Comparative Study on Synthesizing Reconfigurable Time-Modulated Linear Arrays using Differential Evolution, Artificial Bee Colony and Particle Swarm Optimization

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Abstract. This paper presents a new technique based on optimization tools to design phase only, digitally controlled, reconfigurable antenna arrays through time modulation. In the proposed approach, the on-time durations of the time-modulated elements and the static amplitudes of the array elements are perturbed in such a way that the same on-time sequence and discrete values of static amplitudes for four bit digital attenuators produces either a pencil or a flat-top beam pattern, depending on the suitable discrete phase distributions of five bit digital phase shifters. In order to illustrate the technique, three optimization tools: differential evolution (DE), artificial bee colony (ABC), and particle swarm optimization (PSO) are employed and their performances are compared. The numerical results for a 20-element linear array are presented.

1. Introduction
Multiple radiation patterns from a single antenna array find applications in the field of satellite and military communication, surveillance and radar engineering. Depending on the applications, it is required to synthesize the antenna patterns with some stringent specifications such as low side lobe level (SLL), low ripple (R), sharp transition (T) for flat-top (sector) pattern or narrow first null beam-width (FNBW) for pencil beam pattern. Syntheses of such patterns using conventional antenna array (CAA) synthesis methods need relatively high value of dynamic range ratio (DRR) [1] which results in different sources of errors such as systematic and mechanical errors those degrade the array performance. On the other hand, time-modulation technique is attractive to synthesizing low / ultralow SLL pattern with low DRR [2 - 4] or in uniform amplitude array [5 - 6].

Different population based stochastic techniques such as differential evolution (DE) [2-4, 6]; particle swarm optimization (PSO) [7] and artificial bee colony (ABC) [5, 8] play an important role to reducing/controlling the power losses due to sideband radiations that result from the periodical commutations of the antenna elements [9]. To the best of author’s knowledge, comparative study in synthesizing reconfigurable antenna arrays through time modulation using different optimization tools has not been reported. The effectiveness of the technique as proposed in [4] has been used in synthesizing low side lobe pencil beam patterns only. In this paper, this technique is used to synthesize a digitally controlled dual beam (flat-top and pencil) pattern with phase only difference and the performances of three efficient optimization tools such as DE, ABC and PSO; in solving such problem have been studied.
Table 1: Desired and obtained values of the design parameters of the synthesized patterns.

|                         | SLL (dB) | Ripple (dB) | FNBW (deg) |
|-------------------------|----------|-------------|------------|
|                         | Desired  | Obtained    | Desired    | Obtained     |
| Flat-top                | -25.0    | -24.78DE    | 0.5        | 0.67DE       |
|                         |          | -22.22ARC   | 0.48ABC    |              |
|                         |          | -24.31PSO   | 0.53PSO    |              |
| pencil                  | -25.0    | 25.0        | -25.0      |              |
|                         |          | 25.69       | -25.0      |              |

2. Theory

Let us consider a broadside time modulated linear array antenna (TMLAA) of 2N isotropic elements that are symmetrically placed along the x-axis with inter element spacing of d such that array center coincides with the origin of reference coordinate axis. Let us further assume that, excitation amplitudes $A_p$, phases $\alpha_p$ and normalized on-time sequences $\tau_p \forall p \in [1, N]$ of radiating elements are also symmetrical with respect to the array center. Due to the periodical excitation of the array elements, the array factor expression at k-th harmonics can be obtained as, in (1), [2, 9].

$$ A_F(u,t) = 2e^{j2\pi(f_0 t + f_m)} \sum_{p=1}^{N} \left| \tau_p A_p e^{j\alpha_p} \sin(k \pi \tau_p) e^{-j2\pi \frac{m-1}{2} u} \right| $$

Where $f_m = 1/T_m$ is the modulation frequency with $T_m$ being the modulation period; $f_0$ is the frequency of the operating signal with $\lambda$ being the wavelength; $u = \cos \theta$ when $\theta$ is the observation angle measured from the array axis.

