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DOA Estimation of Uncorrelated and Coherent Signals in Multipath Environment Using ULA Antennas

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ABSTRACT: A Smart antenna plays an important role in advanced wireless communication systems. One of the most important property of smart antenna is that it is capable of directing its main beam towards the direction of desired signal and forming the nulls in the direction of interfering signals. The various Direction of Arrival (DOA) estimation algorithms are used to locate the desired signal in smart antenna system. This paper presents an effective spatial differencing method for DOA estimation of multiple uncorrelated and coherent narrowband signals. In this method, uncorrelated sources are estimated using conventional subspace methods and the remaining coherent signals are estimated using the spatial differencing technique. The performance of this DOA estimation algorithm based on Uniform Linear Array (ULA). Simulation results shows that proposed method can obtain higher resolution and accuracy as the number of array elements increases.

KEYWORDS: Smart antenna, DOA, Spatial differencing, Coherent signals, ULA.

I. INTRODUCTION

DOA estimation for signals impinges on an antenna array is a very important issue for wireless communication systems. Several high resolution methods have been proposed and developed for finding direction of arrival (DOA) such as multiple signal classification (MUSIC) [1] and estimation of signal parameter via rotation invariance techniques (ESPRIT) [2]. But, this methods applicable only when the signals are uncorrelated and there is a need for large number of signal snapshots. However, in real environments the signals are coherent or correlated due to multipath propagation. Those high resolution methods will fail in such environments since they essentially require the signals to be uncorrelated.

A commonly applied decorrelation methods to address this problem is spatial smoothing technique. In this technique the original array is divided in to multiple overlapping sub-arrays, and then averages the sub-arrays output covariance matrices to form the spatially smoothed covariance matrix [3]. This method does not work well as the signals become highly correlated. Under a mild restriction, the required number of antennas can be further reduced by using an improved spatial smoothing scheme referred to as the forward backward spatial smoothing (FBSS) technique [4]. With the combination of FBSS technique and MUSIC to estimate DOAs. This method is referred to as FBSS MUSIC. Unfortunately, this technique requires the number of sensors in each sub array should be greater than the number of signals and the number of sub arrays is greater than or equal to the number of signals. Sarkar and Hua [5], [6] utilized the matrix pencil (MP) based on the spatial samples of the data. The analysis is done by snapshot-by-snapshot basis, therefore non-stationary environments can be handled easily. Matrix pencil method can find DOA easily without performing the additional processing of spatial smoothing as required in some of the conventional covariance matrix based techniques. However, the required signal-to-noise-ratio (SNR) is too high to put the method in to application. An ESC [7] method is proposed for the estimation of DOA in the presence of uncorrelated and coherent signals. The uncorrelated signals are estimated firstly by using the conventional subspace methods and their contribution is eliminated by ESC of the array. Finally, the remaining coherent signals are estimated by utilizing the non-Toeplitz

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matrix. The number of signals resolved by the ESC method can exceed the number of array elements. However, the computational cost of the ESC method is high, whereas, the performance degrades with utilizing only one constructed matrix. A spatial smoothing differencing method is presented in [8]. It utilizes the forward smoothing matrix and the backward smoothing matrix to eliminate the uncorrelated sources. This method can resolve more sources. Unfortunately, the differencing matrix is rank deficient for odd number of coherent signals after the covariance matrix of uncorrelated signals is subtracted. Thus, it needs extra processing to recover the rank. Some methods based on a higher order cumulants are proposed in [9], [10] to resolve more signals. However, these methods require a more number of snapshots and call for an enormous amount of computations.

In this letter, a new spatial differencing method is proposed for DOA estimation in the presence of uncorrelated and coherent signals coexist. The uncorrelated signals are estimated firstly using conventional subspace methods, and their contribution is eliminated by exploiting the proposed 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. The signal model is presented in section 2. Section 3 focused on DOA estimation of the proposed method and related formulations. In section 4, simulation results are presented to illustrate the performance of the proposed method. Finally, section 5 concludes the paper.

II. SIGNAL MODEL

Consider K narrow band signals $s(t)$, from directions $\theta_i\,(i = 1,2,\dots,K)$, impinging on a uniform linear array (ULA) composed of N isotropic sensors equispaced by d. Let $a(\theta_i)$ be the steering (or) response vector of the array given by

$$a(\theta_i) = \left[1, e^{-j2\pi d/\lambda \sin(\theta_i)}, \dots, e^{-j2\pi(N-1)d/\lambda \sin(\theta_i)}\right]^T$$

Where superscript "T" denote the transpose operator and λ denote the carrier wavelength of the signal.

