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DISPLACED SENSOR ARRAY FOR IMPROVED SIGNAL DETECTION UNDER GRAZING INCIDENCE CONDITIONS

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Abstract—This paper proposes a displaced sensor array (DSA) configuration for estimating the angles of arrival of narrowband sources arriving at grazing incidence directions. Unlike the conventional uniform linear array (ULA) where all the array elements are aligned along one axis, the proposed DSA configuration comprises two displaced ULAs aligned on two parallel axes in the vertical plane. The steering vectors of the two parallel arrays differ from each other by only two multiplicative phase terms that represent the space factors due to the vertical separation and horizontal displacement of the two arrays. This makes the computational load of using MUSIC algorithm with the proposed DSA configuration identical to that of ULA yet the accuracy is much higher especially for cases involving narrowband sources arriving at grazing incidence angles. Simulation results obtained show that the proposed DSA configuration outperforms the conventional ULA in terms numerical accuracy and angular resolution.

1. INTRODUCTION

Smart antennas are set to revolutionize the wireless communications industry with their enormous potential to enable the development of more powerful, cost-effective, and efficient wireless systems. While alternative techniques such as lower noise amplifiers and wider bandwidths can be used to improve the performance of wireless systems, they cannot compare with smart antennas, which essentially merge an antenna array with a digital signal processing (DSP) capability, in terms of enhancing their range, speed, and capacity [1]. The development of low cost DSPs will allow smart antennas also to be used in a wide range of wireless applications such as worldwide interoperability for microwave access (WiMax) and voice over wireless fidelity (VoWi-Fi). The advantages of smart antennas have already been exploited in various wireless technologies including OFDM [2], WCDMA [3], and mobile ad-hoc networks (MANETs) [4].

Recent research efforts into smart antennas have varied from array pattern synthesis based on null steering and multi-user beamforming using a phase control method [5], to augmentation of anti-jam GPS smart antenna system using direction estimation algorithm [6], to a performance study of circular and hexagonal array geometries for smart antenna applications [7], to a comparison between circular and hexagonal array geometries for smart antenna systems using particle swarm optimization [8]. Other research efforts have recently focused on the development of an adaptive and a switched beam smart antenna system for wireless communications [9], tapered beamforming method for uniform circular arrays [10], optimization of the radiation pattern of the antenna array in the direction finding system [11], beam steering with null and excitation constraints for linear antenna arrays [12], and finally DOA estimation bias from inaccurate knowledge of the antnenna array response [13]. The emphasis in this paper is to develop a displaced sensor array (DSA) for smart antenna applications that can be used for an accurate DOA estimation of narrowband signals arriving at grazing incidence directions.

A smart antenna system at the base station of a cellular mobile system is depicted in Figure 1. It consists of a uniform linear array (ULA) for which the current amplitudes are adjusted by a set of complex weights using an adaptive beamforming algorithm. The adaptive beamforming algorithm optimizes the array output beam pattern such that maximum radiated power is produced in the directions of desired mobile users and deep nulls are generated in the directions of undesired signals representing co-channel interference from mobile users in adjacent cells. Prior to adaptive beamforming, the angles of arrival of narrowband sources from desired mobile users must be estimated using a direction of arrival (DOA) estimation algorithm [14]. This paper deals with the first part of the smart antenna system with an emphasis on estimating the angles of arrival of narrowband sources arriving at close to the array endfire direction, i.e., grazing incidence with respect to the array axis. For that purpose, a high-resolution DOA estimation algorithm known as MUltiple SIgnal Classification (MUSIC) is used to produce an angular spectrum in which the location of peaks would correspond to the desired angles of arrival of incident narrowband sources.

Due to practical considerations it is desirable to design smart antenna systems with smaller size. This can be done by employing

