as the error is not too large (this requirement is reasonable in practice). For example, one can modify the time delay correlation as:

$$\begin{aligned} R(kT^*) = & \; R(247i) + R(247i)^H + R(248i) + R(248i)^H \\ & + R(249i) + R(249i)^H + R(250i) + R(250i)^H \\ & + R(251i) + R(251i)^H + R(252i) + R(252i)^H \\ & + R(253i) + R(253i)^H \end{aligned} \tag{17}$$

By simulation one can see that, when the estimate error of periods happens, the coefficient of BNMF drop 0.3 in input SNR 0 dB.

4.4. Comparison with the Cancellation Algorithm

In this section, we compare our method with the cancellation. In case of input SNR is $-30\,\mathrm{dB}$ and samples length is $1e5$, the cancellation-based MF can improve the SNR $50\,\mathrm{dB}$. But the computational cost is huge. For example, the computational complexity in least square (LS) filter lies mainly in the matrix inversion operation (with response to $O[NL^2 + L^2 \log L]$, where N is the samples length and L is weight vector $a(L \times 1)$) [17]), even for the batch approach. The computational cost in least mean squares (LMS)-cancellation is also high ($O(\mathrm{CIC}) + O(\mathrm{LPF}) + O(\mathrm{FFT})$ [37]). But in our method, the computational load is rather small. Only one matrix inversion is required (with the computational complexity $O[M^3/3]$, where M is the number of antennas) in the whitening, and the convergence can be archived after 7 times iteration in the extraction. Furthermore, our method can also achieve the improved SNR $40\,\mathrm{dB}$ with samples length only 2000 (this result is achieved before the matched filtering). The short samples length indicates our method can be applied fast time-varying environment.

5. DISCUSSION AND CONCLUSION

For the target signal is usually buried in DMC, the cancellation in matched filtering has been adopted to reject the DMC, but the computational cost is high. In this paper, we introduce the BSE to directly extract the target signal from the surveillance antenna, cancellating the DMC from surveillance antenna is not needed any more, reference antenna, neither. Therefore, a novel PCL configuration is established. The computational load of BSE-based TDE is dramatically reduced compared with the conventional cancellation. At the same time, by exploiting the oblique projector and cyclostationarity, our approach can gain higher estimated accuracy than other BSS methods applied in conventional radar and sonar, in which the signal and channel characteristics aren't considered. The simulations indicate that the improved SNR by our method satisfies the location requirements of the PCL system. Since the PCL system configuration for different illuminator is the same, our method can be applied to other illuminators. For example, for the orthogonal frequency division multiplexing (OFDM) illuminator, one can exploit the cyclostationarity of cyclic prefix (CP) or pulse shaping filter to enhance the target signal in low SNR.

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