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An Efficient DOA Estimation Algorithm for Smart Antenna Systems in Multipath Environment

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Abstract: This study proposes an efficient Direction of Arrival (DOA) estimation algorithm with Uniform Linear Array (ULA) for smart antenna systems in multipath environment. To cope with the coherent signals caused by multipath propagation, the proposed algorithm first exploits an extended covariance matrix, achieves the maximum singular vector for the information of the coherent signals. Finally the proposed algorithm constructs a Toeplitz matrix to resolve the coherent signals. In the case of DOA estimation for three coherent signals, at RMSE = 0.4, the proposed algorithm results in a gain improvement of about 3 dB over the Estimation of Signal Parameter via., Rotational Invariance Techniques (ESPRIT)-like algorithm and about 7.5 dB over the Forward Backward Spatial Smoothing (FBSS) algorithm. Theoretical results also demonstrate the proposed algorithm can resolve more coherent signals.

Key words: Direction of arrival, uniform linear array, coherent signals

INTRODUCTION

In recent years, smart antenna becomes a very hot research. Smart antenna systems can significantly improve the efficiency of wireless communications (Stutzman *et al*., 2000; Kiong *et al*., 2006). Smart antenna systems often adjust the phase of array antennas with adaptive beamforming. The beamforming approaches require users' Direction of Arrivals (DOAs) to generate radiation pattern (Dandekar *et al*., 2003; Naik *et al*., 2010). Therefore, DOA estimation is a very important research issue in smart antenna systems.

Some DOA estimation methods including multiple signal classification (MUSIC) (Charge *et al*., 2001; Schmidt, 1986) and Estimation of Signal Parameter via., Rotational Invariance Techniques (ESPRIT) (Mathews, 1996), have been developed over the years. However, there are often coherent signals in wireless multipath environment and those high-resolution methods will fail in such scenario. The conventional decorrelating DOA methods, such as Forward Backward Spatial Smoothing (FBSS) (Wu and Luo, 2004), can be used to resolve the coherent signals, but perform worse in low SNR. Han and Zhang (2005) proposed a Toeplitz-like method to realize a better DOA estimation of the coherent signals, but the main disadvantage of the method is that the number of coherent signals can be resolved is at most half of the number of array elements.

This study presents an efficient DOA estimation algorithm for smart antenna systems in multipath. First, an extended covariance matrix is constructed, then the special singular vector corresponding to the maximum singular value which is called the maximum singular vector, is estimated. By exploiting the maximum singular vector, a Toeplitz matrix is constructed to resolve the coherent signals. The proposed algorithm can improve the performance of DOA estimation for coherent signals, especially in low SNR and resolve more signals than the conventional algorithms.

SYSTEM MODEL

Figure 1 depicts a smart antenna system with a Uniform Linear Array (ULA) in multipath environment. The smart antenna system has three parts-the multi-channel receiver, DOA estimator and DOA based beamformer.

Consider a narrowband far-field signal s(t) propagates through a multipath channel along K distinct paths and impinges on an M-element ULA, where, λ is the carrier wavelength of the signals and d is the distance between adjacent elements. The coherent signal coming from the direction θ_k is corresponding to the signal $s_k(t)$ with power σ^2_k, k = 1, ..., K. When the antenna array receives the coherent signals, a multi-channel receiver generates digital signals for the receiving signals. Then the DOA estimator calculates the DOAs of the coherent signals and the DOA based beamformer generates the weighting vectors for the signals with the estimated DOAs.

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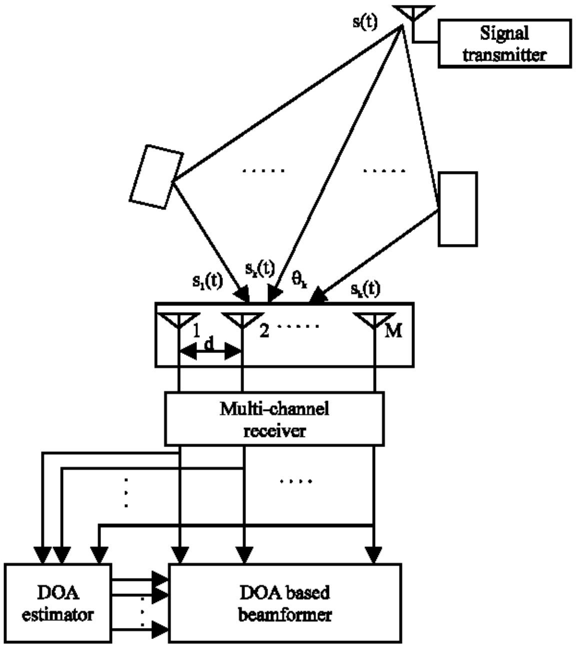

