Sidelobe Reduction in a Planar Array using Genetic Algorithm under Backlobe Reduction Condition

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ABSTRACT

The peak sidelobe level (PSL) minimizing amplitude weights for planar array, with 3D beamforming under the backlobe level reduction (BLL) condition is proposed. Binary genetic algorithm (BGA) is performed on the amplitude weights to achieve low PSL. BLL reduction condition for the inter-element distance between the antenna elements is applied to achieve reduced BLL. Earlier studies only focus on minimizing sidelobe level of planar array. BLL reduction condition has not yet been applied for planar array case. Hence a different way of achieving the amplitude weights to reduce PSL with 3D beamforming using BGA, under the BLL reduction condition is proposed in this paper. Obtained PSL and BLL for 5×5 planar array by applying optimized weights under BLL condition is -20.89 dB and -2.37 dB respectively. PSL is reduced by 8.84 dB compared to 5×5 uniform planar array. BLL is reduced by 2.37 dB compared to planar array discussed in existing research work

Keywords: 3D beamforming, BGA, BLL reduction, PSL reduction, planar array.

1. INTRODUCTION

Antenna array has been extensively analysed since early 20th century [1]. The most popular types of antennas used for radar, satellite or mobile communications is phased antenna array. Phased antenna arrays produce highly directive main beam in a particular targeted direction without physical change in any antenna elements in an array, but by varying the phases of excitation currents fed to different antenna elements [2]. Hence phased array can be efficiently used in wireless communications by scanning the main beam in the direction of varying traffic conditions. As the number of antenna elements increase, main lobe narrows, and many sidelobes occur at different scanning angles [3]. With the increase in sidelobes and backlobe at different scanning angles, interference increases in the network. Therefore reducing sidelobes and backlobe is an important challenge in an antenna array. The controls in an antenna array for beamforming are geographical configuration e.g., linear, planar, circular, displacement between elements, excitation amplitude of each antenna element, excitation phase of each antenna element, pattern of each element [4]. The objective to change the controls is for obtaining higher directivity, higher gain, narrower beamwidth, diversity reception, estimating the direction of arrival of a signal, and sidelobe level minimization. Some controls are found to be effective for specific objective function. In particular, optimizing amplitude weight is an efficient way to reduce sidelobe level in an antenna array [1]. Hence, amplitude weights are optimized in this paper, to achieve low PSL and BLL in a planar array. In transmitting antennas, sidelobes and backlobe radiations waste energy and it increase interference to other equipments [5]. The most elementary geographical configuration is linear array in which array elements lie in a straight line. The elements may be or may not be equally spaced. When array elements are placed in a plane it is planar array, planar arrays may be circular or rectangular.

Array factor of endfire array forms the main beam along the axis of linear array. Endfire condition results when main beam is facing towards either 0° or 180°.In many applicatons, antennas need to beamform a single pencil beam in a particular direction. Single pencil beam can be achieved by proper design of endfire array. Main beam can be steered to a particular direction by controlling the phase, by applying linear phase taper to compensate for the phase delay of particular beamforming angle [2]. Linear arrays are capable of 2D beamforming, they are capable of horizontal/azimuth beamforming. Planar arrays are capable of 3D beamforming. 3D beamforming combines horizontal/azimuth beamforming and multiple input multiple output schemes, with vertical/elevation beamforming [6].

The BLL can be reduced by decreasing the spacing between the antenna elements below a half-

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wavelength. BLL reduction has been studied in linear arrays [7], and beamforming conditions have been applied in linear and planar arrays [4]. However the combinations of BLL reduction condition, beamforming condition with sidelobe reduction using GA to optimize the amplitude weights have not yet been applied in planar arrays.

There are several candidates for optimization algorithms. Traditional options use gradients or random search processes. Gradient method converges fast to a solution, but may get stuck in local minima. Gradient calculations can be done only on continuous parameters. Random search method does not need gradient calculations, hence can be applicable for the functions that are not differentiable. Random search algorithm works by iteratively moving to better solution in search space. As number of variables increase search space increases too. Therefore the number of random searches has to be increased to get global optimum in large search space. Thus the optimization process becomes very slow. There are many parameters to be optimized in electromagnetic problems as amplitudes and phases of all of the antenna elements in an array. When the antennas are massive, the possibilities of parameters increase so in this case exhaustive search gets impractical too; to obtain the optimal parameter values [8].

