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REGULAR PAPER

Directivity maximization and optimal far-field pattern of time modulated linear antenna arrays using evolutionary algorithms

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ABSTRACT

In this paper evolutionary algorithm based design of time modulated 16-element linear antenna array with improved directivity and side lobe level (SLL) with low radiated power at sideband harmonics has been dealt with. In time modulated linear antenna array time is used as fourth dimensional parameter. The comparative study has been made with all the possible combinations of control parameters like constant excitation amplitude, inter-element spacing, and "time" as the fourth dimension. The same array radiates at various harmonic frequencies. In this paper the authors have considered only two harmonic frequencies; first sideband frequency and second side band frequency. Various simulation results are presented showing better side lobe performance, better side band performance and improved directivity with respect to the uniform case. The statistical analysis and *t*-test have been done to prove the superior performance of differential evolution with wavelet mutation (DEWM) better than real coded genetic algorithm (RGA), particle swarm optimization (PSO), and differential evolution (DE).

1. Introduction

Time modulated linear antenna arrays have attracted the antenna designers for their advantages over conventional array antennas for a few years. Previous research works have shown time modulated linear antenna array is attractive for the synthesis of low/ultralow side lobes [1–11]. As compared to conventional antenna array, the time modulated antenna array introduces a fourth dimension – time – into the design. Consequently, it has more flexibility. A lot of research works have been carried out to minimize the side lobe in the past decade [4–21]. Time modulated array was first investigated fifty years ago as the means of low cost beam steering in the antenna array [1,2]. The concept of time modulated array may be explained with reference to Fig. 1, which shows the conventional linear array topology to which switches have been included in the feed network connecting the outputs of the array elements to the adder. If all the element switches are closed the array behaves as a normal linear antenna array [18]. There is fundamental problem associated with time modulated linear array that is it generates harmonics, or sidebands at multiples of the switching frequency [2–12]. These harmonics are generally unwanted as they waste energy and may cause interference in other parts of radio spectrums. Therefore in time modulated arrays, time is exploited as an additional degree of freedom for the array synthesis in order to control the radiated beam [6,12]. More specifically, by properly turning ON and OFF the array elements according to a suitable time sequence, the synthesis of patterns with low side lobe level is obtained and the opportunity of optimizing the array performance in the time varying wireless scenario is enabled [18]. Unfortunately the undesired sideband radiation (SR) represents non-negligible loss of radiated power. In order to overcome such an impasse and to improve the performance of the array, various evolutionary algorithms like genetic algorithms (GAs) [18,22] particle swarm optimization (PSO) [23–26] and Differential Evaluation (DE) [27–29] have been used to solve this problem. The limitations of RGA, PSO and DE are that they may be influenced by premature convergence and stagnation problem. In order to overcome these problems, differential evolution with wavelet mutation (DEWM) [30,31] has been employed in this work. The control of side lobe and sideband levels opens up the branch for reconfigurable applications, provided the circuitry needed for time modulation is more flexible and easier to realize than the array with conventional feed networks, indeed for the same purpose. The statistical analysis and *t*-test [32] have been done to prove the superior performance of DEWM.

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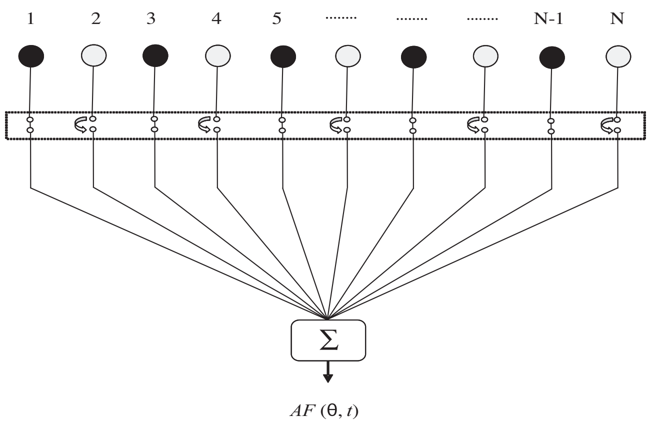

Fig. 1. Generalized switching scheme of time modulated linear antenna array.

2. Design equations

Let us consider a broadside linear antenna array of N isotropic sources lying along the z-axis. The array is symmetric in both the geometry and excitation with respect to the array centre. Its array factor is given by following expression:

$$AF(\theta) = \sum_{n=1}^{N} I_n \exp\left\{jK(n-1)d\sin\theta\right\} \tag{1}$$

where θ = angle of radiation of electromagnetic plane wave; d = spacing between elements; K = propagation constant; N = total number of elements in the array; I_n = excitation amplitude of nth element.