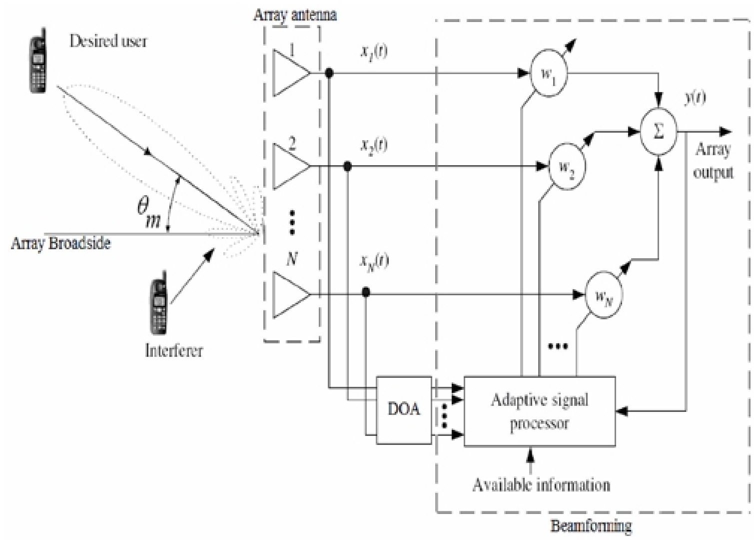

Figure 1. A functional block diagram of a smart antenna system.

a ULA with smaller aperture. The inter-element spacing in a ULA is usually maintained to $\lambda/2$ in order to reduce the effects of inter-element mutual coupling and avoid spatial aliasing as well. Hence, for the conventional ULA the array aperture can be reduced only by decreasing the number of antennas in the array. This will, however, limit the array capability of handling more incident signals from mobile users resulting in a reduction in the system capacity. It is therefore desirable to design a smart antenna system which can handle more signals without increasing the array aperture significantly. This can be achieved using the displaced sensor array (DSA) configuration presented in this paper which consists of two parallely-displaced ULAs that are aligned in the vertical plane.

The paper is organized as follows: Section 2 compares the conventional ULA configuration with the proposed DSA configuration. Advantages of using the DSA configuration are outlined in Section 3. Section 4 then describes the signal model based on the DSA configuration and derives the corresponding covariance matrix. The theory of DOA estimation based on using MUSIC with the proposed DSA configuration is then presented in Section 5. Section 6 presents simulation results showing the limitations of ULA configuration and significant improvements obtained when using the DSA configuration for estimating narrowband source signals arriving at grazing incidence directions. Finally, conclusions are given in Section 7.

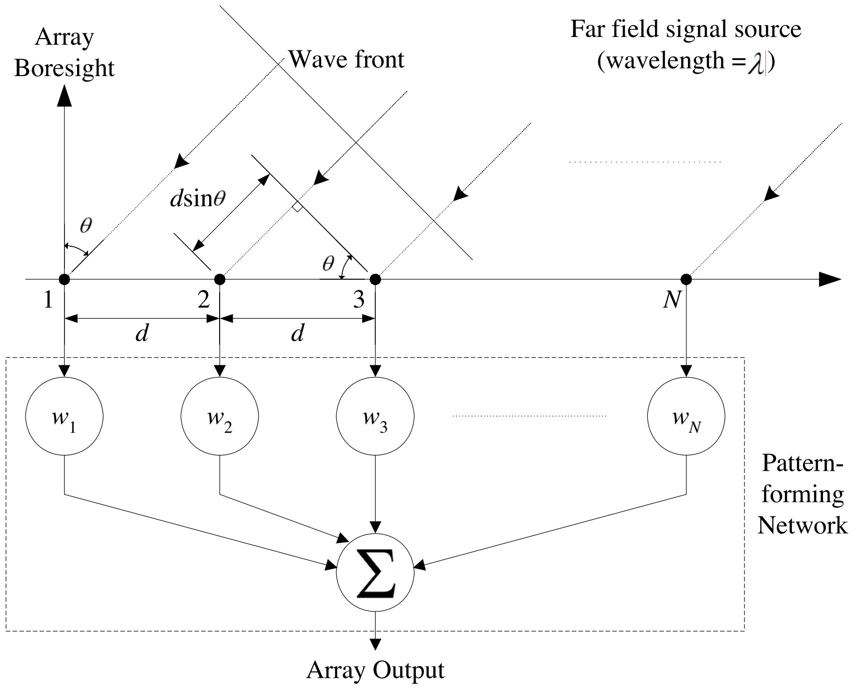

Figure 2. Geometry of a Uniform Linear Array (ULA) of N sensors that are equally spaced apart a distance $d = \lambda/2$.

