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Article

A Smart Antenna System for Radar Communication Exploiting Modified Uniform Circular Array

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A B S T R A C T

There are lots of spectrum estimation methods are there in array signal processing. Until today, most of the Directions of Arrival (DoA) algorithms are presented using large samples. This research work proposes a new DOA algorithm using single signal snapshot, which is the worst case scenarios in the array signal processing. Meanwhile the proposed method uses a Uniform Circular Array (UCA) to resolve multiple targets for complete 360º range without using the forward/ backward spatial smoothing of sample covariance matrix. This minimizes the complexity of computation and enhances the speed of execution. Usually, spatial smoothing methods using 100 samples require execution time of about 20 seconds for DOA estimation (using i3, 2GHz CPU processor). Since, the proposed method can resolve the multiple targets using single snapshot requires about only 2 seconds using the same processor. Hence the proposed algorithm is computationally efficient and can be used for advanced radar and sonar applications.

Keywords: DOA, Snapshot, MUSIC, ESPRIT, Capon, ULA, UCA, VUCA

Introduction

DOA estimation algorithms are widely used in wireless communication applications including radar,[1,2] cellular communication[2] and sonar etc.[3,4] Most of the research work in literature uses a ULA for spectral estimation of desired signals since DOA estimation using a UCA is always a challenging thing.[5-6] Recently, large scale UCA has been considered as one the most promising methods in array signal processing (e.g., millimeter wave and massive MIMO communication).[7] Single snapshot spectrum estimation methods are attractive in the wireless communication application due to the following reasons.

- The time of computation and execution can be reduced by using single snapshots
- Some added simplifications are possible by the use of single signal sample. The reaction speed can be increased instantaneously after measurement without waiting for large snapshots
- Clutter can superpose few samples. Such samples cannot be used for DOA estimation

Related Work

Most of the research work[8-12] especially for DOA estimation using single snapshot uses a Uniform Linear Array (ULA) as an array configuration. However, the most of the practical applications require UCAs. The key feature is, UCAs are able to provide 360º coverage in azimuth and 180° coverage in elevation.[13] DOA estimation using UCAs are attractive antenna array configurations for performance driven communication systems. Multipath propagation or intentional jamming in mobile communication yields coherent signals.[14-16] The ESPRIT and the root-MUSIC algorithms might not work well to estimate the DOA of coherent signals. To overcome this problem, spatial smoothing and subspace smoothing have developed. But these methods require large amount of snapshots, this increases the computational burden. As a result of this, it requires more time to execute.[17,18]

Most of the classical and recent DOA algorithms require large antenna array samples (snapshots), which increases the computational load of the system.[19] Most of the times few snapshots may available at the receiver, especially in driver assistant systems, for which few or in the worst case only one sample is available for estimation of incoming signal.[20]

In such cases, single snapshot based algorithms plays a vital role. We proposed the new method which does not require the use of forward or backward spatial smoothing of SCM. This minimizes the complexity of computation and enhances the speed of execution.

In this work, the DOA method of[6] is modified to overcome aforementioned drawbacks. The proposed spectral estimation technique for DOA estimation is the enhanced version of aforementioned work, which gives 360^{O} signal detection and estimation efficiently. The performance of proposed algorithm with single snapshot is compared with spatial smoothing methods with 100 snapshots.

The computation time is decreased as the single snapshot case allows some additional simplifications in DOA estimation.

Array Signal Model

Consider an UCA with M antenna elements as shown in Figure 1. Consider these antenna elements are identical, unidirectional and distributed uniformly over UCA with radius of circle $r = \lambda.$ Let us assume that at time n, p(p<M) narrow-band signals impinge the UCA with elevation angle θ and azimuth angle Φ in far fields. Let N represents the number snapshots observed by the array.

The signal output at the mth antenna can be expressed as:

$$\mathbf{a}(n) = \sum_{p=1}^{P} \mathbf{a}_m(\theta_p)\mathbf{s}_p(n) + \mathbf{n}(n) \quad (1)$$

Where, $\mathbf{s}(n), \mathbf{a}(\theta) \, and \, \mathbf{n}(n)$ are desired signal, steering vector and noise signal respectively. Equation (1) is represented as:

$$\mathbf{x}(k) = \mathbf{A}(\theta)\mathbf{s}(n) + \mathbf{n}(n) \quad (2)$$

where

$$\mathbf{A}(\theta) = [\mathbf{a}(\theta_1), \mathbf{a}(\theta_2), ..., \mathbf{a}(\theta_p)]^T$$

$$\mathbf{s}(n) = [\mathbf{s}_1(n), \mathbf{s}_2(n), ..., \mathbf{s}_p(n)]^T$$

$$\mathbf{x}(k) = [\mathbf{x}_1(n), \mathbf{x}_2(n), ..., \mathbf{x}_p(n)]^T$$

$$n(n) = [n_1(n), n_2(n), ..., \mathbf{n}_{M-1}(n)]^T$$

Now, matrix form of received signal is represented as:

X=AS+W (3)

Where, X represents the M×1 signal vector, S represents the p x 1 envelopes of complex signal and W is the noise matrix.

