

Phased Arrays Operating in a Near Field Environment

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ABSTRACT:

An adaptive methodology is presented that can not only deal with realistic antenna elements operating in a real environment but can also handle the effects of mutual coupling between the antenna elements. In addition, one can incorporate in this methodology the effects of near field scatterers and use of dissimilar antenna elements in the array. The analysis is carried out by using a dynamic electromagnetic analysis tool. In addition, an array transformation technique is used to mitigate the various complex electromagnetic effects in a non-uniformly spaced non-planar array in the presence of the mutual coupling and transform the problem to that of a virtual linear array of uniformly spaced isotropic point radiators operating in free space. The preprocessed data from the interpolated virtual array is analyzed using a direct data domain least squares approach utilizing a single snapshot of data to estimate the strength of the signal of interest arriving from a known direction in the presence of coherent strong jammers, clutter and thermal noise. In addition, this methodology is quite amenable to real time processing.

I. INTRODUCTION

In conventional adaptive algorithms, the statistical approach based on forming an estimate of the covariance matrix of the received antenna voltages (measured voltages at the antenna terminals) without the signal is frequently used. However, these statistical algorithms suffer from two major drawbacks. First, they require independent identically distributed secondary data to estimate the covariance matrix of the interference. The formation of the covariance matrix is quite time consuming and so is the evaluation of its inverse. Unfortunately, the statistics of the interference may fluctuate rapidly over a short distance limiting the availability of homogeneous secondary data. The resulting errors in the covariance matrix reduce the ability to suppress interference. The second drawback is that the estimation of the covariance matrix requires the storage and processing of the secondary data. This simply cannot be accomplished in real time for most applications.

Recently, a direct data domain algorithm has been proposed to overcome these drawbacks of a statistical technique.. In that approach one adaptively minimizes the interference power while maintaining the gain of the antenna array along the direction of the signal. Not having to estimate a covariance matrix leads to an enormous savings in memory and computer processor time and makes it possible to carry out an adaptive process in real time. The novelty of the proposed approach is that we analyze the antenna systems as spatial filters instead of treating them as temporal channels.

The use of real antenna elements and not omni directional point sources in an actual antenna array will also require an investigation into the capabilities of the direct data domain algorithms to perform adaptivity in non-ideal situations such as in the presence of mutual coupling between the elements of the array, near-field scatterers and obstacles located close to the array. This could also involve the various platform effects on which the antenna array is mounted. Most adaptive algorithms assume that the elements of the receiving array are independent isotropic point sensors that do not reradiate the incident electromagnetic energy. It is further assumed that the array is isolated from its surroundings. However, in a practical case, array elements have a finite physical size and reradiate the incident fields. The reradiated fields interact with the other elements causing the antennas to be mutually coupled. However, in a more practical environment the presence of near field scatterers (i.e. building, the structure on which the array is mounted) will have effects on the array elements. The effects of these near field elements are similar to the effects of mutual coupling between the elements of the array. These environmental scatterers necessitate the development of a compensation matrix, which depends on the direction of arrival of signals including the undesired ones. In this paper, we shall use the measured steering vector in an interpolation technique, which is contaminated by the presence of near field scatters as well as by the mutual coupling between the elements of the real array, to obtain the compensation matrix for a more accurate numerical analysis.

This presentation is divided into two distinct parts. In the first part we use the electromagnetic analysis along with an interpolation algorithm to transform the voltages that are measured/computed in a real array containing realistic antenna elements receiving signals in the presence of near field scatterers to a uniform linear virtual array (ULVA) consisting of

isotropic omni directional point radiators. In this way we not only take into account the effects of mutual coupling and the near field scattering effects of the antenna array produced by the signal of interest but also due to the strong coherent interferers whose directions of arrival are unknown. During the second phase of the processing, these transformed voltages induced in the ULVA are processed by a direct data domain least squares method. In this phase, the goal is to estimate the complex signal amplitude given the direction of arrival in a least squares fashion when the signal of interest (SOI) is contaminated by strong interferers which may come through the main lobe of the array, clutter and thermal noise. The advantage of this methodology is that no statistical description of the environment is necessary and since we are processing the data on a snapshot-by-snapshot basis this new technique can be applied to a highly dynamic environment.