2. ARRAY CONFIGURATION

The standard array geometry that has been used for smart antenna systems is the uniform linear array (ULA) depicted in Figure 2. A uniform linear array (ULA) consists of N elements that are spaced apart by half wavelength ($d = \lambda/2$). The inter-element spacing in a ULA is chosen to be $\lambda/2$ in order to reduce mutual coupling effects which deteriorate the performance of the DOA estimation algorithm as demonstrated in [15–20]. If the inter-element spacing is chosen to be smaller than $\lambda/2$, mutual coupling effects then cannot be ignored and the DOA estimation algorithm fails to produce the desired peaks in the angular spectrum. On the other hand, increasing the inter-element spacing beyond $\lambda/2$ results in spatial aliasing which takes the form of unwanted or misplaced peaks in the angular spectrum. It is therefore concluded that $d = \lambda/2$ represents the optimum value for the inter-element spacing in a ULA.

The main advantage is using a ULA is that it has the simplest geometry, an excellent directivity, and produces the narrowest main-lobe in a given direction in comparison to other array geometries. However, a ULA does not work equally well for all azimuth directions [7, 8]. This major drawback can be resolved by employing other array geometries, such as circular and hexagonal, at the price of a more complex array structure and large array aperture making such array geometries inappropriate to be used at the antenna base stations. It is therefore desirable to develop a new array configuration which is based on the ULA yet performs equally well for all azimuth directions. This paper presents such a configuration which is shown to have equally improved performance for all azimuth angles.

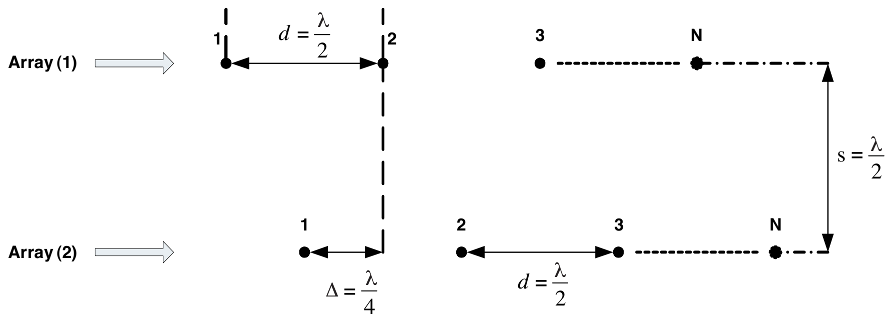

Figure 3. Displaced Sensor Array (DSA) configuration consists of two parallely-displaced arrays in the vertical plane displaced horizontally by a distance $\Delta = \lambda/4$ and separated vertically by a distance $s = \lambda/2$.

The DSA configuration is depicted in Figure 3, and was first presented by Shubair [21, 22]. It consists of two parallel ULAs displaced horizontally by a distance $\Delta = \lambda/4$ and separated vertically by a distance $s = \lambda/2$, as shown in Figure 3. Each of the two parallel ULAs consists of N linear equispaced omnidirectional sensors with inter-element spacing $d = \lambda/2$. The two parallel ULAs are positioned along the x axis with an azimuth angle θ_m measured with respect to the z axis. It is assumed that the DSA configuration receives M narrowband source signals $s_m(t)$ from incidence directions $\theta_1, \theta_2, \ldots, \theta_M$.

3. ADVANTAGES OF DSA CONFIGURATION

The DSA configuration shown in Figure 3 has several advantages. First, it maintains almost the same radiation aperture as the ULA yet it can resolve more narrowband sources since it comprises twice the number of sensors of a ULA. Second, the horizontal displacement between the two parallel arrays in the DSA configuration allows for resolving correlated narrowband source signals without having to apply spatial smoothing techniques. Third, in the DSA configuration, the steering vectors of the two parallel arrays differ from each other by only two multiplicative phase terms that represent the space factors due to the vertical separation and horizontal displacement of the two arrays. This makes the computational load of using MUSIC algorithm with the proposed DSA configuration identical to that of ULA. Finally, the vertical separation between the two parallel arrays in the proposed DSA configuration allows for resolving signals arriving at grazing incidence (endfire) directions in the vertical plane. This latter feature is the emphasis of this paper.

