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Research Article

Direction Finding for Passive Bistatic Radar in the Presence of Multipath Propagation

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In the case of multipath propagation for passive bistatic radar (PBR) using uncooperative frequency agile-phased array radar as an illuminator, a new direction-finding method is proposed to deal with the scenario where the coherent and uncorrelated signals are closely spaced or in the same direction. Firstly, spatial difference technique is used to eliminate uncorrelated signals. Then, in order to avoid the cross-terms effect and improve the resolution of coherent signal, the iterative adaptive method (IAA) is adopted for the rearranged spatial difference matrix. Finally, the direction of arrival (DOA) of the target signal is obtained by the reconstruction of the interference-plus-noise covariance matrix. Compared with previous studies, this method has better performance in the case of low signal-to-noise ratio (SNR) and limited number of snapshots.

1. Introduction

Passive bistatic radar (PBR) can detect and locate targets by exploiting an uncooperative illuminator. Because of the advantages of low cost and covert detection, various civil illuminators such as FM radio [1–4], digital video broadcasting (DVB), digital audio broadcasting (DAB) [5–7], and navigation satellite [8] have been applied to PBR. However, the transmitted signal is not specially designed for radar, and the detection distance is relatively short. In addition, the ambiguity function usually has undesired peaks or high sidelobes [9, 10]. Compared with the above illuminators, the transmission signal of special radar usually has ideal ambiguity function and higher power. At present, the very high frequency (VHF), band frequency agility, and phased array technology are widely applied in radar system, which can provide higher sensitivity for stealth targets and flexible beam scanning [11, 12]. Using frequency agile-phased array radar as a transmitter can expand the range of available illuminators and further improve the performance of PBR radar but suffers from the signal processing of PBR radar such as low signal-to-noise ratio (SNR) and limited snapshots. In particular, the target signal and its multipath signal are coherent, which may be closely spaced in the main lobe. At the same time, a transmission signal may be in the same direction as the desired signal, which may be received from the sidelobes simultaneously. Therefore, direction finding in multipath environment becomes difficult for PBR.

At present, many high-resolution algorithms for direction of arrival (DOA) estimation have been proposed to solve the coexistence of coherent and uncorrelated signals [13–16]. With the aid of forward/backward preprocessing for spatial smoothing, the coherent signals can be effectively resolved. However, the decorrelation of spatial smoothing technology is achieved at the cost of reducing the array aperture, which further leads to increasing the main lobe width and reducing the accuracy of direction finding. Besides, spatial smoothing methods may lead to signal cancellation when the coherent and uncorrelated signals come from the same direction [17]. Noticeably, the coherent and uncorrelated signals in the multipath environment can be resolved by exploiting the spatial-differencing technology [18–22]. Herein, the uncorrelated signals can be eliminated and the remaining coherent signals can be resolved. However, the method in [17] requires constructing the covariance matrix of uncorrelated signals, which makes it difficult to achieve. The method in [18] suffers from rank deficient and lacks theoretical proof. The methods in

[19, 20] are only suitable for the case of large number of snapshots. Since the problem of cross-terms effect in [21, 22] is solved by dealing with uncorrelated signals, the direction finding may not be estimated correctly in the scenario of limited snapshots. Recently, the iterative adaptive approaches (IAA) in [23–28] are proposed to resolve the closely spaced coherent signals, which have satisfactory performance in low SNR and limited snapshots [29, 30]. Unfortunately, the above-mentioned methods will fail when coherent and uncorrelated signals are in the same direction.

Therefore, the motivation of this paper is to achieve direction finding in multipath environment for PBR by exploiting an uncooperative frequency agile-phased array radar as an illuminator. Firstly, the spatial-differencing technique is exploited to eliminate the uncorrelated signals. Then, in order to avoid effect of cross-terms and improve the accuracy of the remaining coherent signals, the IAA algorithm is exploited with respect to a rearranged spatial difference matrix. Finally, the reconstruction of interference-plus-noise covariance matrix is exploited to obtain the DOA of desired signal. Compared with the existing methods, simulation results demonstrate that the proposed method can improve performance in low SNR with limited snapshots.

