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DOA ESTIMATION OF MULTIPATH SIGNALS USING UCA ANTENNAS

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ABSTRACT

Direction of arrival (DOA) estimation is a major problem in array signal processing. A new direction of arrival (DOA) estimation method is proposed for estimation of both uncorrelated and coherent signals in multipath environment. In the proposed method, uncorrelated signals are estimated using conventional sub space based methods and the remaining coherent sources are estimated using three difference covariance matrices. The performance of this DOA estimation algorithm is based on uniform circular array (UCA). The simulation results shows that proposed method can obtain higher resolution and accuracy as the number of array elements and the number of snapshots increases.

Key words: direction of arrival (DOA), coherent signals, spatial differencing, uniform circular array (UCA)

I. INTRODUCTION

Antenna arrays are being widely used in GPS applications, to estimate the direction of signals as well as to reject interferences. But the signal bandwidth of GPS is only several megahertz's (MHZ), so multipath signals will be correlated with the direct path signals. This makes much more difficult to estimate the DOA of these signals. Several prominent algorithms have been proposed and developed for finding direction of arrival such as multiple signal classification (MUSIC) [1] and estimation of signal parameters via rotation invariance techniques (ESPRIT) [2] and smooth music [3]. However, these high resolution methods are unable to handle coherent (correlated) signals in multipath propagation environment.

An effective method have been proposed to decor relate the coherent signals is spatial smoothing technique. This technique is based on a pre-processing scheme that partitions the original array in to several overlapping sub arrays and then averages the output of sub array covariance matrices to construct a spatially smoothed covariance matrix [4]. Under a mild restriction the required number of sensors can be reduced by using an improved spatial smoothing technique referred to as the forward backward spatial smoothing (FBSS) technique [5]. The spatial smoothing technique is a high-resolution Eigen decomposition algorithm in the presence of signal correlation. The most restrictive aspect of the spatial smoothing technique is that it requires a certain class of array geometries which have identical sub arrays, such as uniform linear array (ULA), which limits range of application. An important disadvantage of the ULA geometry in DOA estimation is that it can only provide the 90° of coverage in azimuthal plane.

Because of the capability of full range coverage in the azimuth plane, uniform circular arrays (UCA) are widely used in radar and wireless communication system. Circular arrays are non uniform linear arrays, hence, the circular array manifold does not have the vandermonde form so the preprocessing schemes like spatial smoothing cannot be directly applied to the uniform circular arrays, which makes more complex for DOA estimation for coherent signals. The common method for solving this problem is to transform the uniform circular array to a virtual uniform linear array to reconstruct a manifold with the vandermonde structure. However these methods work well only when the array has a large number of antenna elements, otherwise estimation performance may be deteriorate due to the beam space transform error caused by small number of antenna elements.

In this paper, a new spatial differencing method is proposed for DOA estimation in the presence of coexistence of uncorrelated and coherent signals based on UCA. Firstly, the received data matrix is constructed by using the symmetric configuration of UCA then the uncorrelated signals are estimated using conventional subspace methods, and their contribution is eliminated by exploiting the spatial differencing method, such that only coherent signals remain in the spatial differencing matrix to estimate the coherent signals.

The rest of the paper is organized as follows. Section 2 includes the signal model for the UCA. Section 3 is focused on DOA estimation of the proposed method and related formulations. In section 4, simulation results are presented using the MATLAB to illustrate the effectiveness of the proposed method. Finally, section 5 concludes the paper.

II. DATA MODEL

Consider a uniform circular array (UCA) consisting of N isotropic sensors uniformly spaced on the circle with radius *r*. Fig 1 shows the geometry of uniform circular array (UCA) which consist of N element uniformly distributed isotropic antenna elements. The array factor for this configuration at a far field point of $(\theta, \emptyset)$ is given by

$$A(\theta,\emptyset) = \sum_{n=1}^{N} exp\left(-j\frac{2\pi r}{\lambda}\sin\theta\cos\left(\emptyset - \frac{2\pi(n-1)}{N}\right)\right)$$

Where λ is the signal carrier wavelength, θ and Ø are the elevation and azimuth directions of arrival of the signal.