Assume that the 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 directions $\theta_i, i = 1,2,\dots,D$ and $\theta_{il}, i = D+1, D+2,\dots,D+L$ and $l = 1,\dots,p_k$. Where p_k is the multipath signal for each source.

The $N \times 1$ received data vector X(t) can be modeled as

$$\begin{aligned} X(t) &= \textstyle\sum_{i=1}^{D} a(\theta_i)\, s_i(t) + \sum_{i=D+1}^{D+L} \sum_{l=1}^{p_i} a(\theta_{il})\rho_{il}\, s_i(t) + n(t) \\ &= A_u s_u(t) + A_c s_c(t) + n(t) \\ &= As(t) + n(t) \end{aligned}$$

Where $a(\theta_i)$ is the steering vector. ρ_{il} is the fading coefficient of the lth multipath propagation corresponding to the ith source, $\rho_i = \left[\rho_{i1},\dots,\rho_{ip_i}\right]^T$. $A = [A_u\ A_c]$ in which $A_u = [a(\theta_1),\dots,a(\theta_D)]$, $A_c = [A_1\rho_1,\dots,A_L\rho_L]$ with $A_i = \left[a(\theta_{i1}),\dots,a(\theta_{ip_i})\right]$. $s(t) = [s_u^T(t)\ s_c^T(t)]^T$ 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 $n_i(t)$ denoting the additive noise vector of the ith sensor with power σ_n^2. It is assumed that all sources $s_1,\dots,s_D,s_{D+1},\dots,s_{D+L}$ are uncorrelated with each other. Furthermore, $D + L < N$. And the noise is a complex Gaussian random process with zero-mean and variance σ_n^2 and uncorrelated with sources. Under these assumptions, the covariance matrix R of array output is given by,

$$\begin{aligned} R &= E\{X(t)X^H(t)\} \\ &= AR_sA^H + \sigma_n^2 I_N \\ &= A_uR_uA_u^H + A_cR_cA_c^H + \sigma_n^2 I_N \end{aligned}$$

Where $E\{\cdot\}$ denotes the statistical expectation and H denotes the conjugate transpose respectively. $R_u = diag\{\sigma_1^2,\dots,\sigma_D^2\}$ 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 $s_c(t)$. $A = [A_u\ A_c]$, $R_s = blkdiag\{R_u, R_c\}$ is the signal covariance matrix. I_N denotes the $N \times N$ identity matrix.

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III. DOA ESTIMATION

In this section, we describe the DOA estimation of both uncorrelated and coherent sources.

A. *DOA Estimation of the Uncorrelated Sources*

Here, the DOAs of the uncorrelated sources are estimated firstly. The Eigen decomposition of matrix R can be written as

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

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 subspaces called the signal subspace U_s =$[u_1, \dots, u_D]$ and the noise subspace $U_n = [u_{D+1}, \dots u_N]$.Since the steering vectors corresponding to the signal components are orthogonal to the noise subspace eigen vectors. Therefore

$$h(\theta) = |a_i^H U_n|^2 = 0 \qquad i = 0,1, \dots, D$$

Then the DOAs of the uncorrelated signals can be estimated by locating the peaks of spatial differencing (SD) algorithm spectrum can be expressed as

$$P_{SD}(\theta) = \frac{1}{a^H(\theta) U_n U_n^H a(\theta)}$$

B. *DOA Estimation of the Coherent Sources*

In this section, the spatial smoothing is performed on correlation matrix R to find out the DOAs for the coherent signals. In spatial smoothing, the N elements are subdivided in to p overlapping sub arrays, each with n elements. For example sub array 0 would include the elements from 0 to $n-1$, sub array 1 elements from 1 to n, etc. Therefore, the number of sub arrays $p = N - n + 1$. Using the data from each sub array, p covariance matrices are estimated. The k^{th} sub array covariance matrix is given by

$$R_k = K_k R K_k^H$$

Where K_k is the selection matrix with dimension$(N-p+1) \times N$ and R is the covariance matrix of the received signal $X(t)$.The selection matrix K_k is defined as

$$K_k = \left[0_{(N-p+1)\times(k-1)}\; I_{(N-p+1)}\; 0_{(N-p+1)\times(p-k)}\right]$$

In which I denotes the $(N-p+1) \times (N-p+1)$ identity matrix.

