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Evolutionary Computing Based Antenna Array Beamforming with Low Probabality of Intercept Property

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Abstract: In this work we have proposed a new approach for array antenna beamforming based on evolutionary computing, which offers low probability of intercept. These active array antennas are highly vulnerable to intercept receivers due to their high-gain. The detection performance of proposed approach remains unchanged as the amount of energy on the target is same as that of the high gain beam pattern, while the intercept range of the enemy receiver has been greatly reduced. In this paper, the set of complex weights for synthesis of high gain beam pattern using spoiled set of basis patterns is derived using genetic algorithm. The two major advantages of proposed algorithm are the improved performance and at the same time the low complexity specifically by avoiding the matrix inversions. Simulation results ensure that the beam synthesized by this technique is at par with the existing LPI beamforming techniques employing phased arrays.

Key words: Beamforming · Genetic algorithm · Low probability of intercept antenna · Pattern Search

INTRODUCTION

Active and/or mono-static radars are very likely to be detected by jammers and intruders due to the amount of energy transmitted towards the target based on conventional techniques. It is very common that intruders exploit, degrade and prevent radar operations and capabilities [1]. This competition between the radar and intruders is termed as electronic warfare (EW) [2, 3]. The phased array antennas, which have the advantage of much higher gain with respect to isotropic antennas, are very likely to be detected and exploited by the intruders. On the other hand, the advantage of phased array antennas is their detection performance which is very high.

Various techniques have been proposed to achieve LPI while ensuring the effective detection range. Three widely used LPI techniques include i) spreading energy in time domain using high duty cycle waveforms ii) spreading energy in frequency domain using wide-bandwidth waveforms and iii) spreading energy in spatial domain using broader transmit antenna beams [4-9]. Combination of these techniques is also used to enhance the performance [1, 8]. The most common among the above techniques are high duty cycle, wide-bandwidth waveforms which are widely exploited in LPI applications [10]. Suppression of side lobes can also reduce the probability of being detected, to some extent, in the side lobe search regions. In [11], a pseudo random frequency jitter was introduced to the carrier frequency that helps to design an LPI waveform for OFDM systems. In [12], LPI performance analysis using time-energy management techniques for Digital Array Radar (DAR) has been presented.

Alongwith the waveform design, various other techniques are available in literature that improve the LPI performances using different types of antennas modifications. Antenna hopping technique as proposed by E.J. Baghdady has two or more spaced antennas connected with a single input or output through a switch [13]. Another technique employs MIMO antennas, in which actual transmit beam is shaped in such a way that limits the antennas radiations in desired directions and hence to achieve LPI property [14]. Similarly in [15], LPI property for a network, using technique of frequency hop multiple access, is evaluated. It is assumed that intruder decides whether a network is operational or not, based on the energy received from transmitter. One of the methods

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proposed in recent past to achieve LPI is presented in [1], in which case the high-gain scanned patterns are spoiled to get series of low-gain spoiled basis patterns. The spoiled patterns are formed by applying a selected phase shift to each array element. These spoiled beam patterns are coherently combined using complex weights to generate the overall effect of high gain pattern in desired direction. Since the total energy on the target is same hence the detection performance of antenna remains unchanged. These spoiled beam patterns ensure significant reduced peak power in any direction and hence the radar probability of being detected is reduced [1].

In this paper, genetic algorithm (GA) is being proposed to compute the complex weights for synthesizing the high-gain beam using a series of low-gain spoiled patterns. The fitness evaluation function for this algorithm is mean square error which is used to evaluate the error between the desired beam and the synthesized one using set of complex weights. The proposed algorithm is tested for simulated environment containing Additive White Gaussian Noise (AWGN). The proficiency and effectiveness of these schemes are tested on the basis of Monte Carlo simulations.

The rest of the paper is organized as follows: In section-II problem is formulated, section-III discusses the proposed methodology, section-IV is for the simulation results and section V concludes and gives future work direction.