Fig. 1: Block diagram of smart antenna system in multipath environment

The antenna array out vector x(t) can be written as:

$$\begin{aligned} x(t) &= [x_1(t), x_2(t), \ldots, x_M(t)]^T \\ &= \sum_{k=1}^{K} a(\theta_k)\rho_k s(t) + n(t) \\ &= As_c(t) + n(t) \end{aligned} \tag{1}$$

where, the superscript T denotes the transpose:

$$a(\theta_k) = [1, e^{-j2p\frac{d}{\lambda}\cos\theta_k}, \ldots, e^{-j2p\frac{d}{\lambda}(M-1)\cos\theta_k}]^T$$

is the steering vector, ρ_k (k = 1, ..., K) is the amplitude fading and phase difference coefficient of the k coherent signal, A = [$a(\theta_1)$, $a(\theta_2)$, ..., $a(\theta_K)$], the vector $s_c(t)$ = [$s_1(t)$, $s_2(t)$, ..., $s_K(t)]^T$ and n(t) is the noise vector with the power of each entry equal to σ^2_n. And we assume that the entries of $s_c(t)$ and n(t) are zero mean wide-sense stationary random processes and are uncorrelated to each other.

DOA ESTIMATION

With the vector x(t), an extended-data vector is formed as:

$$y(t) = \begin{bmatrix} x(t) \\ x^*(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A^* \end{bmatrix} \begin{bmatrix} s_c(t) \\ s_c^*(t) \end{bmatrix} + \begin{bmatrix} n(t) \\ n^*(t) \end{bmatrix} \tag{2}$$

where, the superscript * denotes the complex conjugate.

The correlation matrix for the extended data model is given as:

$$R_y = E\left[y(t)y^H(t)\right] = \begin{bmatrix} A \\ A^*F^* \end{bmatrix} R_s \begin{bmatrix} A \\ A^*F^* \end{bmatrix}^H + \sigma_n^2 I \tag{3}$$

where, the superscript H denotes the complex conjugate transpose, Φ is a diagonal matrix, R_s is the correlation matrix of $s_c(t)$ and I is the 2 M-dimensional identity matrix. The extended model allows to increase the observation space and estimation accuracy while keeping the dimension of the signal subspace unchanged.

The extended covariance matrix can be calculated as:

$$R_y = \begin{bmatrix} R_{xx} & R_{xx^*} \\ R^*_{xx^*} & R^*_{xx} \end{bmatrix} \tag{4}$$

where, the matrices R_{xx} and R_{xx^*} are the autocorrelation matrix and the conjugate autocorrelation matrix of x(t) with N snapshots, respectively and can be estimated by:

$$R_{xx} = \frac{1}{N}\sum_{n=1}^{N} x(t_n)x^H(t_n) \tag{5}$$

$$R_{xx^*} = \frac{1}{N}\sum_{n=1}^{N} x(t_n)x^T(t_n) \tag{6}$$

By computing the Singular Value Decomposition (SVD) of R_y, a K-dimensional signal subspace and an orthogonal (2M-K)-dimensional noise subspace can be determined. Then the matrix R_y can be written as:

$$R_y = \begin{bmatrix} U_{sy} & U_{ny} \end{bmatrix} \begin{bmatrix} S_{sy} & 0 \\ 0 & S_{ny} \end{bmatrix} \begin{bmatrix} V_{sy} & V_{ny} \end{bmatrix}^H \tag{7}$$

where, U_{sy} spans the signal subspace, U_{ny} spans the noise subspace and the diagonal elements of the diagonal matrices Σ_{sy} and Σ_{ny} are arranged in the decreasing order.