II. PROBLEM FORMULATION

Consider an array composed of N sensors separated by a distance d . We assume that narrowband signals consisting of the desired signal plus possibly coherent multipaths and jammers with center frequency f_0 are impinging on the array from various angles θ , with the constraint $0 \leq \theta \leq 180^\circ$. For sake of simplicity we assume that the incident fields are coplanar and that they are located in the far field of the array. However, this methodology can easily be extended to the non-coplanar case without any problem including the added polarization diversity.

Using the complex envelope representation, the $N \times 1$ complex vectors of phasor voltages $[\underline{x}(t)]$ received by the antenna elements at a single time instance t can be expressed by

$$[\underline{x}(t)] = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_N(t) \end{bmatrix} = \sum_{k=1}^m [\underline{a}(\theta_k)]s_k(t) + n(t) \quad (1)$$

where $s_k(t)$ denotes the incident signal from the k^{th} source directed towards the array at the instance t . $[\underline{a}(\theta)]$ denotes the steering vector of the array toward direction θ and $[n(t)]$ denotes the noise vector at each of the antenna elements. It is important to note that the array elements can be dissimilar and they can be non coplanar and may even be non-uniformly spaced. Here, the angle θ is measured from the broadside direction. We now analyze the data using a single snapshot of voltages measured at the antenna terminals.

Using a matrix notation, (1) becomes

$$[\underline{x}(t)] = [A(\theta)] [s(t)] + [n(t)] \quad (2)$$

where $[A(\theta)]$ is the $N \times m$ matrix of the steering vectors, referred to as the array $[A(\theta)] = [a(\theta_1) \ a(\theta_2) \ \dots \ a(\theta_m)]$. In a typical calibration methodology, a far field source $s_k(t)$ is placed along the directions θ_k and then $[\underline{x}(t)]$ is the voltage measured at the feed point of the antenna elements in the array. Here $[s(t)]$ is a $m \times 1$ vector representing the various signals incident on the array at time instance t . In practice, this array manifold for a real array is contaminated by both effects of non-uniformity in the individual elements and the inter element spacing may also be non-uniform to achieve greater aperture efficiency. Furthermore, there are mutual couplings between the antenna elements in the array, which undermine the performance of any conventional adaptive signal processing algorithm.

Hence, our problem can be stated as follows: Given the sampled data vector snapshot $[\underline{x}(t)]$ at a specific instance of time, how do we recover the desired signal arriving from a given look direction while simultaneously rejecting all other interferences which may be coherent. Most signal processing techniques are based on the fact that a far-field source presents a linear phase front at the elements of the antenna array. However, as we shall demonstrate that the non-uniformity of a real array and the presence of mutual coupling between the elements of the real array and scatterers located close to the array undermines the ability of any adaptive algorithm to maintain the gain of the array along the direction of the signal while simultaneously rejecting the interferences. To compensate for the lack of non-uniformity of the real array and mutual coupling effects, we propose an interpolation technique based on the method of least squares which incorporates all the electromagnetic coupling effects. With appropriate preprocessing using Maxwell's equations, any adaptive technique can be applied to real antenna arrays located in any arbitrary environment. However, the use of a direct data domain least squares procedure makes it possible to implement the algorithm in hardware and the solution can be obtained in almost real time.

III. AN ARRAY TRANSFORMATION TECHNIQUE USING LEAST SQUARES WHICH ACCOUNTS FOR ALL THE ELECTROMAGNETIC EFFECTS LIKE MUTUAL COUPLING AND PRESENCE OF NEAR FIELD SCATTERERS.

For the first step of this adaptive method we transform the voltages that are induced in the actual antenna elements operating in any environment to a set of equivalent voltages that would be induced in a ULVA consisting of omnidirectional point

radiators located in free space. The presence of mutual coupling between the antenna elements and existence of near field scatterers also disturb the capability of any algorithm to maintain the gain of the array along the direction of the signal while simultaneously rejecting the strong time varying coherent interferences. Hence, we need to preprocess the data to account for these undesired electromagnetic effects.

