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Two-stage DOA estimation for CDMA multipath signals

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ABSTRACT

This paper mainly estimates the direction-of-arrival (DOA) of the code-division multiple access (CDMA) signal in a multipath environment using a two-stage procedure. In general, in a multipath environment, signal DOA would nominally be a DOA phenomenon, causing the DOA estimation method to be biased. However, if the received signal is first projected onto an appropriate beamspace, then the multipath effect will decrease. Therefore, we have proposed a two-stage method to address this issue. The procedure that we used is as follows: first, we used the received signal and particle swarm optimization (PSO) to estimate the signal DOA. Second, the DOA estimated in stage I was used to set up the beamspace multiple signal classification (BMUSIC) method, after which Taylor expansions were used to expand the stage I DOA and to set up a first-order iteration BMUSIC (IBMUSIC) method, the purpose of which was to reduce the multipath effect and the search complexity. This method was a DOA estimation method that combined PSO/IBMUSIC and aimed to reduce the search complexity and estimation bias for multipath signals. Finally, several simulation examples were used to illustrate the designed procedure and confirm the performance of this method.

1. Introduction

Code-division multiple access (CDMA) has been adopted as the third-generation mobile wireless communication standard in spread-spectrum technology. The use of CDMA spread-spectrum technology and special coding methods can increase the effective use of bandwidth and resistance to interference. For this reason, it has attracted substantial attention in recent years [8,16]. In many practical applications, the reflection and scattering signal source from multipath transmissions causes the signal energy to be around the vicinity the DOA, thus leading to a nominal DOA phenomenon. This kind of scattered DOA phenomenon can cause a significant degradation of DOA estimation performance, even at low levels [2,3,22].

Accurate user positioning is very important in mobile wireless communication services; therefore, an array signal has been developed to improve CDMA system performance [8] and provide an accurate user positioning system [11,23]. In CDMA systems, each user uses a unique pseudo-noise (PN) code to encode their data. During each user's transmission, the data of other users are considered a source of multiple access interference (MAI). Exporting the received data using a code-match filter and array signal technology can convert the problem of estimating the DOA from multiple user sources into that of there being only one target signal source in a noisy environment. The advantage of using a code-match filter in a CDMA system has been confirmed to provide unbiased and low-MSE (mean-square-error) [23], DOA estimation using traditional multiple signal classification (MUSIC) [21], minimum variance distortionless response (MVDR) [4] and estimation of signal parameters via rotational invariance techniques (ESPRIT) [20] estimation methods. However, these estimation methods can bias the estimation of DOA due to the existence of multipath signals [2,22]. In addition, the search complexity

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and the estimation accuracy of these methods depend on the search grid number and size used during the search; thus, the methods are time consuming and impractical. A high-efficiency method was proposed by Rao and Hari [19], who used polynomial roots to set up the search. However, the accuracy of this method will be low for a low signal-to-noise ratio (SNR) and for MAI, and selection of an inappropriate root will generally cause serious bias. Another high-efficiency method, GA/IMUSIC [10], can provide good DOA estimation and a high-efficiency search in the presence of a low SNR, but this method cannot solve the multipath effect. In addition, the CDMA signal in a multipath environment will transform the DOA estimation issue into an even more complicated, nonlinear problem. Many local solutions exist, and when using GA/IMUSIC the estimation bias is usually worse than that obtained when using traditional methods [4,20,21].

In summary, this paper proposes a method for the low-complexity calculation and accurate DOA estimation of CDMA multipath signals. In this paper, the multipath fading channel uses the Rayleigh (or Rician) distribution and the statistical property of a known channel. The fading coefficient of each multipath signal utilizes a Gaussian random process in the model [25]. Under multipath fading, the DOA estimation has many local solutions, and the complexity increases. Therefore, this study has two stages. In the first stage, the signal DOA is estimated using particle swarm optimization (PSO). The second stage involves the use of the beamspace MUSIC (BMUSIC) method using the DOA estimated in stage I to reduce the estimation bias caused by multipath signals; this method is then expanded to estimate DOA using a first-order Taylor approximation expansion and a first-order iteration BMUSIC (IBMUSIC) method, which simplifies the problem to that of a one-dimensional search.

Many studies have already been conducted on applications of PSO [5,7,11,12,24], and the development of PSO was inspired by animal social behavior, such as that of birds, bees, and fish [12]. PSO is a parallel whole-region search technology, in which each possible solution is termed a particle, and the particle adjustment method mainly depends on the previous best solution and the overall (i.e., over all particles) best solution. Because PSO can search many spatial points at the same time, the potential for convergence to a local solution is decreased, and it is not necessary to determine whether the search function is differentiable or continuous. PSO/IBMUSIC combines the advantages of PSO and IBMUSIC to achieve weak dependence on the initial parameters and fast convergence to the correct DOA estimate. The search method starts a multipoint search using pure PSO and ends with an iterative search using pure IBMUSIC. The transition from PSO to IBMUSIC occurs when the overall best solution of same space remains the same L_i generations [9]. Finally, the algorithm uses the results of simulations to show that this PSO/IBMUSIC method is very suitable for CDMA signal DOA estimation in multipath environments.

The rest of this paper is organized as follows. The next section outlines the problem description. The third section presents the details of combining PSO and the IBMUSIC approach to DOA estimation. Numerical simulation results that demonstrate the effectiveness of the proposed method are showcased in the fourth section. The final section summarizes our conclusions regarding the proposed method.