As shown by Charge *et al.* (2001), for any DOA θ_k, there are two signal components in U_{sy}-a nonconjugate signal component and a conjugate signal component which are two submatrices of the same dimension and can be viewed as two sets of signals with the same DOA. One component of the special singular vector which corresponds to the maximum diagonal element of Σ_{sy}, can be found as follows:

$$U_{sm} = \sum_{k=1}^{K} b_k a(\theta_k) = AB \tag{8}$$

where, $B = [b_1, b_2, ..., b_K]^T$, $U_{sm} = [u_{s,1}, u_{s,2}, ..., u_{s,M}]^T$ and with the elements of U_{sm}, the following Toeplitz matrix is constructed as:

$$R_c = \begin{bmatrix} u_{s,1} & u_{s,2}^* & \cdots & u_{s,M}^* \\ u_{s,2} & u_{s,1} & \cdots & u_{s,M-1}^* \\ \vdots & \vdots & \ddots & \vdots \\ u_{s,M} & u_{s,M-1} & \cdots & u_{s,1} \end{bmatrix} \quad (9)$$

Substituting the elements of U_{sm} from Eq. 8 into 9, R_c can be written as:

$$R_c = [AB, AC^{-1}B, ..., AC^{-(M-1)}B] = ADA^H \quad (10)$$

Where:

$$C = \mathrm{diag}\left(e^{-j2p\frac{d}{\lambda}\cos\theta_1}, e^{-j2p\frac{d}{\lambda}\cos\theta_2}, \ldots, e^{-j2p\frac{d}{\lambda}\cos\theta_K} \right)$$

and $D = \mathrm{diag}\ [b_1, b_2, \ldots, b_K]$. Since, A is a Vandermonde matrix, rank (R_c) = rank (D) = K. When K = M-1, it is enough to decorrelate all the coherent signals.

Perform the SVD on R_c and obtain:

$$R_c = [U_{sc} \quad U_{nc}] \begin{bmatrix} S_{sc} & 0 \\ 0 & S_{nc} \end{bmatrix} [V_{sc} \quad V_{nc}]^H \quad (11)$$

where, U_{sc} spans the signal subspace and U_{nc} spans the noise subspace. Then the spatial spectrum for the coherent signals is given by:

$$P(\theta) = \frac{1}{a^H(\theta) U_{nc} U_{nc}^H a(\theta)} \quad (12)$$

The proposed method is summarized as:

Step 1: Construct the extended-data vector y(t) and calculate the matrix R_y
Step 2: Compute the SVD of R_y and find the vector U_{sm}
Step 3: Construct the Toeplitz matrix R_c by U_{sm}
Step 4: Compute the SVD of R_c and the obtain singular vector U_{nc},
Step 5: Find the K maxima of $P(\theta_k)$ (k = 1, …, K), where, θ_k is the direction corresponding to the k coherent signal

In a smart antenna system with M array elements, the DOA estimator with the FBSS method can estimate at most [2M/3] coherent signals and the estimator with the ESPRIT-like method can estimates at most [(M-1)/2] coherent signals, where [.] is a rounding operator. These conventional DOA estimation methods are all at the cost of a reduction in array aperture. However, in the proposed method, a Topelitz matrix is constructed which has been theoretically proven to resolve M-1 coherent signals.

SIMULATION RESULTS

In the simulations, the computer simulations about the DOA estimation methods in multipath environment are presented. A ULA with half-wavelength interspacing is employed. Figure 2-3 show the comparison between the FBSS method, the ESPRIT-like method and the proposed method. Five hundred Monte Carlo trials are performed for each experiment.

Figure 2 shows the detection probability of the conventional and proposed methods when the SNR

