2-D D^{3}LS Algorithm with Mutual Coupling

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ABSTRACT: New adaptive algorithm of direct data domain is presented which can recover the signal in the presence of mutual coupling. The proposed algorithm can estimate the coupling coefficients without utilizing any auxiliary sensors. Numerical simulation shows that the proposed algorithm can accurately recover the signal in the presence of mutual coupling. Int J RF and Microwave CAE 21:371–375, 2011.

Keywords: 2D-D^{3}LS; mutual coupling; signal recovery

I. INTRODUCTION

In array signal processing, most adaptive algorithms assume that the array elements are isotropic sensors; thus the mutual coupling effects are ignored. However, in practical applications, each array element receives signals reradiated from other sensors within the array [1]. The performance of an adaptive antenna array is drastically affected by the existence of the mutual coupling effect between antenna elements [2, 3]. Many efforts have been made to compensate for this impact on Uniform Linear Array (ULA) and Uniform Circular Array (UCA) [4–7], but few authors have dealt with 2-D cases and considered the effect of mutual coupling or any other array errors [8, 9]. Unfortunately, the mutual coupling matrix tends to change with time due to the environmental factors; therefore, it is impossible to fully eliminate its effect and predict its variability. The most likely way is to carry out some techniques for calibration. However, these procedures are time consuming and very expensive [10, 11]. Svantesson [4] has shown that the coupling between neighbouring elements with the same interspace is almost the same, and the magnitude of the mutual coupling coefficient between two far apart elements is so small that can be approximated to zero. Thus, a banded symmetric Toeplitz matrix can be used as a model for the mutual coupling of ULA and URA [9].

The Direct Data Domain Least Squares (D^{3}LS) algorithms [12, 13] have been proposed to overcome the drawbacks of statistical techniques and utilizing one snapshot makes it possible to carry out an adaptive process in real time. The algorithm is to adaptively recover a desired signal while simultaneously rejecting all other interference. The performance of this algorithm affected by the Mutual Coupling (MC) effect, too [14].

In this article, using the D^{3}LS algorithm properties, a new adaptive algorithm is proposed, which can estimate and compensate the mutual coupling. So the amplitude of the desired signal can be recovered in the presence of mutual coupling, without using any auxiliary sensors or calibration sources. Numerical simulation illustrates that the proposed algorithm can work accurately in the presence of mutual coupling.

II. 2-D D^{3}LS ALGORITHM

Consider a URA consisting of $N \times P$ equally spaced elements in rows and columns. The elements are parallel thin dipoles. The dipoles are z-directed, of length L and radius a. The array receives a signal from a known direction (θ_0, ϕ_0) and M interferers with unknown directions, (θ_m, ϕ_m), $m = 1, 2, \ldots, M$ as shown in Figure 1.

Ignoring the mutual coupling effect of the antenna array, the 2D-D^{3}LS algorithm is given by Refs. [12, 13] as follows:

$$\begin{bmatrix} \mathbf{b_1} & \mathbf{b_2} & \cdots & \mathbf{b_{K_2-1}} & \mathbf{b_{K_2}} \\ \mathbf{D_1} & \mathbf{D_2} & \cdots & \mathbf{D_{(K_2-1)}} & \mathbf{D_{K_2}} \\ \mathbf{D_2} & \mathbf{D_3} & \cdots & \mathbf{D_{K_2}} & \mathbf{D_{(K_2+1)}} \\ \vdots & & & & \\ \mathbf{D_{(K_2-1)}} & \mathbf{D_{K_2}} & \cdots & \mathbf{D_{(P-2)}} & \mathbf{D_{(P-1)}} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_K \end{bmatrix} = \begin{bmatrix} G \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (1)$$

$$\mathbf{b_1} = [1 \quad \beta \quad \ldots \quad \beta^{K_1-1}], \ \mathbf{b_i} = \alpha^{i-1}\mathbf{b_1} \quad (2)$$

