Mutual coupling in adaptive circular arrays

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1 Introduction

Research efforts have proven that communication systems which employ base station antenna arrays with digital beamforming potentially provide significant increase in capacity. Therefore, methods to accurately predict the performance of these systems are required. One such method considers the electromagnetic behavior of the base station antenna array to evaluate the system performance [1]. This behavior of antenna array structures is usually modeled by combining the radiation patterns of the individual antenna elements via vectorial superposition (in amplitude and phase). However, when a pair of antennas are in close proximity to each other, whether one or both antennas are in transmitting and/or receiving mode, some of the energy that is primarily intended for one antenna is coupled the other, and is referred to as *mutual coupling* (MC). The amount of MC depends on the radiation characteristics of each antenna, the relative separation between the pair of antennas and the relative orientation of each antenna. Unfortunately, in most of the methods using superposition models, the detrimental effects of MC in closely-spaced antenna elements are ignored leading, thus, to less accurate system performance predictions [2].

However, is well known that the MC between antenna elements in an array can strongly affect their transmiting/receiving characteristics. For example, in direction-finding applications of antenna arrays, the *direction of arrival* (DOA) estimates can be very sensitive to MC, and such effect needs to be properly accounted for [3]. An effective way to describe and compensate for the coupling effect is through the use of a coupling matrix which relates the active element patterns of the individual elements in the presence of the array environment to the idealized, free-standing element patterns. An estimation of the coupling matrix can be derived by measuring the actual array response at a few known incident angles during a preceding calibration process [3]. Such a technique has been proven effective in many simulation and measurement results involving simple antenna structures.

On the other hand, the investigation of adaptive antenna, until now, has primarily involved the use of *Uniform Linear Arrays* (ULAs) or *Uniform Rectangular Arrays* (URAs) configurations. Different algorithms have been proposed for the estimation of the DOAs and several adaptive techniques have been examined for the shaping of the radiation pattern under certain constraints imposed by the wireless environment. *uniform linear arrays* (ULAs) have been mostly studied in literature for adaptive antennas. However, their "field of view" is limited and, also, they are aesthetically unappealing. Therefore, in scenarios where 360° field of view is required, common in cellular phones, the natural choice is a *uniform circular array* (UCA) for a smart antenna. Adaptive beamforming algorithms have proven to be effectively the same for UCAs, as well.

In [1,2], the authors outline and compare several methods which account of MC effects in antenna arrays. However, they consider the beampattern synthesis model, where the only objective is to focus the beam pattern maximum towards a desired direction. In this case, the information from MC is applied to the excitation currents of the antenna elements which can be derived in closed form. In this paper we extend the study of MC effects in the adaptive beamforming model, where the objective is to achieve null steering (form ideally nulls towards the directions of interfering signals) beyond driving the maximum towards the angle of the desired signal. Basically, the technique we propose is a combination of a classical beamforming method employing the well documented LMS algorithm and a classical method which considers the MC effects in antenna arrays, the induced EMF (electromagnetic fields method). Our purpose is to emphasize the necessity that MC effects should be taken into account during the adaptation process. To do so, we demonstrate the degradation in performance when the same results obtained from adaptation in ideal conditions (in the absence of MC) are applied in a real scenario (in the presence of MC).

2 Uniform circular array antenna in azimuth

Figure 1(a) shows the configuration of a UCA, with radius a and consisting of N elements, located on the $x-y$ plane. All the elements in the array are identical and assumed omnidirectional. The direction of the arriving signal is determined by the elevation and azimuth angles θ and ϕ, respectively. Each element in the array is connected to a single multiplying coefficient, I_n, which basically represents complex current excitation. The calculation of the multiplying coefficients is based on the adaptive algorithm, LMS in our case, in a way to meet the desired radiation characteristics. As in most practical cases, it is assumed that the incoming signals to the base station antenna array arrive from almost constant elevation angles, and without loss of generality, we consider $\theta \approx 90°$. The inter-element spacing along the circumference is d_c. For a well-correlated circular array antenna, it is widely known that d_c should not exceed half wavelength ($\lambda/2$). With reference point at the origin (center of the circle), the phase at the n_{th} element is given by

$$\Phi(n) = \frac{2\pi f}{v_0} a \cos(\phi - \phi_n) \tag{1}$$

where f is the frequency of operation and $\phi_n = \frac{2\pi n}{N}$, $n = 1, 2, \ldots, N$. Note that for elevation angle $\theta \neq 90°$, (1) should be multiplied with $\sin\theta$, as well, to include the phase difference due to elevation.

