

A New Conformal Conical Phased Array Antenna for Surveillance Radars

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Abstract—In this paper a new conformal array antenna of conical structure has been proposed. A conical phased array antenna can steer the radar beam electronically in both azimuth and elevation to cover a hemi-sphere mesh surrounding the radar antenna. Beam steering can be accomplished either continuously or discretely at definite directions. The proposed technique not only overcomes the limitations of mechanical steering systems and surveillance radar dead cone but also improves the radar tracking capability. Moreover, it is suitable to be used in MIMO radars and enemy deception systems. Element weights of the conical phased array antenna are used four famous window functions known as, Chebychev, Hamming, Hanning, and Kaiser window. The windowing process improves the beam pattern peak side lobe level (PSLL) while maintaining a narrow beam width. A high resolution phase shifter and adaptive attenuator have been used for each element to acquire both the desired phase and the weight for conical array beam pattern. Beam pattern is simulated and tested using a Matlab Program.

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1. INTRODUCTION

A conformal antenna is one which adapts to a specific shape. The main goal is to design an antenna which can be integrated with the structure and does not produce an extra drag. In the past, three linear array antennas were used in many systems, such as cellular phone base stations. Each linear array covers 120 degrees. Development in coverage angle was achieved to reach 140 degrees with overlapping coverage zones [1]. Unfortunately, this causes more complexity in signal processing and feeding networks. So, the conformal phased array antenna appears to be the suitable methodology for a completely spherical covering zone with simple feeding networks. In the early development of conformal phase array antennas, a limited scanning angle up to ± 50 degrees was achieved [2]. On the other hand, a conformal array antenna with omnidirectional beam pattern can cover a complete spherical zone [3]. An omnidirectional conformal antenna can be used in local broadcastings or weather radars but is not suitable for direction finding wireless systems. Currently conformal array antennas using switched Butler Matrix or switched serial networks were used as directive antennas in direction

finding systems [4-5]. The main drawback of using switched conformal array antennas is that they provide a switched beam pattern. Switched beam pattern does not introduce a satisfactory degree of continuous scanning, and it introduces a relatively small gain of few decibels, which is not suitable in radar application. Therefore, digital feeding networks using digital phase shifters and adaptive attenuators should be used [6]. Digital phase shifters play the main role of steering the antenna beam pattern over a spherical coverage zone. Adaptive attenuators are used to control the excitation of elements. Uniform excitation or distribution for conformal array antenna elements gives poor parameters such as high peak side lobe level [7]. So conformal array antenna excitations, dimensions, or number of elements should be optimized to get better performance. Optimization processes were applied to distribution of elements over antenna curved surface using method of moment and spectral domain approach [8]. These optimization processes give a better performance through the simulation results. A further optimization for location of elements over the conformal array surface was achieved to minimize the beam pattern side lobe level using particle swarm optimization [9]. Optimizing approaches based on the G.A have been used over a number of elements that form the circular array antenna to get lower side lobe level [10]. Also the new proposed conformal phased array antenna is optimized using G.A to get optimum element weights for minimum peak side lobe level while maintaining narrow half power beam width. Elements are distributed on a cone surface having distance greater than the half wave length to overcome mutual coupling between different elements [11].

2. THEORY OF CONICAL ARRAY ANTENNA

Figure 1 shows the conical array antenna structure. A circular array is the building block of conical array. Repetitive circular sub-arrays above each other with linearly descending diameters can form a conical array. N circular sub-arrays with each having M elements at the circle perimeter form a conical array with NM elements. The nm^{th} element has w_{nm} weight and β_{nm} phase shift. L is the total cone length while θ_o is the half cone angle. Inclination distance between two successive circular arrays is

$$d = \frac{L}{N \cos \theta_o} \quad (1)$$

Observing the electromagnetic field at the cone tip from a target oriented at a general point with spherical coordinates (r, θ, ϕ) , due to the spatial distribution of elements, the array factor can be realized as