Problem Formulation: Consider a uniform linear array (ULA) having inter-element distance d shown in Figure 1.

The output of ULA is given as:

$$h(\Psi_0) = 1 + e^{j\Psi_0} + e^{j2\Psi_0} + ... + e^{j(N-1)\Psi_0} \tag{1a}$$

Equation (1a) can be written as:

$$h(\Psi_0) = \sum_{n=0}^{N-1} e^{j(n)\Psi_0} \tag{1b}$$

where $\Psi_0 = kd\sin(\theta) - kd\sin(\theta_0)$ and k = $2\pi/\lambda$. The pattern defined in (1) has a high-gain main lobe in the direction of spatial angle θ_0 measured from the broadside of the array and θ is the entire surveillance region vector i.e. [-π/2π/2]. This high gain beam pattern can be scanned throughout

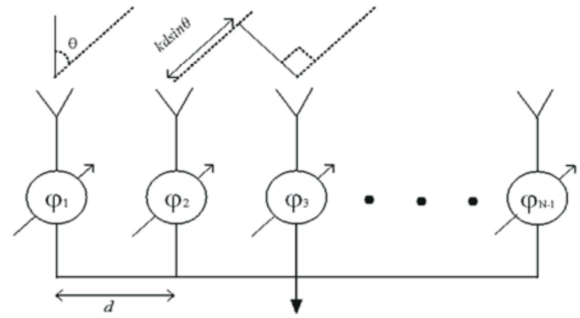

Fig. 1: N-element Phased Array Antenna. φ_n represent the phase shift values for spoiling beam

the search region by applying a linear progressive phase shift across the array. Fundamental phase scan shift is defined as $\gamma = 2\pi/N$.

Defining $\Psi_m = \Psi_0 + m\gamma, m = 0,1,2,...,(N-1)$, the remaining set of N-1 scanned pattern throughout the search region we get:

$$h(\Psi_m) = \sum_{n=0}^{N-1} e^{j(n)\Psi_m}; m = 1,2,...,(N-1) \tag{2}$$

To ensure the LPI property, these high gain scanned pattern are spoiled in a way that their peak power in any particular direction reduces significantly. In [1], quadratic phase variance technique has been introduced to find a set of phase values (φ_n) to defocus the main beam and simultaneously to reduce its gain. The corresponding phase shift values from the set φ_n are applied to each element of array antenna respectively as shown in Fig 1. This set of spoiled beam patterns is defined as set of basis patterns.

These N basis patterns $l(\Psi_m)$; m = 1,2,..,(N-1) are expressed as:

$$\begin{aligned} l(\Psi_0) &= 1 + e^{j\varphi_1}e^{j\Psi_0} + e^{j\varphi_2}e^{j2\Psi_0} + ... + e^{j\varphi_{N-1}}e^{j(N-1)\Psi_0} \\ l(\Psi_1) &= 1 + e^{j\varphi_1}e^{j\Psi_1} + e^{j\varphi_2}e^{j2\Psi_1} + ... + e^{j\varphi_{N-1}}e^{j(N-1)\Psi_1} \\ &\vdots \\ l(\Psi_{N-1}) &= 1 + e^{j\varphi_1}e^{j\Psi_{N-1}} + e^{j\varphi_2}e^{j2\Psi_{N-1}} + ... + e^{j\varphi_{N-1}}e^{j(N-1)\Psi_{N-1}} \end{aligned} \tag{3}$$

These N steered versions of the fundamental beam patterns are linearly independent [1]. The basic objective is to construct the high gain beam pattern with the linear combination of set of these spoiled beams $l(\Psi_m)$, such that $\hat{h}(\Psi_m)$ is closest to $h(\Psi_m)$ in the mean square error sense.