After applying time modulation equation (1), [3] can be re-written as

$$AF(\theta, t) = e^{j2\pi f_0 t} \sum_{n=1}^{N} I_n U_n(t) \exp\left\{jK(n-1)d\sin\theta\right\} \tag{2}$$

In the time modulation, each element of the linear array is controlled by high speed periodic Radio Frequency (RF) switch [3]. The periodic switch-on time sequence function is given by

$$U_n(t) = \begin{cases} 1 & \text{for} \quad 0 \le t \le \tau_n \\ 0 & \text{others} \end{cases}$$

Suppose the array operates at operating frequency f_0 in (Hz) and T_0 is the time period of the operating frequency. Time modulation period of the modulating switch $U_n(t)$ is T_p, implying time modulation frequency $F_p = 1/T_p$. Generally the time modulation frequency F_p is much lower than the operating frequency f_0. It means that $T_p > T_0$. Operating frequency f_0 and time modulation frequency F_p are independent of each other. Now, instated of exciting each element continuously, each element is turned 'ON' for the fixed time duration of τ_m with a pulse repetition frequency of $F_p = 1/T_p$; T_p is the pulse repetition period lying in the range $\tau_m \le T_p > T_0$. After the time modulation due to the high frequency RF switch $U_n(t)$, the antenna will not only radiate at the operating frequency (f_0) but also it will radiate at different harmonics of modulating frequency (F_p). Harmonics of the radiation pattern are not because of operating frequency of the signal but they are due to the periodic switch $U_n(t)$. Switch-on time of each element of the linear array is $\tau_n(0 \le \tau_n \le T_p)$, where T_p is the modulation period. The periodic switch ON–OFF function $U_n(t)$ in time domain representation can be decomposed into Fourier series in frequency domain, as given by

$$U_n(t) = \sum_{m=-\infty}^{\infty} i_{mn} e^{j2\pi m F_p t} \tag{3}$$

where

$$i_{mn} = \frac{I_n \tau_n}{T_p} \sin c(\pi m F_p \tau_n) e^{-j\pi m F_p \tau_n} \tag{4}$$

(4) shows the current excitation value for the mth harmonic of the RF switch modulation frequency. $m = 0$ holds good for the operating frequency. Complex amplitude coefficients at the centre frequency (f_0), the first side band frequency ($f_0 + F_p$) and the second sideband frequency ($f_0 + 2F_p$) are given as follows:

$$i_{0n} = \frac{I_n \tau_n}{T_p} \tag{5}$$

$$i_{1n} = \frac{I_n \tau_n}{T_p} \sin c(\pi m F_p \tau_n) e^{-j\pi m F_p \tau_n} \tag{6}$$

$$i_{2n} = \frac{I_n \tau_n}{T_p} \sin c(2\pi F_p \tau_n) e^{-j2\pi F_p \tau_n} \tag{7}$$

With the help of (3) and (4), (2) can be re-written as (8).

$$AF(\theta, t) = \sum_{m=-\infty}^{\infty} \sum_{n=1}^{N} i_{mn} \exp\left\{jK(n-1)d\sin\theta\right\} e^{j2\pi(f_0 + m\cdot F_p)t} \tag{8}$$

The far field of (8) contains mth harmonic frequency components $m{\cdot}F_p$, where $m = 0, \pm 1, \pm 2, \ldots, \pm\infty$. It is worth noting that (8) is the sum of infinite number of harmonic components, whose mth order harmonic frequency component can be written as:

$$AF_m(\theta, t) = e^{j2\pi(f_0 + m\cdot F_p)t} \sum_{n=1}^{N} i_{mn} \exp\left\{jK(n-1)d\sin\theta\right\} \tag{9}$$

From (9) one can express the following array factors $AF_0(\theta,t)$, $AF_1(\theta,t)$ and $AF_2(\theta,t)$ for the operating frequency, the first positive side band, and the second positive sideband, respectively.

$$AF_0(\theta, t) = e^{j2\pi f_0 t} \sum_{n=1}^{N} \frac{I_n \tau_n}{T_P} \exp\left\{jK(n-1)d\sin\theta\right\} \tag{10}$$

$$AF_1(\theta, t) = e^{j2\pi(f_0 + F_p)t} \sum_{n=1}^{N} \frac{I_n \tau_n}{T_P} \sin c\ (\pi F_p \tau_n) \times \exp\left\{jK(n-1)d\sin\theta\right\} e^{-j\pi F_p \tau_n} \tag{11}$$

$$AF_2(\theta, t) = e^{j2\pi(f_0 + 2F_p)t} \sum_{n=1}^{N} \frac{I_n \tau_n}{T_P} \sin c\ (2\pi F_p \tau_n) \times \exp\left\{jK(n-1)d\sin\theta\right\} e^{-j2\pi F_p \tau_n} \tag{12}$$

Thus, (10), (11) and (12) show the respective expressions for complex amplitudes at f_0, $f_0 + f_p$ and $f_0 + 2F_p$, which can be used to synthesize the desired radiation pattern.

To calculate the directivity of time modulated linear antenna arrays, the total power radiated should include the power at the