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Original Article

Cockroach Swarm Optimization for Side Lobe Level Reduction in Linear Array Antenna

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Abstract *- In this work, the cockroach swarm optimization (CSO) technique was investigated for its potential to reduce side lobe levels of an array of linear antennae. This optimization technique is applied for antenna synthesis for the first time by the authors. Variations in the excitation phase, number of elements, and inter-element spacing were also investigated to determine their effects on the antenna's side lobe level (SLL). The objective of this work is to optimize the inter-element distance and the strength of the excitation signal using Cockroach Swarm Optimization. In order to achieve this goal, an objective function was developed for optimizing antenna parameters. MatLab was used to generate the cockroach swarm optimization algorithm. Excitation amplitude, inter-element spacing, and phase are the optimal antenna parameters that were considered. The research findings show that the side lobe level is minimized at an inter-element spacing of 0.5, which is in tandem with results obtained from literature using another analytical and numerical approach. The proposed CSO algorithm achieves peak SLL values of -13.10, -17.26, -24.14, and -28.05 dB for uniform inter-element spacing and excitation phase when 4, 8, 12, and 16 antenna elements are selected, respectively. Minimum HPBW values are 15 degrees, 11 degrees, 9 degrees, and 7 degrees. Not only were side lobes reduced, but the beam's breadth was also drastically reduced by 15%. The beam's diameter was narrowed to show increased directivity while the sidelobe level was decreased. For the number of elements N=16, the SLL is decreased by 1.29 dB, and the HPBW is decreased by 2° compared to particle swarm optimization. In the case of N = 12, reductions of 0.8 dB in SLL and 2° in HPBW are seen. The SLL and HPBW both decrease by 1.29 dB and 2° for N = 16. Also, when N=4, SSL= -17.1, HPBW=15°, N=8, SSL=-19.1 HPBW=12°. The research findings may find application in creating low-processing-burden smart antenna design.*

Keywords *- Array Factor (AF), Cockroach Swarm Optimization (CSO), Directivity, First Null Beam Width (FNBW), Linear antenna array, Side Lobe Level (SLL).*

1. Introduction

An antenna is any device that serves as a transducer for transmitting or receiving electromagnetic waves. In most cases, it can be compared with a radio's sending or receiving capabilities. Single-element antennas have reduced gain and directivity; to obtain a high-gain antenna, a number of individual antenna elements are constructively combined into an array of antennas with a defined geometrical configuration. This, however, increases the signal strength and, thus, the capacity, link quality, and coverage. Most wireless or mobile communication systems are essentially accomplished by employing antenna arrays [1]. There are numerous applications where the radiation pattern of the array, specifically its directivity and side lobe level, must conform to strict standards[2].

In this case, optimizing a trade-off between the two features is essential for real-time application. The improvement of communication systems depends on the reduction of side lobe levels (SLL). One of the most important applications of digital beamforming is that it reduces the effect of interference from sources other than the main lobe. This decrease in interference allows for more signals to be transmitted through the communication system. Some new optimization strategies have emerged that fundamentally differ from the more common mathematical programming methods. The majority of these methods are grounded in the peculiarities and mechanisms of biological, molecular, insect swarm, and neural structures[3]. By employing an optimization objective function, these algorithms can achieve side lobe suppression and null control[4].

Cockroach swarm optimization, simulated annealing, tabu search, microbial algorithms, and particle swarm optimization are all examples of metaheuristic approaches[4], [5] [6]. The Taguchi method and particle swarm optimizers have been applied to antenna arrays' design. Multiple cockroach biological behaviors are imitated in cockroach swarm optimization. These include combining living things and searching for food, relocating nests, treating each individual fairly, etc. It is assumed that the solution that has been searched as the food can divide up some fresh food around the solution's position so that cockroaches can crawl through the solution space and find the best one. Experimental results favor the CSO over particle swarm optimization for other applications. Understanding and determining how cockroach swarm

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optimization can reduce the number of side lobes produced by a linear array antenna becomes fundamentally important.