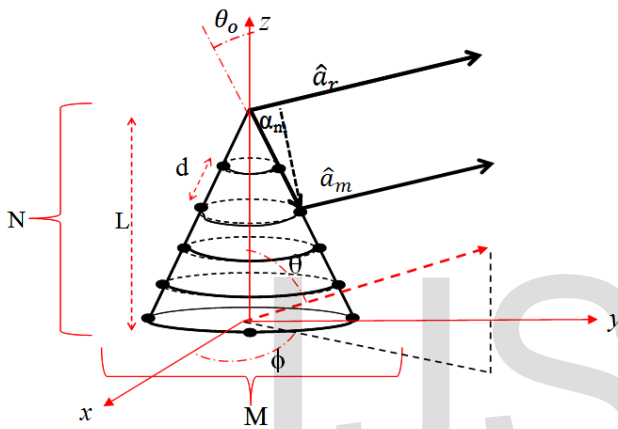


Figure 1- Conical Array Antenna.

$$AF(\theta, \phi) = w_{1,1} e^{j(kd \cos \alpha_1 + \beta_{1,1})} + w_{2,1} e^{j(2kd \cos \alpha_1 + \beta_{2,1})} + \dots + w_{N,1} e^{j(Nkd \cos \alpha_1 + \beta_{N,1})} + w_{1,2} e^{j(kd \cos \alpha_2 + \beta_{1,2})} + \dots + w_{N,M} e^{j(Nkd \cos \alpha_M + \beta_{N,M})} \quad (2)$$

$$AF(\theta, \phi) = \sum_{m=1}^M \sum_{n=1}^N w_{n,m} e^{j(nkd \cos \alpha_m + \beta_{n,m})} \quad 1 \leq n \leq N, 1 \leq m \leq M \quad (3)$$

where $k = 2\pi/\lambda$ is the angular wave number, λ is the wave length, α_m is the solid angle between target unitvector (\hat{a}_r) and m^{th} element unit vector (\hat{a}_m) and $w_{nm} = 1$ for uniform excitation.

$$\hat{a}_r = (\sin \theta \cos \phi \hat{i} + \sin \theta \sin \phi \hat{j} + \cos \theta \hat{k}) \quad (4)$$

$$\hat{a}_m = (\sin \theta_o \cos \phi_m \hat{i} + \sin \theta_o \sin \phi_m \hat{j} - \cos \theta_o \hat{k}) \quad (5)$$

where $\phi_m = 2\pi m/M$ is the angular position of m^{th} element. $\cos \alpha_m$ is the dot product between the mentioned unit vectors and can be found as:

$$\cos \alpha_m = \hat{a}_m \cdot \hat{a}_r = (\sin \theta_o \cos \phi_m \hat{i} + \sin \theta_o \sin \phi_m \hat{j} - \cos \theta_o \hat{k}) \cdot (\sin \theta \cos \phi \hat{i} + \sin \theta \sin \phi \hat{j} + \cos \theta \hat{k}) = \sin \theta \sin \theta_o \cos(\phi - \phi_m) - \cos \theta \cos \theta_o \quad (6)$$

The maximum of AF occurs at:

$$nk d \cos \alpha_m + \beta_{n,m} = 0 \quad (7)$$

$$\beta_{n,m} = -nk d \cos \alpha_m = -nk d (\sin \theta_i \sin \theta_o \cos(\phi_i - \phi_m) - \cos \theta_i \cos \theta_o) \quad (8)$$

Where θ_i, ϕ_i are the elevation and azimuth angles of the main lobe, respectively. Using the above formula, the phase shift of the nm^{th} element can be realized to steer the beam through a hemi-sphere scanning cell. The weight w_{nm} may be uniform or may be in any form according to the designer's needs. Weights are optimized to obtain beam pattern with minimum peak side lobe level.