This can be done as follows:

$$\begin{bmatrix} \hat{h}(\Psi_0) \\ \hat{h}(\Psi_1) \\ \vdots \\ \hat{h}(\Psi_{N-1}) \end{bmatrix} = \begin{bmatrix} w_{0,0} & w_{0,1} & \cdots & w_{0,N-1} \\ w_{1,0} & w_{1,1} & \cdots & w_{1,N-1} \\ \vdots & & \ddots & \vdots \\ w_{N-1,0} & w_{N-1,0} & \cdots & w_{N-1,N-1} \end{bmatrix} \begin{bmatrix} l(\Psi_0) \\ l(\Psi_1) \\ \vdots \\ l(\Psi_{N-1}) \end{bmatrix} \tag{4}$$

The problem is how to compute the set of complex weights using genetic algorithm (GA). The set of spoiled beams $l(\Psi_m)$ is represented in vector form as $I_{N\times1}$.We want to generate the high gain beams $h(\Psi_m)$ using the linear combination of these spoiled beams. The vector form of $\hat{h}(\Psi_m)$ and complex weights matrix are denoted by $\hat{\mathbf{h}}_{N\times1}$ and $\mathbf{w}_{N\times N}$ respectively. The equation (4) can be expressed as:

$$\hat{\mathbf{h}} = \mathbf{Wl} \tag{5}$$

MATERIALS AND METHODS

The contest between radars systems and electronic devices that are used to degrade, exploit or effect the radar operations is always there. Active radars have the advantage of high detection rate of target based on the energy transmission. On the contrary, active radars are very likely to be visible to intruders. Therefore, in this respect active radars need to be hidden from intruders in some sense without affecting the detection performance. LPI techniques are used to hide the active radars from intruders. In [1], an LPI technique is used to spoil the phased array antenna beam patterns using the set of phase angles to spread the high-gain beam pattern in the entire search region. Once the spoiled beam patterns are achieved, the linear combination of them is used to synthesize the high gain pattern in the desired direction. The complex weights used for linearly combining the spoiled beams are derived taking the inverse of a matrix [1].

Evolutionary computing techniques have been extensively utilized to solve the problems of array signal processing. GA is a promising candidate of evolutionary computing techniques which is used to find the set of complex weights. A trailered GA hybridized with Pattern Search (PS) is used to derive the complex weights in the presence of AWGN noise. The steps used in implementation of proposed algorithm are summarized below:

Algorithm 1: Genetic Algorithm

Step 1: Generate appropriate number of random units (chromosomes) in which each unit contain unknown parameters (genes). This set of chromosomes is generated between the upper and lower limit suitable for the unknown complex weights.

Step 2: Calculate the fitness of each chromosome using the fitness function.

The fitness function is given as:

$$D_m = (1/M)\times\sum_{i=1}^{M}\left|h_m(i) - y_m(i)\right|^2, m = 0,1,2,...,(N-1)$$

where h_m denotes m^{th} element of the vector h; M= *length* (h_m) and

$$y_m = \sum_{j=0}^{N-1}\mathbf{W}_{m,j}l(\Psi_j)$$

This procedure is repeated for all the rows of the weight matrix. These chromosomes are sorted regarding their fitness values.

Step 3: Crossover operation will produce offspring from the selected set of parents.

Step 4: Generation of new population.

Step 5: Mutation (optional)

When there is no improvement in fitness in generation or problem converges fast, mutation operation is performed.

Step 6: Stopping criteria.

Stopping criterion is prepared, keeping in mind the best possible value a fitness function can achieve. The algorithm terminates when that fitness value stopping criteria or the given number of cycles is reached. Else go to step 3.

GA Hybridized with PS: To improve the results for AWGN scenario, the hybridization of GA with Pattern Search (PS) is very useful. GA hybridized with PS outperforms GA alone.

RESULTS AND DISCUSSION

A linear array with 32 elements is considered (N=32) for evaluation of proposed technique. The inter-element distance is the same for the whole array ($d = \frac{\lambda}{2}$).

