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Beam Steering of Time Modulated Antenna Arrays Using Particle Swarm Optimization

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Abstract— In this paper, a simple switching process is employed to steer the beam of a vertically polarised circular antenna array. This is a simple method, in which the difference resulting from the induced currents when the radiating/loaded element is connected/disconnected from the ground plane. A time modulated switching process is applied through particle swarm optimisation.

1. INTRODUCTION

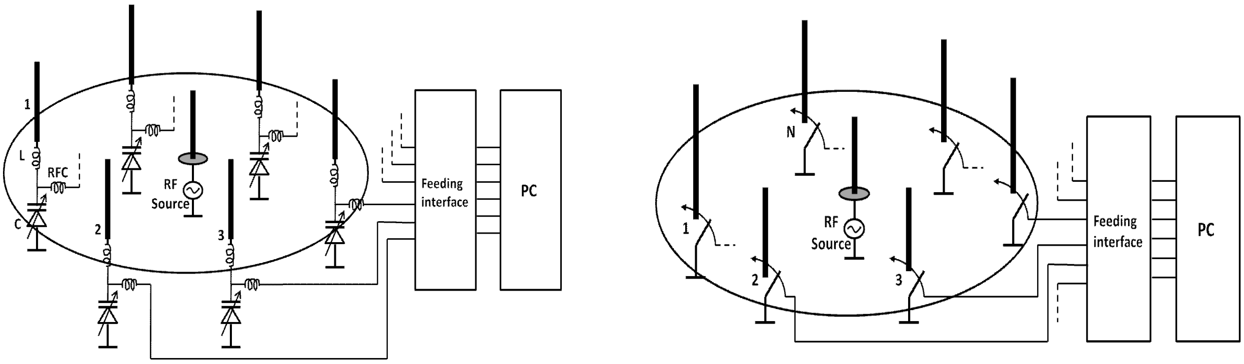
The current growth in the wireless communications industry has brought about the need for greater performance through improved capacity, data rates and reduce interference [1, 2]. The application of beam forming techniques on multiple-antenna arrays has increased in importance in the commercial wireless sector [3–6]. There are two generic approaches to beam-forming: dynamic phased array beam-forming, and adaptive beam-forming. In dynamic phased array beam-forming, the gain is maximised towards an intended user or target. Adaptive beam-forming places the nulls of an array pattern towards interfering or redundant signals, in addition to directing the maximum beam of the array towards the intended user (signal) [7]. Although adaptive beam-forming may be the preferred method, there are issues in the multi-criteria optimisation required to steer the main-lobe of the array in the desired direction(s), in a dynamically changing signal environment. This optimisation will operate through the amplitude and phase of each element, either continuously, or in discrete steps. The performance of the array is affected principally by its geometry and radiation pattern.

Most previous research on beam steering has been for linear [9], circular or planar arrays [2–8, 10], although it may be applied to other geometries. The uniform linear array provides the simplest array geometry, and the array processing is straight forward, however, it does not provide full view in the azimuthal range because of its use of edge elements. Even though this limitation can be overcome by use of several uniform arrays placed in a triangular or rectangular shape, this solution intrinsically increases costs and processing overheads. Beams formed by uniform linear arrays tend to broaden in a significant manner when the array is steered away from its bore sight. Uniform rectangular arrays, which have no omnidirectional elements are also unable to provide full azimuthal coverage. Uniform circular arrays on the other hand, provides full view of the azimuthal range, and depending on the element radiation pattern, can also provide a certain degree of source elevation information. By breaking down the array excitation into series of symmetrical spatial components, circular arrays have been shown to have a high potential of overcoming the effects of mutual coupling in antenna arrays.

Phase shifting is the most popular method of realizing beam steering. The feed to each element is varied such that the received or transmitted signals from all the elements are in phase in a given direction. Phase shifting may realised using ferrite or electronic phase shifters at RF (or IF), or by using digital signal processing at the baseband.

Beam steering may also be realised through a time modulated array in which RF switches are used to control the ON and OFF time of the radiator elements to obtain a time average radiation pattern at the fundamental frequency, and with low side lobes. This method is constrained by the generation of spurious signals which occur as multiples of the fundamental frequency, which contributes to energy losses, as well as interference. This constraint may be turned into an advantage if through a simultaneous scan operation, based on time modulation, the unwanted sideband beams are used to point in another direction. This method may be seen as preferable in broadband operations as the shape of the main beam will remain constant over a broad bandwidth.