For an $N \times N$ covariance matrix R, a p^{th} order spatial differencing matrix D_p is defined as

$$D_p = \frac{1}{p} \sum_{k=1}^{p} \{R_1 - J_{N-p+1} R_k^* J_{N-p+1}\}$$

Where R_1 is the 1^{st} sub array covariance matrix, $R_1 = K_1 R K_1^H$.

R_k is the k^{th} sub array covariance matrix.

The superscript $(\cdot)^*$ denotes the complex conjugation without transposition.

J is an $(N-p+1) \times (N-p+1)$ exchange matrix, where the 1 elements reside on the counter diagonal and all other elements are zero.

The two important properties of spatial differencing matrix D_p has only coherent components remain in the spatial differencing matrix, if D_p is the spatial differencing matrix of the array covariance matrix R, and the rank of spatial differencing matrix is equal to the number of coherent sources, if $p \geq max_k p_k$ $(k \in \{1, \dots, L\})$ and $N - p + 1 > P = \sum_{k=1}^{L} p_k$.

The Eigen decomposition of D_p can be expressed as

$$D_p = U_p \Sigma_p U_p^H = U_{ps} \Sigma_{ps} U_{ps}^H + U_{pn} \Sigma_{pn} U_{pn}^H$$

Where $U_p = [u_1, \dots u_{N-p+1}]$ is a unitary matrix. $\Sigma_p = diag\{\lambda_1, \dots \lambda_{N-p+1}\}$ with $|\lambda_1| \geq \cdots |\lambda_p| > |\lambda_{P+1}| = \cdots = |\lambda_{N-p+1}| = 0$. $U_{ps} = [u_1, \dots, u_P]$, $\Sigma_{ps} = diag\{\lambda_1, \dots \lambda_P\}$, $U_{pn} = [u_{P+1}, \dots, u_{N-p+1}]$, $\Sigma_{pn} = diag\{\lambda_{P+1}, \dots, \lambda_{N-p+1}\}$.

The columns of U_{ps} span the signal subspace, which is orthogonal to the noise subspace spanned by the columns of U_{pn}. Therefore,

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$$f(\theta) = \left|a^H(\theta)U_{pn}\right|^2 = 0$$
For $\theta = \theta_{kl}, \forall\, k \in (1, \dots, L), \forall\, i \in (1, \dots, p_k)$.

Then the DOAs of the coherent signals can be estimated by locating the peaks of the spatial differencing (SD) algorithm spectrum can be expressed as

$$P_{SD}(\theta) = \frac{1}{a^H(\theta)U_{pn}U_{pn}^H a(\theta)}$$

C. *Summary of the Spatial Differencing Algorithm*

Spatial differencing method for DOA estimation under the coexistence of both uncorrelated and coherent signals can be summarized as follows.

1. Consider the input signal as
$$X(t) = \sum_{i=1}^{D} a(\theta_i)\, s_i(t) + \sum_{i=D+1}^{D+L} \sum_{l=1}^{p_i} a(\theta_{il})\rho_{il}\, s_i(t) + n(t)$$

2. Estimate the correlation matrix R using the input signal $X(t)$.
$R = \frac{1}{N_s}\sum_{k=1}^{N_s}\{X(t)X^H(t)\}$

Where N_s is the number of snapshots.

3. Compute the eigen decomposition of R and estimate the number of received signals K.
4. Estimate the DOAs of uncorrelated signals by making use of $h(\theta)$.
5. Calculate the spatial differencing matrix D_p.
6. Perform the eigen decomposition of D_p and estimate the number of coherent signals P.
7. Estimate the DOAs of coherent signals by making use of $f(\theta)$.

IV. RESULTS AND DISCUSSION

In this section, we present simulation results to evaluate the performance of the proposed method. Simulation results are carried out for ULA with 20 numbers of elements and 100 numbers of snapshots. The performance of this algorithm has been analyzed by considering the Root Mean Square Error (RMSE) as a function of array elements, function of snapshots and as a function of sub arrays. The RMSE of the DOA estimates 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 estimated angles and θ_i is the given angles.