4. SIGNAL MODEL USING DSA CONFIGURATION

The received signal vector denoted by $\mathbf{x}(t)$ includes an addictive Gaussian noise with zero mean when the received signals are assumed to be direct line of sight to the antenna arrays and not correlated with the noise signal. At a particular instant of time $t = 1, 2, \ldots, K$, where K is the total number of snapshots taken, the desired users signal vector $\mathbf{x}(t)$ is given by

$$\mathbf{x}(t) = \sum_{m=1}^{M} \left[\mathbf{a}_1(\theta_m) + \mathbf{a}_2(\theta_m)\right] s_m(t) + \mathbf{n}(t) \tag{1}$$

where $\mathbf{n}(t)$ is the sensor noise vector modeled as temporally white and zero mean complex Gaussian process, $\mathbf{a}_1(\theta_m)$ and $\mathbf{a}_2(\theta_m)$ are the steering (or response) vectors for the two parallel arrays with respect to θ_m, which represents the angle of arrival of the mth signal. The first steering vector $\mathbf{a}_1(\theta_m)$ has dimensions $N \times 1$ and represents the space factor of the first array with respect to direction θ_m. It is given by

$$\mathbf{a}_1(\theta_m) = \{\exp\left[j(n-1)\psi_m\right]\}^T \qquad :1 \leq n \leq N \tag{2}$$

where $\{\}^T$ is the transposition operator and ψ_m represents the electrical phaseshift from element to element along the array defined as

$$\psi_m = 2\pi(d/\lambda)\sin\theta_m \tag{3}$$

where d is the inter-element spacing and λ is the wavelength of the received signal. The second steering vector $\mathbf{a}_2(\theta_m)$ has dimensions $N \times 1$ also and represents the space factor of the second array with respect to direction θ_m. It is given by

$$\mathbf{a}_2(\theta_m) = \mathbf{a}_1(\theta_m) \cdot F_s(\theta_m) \cdot F_\Delta(\theta_m) \tag{4}$$

where $F_s(\theta_m)$ and $F_\Delta(\theta_m)$ represent the space factors due to the vertical separation s and horizontal displacement Δ of the two parallel arrays, respectively. These are given by

$$F_s(\theta_m) = \exp\left[-j2\pi\left(\frac{s}{\lambda}\right)\cos\theta_m\right] \quad (5)$$

$$F_\Delta(\theta_m) = \exp\left[-j2\pi\left(\frac{\Delta}{\lambda}\right)\sin\theta_m\right] \quad (6)$$

The combination of all possible steering vectors forms the array manifold (or steering vector) matrices $\mathbf{A}_1$ and $\mathbf{A}_2$ of size $N \times M$ each, i.e.,

$$\mathbf{A}_1 = [\mathbf{a}_1(\theta_1), \mathbf{a}_1(\theta_2), \ldots, \mathbf{a}_1(\theta_M)] \quad (7)$$

$$\mathbf{A}_2 = [\mathbf{a}_2(\theta_1), \mathbf{a}_2(\theta_2), \ldots, \mathbf{a}_2(\theta_M)] \quad (8)$$

The received signal vector $\mathbf{x}(t)$ of (1) can then be written as

$$\mathbf{x}(t) = [\mathbf{A}_1 + \mathbf{A}_2]\, s(t) + \mathbf{n}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t) \quad (9)$$

where the overall array manifold matrix $\mathbf{A} = \mathbf{A}_1 + \mathbf{A}_2$. The conventional (forward only) estimate of the correlation matrix is defined as

$$\mathbf{R} = E\{\mathbf{x}(t)\mathbf{x}^H(t)\} \quad (10)$$

where $E\{\cdot\}$ represents the ensemble average; and $(\cdot)^H$ is the Hermitian transposition operator. Equation (10) can be approximated by applying temporal averaging over K snapshots (or samples) taken from the signals incident on the sensor array. This averaging process leads to forming a spatial correlation matrix $\mathbf{R}$ given by [23]

$$\mathbf{R} = \frac{1}{K}\sum_{k=1}^{K}\mathbf{x}(k)\mathbf{x}^H(k) \quad (11)$$

Substituting for $\mathbf{x}(t)$ from (9) in (11) yields

$$\mathbf{R} = \frac{1}{K}\sum_{t=1}^{K}\mathbf{A}\left[\mathbf{s}(k)\mathbf{s}(k)^H\right]\mathbf{A}^H + \mathbf{n}(k)\mathbf{n}(k)^H \quad (12)$$

Finally, Equation (12) can be written in compact form as

$$\mathbf{R} = \mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H + \sigma_n^2\mathbf{I} \quad (13)$$

where $\mathbf{R}_{ss} = E\{\mathbf{s}(t)\mathbf{s}^H(t)\}$ is an $M \times M$ source waveform covariance matrix, σ_n^2 is the noise variance, and $\mathbf{I}$ is an identity matrix. In general the array correlation matrix obtained in (13) is referred as the covariance matrix only when the mean values of the signals and noise are zero. The arriving signals mean value must be necessarily zero because antennas can not receive d.c. signals.