1.1. Statement of the Problem

In most cases, linear array antennas are deployed because of the inherent flexibility they provide in terms of electronically directing the beam, in addition to the requirement for specialized multi-function radar and other beamforming applications. The side lobe is the problem's primary source, resulting in a waste of energy in an unwanted direction. This paper adopts a scheme that uses cockroach swarm optimization to synthesize linear antenna arrays. It is necessary to state that; this scheme, though in existence, is applied for antenna synthesis by the paper's authors for the first time. An input parameter for the desired pattern of radiation is taken in by the algorithm, which then calculates the excitation coefficients necessary to obtain the required radiation. The optimal element spacing and excitation coefficients will result when this pattern is used in the synthesis scheme. These are the factors that will lead to the greatest possible reduction in side lobe level while using the fewest possible array elements.

1.2. Review of Related Literature

Particle swarm optimization (PSO), ant colony optimization (ACO), and bee colony optimization (BCO) are a few examples of Swarm Intelligence algorithms that have been applied to the study of side lobe optimization. These algorithms, which take their clues from the cooperative nature of insects and other animals, have been shown to be successful at solving global optimization problems in the literature. As seen in [7], the PSO proposed by Kennedy and Eberhart (1995) has been successfully applied to a wide variety of problems (Omar and Cees, 2009). There have been numerous applications of Dorigo's (1992) ACO (Radwan et al., 2011). [8], [9]. BCO was first introduced by Pham et al. in 2005 and then implemented in the real world by [10], [11]. By employing an optimization objective function, these algorithms can achieve side lobe suppression and null control [4]. Such metaheuristic techniques as Genetic Algorithms, Simulated Annealing, Tabu Search, Memetic Algorithms, Cockroach Swarm Optimization, Particle Swarm Optimizers, and the Taguchi technique have all been applied to the design of antenna arrays. Both [12] and [13] used the inter-element spacing, excitation amplitude, and excitation phase of the individual antenna array to investigate the enhancement in performance. This study used Invasive Weed Optimization (IWO [14][16] For antenna arrays with uneven spacing, Ishimaru (2013) suggested an alternative approach using Poisson's Sum formula and redefining the source function. In his study, Sandler (2014) aimed to evaluate the relative merits of symmetrical and asymmetrical arrays. Using a probabilistic approach, Lo (2005) analyzed very large arrays with arbitrary spacing. Some array elements were found to have a strong correlation with the sidelobe level, while the aperture size had only a moderate correlation with directivity.

In a talk, William N. Gwinn (2014) described a phased antenna array with a thinned aperture that can be controlled deterministically. [17], published a minimax-max-min strategy for achieving a Dolph-Chebyshev array-like uniformity of side lobes. Iteratively solving a min-max-max-min problem employs the most up-to-date version of the simplex method from the field of linear programming. Byon Kun Chang, et al. (2016) developed the weighted least square method for optimally thinning antenna arrays.

The cockroach optimization algorithm, which incorporates recent developments in swarm intelligence, is used in this work to optimize the side lobe. Maximum Efficiency through Ant Colony Optimization (CSO), individual antenna elements are constructively combined into an array of antennas with a defined geometrical configuration. This, however, increases the signal strength and, thus, the capacity, link quality, and coverage. Most wireless or mobile communication systems are essentially accomplished by employing antenna arrays (Panduro, 2005). There are numerous applications where the radiation pattern of the array, specifically its directivity and side lobe level, must conform to strict standards (Guney et al., 2007).

