Beam Steering and Null Placement in a Time Modulated Linear Antenna Array Using NPSOWM

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***Abstract* – Steering the main beam of a time modulated antenna array (TMAA) with low side lobe level (SLL) as well as deeper null placement in the interfering direction is proposed in this paper. A linear array of 18 elements is considered with sequential switching applied to each individual element of the antenna array. Beam steering is achieved by proper controlling of the radiation pattern at fundamental and multiple harmonic frequencies. A novel particle swarm optimization with wavelet mutation (NPSOWM) is used to decrease the overall side lobe level and imposing of deeper nulls in the direction of interference. Switching time sequences and inter element spacing between radiating elements are optimized to get the desired radiation pattern with minimal changes in first null beam width (FNBW).**

***Keywords* – Linear antenna array, Side lobe level, Beam steering, Time modulation, Switching, Nulls, Particle swarm optimization**

I. INTRODUCTION

Wireless Communication plays a very important role in our daily lives. As the number of users are rapidly increasing, the challenge of point to point communication also increases proportionately. Therefore, the demand of highly directive and non-interfering communication is the growing need of modern age technology. For secure and point to point communication, an arrangement of multiple radiating elements instead of a single element has become the obvious choice. Single element antenna has broad radiation pattern with low directivity. For the long-distance communication of modern edge highly directive antenna radiation patterns are required. This can be accomplished either by increasing the electrical size of the antenna or by an arrangement of multiple radiating elements with specific electrical and geometrical configuration acting as an array. Fields from multiple radiating elements can add either constructively in some direction giving high directivity or destructively in some other direction producing null pattern [1]. Controlling three basic parameters such as amplitude, phase and spacing between radiating elements, desired array pattern can be generated [2]. To overcome large dynamic range ratio (DRR) problem of conventional antenna array, the concept of time modulation is introduced [3]. This fourth dimension 'Time' added the much-needed flexibility to control the radiation pattern that produces low side lobe level for a particular region of the pattern with smallest possible sacrifice in first null beam width [4]. By proper control of switching times of the array elements, a highly directive main beam pattern as well as low side lobes can be achieved at the fundamental frequency [5]. With time-switching, unwanted radiation at multiple harmonics are generated [6]. But in certain situations, this can be exploited to get radiation patterns at harmonic frequencies that can produce harmonic beam steering [7].

Time Modulation based 18-element linear antenna array is considered here for beam steering and to achieve low side lobe levels with deep null placement in the direction of interference. Radiating elements are sequentially energized along the broadside direction of the array. By this way, a linear time delay is added in the switching time sequence and directional radiation patterns for harmonic frequencies are generated at specific steering angles. Deep nulls at unwanted direction with low SLLs can be achieved at harmonics using evolutionary optimization techniques.

Evolutionary algorithms for optimizing antenna designs has shown tremendous growth in recent years. NPSO with wavelet mutation (NPSOWM) is used here for an 18-element linear antenna array to fulfill multiple objectives of optimization with sequential time switching.

Basic ideas of time modulation and design equations of time modulation-based linear antenna arrays are covered in Section II. Modified version of particle swarm optimization is briefed in Section III. Measured results are presented in Section IV. Conclusive statements have been included in Section V.

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II. Theory And Design Equations

Time modulation-based antenna array can be controlled with periodic pulses of variable width feeding separately into each element [8]. The nonlinearity of antenna array with modulated time sequence can lower the side lobe levels with improvement in directivity [9]. The Time-Switched array is capable of producing higher gain at desired direction and lower gain at interferer direction with proper control of harmonics [10]. Steering the main beam of the antenna is a spatial filtering technique that enhance the radiation at particular direction by rejecting unwanted signals from others with a progressive phase shift [11].