5. DOA ESTIMATION ALGORITHM

A common subspace-based DOA estimation algorithm is MUSIC (MUltiple SIgnal Classification) [14]. This method is based on the eigen-decomposition of the covariance matrix $\mathbf{R}$ into a signal subspace and noise subspace. The algorithm starts by expressing the covariance matrix $\mathbf{R}$ obtained in (13) as

$$\mathbf{R} = \mathbf{J}\mathbf{R}^*\mathbf{J} \tag{14}$$

where $\mathbf{J}$ is the exchange matrix with ones on its anti-diagonal and zeros elsewhere; and $(\cdot)^*$ stands for complex conjugate. The covariance matrix $\mathbf{R}$ in (14) is known to be centro-Hermitian if and only if $\mathbf{R}_{ss}$ is a diagonal matrix, i.e., when the signal sources are uncorrelated.

It can be shown [15, 16] that the covariance matrix $\mathbf{R}$ obtained in (13) has M signal eigenvalues with corresponding eigenvectors $\mathbf{v}_1, \ \mathbf{v}_2, \ldots, \mathbf{v}_M$, i.e.,

$$\mathbf{V}s = [\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_M] \tag{15}$$

The remaining $N - M$ eigenvalues of the covariance matrix $\mathbf{R}$ represent noise eigenvalues with corresponding eigenvectors $\mathbf{v}_{M+1}, \ \mathbf{v}_{M+2}, \ldots, \mathbf{v}_N$, i.e.,

$$\mathbf{V}_n = [\mathbf{v}_{M+1}, \mathbf{v}_{M+2}, \ldots, \mathbf{v}_N] \tag{16}$$

Hence, the eigen-decomposition of the covariance matrix in (13) can be defined in a standard way as [23]:

$$\mathbf{R} = \mathbf{V}\Pi\mathbf{V} = \mathbf{V}_s\Pi_s\mathbf{V}_s + \sigma^2\mathbf{V}_n\mathbf{V}_n^H \tag{17}$$

where the subscripts s and n stand for signal- and noise-subspace, respectively. In (17) Π_s is defined as

$$\Pi_s = diag\{\lambda_1, \lambda_2, \ldots, \lambda_M\} \tag{18}$$

where $\lambda_1, \lambda_2, \ldots, \lambda_M$ are the eigenvalues of the signal subspace. The normalized MUSIC angular spectrum is defined as [23, 24]

$$P(\theta) = \frac{\mathbf{A}^H\mathbf{A}}{\mathbf{A}^H\mathbf{V}_n\mathbf{V}_n^H\mathbf{A}} \tag{19}$$

By examining the denominator in (19) it is evident that peaks in the MUSIC angular spectrum occur at angles θ for which the array manifold matrix $\mathbf{A}$ is orthogonal to the noise subspace matrix $\mathbf{V}_n$. Those angles θ define the desired directions-of-arrival of the signals impinging on the sensor array.

The number of signals that can be detected is restricted by the number of elements in the sensor array. In [15] and [16] it was verified that an N element sensor array can detect up to $N-1$ uncorrelated signals. This number reduces to $N/2$ signals if they are correlated. A comprehensive performance evaluation of the MUSIC algorithm for DOA estimation can be found in [15–20].

6. SIMULATION RESULTS

Simulation results are obtained for MUSIC-based DOA estimation using ULA with $N = 4$ elements and proposed DSA configuration with total number of elements $2N = 8$ in the two parallel array. Inter-element spacing of $d = \lambda/2$ is maintained in both configurations in order to reduce mutual coupling effects which deteriorate the performance of MUSIC algorithm. Simulation results are presented in the form of the MUSIC angular spectrum in which peaks indicate the desired angles of arrival for the narrowband sources being detected. We have assumed a signal-to-noise ratio $SNR = 20\,\text{dB}$ and the number of snapshots $K = 1000$.

