PAPER

Experimental Study on MUSIC-Based DOA Estimation by Using Universal Steering Vector

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SUMMARY MUSIC-based estimation of direction of arrival (DOA) using universal steering vector (USV) is experimentally studied. A four-element array antenna and a four-channel receiver are employed for the experiment. In order to improve the accuracy of DOA estimation, USV which has already included the effect of mutual coupling between array elements and effect of array elements themselves is compensated to further include the electric delay and loss of four channels in the receiver. The compensated USV (C-USV) approach proposed in this paper does not need the time-consuming measurement of array element pattern because the compensating matrix for USV is obtained by measuring the S parameters between RF input ports of the feeding cables and IF output ports of the receiver. The experimental results of MUSIC-based DOA estimation show that C-USV approach is an accurate, effective and practical method for the MUSIC-based DOA estimation.
key words: *MUSIC, direction of arrival, array antenna, array element pattern, mutual coupling, steering vector, MoM*

1. Introduction

It is well-known that the accuracy of DOA estimation using the MUSIC algorithm might be degraded significantly due to the effects of the mutual coupling among receiving array elements. Many efforts have been made to establish compensation approaches which can remove the effect of the mutual coupling from the received voltage at the terminals of the array antenna [1]–[9]. In most of the proposed compensation approaches, a compensation matrix is evaluated by calibrating the receiving signal to compensate the received signal or the steering vector to exclude the mutual coupling effect in order to improve the accuracy of DOA estimation. However, the compensation matrix is usually dependent on the searching direction which is an unknown parameter in the MUSIC algorithm. In order to solve this problem, the compensation matrix is prepared for all the possible DOA experimentally or numerically before DOA estimation, which is called the array manifold. A huge storage is required to store the manifold in the MUSIC processing because the array manifold has to be recorded in a fine angle-resolution. It was demonstrated by the present authors that if the universal steering vector (USV), whose elements are equivalent to array element patterns including the effect of the mutual coupling, is used instead of the array factor or the conventional steering vector (CSV), DOA can be accurately estimated [10], [11]. In [10], a 2-element monopole-PIFA array antenna which is mounted on a metal box is used as the receiving array antenna, the simulation results have shown the validity of the MUSIC-based DOA estimation by using USV for array antenna with arbitrary structure. Furthermore, a convenient method to evaluate USV for the receiving array antenna with an arbitrary geometry having a strong mutual coupling between array elements was also introduced [10]. Fundamentally, USV can be recognized as the compensated CSV which includes the effect of the mutual coupling between the array elements. USV can be expressed mathematically as the multiplication of the compensation matrix with CSV. The important fact is that the compensation matrix involved in USV depends on the searching directions. In [11], the DOA is searched in three dimensions by using a 3-element monopole-PIFA-PIFA array antenna.

However, the effectiveness of USV was only demonstrated by the numerical simulation. Actually, USV includes only the mutual coupling effect of the array antenna. In a practical situation, the received signal is also affected by the electric delay and transmission loss of different receiving channels of the receiver. Neglect of these effects may also degrade the accuracy of DOA estimation. Therefore, the effects of electric delay and loss of different channels in the array receiver should be involved in USV, to improve the accuracy of DOA estimation in practical DOA measurement.

In this paper, an experimental approach of MUSIC-based DOA estimation by using USV is presented. A four-channel array antenna receiver is used to measure DOA experimentally. The original USV is compensated by a 4 by 4 matrix which is the S parameters between the input ports of the feeding cables to the receiving array antenna and the intermediate frequency (IF) output ports of the receiver. The compensated USV (C-USV) is then applied to the MUSIC-based DOA estimation. In Sect. 2, the theory and the experimental setup for MUSIC-based DOA estimation using USV are described and the measurement procedure is also presented. In Sect. 3, the approach to develop C-USV is described. In Sect. 4, the estimated results by C-USV are compared with that by the original USV to demonstrate the effectiveness of C-USV.