Genetic algorithm (GA) is was first introduced by Holland [9], and Goldberg applied it to many practical problems [10]. GA is a global numerical optimization method based on biological genetic recombination and evolution. GA encodes the parameters into binary bits called genes and repeatedly performs natural selection: the best chromosomes are selected, then they undergo mating, and mutation until it gets the final optimal result [3]. GA is integer optimization method and can be applied to non-linear problems [11]. GA has the ability to escape from local maxima and minima. It is suitable for problems with large number of variables [3]. Here GA is used to optimize amplitude weights of synthesized beam pattern of planar array using window functions, in order to achieve the minimum PSL with narrower beamwidth. Optimized results are compared with synthesized pattern using Gaussian, Kaiser, Hamming and Blackman weights coefficients [12].

Two dimensional window functions can be applied in planar array to synthesize the radiation pattern with low sidelobe level. In two-dimension window, amplitude weights are applied to antenna elements based on their corresponding definitions. Two dimensional window functions used in planar array design are derived from one dimensional window e.g., rectangular, triangular, Barlett, Hanning, Hamming, Blackman, Parzen, Priestly, Daniell, Sasaki windows. Amplitude weights are applied according to different windows, in order to compute the radiation pattern. Windows used in high-order statistics estimation can be efficiently used in planar array to reduce the sidelobe level [13].

For planar array, particle swarm optimization (PSO) algorithm has been used to find elements locations of planar that reduce sidelobe level and or null placement in certain directions [14]. It is based on the behaviours of swarms (bees or birds. Information is exchanged between particles of swarms to explore the search. PSO performs the local and global searches [15]. It is mainly designed for continuous variables whereas the GA mentioned earlier is mainly designed for binary variables. In BGA, the variables are represented in binary. BGA provides slightly reduced sidelobe level and beam shape compared to Binary PSO. BGA is more flexible, easy to implement and suitable for multi objective optimization [16].

In the existing research works, the main focus is on reducing sidelobes but BLL is not analysed. This paper considers and analyses, and successfully reduces both sidelobes and backlobe. The reduction is confirmed by a simulation using a 5×5 planar array. BGA is used for optimization process since the objective function is to minimize PSL under BLL and 3D beamforming conditions, and it's a non-linear function having multiple minima so the classical optimization method such as gradient search is not suitable. Exhaustive search method is also impractical too, since the possible combination of amplitude weights becomes prohibitively large as the number of bits representing quantized amplitude weights and number of antenna elements increases. Given a desired direction, 3D beamforming condition is applied on progressive phase shifts of the elements in the xy plane. BLL reduction condition is also applied on the spacing between antenna elements. Then BGA is applied to find amplitude weights that achieve lowest possible PSL under the BLL reduction and 3D beamforming conditions.

2. SYSTEM MODEL

The radiating elements in the antenna array under consideration are considered to be isotropic point sources. The expression for the array factor of a planar array is given by (1). We consider rectangular planar array of equidistant isotropic antennas, in xy plane with M_x number of antenna elements along the x direction and N_y number of antenna elements along the y direction (see Fig. 1). The array factor AF_{XY} for the planar array is given by [4]:

$$(AF)_{XY} = \sum_{m=1}^{M_x} \sum_{n=1}^{N_y} I_{mn} e^{j(m-1)(kd_x \sin\theta \cos\phi + \beta_x)} e^{j(n-1)(kd_y \sin\theta \sin\phi + \beta_y)} \quad (1)$$