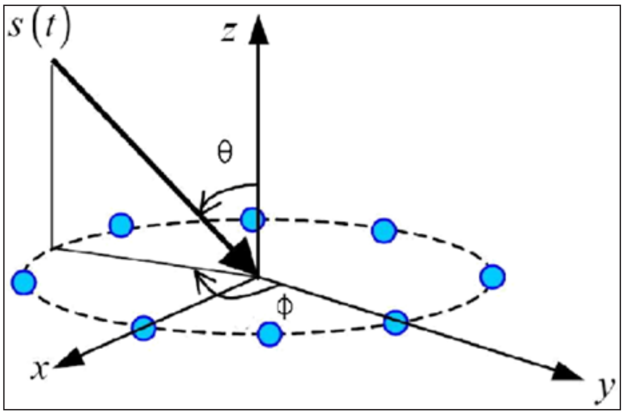

Figure 1.Uniform Circular Array

The array manifold vector which is responsible for steering is represented as:

$$\mathbf{A} = [\mathbf{a}_1(\xi, \Phi), ..., \mathbf{a}_P(\xi, \Phi)] \quad (4)$$

Where, each column is of form:

$$\mathbf{a}(\theta) = \begin{bmatrix} \exp(j\xi \cos(\Phi_p - v_0)), ... \\ \exp(j\xi \cos(\Phi_p - v_{M-1})) \end{bmatrix} \quad (5)$$

Here, $\theta = (\xi, \Phi)$ represents the elevation angle which depends on ξ. This is utilized to represent the directions of arriving sources. Let $\xi = \vartheta r \sin\theta$, where r denotes the radius, represents the wave number represents the location of array.

The azimuth angle is measured counter clockwise from the axis. Let the noise is white Gaussian with zero mean and variance.

Since Vandermonde structure[6] does not agree with the A (array manifold vector), decorrelated algorithms cannot be used to the uniform circular array. In our approach, we have transformed the virtual UCA (VUCA) to a 2h+1 virtual array. This form of structure can be applied to the decorrelated algorithms. Let us use the transformation matrix to apply the mode excitation technique.

We know that the observation vector is:

$$\mathbf{x}(n) = \mathbf{A}(\Phi)\mathbf{s}(n) + \mathbf{n}(n) \quad (6)$$

Let us define the matrix Where, denotes the (2h+1) × M submatrix of the spatial discrete Fourier transform, which is expressed as:

$$\zeta = \frac{1}{\sqrt{M}} \quad (7)$$

and is the diagonal matrix of size (2h+1) × (2h+1), which is expressed as:

$$\aleph = diag\left\{\frac{1}{\sqrt{M} j^n \aleph_n(\mathbf{r})}\right\}, \quad n = -h, ..., 0, ...h. \quad (8)$$

A UCA can intrigue maximum of $h \approx v_o r$ mode numbers.

This matrix is very helpful for protecting the angledependent phase. In (8), represents the n-order first kind of the Bessel function.

The array manifold vector of VULA if can be expressed as:

$$\mathbf{A}(\Phi) \quad (9)$$

Where $\mathbf{A}(\Phi)$ has a size of (2h+1)×p

Proposed Single Snapshot UCA-DOA Estimation Method

We know that the Forward/ Backward (FB) averaging is the most commonly used technique in ULA, however this method cannot be applied to UCA for decorrelating. Alternative Forward/ Backward (AFB) technique and propagator method were used.[9,10] But the major drawback of these methods is that they use large snapshots.

In this work we propose a new UCA-DOA method which uses only one snapshot for coherent DOA estimation.

Let the signal vector $\mathbf{x}(n)$ is represented as:

$$\mathbf{x}(n) = [\mathbf{x}_{-h}(n)\,\mathbf{x}_{-h+1}(n)\cdots\mathbf{x}_{h}(n)]^{T} \quad (10)$$

Here above matrix has a form similar to the ULA. Using this matrix, (h+1)×(h+1) Hermitian Toeplitz matrix. Since the rank is higher than the covariance matrix of the received vector, the proposed UCA-DOA METHOD can estimate the DOAs up to h coherent sources.