2. Problem description

Consider a DOA scenario in a baseband CDMA system with P users. Let the bit duration T_b be equal to the processing gain L times the chip duration T_c. The multipath reflections are assumed to follow the local scattering model [6,14], and each user's signal (which has a scattered multipath) can be well approximated by a single point source that has an angle spread $\Delta\theta$ and lies within some angular interval centered on the line-of-sight angle θ_p, $p = 1, 2, \ldots, P$. For each θ_p, there are a set of J random multipath angles that are uniformly distributed over the interval $[\theta_p - 0.5\Delta\theta, \theta_p + 0.5\Delta\theta]$. After demodulation and chip sampling, the received signal across a uniform linear array (ULA) with M elements at the kth bit interval can be represented as

$$\mathbf{X}(k) = \sum_{p=1}^{P}\sum_{j=1}^{J}\alpha_{p,j}\mathbf{a}(\theta_{p,j})r_p(k)\mathbf{c}_p^T + \mathbf{N}(k) = \sum_{p=1}^{P}\mathbf{g}_p r_p(k)\mathbf{c}_p^T + \mathbf{N}(k) \tag{1}$$

where $\mathbf{X}(k)$ is an $M \times L$ matrix, $\alpha_{p,j}$ is the associated complex gain due to the slow-fading assumption, $r_p(k) = e_p\, h_p(k)$, e_p is the signal amplitude of the pth user, and $h_p(k) \in \{-1,1\}$ is the kth data bit of the pth user, spread by the PN codeword $\mathbf{c}_p$. $\mathbf{N}(k)$ is the spatially and temporally white complex Gaussian noise with zero mean and variance σ_n^2, and $\mathbf{g}_p$ is the composition of J paths for the pth signal. Let $a_m\ (\theta_{p,j}) = \exp[-i2\pi d(m-1)\sin\theta_{p,j}/\beta]$ denote the response of the mth sensor array of the jth path from the pth signal, where $i = \sqrt{-1}$, d is the sensor spacing, and β is the wavelength of the signal carrier. $\mathbf{a}(\theta_{p,j}) = [a_1(\theta_{p,j})\ a_2(\theta_{p,j}) \cdots a_M(\theta_{p,j})]^T$ is the response vector of the jth path from the pth user signal with direction angle $\theta_{p,j}$. For convenience, we will assume that p is the first user of interest. After passing through the code-matched filter, the despread signal at the kth bit interval is given by

$$\mathbf{y}(k) = \mathbf{X}(k)\mathbf{c}_1 = Lr_1(k)\mathbf{g}_1 + \sum_{p=2}^{P}\mathbf{g}_p r_p(k)q_{p1} + \mathbf{n}_1(k) = Lr_1(k)\mathbf{g}_1 + MAI + \mathbf{n}_1(k) \tag{2}$$

where $q_{p1} = \mathbf{c}_p^T\mathbf{c}_1$ and $\mathbf{n}_1(k) = \mathbf{N}(k)\mathbf{c}_1$. The second term on the right-hand side of Eq. (2) can be viewed as the MAI [17]. Thus, this second term can be included into the noise term $\mathbf{n}_1(k)$, and the composite vector is replaced using a new nomenclature as $\mathbf{n}_1'(k)$ with zero mean and variance $\sigma^2_{n_1'}$ [13]. Then, equation (2) can be rewritten as

$$\mathbf{y}(k) = Lr_1(k)\mathbf{g}_1 + \mathbf{n}'_1(k). \tag{3}$$

It can be seen that the first term in Eq. (3) is not correlated with the last term in Eq. (3); therefore, the covariance matrix of $\mathbf{y}(k)$ can be written as

$$\mathbf{R} = E\{\mathbf{y}(k)\mathbf{y}^H(k)\} = L^2e_1^2\mathbf{g}_1\mathbf{g}_1^H + \sigma_{n'_1}^2\mathbf{I}_M = L^2e_1^2\sum_{j=1}^{J}\|\alpha_{1,j}\|^2\mathbf{a}(\theta_{1,j})\mathbf{a}^H(\theta_{1,j}) + \sigma_{n'_1}^2\mathbf{I}_M \tag{4}$$

where $E\{\cdot\}$, $\|\cdot\|$, and the superscript H denote the expectation, 2-norm, and complex conjugate transpose, respectively. $\mathbf{I}_M$ is the identity matrix with size $M \times M$. For finite received signal samples, the received signal correlation matrix $\mathbf{R}$ is replaced by the estimated sample average $\widehat{\mathbf{R}}$, which can be obtained as outlined in [6] as

$$\widehat{\mathbf{R}} = \frac{1}{N}\sum_{k=1}^{N}\mathbf{y}(k)\mathbf{y}^H(k) \tag{5}$$

where N is the total number of observed bits. The eigendecomposition of matrix Eq. (5) can be expressed as

$$\widehat{\mathbf{R}} = \sum_{m=1}^{M}\lambda_m\mathbf{e}_m\mathbf{e}_m^H = \lambda_1\mathbf{e}_1\mathbf{e}_1^H + \mathbf{E}_n\mathbf{\Lambda}_n\mathbf{E}_n^H \tag{6}$$

where $\lambda_1 \geqslant \lambda_2 = \lambda_3 = \cdots = \lambda_M = \sigma_{n'_1}^2$ are the eigenvalues of $\widehat{\mathbf{R}}$ and $\mathbf{e}_m$ denotes the eigenvector associated with λ_m for $m = 1, 2, \ldots, M$. Moreover, $\mathbf{e}_1$ and $\mathbf{E}_n = [\mathbf{e}_2,\ldots,\mathbf{e}_M]$ are orthogonal and span the signal with a composition of J paths and the noise subspace corresponding to $\widehat{\mathbf{R}}$, respectively. $\mathbf{\Lambda}_n = \sigma_{n'_1}^2\mathbf{I}_{M-1}$ is the noise eigenvalue matrix. Furthermore, $\mathbf{e}_1$ spans the same signal subspace with the composition of the J paths signal. Thus, we obtain $\mathbf{E}_n^H\mathbf{e}_1 = \mathbf{0}$ and $\mathbf{e}_1^H\mathbf{E}_n = \mathbf{0}$. The MUSIC estimator estimates the DOA of the desired user based on the highest peak of the following spectrum [21]:

$$S_{MUSIC}(\theta) = \max_\theta K(\theta) = \max_\theta \frac{1}{|\mathbf{a}^H(\theta)\mathbf{E}_n\mathbf{E}_n^H\mathbf{a}(\theta)|} \tag{7}$$

where $\mathbf{a}(\theta) = [\,a_1(\theta) \quad a_2(\theta) \quad \cdots \quad a_M(\theta)\,]^T$ is the spatial scanning vector and $\theta \in [-90°,90°]$ varies within the entire search space. It is noted that the DOA estimation attempts to determine the maximum of the spectrum cost function and the minimum of their denominators (the null spectrum). The spatial vector $\mathbf{a}(\hat{\theta}_1)$can be estimated using the maximum cost function K as follows:

$$\mathbf{a}(\hat{\theta}_1) = \max_\theta K(\theta) \simeq \min \mathbf{E}_n^H\mathbf{g}_1 = \min \mathbf{E}_n^H\sum_{j=1}^{J}\alpha_{1,j}\mathbf{a}(\theta_{1,j}) \simeq \min \mathbf{E}_n^H\sum_{j=1}^{J}\mathbf{a}(\theta_1 + \Delta\theta_j) \tag{8}$$

where $\Delta\theta_j$ is the angle spread caused by the jth path with a uniform distribution. The estimation of $\hat{\theta}_1$ based on Eq. (8) contains multipath signal bias. To obtain an unbiased estimation, the post-despreading signal $\mathbf{y}(k)$ can be passed through the signal space $\mathbf{e}_1$ by the steering vectors, which reduces the multipath effect [2,22]. In this paper, we propose a beamspace approach, which first passes the original post-dispreading signal $\mathbf{y}(k)$ into a subspace of beamspace and then processes the beamspace data using well-known direction-finding algorithms such as MUSIC.

In general, the cost function K(used in Eq. (7)) is a very highly nonlinear function with probability θ. Many local maxima may exist. It is very difficult to determine the global maximum of K in Eq. (7) using conventional searching methods. PSO methods use optimization and evolutionary computation learning algorithms. Therefore, in this study, the use of PSO methods to search the neighborhood of the signal direction for the initial angle of the IBMUSIC estimator and rebuild the received data is passed through the signal space. The IBMUSIC estimator, which utilizes a first-order Taylor series approximation to the spatial scanning vector in terms of estimating deviation, results in a reduction to a simple one-dimensional optimization problem [10].

3. PSO/IBMUSIC estimator

3.1. The PSO-based estimator

In recent years, PSO is often used in industrial system applications because of its good efficiency in the treatment of many nonlinear or modeless optimization problems [7,15,18]. The use of PSO was proposed in 1995 [12], and related PSO analysis and applications have matured [7,15,18]. This technique is a randomly optimized calculation method, based on a population [1,12], that attempts to find the program that yields the best solution.

In this paper, we proposed to solve the optimization problem of equation (7) using PSO. We wish to discover the maximal value of Eq. (7) that is equivalent to the best-fit value obtained during the searching process. Using an intuitive method, we defined the fitness function as:

$$Fit(\theta) = K(\theta) = \frac{1}{\left|\mathbf{a}^H(\theta)\mathbf{E}_n\mathbf{E}_n^H\mathbf{a}(\theta)\right|} \tag{9}$$

Our purpose was to achieve maximum fitness; therefore, we used PSO to produce an optimized solution. Each group within the PSO is composed of many particles, and each particle represents a feasible solution and has its own position and speed. In this study, we randomly generated the initial values for particle position and speed. Then, the development pattern of each particle involves three pathways: (1) the previous direction of movement, (2) the optimized solution for the direction of movement to that point, and (3) the group-optimized solution up to that point. Moving the particles in this way enables the properties of particles to be added during the next generation.

In the following text, we will introduce the related details on how to use PSO to solve the DOA estimation problem. The first step is to randomly generate the position and speed of S particles. In generation t, the position and speed of particle i are represented as $\theta_i(t)$ and $v_i(t)$, respectively. Then, the updated speed and position of particle i are:

$$v_i(t+1) = \chi \cdot v_i(t) + k1 \cdot \varphi 1 \cdot (l_i - \theta_i(t)) + k2 \cdot \varphi 2 \cdot (g - \theta_i(t)) \tag{10}$$
$$\theta_i(t+1) = \theta_i(t) + v_i(t+1) \tag{11}$$

where $0 \leqslant \chi < 1$ is an inertia weight, $k1$ and $k2$ are positive constant parameters termed acceleration coefficients, $\varphi 1$ and $\varphi 2$ are uniformly distributed random numbers in the range $[0,1]$, l_i is the individual best position of the ith particle thus far, and g is the best position found by the entire swarm so far.

Eqs. (10) and (11) are patterns of updated speeds and positions for each particle. After each particle is updated, we used Eq. (9) to calculate the fitness value. If the new particle fitness value is higher than the previous optimized solution, the optimized solution will be replaced by the new particle. If the overall optimized fitness value of the new particle is higher than that of the overall optimized solution, then the overall optimized solution is replaced by the new particle. Because this process is repeated, the entire particle will approach the overall optimized solution.