2. MUSIC-Based DOA Estimation by Using USV

When the polarization and the number of paths L of the in-

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cident waves are known in advance, DOA estimation based on the MUSIC algorithm can be achieved by searching the peaks of the MUSIC spectrum,

$$P_{MU}(\theta,\phi) = \frac{[A^u(\theta,\phi)]^H [A^u(\theta,\phi)]}{[A^u(\theta,\phi)]^H [E_N] [E_N]^H [A^u(\theta,\phi)]} \quad (1)$$

where θ and ϕ are the searching angles, M is the number of array element and $[E_N]$ is the $M \times (M - L)$ matrix whose columns are M noise eigenvectors of the covariance matrix $[R_{vv}]$, which is defined by

$$[R_{vv}] = E\left([V^r][V^r]^H\right) \quad (2)$$

where $E(\,)$ denotes the statistical expectation and superscript H denotes the complex conjugate transpose. $[V^r]$ is a vector which includes M elements representing the signals received by array elements.

$A^u(\theta,\phi)$ in Eq. (1) is USV rather than the array factor. The elements of USV, as a function of (θ,ϕ), are in correspondence to the array element patterns of M-element array antennas for the incident waves having the same polarization. USV can be evaluated efficiently by using the method of moments (MoM) [10].

It is assumed that an array antenna with arbitrary geometry is used as the receiving array for DOA estimation. In the MoM analysis, the ith element of the array is divided into N_i^s segments and the total number of the segments of the array is $N(=\sum_{i=1}^{M} N_i^s)$. The matrix equation for unknown currents on all segments is obtained by

$$[Z]\,[I] = \left[V^{inc}(\theta,\phi)\right] \quad (3)$$

where $[I]$ is the current vector with a dimension of N representing the unknown currents on all segments. $[Z]$ is the $N \times N$ impedance matrix whose element z_{ij} represents the mutual impedance between ith and jth segments. The impedance matrix $[Z]$ is independent of the incident wave. $[V^{inc}(\theta,\phi)]$ is N voltage vector representing the incident voltage on N segments due to the incident plane wave $\vec{E}^{inc}(\theta,\phi)$ coming from direction of (θ,ϕ). The incident voltage $v_i^{inc}(\theta,\phi)$ on ith segment can be expressed by

$$v_i^{inc}(\theta,\phi) = \int w_i \hat{l} \cdot \vec{E}^{inc}(\theta,\phi) dl. \quad (4)$$

where w_i is the ith weight function. $\hat{l}$ is the tangential direction of dipole segment.

Once $[V^{inc}(\theta,\phi)]$ vector and $[Z]$ matrix are evaluated, the unknown current vector $[I]$ can be obtained by

$$[I] = [Y]\left[V^{inc}(\theta,\phi)\right] \quad (5)$$

where $[Y]$ is the inverse matrix of $[Z]$, i.e., the admittance matrix. Since the currents at the segments of receiving terminals (feeding points) are part of $[I]$, they can be extracted from Eq. (5) and expressed as

$$\left[I^{ter}\right] = \left[Y^{ter}\right]\left[V^{inc}(\theta,\phi)\right] \quad (6)$$

where $[I^{ter}]$ is the current vector with dimension of M representing the currents at the receiving terminals and $[Y^{ter}]$ with dimension of $M \times N$ is the part of $[Y]$, corresponding to the mutual admittances between the segments at the terminals and all the segments of the array elements. Assuming that each terminal of the array element is loaded by an impedance of z_l, USV is given by

$$[A^u(\theta,\phi)] = z_l[Y^{ter}][V^{inc}(\theta,\phi)]. \quad (7)$$

Although the $[A^u(\theta,\phi)]$ in (7) has to be evaluated for every searching angle (θ,ϕ) in the spatial spectrum, since $[Y^{ter}]$ is independent of the searching angle and can be calculated and stored before DOA estimation, the calculation of $[A^u(\theta,\phi)]$ in (7) only requires evaluation of $[V^{inc}(\theta,\phi)]$ and a multiplication of $M \times N$ matrix by N vector. Thus, the computational cost for obtaining $[I^{ter}]$ in (6) is not so large. Furthermore, it is clear that $[Y^{ter}]$ includes the effect of the mutual coupling not only from the terminal segments, i.e., the feed points, but also from all the segments of the antennas. That is why the compensation approach using USV is applicable to the array antennas with arbitrary structure, while the compensation methods based on [1] are effective only for array antennas composed of elements having single-mode structure.

