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ORIGINAL RESEARCH ARTICLE

OPTIMIZING ENERGY UTILIZATION IN UNEQUALLY SPACED LINEAR ARRAY FOR SMART ANTENNA

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ABSTRACT

Radiation in the form of unwanted patterns, energy wastage and reduction is caused by high side lobe levels in a radiation pattern. This, in turn, affects the overall performance of the antenna. The purpose of this work is to improve the performance of a smart antenna by optimizing the radiation pattern using the genetic algorithm. Optimal antenna parameters that would minimize side lobe level were obtained using genetic algorithm. Simulations were carried out to determine the impact of the increase in inter-element spacing on array factor and beamwidth using the optimal antenna parameters. The optimal arrangement of inter-element spacing and number of elements in unequally spaced antenna elements were then considered. The array factor model for a uniform linear array of elements was used to obtain the optimum weights that would give the desired radiation pattern with reduced side lobe level. Results for the unequally spaced linear arrays revealed that non-tapered arrangement among all the possible configurations gave the best improvement in the side lobe level. The outcome of this improvement is an optimized radiation pattern which is expected to aid the reduction of radiated power wasted in the side lobes of linear arrays in antenna systems.

1.0 Introduction

Antenna arrays are widely used in wireless communications. An antenna with higher directivity and lower Side Lobe Level (SLL) is usually preferred. In an antenna radiation pattern, nulls are directed towards interfering signals while the main beam is pointed towards signals-of-interest. A single element antenna has limited performance. Thus, antenna arrays are used to achieve low side lobes, narrower beamwidth, gain and higher directivity (Balanis, 2016). An antenna array consists of radiating elements of an antenna connected electrically and geometrically. The radiation pattern of an antenna array is formed by the contribution of the pattern of each element. Several variables could be used to determine the general radiation pattern of an antenna array. These include the geometrical configuration of the array, the relative displacement between elements, excitation amplitude of individual elements, excitation phase of individual elements, and relative pattern of the individual elements (Lakshmi and Raju, 2011). In the wireless communication systems, the purpose of using array antennas is to separate the desired signal from unwanted interferences.

It is usually desired in the antenna arrays that the height of side lobes be kept low to optimize energy utilized. But the level of the side lobes in a normal radiation pattern is usually high thereby causing unwanted radiation in undesired patterns, energy wastage and reduction in the overall performance of the antenna. Lower side lobe antenna arrays are becoming increasingly important. It is, therefore, necessary to discover faster and more reliable methods at arriving at the optimum solution to support the development of high-performance components in electronic communication systems, particularly those in complex environments. This motivates the simulation of the antenna radiation pattern carried out in this research work using unequally spaced linear array elements to optimize the performance of smart antennas.

The research aims to improve the performance of an unequally spaced linear array antenna by optimizing the energy utilized in the radiation pattern. The following are the specific objectives that helped achieve this aim: determining the optimal inter-element spacing, arrangements and the number of elements in an unequally spaced linear antenna array. The scope is limited to unequally spaced linear arrays in antenna systems and particularly focused on the reduction of radiated power wasted in the side lobes.

Review of Literature on Arrays

Sanchez, Covarrubias-Rosales and Panduro, (2009) used Legendre functions for the optimization of linear and planar arrays. This produced some reduction in the side lobe level, half-power beam width as well as a better directivity for non-uniform linear and planar arrays than in the uniform ones. Kumar and Branner, (1999) used a simple inversion algorithm to determine the inter-element spacing in linear arrays. The work revealed some improvement in unequally spaced linear array compared to an equally spaced array with the same number of elements. In Abdullah et al. (2012), a combination of Method of Moments (MoM) and Genetic Algorithm (GA) was used for linear antenna arrays to obtain a maximum side lobe level reduction. Side lobe level reduction was achieved with a reduced number of antenna elements while keeping the main lobe beamwidth intact.