A. Design Equations

A broadside linear array of an even number of isotropic elements N positioned along z-axis is considered here [12]. High-speed RF switch controls individual element of the array with different amplitude excitations for a set of N elements. Assuming that the array is transmitting a rectangular pulse of width T and a pulse repetition frequency of $f_{\mathrm{prf}} = 1/\mathrm{T_p}$ where $\mathrm{T_p}$ is the pulse repetition period, the array factor for the array considered here is given by,

$$AF(\theta) = \sum_{n=1}^{N} I_n exp\{jk(n-1)dsin\theta\} \quad (1)$$

where θ is the angle of radiation with respect to array main axis, d is the spacing between radiating elements, k is the propagation constant, N is the number of radiating elements, $\mathrm{I_n}$ is the amplitude excitation of $\mathrm{n^{th}}$ element.

After applying Time Modulation, the array factor for N element linear array can be modified from Equation (1) as:

$$AF(\theta,t) = e^{j2\pi f_0 t} \sum_{n=1}^{N} I_n U_n(t) exp\{jk(n-1)dsin\theta\} \quad (2)$$

where $U_n(t)$ is periodic function of time sequence where the element is switched on for $\tau_n (0 \leq \tau_n \leq T)$.

Switching scheme applied in the time modulation based linear antenna array is described here [13]. Time domain representation of $\mathrm{U_n(t)}$ can be decomposed into Fourier components in frequency domain as

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

where $i_{mn=\frac{\mathrm{I_n}\tau_n}{\mathrm{T_p}}} sinc(\pi mFp\tau_n) e^{-j\pi mFp\tau_n}$ (4)

Equation (4) represents the excitation currents applied to the $\mathrm{m^{th}}$ harmonic frequency of modulation such as m=0 resembles to the fundamental frequency. From (2), (3) and (4) $\mathrm{AF}(\theta, \mathrm{t})$ can be expressed into Fourier series as:

$$AF(\theta,t) = \sum_{m=-\infty}^{\infty} \sum_{n=1}^{N} i_{mn} exp\{jk(n-1)dsin\theta\} * \{e^{j2\pi(f_0+mFp)t}\} \quad (5)$$

mFp represents the harmonic component of the pattern where m= 0, ±1, ±2, ±3…. ±∞ and the array factor for the frequency component of $\mathrm{m^{th}}$ order after putting the value of i_{mn} is given as:

$$\mathrm{AFm}(\theta, \mathrm{t}) = e^{j2\pi(f_0+mFp)t} \sum_{n=1}^{N} i_{mn} exp\{jk(n-1)dsin\theta\} \quad (6)$$

and $|AFm(\theta,t)| = |\sum_{n=1}^{N} i_{mn} exp\{jk(n-1)dsin\theta\}|$ (7)

From this expression, the fundamental, first positive and first negative harmonic frequencies can be found at $\mathrm{f_0}$, $(\mathrm{f_0} + \mathrm{Fp})$, $(\mathrm{f_0} - \mathrm{Fp})$ respectively [14]. Optimized radiation pattern at these frequencies with proper switching can be used for steering the main beam of the antenna array [15].

B. Evolutionary Technique Applied

Evolutionary algorithms are adaptive learning based heuristic search methods which is highly efficient to produce intelligent optimization schemes. A Novel PSO associated with wavelet mutation (NPSOWM) is employed here for optimizing the side lobe levels and the spacing between the elements of antenna array. The best possible result is obtained from NPSOWM with population of 120, maximum generation of 200.

C. Selection Parameters of Antenna Array

A broadside linear antenna array with isotropic elements is considered in this paper. Thus, the parameters that are in hand are the switching time sequences of each element (μs) and spacing between them in terms of λ (used to compute the location of the elements). Initially, the non-optimized array structures are assumed to have uniform excitation amplitude distribution (normalized to 1) and uniform spacing between radiating elements set to λ/2. A sequential switching scheme with modified inter element spacing is considered for 18 radiating elements where each radiating element is sequentially energized for 1/18th of the normalized modulation period. The cost function, designed as a minimization problem is expressed as:

$$CF = w_1 * SLL_{max}^{g}|_{\mathrm{f0}} + w_2 * SBL_{max}^{g}|_{\mathrm{f0+mFp}} \quad (8)$$

where g is the number of iterations, w_1 and w_2 are the weighting factors, SLL_{max} is the maximum SLL at the fundamental frequency and SBL_{max} is the maximum side band level at $\mathrm{m^{th}}$ harmonic frequency. Here, fundamental frequency (m=0) as well as first positive (m=+1), second positive (m=+2), third positive (m=+3) and first negative (m=–1) harmonics are considered for 18-element array.