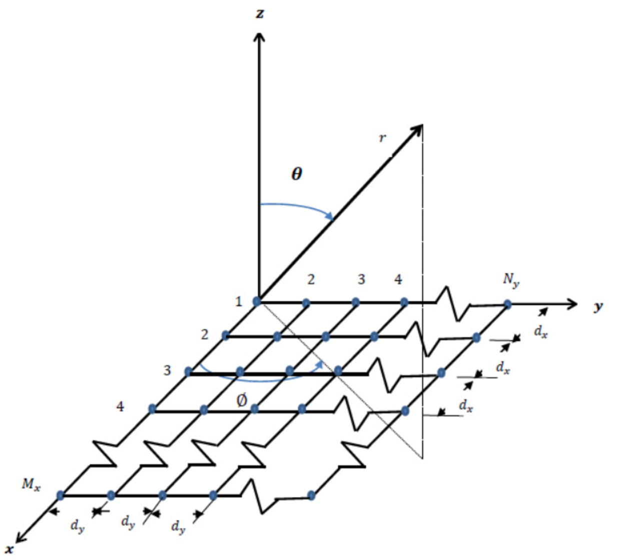


Fig.1: *$M_x \times N_y$ Elements Planar Array [4].*

where I_{mn} is the excitation current fed to each antenna element, d_x is the inter-element distance in the x direction, d_y is the inter element distance in the y direction, $k = 2\pi/\lambda$ is the propagation constant with the wavelength λ, θ is the angle of incidence with respect to the z direction, ϕ is the azimuth angle with respect to the x direction and β_x, β_y are the progressive phase shifts along the x and y directions. Linear arrays can only scan the main beam in one plane, either θ elevation plane or ϕ azimuth plane. Planar arrays can scan the main bean in both θ elevation plane and ϕ azimuth plane.

3. PROPOSED OPTIMIZATION

3.1 Backlobe Reduction and 3D Beamforming Conditions

Backlobe condition is applied in inter element spacing and for 3D beamforming, the conditions are applied in progressive phase shifts. They are explained in detail below.

3.1.1 Backlobe Reduction Condition

In the case of linear array, endfire condition occurs when $\theta_0 = 0°$ or $\theta_0 = 180°$. Linear array is assumed to be lying on the z axis. This results in $\beta_z = -kd_z cos\theta_0 = -kd_z$ or kd_z where d_z is the inter-element distance between antenna elements, β_z is the progressive phase shift along the z axis. The arrays for which $\beta_z = \pm kd_z$, are referred as ordinary endfire arrays. If inter-element spacing between two antenna elements is half the wavelenghth, there will be two identical endfire lobes at 0°and 180°. The visible region is defined as $\beta_z + kd_z cos\theta_0$. When $d_z = 0.5\lambda$, visible region, $2kd_z$ becomes 2π. Hence one of the identical unwanted main lobe or BLL can be reduced by reducing the inter-element distance below half the wavelength. The BLL can be reduced by reducing the visible region. Width of grating lobe from main lobe to null is $2\pi/M_z$ where M_z is the number of antenna elements lying on the z axis, most of the grating lobes can be eliminated by reducing the visible region at least below $2\pi - \pi/M_z$ [7]. Therefore for linear case, back lobe reductions condition is given by (2).

$$d_z \leq \frac{\lambda}{2}(1 - \frac{1}{2M_z}) \tag{2}$$

Hence the condition for linear antenna array case has been extended to the planar antenna array, for inter-element distance between antenna elements lying in xy plane as shown in (3) and (4).

$$d_x \leq \frac{\lambda}{2}(1 - \frac{1}{2M_x}) \tag{3}$$

$$d_y \leq \frac{\lambda}{2}(1 - \frac{1}{2N_y}) \tag{4}$$

3.1.2 3D Beamforming Condition

Planar arrays can beamform along particular azimuth and elevation direction. In order to beamform in planar array, conditions (5) and (6) are applied [4].

$$\beta_x = -kd_x \sin\theta_0 \cos\phi_0 \tag{5}$$

$$\beta_y = -kd_y \sin\theta_0 \sin\phi_0 \tag{6}$$

where ϕ_0 is the particular azimuth direction with respect to the x-axis, and θ_0 is the particular elevation direction with respect to the z-axis, for 3D beamforming.