Experimental setup for the MUSIC-based DOA estimation in this paper is shown in Fig. 1. The incident waves of different paths are generated by different vector signal generators (SG). The incident signals have a carrier frequency of 2.452 GHz and modulated by W-CDMA protocol with different pseudo-noise (PN) codes so that the incident

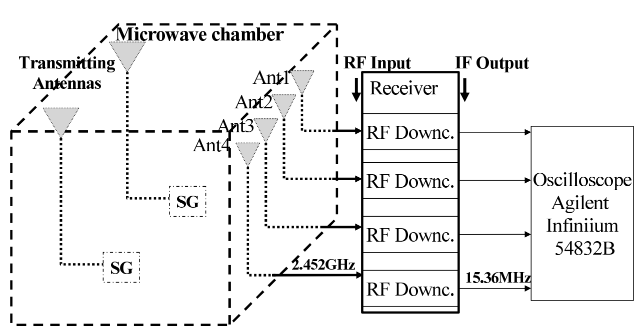

Fig. 1 Experimental setup for DOA estimation.

paths are incoherent with each other. Figure 2 shows the receiving array antenna which is composed of four monopole elements with a reflector and is connected to a four-channel receiver which demodulates W-CDMA signals. The measurement is made in a microwave anechoic chamber. Experiment of DOA estimation is carried out through the following procedure.

1. Two W-CDMA modulated waves with different PN codes at carrier frequency of 2.452 GHz are generated by two vector signal generators and transmitted by two antennas.
2. W-CDMA modulated waves are received by the four-element array antenna connected with the W-CDMA receiver.
3. Received RF signals are down-converted into IF signals at 380 MHz and further into 15.36 MHz.
4. IF signal streams of the four channels are received at the IF output ports of the receiver by a four-channel digital oscilloscope. The received IF signals are sampled and transferred to a data memory.
5. Recorded time-domain data are further transformed into frequency-domain data by using FFT. The complex frequency spectrums around the center frequency of 15.36 MHz are used for calculating the covariance matrix for DOA estimation at off-line mode.

USV of the receiving array antenna is calculated by using the analysis model shown in Fig. 3 where the ground plane and the reflector plane are modeled by a wire-meshed structure for MoM analysis.

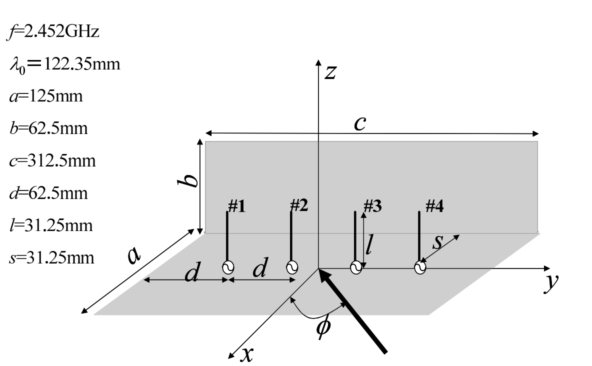

Fig. 2 Geometry of receiving array antenna.

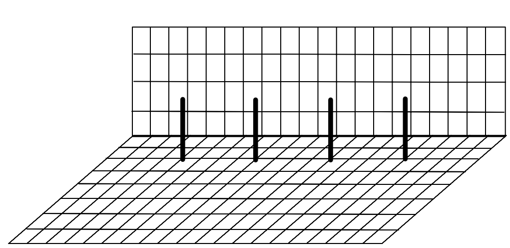

Fig. 3 Wire-Grid model for MoM analysis.

3. Compensated USV

The accuracy of the MUSIC-based DOA estimation by using USV is high enough when only the mutual coupling among the antenna elements and the reflector is considered. However, in the practical DOA estimation system, the electric delay and transmission loss of the RF cables connecting the receiving antenna to the receiver, and the differences of four-channel signal receiver may degrade the accuracy of DOA estimation and should be taken into account as well. Therefore, a compensated USV (C-USV) is introduced in order to include the characteristics of the array antenna, the RF cables and the receiver.

Although the effect of mutual coupling between array elements depends on DOA of incident waves, or the searching directions, the effect due to the RF cables connecting the receiving array antenna to the receiver, and the transmission line inside the receiver is independent of the searching directions. The latter effect can be included by a compensation matrix $[C]$ which is equivalent to a s_{21} parameter between RF input ports of the feeding cables and IF output ports in the receiver. Therefore, C-USV can be obtained by multiplying the compensation matrix $[C]$ with the USV as the following

$$[A^{u2}] = [C][A^{u1}] \tag{8}$$

where $[A^{u1}]$ and $[A^{u2}]$ denote USV and C-USV, respectively. Since the receiver has four receiving channels, the dimension of $[C]$ is 4×4, its element $c_{ij}(i = 1, \ldots, 4, j = 1, \ldots, 4)$ is obtained by measuring the s_{21} between ith RF input port and jth IF output port. The experimental setup for measuring $[C]$ is shown in Fig. 4. In S parameter measurement, it is required to convert the IF signal at 15.36 MHz into RF frequency at 2.452 GHz through two steps. The local signal for up-conversion is generated by the same source for down-conversion in the receiver. The measured matrix $[C]$ based on the above method is not equivalent to that of real 4-channel RF down-converter circuits due to two additional mixers. However, because the same up-conversions are used