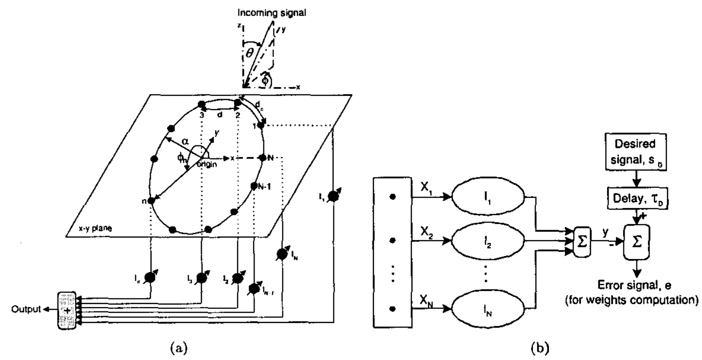


Figure 1: (a) Incoming signal arriving at an N-element uniform circular array with elevation angle θ and azimuth angle ϕ. Each element n is excited by a current I_n. (b) Processing of the incoming signals for enhancement of the desired signal and suppression of the interferences.

3 Adaptive weight calculation

The LMS algorithm is a popular algorithm in the field of adaptive beamforming using antenna arrays. This has applications in many areas like signal recovering, interfering cancellation, space-time modulation and coding [4]. Figure 1(b) demonstrates the adaptive beamformer employing the LMS algorithm and indicates the incoming signals along with their processing. It is desired for the adaptive array to direct its maximum towards ϕ_0, the *direction of arrival* (DOA) of the useful signal s_0. Simultaneously, it must cancel out all the I present interferers, s_i, $i = 1, 2, \ldots, I$, by forming nulls towards their DOAs. At the receiver, it is assumed that an estimate of the desired signal s_0 is available during the training period of the adaptation whereas the angle ϕ_0 is unknown. The LMS algorithm is a very simple way to direct the *mean square error* (MSE) towards zero, in estimating the optimal excitation currents. For the system of N adaptive multipliers, using the received signal at the n_{th} element, $x_n(t)$ for the excitation current of the n_{th} element, I_n, we can write

$$I_n(t+\Delta t) = I_n(t) + \mu e(t) x_n(t) \quad (2)$$

where μ is the convergence factor or step size of the LMS and Δt is the time interval between two successive iterations. Essentially, μ controls the stability of the calculations. Also, it controls the convergence speed of adaptation, or, equivalently, the number of necessary iterations until convergence is achieved.

4 The Induced EMF Method

The induced EMF method is a classical method of computing the self and mutual impedances of a collection of two-port networks such as antenna arrays. Although the method is restricted to side-by-side, collinear, and parallel in echelon elements and does not account for the radius of the wires and the gaps at the feeds, its advantage is that it leads to closed-form solutions which provide adequate design data [1]. Using the induced EMF method, an N-element can be represented as an N-port network. The goal of representing the array in this way is exploit the associated circuit parameters, especially the driving-point impedances [2]. These impedances can be organized into a matrix, $\mathbf{Z} \in \mathbb{C}^{N\times N}$, which contains the information on the MC effects in the array. Each element of the mutual impedance matrix, Z_{mn}, $1 \le m, n \le N$, for an array antenna of N elements, generated by the induced EMF method can be further used to perform beam pattern synthesis. For equal length, side-by-side, and identically oriented dipoles, using the induced EMF method we obtain the self and mutual impedance formulas given by King [5]

$$Z_{mn} = \begin{cases} 30\left[C + ln\left(4\beta l\right) - Ci\left(4\beta l\right)\right] + j30Si\left(4\beta l\right), & m = n \\ R_{mn} + jX_{mn}, \quad m \neq n \end{cases} \quad (3)$$

where

$$\begin{aligned} R_{mn} = 30 \{ & \cos(2\beta l)\left[Ci(u_0) + Ci(v_0) - 2Ci(u_1) - 2Ci(v_1) + 2Ci(\beta d)\right] + \\ & + \sin(2\beta l)\left[-Si(u_0) + Si(v_0) + 2Si(u_1) - 2Si(v_1)\right] + \\ & + \left[-2Ci(u_1) - 2Ci(v_1) + 4Ci(\beta d)\right]\} \end{aligned}$$