3. SIMULATION PROCESS

The simulation is done using Matlab program environment, Selecting the cone dimensions as $L=10\lambda, \theta_o=38.3^\circ$ and $N=M=12$ leads to $s_{min} = 0.682 \lambda$, which is suitable for mutual coupling avoidance. Phase shifters can adapt the phase of each element. So the beam can be steered over a hemi-sphere coverage cell with 70° in elevation and 360° in azimuth. Higher resolution in phase shift selecting for each element leads to higher resolution in beam steering. Scanning rate for these types of antenna depends on the switching rate of phase shifters which can steer up to two degrees at $10 \mu\text{sec}$. Thus, the beam can steer over the whole hemi-sphere coverage cell at 81 msec , i.e. more than 740 revolutions per min [13-14]. Antenna gain 'G' can be calculated as [15-16]:

$$G = \frac{4\pi}{\theta_1 \theta_2} \quad (13)$$

where θ_1 and θ_2 are the HPBW in E-plane and H-plane, respectively. Element weights have been used Chebychev, Hamming, Hanning, and Kaiser window functions, to be below 6° , weights with an 11×12 element array and with weight precision less than 10^{-3} which can be practically implemented. Due to the asymmetrical shape of conical array antenna in elevation, element weights have to be adapted during beam steering. Digital RF adaptive CMOS attenuator can be a suitable variable attenuator for controlling element weight [17]. It has a resolution up to -30dB . Element weights are substituted then; code words of binary bits corresponding to the desired phase and amplitude are introduced to variable phase shifters and adaptive attenuators, respectively.

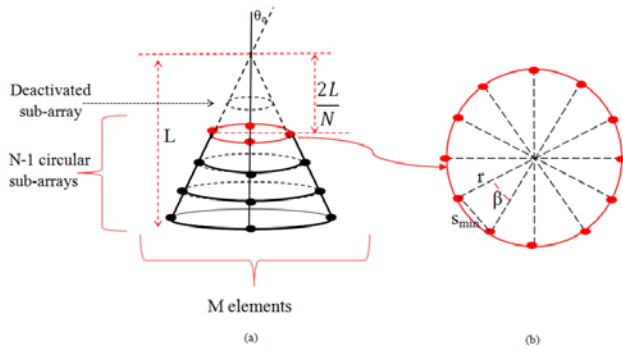


Figure 2- Array Antenna Structure
 (a) Conical Array, (b) Circular Sub-array

Conical array antenna polarization does not depend only on single element polarization. Due to the curved surface of the array antenna, some elements would appear cross-polarized to others, causing high polarization loss factor (*PLF*). To overcome this problem, a simple solution is orientating the dipoles vertical axis (polar or polarization reference axis) to coincide with the cone axis. Otherwise, a polarization control device using a variable power divider *VPD* as in Figure 3 should be used for each element [18]. There are many possible element designs: crossed dipoles, crossed slots, and crossed notch elements. Orthogonal feeds can be used in many radiators such as patches, square and circular wave guides, and so on. With two-port elements, the radiated polarization can be set by feeding the two ports with proper amplitudes and phases. Feeding the two with equal amplitudes results in 45° slant polarization; any orientation can be obtained by a proper amplitude ratio. A variable power divider is a suitable circuit for realizing this.

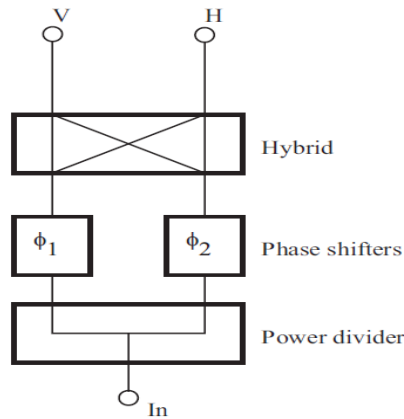


Figure 3- Variable Power Divider

Table 1. Comparison between types of conformal arrays

Array Parameters	Array Type		
	Conformal	Uniform	Weighted
PSLL(dB)	-12	-16	-19.08
Mean SLL (dB)	-----	-18.8	-22.7