Maharimi et al. (2012) showed the effect of spacing and number of elements on gain and half-power beamwidth (HPBW). The study showed an increase in the H PBW and the number of side lobes as the inter-element spacing increased while the gain remained the same. However, there was an increase in gain with an increasing number of elements. Further work was done on the unequal spacing technique to reduce the side lobe level and the number of elements of a linear antenna array. The paper showed that an unequally spaced antenna with a lower number of elements produced better side lobe level, same half-power beamwidth and similar antenna gain when compared with an equally spaced antenna with little more elements than it. Some years after, Mahmoud (2016) synthesized unequally-spaced linear array using modified central force optimization (CFO). The modification of the CFO algorithm was based on the concept of combining the social thinking value of particle swarm optimization with the original CFO search pattern and some time-varying acceleration coefficients. The outcome produced minimal side lobe levels but the computational complexity of the algorithm compared to other optimization techniques was not reviewed.

Gangwar, Singh and Singh (2017) considered computational efficiency of a new approach for the synthesis of a uniformly excited unequally spaced linear antenna. An inertia-weight particle swarm optimization technique was utilized. Numerical analyses were carried out on 16- and 32-element linear arrays and results revealed outstanding results. The results showed that simpler methods to accomplish optimized results can still be further achieved. Liu et al. (2017)

proceeded with improvement by utilizing a virtual active element pattern (AEP) expansion method for the synthesis of the unequally spaced array. Fast Fourier Transform was utilized for iterative processing which led to the development of a novel iterative synthesis method. You et al. (2017) utilized another method of synthesizing unequally spaced linear arrays using convex optimization. The excitation vector and auxiliary weighting vector are alternately selected as optimization variables in the study. The results also contributed to improvements in beamforming and side lobe level reduction.

Sudhakar and Ravindranadh (2017) focused on obtaining the desired shaped beam array by using Woodward synthesis technique. This was accomplished by acquiring the required amplitude distribution that would produce the desired beam shapes. This worked well for larger arrays, but there were deviations from the desired shape for small arrays. Simultaneous adaptive processing was also carried out at multiple frequencies using one type of antenna array by Salama et al. (2017) and Salama (2019). The antenna used, consisting of a dissimilar antenna with nonuniformly spaced elements which were deployed above an imperfect ground plane. The outcome of these was an effective design which was robust to interferers from multiple directions and frequencies, which could be non-coherent. However, the focus of these studies was not on energy optimization.

Li et al. (2018) made the effort of simulating patch antenna arrays by Ansys HFSS software for the design of a 15.5 **λλ** linear array. Genetic algorithm was also used but for one specific form of configuration. Another study by Singh and Salgotra (2018) utilized an enhanced version of Firefly algorithm to provide a better solution at a fast rate. Partial Element Equivalent Circuit (PEEC) approach was employed by Moreno et al. (2019) using a new nature-inspired Cheetah metaheuristic. Miranda et al. (2018) utilized PSO algorithms for the Antenna Pattern Synthesis, while Singh and Salgotra (2018) used the flower pollination algorithm. All these algorithms contributed to the optimal design of antennas with non-uniform spacing between the array elements. However, only specific configurations were used. While acknowledging all the contributions made, the current paper builds on these research efforts by exploring various configurations for the unequally spaced linear array to optimize energy consumption through the reduction of sidelobe level.

2.0 Methods

Linear arrays consist of radiating elements spaced in a straight line. The radiation pattern of the array is a weighted sum of radiating elements' patterns and its directivity is achieved by changing the weight coefficients that are calculated using an adaptive algorithm. The unequally spaced symmetrical arrangement can be classified into space-tapered (ST) arrays and non-tapered (NT) arrays (Tan et al., 2010). The inter-element spacing increases from the centre of the array towards the end for the space-tapered arrangement (Figure 1). However, the inter-element spacing decreases from the centre of the array towards the end for non-tapered arrangement (Figure 2) (Maharimi et al., 2012).