This case is where optimizing a trade-off between the two features is essential for real-time application. The improvement of communication systems depends on the reduction of side lobe levels (SLL). One of the most important applications of digital beamforming is that it reduces the effect of interference from sources other than the main lobe. This decrease in interference allows for more signals to be transmitted through the communication system. Some new optimization strategies have emerged that fundamentally differ from the more common mathematical programming methods. The majority of these methods are grounded in the peculiarities and mechanisms of biological, molecular, insect swarm, and neural structures (Rao, 2009). By employing an optimization objective function, these algorithms can achieve side lobe suppression and null control (Khodier, 2005).

Cockroach swarm optimization, simulated annealing, tabu search, microbial algorithms, and particle swarm optimization are all examples of metaheuristic approaches (Asianuba & Nzeako, 2017). The Taguchi method and particle swarm optimizers have been applied to antenna arrays' design. Multiple cockroach biological behaviors are imitated in cockroach swarm optimization. These include combining living things and searching for food, relocating nests, treating each individual fairly, and so on. It is assumed that the solution that has been searched as the food can divide up some fresh food around the solution's position so that cockroaches can crawl through the solution space and find the best one. Experimental results favor the CSO over particle swarm optimization for other applications. Understanding and determining how cockroach swarm optimization can reduce the number of side lobes produced by a linear array antenna becomes fundamentally important.

2. Method for Cockroach Swarm Optimization (CSO)

1. Give the cockroaches a random starting location and speed:
   Each particle enters the solution space at a different random position, with a different random velocity in the same direction and of the same magnitude, to begin the search for the (Cockroach individual optimal) Pi.
2. Methodically reposition the cockroach throughout the space of possible solutions:
   Next, scatter the cockroaches throughout the entire area where the problem exists as though they were a swarm. The program individually manipulates each cockroach in the swarm as it cycles through them all.

These steps are performed separately on each cockroach:

(a) Evaluate the cockroach's fitness relative to Pg and Pi (global and local optimums, respectively). An appropriate fitness value for the cockroach's current location is provided by the fitness function in the solution space. The correct location is substituted for the current one if the value is higher than the value at the relevant Pi for that cockroach or the Pg.

(b) The cockroach's velocity must be tweaked, a fundamental part of the overall optimization. The cockroach's velocity varies with the positions of Pi and Pg. It travels more quicker in the direction of these optimal locations.

INPUT: Fitness function:(x), $x \in RD$
set parameters and generate an initial population of cockroach
set $pg = x1$
for i=2 to N **do**
  if $f(xi) < f(pg)$ **then**
    $pg = xi$
  end if
end for
for t=1 to Tmax **do**
  for i=1 to N **do**
    for j=1 to N **do**
      if abs$(xi - xj)$ < visual; $f(xj) < f(xi)$ **then**
        $pi = xi$
      end if
    end for
    if $pi == xi$ **then**
$xi = w \cdot xi$ + step · rand · $(pg - xi)$
    else
      $xi = w \cdot xi$ + step · rand · $(pi - xi)$
    end if
    if $f(xi) < f(pg)$ **then**
      $pg = xi$
    end if
  end for
  if Hunger == $t$hunger **then**
    $xi = xi + (xi - ct) + x$fd)
    hunger$i$ = 0
    Increment hunger$i$ counters
  end if
  for i=1 to N **do**
    $xi = xi$ + rand(1, D)
    if $f(xi) < f(pg)$ **then**
      $pg = xi$
    end if
  end for
  k = randint([1, N])
  $xk = pg$;
end for
Check termination condition

An improved cockroach swarm optimization algorithm

2.1. Localizing Cockroach Swarm Optimization (CSO) to Antenna Array

Cockroach swarm optimization (CSO) is a global optimization method that uses a population approach to solving problems. It is based on research into how cockroaches behave when they are hungry. Researchers are very interested in how they get their nourishment. The entire concept of "hunting" is incidental food discovery made easier by using established pathways acquired through expertise. The CSO method takes advantage of various cockroach behaviors, including: a. moving in swarms to represent the various array elements; b. scattering or running away from the light symbolizes finding an element configuration that best suits the antenna for optimum performance.