Let us consider, Number of incident signals 5 in which the first 2 signals are uncorrelated coming from $[10^\circ, 50^\circ]$ and the remaining 3 signals are coherent with 2 multipaths for each source coming from $[-10^\circ, 20^\circ, -30^0, 40^0, -50^\circ, 60^\circ]$. The figure *1*, figure *2* and figure *3* shows the spectrum of the received signals located at $[10^\circ, 50^\circ, -10^0, 20^0, -30^\circ, 40^\circ, -50^\circ, 60^\circ]$, spectrum of the uncorrelated signals located at $[10^\circ, 50^\circ]$ and the spectrum of the coherent signals located at $[-10^\circ, 20^\circ, -30^\circ, 40^\circ, -50^\circ, 60^\circ]$, respectively.

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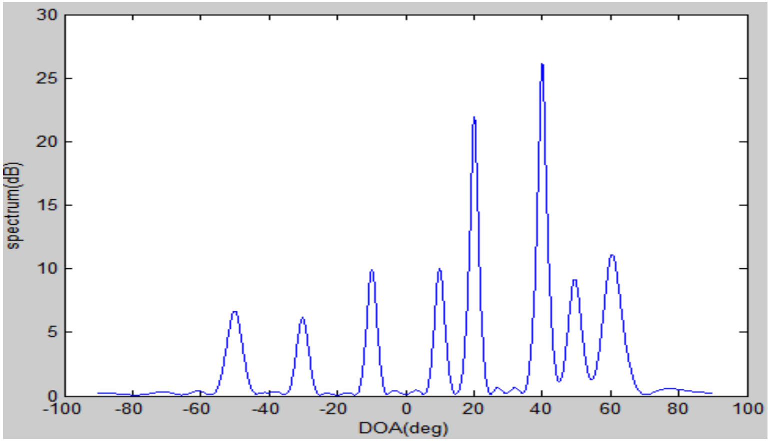

Figure 1: Array pattern of received signal

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

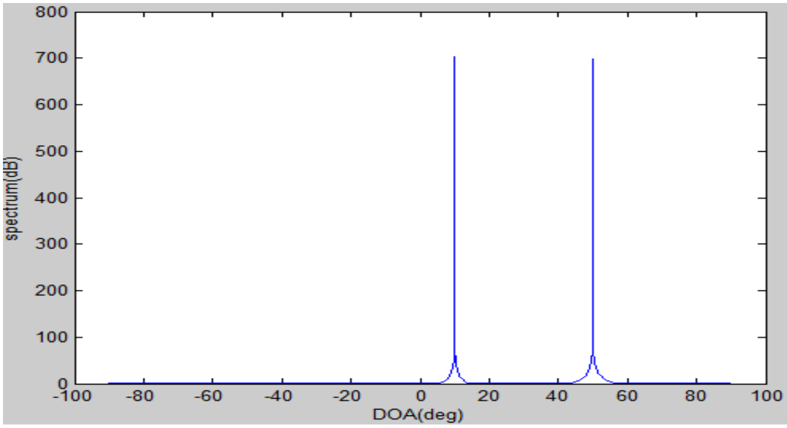

Figure2: Array pattern of uncorrelated signal

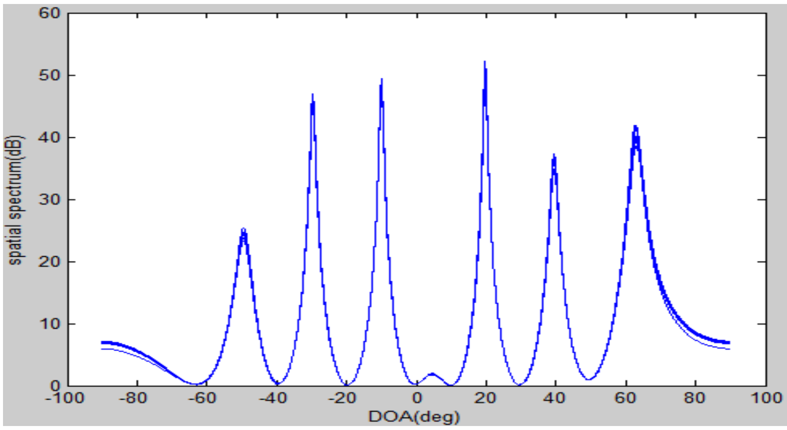

Figure 3: Array pattern of coherent signals

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Performance Analysis:

Spectrum of coherent signals for varying number of array elements:

Figure 4 represents that as the number of array elements increase from *20* to *40*, resolution capability of the spectrum of spatial differencing method for coherent signals increases and the peaks in the spectrum become sharper.