Eq. (8) suggests that the direct estimation of DOA causes bias due to multipath effects. To obtain an estimate without bias, we propose to use the IBMUSIC method, which is described in the following section.

3.2. IBMUSIC estimator

From Eq. (8) above, DOA estimation generates multipath bias. To realize unbiased estimation and reduce the calculation time, we propose an IBMUSIC method in this paper. We first converted the CDMA signals received by an array antenna using a spread-spectrum solution. The converted signal was passed through a beamspace [2], and an iteration IMUSIC method was established. The relevant flowchart is illustrated in Fig. 1. In the beamforming process, the signals from the spread spectrum solution were passed directly through a beamforming instrument. We assumed the following beamspace matrix:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{a}_1(\hat{\theta}_1) & \mathbf{a}_2(\hat{\theta}_1 + \xi_1) & \cdots & \mathbf{a}_B(\hat{\theta}_1 + \xi_{B-1}) \end{bmatrix} \tag{12}$$

where $\mathbf{Q}$ is an $M \times B$ beamspace matrix, ξ_i (for $i = 1,2,\ldots,B-1$) is uniformly distributed and is a small value, and $\hat{\theta}_1$ is the DOA estimated in the first stage. In this paper, the value of $\hat{\theta}_1$ is based on the PSO estimator. The received signal passed through the beamspace can then be written as (based on [2])

$$\mathbf{z}(k) = \mathbf{Q}^H\mathbf{y}(k) = Lr_1(k)\mathbf{Q}^H\mathbf{g}_1 + \mathbf{n}_z \tag{13}$$

where $\mathbf{n}_z = \mathbf{Q}^H\mathbf{n}_1'(k)$. Similar to the element space domain, the covariance matrix of $\mathbf{z}(k)$ can be written in the beam domain as

$$\mathbf{R}_z = \mathrm{E}[\mathbf{z}(k)\mathbf{z}(k)^H] = \mathbf{Q}^H\mathbf{R}\mathbf{Q} = \sum_{m=1}^{B}\kappa_m\mathbf{b}_m\mathbf{b}_m^H = \kappa_1\mathbf{b}_1\mathbf{b}_1^H + \mathbf{B}_z\Lambda_z\mathbf{B}_z^H \tag{14}$$

where $\kappa_1 \geqslant \kappa_2 = \kappa_3 = \cdots = \kappa_B = \sigma_{n_z}^2$ are the eigenvalues of $\mathbf{R}_z$ and $\mathbf{b}_m$ denotes the eigenvector associated with κ_m for $m = 1, 2, \ldots, B$. $\mathbf{B}_z = [\mathbf{b}_2,\ldots,\mathbf{b}_B]$ and $\Lambda_z = \sigma_{n_z}^2\mathbf{I}_{M-1}$. If we set $\mathbf{Q}^H\mathbf{a}(\theta) = \mathbf{f}(\theta)$, the MUSIC estimator power spectrum in the beamspace domain can be written as

$$S_{BMUSIC}(\theta) = \max_{\theta} K_B(\theta) = \max_{\theta}\frac{1}{|\mathbf{f}(\theta)^H\mathbf{B}_z\mathbf{B}_z^H\mathbf{f}(\theta)|} \tag{15}$$

Under normal conditions, $K_B(\theta)$ is a complicated nonlinear function of θ. To reduce the complexity of the calculation, we estimated the DOA using PSO and Eq. (15) and represented equation (15) with a first-order Taylor series approximation. This DOA search can be replaced by the differential variation of the first-order Taylor series approximation, and therefore, the problem can be reduced to a simple one-dimensional search problem [10]. Based on Eq. (15), the fitness function of BMUSIC searches for the maximum value, which is the same as searching for the minimum value of the denominator of equation (15). Eq. (15) can be represented as

$$\min_{\theta}\ [\mathbf{f}(\theta)]^H\mathbf{B}_z\mathbf{B}_z^H[\mathbf{f}(\theta)]. \tag{16}$$