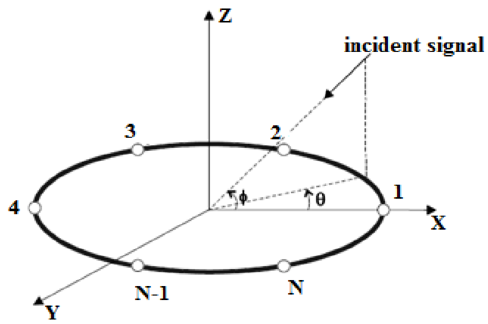

Fig: uniform circular array configuration

Assume K narrowband signals impinging with unknown DOAs on the array without loss of generality. Assume that first D signals are uncorrelated and the rest are L groups of $P = K - D$ coherent signals are impinges on a N element antenna array from the direction$(\theta, \emptyset)_i$, $i = 1,2,\dots,D$ and $(\theta,\emptyset)_{il}, i = D+1,\dots,D+L$ and $l = 1,\dots,p_k$ where p_k is the multipath signals for each source.

The $N \times 1$ array output vector $X(t)$ can be modeled as

$$X(t) = [x_1(t),\dots,x_N(t)]^T = \sum_{i=1}^{D} A(\theta,\emptyset)_i\, s_i(t) + \sum_{i=D+1}^{D+L}\sum_{l=1}^{p_i} A(\theta,\emptyset)_{il}\,\rho_{il}\, s_i(t) + n(t)$$

$$= A_u s_u(t) + A_c s_c(t) + n(t)$$
$$= As(t) + n(t)$$

Where

$A(\theta,\emptyset) = [a(\theta_1,\emptyset_1),\ a(\theta_2,\emptyset_2),\ \dots,\ a(\theta_K,\emptyset_K)]$ is the steering vector which is a $N \times K$ matrix, and $a(\theta_i,\emptyset_i) = [a_1, a_2,\dots,a_N]^T$ is the $N \times 1$ steering vector with $a_N = exp\left[-j\frac{2\pi r}{\lambda}\sin\theta_i\cos\left(\emptyset_i - \frac{2\pi(N-1)}{N}\right)\right]$ where λ is the signal wavelength, subscript T represents the transpose operator, θ and $\emptyset$ are the elevation and azimuth directions of arrival of the signal, and ρ_{il} is the fading coefficient of the 'l' th multipath propagation corresponding to the i^{th} source, $\rho_i = [\rho_{i1},\dots,\rho_{ip_i}]^T$. $A = [A_u, A_c]$ in which $A_u = [a(\theta_1,\emptyset_1), a(\theta_2,\emptyset_2),\dots,a(\theta_D,\emptyset_D)]$, $A_c = [A_1\rho_1,\dots,A_L\rho_L]$

with

$A_i = [a(\theta_{i1},\emptyset_{i1}),\dots,a(\theta_{il},\emptyset_{il})]$.

$s(t) = [s_u{}^T(t)\ s_c{}^T(t)]^T$

in which $s_u(t) = [s_1(t), \dots, s_D(t)]^T$ and $s_c(t) = [s_{D+1}(t), \dots, s_{D+L}(t)]^T$. $n(t) = [n_1(t), \dots, n_N(t)]^T$ with $n_i(t)$ denotes the additive noise of the i^{th} sensor with power σ_n^2.