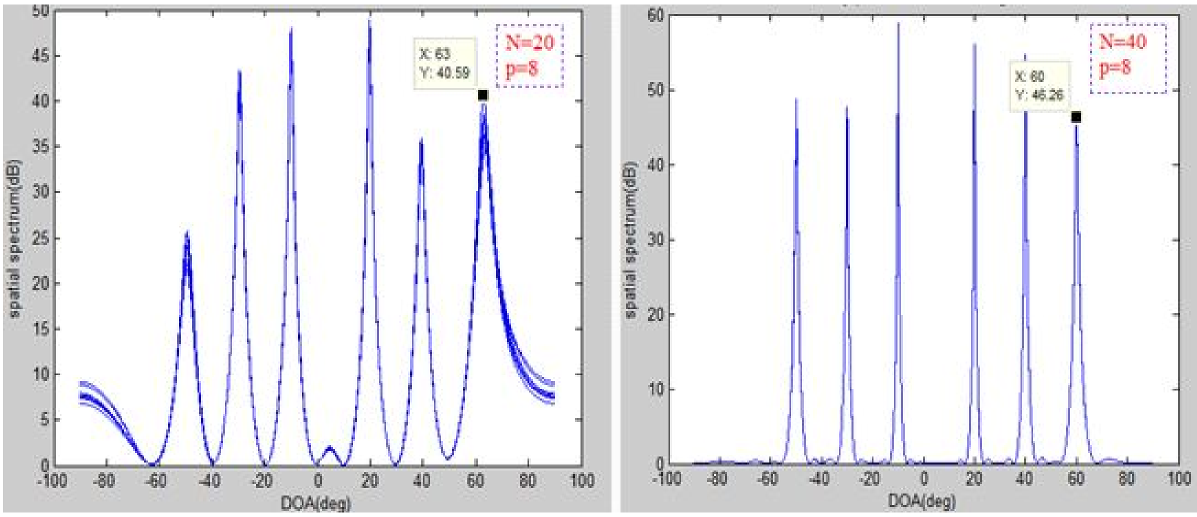

Figure*4*: Array pattern of coherent signals for varying number of elements

Spectrum of coherent signals for varying number of snapshots:

Figure 5 indicates that as the number of snapshots increases from 100 to 500, the peaks in the spectrum becomes sharper and the resolution capability of the spectrum increases.