2. Problem Description

As shown in Figure 1, the PBR system includes a surveillance antenna, a reference antenna, and a receiver. Noticeably, the anti-interference ability and detection probability can be improved by exploiting the frequency agility-phased array radar as a transmitter. Meanwhile, the phased array technology can provide more degrees of freedom and flexible beam patterns, which can simultaneously detect and locate different targets. Figure 2 illustrates the frequency agility and beam scanning. Since the frequency agility technology can destroy the coherence between pulses, the rapidly changing beam scanning makes PBR unable to predict the next beam position in the case of low SNR and limited number of snapshots. Furthermore, the received signals are a mixture of coherent and uncorrelated signals in multipath propagation. On the one hand, the target signal is coherent to the multipath signal and closely located within the main lobe. On the other hand, the transmitted signals of illuminators may be received together in the same direction as the desired signal. Therefore, the problem of direction finding for PBR in multipath propagation can be considered as eliminating uncorrelated signals and resolving coherent signals in the case of limited snapshots and low SNR.

3. Signal Model

Assuming that K narrowband signals are incident on a uniform linear array (ULA) with N isotropic sensors and the first sensor of ULA is regarded as reference point, the steering vector can be expressed as

$$a(\theta) = \left[1, \exp\left(-j2\pi\left(\frac{d}{\lambda}\right)\sin\theta\right), \cdots, \exp\left(-j2(N-1)\pi\left(\frac{d}{\lambda}\right)\sin\theta\right)\right]^T, \tag{1}$$

where the superscript $[]^T$ denotes the transpose operator, d denotes the spacing of sensors, λ denotes the wavelength of signal, and θ denotes the direction of narrowband signal.

Assuming that K_c coherent signals and $K - K_c$ uncorrelated signals are received simultaneously by the PBR, the array output vector $x(t)$ is given by

$$\begin{aligned} x(t) &= x_d(t) + x_c(t) + x_u(t) + n(t) \\ &= a(\theta_0)s_0(t) + \sum_{k=1}^{K_c-1}\rho_k a(\theta_k)s_0(t) + \sum_{k=K_c}^{K-1} a(\theta_k)s_k(t) + n(t) \\ &= \sum_{k=0}^{K_c-1}\rho_k a(\theta_k)s_0(t) + \sum_{k=K_c}^{K-1} a(\theta_k)s_k(t) + n(t) \\ &= As(t) + n(t), \end{aligned} \tag{2}$$

where $x_d(t)$ denotes the desired signal, $x_c(t)$ denotes the remaining $K_c - 1$ coherent signals with complex reflection coefficient ρ_k, $x_u(t)$ denotes the uncorrelated signals, $n(t)$ denotes the additive Gaussian noise, $A = [A_c, A_u]$ denotes steering matrix with $A_c = [a(\theta_0), \rho_1 a(\theta_1), \cdots, \rho_{K_c-1}a(\theta_{K_c-1})]$, and $A_u = [a(\theta_{K_c}), a(\theta_{K_c+1}), \cdots, a(\theta_{K-1})]$ and $s(t) = [s_c(t), s_u(t)]^T$ denote the vector of the coherent signals and the uncorrelated signals.

4. Proposed Algorithm

In this section, a novel method for PBR is proposed to solve the direction finding in multipath environment. The steps are introduced in detail in the following.

4.1. Elimination of Uncorrelated Signals. In this subsection, the uncorrelated signals are eliminated from the received signals. Herein, the covariance matrix of array output can be calculated as

$$R = E\{x(t)x^H(t)\} = A_c R_c A_c^H + A_u R_u A_u^H + \sigma^2 I_N, \tag{3}$$

where $R_c = \text{diag}\{\sigma_0^2, \cdots, \sigma_{K_c-1}^2\}$ denotes the covariance matrix of coherent signals and $R_u = \text{diag}\{\sigma_{K_c}^2, \cdots, \sigma_{K-1}^2\}$ denotes the covariance matrix of uncorrelated signals, I_N denotes the N dimensional identity matrix, and σ^2 denotes the variance of additive Gaussian white noise.