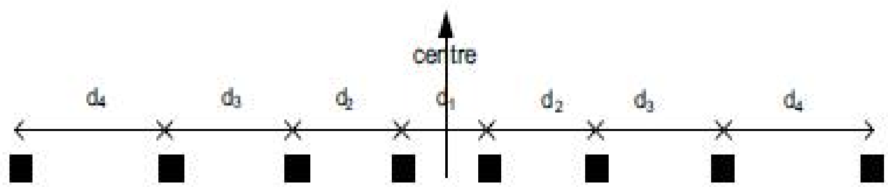

Figure 1: Symmetric Unequal Spacing Arrangement

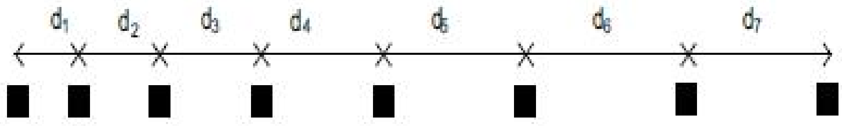

Figure 2: Asymmetric Unequal Spacing Arrangement

The array factor for a uniform linear array of N elements with an inter-element spacing d is given by Eqn. 1 (Balanis, 2016):

$$AF(\theta) = \sum_{n=1}^{N} I_n e^{j(n-1)kd\cos\theta} = \sum_{n=1}^{N} I_n\, e^{j(n-1)\varphi} \quad (1)$$

where:

In is the excitation of the element n.

k is the wave number.

d is the spacing between the elements.

Letting:

$$z = x + jy = e^{j\varphi} = e^{j(kd\cos\theta)} \quad (2)$$

Expanding and rearranging (1) gives Eqn. 3

$$AF(\theta) = \sum_{n=1}^{N} a_n z^{n-1} \quad (3)$$

The goal of the optimization process is to achieve a reduced side lobe level of the radiation pattern and a narrow main beamwidth. Hence, the problem formulated is aimed at obtaining the optimum weights that give a radiation pattern with reduced Side Lobe Level (SLL) (Balanis, 2016). This objective is achieved by Eqn. 4(Balanis, 2016)

$$\min SLL = 20\log\left(\frac{abs(AF_i)}{\sum_{j=1}^{N} abs(AF_j)}\right) \quad (4)$$

where: AFi = contribution of element i to array factor AF(θ)

Subject to:

$$a_n z^{n-1} \leq z^{n-1} \forall\, 1 \leq n \leq N$$
$$0.5\lambda \leq d \leq \lambda$$
$$\theta \leq 90°$$
$$a_n \geq 0 \quad \forall\, 1 \leq n \leq N$$

2.1 Simulation of Methods

A linear array of antennas with unequal inter-element spacing and N elements in the array was considered. A specific Signal-to-Noise Ratio (SNR) of 20dB is used and the noise is Gaussian and independent from one antenna to the next. The distances for an unequal spaced linear array of an antenna with N-element are non-uniform in the arrangement. The configurations were arranged using the symmetrical and asymmetrical arrangement. These configurations were simulated using MATLAB. Optimization toolbox with ga-Genetic Algorithm solver in MATLAB was used in the experiments for all the possible types of unequal inter-element spacing arrangements. The effects of different unequal inter-element spacing on the side lobe level and beamwidth were investigated.

Genetic Algorithm (GA) is a biologically inspired optimization method using the principle of evolution. The use of GA started in the 1970s in Holland. However, it became widely known after Goldberg's research (Grajeda, 2011; Laseetha and Sukanesh, 2011). GA comprises a set of individuals called population. These individuals are called chromosomes and each individual is represented by binary strings of 0s and 1s. Each individual is a point and possible solution in the solution space. The next generation is selected based on a fitness function which gives higher values for fitter chromosomes. Afterwards, two random pairs are taken for reproduction. In reproduction, crossover and mutation take place to give better offspring from the parent generation. Genetic algorithm helps solve non-linear multivariable problems.

Genetic Algorithm was used to obtain optimal weights for each antenna element using symmetric and asymmetric spacing for the different number of elements and a small increase in inter-element spacing (lambda). Using GA helped to get the best combination of inter elements which would give rise to a lower array factor thereby producing a much lower level in the side lobes.