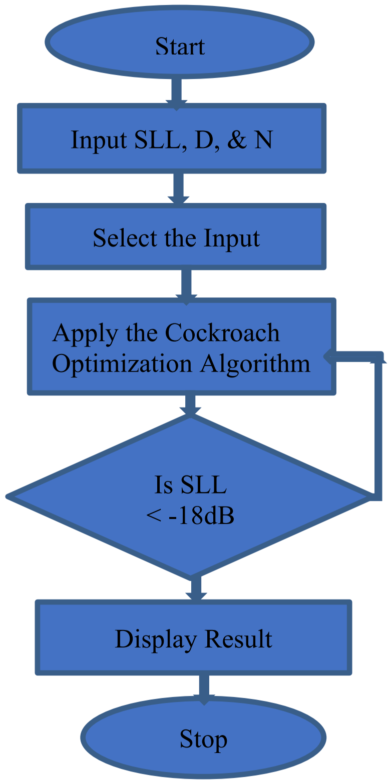

Fig. 2 Cockroach swarm optimization flowchart in its most rudimentary form

The demand for ideal antenna element spacing is represented by ruthless behavior.

It also needs a stopping standard; when the ideal antenna spacing and element count have been achieved, the standard has been satisfied. The prevention of circumstances that the algorithm stores in a local optimum are the reason scattering or escape from the light (the symbolizes looking for a condition of elements that suits the antenna best for optimal performance) is particularly important.

2.2. Linear Antenna Array (LAA)

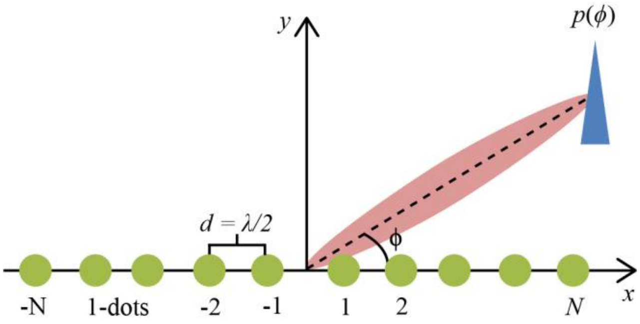

Fig. 3 Geometry of 2N-element-symmetric LAA placed along the x-axis

Figure 3 depicts a linear antenna array (LAA) with 2N elements arranged symmetrically along the x-axis.

Each part of the LAA is assumed to be an isotropic radiator. With the help of the superposition principle of electromagnetic waves, the AF of a linear antenna array can be expressed as follows:

$$AF(\emptyset) = \sum_{n=-N}^{N} \quad I_n cos\ [kx_n\ cos\ cos\ (\emptyset)\ + \varphi_n] \qquad (1)$$

Given a certain wavenumber k, I_n denotes the nth element's excitation current, φ_n denotes its phase, X_n denotes its position and $\emptyset$ denotes the azimuth angle from the positive x-axis.

2.3. Objective Function Definition

Equations 2 and 3 pertain to the beam width stated as the first null bandwidth, respectively. The optimization problem in this study is considered a minimization problem where the SLL has to be minimized (FNBW). Consequently, the expressions listed below are correct.

$$J = \{\{20\ log\ log\ |AF(\theta)|\ \}\} \qquad (2)$$

$$J = W_1[(SLL_i - SLL_0)] + W_2[(HPBW_i - HPBW_0)] \qquad (3)$$

According to the array pattern parameters, FN is the first null in degrees, SLL_i and SLL are the intended and computed values of the SLL, respectively, and $HPBW_i$ and $HPBW_0$ are the desired and computed values of the HPBW. The objectives for the thinning array are the intended values; W_1 and W_2 are significant weights used to regulate each component's relative relevance in Equation 3. The choice of $W_1 > W_1$ is made because minimizing SLL is the main objective.