The optimisation techniques utilise random transition rules rather than deterministic ones, they are not limited by local minima, and can be efficient in large scale optimisation problems. Prominent



(a) (b)

Figure 1: Beam steering ring antenna array; (a) Using capacitive loaded elements, (b) Using simple time switches.

optimisation algorithms that have been applied in previous research on beam steering are genetic algorithm, ant colony optimisation and PSO. Among these, PSO is our algorithm of choice as it is simpler to implement, uses fewer parameters, and has the ability to perform local search, control convergence, and is insensitive to scaling of design variables [11].

This paper describes a simple beam steering exercise for a circular array, using time modulated elements, through switching the conducting current from each radiator to the ground plane. The differenced values of the currents for switch states are used to fully generate the required radiation pattern, with beam steering control facilitated by particle swarm optimisation (PSO). The present work demonstrates the method by simply connecting one element at a short time of one harmonic cycle, and leaving the others disconnected to ground plane. Several results are presented to validate the concept of this method.

2. ANTENNA MODEL AND ANALYSIS

The vertically polarised antenna geometry is given in Figure 1. The field pattern can be given by,

$$E = E_m + \sum_{i=1}^{N} (E_i) \tag{1}$$

For the horizontal polarisation case, then $E_m = 0$. Taking the central element as the reference element, and assuming all the radiators are quarter-wavelength, then Eq. (1) can be approximated by the following form:

$$E = I_m \left(\hat{d}_m \cdot \hat{u}_\theta \hat{a}_\theta + \hat{d}_m \cdot \hat{u}_\phi \hat{a}_\phi\right) + \sum_{i=1}^{N} \left\{ I_i \begin{bmatrix} \hat{d}_{ei} \cdot \hat{u}_\theta \hat{a}_\theta + \\ \hat{d}_{ei} \cdot \hat{u}_\phi \hat{a}_\phi \end{bmatrix} e^{-jk\bar{P}_i \cdot \hat{r}} \right\} \tag{2}$$

where d_m and d_e are unit vectors describing the orientations of the main and outer elements. These may be simply defined as,

$$\hat{d} = \sin(\theta_d)\cos(\phi_d)\hat{a}_x + \sin(\theta_d)\sin(\phi_d)\hat{a}_y + \cos(\phi_d)\hat{a}_z \tag{3}$$

θ_d, and ϕ_d are the zenith and azimuth. I_m and I_i are the current maxima of the main elements, and the ith outer elements, respectively. The ith $\hat{r}$, $\hat{u}_\theta$ and $\hat{u}_\theta$; position vector of the ith radiator is denoted by p_i, with reference to Figure 1, this vector can be written as,

$$\bar{p}_i = r_a \cos\phi_i \hat{a}_x + r_a \sin\phi_i \hat{a}_y \tag{4}$$

The unit vectors ($\hat{r}$, $\hat{u}_\theta$ and $\hat{u}_\phi$) are given by the following:

$$\hat{r} = \sin\theta\cos\phi\hat{a}_x + \sin\theta\sin\phi\hat{a}_y + \cos\theta\hat{a}_z \tag{5}$$

$$\hat{u}_\theta = \cos\theta\cos\phi\hat{a}_x + \cos\theta\sin\phi\hat{a}_y + \sin\theta\hat{a}_z \tag{6}$$

$$\hat{u}_\phi = -\sin\phi\hat{a}_x + \cos\phi\hat{a}_y \tag{7}$$

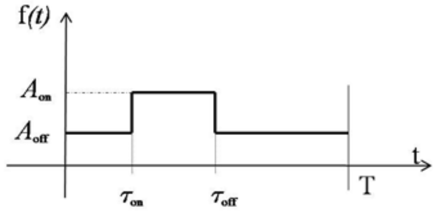


Figure 2: The variation of current over one time cycle.

Using the time switching process on these elements, the fields may still be expressed by Eq. (2). It should be noted that,

$$\frac{|E_{\text{ion}}(\theta)|}{\max|E_{\text{ion}}(\theta)|} \approx \frac{|E_{\text{ioff}}(\theta)|}{\max|E_{\text{ioff}}(\theta)|} \tag{8}$$

In other words, the normalized fields due to ON and OFF states on the ith vertically polarised radiator are equivalent. These assumptions are based on the separation distance, d_s, for each radiator from the ground plane to be $d_s << \lambda$. The induced current on the ith radiator for ON and OFF shown in Figure 2 are expressed byA_{on} and A_{off}, respectively. The limited time constraint is applied on ith radiator as $|\tau_{\text{off}} - \tau_{\text{on}}| < T$.