Herein, the covariance matrix of array output can be rewritten as

$$\bar{R} = \bar{R}_u + \bar{R}_c + \sigma^2 I_n, \tag{4}$$

where the (i, j) element in $\bar{R}_u$ is given by

$$\bar{R}_u(i, j) = \sum_{k=K_c}^{K-1} \sigma_k^2 v_k^{i-j}. \tag{5}$$

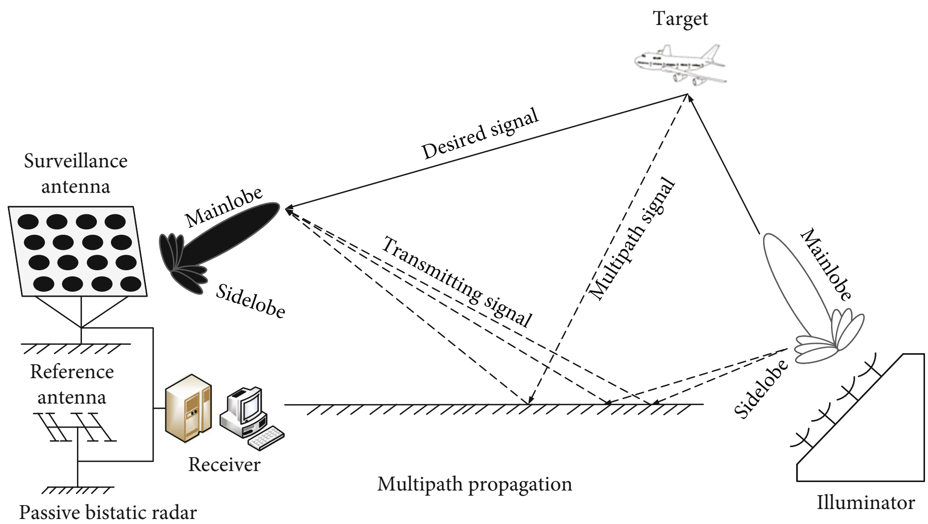

Figure 1: The diagram of direction finding for PBR in multipath propagation.

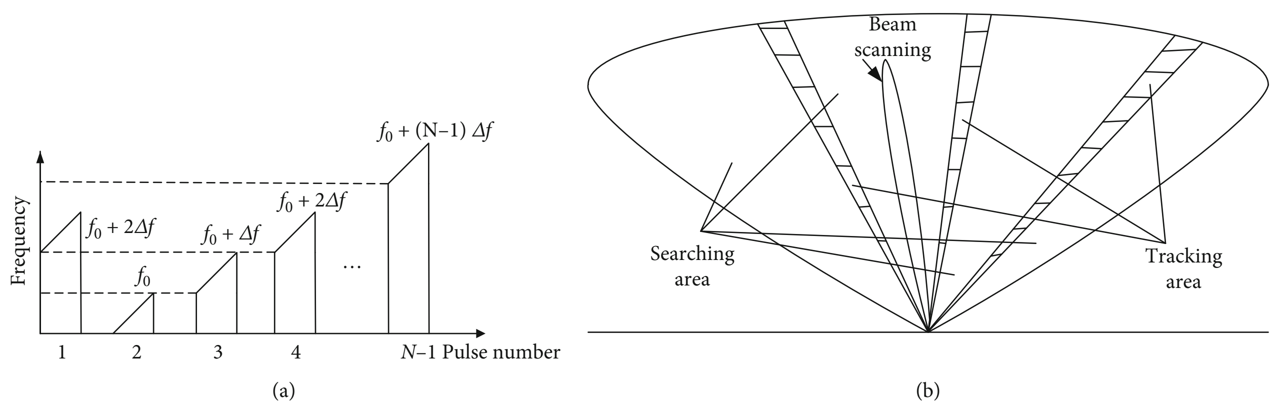

Figure 2: The diagram of (a)frequency agility between pulses and (b) flexibility of beam scanning.

Apparently, $\bar{R}_u$ is a Toeplitz Hermitian matrix which satisfies

$$J\bar{R}_u^T J = \bar{R}_u, \tag{6}$$

where J stands for the exchange matrix with ones on antidiagonal and zeros elsewhere. Since the covariance matrix of correlated or coherent signals is only a Hermitian matrix and the covariance matrix of uncorrelated signals is a Toeplitz Hermitian matrix, a spatial difference matrix is constructed to eliminate uncorrelated signals, which can be expressed as

$$\begin{aligned} R_d &= \bar{R} - J\bar{R}^T J = \left(\bar{R}_u + \bar{R}_c + \sigma^2 I_n\right) - J\left(\bar{R}_u + \bar{R}_c + \sigma^2 I_n\right)^T J \\ &= \bar{R}_c - J\bar{R}^T{}_c J. \end{aligned} \tag{7}$$

Theoretically, only coherent signals remains in R_d. By performing eigenvalue decomposition (EVD), the spatial difference matrix R_d can be expressed as

$$R_d = U_d \Lambda_d U_d^H. \tag{8}$$

Since the diagonal value of Λ_d contains pairs of mutually opposite eigenvalues, the cross-terms effect will lead to the failure of direction finding.