3. Results and Discussion

The cockroach optimization algorithm is implemented using the MATLAB R2021a program. First null beam width (FNBW) and side lobe level (SLL) optimization for different element counts and spacing in an array produces the desired results.

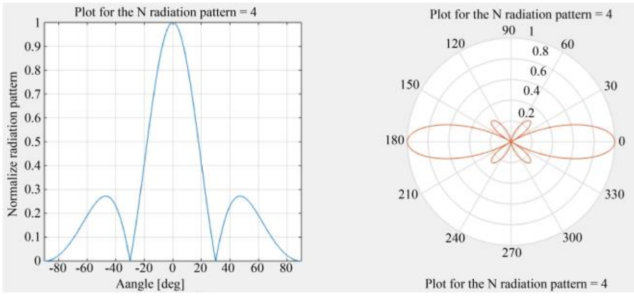

Fig. 4 Radiation Pattern for 4 Numbers of Elements

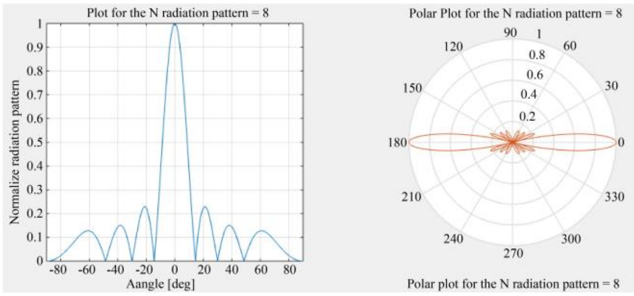

Fig. 5 Radiation Pattern for 8 Numbers of Elements

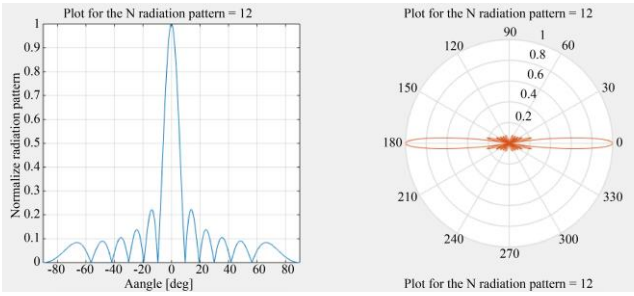

Fig. 6 Radiation Pattern for 12 Numbers of Elements

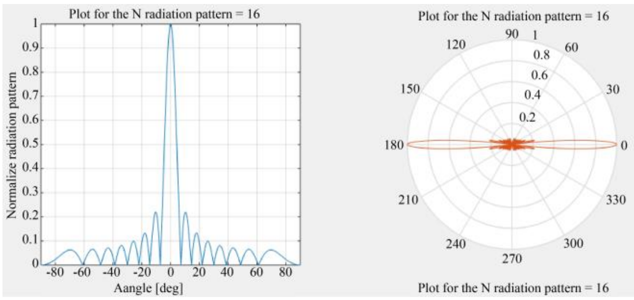

Fig. 7 Radiation Pattern for 16 Numbers of Elements

Table 1. Optimized Values for Excitation Amplitude with Fixed Spacing and Phase

Amplitude	N equals 16	N equals 12	N equals 8	N equals 4
a1	0.2127	0.3087	0.3881	0.3087
a2	0.2287	0.3938	0.4097	0.2287
a3	0.3606	0.4444	0.6289	0.3606
a4	0.3606	0.4444	0.6289	0.3606
a5	0.3606	0.5530	0.6322	0.3606
a6	0.5198	0.7159	0.6778	0.5198
a7	0.5627	0.7115	0.6008	
a8	0.6373	0.7725	0.6012	
a9	0.6496	0.6733	0.4768	
a10	0.7127	0.6166	0.5620	
A11	0.7088	0.5146	0.2291	
a12	0.5694	0.3158		
a13	0.5113	0.3113		
a13	0.4545	0.3158		
a14	0.2761	0.3113		
a15	0.2228			
a16	0.1693			
a13	0.4545			