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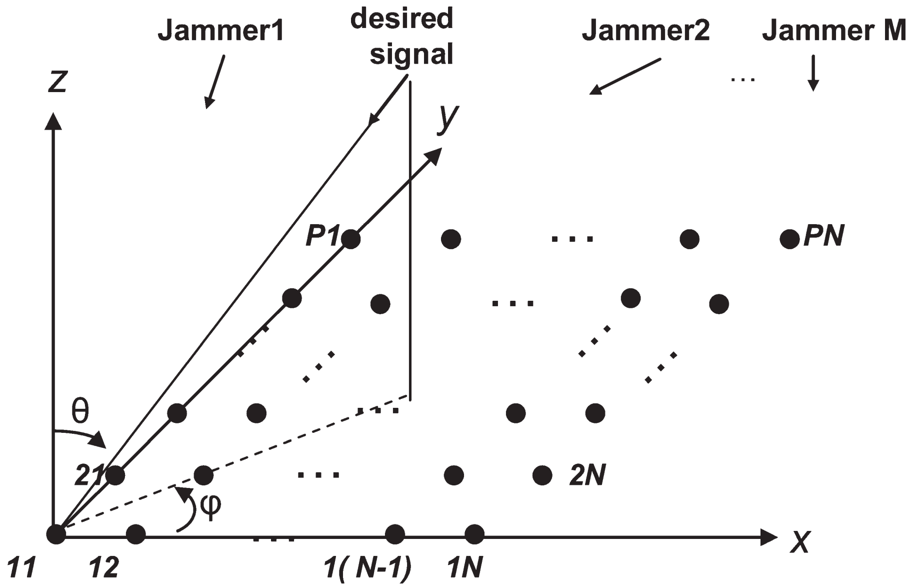

Figure 1 URA with $N \times P$ elements.

$$\mathbf{D_i} = \begin{bmatrix} (x_{i1} - \beta^{-1}x_{i2}) & \ldots\ldots & (x_{iK_1} - \beta^{-1}x_{i(K_1+1)}) \\ -\alpha^{-1}(x_{(i+1)1} - \beta^{-1}x_{(i+1)2}) & & -\alpha^{-1}(x_{(i+1)K_1} - \beta^{-1}x_{(i+1)(K_1+1)}) \\ \vdots & & \vdots \\ (x_{i(K_1-1)} - \beta^{-1}x_{iK_1}) & \ldots\ldots & (x_{i(N-1)} - \beta^{-1}x_{iN}) \\ -\alpha^{-1}(x_{(i+1)(K_1-1)} - \beta^{-1}x_{(i+1)K_1}) & & -\alpha^{-1}(x_{(i+1)(N-1)} - \beta^{-1}x_{(i+1)N}) \end{bmatrix} \quad (3)$$

where the first row of the matrix in (1) is the constraint to the desired signal which produces a gain factor of G. x_{ij} is the received signal of the ij th antenna element. $\mathbf{W} = [w_1, w_2, \ldots, w_k]$ is the weight vector given by solving (1) and $K = K_1K_2$, $K1 = (N+1)/2, K2 = (P+1)/2$ [13]. The α and β are given as:

$$\beta = \exp(j2\pi\frac{d}{\lambda}\sin\theta_0\cos\varphi_0)$$
$$\alpha = \exp(j2\pi\frac{d}{\lambda}\sin\theta_0\sin\varphi_0) \quad (4)$$

So, the D^3LS algorithm can adaptively reject (K_1-1)(K_2-1) interferences and recover the desired signal, S, as [13, 14]

$$S = \frac{1}{G}\mathbf{W}^T[\mathbf{x}]_K \quad (5)$$

where S is the complex amplitude of the signal, the superscript $(\bullet)^T$ denotes transpose operation, $[\mathbf{x}]_\mathbf{K}$ is also a K $\times$ 1 vector which is composed of received signals of the sub-array with its rows from 1 to K_1 and its columns from 1 to K_2.

III. THE PROPOSED ALGORITHM

It is assumed that each sensor is affected by the coupling of the eight sensors around it, which is shown in Figure 2.

Then, the mutual coupling matrix can be expressed as

$$\mathbf{C} = \begin{bmatrix} \mathbf{C_1} & \mathbf{C_2} & 0 & \ldots & 0 & 0 & 0 \\ \mathbf{C_2} & \mathbf{C_1} & \mathbf{C_2} & \ldots & 0 & 0 & 0 \\ \vdots & \ddots & \ddots & & \vdots & & \\ 0 & 0 & 0 & \ldots & \mathbf{C_2} & \mathbf{C_1} & \mathbf{C_2} \\ 0 & 0 & 0 & \ldots & 0 & \mathbf{C_2} & \mathbf{C_1} \end{bmatrix}_{PN\times PN} \quad (6)$$

where $\mathbf{C_1}$ and $\mathbf{C_2}$ are $N \times N$ sub-matrix of $\mathbf{C}$ and can be given as follows:

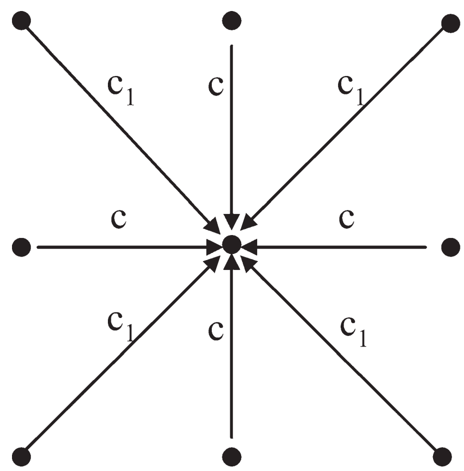

Figure 2 Scheme of mutual coupling.

TABLE I Parameters for the Desired Signal and Interferers

	Magnitude	Phase	θ_s	ϕ_s
Signal	0dB	0	75°	45°
Jammer1	20dB	0	70°	15°
Jammer2	20dB	20	30°	−40°
Jammer3	40dB	−10	60°	30°

$$\begin{aligned} \mathbf{C_1} &= toeplitz([1, c, 0, ..., 0]) \text{ and} \\ \mathbf{C_2} &= toeplitz([c, c_1, 0, ..., 0]) \end{aligned} \tag{7}$$

Thus, the received signals vector in the presence of mutual coupling is $\mathbf{x_c} = \mathbf{Cx}$. Therefore, using the D^{3}LS algorithm properties, the coupling coefficients are obtained without using any auxiliary sensors. In the presence of mutual coupling, for the elements in the edge of URA, the following can be written:

$$\begin{aligned} x_{c11} &= (1 + \beta c + \alpha c + \alpha\beta c_1)S \quad + \text{Interferers} \\ x_{c12} &= \beta s_{11} + (c + \alpha c_1)S \quad + \text{Interferers} \\ x_{c21} &= \alpha s_{11} + (c + \beta c_1)S \quad + \text{Interferers} \\ x_{c22} &= \beta s_{21} + (c_1 + \alpha c + \alpha^2 c_1)S + \text{Interferers} \end{aligned} \tag{8}$$

where x_{cij} is the received signal of the *ij*th antenna element in the presence of mutual coupling. When no interference exists, these equations can be solved through (8) to determine c and c_1:

$$\begin{aligned} \frac{-\alpha^{-1}(x_{c11}-\beta^{-1}x_{c12})}{(x_{c11}-\beta^{-1}x_{c12})-\alpha^{-1}(x_{c21}-\beta^{-1}x_{c22})}-\alpha &= \frac{c}{c_1} \\ \frac{\alpha^{-1}\beta^{-1}x_{11}}{(x_{c11}-\beta^{-1}x_{c12})-\alpha^{-1}(x_{c21}-\beta^{-1}x_{c22})} &= \frac{1}{c_1}+(\alpha+\beta)\frac{c}{c_1}+\alpha\beta \end{aligned} \tag{9}$$

Having estimated c/c_1 from the first equation mentioned above, c_1 can also be estimated using the second equation. Now, the signal can be recovered as:

$$\tilde{S} = \frac{1}{G}\left(\mathbf{w_c}^T\left[\tilde{\mathbf{C}}^{-1}\mathbf{x_c}\right]_K\right) \tag{10}$$

where $\mathbf{w_c}$ is the weight vector in the presence of mutual coupling and $\tilde{S}$, $\tilde{\mathbf{C}}$ are the estimation of S, $\mathbf{C}$. In the above process, we only consider the mutual coupling from the eight neighboring sensors as shown in Figure 2, because the mutual coupling of the URA is more complex than the ULA and UCA. However, the proposed method can also be applied to more complicated coupling conditions.

IV. NUMERICAL SIMULATIONS

In this section, some examples illustrate the effectiveness of compensation method in the proposed algorithm. Consider a URA consisting of 5 × 5 elements illuminated by one desired signal and three jammers. The array elements are equally spaced in rows and columns with a distance of $\lambda/2$, where λ is the wavelength. The dipoles are z-directed and each dipole is 0.5λ long and $\lambda/200$ in radius and all the elements are loaded with a terminal load of $Z_L = 50$ Ω. Banded symmetric toeplitz matrix used as a model for the mutual coupling of URA [9]. Then, the coupling coefficients are obtained using the Method of Moments (MoM). For an accurate analysis, multiple basis functions per element are used. Using a Galerkin formulation, the entries of the MoM impedance matrix measure the interaction between the basis functions [14].