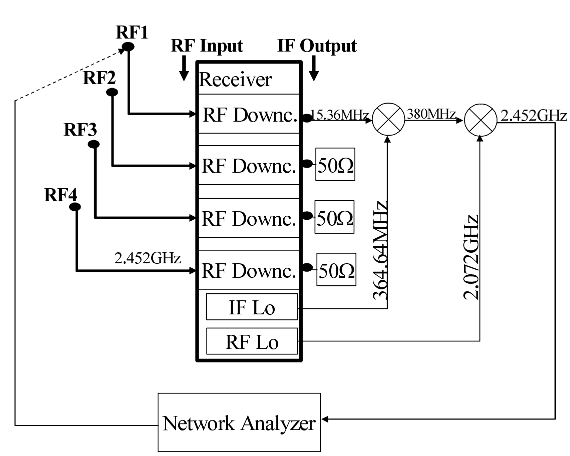

Fig. 4 Experimental setup for measuring elements of matrix $[C]$.

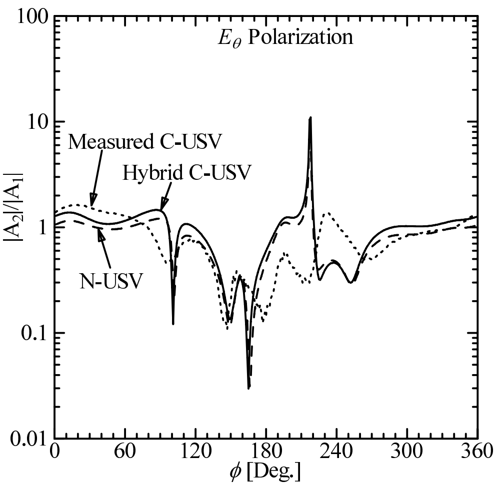

Fig. 5 Normalized magnitude of array element pattern of #2 versus azimuth angle.

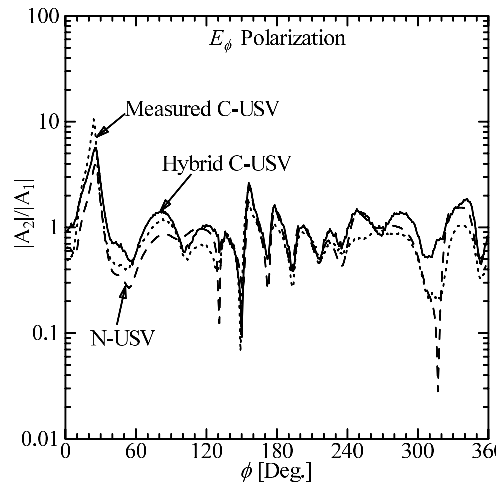

Fig. 7 Normalized magnitude of array element pattern of #2 versus azimuth angle.

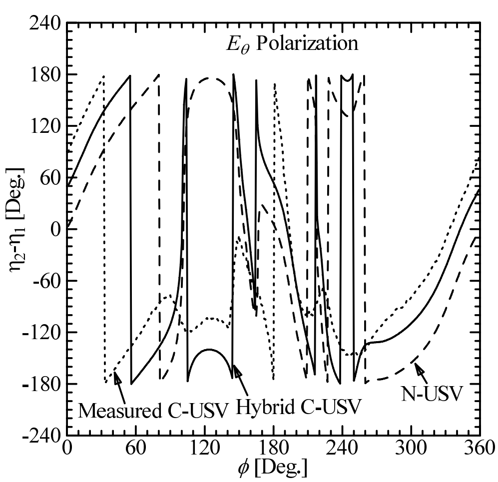

Fig. 6 Normalized phase of array element pattern of #2 versus azimuth angle.