Table 1: Settings of the Algorithms

GA		PS	
Parameters	Settings	Parameters	Settings
Population Size	20	Mesh initial size	1.0
Chromosome Size	64	Mesh Maximum size	Inf
Creation function	Uniform	Initial penalty	10
Selection function	Stochastic Uniform	Penalty factor	100
Reproduction crossover frac.	0.6	Bind tolerance	1e-3
Mutation function	Adaptive heuristic	Mesh Tolerance	1e-6
Crossover function	Heuristic	Max iterations	6400
Migration direction	Both	Max Func. Evaluation	128k
Hybrid function	None	Time limit	Inf
No of generations	1000	X tolerance	1e-6
Function tolerance	1e-10	Function Tolerance	1e-6
Nonlinear constraint tolerance	1e-10	Nonlinear constraint tolerance	1e-6

Mean square Error (MSE) between desired and estimated beam patterns is used as fitness function. Simulations are done using the optimtool of MATLAB R2012b. Both cases (i.e. no noise and presence of noise) are taken into account and simulation results show the performance of GA and GA hybridized with PS. Table 1 gives details about parameter setting for GA and PS algorithms.

The gain comparison between high gain beam pattern and spoiled beam pattern is shown in Fig 2. The fundamental ULA beam pattern has high-gain while the processed spoiled beam is defocused and has low-gain.

The defocused and spoiled beam pattern is achieved by adding defined phase shift values (i.e. set of φ_n shown in Fig.1) to each element of ULA. It can be seen that high gain beam pattern has 15dB gain. On the other hand, the spoiled beam pattern has gain of 1.7dB that is significantly lower than that of the fundamental pattern. Other high-gain patterns as well as spoiled low gain basis patterns throughout the search region can be formed by putting on linear phase progression to these fundamental patterns.

Fig. 3 shows the first five spoiled patterns from the set of basis patterns. These patterns have very low-gain and thus ensure the LPI property. Once the spoiled basis patterns are known, the linear combination of these basis pattern can synthesize high-gain pattern in any desired direction.

The performance of GA in the presence, as well as, in the absence of AWGN is discussed below.

CASE 1: No Noise

It is assumed that no AWGN noise disturbs the process of spoiling high gain beam patterns. To insure the LPI property, high gain beam patterns are synthesized in

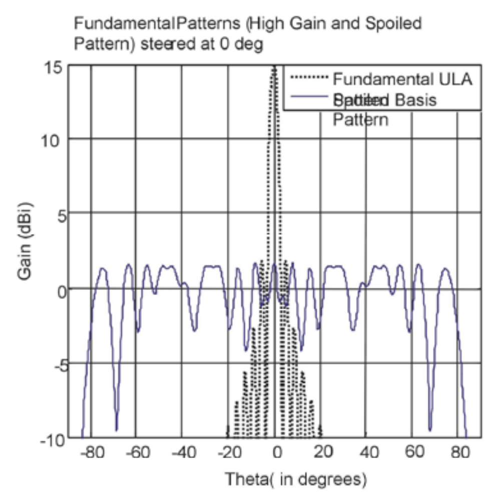

Fig. 1: Comparison between High gain beam pattern and fundamental spoiled beam pattern for a 32-element linear phased array, steered at 0 deg