Table 2. Results of Optimized Inter-element Spacing Compared with PSO (Saeed et al., 2017)

Algorithm Used	Cockroach Swarm Optimization				Particle Swarm Optimization (Saeed et al., 2017)		
Number of elements	4	8	12	16	10	12	16
SLL	-17.10	-19.10	-25.09	-29.58	-17.26	-24.14	-28.05
HPBW	15	12	7	5	11	9	7

Table 2 provides the optimal inter-element spacing values, and Results from various spacing distances between elements are compared in Table 3. By increasing N to 16, we discovered that the HPBW could be minimized to within 5° and the SLL could be reduced to within -29.08 dB. Contrast this with the results achieved by Saeed et al. (2017), who used particle swarm optimization to decrease the SLL by 1.53 dB and the HPBW by 2.0°.

3.2. Optimization of Excitation Amplitude and Inter-element Spacing

The excitation amplitude and inter-element spacing are both optimized using the Cockroach Swarm Optimization technique**.** By applying the fitness function given by equation 1, we can determine the optimal amplitude and position to minimize the SLL and the HPBW. Tables 3 and 4 show results when comparing particle swarm optimization, used by Saeed et al. (2017)., to the original study's N values of 12, 16, 8, and 4.

Table 3. Optimized Values for Spacing with Fixed Excitation Amplitude and Phase.

Distance	N=16	N=12	N=8	N=4
d1	0.7751	0.7141	0.7011	0.6000
d2	0.8043	0.7050	0.5221	0.5421
d3	0.6268	0.5386	0.4384	0.4484
d4	0.5286	0.5143	0.4200	0.4133
d5	0.5120	0.4010	0.4680	0.4580
d6	0.4044	0.5018	0.4230	0.5926
d7	0.4167	0.6236	0.4123	
d8	0.4064	0.7118	0.6222	
d9	0.4900	0.8274		
d10	0.5084	0.5958		
d11	0.4631			
d12	0.7018			
d13	0.7416			

Table 4. Results of optimization of excitation amplitude and Inter-element Spacing Compared with PSO (Saeed et al., 2017)

Algorithm Used	Cockroach Swarm Optimization				Particle Swarm Optimization (Saeed et al., 2017)	
N	4	8	12	16	12	16
SLL	-17.1	-19.1	-29.09	-32.58	-28.29	-31.29
HPBW	15	12	7	5	9	7

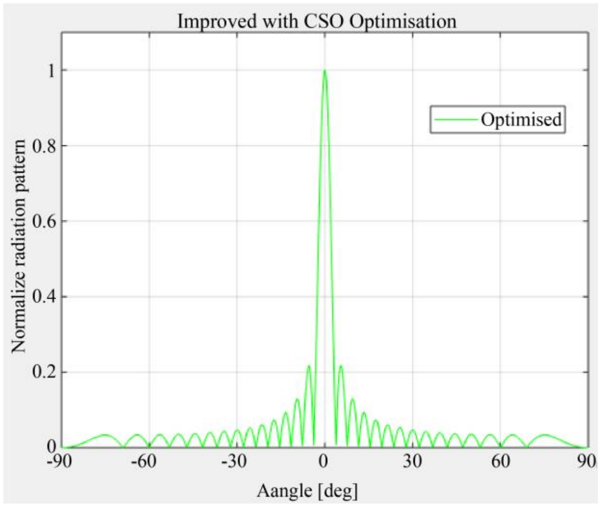

Fig. 8 The optimized normalized beam form

Table 4 depicts that when N equals 16 is used, the SLL is reduced by 1.29 dB, and the HPBW is reduced by 2° compared to PSO, while when N equals 12 is used, the SLL is improved by 0.8 dB, and the HPBW is improved by 2°.