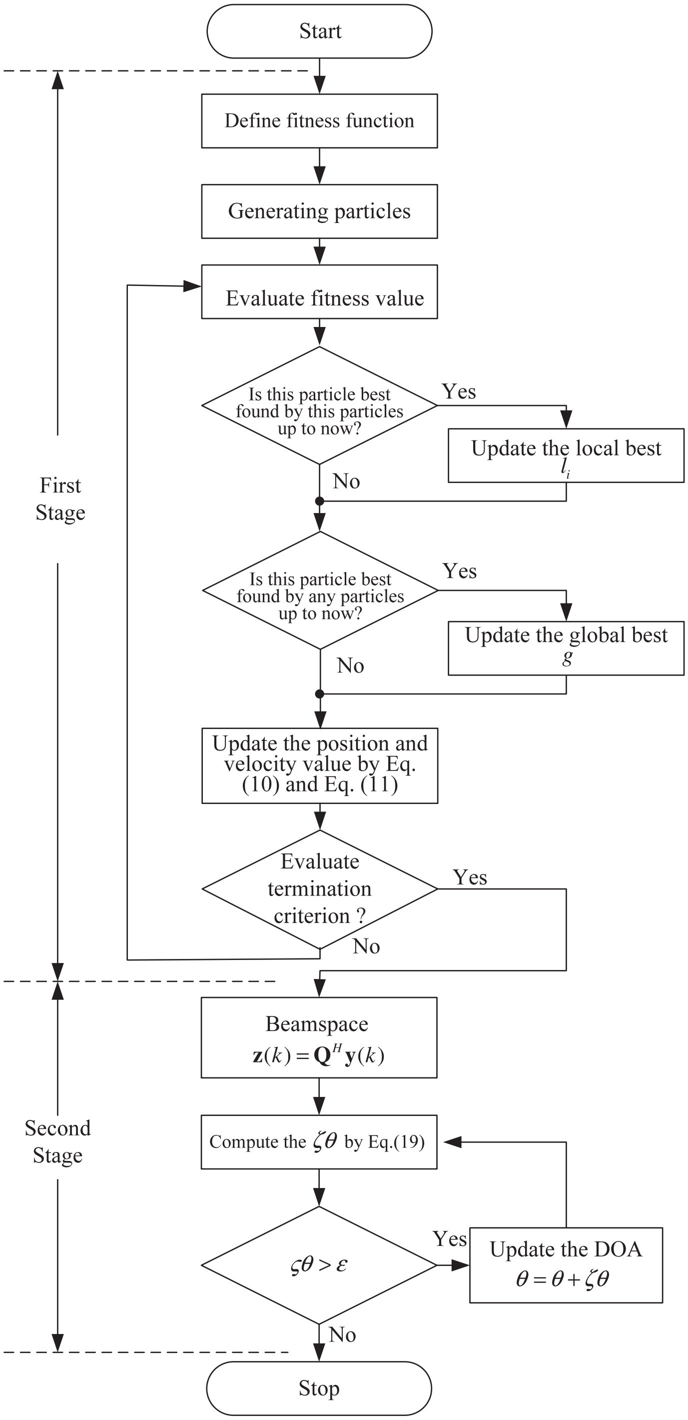

Fig. 1. The flowchart of the proposed method.

In a small region $\zeta\theta$, which is the assumed initial angle of arrival θ_0, $\mathbf{f}(\theta)$ can be approximated by a first-order Taylor series:

$$\mathbf{f}(\theta) = \mathbf{f}(\theta_0 + \zeta\theta) \simeq \mathbf{f}(\theta_0) + \zeta\theta\mathbf{f}'(\theta_0), \tag{17}$$

where $\mathbf{f}'(\theta_0) = \frac{d}{d\theta}\mathbf{f}(\theta)|_{\theta=\theta_0}$. Substitution of Eq. (17) into Eq. (16) results in

$$\min_{\zeta\theta}[\mathbf{f}(\theta_0) + \zeta\theta\mathbf{f}(\theta_0)]^H \mathbf{B}_z \mathbf{B}_z^H [\mathbf{f}(\theta_0) + \zeta\theta\mathbf{f}(\theta_0)]. \tag{18}$$

This is a simple one-dimensional optimization problem. It can then be easily shown that the optimum $\zeta\theta$ is given by:

$$\frac{d\left\{[\mathbf{f}(\theta_0)+\zeta\theta\mathbf{f}(\theta_0)]^H\mathbf{B}_z\mathbf{B}_z^H[\mathbf{f}(\theta_0)+\zeta\theta\mathbf{f}(\theta_0)]\right\}}{d(\zeta\theta)}=0\Rightarrow\zeta\theta=-\frac{Re[\mathbf{f}^H(\theta_0)\mathbf{B}_z\mathbf{B}_z^H\mathbf{f}'(\theta_0)]}{[\mathbf{f}'(\theta_0)]^H\mathbf{B}_z\mathbf{B}_z^H\mathbf{f}'(\theta_0)} \tag{19}$$

The differential variation value $\zeta\theta$ in Eq. (19) has the characteristic that when the value of $\zeta\theta$ is small, a solution is possible (local or overall), and when the value of $\zeta\theta$ is large, a solution is still rather distant (local or overall). In addition, if the initial angle θ_0 is far from the real direction angle θ_1, it is very difficult to find the overall optimized solution in Eq. (17). Therefore, we first searched for a sound θ_0 and then updated the value of DOA using the $\zeta\theta$ property. The procedure is described as follows:

1. Set a search deviation precision value ε.
2. Use the value of DOA estimated using PSO to set $\hat{\theta}_1$ as the initial value for IBMUSIC $\theta_0=\hat{\theta}_1$, and use beamspace matrix $\mathbf{Q}$ as the information for establishing $\mathbf{z}(k)$ in Eq. (13).
3. Calculate the value of $\zeta\theta$ in Eq. (19).
4. If $\zeta\theta>\varepsilon$, update the value of θ_0 to $\theta_0=\theta_0+\zeta\theta$ and repeat steps (3) and (4) until $\zeta\theta\leqslant\varepsilon$. Then, θ_0 becomes the estimated value of the DOA.

3.3. Combining PSO and the IBMUSIC estimator

The PSO method is not affected by the initial value and converges rapidly. For IBMUSIC methods that require accurate initial values, the PSO method is useful. Therefore, we combined the properties of these two methods and developed a combined PSO/IBMUSIC estimator. In the combined PSO/IBMUSIC method, the search process begins with pure PSO and ends with pure IBMUSIC. The conversion from PSO to IBMUSIC occurs at the overall optimized particle in PSO. Through L_i, the unchanged condition is met [10]. Based on the above analysis, the steps used in the design process for DOA estimation with PSO/IBMUSIC are as follows:

1. Use the speed and position of a randomly generated S-particle group.
2. Use Eq. (9) to calculate the fitness value of each particle.
3. Update the particles using PSO. The updated position and speed are obtained using Eqs. (10) and (11).
4. Repeat steps two to four until the overall optimized particle remains the same after L_i generations.
5. Set a search deviation precision value ε.
6. Use the DOA estimate provided by PSO to set $\hat{\theta}_1$ as the initial value for IBMUSIC $\theta_0=\hat{\theta}_1$ and beamspace matrix $\mathbf{Q}$ as the information for establishing $\mathbf{z}(k)$ in Eq. (13).
7. Calculate the value of $\zeta\theta$ in Eq. (19).
8. If $\zeta\theta>\varepsilon$, update the value of θ_0 to $\theta_0=\theta_0+\zeta\theta$ and repeat steps (7) and (8) until $\zeta\theta\leqslant\varepsilon$. Then, θ_0 becomes the estimated value of DOA. The PSO/IBMUSIC flow chart is shown in Fig. 1.