4.2. Direction Finding of Desired Signal. In order to improve the resolution of coherent signals and avoid the effects of cross-term, the IAA-based spatial spectrum estimation algorithm is proposed to achieve high-accuracy direction finding in multipath environment. Herein, the spatial difference matrix is rearranged by taking the absolute values in Λ_d, which is given by

$$R_D = U_d |\Lambda_d| U_d^H. \tag{9}$$

Clearly, we can rewrite Equation (3) as

$$R = E\left\{x(t)x^H(t)\right\} = A_u R_u A_u^H + A_c R_c A_c^H + \sigma^2 I_n = \bar{A}\bar{P}\bar{A}^H, \tag{10}$$

where $\bar{A}$ denotes the reconstructed array flow pattern and can be expressed as

$$\begin{aligned}\bar{A} &= [A_c, A_u, I_N] \\ &= \left[a(\theta_0), \rho_1 a(\theta_1), \cdots, \rho_{K_c-1} a\left(\theta_{K_c-1}\right), a\left(\theta_{K_c}\right), \cdots, a(\theta_{K-1}), I_N\right] \\ &= [\bar{a}(\theta_0), \cdots, \bar{a}(\theta_K), \cdots, \bar{a}(\theta_{K+N})].\end{aligned} \tag{11}$$

$\bar{P}$ denotes the signal power matrix and can be expressed as

$$\bar{P} = \text{blkdiag}\left\{P_c, P_u, \sigma^2 I_N\right\} = \text{diag}\left\{\bar{P}_0, \cdots, \bar{P}_K, \cdots, \bar{P}_{K+N}\right\}. \tag{12}$$

According to the IAA algorithm [25], the noise covariance matrix corresponding to θ_q can be expressed as

$$\Gamma_q = \Omega - \tilde{P}_q a\left(\theta_q\right) a^H\left(\theta_q\right), \tag{13}$$

where $\Omega = \Phi \tilde{P} \Phi^H$, $\tilde{P} = \text{diag}\left\{\tilde{P}_1, \tilde{P}_2, \cdots, \tilde{P}_Q\right\}$, and $\tilde{P}_q$ denotes the power corresponding to θ_q. According to the least squares method, the objective function can be expressed as

$$\begin{aligned}\min\ \Psi &= \sum_{n=1}^{N} \left\| x(t) - s_q(t) a\left(\theta_q\right) \right\|^2_{\Gamma_q^{-1}} \\ &= \sum_{n=1}^{N} \left(x(t) - s_q(t) a\left(\theta_q\right)\right)^H \Gamma_q^{-1} \left(x(t) - s_q(t) a\left(\theta_q\right)\right),\end{aligned} \tag{14}$$

where $s_q(t)$ denotes coherent signal at the t-th snapshot corresponding to θ_q. The objective function can obtain the minimum value when $\partial\Psi/\partial s_q(t) = 0$, and $s_q(t)$ can be expressed as

$$s_q(t) = \frac{a^H\left(\theta_q\right)\Gamma_q^{-1} x(t)}{a^H\left(\theta_q\right)\Gamma_q^{-1} a\left(\theta_q\right)}. \tag{15}$$

By exploiting the matrix inversion theorem, $s_q(t)$ can be rewritten as

$$s_q(t) = \frac{a^H\left(\theta_q\right)\Omega^{-1} x(t)}{a^H\left(\theta_q\right)\Omega^{-1} a\left(\theta_q\right)}. \tag{16}$$

Hence, the weight vector of the coherent signals is calculated as

$$w_q = \frac{\Omega^{-1} a\left(\theta_q\right)}{a^H\left(\theta_q\right)\Omega^{-1} a\left(\theta_q\right)}. \tag{17}$$

Thereby, the signal power of corresponding direction can be expressed as

$$\tilde{P}_q = w_q^H R_D w_q. \tag{18}$$

By substituting (9) and (17) into (18), the remaining coherent signals can be resolved in this stage. However, some false peaks may emerge in the spatial spectrum, which degrade the accuracy of direction finding to some extent.

Herein, the interference-plus-noise covariance matrix in [30, 31] is utilized to acquire spatial spectrum, which can be expressed as

$$\widehat{R}_{i+n} = \int_{\bar{\Theta}} \tilde{P}_q(\theta) \bar{a}(\theta) \bar{a}^H(\theta) d\theta, \tag{19}$$

where Θ denotes an angular sector, and $\bar{\Theta}$ denotes the complement sector of Θ. It can be noticed that $\bar{\Theta} \cup \Theta$ covers the entire spatial domain, while $\bar{\Theta} \cap \Theta$ is empty. Based on (16), the direction finding can be acquired accurately. Finally, the spatial power spectrum is calculated as

$$P(\theta) = \frac{1}{\bar{a}^H(\theta)\widehat{R}_{i+n}^{-1}\bar{a}(\theta)}. \tag{20}$$