3.0 Results and Discussion

Having obtained the optimal inter-element distances which indicated an interval of about 0.04λ, the arrangement of these distances was then put into consideration. The number of elements considered for this work was 18 and 20 elements. GA is used to optimize the weights obtainable for each antenna element. The results, which are shown in Figures 3-8 show the array factor versus the angle of arrival of the signal for the various spacing arrangements, are presented in the following subsections.

3.1 Asymmetric Element Arrangement

This arrangement is as explained earlier where the inter elements spacing are arranged in ascending or descending order. The simulation was carried out with the simulation parameters earlier highlighted as well as the optimal array factor, weights and optimal inter-element spacing obtained through genetic algorithm. The radiation pattern using the asymmetric arrangement for 18 and 20 elements is as shown in Figure 3 and Figure 4 respectively.

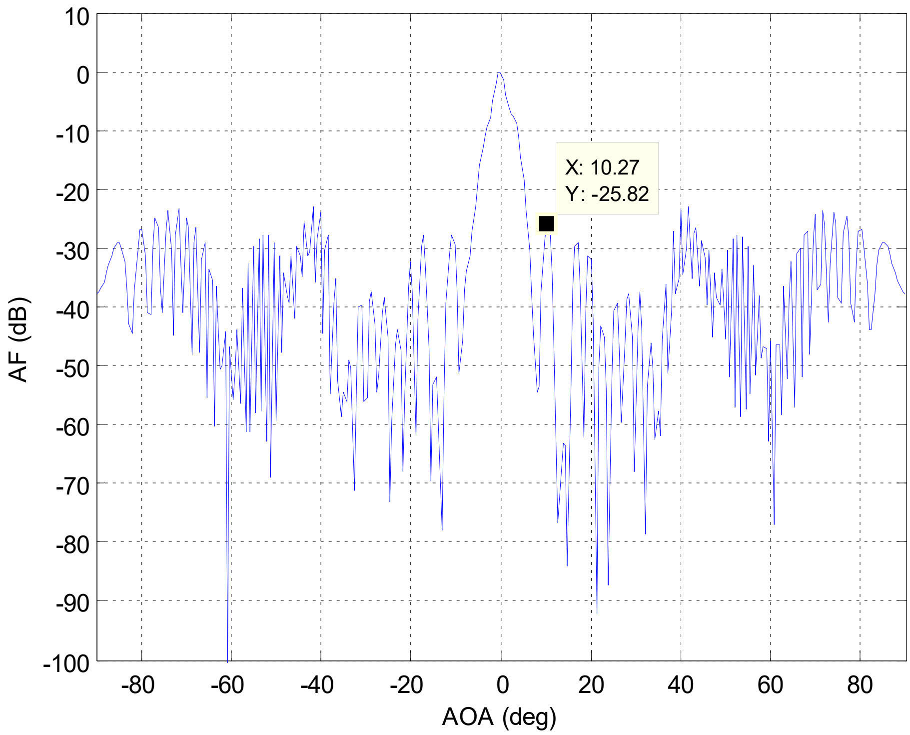

Figure 3: Radiation Pattern for 18 elements using the asymmetric arrangement

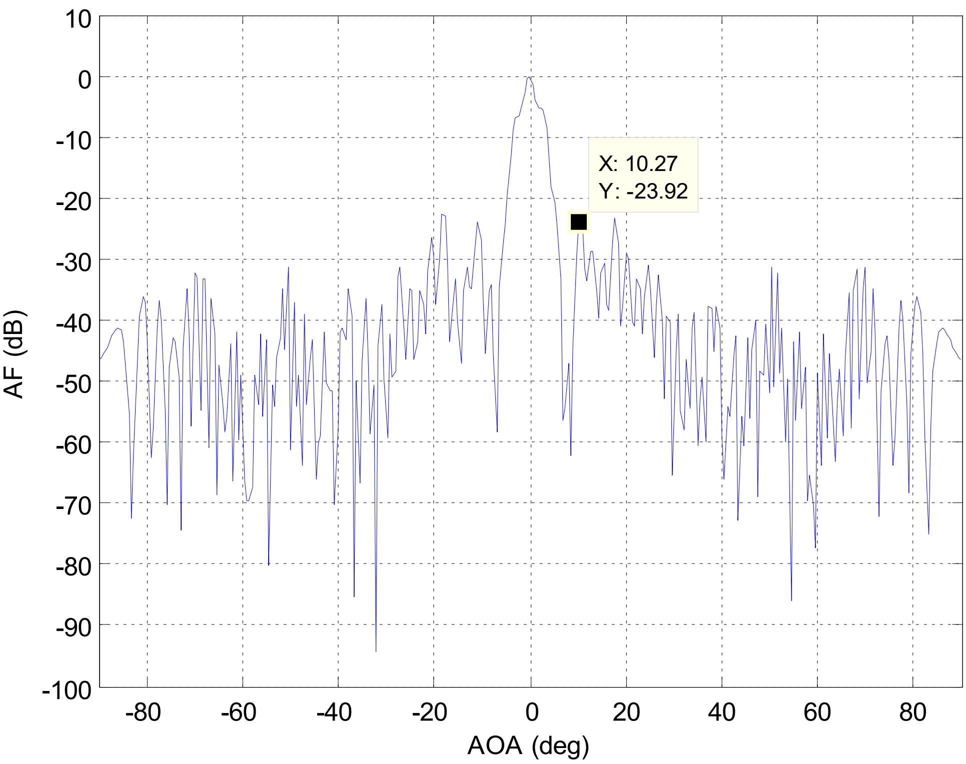

Figure 4: Radiation Pattern for 20 elements using the asymmetric arrangement

The results shown in Figures 3 and 4 are the radiation patterns obtained for 18 and 20 elements respectively using asymmetric spacing arrangement. It can be observed from the results that the side lobe level was about 25.8dB which is not as low as the results obtained when experiments were conducted with equally spaced antenna elements. The side lobes for the asymmetric spacing were also not as well spread when compared to the pattern obtained with equally spaced antenna elements. This arrangement is therefore not recommended.

3.2 Space-Tapered Element Arrangement

Space-Tapered is a symmetric arrangement where the unequal distances spread out from the centre. Simulations for this arrangement was done using similar parameters as in the asymmetric arrangement based on optimum array factor, weights and inter-element spacing obtained after the use of genetic algorithm The results obtained especially for the 18 and 20 elements were different from the asymmetric results as clearly seen and presented as shown in Figures 5 and 6 respectively.