The array covariance matrix at the output of UCA can be expressed as

$$R = E\{X(t)X^H(t)\}$$
$$= AR_sA^H + \sigma_n^2 I_N$$
$$R = A_u R_u A_u^H + A_c R_c A_c^H + \sigma_n^2 I_N$$

Where $E\{\cdot\}$ denotes the statistical expectation operation and H denotes the hermitial transpose, respectively. $R_s = E\{s(t)s^H(t)\}$ is the covariance matrix of the source signal. $R_u = diag\{\sigma_1^2, \dots, \sigma_D^2\}$ is the covariance matrix of the uncorrelated signal $s_u(t)$. $R_c = diag\{\sigma_{D+1}^2, \dots, \sigma_{D+L}^2\}$ is the covariance matrix of the coherent signal $s_c(t)$. I_N denotes the $N \times N$ identity matrix.

III. DOA ESTIMATION

In this section, the DOA estimation of both uncorrelated and coherent signals are presented.

DOA estimation of the uncorrelated sources:

Here, we firstly estimate the DOAs of the uncorrelated sources. The eigen decomposition of matrix R can be written as

$$R = \sum_{i=1}^{N} \lambda_i u_i u_i^H$$
$$= \sum_{i=1}^{D} \lambda_i u_i u_i^H + \sum_{i=D+1}^{N} \lambda_i u_i u_i^H$$
$$= U_s \Sigma_s U_s^H + U_n \Sigma_n U_n^H$$

Where λ_i and u_i are the i^{th} eigen value and eigen vector, respectively. The eigen values and eigen vectors of the covariance matrix can be split in to two orthogonal subspace called the signal subspace $U_s = [u_1, \dots, u_n]$ and the noise subspace $U_n = [u_{D+1}, \dots, U_N]$. Since the signal subspace is orthogonal to noise subspace. Therefore

$$h(\theta, \emptyset) = |A^H(\theta, \emptyset)U_n|^2 = 0,$$
$$i = 0, 1, \dots, D.$$

Then the DOAs of the uncorrelated sources can be estimated by locating the peaks of spatial differencing algorithm can be expressed as

$$P_{SD}(\theta, \emptyset) = \frac{1}{A^H(\theta, \emptyset)U_n U_n^H A(\theta, \emptyset)}$$

DOA estimation of the coherent sources:

The straight forward way of estimating the DOAs of coherent signals is by using spatial smoothing method, but this method is only based on several identical sub arrays which are not the case for a circular array. Instead of spatial smoothing technique spatial differencing method is proposed for decorrelation of coherent signals using circular arrays by constructing three different covariance matrices as follows

$$R_1^d = R - R^* + JRJ - JR^*J$$
$$R_2^d = R - R^* - JRJ + JR^*J$$
$$R_3^d = R + R^* - JRJ - JR^*J$$

Where R is the covariance matrix of the coherent signal and J is an exchange matrix with ones on its anti diagonal and zeros elsewhere.

The eigen decomposition of R_k^d $(k = 1,2,3)$ can be expressed as

$$R_k^d = U_{sk} \Sigma_{sk} U_{sk}^H + U_{nk} \Sigma_{nk} U_{nk}^H$$

Where $U_{sk} = [u_1, \dots, u_P]$ is the signal subspace and $U_{nk} = [u_{P+1}, \dots, u_N]$ is the noise subspace. The columns of U_{sk} span the signal subspace, which is orthogonal to noise subspace spanned by the columns of U_{nk}. Therefore,

$$f(\theta, \emptyset) = |A^H(\theta, \emptyset)U_{nk}|^2 = 0$$

Thus, the spatial spectrum function of spatial differencing algorithm is

$$P_{SD}(\theta, \emptyset) = \frac{1}{A^H(\theta, \emptyset)U_n U_n^H A(\theta, \emptyset)}$$

Where $U_n = [U_{n1}, U_{n2}]$ or $U_n = [U_{n1}, U_{n3}]$ the choice of which U_n to use is depends on the noise model of the array. If the noise is uncorrelated between signals but has a different power between signals then $U_n = [U_{n1}, U_{n3}]$, while if the noise is correlated between signals but has a equal power between signals then $U_n = [U_{n1}, U_{n2}]$. Where $U_n = [U_{n1}, U_{n2}, U_{n3}]$ is the noise subspace.