4.3. Discussion of Proposed Method. The flow of the proposed algorithm is summarized in Figure 3. Herein, the coexistence of coherent and uncorrelated signals are received together in the PBR system, which are closely spaced or in the same direction. The uncorrelated signals are firstly removed by building spatial difference matrix. Then, in order to improve the accuracy of the remaining coherent signals and avoid the effect of cross-terms, the IAA algorithm is performed with respect to a rearranged spatial difference matrix. Finally, the DOA of the desired signal is obtained from a new spatial spectrum by using the reconstruction of interference-plus-noise covariance matrix. It can be noticed that our proposed algorithm includes the advantages of spatial-differencing technique and IAA method. When the uncorrelated signal and coherent signal are in the same direction, the proposed algorithm can eliminate uncorrelated signal in multipath environment. In practical applications, the performance of spatial difference technology is significantly reduced in limited snapshots and low SNR. However, the proposed algorithm has satisfactory performance. Besides, the proposed algorithm can deal with the coherent and uncorrelated signals, respectively, which can improve the speed of DOA estimation in practical application.

5. Simulation Results

In this section, we investigate and analyze the performance of our proposed algorithm. The VHF band frequency agile-phased array radar is used as illuminator in the PBR system. The ULA with 16 omnidirectional sensors is considered as the surveillance antenna, and the half power width of main lobe is calculated as $\theta_{0.5} = 6.4°$. In the simulation, the scanning gird is from -90° to 90°, and the interval between adjacent grid points is 0.1°.

5.1. Effectiveness of Direction Finding. In the first simulation, the DOAs of three uncorrelated signals are set to [−30° 2° −25°], the DOAs of two coherent signals are set to [−3° 2°],

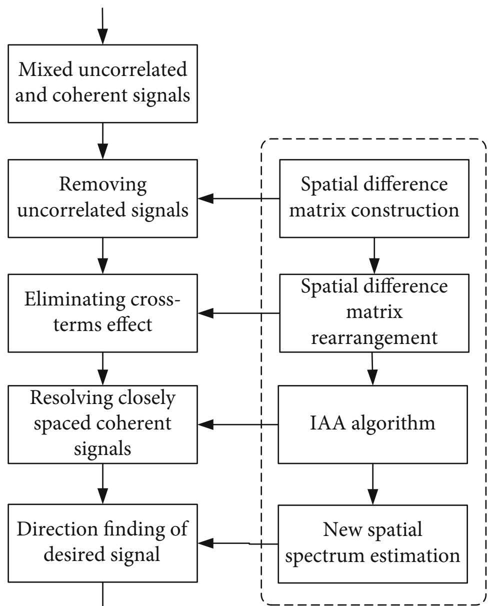

Figure 3: Flow of the proposed method.

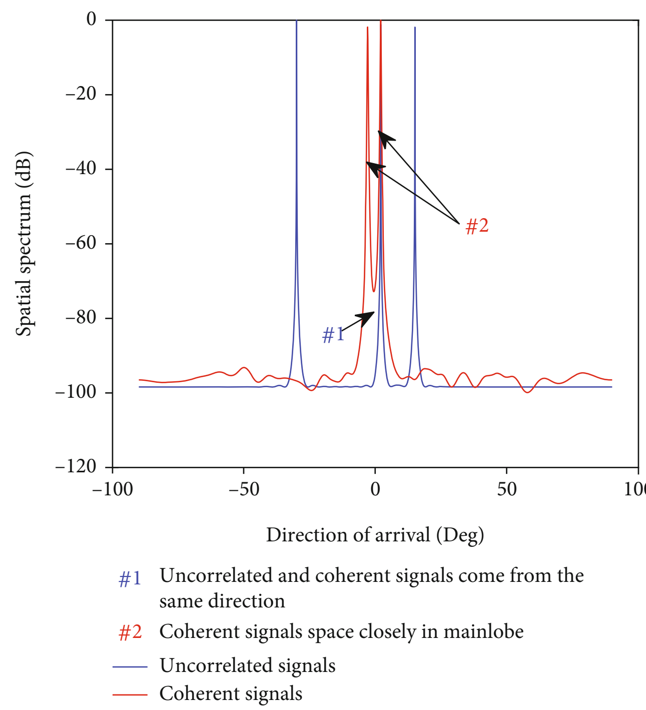

Figure 4: Spatial spectrums of the coherent and uncorrelated signals.

and the complex reflection coefficient of coherent signals are set to $[1\ 0.3837 + j0.9017]$. It can be noticed that one of uncorrelated signals comes from the same direction as desired signal, and two coherent signals are close in the main lobe. The SNR and snapshot number in the simulation are, respectively, set to 10 dB and 100. Figure 4 displays the spatial spectrum of the coherent and uncorrelated signals, and Figure 5 displays the direction finding of the desired signal. It can be noticed that the proposed algorithm can successfully eliminate the uncorrelated signals and effectively resolve the coherent signals. Therefore, the proposed algorithm has satisfactory performance in the coexistence of coherent and uncorrelated signals in multipath environment.