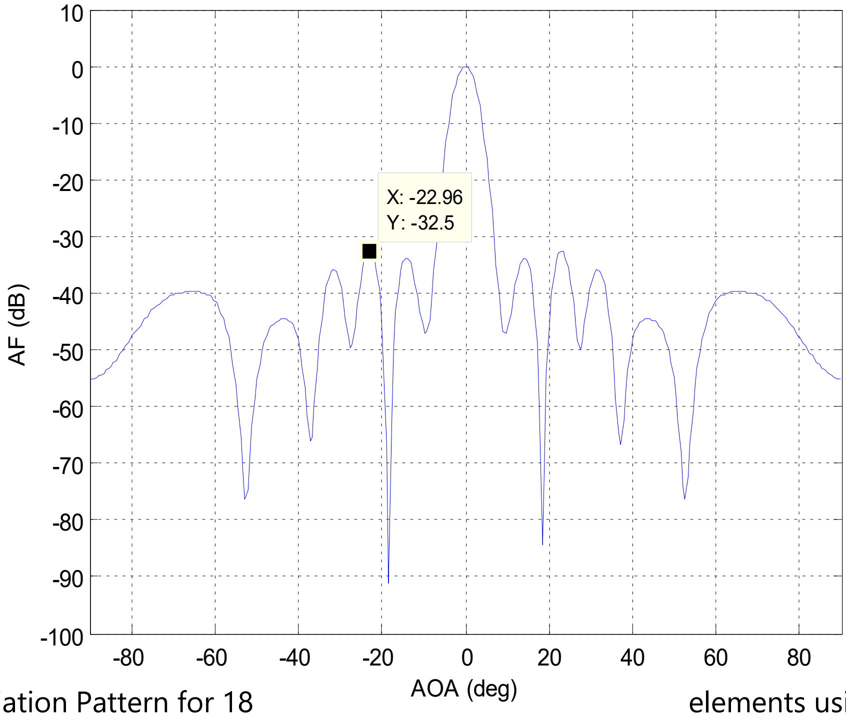

Figure 5: Radiation Pattern for 18 elements using the space-tapered arrangement

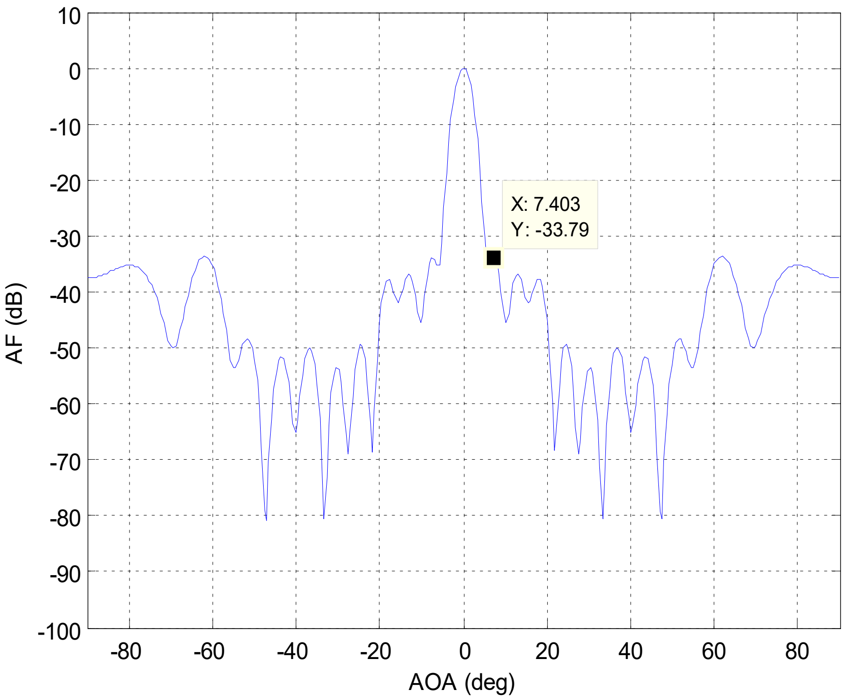

Figure 6: Radiation Pattern for 20 elements using the space-tapered arrangement

The results presented in Figures 5 and 6 depict the observations made when the inter-element spacing was arranged in space-tapered order for 18 and 20 elements respectively. It is noted that the side lobe level reduced significantly beyond the level where the equally spaced antenna elements reached. This value (-33.79dB) indicated a significant improvement compared to the value obtained when equal inter-element spacing was used. The beamwidth also reduced to about 12° which was lower than that of equally spaced antennas. Another significant observation made was the fact the side lobes were well laid out contrary to the irregular layout observed when the asymmetric arrangement was utilized.

3.3 Non-Tapered Element Arrangement

This is another form of symmetric arrangement where the inter-element spacing decreases outwards from the centre. The parameters used in this simulation were similar to that used to produce the results in Figures 3-6 except for the arrangement pattern. The significant changes occurred when the elements were increased to 18 elements. The results presented, therefore, are for 18 and 20 elements. This form of arrangement gave significant results as shown in Figures 7 and 8 respectively.