Summary of the spatial differencing algorithm:

Spatial differencing method for DOA estimation of both uncorrelated and coherent signals using UCA can be summarized as follows.

1. Collect the data and estimate the auto covariance matrix$R$.

$$X(t) = \sum_{i=1}^{D} A(\theta, \emptyset)_i s_i(t) + \sum_{i=D+1}^{D+L} \sum_{l=1}^{p_i} A(\theta, \emptyset)_{il} \rho_{il} s_i(t) + n(t)$$

And the covariance matrix is given as

$$R = \frac{1}{N_s}\sum_{k=1}^{N_s}\{X(t)X^H(t)\}$$

2. Compute the eigen decomposition of R and estimate the number of received signals K.
3. Estimate the DOAs of uncorrelated signals by making use of $h(\theta, \emptyset)$.
4. Calculate three different covariance matrices R_k^d $(k = 1,2,3)$.
5. Compute the eigen decomposition of R_k^d and estimate the number of coherent signals P.
6. Estimate the DOAs of coherent signals by making use of $f(\theta, \emptyset)$.

IV. SIMULATION RESULTS

In this section, simulation results are presenting to evaluate the performance of the proposed method. Simulation results are carried out for UCA with 20 number of elements and 100 number of snapshots. The performance of this proposed method has been analyzed by considering the root mean square error (RMSE) as a function of number of snapshots and number of array elements. The RMSE of the direction of arrival (DOA) estimate is defined as,

$$RMSE = \sqrt{\frac{1}{100K}\sum_{n=1}^{100}\sum_{k=1}^{K}\left(\hat{\theta}_k(n) - \theta_i\right)^2}$$

Where K is the number of all incident signals, $\hat{\theta}_k(n)$ is the estimated angles and θ_i is the given angles.

Let us consider the 5 incident signals from elevational direction in which the first 2 signals are uncorrelated coming from $[20^\circ, 60^\circ]$ and the remaining 3 signals are coherent with 2 multipaths for each signal coming from $[-20^\circ, 30^\circ, -40^\circ, 50^\circ, -60^\circ, 10^\circ]$. The Fig 1,2 and 3 shows the spectrum of the received signals from elevational direction located at $[10^\circ, 20^\circ, -20^\circ, 30^\circ, -40^\circ, 50^\circ, 60^\circ, -60^\circ]$, spectrum of the uncorrelated signals from elevational direction located at $[20^\circ, 60^\circ]$ and spectrum of the coherent signals from elevational direction located at $[-20^\circ, 30^\circ, -40^\circ, 50^\circ, -60^\circ, 10^\circ]$, respectively.

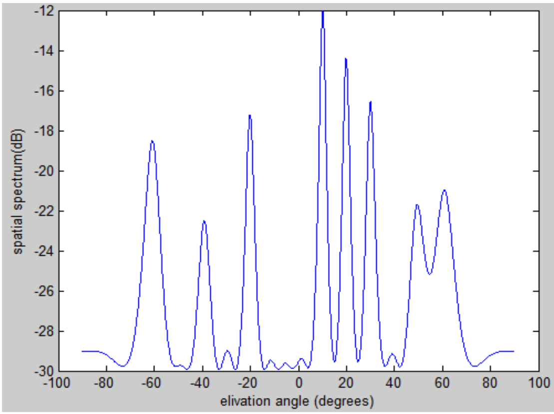

Fig 1: spectrum of received signal

The direction of arrival is estimated by spatial differencing method using uniform circular array by taking 20 number of elements and 100 number of snapshots. The peaks in figures coinciding with real DOA, which proves the validity of the system.

Performance analysis:

Spectrum of coherent signals for varying number of elements from 20 to 60:

Fig 4 represents that as the number of array elements increases from 20 to 60, the resolution capability of the spectrum using spatial differencing method for coherent signals increases and the peaks of the spectrum becomes sharper.