6.1. Results Showing Limitation of Conventional ULA

Figure 4 depicts the MUSIC angular spectrum obtained using conventional ULA for three cases each of which include two angles of arrival to be detected. In the first case the two angles of arrival to be detected are AOA=($-30°$, $30°$) for which the angular separation is $\Delta\theta = 60°$. In the second case the two angles of arrival to be detected are AOA=($-60°$, $60°$) for which the angular separation is $\Delta\theta = 120°$. Finally, in the third case which denotes grazing incidence the two angles of arrival to be detected are AOA=($-90°$, $90°$) for which the angular separation is $\Delta\theta = 180°$. It is evident from Figure 4 that DOA estimation using MUSIC works well only for the first two cases when the angles of the arrival are close to the array boresight (broadside direction). On the other hand, for the third case which denotes grazing incidence conditions, the incoming signals are incident at angles close to the array endfire direction ($\theta = \pm 90°$) and the ULA fails to detect the signals as evident from the absence of peaks in the MUSIC angular spectrum shown in Figure 4. This example shows the

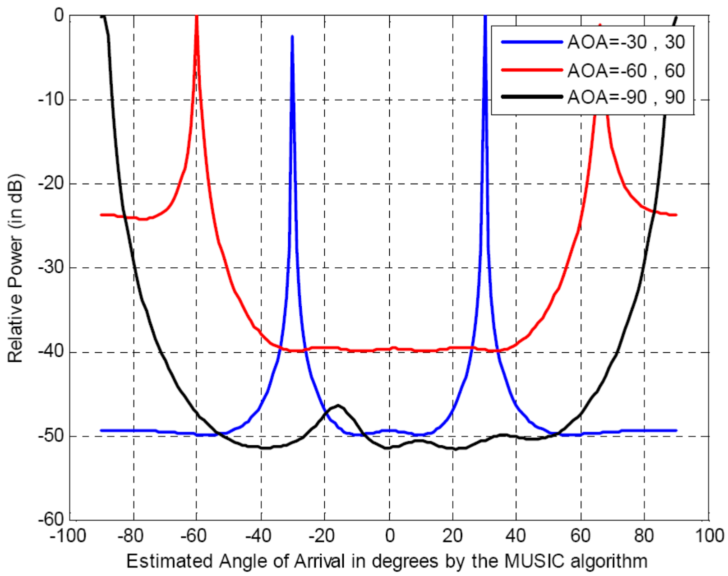

Figure 4. MUSIC angular spectrum for different angles of arrival.

need for a modified sensor array geometry such as the proposed DSA configuration.

6.2. Comparison of Conventional ULA and Proposed DSA

Figure 5 depicts the MUSIC angular spectrum using both conventional ULA and proposed DSA for the case involving two narrowband sources arriving at angles $\theta_1 = -75°$ and $\theta_2 = 75°$ which are close to grazing incidence ($\theta = \pm 90°$). It is evident from Figure 5 that the DSA configuration was capable of resolving the two narrowband signals in the form of two sharp peaks in the MUSIC spectrum, whereas the conventional ULA failed to detect them. This result is further confirmed by comparing the results obtained in Figure 6 using the conventional ULA with those obtained in Figure 7 using the proposed DSA configuration, for multiple cases involving two grazing incidence angles each. For all cases investigated, the DSA configuration was capable of detecting the two grazing incidence narrowband signals in the form of two sharp peaks as shown in Figure 7, whereas the conventional ULA failed to resolve the two signals as evident by the absence of peaks in the MUSIC angular spectrum in Figure 6.

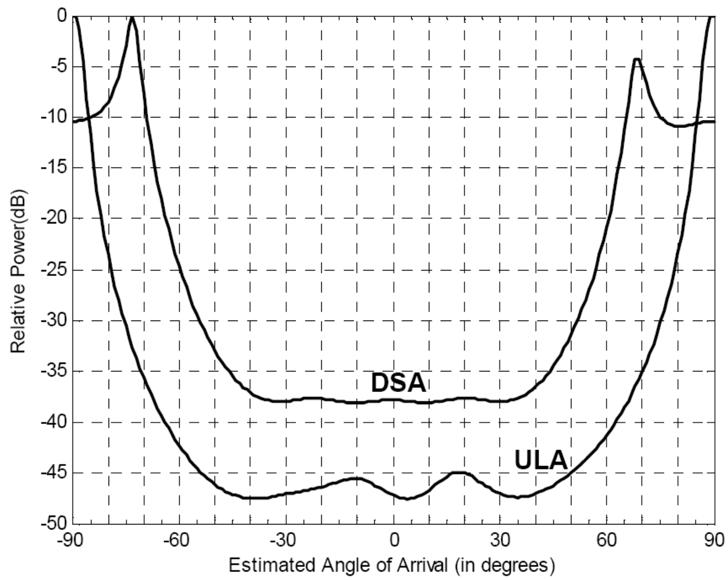

Figure 5. MUSIC angular spectrum using both ULA and DSA.