3.3. Parametric Shifts in Linear Arrays of Antennas

For the i-th element, we can see how the excitation amplitude, inter-element separation, and excitation phase can be altered. The effects of these factors on an optimal design have been analyzed using a MATLAB procedure based on Equation 2, and the array factor has been plotted as a function of various control parameters in the figures above. In this study, the array's element count was modified to produce a more directed beam.

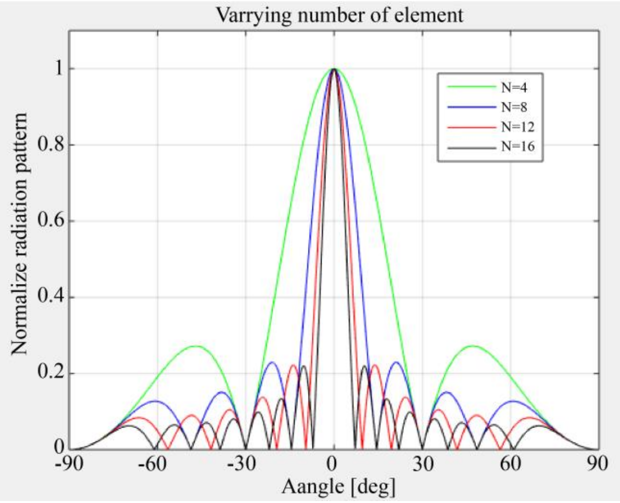

Fig. 9 Radiation Pattern Varying Numbers of Elements

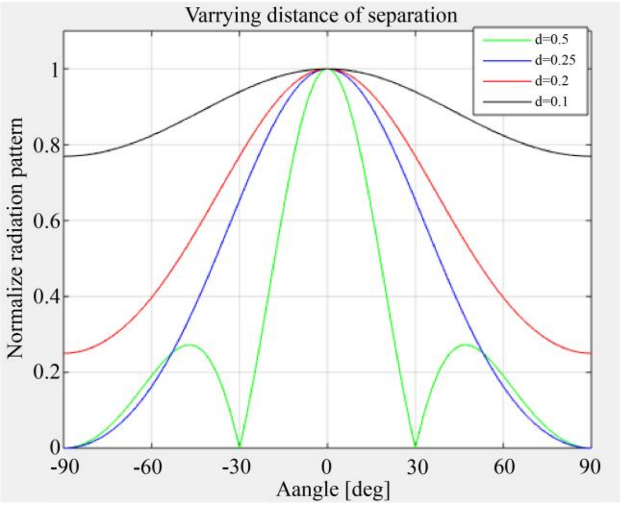

Fig. 10 Radiation Pattern for Varying Distance Separation of Elements

In the legends of Figures 9, 10, 11, and 12, N represents the total number of antenna elements in an array, d represents the distance between adjacent antenna elements, and phase represents the direction in which the antenna is excited. By increasing the number of arrays for each antenna element from 4 to 16 while keeping the distance between the elements at 0.5 dB, side lobe levels and the width of the initial null beam were reduced. Increases in pattern directivity are shown as the number of elements in an array grows (see Figure 9). By increasing the distance between arrays of an antenna element by a factor of 0.1 from 0.1 to 0.5 while keeping the total number of array elements at 16, the first null beam width and the side lobe levels were reduced (see Figure 10). The results show that its pattern directivity grows as more elements are added to the array. Figures 11 and 12 show the results of varying the excitation phase from 0 to 30, 60, and 80 degrees, using an array size of 16 elements and a spacing of 0.5. The polar version of Figure 11 is shown in Figure 12. It was determined that the beam width is unaffected, and the amount of side lobes is also consistent.