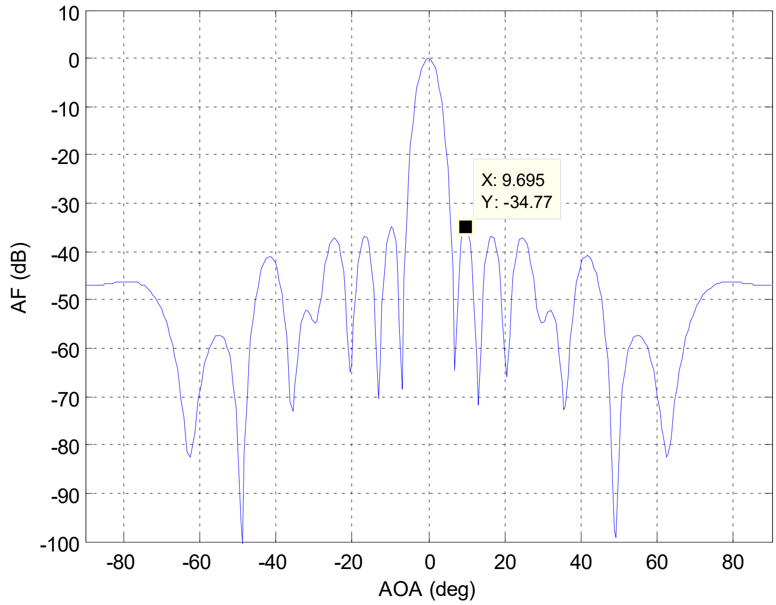

Figure 7: Radiation Pattern for 18 elements using the non-tapered arrangement

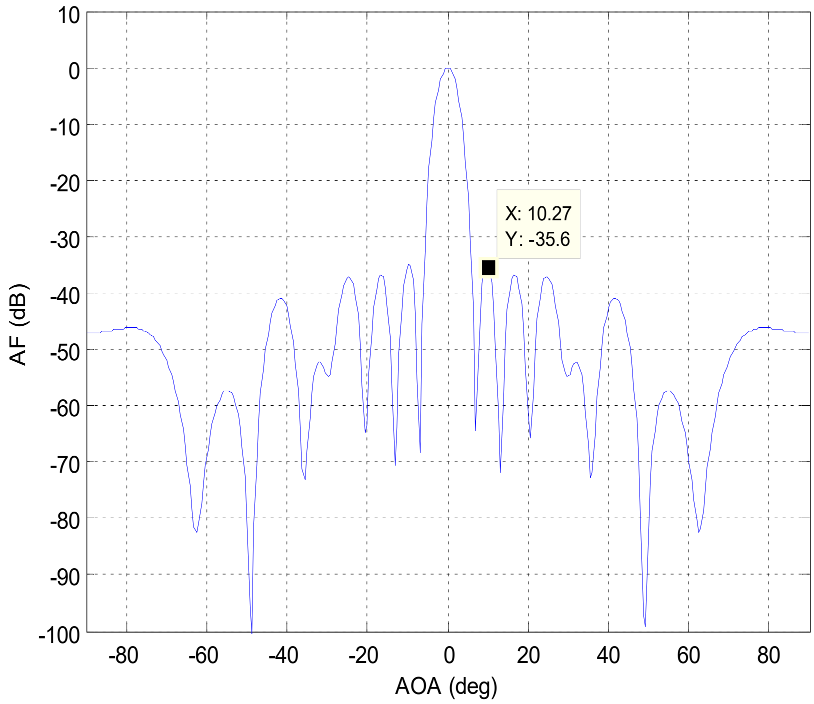

Figure 8: Radiation Pattern for 20 elements using the non-tapered arrangement

The results shown in Figures 7 and 8 showed better improvements in the side lobe level as well as the beamwidth. The side lobe level was further reduced to -35.6dB while the beamwidth obtained was 13.26°. The non-tapered arrangement, therefore, gave the best result in terms of side lobe level while the space-tapered gave the best result in terms of beamwidth.

The three inter-element spacing arrangements used were then compared in terms of their side lobe level and beamwidth. This was done to have a clearer of the results. The results of the comparison obtained are presented in Figures 9 and 10 respectively.