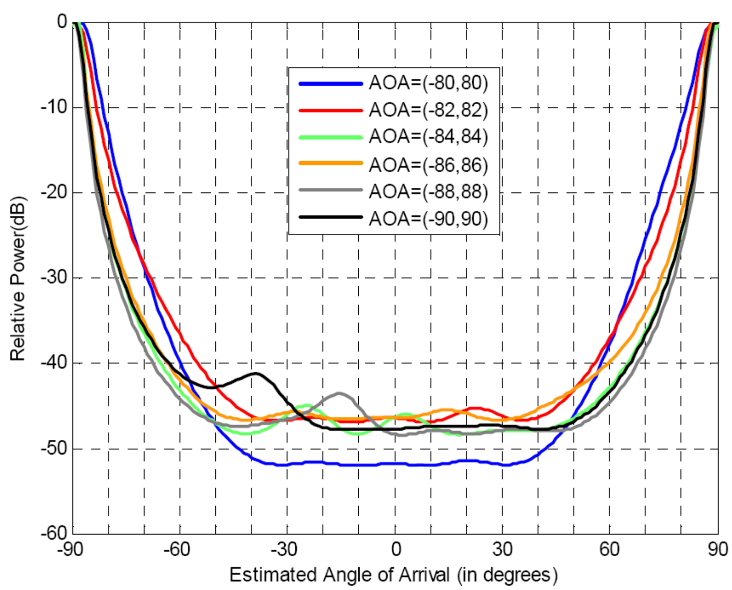

Figure 6. MUSIC angular spectrum using ULA.

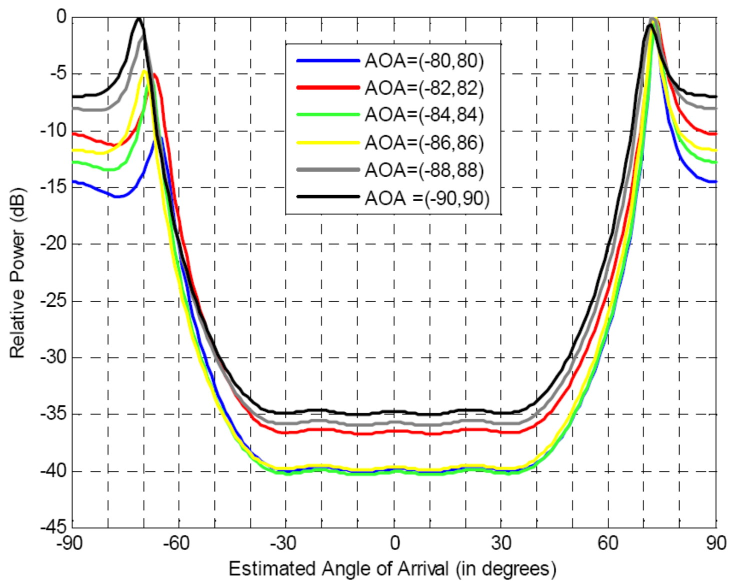

Figure 7. MUSIC angular spectrum using DSA.

7. CONCLUSIONS

In conclusion, we have proposed a displaced sensor array (DSA) configuration for high resolution DOA estimation of narrowband sources especially for cases involving signals arriving at grazing incidence (array endfire) directions. The proposed DSA configuration maintains almost the same radiation aperture as the ULA yet it can resolve more narrowband sources since it comprises twice the number of sensors when compared to the ULA. Moreover, in the DSA configuration, the steering vectors of the two parallel arrays differ from each other by only two multiplicative phase terms which represent the space factors due to the vertical separation and horizontal displacement of the two arrays. This makes the computational load of using MUSIC algorithm with the proposed DSA configuration identical to that of ULA. Finally, the vertical separation between the two parallel arrays in the proposed DSA configuration allows for resolving signals arriving at grazing incidence in the vertical plane. Simulation results for cases involving narrowband sources arriving at grazing incidence angles showed that the proposed DSA configuration outperforms the conventional ULA in terms numerical accuracy and angular resolution.

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