4. Simulation

In this section, we use two simulation examples to prove the feasibility of DOA estimation for CDMA signals under multipath conditions and to compare the results obtained here with those from other methods, including MUSIC [21], MVDR [4], GA [9], PSO [7], and GA/IMUSIC [10]. Regarding the evaluation criteria, various statistical data obtained from references [8,23] are used to compare the performance of the various methods. The root mean square error (RMSE) is the most frequently used performance indicator, and in this paper, the definition of DOA estimation RMSE is:

$$\mathrm{RMSE}_{\hat{\theta}_1}=\sqrt{\left[(1/F)\sum_{j=1}^{F}(\hat{\theta}_j-\theta_1)^2\right]} \tag{20}$$

where F is the number of Monte Carlo (MC) simulations. In the simulation examples, the CDMA signal uses a binary phase-shift keying (BPSK) modulation signal with PN code size 39, and the background noise is assumed to follow a white complex Gaussian distribution with a mean of zero and unit variance. The deviation precision ε and searching grid size $\tau$for MUSIC and MVDR are all set to 0.002°, the beamspace is set to $B=5$ and $\xi=2$, and the relevant parameters for the GA calculation are set as follows [9]:

$$T=50,\quad p_m=0.1,\quad p_c=0.8,\quad l=17,\quad L_g=50 \tag{21}$$

where T is the population size of the GA, p_m is the mutation probability, p_c is the crossover probability, l is the length of the genetic, and L_g is the number of generations. The relevant parameters for the PSO calculation are set as follows [7]:

$$k1=k2=2.1,\quad \chi=0.729,\quad S=50,\quad L_p=50 \tag{22}$$

where $k1$ and $k2$ are acceleration coefficients, χ is the inertia weight, S is the population size of the PSO, and L_p is the number of generations. In all simulations, the results are averaged over $F = 100$ independent runs.

Example 1. Consider active CDMA signals from three users ($P = 3$) with $J = 4$ paths and a ULA with $M = 8$ omnidirectional elements spaced half a wavelength apart. The desired signal is located on the array broadside ($\theta_1 = 5°$), and the impinging angles of all two uncorrelated interferers with an equal power interference-to-noise ratio (INR) = 5 dB are $[-30°, 30°]$. All of the signals had incident angles uniformly distributed over the angular interval $[\theta - 0.5\Delta\theta \quad \theta + 0.5\Delta\theta]$, where the angular spread was $\Delta\theta = 5°$; and all of the signal powers were set to a normalized distribution such that all multipath rays were of equal power with a fixed amplitude scale of $1/\sqrt{J}$. Each scatter was spatially independent and identically distributed. The additive noise was assumed to be zero-mean spatially white with unit variance and was uncorrelated with all signals.

Among the simulation results, Fig. 2 illustrates the IBMUSIC method; the initial values are depicted as a histogram with random average scores in the range $[-90°, 90°]$. In Fig. 2, approximately 15.8% of the estimated DOA values fall in the range $[2°, 8°]$; the average search includes 569 iterations, and therefore, the performance and convergence number of the IBMUSIC method can be easily affected by the initial values used, leading to poor results. Table 1 compares the RMSE of the method proposed in this paper with other methods; although the evolutionary methods (GA, PSO) use shorter searching times (defined as: population × evolution generations) compared with traditional MUSIC and MVDR searching methods, their estimation accuracy is poorer. The reason for this is that the DOA estimation of CDMA signals in multipath environments is

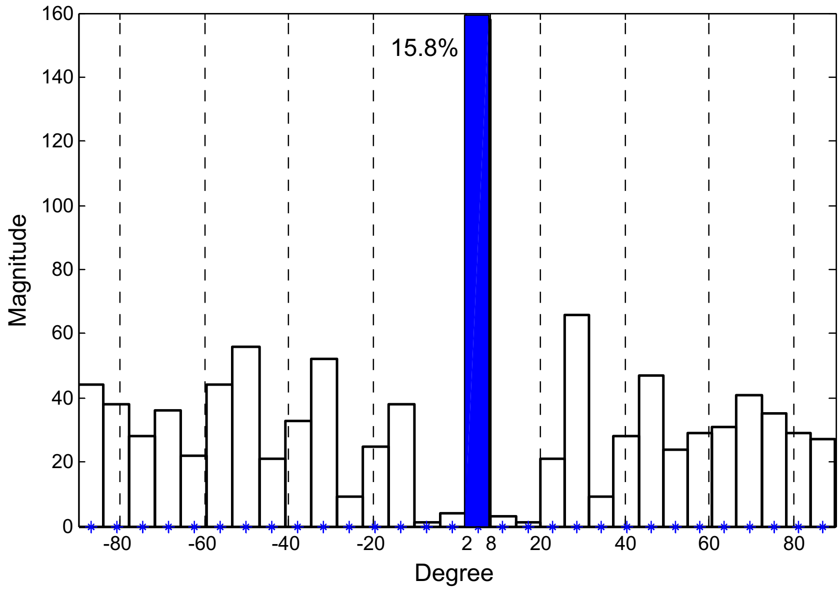

Fig. 2. The DOA estimation histogram of IBMUSIC with random initial values for Example 1 under SNR = 25 dB.