The preprocessing is to compensate for the lack of non-uniformity in a real array contaminated by the mutual coupling effects between the various elements. The methodology is similar to the one described in [10-12]. The procedure is based on transforming the non-uniformly spaced array into a uniform linear virtual array (ULVA) consisting of isotropic point radiators operating in vacuum through the use of a transformation matrix. Our basic assumption is that electrical characteristics of the array corresponding to the ULVA can be obtained through an interpolation of the real array, which is disturbed by various undesired electromagnetic couplings. The goal is to select the best-fit transformation, $[T]$, between the real array manifold, $[A(\theta)]$, and the array manifold corresponding to a uniform linear virtual array (ULVA) consisting of isotropic point radiators, $[\bar{A}(\theta)]$, such that $[T][A(\theta)] = [\bar{A}(\theta)]$ for all possible angles θ within a predefined sector. In this way we not only compensate for the for the various electromagnetic effects associated with the SOI but also correct for the interactions associated with coherent strong interferers whose direction of arrival we don't know. Since such a transformation matrix is defined within a predefined sector, the various undesired electromagnetic effects such as non-uniformity in spacing and mutual coupling between the elements and presence of near field obstacles for an array is made independent of the angular dependence. Finally, one can obtain the corrected input voltages in which all the undesired electromagnetic effects are accounted for and the measured snapshot of the voltages are transformed to that which will be obtained for a ULVA. Let that set be denoted by $[x_c(t)]$. Its value can be obtained through $[x_c(t)] = [T][x(t)]$. Next, we can apply the direct data domain algorithms to the preprocessed corrected voltages $[x_c(t)]$ without any significant loss of accuracy. Next a direct data domain least squares algorithm is now applied to the processed voltage sets $[x_c(t)]$ to obtain the complex amplitude corresponding to the signal of interest in a least squares fashion.

IV. NUMERICAL EXAMPLES

We consider a semi circular array consisting of half wave dipoles as shown in Figure 1. It consists of 24 half-wave thin-wire dipole antenna elements. Each element is identically loaded at the center by 50Ω . The radius of the semicircular array is 3.82 wavelength. The dipoles are z-directed, of length $L = \lambda/2$ and radius $r = \lambda/200$, where λ is the wavelength of operation. The magnitude of the incident SOI is varied from 1 V/m to 10.0 V/m in steps of 0.01 V/m while maintaining the jammer intensities constant, which are arriving from -20° , 10° , 40° , 50° . The signal-to-thermal noise ratio at each antenna element is set at 20 dB. All signals intensities and directions of arrival are summarized in Table I and are given by

Table I Parameters of the Signals

	Magnitude	Phase	DOA
Signal	1.0 - 10.0 V/m	0.0	10
Jammer #1	1.0 V/m	0.0	-20
Jammer #2	1.0 V/m	0.0	40
Jammer #3	1.0 V/m	0.0	50

Here, we consider the effects of a large near field scatterer located close to a semicircular array. As shown also in Figure 1, there is a large structure located within a distance, which is 5 times the radius of the semicircular array and is oriented located along the direction of -20° . The width of the structure is 7.26λ and its height is 15.28λ . Hence, the semicircular array and the scatterer have strong electromagnetic coupling in addition to the presence of mutual coupling between the elements. We again consider the case of four incoming signals from -20 , 10 , 40 , 50° .

After we compensate for the various electromagnetic couplings and project the data to that due to a ULVA, we solve for the weights $[W]$ using the direct data domain least squares algorithm. Then, we estimate the amplitude of the desired signal. Figures 2-(a) and (b) plots the amplitude and the phase for the SOI both in the presence and in the absence of mutual coupling between the elements of the array and the scatterer located close to the array. As can be seen, after compensation of the undesired electromagnetic effects, the expected linear relationship is clearly seen, implying that the jammers have been nulled and the SOI estimated with a good accuracy.

The adapted beam patterns associated with this example are shown in Figures 3-(a) and (b) for the two cases considered above. When the mutual coupling is neglected the beam pattern in Figure 3-(a) clearly indicates that the interferers have not been nulled in a correct fashion. However, when the electromagnetic effects have been appropriately accounted, for the beam points correctly along the direction of SOI while simultaneously placing deep nulls along the direction of the interferers.