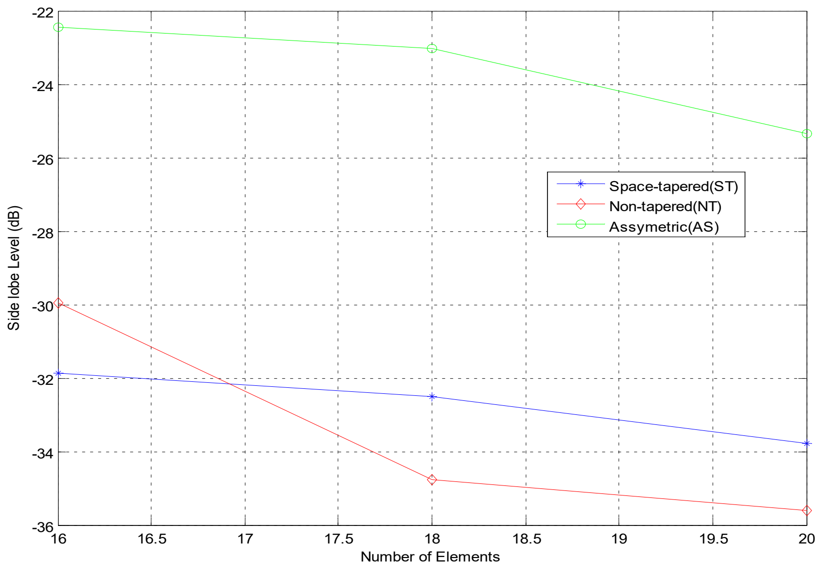

Figure 9: Comparison of arrangement on side lobe level

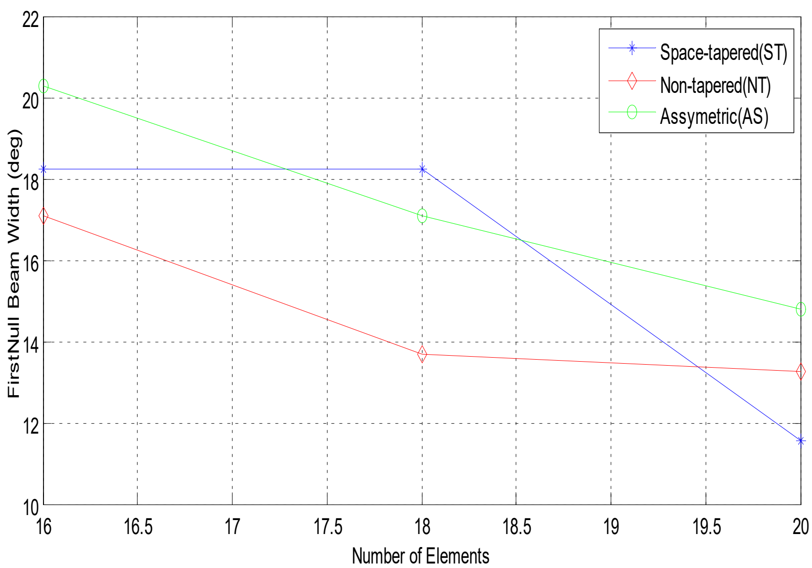

Figure 10: Comparison of arrangement on beamwidth

Figure 9 shows the comparison of side lobe level versus the number of elements for the space-tapered, non-tapered, and asymmetric element arrangements. The non-tapered arrangement gave the best result while the asymmetric gave the worst side lobe level.

Figure 10 presents the comparison of beamwidth versus the number of elements for the space-tapered, non-tapered, and asymmetric element arrangements. The space-tapered arrangement gave the best result of the three arrangements while the asymmetric arrangement gave the worst beamwidth value.

4.0 Conclusion

The research aimed to improve the performance of an unequally spaced linear array antenna by optimizing the energy utilized in the radiation pattern. This was achieved using GA with consideration for several configurations. The technique used was to first obtain weights which would produce optimum output for 18 to 20 elements. The best combination of inter-element distances which would give a much lower level in the side lobes was then searched for using GA. The optimum interval obtained was 0.04λ. The arrangement of these distances was then explored to identify the most effective configuration which reduces the side lobes optimally without compromising the performance of the antennae. This was a major contribution of this paper as most research in unequally spaced linear array did not consider several other configurations. The space-tapered arrangement in this study gave a better beamwidth compared to other configurations. The Non-Tapered configuration gave the best result with an improvement in the sidelobe level (SLL) of approx. 3.5dB for 20 elements. This improvement is significant compared to results obtained with the equally spaced linear array. It reveals that with a smaller number of antenna elements using non-uniform inter-element spacing, energy wasted through the side lobes can be significantly reduced.

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