Table 1
DOA estimation and search number using the MUSIC, MVDR, GA-based, PSO-based, GA/IMUSIC, and proposed methods in Example 1.

Estimators	SNR	Number of searches		Estimation error ($\lvert\theta - \hat{\theta}\rvert$)
		Iterations	Total number of function evaluations[a]	
Example 1				
MUSIC	0 db	90001		5.2469
	25 db	90001		1.5661
MVDR	0 db	90001		1.6954
	25 db	90001		1.6771
GA	0 db		2500(50 × 50)	10.5228
	25 db		2500(50 × 50)	1.6108
PSO	0 db		2500(50 × 50)	10.6565
	25 db		2500(50 × 50)	1.5370
GA/IMUSIC	0 db	11	900(50 × 18)	10.5188
	25 db	11	850(50 × 17)	1.5670
Proposed	0 db	20	650(50 × 13)	0.3968
	25 db	21	600(50 × 12)	0.3905

[a] Total number of function evaluations: population size × number of generations.

quite complicated, whereas traditional MUSIC and MVDR methods perform searches over the full search space, and their search times are directly affected by the size of the searching accuracy grid τ. In addition, the estimation of DOA using GA and GA/IMUSIC are almost equally poor, as shown in Eq. (8), and many local solutions exist. Because GA/IMUSIC cannot escape from these local solutions, these two methods have nearly the same performance, suggesting that GA/IMUSIC cannot deal with this type of problem. Regarding the RMSE values for performance evaluation listed in Table 1, the estimation of DOA is very inaccurate if multipath effects are not considered; this is also the main reason that we adopted a two-stage method to address this issue. Table 1 shows that the method proposed in this paper is much better than the other methods tested, and the search times are very low. In particular, when SNR = 0, the RMSE of the method proposed in this paper is four

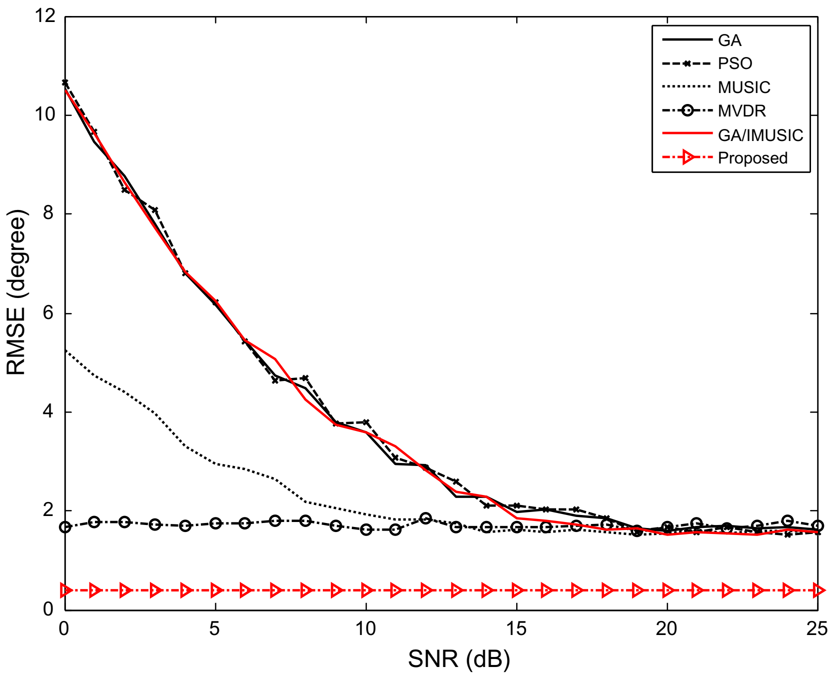

Fig. 3. RMSE of DOA estimation versus the SNR of the desired user in Example 1.

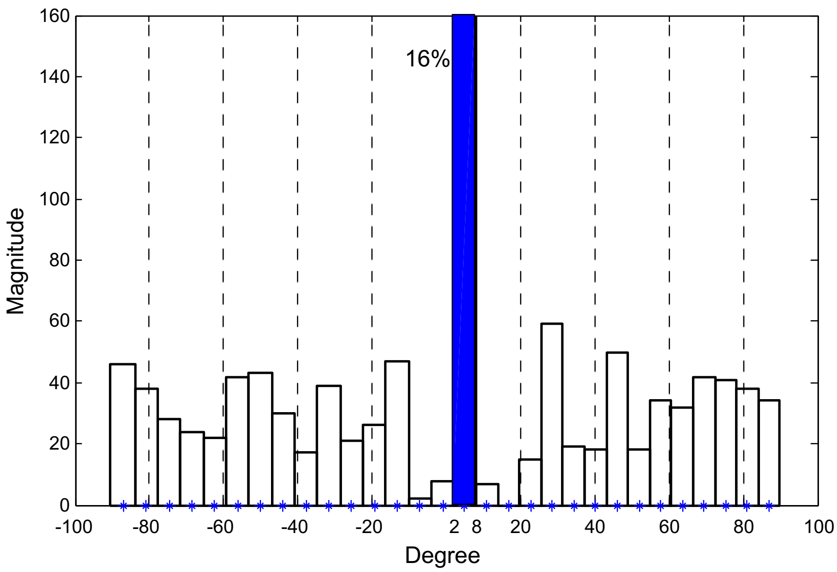

Fig. 4. The DOA estimation histogram of IBMUSIC with random initial values for Example 2 under SNR = 25 dB.

times smaller than that of the other methods tested. Fig. 3 compares the performance evaluated for various methods using different values of SNR. Apparently, the combined PSO/IBMUSIC has good performance under various values of SNR, particularly in low-SNR environments.