The covariance matrix can be obtained from the Hermitian Toeplitz matrix. The Singular Value Decomposition (SVD).

Now, p number of coherent sources can be estimated from the number of dominant singular values. In MATLAB notation.

Let us consider a matrixof (h+1)×(h+1) size for the p largest eigenvalues.

The rows collection from 1 to h and (2:h+1,:) is the rows collection from 2 to h+1.Here represents the pseudo-inverse.

The DOAs can be estimated from the largest eigenvalues.

Result and Discussion

Let us consider a UCA as an antenna array configuration for simulation of proposed algorithm. Let the size of the received signal matrix 'X' can be calculated as:

- The size of matrix 'X' for the classical method = (2h+1) x100(snapshots) = 9 x 100 = 900
- The size of matrix 'X' for the proposed methods = (2h+1) x 1(snapshot) = 9 x 1= 9

Root Mean Square Error (RMSE) performance of DOA algorithms can be analyzed using Monte Carlo simulations, which is expressed as:

$$RMSE = \sqrt{\sum_{l=1}^{L} \frac{(\Phi_{\ell}^{*} - \Phi_{\ell})^{2}}{L-1}} \quad (11)$$

The parameters used for the simulation of proposed single snapshot UCA-DOA METHOD are tabulated in Table 1.

Table 1.Experimental Parameters

Sr. No.	Parameters	Values
1.	Array Configuration	UCA
2.	Array elements (M)	10-100
3.	Pass band frequency Range	(3-4)GHz
4.	Spacing between antennas(d)	d = λ/2
5.	Snapshots (N)	1 and 100
6.	SNR	-5 to 40 dB
7.	Base band frequency	1 KHz

RMSE verses SNR

Let us study the performance of proposed algorithm for widely spaced and closely spaced targets.

Let us consider the two equi-powered coherent sources impinge UCA consisting of M=10 antenna elements at 50° and 250°. Let the noise be additive white Gaussian with zero mean σ^2 variance, SNR=10dB, N=1(single snapshot) and d=λ/2. In this experiment, L= 200 Monte Carlo trails are used for each SNR.

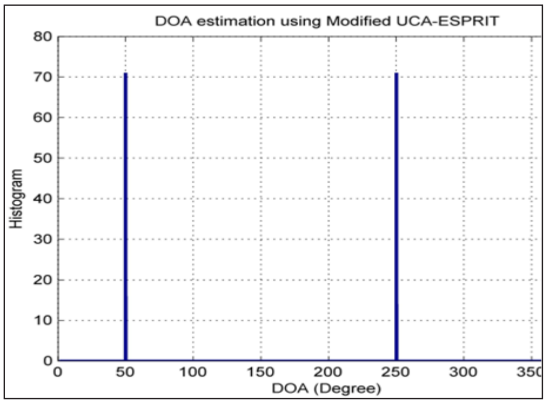

Figure 2.DoA Estimation of proposed UCA-DOA Method (M=10, N =1,p=2 for Targets 50° and 250°)

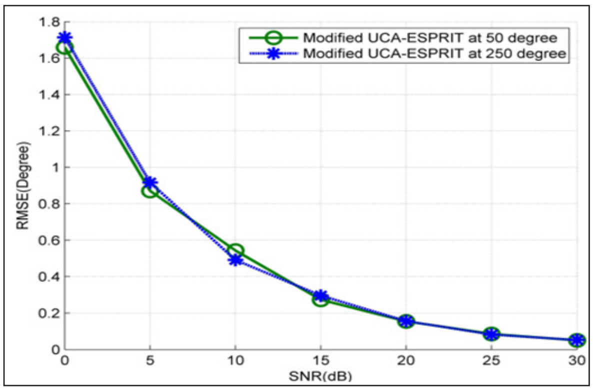

Figure 3.RMSE Angle Error Performance of Modified UCA -DOA Method (for M=10, N =1,p=2, Targets 50° and 250°)

Figure 2 and 3, show the histogram and RMSE performance of proposed UCA-DOA METHOD for DOA estimation for two widely spaced targets (50° and 250°). Now let us consider equi-powered coherent sources impinge UCA at 10° and 30° keeping other parameters unchanged. Computer simulations of this case are shown in Figure 4 and 5. Figure 4, is the histogram and Figure 5, is the RMSE performance for two closely spaced (10° and 30°) targets.