The Fourier series coefficient for this pulse shape, can be given (using [2]):

$$f_{mi} = A_{\text{off}} T \sin c(0.5\pi m T) e^{-j0.5\pi m T} + (A_{\text{ion}} - A_{\text{ioff}}) \frac{\sin(\pi m(\tau_{\text{ioff}} - \tau_{\text{ion}}))}{\pi m} e^{-j\pi m(\tau_{\text{on}}+\tau_{\text{off}})} \tag{9}$$

Using the results in [2], the time switching can be found subject to the weighted induced currents (w_i) assumed over the antenna structure. This can be put into similar format as following:

$$\frac{\sin(\pi m(\tau_{\text{ioff}} - \tau_{\text{ion}}))}{\pi m} e^{-j\pi m(\tau_{\text{on}}+\tau_{\text{off}})} = \frac{w_i - A_{\text{off}} T \sin c(0.5\pi m T) e^{-j0.5\pi m T}}{(A_{\text{ion}} - A_{\text{ioff}})} = w_{di} \tag{10}$$

Assuming the same procedure used in [2], the switch-on and switch-off of the ith element can be given as follows:

$$\tau_{\text{ioff}} = \frac{1}{2\pi m}\left(\frac{\gamma_i}{\pi m} + \frac{1}{\pi m}\sin^{-1}\pi m\,|w_{di}|\right) \tag{11}$$

$$\tau_{\text{ion}} = \frac{1}{2\pi m}\left(\frac{\gamma_i}{\pi m} - \frac{1}{\pi m}\sin^{-1}\pi m\,|w_{di}|\right) \tag{12}$$

The induced currents A_i^{on} and A_i^{off} are known for all cases that can be considered within the antenna operation. It should also be noted, for a given baseband bandwidth B_a, the time period T might be predicted by $T > 1/B_a$. Thus, the ith element times, i.e., switch-on and switch-off can be easily determined.

3. LOCUS VARIATION OF THE WEIGHTING COEFFICIENTS

The boundary variations of the weighted coefficients can be estimated subject to Eqs. (11) and (12). This can be explained in following example when m equals 1. It should be noted that the coefficient w_{di} can be given by the following inequality:

$$\left|\frac{w_i - A_{\text{off}}\sin(0.5\pi)e^{-j0.5\pi}}{(A_{\text{ion}} - A_{\text{ioff}})}\right| \leq \frac{1}{\pi} \tag{13}$$

The above equation may be reduced further:

$$\pi\left|\frac{w_i - jA_{\text{off}}/\pi/2}{(A_{\text{ion}} - A_{\text{ioff}})}\right| \leq 1 \tag{14}$$

Substituting $w_i = x + jy$ into Eq. (14),

$$\left(x - \frac{\pi}{2}a_{if}\right)^2 + \left(y + \frac{\pi}{2}a_{rf}\right)^2 \leq \frac{1}{\pi^2}|A_{\text{ion}} - A_{\text{ioff}}|^2 \tag{15}$$

where a_{rf} and a_{if} are the real and imaginary parts of the complex current in the off state. Thus, the locus variation can be simplified using polar co-ordinates as follows:

$$x = a + r_d \cos\phi \quad y = b + r_d \sin\phi \tag{16}$$

where:

$$r_d = \frac{1}{\pi}\left|A_{\text{ion}} - A_{\text{ioff}}\right| \quad a = \frac{2}{\pi}a_{if} \quad b = -\frac{2}{\pi}a_{rf}.$$

4. SIMULATION RESULTS

Two examples are considered for this method. For each case a six element ring array of radius 0.375 wavelength is used. For the first example all the elements were fed through switching process, in which the mutual coupling is ignored, and no feed element is considered. Figure 3 shows the radiation pattern for four selected steering angles, and their time switching sequence is presented in Figure 4.

Clearly, the required overlap switching for these elements is a very difficult task when mutual coupling is present.

In the second example, mutual coupling is included, and the feed line at the centre is applied. The induced currents were computed, when one element is on, and others are off. These are recorded as input data to the PSO. The radiation pattern requested for a few particular directions and their associated time sequences are presented in Figures 5 and 6. The overlap switching process is totally eliminated.

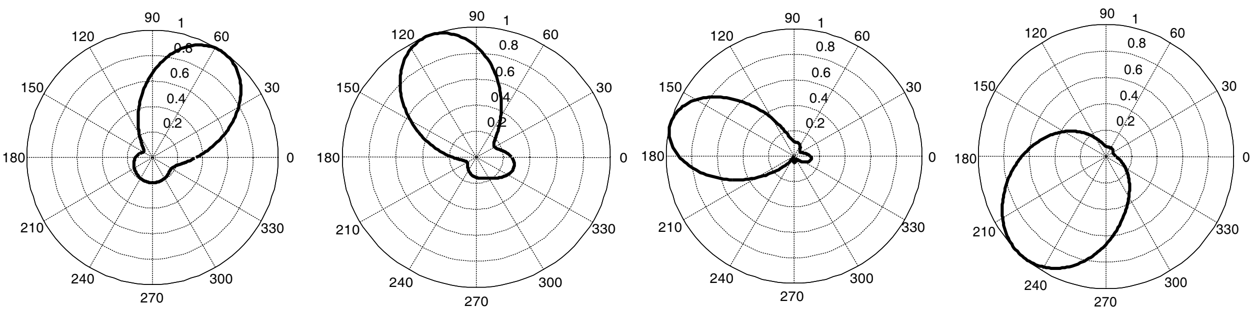


Figure 3: The radiation pattern of the beam steering angles 57°, 110°, 165°, 228°.