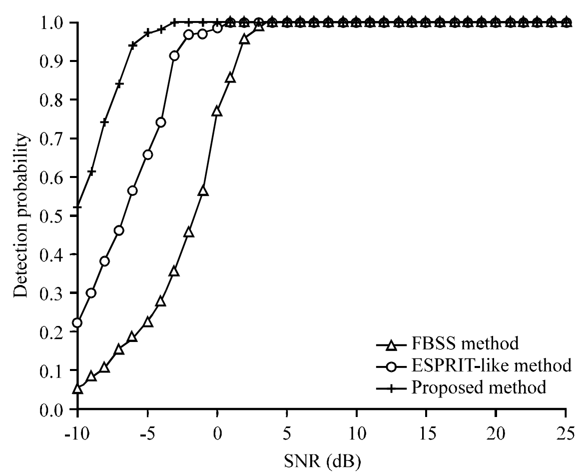

Fig. 2: Detection probability versus input SNR for two coherent signals

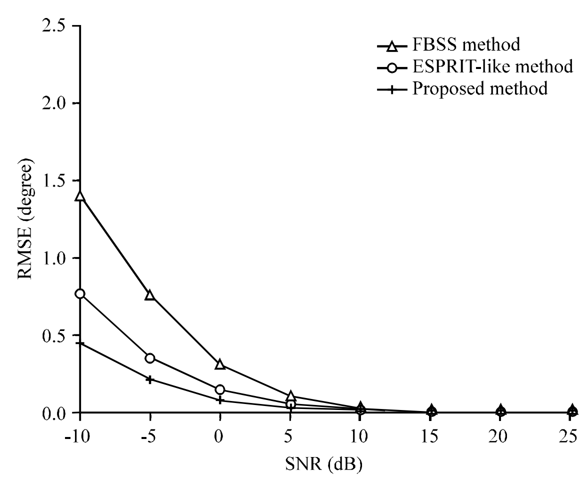

Fig. 3: RMSE of the DOA estimates versus input SNR for three coherent signals

changed. In the first simulation, two coherent signals arrive from [30, 45°] and the amplitude fading and phase difference coefficients of the coherent signals are 0.4527+0.2354 and 0.6182-0.3304j, respectively. The number of snapshots is 200 and the number of array elements is 7. The result illustrates that for low SNR, the success rate of the proposed method is higher than that of the FBSS and ESPRIT-like method. In particular, at SNR = -10 dB, the proposed method can obtain 53% detection rate while the ESPRIT-like and FBSS method can reach only 22 and 5%, respectively. It is because that the maximum singular vector is obtained for the information of the coherent signals in the proposed method, where less power and information is lost in case of low SNR. However, the FBSS and ESPRIT-like method may obtain false DOAs caused by coherent signals in such scenario.

Figure 3 shows the RMSE of the DOA estimates versus input SNR. In the second simulation, three coherent signals arrive from [36, 45, 60°] and the amplitude fading and phase difference coefficients of the coherent signals are 0.8532+0.1526j, -0.7631-0.2635j and 0.3512+0.1436j, respectively. The number of snapshots is 500 and the number of array elements is 7. It can be observed that at RMSE = 0.4, the proposed method achieves a gain improvement of about 3 dB over the ESPRIT-like method and about 7.5 dB over the FBSS method. In the proposed method, the extended array covariance matrix is exploited which allows an increase in resolution power and noise robustness.

In the third simulation, the number of array elements is reduced to 5 and four coherent signals arrive from [18, 36, 90, 120°]. The amplitude fading and phase difference coefficients of the coherent signals are 0.4531+0.3526j, -0.3528+0.2735j, 0.7528-0.0237j and -0.6532-0.3314j, respectively. The SNR is 3 dB for each signal. Figure 4 shows the DOA estimate of all the coherent signals with the proposed method. The proposed method can successfully resolve all the coherent signals. Therefore, the proposed method can assure less reduction in array aperture than the FBSS and ESPRIT-like method.

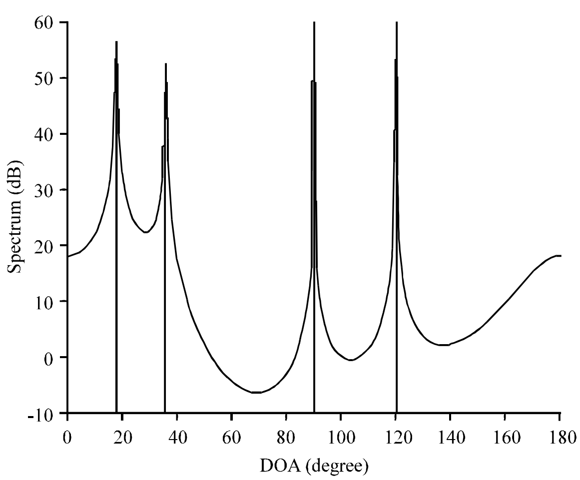

Fig. 4: Spatial spectrum provided by the proposed method for four coherent signals at SNR = 3 dB

CONCLUSION

An efficient DOA estimation algorithm for smart antenna systems in wireless multipath environment has been presented in this study. By computing the SVD of the extended array covariance matrix, the proposed algorithm achieves the maximum singular vector for the information of the coherent signals. Then with the singular vector, a Toeplitz matrix is constructed to resolve the coherent signals. Theoretical results demonstrate that the proposed algorithm allows the DOA resolution of more signals than the FBSS algorithm and the ESPRIT-like algorithm. The proposed algorithm can be a good solution for smart antenna systems in multipath and low SNR.

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