III. Modified Version of PSO Algorithm

Particle Swarm Optimization (PSO) is adaptable, robust population based optimization algorithm which works with non-differential objective functions, unlike classical optimization tools. Standard PSO, developed by Kennedy, Eberhart and Shi is inspired from the behavior of food searching of a swarm of birds [16]. Standard PSO is the simulation development of this nature inspired phenomena in multidimensional space. Certain objective of searching food is modelled as objective function in bird flocking. Each bird or particle knows its best value so far (*pbest*). This corresponds to personal best of each agent. The best value among *pbests* so far can be considered as global best (*gbest*). In Novel PSO (NPSO), by considering the worst position, the agent can restrict itself and always improving for a better position by keeping a limit on worst position of every iteration. NPSO is expressed as

$$V_i^{k+1} = r_2 * sign(r_3) * V_i^k + (1-r_2) * C_1 * r_1 * \left(pbest_i - S_i^k\right)$$
$$+(1-r_2) * C_2 * (1-r_1) * \left(gbest - S_i^k\right)$$
$$+(1-r_2) * C_1 * r_1 * \left(S_i^k - pworst_i\right) \quad (9)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \text{ where } sign(r_3) = \begin{cases} -1, & r_3 \le 0.5 \\ 1, & r_3 > 0.5 \end{cases} \quad (10)$$

where V_i^k is the velocity of ith particle at kth iteration; C_1, C_2 are the positive weighting factors; r_1, r_2 are random numbers between 0 and 1; S_i^k is current position of ith particle at kth iteration; $pbest_i$ is personal best of ith particle at kth iteration; $gbest$ is group best at kth iteration; V_i^{k+1} is updated velocity; S_i^{k+1} is updated position and $pworst_i$ is the personal worst of particle *i*.

NPSO associated with wavelet-based mutation strategy is adopted in this work. Certain seismic signals can be modeled by combining translations and dilations of an oscillatory function with a finite duration called a "Wavelet". NPSO with wavelet mutation (NPSOWM) ensures that every element of the population will mutate with Morlet wavelet dilated by different values of dilation parameters. Details of wavelet mutation is described by Ram G *et al*. in [17].

IV. Measured Results and Discussions

In this section, optimization of antenna parameters for the purpose of beam steering as well as reducing side lobes is presented. Initial values of SLL and first null beam width (FNBW) is calculated considering uniform switching time and λ/2 uniform spacing between radiating elements. The uniform pattern for 18 element arrays is shown in Fig. 1. Calculated FNBW and SLL are 12.6º and -13.2 dB respectively. A conventional time sequence for 18 element arrays is presented in Fig. 2. Here, each radiating element is sequentially energized for 1/18th of the normalized modulation period. Thus, harmonic beam patterns are generated at m=0, ±1, ±2, ±3…. ±∞.