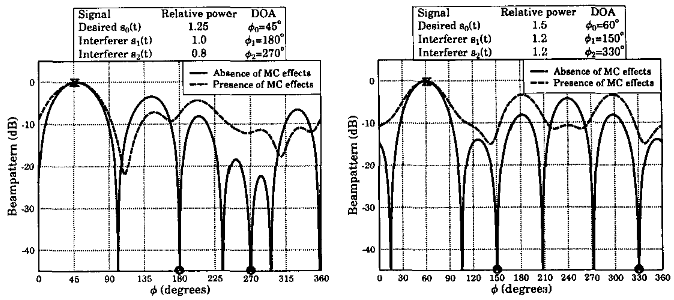
$$\begin{aligned} X_{mn} = 30 \{ & \cos(2\beta l)\left[-Si(u_0) - Si(v_0) + 2Si(u_1) + 2Si(v_1) - 2Si(\beta d)\right] + \\ & + \sin(2\beta l)\left[-Ci(u_0) + Ci(v_0) + 2Ci(u_1) - 2Ci(v_1)\right] + \\ & + \left[2Si(u_1) + 2Si(v_1) - 4Si(\beta d)\right]\} \end{aligned}$$

$$\begin{array}{ll} u_0 = \beta\left(\sqrt{d^2+4l^2} - 2l\right) & u_1 = \beta\left(\sqrt{d^2+l^2} - l\right) \\ v_0 = \beta\left(\sqrt{d^2+4l^2} + 2l\right) & v_1 = \beta\left(\sqrt{d^2+l^2} + l\right) \\ Ci(x) = -\int\limits_x^{\infty} \frac{\cos t}{t} dt & Si(x) = \int\limits_0^{x} \frac{\sin t}{t} dt \end{array}$$

and d is the horizontal distance between the m_{th} and n_{th} dipole antennas, l is half the length of the dipole antenna, β is the wavenumber, namely $\beta = 2\pi/\lambda$, and $C \approx 0.5772$ is the Euler's constant.

5 Simulation results

For the simulation process, we consider a UCA with $d_c = \lambda/2$ and $N = 6$ ($a = \frac{3\lambda}{2\pi}$), identically oriented and parallel to the z axis, half-wavelength dipoles with their feed points (center points) located on the $x-y$ plane. As known, dipole antennas possess omnidirectional radiation property (isotropic in ϕ). Our purpose is to demonstrate the degradation in performance of the adaptive UCA if the MC effects are not considered during the adaptation. At the end of the adjustment process (convergence of the LMS algorithm), we obtain the vector matrix $\mathbf{I}_{NMC} \in \mathbb{C}^{N\times 1}$ which contains the excitation currents I_n, $n = 0, 1, \ldots, N$ along each antenna, necessary to obtain the desired directional pattern without considering MC effects. Then we derive the vector of voltages along each dipole, $\mathbf{V} \in \mathbb{C}^{N\times 1}$, by the matrix operation $\mathbf{V} = \mathbf{Z}_{NMC} \cdot \mathbf{I}_{NMC}$ where $\mathbf{Z}_{NMC} \in \mathbb{C}^{N\times N}$ is the mutual impedance matrix without accounting MC. Essentially, $\mathbf{Z}_{NMC}$ is a diagonal matrix with each element along the diagonal being the self impedance of the half-wavelength dipole ($73.13 + j42.54\ \Omega$). The matrix operation $\mathbf{I}_{WMC} = \mathbf{Z}_{WMC}^{-1} \cdot \mathbf{V}$ is then performed, where $\mathbf{Z}_{WMC}$ is found by (3), to obtain the excitation currents affected now by MC. Figures 2(a) and (b) show the directional patterns for two different parameters of the incoming signals if the same results of adaptation are applied by ignoring or considering MC (excitation currents $\mathbf{I}_{NMC}$ and $\mathbf{I}_{WMC}$, respectively). We observe that when ignoring MC effects, the maximum is directed towards the signal of interest s_0, while very deep nulls are placed towards the interfering signals (s_1, s_2, s_3) providing an excellent performance. However, when MC effects are considered, the nulls are very shallow and misplaced. Additionally, the main beam is wider, thus resulting in reduced directivity. In the configuration we examined, the dipoles are placed in the direction of maximum radiation of each other. This is the worst case scenario, and it leads to very large MC effects and even greater beam pattern distortion.



(a) (b)

Figure 2: Resulting directional patterns in the absence and presence of MC with employment of the LMS adaptive algorithm.

6 Conclusion

A simple technique that underlines the necessity of including MC effects during the adaptation process of an adaptive array is presented in this paper. This is demonstrated by illustrating the degradation in performance of an adaptive uniform circular array if the adaptive beamforming algorithm ignores mutual coupling effects. Simulation results show that by applying the complex excitation currents obtained at the convergence of the adaptive algorithm in ideal conditions, the resulting performance of the adaptive antenna in a real situation, where MC effects are involved, is very poor. As a practical example, a UCA of half-wavelength dipoles was considered. The LMS algorithm was employed for the adaptive beamforming and the MC information was derived using the induced EMF method.

References

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