5.2. Probability of Resolution. The second simulation is performed to analyze the resolution performance of closely spaced signals. Herein, the probability of resolution is defined as

$$\mathrm{P}_r = \frac{T_r}{T}, \tag{21}$$

where T_r and T, respectively, denote the times of successful resolution of coherent signals and the total Monte Carlo trials. In our simulation, the result of DOAs detection is recognized as successful if the angular separation between two coherent signals satisfies that $\Delta\theta = |(\theta_1 - \theta_2)| \leq 1$. The DOA of the first coherent signal is set to 0°, and the DOA of the second coherent signal varies from 0° to 5°. The probability of resolution with 200 Monte Carlo trials is shown in Figure 6, where the SNR is set to 0 dB and 10 dB, while the number of snapshots is set to 10 and 100. It can be noticed that the performance degradation of the algorithm is very small under low SNR, and the performance is improved

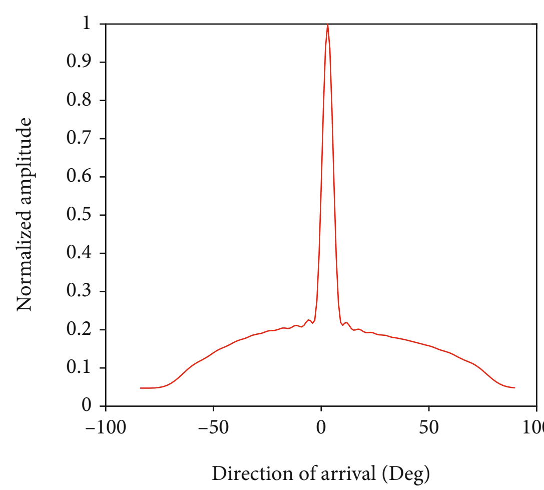

Figure 5: Direction finding of desired signal.

with the increase of SNR. Therefore, the super-resolution performance of the proposed algorithm has been further demonstrated.

5.3. Probability of Detection. In the third simulation, the performance of direction finding of PBR is investigated by comparing with the method in [17–19]. Herein, the detection probability is defined as

$$\mathrm{P}_d = \frac{T_d}{T}, \tag{22}$$

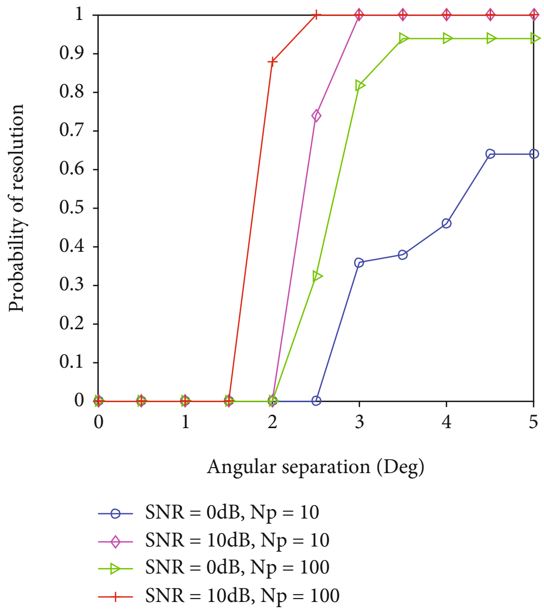

Figure 6: The probability of resolution versus the angular gap.

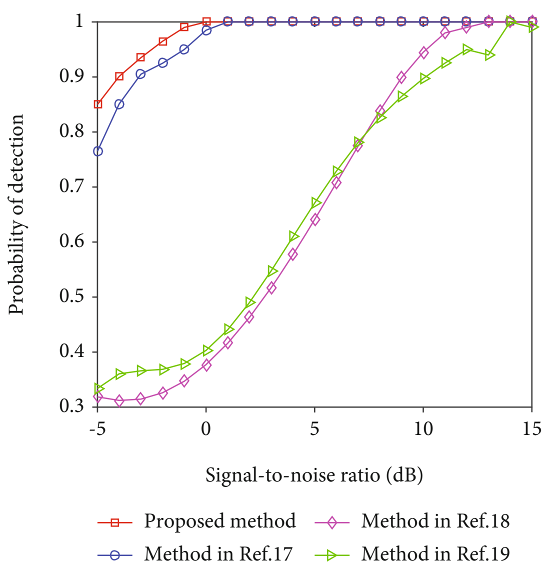

Figure 7: The detection probability versus SNR with $N_p = 100$.