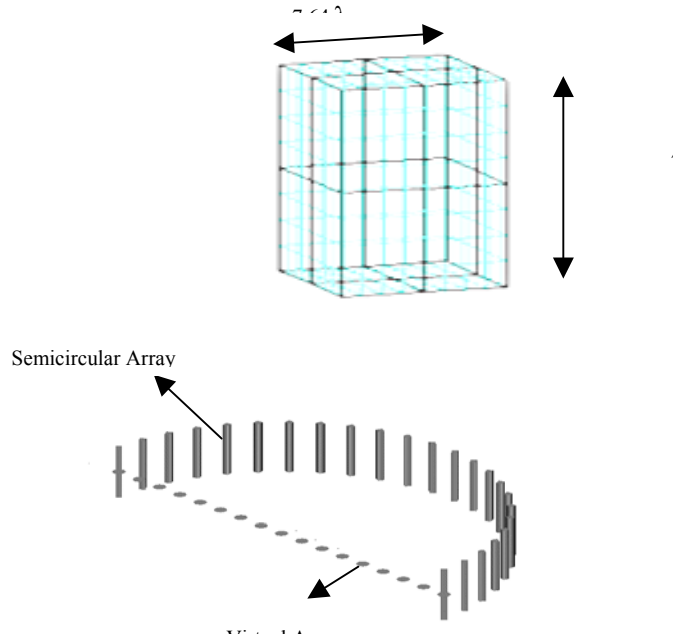


Figure 1: A Semicircular Array operating in the presence of a big obstacle.

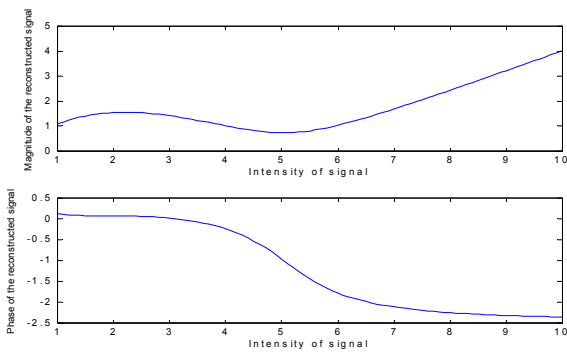


Figure 2-(a): Estimation for the SOI without compensating for the mutual coupling and the near field scatterer.

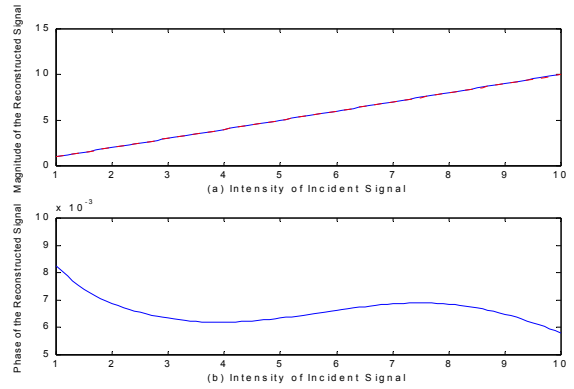


Figure 2-(b): Estimation of the SOI after compensating for the mutual coupling and effect of the near field scatterer.

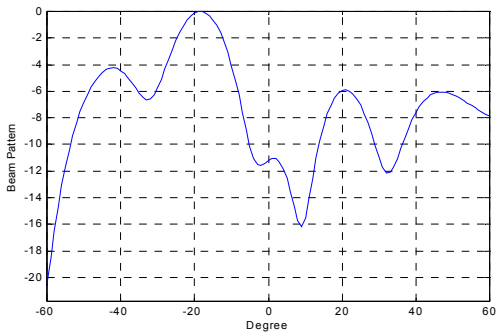


Figure 3-(a): Adapted Beam pattern without compensating for the mutual coupling and near field scatterer.

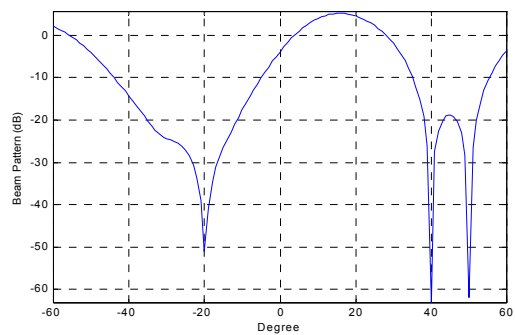


Figure 3-(b): Adapted Beam pattern after compensating for the mutual coupling and the near field scatterer.