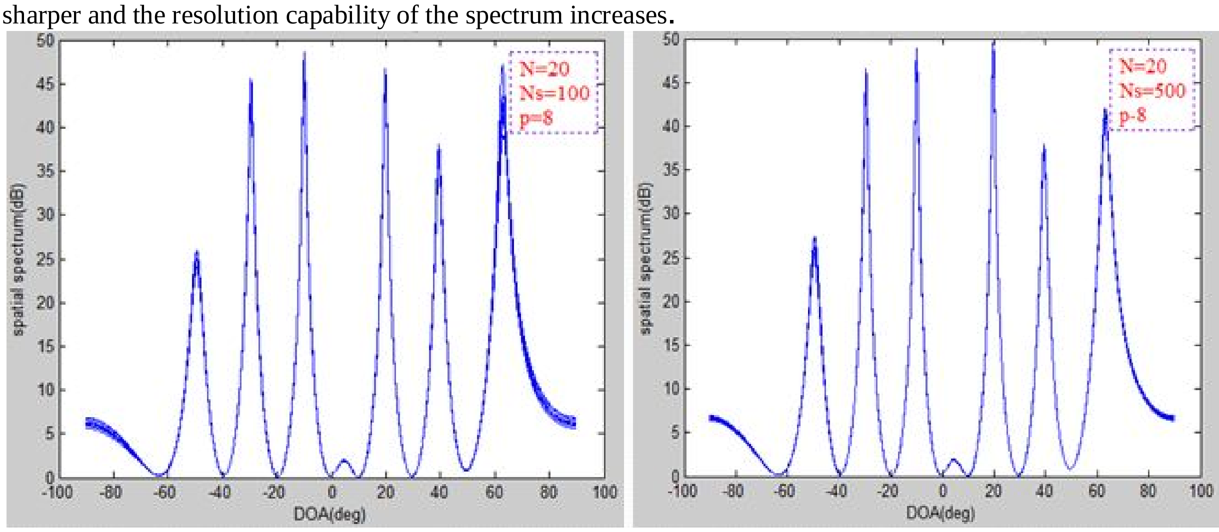

Figure*5*: Array pattern of coherent signals for varying number of snapshots

Spectrum of coherent signals for varying number of sub arrays:

Figure 6 shows the array pattern with the number of sub arrays increases from 8 to 12. The direction of arrival is estimated by spatial differencing method using 20 number of elements and 100 snapshots. From figure 6 we see that the proposed method provide better DOA estimation as the number of sub arrays increases.

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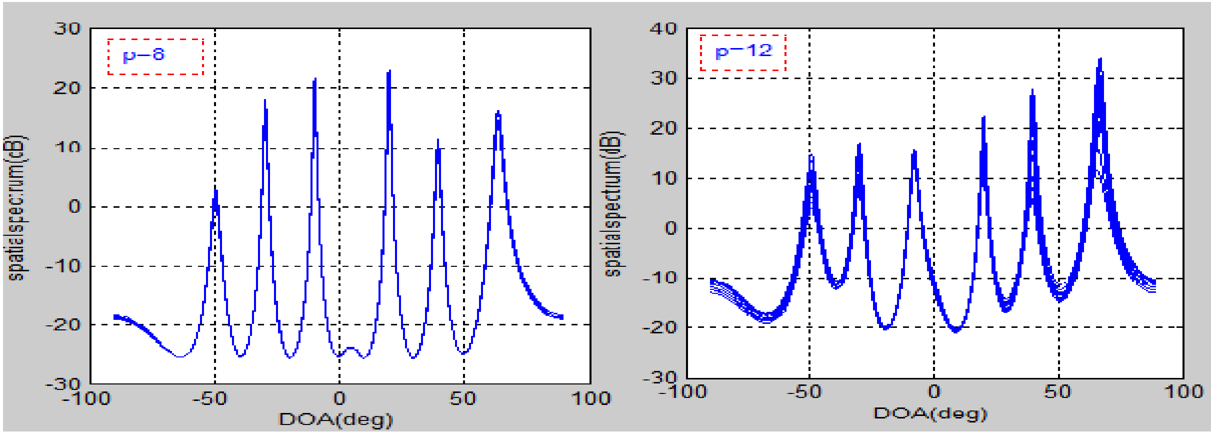

Figure 6: Array pattern versus the number of sub arrays

Figure 7 shows the array pattern with the number of sub arrays ranging from 2 to 4. From this figure we see that the spatial differencing method provides better DOA estimation even using less number of sub arrays.

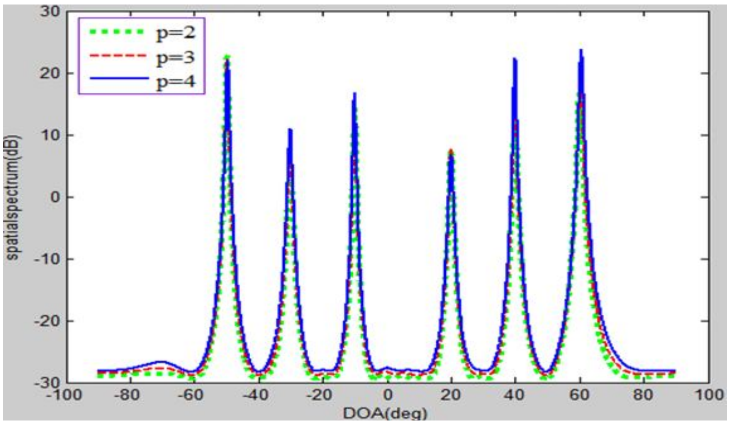

Figure 7: Array pattern versus the less number of sub arrays

The RMSE curve of the DOA estimate versus the number of snapshots for coherent sources is shown in figure 8. The figure illustrate the DOA estimation of proposed method will be more accurate as the number of snapshots increases.