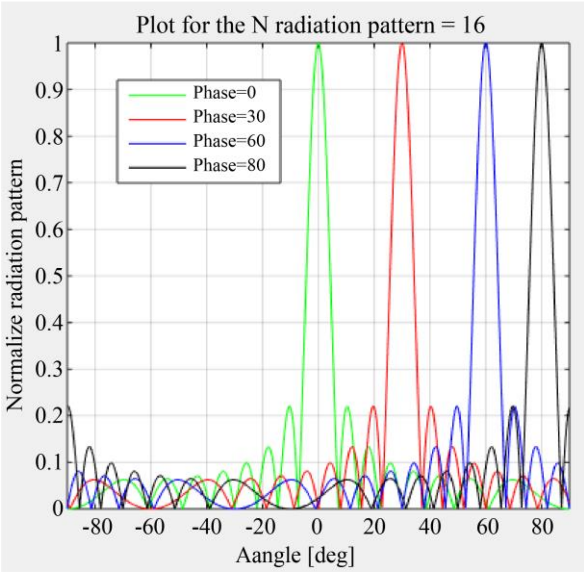

Fig. 11 Radiation Pattern for Varying Excitation Phase

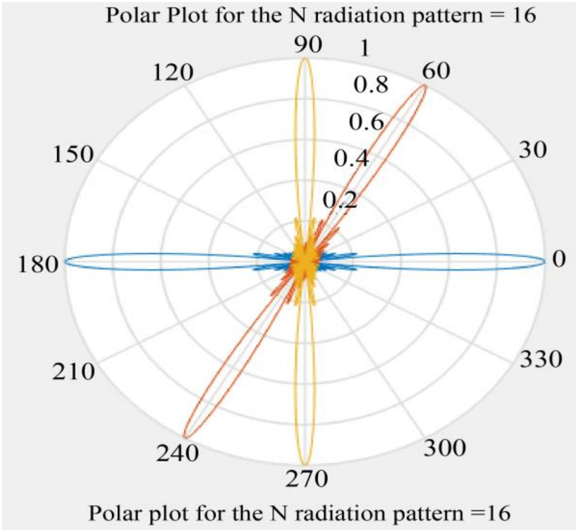

Fig. 12 Polar Radiation Pattern for Varying Excitation Phase

4. Conclusion

In wireless communication, antenna optimization is a major step in the right direction. The Cockroach Swarm Optimization algorithm can wonderfully serve this objective. The term "optimization" refers to the process of designing and running a system or process to achieve the best possible results in a given set of criteria. Cockroach swarm optimization was successfully applied to the study of optimizing a linear array antenna, and the results were analyzed with the help of MATLAB/Simulink. The study results show that the situation has greatly improved with Cockroach Swarm Optimization.

The objective is to boost capacity while keeping or even improving network quality. When considering larger datasets, it becomes clear that the sidelobe level has been suppressed even further. The proposed CSO algorithm achieves peak SLL values of -13.10, -17.26, -24.14, and -28.05 dB for uniform inter-element spacing and excitation phase when 4, 8, 12, and 16 antenna elements are selected, respectively. Minimum HPBW values are 15 degrees, 11 degrees, 9 degrees, and 7 degrees. Figure.8 and Table 4 show that the HPBW dramatically improves, and the SLL is greatly reduced as the number of elements increases.
Our findings from the simulation study support the following hypotheses:

1. As the number of arrays in a linear array antenna grows from 4 to 16, the antenna can concentrate the signal beam in the direction of the source of the signal.
2. A linear array antenna can outperform a single-element antenna because its gain is equal to the sum of the gains of its individual elements.
3. When the number of arrays is held constant, and the distance between them is varied for 0.1, 0.5, and 1 times the wavelength, it was found that antenna elements spaced at half the wavelength (0.5) performed the best. When the distance between elements is either less than half the wavelength or greater than twice the wavelength, the bit error ratio and the grating lobe are both inflated. It is recommended that research be conducted to develop this product into a prototype to bring the work to life. This outcome is in tandem with other approved linear array synthesis approaches. The paper recommends using an AI algorithm to increase the smartness of the antenna in future research

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