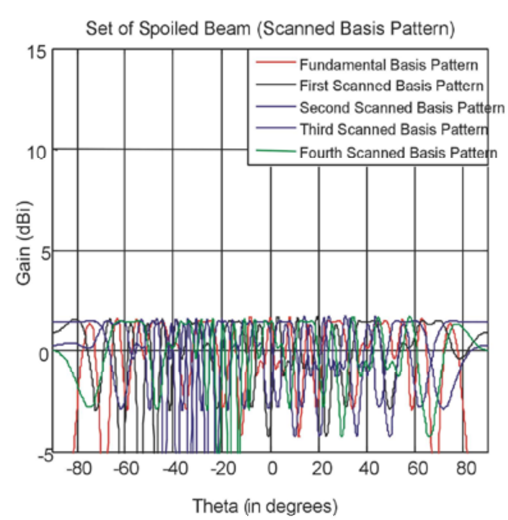

Fig. 2: First five spoiled beam patterns, 5 BASIS PATTERNS

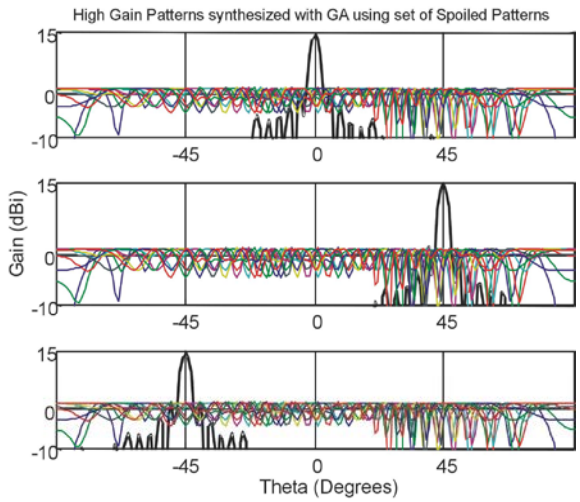

Fig. 3: Synthesis of High Gain Beam by GA steered at 0,-45 and +45 deg respectively.

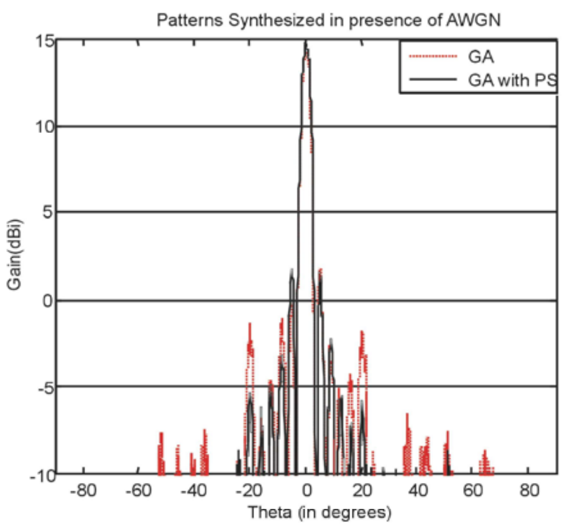

Fig. 4: Comparison between the synthesized beam by GA and Hybridized GA with PS in presence of AWGN Noise

desired direction using linear combination of these spoiled beam patterns. The complex weights, for combining the spoiled beam patterns, are computed using GA algorithm and thus avoiding the inverse of a matrix as used in [1].

Fig. 4 shows the Genetic Algorithm (GA) based synthesized high-gain beam patterns steered at 0°, 45° and -45°. It is vibrant from fig.4 that high gain patterns have the same gain (15dB) in the desired direction as of conventional array antennas as well as the beam formed in [1].

CASE 2: Presence of AWGN

AWGN noise is added to the basis spoiled patterns. It is desired to synthesize a high gain beam pattern in the desired direction with same peak power. To test the performance in this scenario AWGN is added to the spoiled beam patterns ensuring signal to noise ratio (SNR) of 10dB.

Fig. 5 shows the performance comparison between GA and hybridized GA with PS algorithm to synthesize the high gain beam pattern steered at 0°. SNR is 10dB. The hybridized GA with PS algorithm gives better performance than GA. The pattern synthesized by hybridized GA with PS has considerably low side lobes as compared to the GA synthesized beam pattern.

CONCLUSION

In this paper the high gain beam patterns are synthesized by weighted combination of low gain, spoiled pattern. This high gain synthesized beam pattern guarantees the LPI property. The complex weights are calculated using GA algorithm. The performance of GA is tested for no noise as well as the AWGN noise scenarios. The Hybridization of GA algorithm with PS algorithm works better in the presence of AWGN noise. This comes at the cost of enlarged memory and data processing swiftness. In future, other evolutionary computing and swarming techniques can be used for this LPI beamforming application.

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