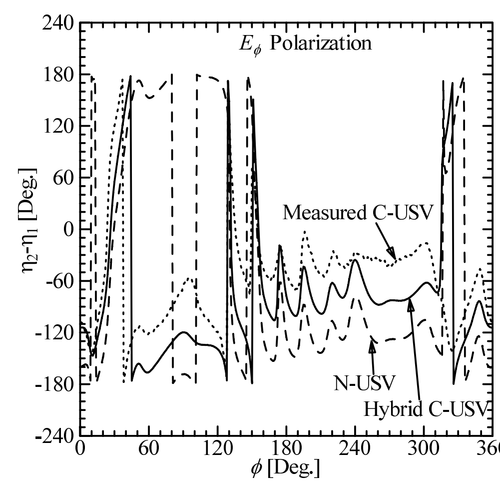

Fig. 8 Normalized phase of array element pattern of #2 versus azimuth angle.

in all 4 channels individually, the effect of these additional circuits to all the elements in $[C]$ is the same and can be approximately described as a complex constant α, therefore the measured $[C]$ can be expressed as $\alpha[C_{real}]$. Furthermore, it can be found that if $[C]$ is replaced with $[C_{real}]$ in MUSIC estimation Eq. (1), the estimation spectrum remains the same.

It should be noted that the present approach using C-USV is different from that using the array manifold. The array manifold approach is also a possible method to exclude the effects due to the mutual coupling of array elements and the receiving circuits, and it can be obtained by measuring the array element patterns at IF ports of the receiver directly if the present measurement setup is available. The array manifold approach is direct and should be accurate. However, the array manifold approach needs a lot of procedures and time to measure the 3-D array element pattern with a high spatial resolution. Sometimes, the measurement becomes extremely difficult when the receiving array antenna is surrounded by complicated scatters [12]. On the other hand, C-USV can be evaluated separately by computing DOA-dependent USV and measuring DOA-independent $[C]$. Although USV is DOA-dependent, it can be easily evaluated with the mentioned numerical method in Sect. 2.

As a measurement result, the compensation matrix $[C]$ of the present DOA measurement system at 2.45 GHz is given by

$$[C] = \begin{bmatrix} 0.77\angle 87^\circ & 0.056\angle 106^\circ & 0.027\angle -84^\circ & 0.0092\angle 117^\circ \\ 0.033\angle 172^\circ & 0.91\angle 134^\circ & 0.060\angle 178^\circ & 0.022\angle 14^\circ \\ 0.0072\angle -18^\circ & 0.022\angle -148^\circ & 0.83\angle 123^\circ & 0.054\angle 112^\circ \\ 0.0092\angle -149^\circ & 0.0096\angle 42^\circ & 0.046\angle 170^\circ & 0.79\angle 129^\circ \end{bmatrix} \tag{9}$$

The normalized magnitude and phase of the array element pattern of #2 element are shown from Figs. 5 to 8. The reference magnitude and phase are the magnitude and phase of the array element pattern of #1 element, respectively. Figure 5 and Fig. 6 are the results for E_θ polarization, while Fig. 7, Fig. 8 are the results for E_ϕ polarization. In these figures, N-USV means the numerical USV obtained by MoM. Hybrid C-USV is the result obtained by numerical USV and measured hybrid C-matrix according to Eq. (7). These data are compared with directly measured array element pattern at IF output ports in the receiver, which is equivalent to the array manifold. It is found that hybrid C-USV is closer to the measured C-USV than N-USV especially in phase, indicating the effectiveness of the compensation of C-matrix.

4. Results of DOA Estimation

The experiment under the environment shown in Fig. 1 was performed in three cases. In case 1, there is only one incident wave with E_θ polarization from direction of $\theta_1 = 90°, \phi_1 = 320°$. In case 2, there is only one incident wave from direction of $\theta_1 = 90°, \phi_1 = 0$, but the polarization is E_ϕ polarization. In case 3, there are two incident waves from direction of $\theta_1 = 90°, \phi_1 = 0$ and direction of $\theta_2 = 90°, \phi_2 = 320°$, respectively, and the incident waves are both E_θ polarization. The SNR for both incident waves is roughly 20 dB, and sample rate of digital oscilloscope (Agilent infiniium 54832B) is set to be 100 MHz, and the snapshot for MUSIC algorithm is set to be 3.