where T_d and T, respectively, denote the times of successful detection and overall Monte Carlo experiments. The result of direction finding is recognized as successful if the difference between the true direction and the estimated direction is less than 1°, i.e., $P_d = 1$ subject to $\Delta\theta = |(\theta_1 - \theta_2)| \leq 1$. Figures 7 and 8, respectively, display the detection probability versus SNR and snapshot number. Since the traditional subspace-based methods essentially reflect the orthogonality between signal and the noise subspace in a certain direction, the performance is significantly reduced under low SNR with limited snapshot number. However, the proposed algorithm utilizes the power of signal, which has satisfactory performance in terms of low SNR with limited snapshot number.

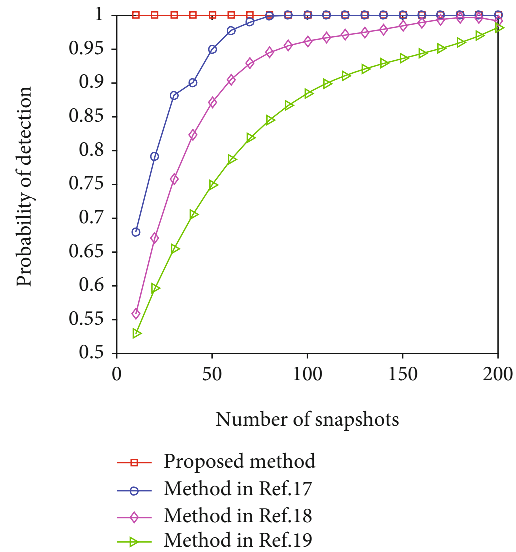

Figure 8: The detection probability versus snapshot number with SNR = 10 dB.

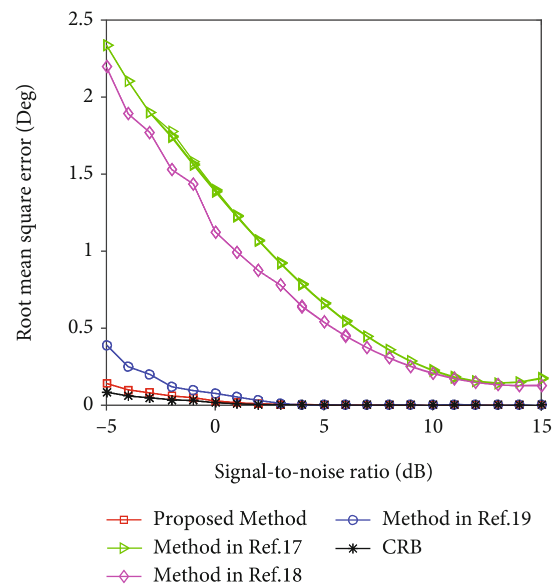

Figure 9: The RMSE of direction finding of desired signal versus SNR.

5.4. RMSE of Direction Finding. In the last simulation, we investigate the root mean square error (RMSE) of proposed method in comparison with the method in [17–19] and Cramér–Rao bound (CRB), where the RMSE is defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{200}\frac{1}{K}\sum_{m=1}^{200}\sum_{k=1}^{K}\left(\widehat{\theta}_k^{(m)} - \theta_k\right)^2}. \tag{23}$$

Figures 9 and 10, respectively, show the RMSE versus SNR and the number of snapshots, where a total of 200 Monte Carlo experiments are utilized in each scenario.

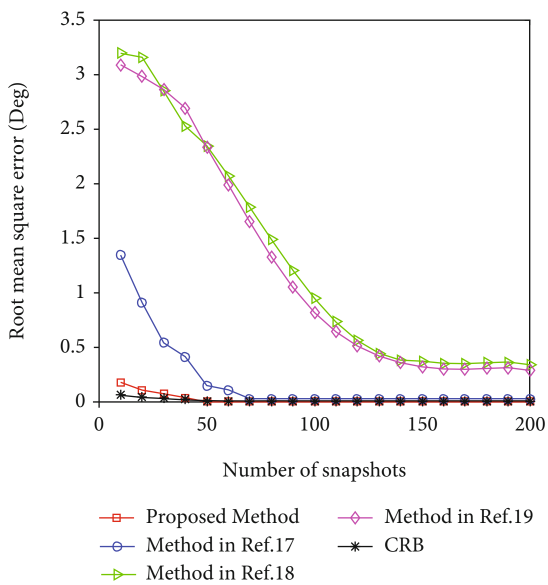

Figure 10: The RMSE of direction finding of desired signal versus snapshot number.