3. Optimization Strategy

In order to reducing the sideband level (SBL), the optimization process is divided in two steps as detail is explained in [4]. In the first step, the dynamic excitations $E_p = A_p \tau_p$ are perturbed in the continuous search space (0.05, 1). $\alpha_p$ is distributed in the discrete search space (-180, 180) by equally dividing 32 steps for the five bit digital phase shifters. The fitness function for this step is defined as

$$ \omega^{(1)}(E_p, \alpha_p) = \sum_{\delta=1}^{2} \sum_{m=1}^{2} W_{m}(\delta) \left| S_{m,\delta}^{(\delta)} - S_{\delta}^{(\delta)} \right| H\left( S_{m,\delta}^{(\delta)} - S_{\delta}^{(\delta)} \right) $$

where, $\delta = 1, 2$ correspond to the flat-top and pencil beam pattern respectively; $m = 1, 2$ are the design parameters and ‘S’ denotes the design specifications of the patterns as given in Table 1. The subscripts ‘d’ and ‘o’ in ‘S’ indicate the desired and obtained valued of the parameters. $W_m$’s are the weighting factor and ‘H’ is the Heaviside step function. In the second step, discrete search space of $A_p$ i.e., (0.25, 1) is equally divided into 16 steps for the four bit digital attenuators. Continuous search space of $\tau_p$ is taken as (0.1, 1). Then, as in [4], the following cost function is used to reduce SBL.

$$ \omega^{(2)}(A_p, \tau_p) = \sum_{\delta=1}^{2} SBL_{\max}^{(\delta)} $$

with $SBL_{\max}$ as the maximum sideband level among the first three sidebands.

Fig.1: Dual beam patterns using DE, ABC and PSO.

Fig.2: Side band levels for the first 20 sideband radiations.
This paper presents a new technique to design reconfigurable time-modulated antenna arrays with higher than that of PSO but it quickly converges to local minima. Although, the initial convergence rate of ABC is better with respect to both ABC and PSO. Although, the initial convergence rate of ABC is high e.g., DRR = 21.09 for DE. In the second step, by redistributing $A_p$ in CAAs, the distribution of $E_p$ and $\alpha_p$ is given in Table 2. It is worth to mention that in CAAs, the distribution of $E_p$ is considered as the static excitation distribution for which DRR value is high e.g., DRR = 21.09 for DE. In the second step, by redistributing $A_p$ and $\tau_p$, SBL$^{max}$ is reduced to below -20 dB (see Fig. 2) as well as the DRR value to '4' (see Table 2). The average convergence characteristics for the two steps of the different algorithms are shown Fig. 3 and 4 respectively. It can be seen that performance of DE in terms of quick convergence and minimizing the fitness function values are better with respect to both ABC and PSO. Although, the initial convergence rate of ABC is higher than that of PSO but it quickly converges to local minima.

### 4. Numerical Results and Discussions

A TMLAA with $2N = 20$, $d = 0.5\lambda$ is considered. To study the performance of the three algorithms, control parameters are set as in [10, 11 and 12]. In the two steps, the same values of common parameters such as number of population 100 and 50; maximum generation 4000 and 100 are set respectively. Also by setting same values of weighting factors i.e., $W_1 = 2$, $W_2 = 6$ for flat-top and $W_1 = 5$, $W_2 = 2$ for the pencil beam; the algorithms are run for 20 trials. A selected pattern is shown in Fig. 1 and the corresponding distributions of $E_p$ and $\alpha_p$ are given Table 2. It is worth to mention that in CAAs, the distribution of $E_p$ is considered as the static excitation distribution for which DRR value is high e.g., DRR = 21.09 for DE. In the second step, by redistributing $A_p$ and $\tau_p$, SBL$^{max}$ is reduced to below -20 dB (see Fig. 2) as well as the DRR value to '4' (see Table 2). The average convergence characteristics for the two steps of the different algorithms are shown Fig. 3 and 4 respectively. It can be seen that performance of DE in terms of quick convergence and minimizing the fitness function values are better with respect to both ABC and PSO. Although, the initial convergence rate of ABC is higher than that of PSO but it quickly converges to local minima.

### 5. Conclusion

This paper presents a new technique to design reconfigurable time-modulated antenna arrays with digitally controlled static excitation amplitudes and phase distributions. The technique successfully
synthesizes the patterns with closed to the desired design specifications. The performances of the three optimization algorithms: DE, ABC and PSO; on solving such problems are studied. Although the performances of the different optimization algorithms are sensitive on the weighting factors of the cost function and for different set of weighting factors final results may be different; in this paper it is observed that DE outperforms over both ABC and PSO.

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