The numerical USV involved in the results shown from Fig. 9 to Fig. 11 is obtained by MoM. The number of segments of the array antenna is 1987, and angle step for $V^{inc}(\theta, \phi)$ is 1 degree. The monopole element with the length of 31.25 mm is divided into three small monopole segments. As shown in Fig. 3, the ground plane in xy-plane is modeled by wire-grids, the division number along x-direction is 8 and that along y-direction is 40. The reflector in yz-plane is also modeled by wire-grids, the division number along y-direction is 40 and that along z-direction is 8. The segment in our MoM code is small overlapped V-type dipole.

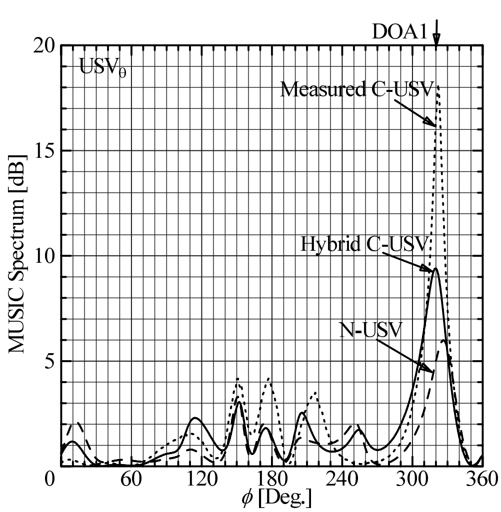

Fig. 9 MUSIC spectrum for case 1.

Figures 9 and 10 show the estimated MUSIC spectrums for case 1 and case 2, respectively. It is found that the accuracy of DOA estimation is improved by using hybrid C-USV for both of the polarizations of the incident wave. Figure 11 shows the estimated MUSIC spectrums for case 3. It is found that DOA estimated by using C-USV has a better accuracy than the results by using USV.

It is also observed that there are some unexpected peaks in MUSIC spectrum in Figs. 9–11, particularly in Fig. 10. The unexpected MUSIC spectrum in our present estimation system is considered to be caused mainly by the poor receiving SNR at several directions, which is directly related with the gain pattern of the receiving antenna, especially for the case of E_ϕ polarization wave where the gain of array antenna is much lower than that of E_θ polarization.

5. Conclusions

MUSIC-based DOA estimation by using USV has been ex-

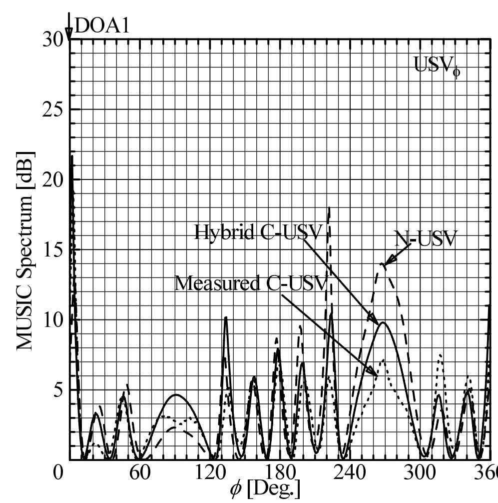

Fig. 10 MUSIC spectrum for case 2.

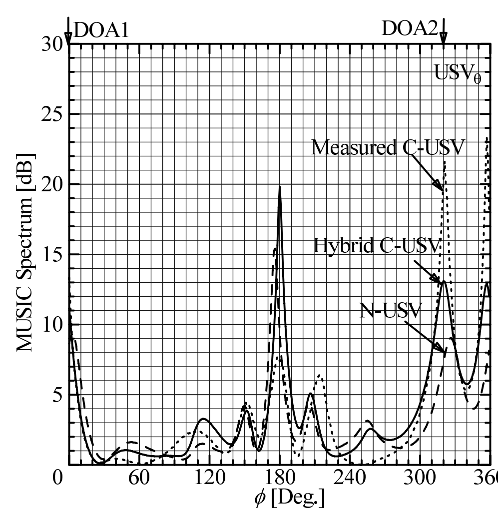

Fig. 11 MUSIC spectrum for case 3.

perimentally studied where a four-element array antenna and a four-channel receiver were employed. In order to improve the accuracy of DOA estimation, the electric delay and loss of four channels in the receiver is further incorporated into the original USV which includes the effect of the mutual coupling between array elements. The matrix for compensating USV can be easily obtained by direct measurement of the S parameters between RF input ports of the feeding cables and IF output ports of the receiver. It has been demonstrated that C-USV approach is an accurate, efficient and practical method in MUSIC-based DOA estimation.

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