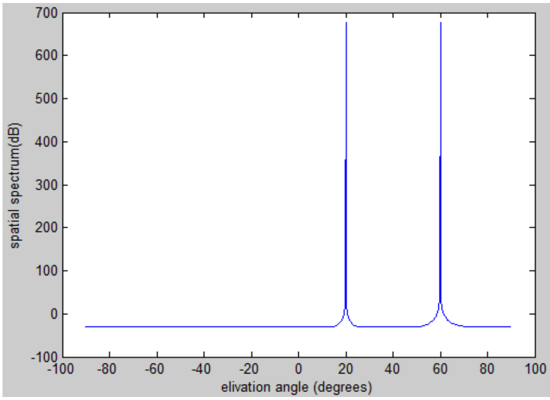

Fig 2: spectrum of uncorrelated signal

The RMSE curve of the DOA estimate versus the number of elements for coherent sources is shown in Fig 5. The figure illustrate the DOA estimation of proposed method will be more accurate as the number of array elements increases.

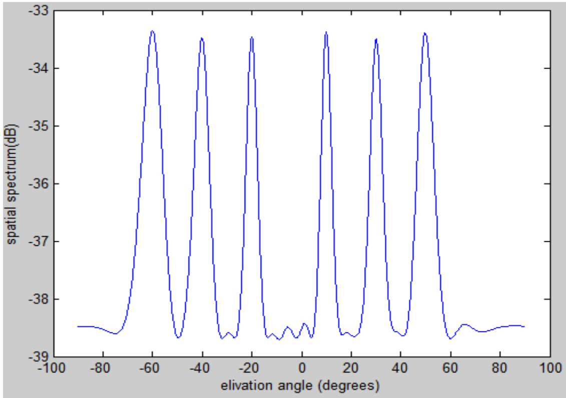

Fig 3: spectrum of coherent signal

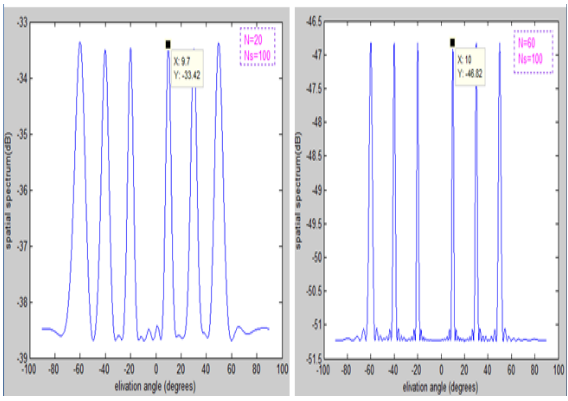

Fig4: spectrum of coherent signals for varying number of elements

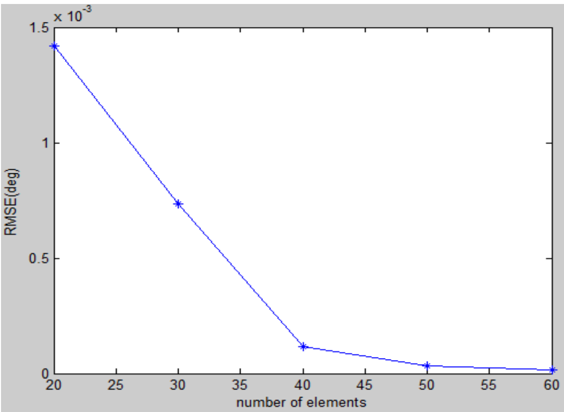

Fig 5: RMSE curve of the DOA estimates versus the number of elements

Uniform circular arrays (UCA) can also be able to provide 360° azimuthally coverage of sources. Let us consider 5 incident signals from azimuthal direction in which first 2 signals are uncorrelated coming from $[150^\circ, 270^\circ]$ and the remaining 3 signals are coherent with 2 multi paths for each signal coming from $[10^\circ, 90^\circ, 200^\circ, 250^\circ, 300^\circ, 350^\circ]$. Fig $6, 7$ and 8 shows the spectrum of the received signals from elevation direction located at $[10^\circ, 90^\circ, 150^\circ, 200^\circ, 250^\circ, 270^\circ, 300^\circ, 350^\circ]$, spectrum of the uncorrelated signals from azimuthal direction located at $[150^\circ, 270^\circ]$ and spectrum of