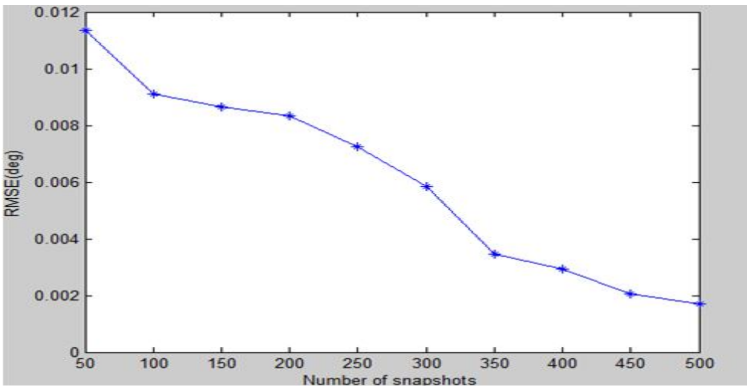

Figure 8: RMSE curve of the DOA estimates versus the number of snapshots

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Figure 9 shows the RMSE curve of the DOA estimates with $p = 2$ sub arrays versus the number of snapshots for coherent sources, this figure illustrates the proposed method provides better DOA estimation even using fewer number of sub arrays.

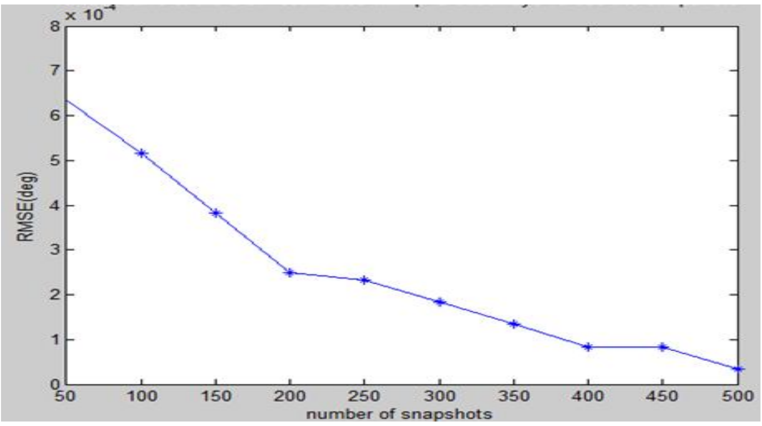

Figure 9 : RMSE curve of the DOA estimates with $p = 2$ sub arrays versus the number of snapshots

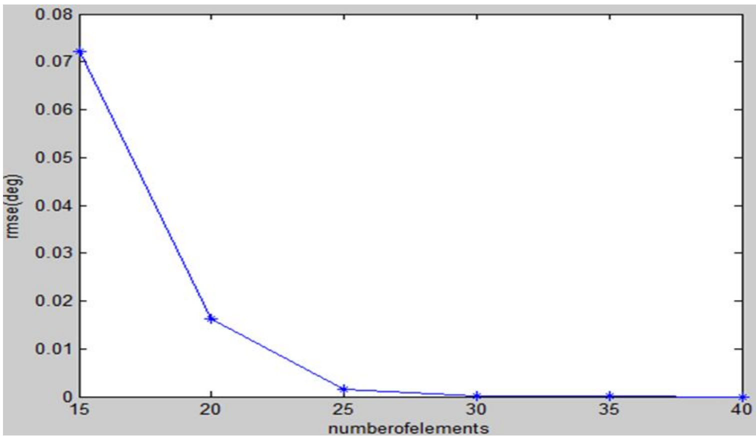

Figure *10*: RMSE curve of the DOA estimates versus the number of elements

Figure 10 represents the RMSE curve of the DOA estimates versus the number of array elements for coherent sources. The figure illustrates that the proposed method provides better DOA estimation as the number of array elements increases so the RMSE is close, but not exactly zero.

V. CONCLUSION

In this paper, a spatial differencing method is proposed based on the symmetric configuration of the ULA. The proposed method can improve the DOA estimation accuracy, as well as increase the maximal number of detectable signals. Simulation results show the performance of the spectrum improves with more number of elements in the array and the higher number of snapshots. These improvements are analyzed in the form of sharper peaks in the spectrum. Results indicate that the RMSE decreases as the number of snapshots and the array elements increases.

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