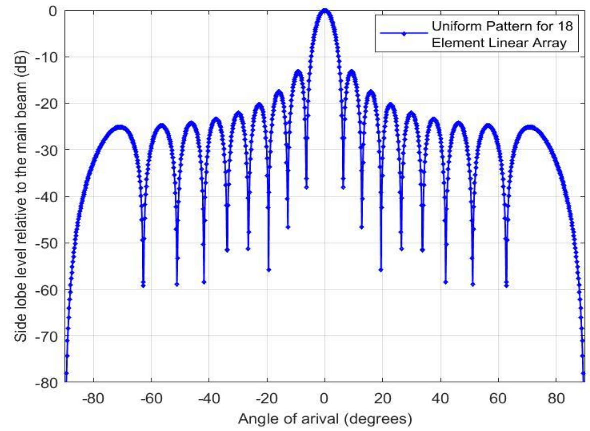

Fig. 1. Uniform pattern for 18-element linear array antenna

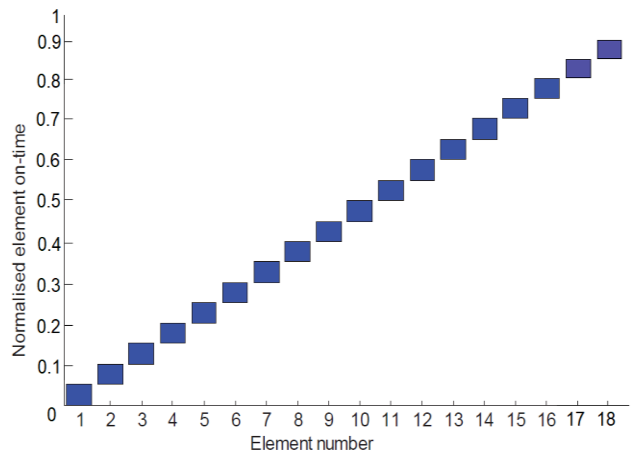

Fig. 2. Sequential time switching of 18-element antenna array

Deep null placement of steered beam pattern for first positive and first negative harmonics are shown in Fig. 3 and Fig. 4 respectively.

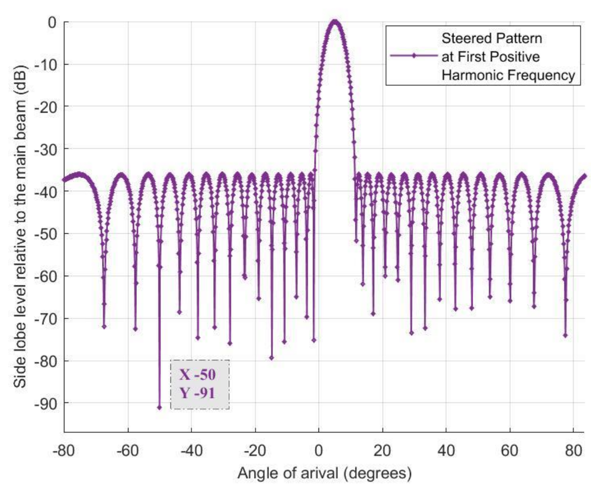

Fig. 3. Steered pattern at first positive harmonic with null at –50º

Steered beam pattern obtained at first positive harmonic shows a deeper null placed at the direction of interference of –50º with –91 dB of SLL. Similarly, the steered pattern of first negative harmonic frequency generates a deeper null at the direction of interference of 50º with –91 dB of SLL. In both cases, the desired signal is along the steered main lobe direction and interference is arriving at –50º and 50º respectively.

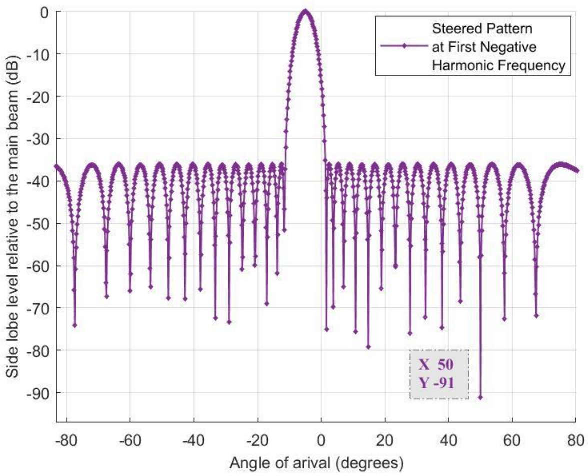

Fig. 4. Steered pattern at first negative harmonic with null at 50º

The pattern at fundamental frequency (m=0) as well as first positive (m=+1), second positive (m=+2), third positive (m=+3) and first negative (m=–1) harmonics are considered here with optimized spacing of 0.8159λ between array elements, the steered pattern has achieved a lower SLL of –36.04 dB and 13.32º FNBW. Changes in FNBW from 12.6 º to 13.32º can be considered as a very small change. That means, beam steering with very low side lobe levels have been achieved without affecting the directivity.