the coherent signals from azimuthal direction located at $[10^\circ, 90^\circ, 200^\circ, 250^\circ, 300^\circ, 350^\circ]$, respectively. Here the simulation results are carried out for UCA with 50 number of elements and 100 number of snapshots.

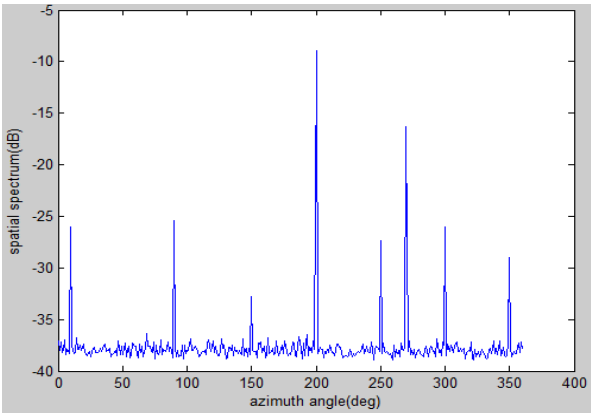

Fig 6: spectrum of received signal from azimuthal direction

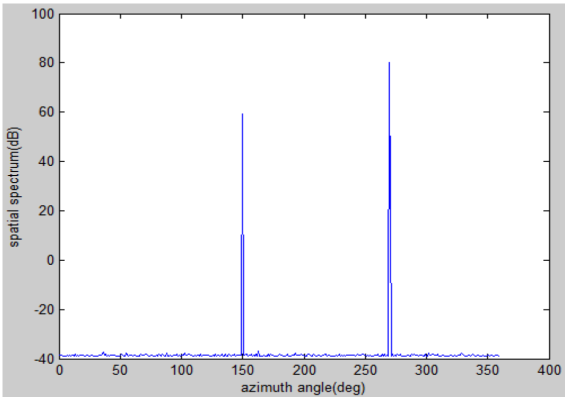

Fig 7: spectrum of uncorrelated signal from azimuthal direction

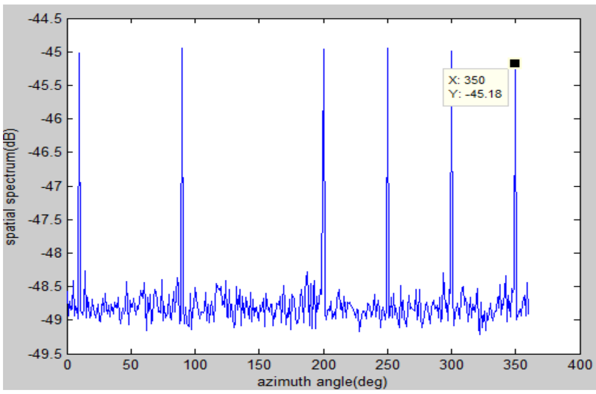

Fig. 8: spectrum of coherent signal from azimuthal direction

The direction of arrival is estimated by spatial differencing method using uniform circular array from azimuthal direction by taking 50 number of elements and 100 number of snapshots. The peaks in spectrum coinciding with real DOA, which proves the effectiveness of the system.

V. CONCLUSION

In this paper, a spatial differencing method is proposed based on symmetric configuration of the UCA. The proposed method can improve the DOA estimation accuracy as well as the maximal number of detectable signals. Simulation results show the effectiveness of the spectrum improves with more number of array elements. These improvements are analyzed in the form of sharper peaks in the spectrum.

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