HPBW (°)	30	6	6
Max Tilting Angle (°)	84	90	90
Antenna Gain (dB)	11.8	30.6	30.6

4. SIMULATION RESULTS

A conical array antenna is tested at four different cases: case (1), weighted by Chebychev window function, case (2), weighted by Hamming window function, case (3) weighted by Hanning window function; and case (4), weighted by Kaiser window function. Table 1 compares a conformal slotted waveguide array antenna and a conformal conical array antenna [19]. An improvement in PSLL with respect to conformal slotted wave guide array has been achieved by 8 dB in addition to gain improvement by 18.8 dB. This improvement in gain occurs due to two factors. The first is the use of conical shape instead of cylindrical shape as in [19]. Conical shape improves the constructive interference at the desired direction and destructive interferences at the undesired directions. So a narrower beam width is achieved and hence a higher gain. The second factor is using 132 elements instead of 35 elements only as in [19]. It is remarked that both the conical phased array antenna and helical antenna with linear-decreasing radii of its turns have the same shape. Figures 4 through 11 the array factor for the four window function compared with the uniform array. Figure 12 through 13 shows the 3D contour plot for the array factor at three desired directions. The proposed antenna has overcome the mechanical steering antenna systems limitations, disadvantages of tracking radars processing, and the dead cone of surveillance radar coverage zone. Conical array antenna permits this type of modern radar to operate in standalone conditions without the need of mutual covering. It also provides an efficient degree of passive deception for enemies, as it can be used at silent sentry radars.