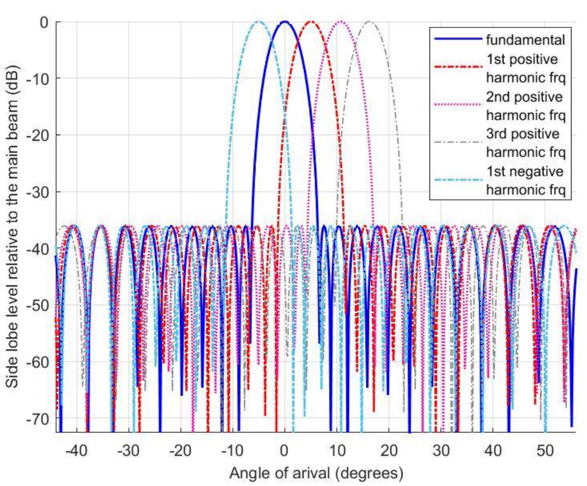

Fig. 5. Steered beam pattern at fundamental frequency, first three positive harmonic frequencies and at the first negative harmonic frequency generated using the sequential switching of Fig. 2. and optimized parameters from NPSOWM

Comparison of beam steered pattern and uniform pattern is tabulated in Table. 1 and the steered pattern of 18-element sequential time switched linear antenna array is presented in Fig. 5.

TABLE. 1. SLL, FNBW AND SPACING BETWEEN RADIATING ELEMENTS FOR UNIFORM AND OPTIMIZED ANTENNA ARRAY

Array Elements	SLL (dB)	FNBW (º)	Inter Element Spacing (λ)
Uniform	–13.2	12.6	0.5
Optimized	–36.04	13.32	0.8159

Best convergence profile for NPSO with wavelet mutation (NPSOWM) out of 50 runs is reported in Fig. 6. All computations were done with MATLAB 9.5 on core i5 (8th Gen) processor, 3 GHz with 8 GB RAM.

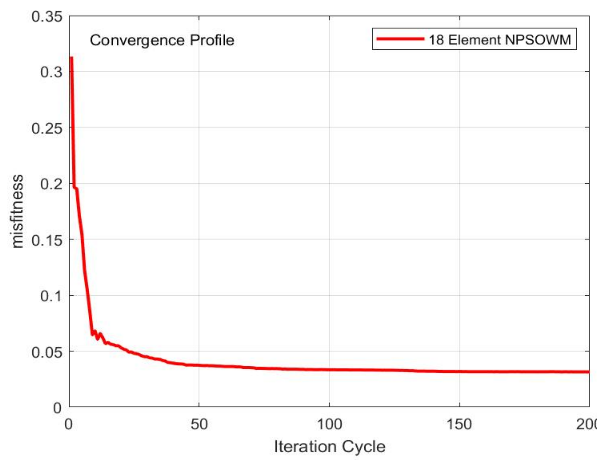

Fig. 6. Convergence curve for 18-element array using NPSOWM

V. CONCLUSION

18-element time modulation-based linear antenna array with sequential time switching and optimized spacing between antenna elements is considered with NPSOWM. Simulated result shows that the unwanted radiations generated at the harmonics of time switched arrays can very well be used to steer the main beam in desired direction by controlling the modulation period of each radiating elements as well as optimization of certain parameters. Deep nulls at unwanted direction to cancel out interferences can also be imposed by using optimization. Thus, Steered beam pattern with reduced side lobe level and deeper nulls can be achieved without sacrificing the directivity of the array antenna.

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