Example 2. Consider active CDMA signals $P = 6$ with $J = 8$ paths, a spread angle $\Delta\theta = 5°$, and a ULA with $M = 8$ omnidirectional elements spaced half a wavelength apart. The desired signal is located on the array broadside ($\theta_1 = 5°$), and the impinging angles of all five uncorrelated interferers with equal power INR = 10 dB are $[-50° \quad -30° \quad -10° \quad 10° \quad 30°]$; the other parameters are the same as those used in Example 1.

Example 2 compares the performance of multiple paths and multiple users. Fig. 4 illustrates the IBMUSIC method, and the initial values are plotted as a histogram: it is shown that the random average score lies in the range [−90°, 90°]. In Fig. 4, approximately 16% of the estimated DOA values lie in the range [2°, 8°], and the average search uses 544 iterations. These results again confirm that the performance and convergence number of this method are easily affected by the initial values chosen. Table 2 compares the RMSE of the method proposed in this paper with that of other methods. In low-SNR

Table 2
DOA estimation and search number using the MUSIC, MVDR, GA-based, PSO-based, GA/IMUSIC, and proposed methods in Example 2.

Estimators	SNR	Number of searches		Estimation error ($\lvert\theta - \hat{\theta}\rvert$)
		Iterations	Total number of function evaluations[a]	
Example 2				
MUSIC	0 db	90001		5.4199
	25 db	90001		1.7874
MVDR	0 db	90001		5.6857
	25 db	90001		4.7633
GA	0 db		2500(50 × 50)	24.4349
	25 db		2500(50 × 50)	1.8792
PSO	0 db		2500(50 × 50)	24.8122
	25 db		2500(50 × 50)	1.8604
GA/IMUSIC	0 db	9	900(50 × 18)	24.1811
	25 db	12	850(50 × 17)	1.8197
Proposed	0 db	75	700(50 × 14)	3.03
	25 db	69	650(50 × 13)	0.9081

[a] Total number of function evaluations: population size × number of generations.

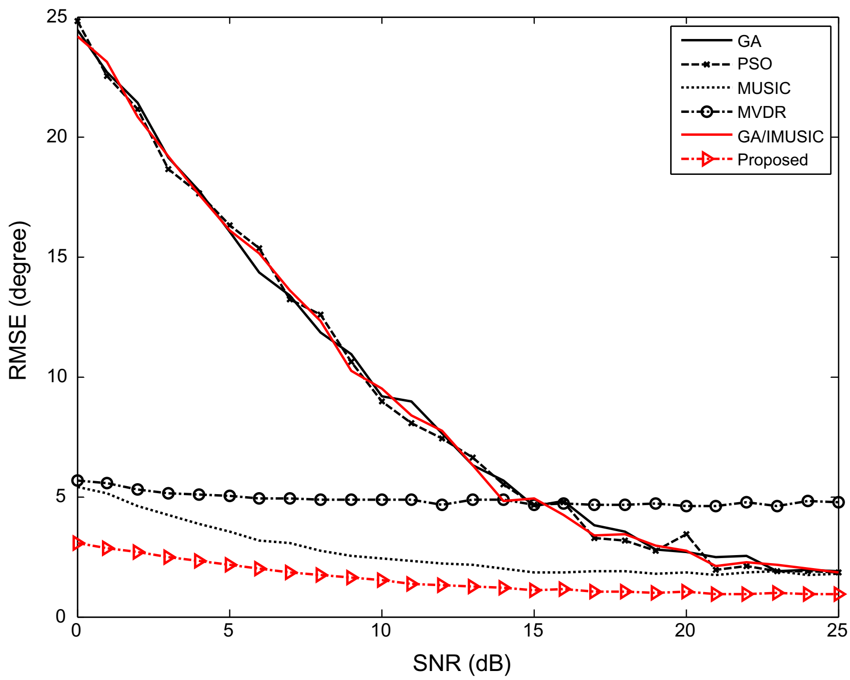

Fig. 5. RMSE of DOA estimation versus the SNR of the desired user in Example 2.

environments, the attempts at estimation using GA, PSO, and GA/IMUSIC almost all failed, whereas the method proposed here provided a good result (Table 2). Fig. 5 shows the performances evaluated under various SNR scenarios. The result again indicates that the PSO/IBMUSIC method not only retains the advantages of the iteration search process but also achieves the accuracy provided by the DOA estimation.

5. Conclusion

This paper proposes an effective method of DOA estimation for CDMA signals in multipath environments. Routine methods such as MUSIC and MVDR generate large biases and require high search times for DOA estimation in these environments. If evolutionary calculation methods such as GA and PSA are used, the search times can be decreased; however, the performance becomes very poor. In particular, under low-SNR conditions, the performance is nearly destroyed. The GA/IMUSIC method also confirmed that if the multipath effect is not addressed, then a large error results in the estimation of DOA. The effectiveness of the IBMUSIC method appears to be determined by the initial values. This paper, therefore, takes advantage of the parallel search method of PSO, which is weakly dependent on the initial values. If good initial values are provided to IBMUSIC, then simulations confirm that the combined PSO/IBMUSIC method provides good performance and is suitable for the DOA estimation of current 3G mobile communications.

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