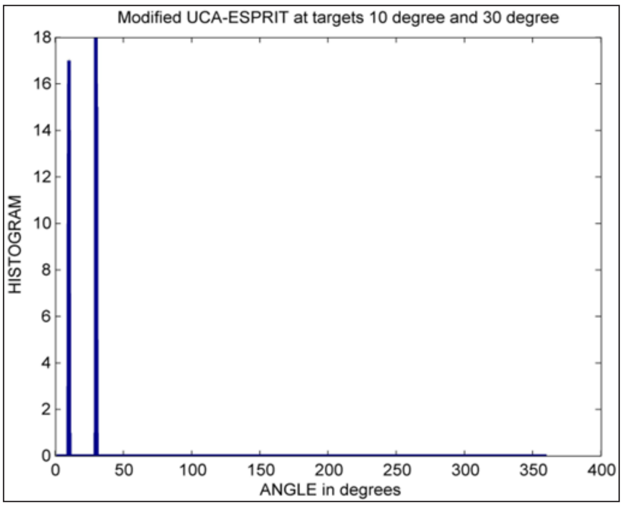

Figure 4.DoA Estimation of Proposed UCA-DOA Method (M=10, N =1,p=2 for Targets 10° and 30°)

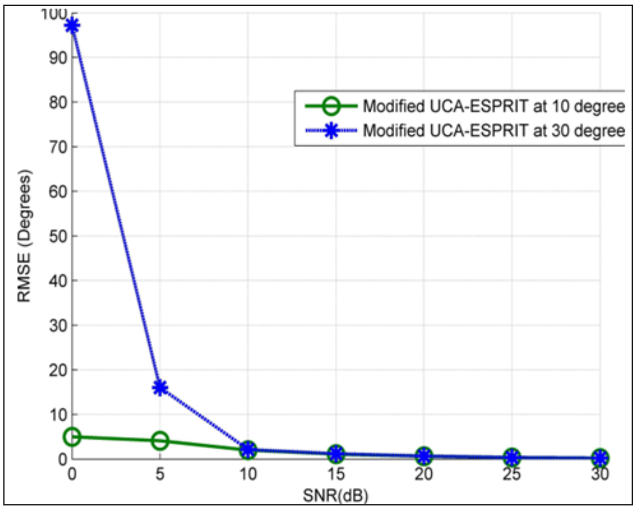

Figure 5.RMSE Performance of Proposed UCA -DOA Method (M=10, N =1, p=2 for targets 10° and 30°)

Figure 6, demonstrates the performances of spatial smoothing methods, namely, ESPRIT,[2] FBSS[3] and UCA-ESPRIT[6] with the proposed single snapshot UCA-DOA method. In this simulation, single snapshot (N=1) is used for proposed method and N =100 snapshots are used for spatial smoothing methods. The range of SNR used is from -5dB to 20dB keeping other parameters unchanged. From Figure 6, it is very clear that the proposed method with single snapshot spatial smoothing methods with 100 snapshots have similar RMSE performance.

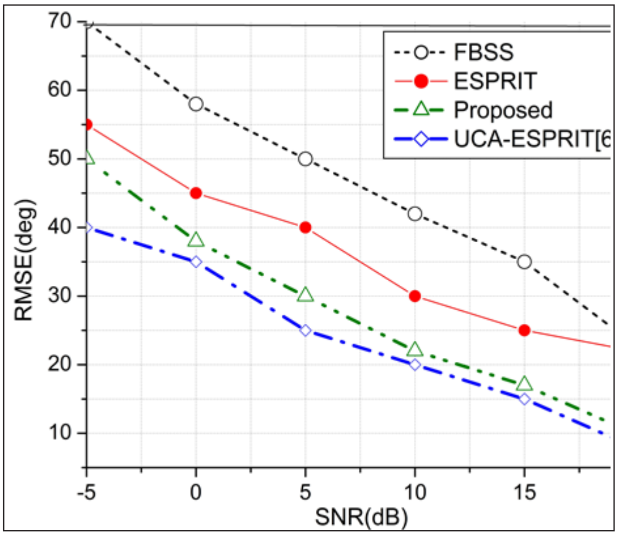

Figure 6.RMSE Performances of Proposed and Classical Methods

Conclusion

In this work, a modified UCA-DOA METHOD algorithm for spectrum estimation using single snapshot is devised. This is the most important advantage of this work, since it is highly useful for real time practical applications. The key idea of the proposed work is the use of mode excitation and Hermitian Toeplitz matrix for complete azimuth spectrum estimation. The performance of the proposed algorithm with single snapshots is similar to spatial smoothing methods with more than 100 snapshots. Hence this algorithm executes 10 times faster compared to spatial smoothing method. It significantly saves the time requirement to execute and also the power consumption. This makes communication system more efficient. Also this method is accurate, less complex, executes faster and works properly in low SNR environment.

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