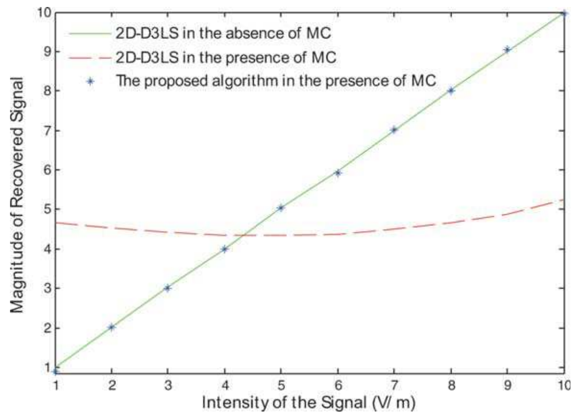

Figure 3 Signal recovery using the proposed and 2D-D^{3}LS algorithm in the presence of mutual coupling.

The signal-to-noise ratio (SNR) is set at 20 dB and other parameters are listed in Table I. The strength of two jammers is assumed to be 20 dB stronger than the signal and the strength of third jammer is assumed to be 40 dB stronger than the signal. The intensity of the desired signal varies from 1.0 to 10 V/m. The number of adaptive weight chosen for our simulation will be 16 [13]. Figure 3 shows the recovering of the signal in the presence of mutual coupling using the proposed algorithm in comparison with the 2D-D^{3}LS algorithm. The expected linear relationship can be clearly seen, implying that the jammers have been nulled and the signal has been correctly recovered.

Next, the performance of the proposed method is illustrated by the various simulations. In the following simulation, we set the mutual coupling coefficients as $c = 0.35 + 0.2j$, $c_1 = 0.1 + 0.1j$. Table II shows the mean values and the Root Mean-Squared Error (RMSE) of the estimated mutual coupling coefficients when SNR varies from 20 to 40 dB. From the results, we know the new algorithm achieves a favorable estimation of mutual coupling coefficients.

Figure 4 shows the RMSE of the estimated amplitude of the desired signal versus SNR.

TABLE II Estimated Mutual Coupling Coefficients Against SNR (c = 0.35 + 0.2j, c_1 = 0.1 + 0.1j)

SNR(dB)		20	30	40
c	Mean	0.354 + 0.198j	0.351 + 0.199j	0.350 + 0.200j
	RMSE	0.022	0.0045	0.0012
c_1	Mean	0.136 + 0.115j	0.101 + 0.100j	0.100 + 0.100j
	RMSE	0.031	0.0056	0.0014

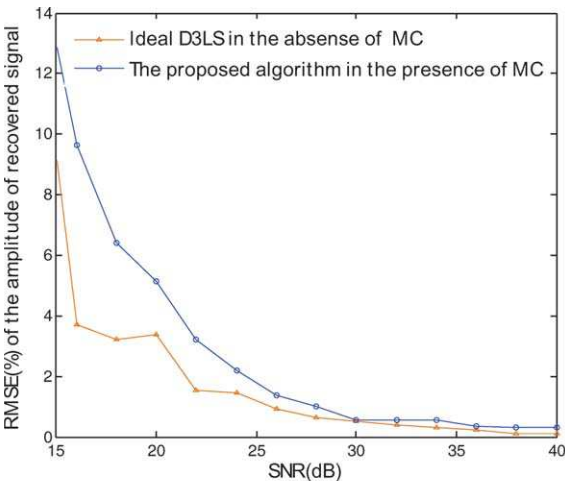

Figure 4 RMSE of the recovered amplitude versus the SNR.

V. CONCLUSIONS

The problem of the 2-D D^3LS algorithm has been studied for recovering of the desired signal in the presence of mutual coupling. Using the properties of direct data domain algorithm, a new formulation has been derived for estimating the mutual coupling coefficients. Numerical simulation confirms that the proposed algorithm is accurate in the presence of mutual coupling.

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BIOGRAPHIES

Ali Azarbar was born in Tehran, Iran, in 1972. He received the B.Sc. and M.Sc. degree, both in Communication Engineering from Sharif University, Tehran, Iran in 1994 and 1997, respectively. He is currently working toward the Ph.D. degree at the Department of science and research, Islamic Azad University, Tehran, Iran. His research interests are in adaptive signal processing algorithms and antenna design.

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