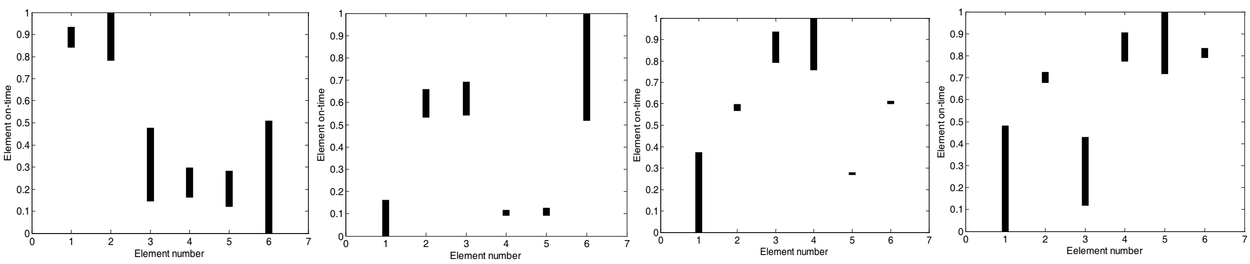


Figure 4: Normalized time-sequence corresponding to the antenna ring array steering angles in Figure 3.

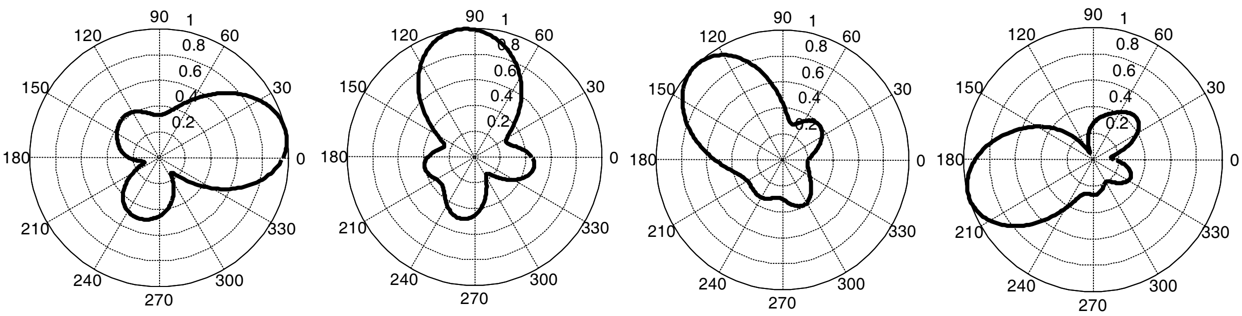


Figure 5: The radiation pattern of the beam steering angles 10°, 100°, 130°, 200°.

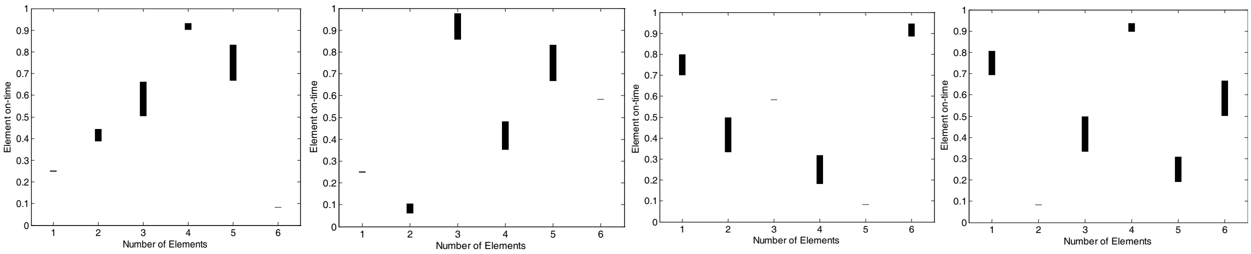


Figure 6: Normalized time-sequence corresponding to the antenna ring array steering angles in Figure 5.

5. CONCLUSION

A simple procedure of beam steered of ring antenna array using time modulated switching process has been presented. The method is quite simple and it could be a good candidate to replace the loaded reactive steered antenna array.

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