For the algorithms in [17, 18], the performance degradation is due to the use of spatial smoothing techniques that reduce the array aperture to obtain the DOA of the target signal. Since the decorrelation process in [17, 18], respectively, utilizes the forward spatial smoothing algorithm and forward/backward spatial smoothing algorithm, the performance of the method in [17] is worse than that of the method in [18]. For the method in [19], the performance of direction finding is close to our method when the SNR changes from the -5 dB to 15 dB. However, when the snapshot number is smaller than 50, the performance degrades significantly. For the proposed method, the IAA algorithm with respect to a rearranged spatial difference matrix is adopted to effectively solve the effect of cross-terms and improve the accuracy of coherent signals. Therefore, our proposed algorithm works well when coherent and uncorrelated signals coexist in the multipath propagation, which can improve performance in terms of low SNR and limited snapshot number.

6. Conclusions

In this paper, we propose a novel direction-finding algorithm for PBR system when coherent and uncorrelated signals coexist in the multipath environment. Firstly, the spatial-differencing technique is exploited to eliminate the uncorrelated signals. Then, in order to address the effect of cross-terms and improve the accuracy of the remaining coherent signals, the IAA algorithm is performed with respect to a rearranged spatial difference matrix. Finally, the DOA of desired signal is obtained by using the reconstruction of interference-plus-noise covariance matrix. Our proposed algorithm combines the advantages of IAA algorithm and spatial-differencing technique. Numerical simulation results demonstrate the performance of the proposed algorithm. Especially, the proposed method can improve the performance under low SNR and limited snapshot number, which can be considered as a feasible solution for PBR system.

Appendix

A. Proof of Avoiding the Effects of Cross-Term

In order to avoid the effects of cross-term in (8), the spatial difference matrix is rearranged by taking the absolute values [20], which is given by

$$R_D = U_d|\Lambda_d|U_d^H. \tag{A.1}$$

Since the column space spanned by U_d is equal to the column space spanned by the steering matrix A_c, we can obtain

$$U_d = A_c T, \tag{A.2}$$

where T denotes a $K_c \times 2K_c$ column full-rank matrix. Then R_D can be expressed as

$$R_D = A_c T|\Lambda_d|^{1/2} M |\Lambda_d|^{1/2} T^H A_c^H, \tag{A.3}$$

where $|\Lambda_d|^{1/2} = \text{diag}\{\gamma_1^{1/2}, \gamma_1^{1/2}, \cdots, \gamma_{K_c}^{1/2}, \gamma_{K_c}^{1/2}\}$ and $M = \text{diag}\{1,-1, \cdots, 1,-1\}$.

In addition, R_D can be rewritten as

$$R_D = \sum_{k=1}^{K_c} \bar{U}_k \bar{\Lambda}_k \bar{U}_k^H, \tag{A.4}$$

where $\bar{\Lambda}_k = \text{diag}\{\bar{\gamma}_k, -\bar{\gamma}_k\}$; $\bar{\gamma}_k$ and $-\bar{\gamma}_k$ denote the eigenvalues of positive and negative pairs, respectively, $k = 1, 2, \cdots, K_c$. $\bar{U}_k = [\bar{u}_k, \bar{u}_k']$, $\bar{u}_k$, and $\bar{u}_k'$ denote the eigenvectors corresponding to $\bar{\gamma}_k$ and $-\bar{\gamma}_k$, respectively. Similarly, since the column space $\bar{U}_D$ spanned by $\bar{U}_k$ and the column space spanned by the steering matrix A_c are equal [32], we can obtain

$$\bar{U}_D = A_{ck}\bar{T}_k. \tag{A.5}$$

Thus, R_D can be rewritten as

$$R_D = A_c \bar{T}\bar{\Lambda} M \bar{\Lambda}^H \bar{T}^H A_c^H. \tag{A.6}$$

where $\bar{T} = \text{blkdiag}\{\bar{T}_1, \bar{T}_2, \cdots, \bar{T}_{K_c}\}$ and $\bar{\Lambda} = \{\bar{\gamma}_1^{1/2}, \bar{\gamma}_1^{1/2}, \cdots, \bar{\gamma}_{K_c}^{1/2}, \bar{\gamma}_{K_c}^{1/2}\}$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

The main idea was proposed by Panhe Hu; Xiaolong Su and Zhen Liu performed the experiments and analyzed the data; Panhe Hu wrote the paper.

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