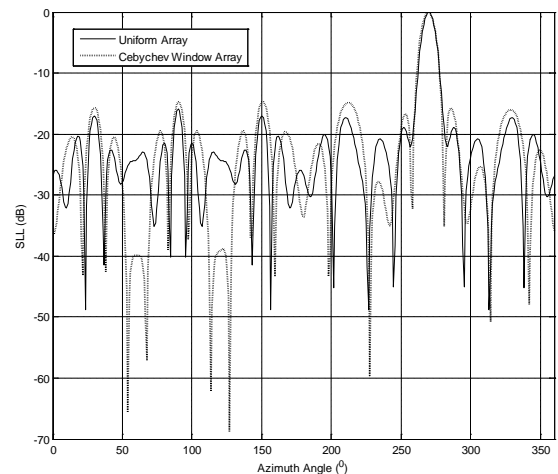


Figure 4- Azimuth array factor with Chebychev weighting

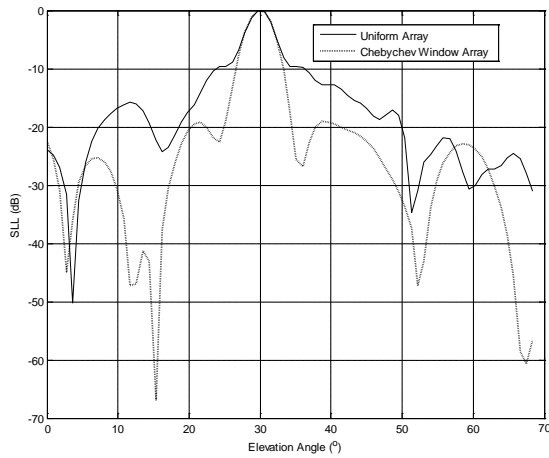


Figure 7- Elevation array factor with Hamming weighting

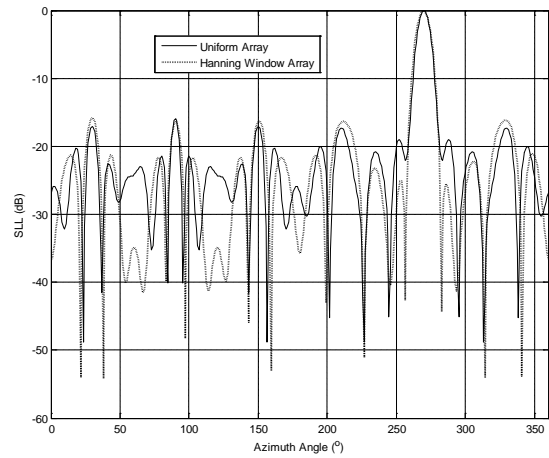


Figure 5- Elevation array factor with Chebychev weighting

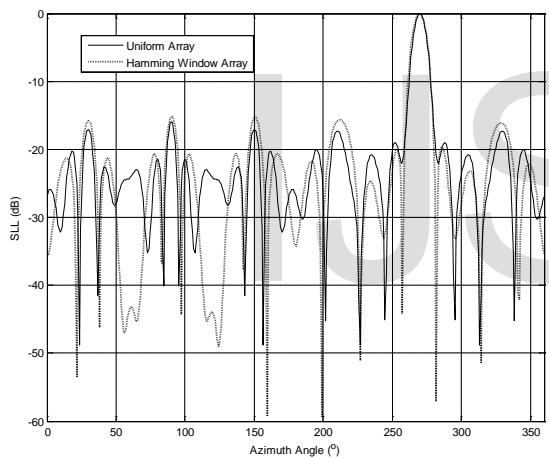


Figure 8- Azimuth array factor with Hanning weighting

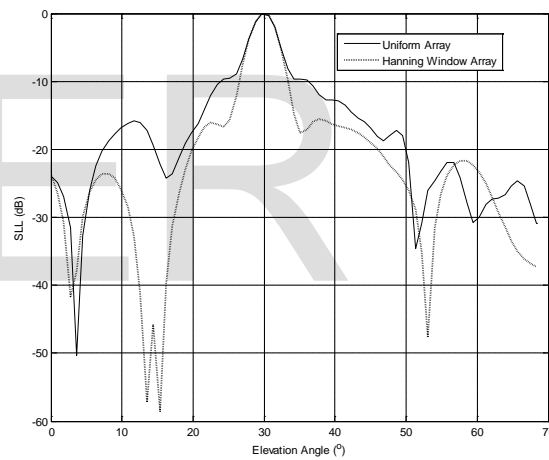


Figure 6- Azimuth array factor with Hamming weighting

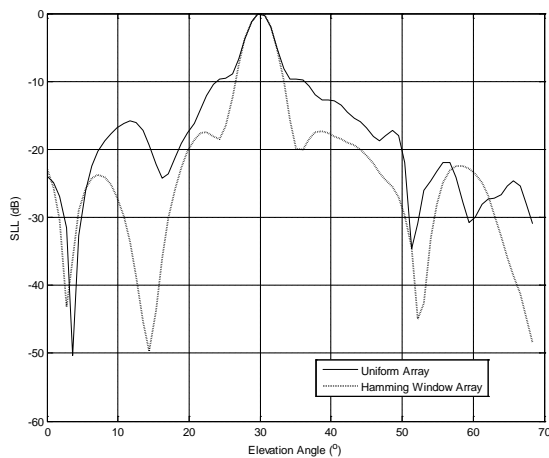


Figure 9- Elevation array factor with Hanning weighting

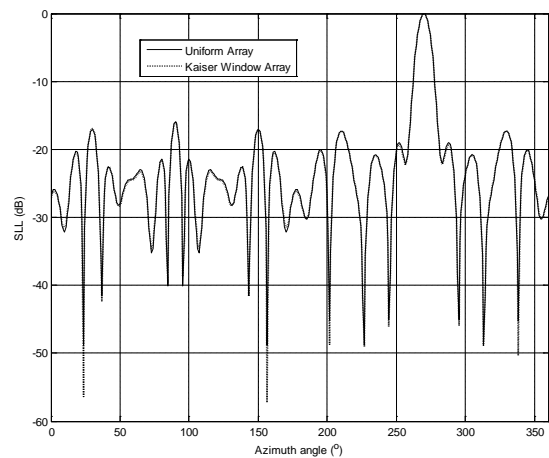


Figure 10- Azimuth array factor with Kaiser weighting

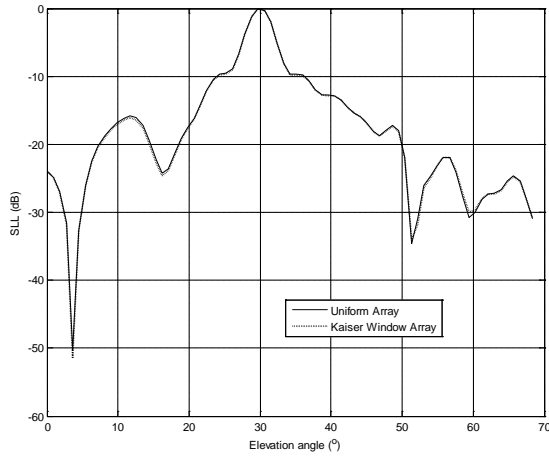


Figure 11- Elevation array factor with Kaiser weighting

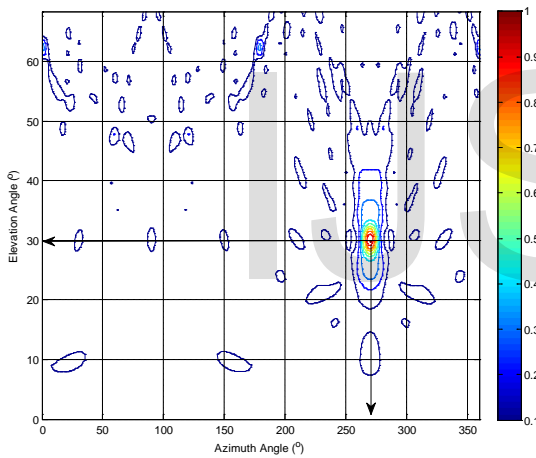


Figure 12- 3D Contour plot for the AF at desired direction

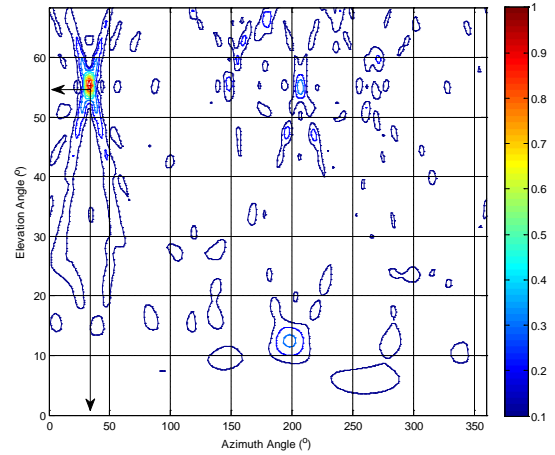


Figure 13- 3D Contour plot for the AF at desired direction

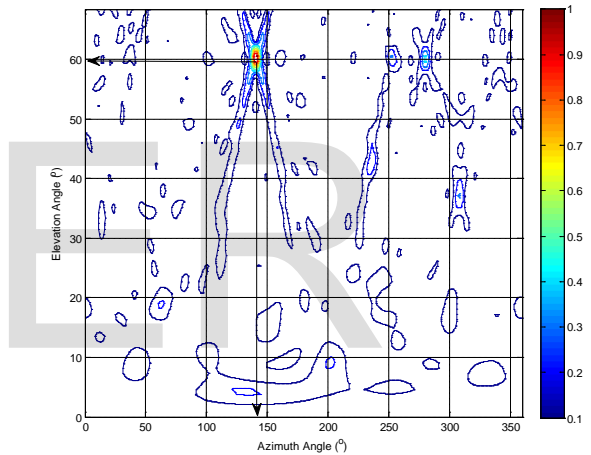


Figure 14- 3D Contour plot for the AF at desired direction

5. SUMMARY

A complete analysis and design for conical array antenna are introduced as an application for modern radar using a high resolution phase shifter. Antenna dimensions and parameters are optimized using a genetic algorithm to obtain minimum peak side lobe level while maintaining a relatively narrow beam width. Physical phenomena such as mutual coupling between elements and polarization loss have been taken in consideration. The designed antenna has been simulated and tested using a Matlab program, with the aid of its graphical capability. The proposed conformal array antenna achieves PSLL of -19.08 dB, MSLL of -22.7 dB and antenna gain of 30 dB. The results are compared with slotted wave guide conformal array antenna results. An improvement in PSLL by 8 dB takes place in addition to gain improvement by 18.8 dB. The proposed antenna has overcome the mechanical steering antenna systems

limitations, disadvantages of tracking radars processing, and the dead cone of surveillance radar coverage zone. Conical array antenna permits this type of modern radar to operate in standalone conditions without the need of mutual covering. It also provides an efficient degree of passive deception for enemies, as it can be used at silent sentry radars.

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