3.1.3 Optimization Problem

BGA is used for optimization process to achieve the amplitude weights for each antenna element under the BLL reduction and 3D beamforming conditions. The cost function is PSL. Hence, the optimization problem is given by,
Objective function: Minimize PSL
where,

$$PSL = \frac{abs(AF_{XY}(\phi_i, \theta_i))}{\max(abs(AF_{XY}(\phi, \theta))}$$

subject to

$$0° \leq \theta_i \leq 180°, \theta_i \neq \theta_0$$
$$0° \leq \phi_i \leq 360°, \phi_i \neq \phi_0$$
$$0° \leq \theta \leq 180°$$
$$0° \leq \phi \leq 360°$$
$$\beta_x = -kd_x \sin\theta_0 \cos\phi_0$$

$$\beta_y = -kd_y \sin\theta_0 \sin\phi_0$$

$$d_x = \frac{\lambda}{2}(1 - \frac{1}{2M_x})$$

$$d_y = \frac{\lambda}{2}(1 - \frac{1}{2N_y})$$

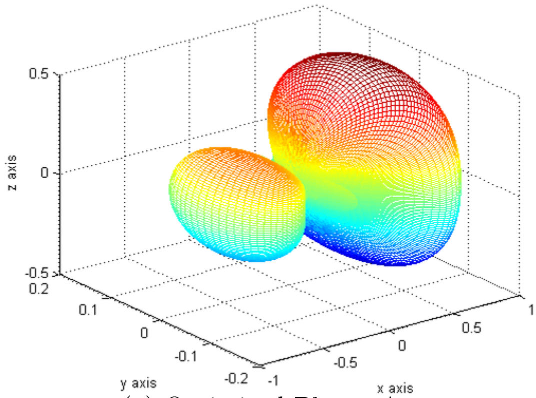
$$\frac{1}{2^b} \leq I_{mn} \leq 1$$

where (ϕ_i, θ_i) is the angle where the maximum peak of sidelobe occur, $AF_{XY}(\phi_i, \theta_i)$ is the array factor at PSL location. b is the number of bits to represent the quantized value of amplitude weights of each antenna element of a planar array. The objective function is a non-linear function, so there are multiple local minima. Since the classical method does not work, BGA is used for optimization process.

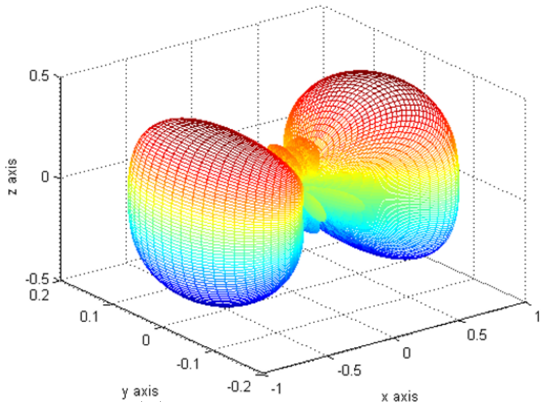
3.2 Binary Genetic Algorithm

GA is a global search algorithm that is based on principles of genetics, natural selection, elitism, mating and mutation. The chromosomes are generated randomly as rows of bit sequence depending on the number of variables, number of bits representing variables and population size.

BGA is used to obtain the optimized amplitude weights to obtain low PSL and simulation is done for 5×5 planar array. Time usage to obtain the optimized amplitude weights for this case is 21 minutes for 30,000 generations. For instance, for the case of 2×2 planar array when amplitude weights are encoded with 4 bits, each element weight has 16 possible quantized values ranging from 0.0625 to 1, with the step size of 0.0625. Hence, there are 65536 amplitude sets of I_{mn}. Using brutforce calculation, the time taken to calculate PSL and BLL for all sets of I_{mn} is 82.78 minutes. Therefore compared to brutforce calculation, the time usage to obtain the amplitude weights using BGA is comparatively so small. For planar array, the multidimensional matrix population is generated, depending on number of variables, b representing variable and population size. In this paper, the number of antenna elements is equal to number of variable, and the cost function or objective function is the PSL. During optimization process, amplitude weights are encoded with 8 bits, hence each element weight has 256 possible quantized values ranging from 0.003906 to 1, with the step size of 0.003906. Hence all of the amplitude weights applied to the entire antenna elements are non-zero values. The future work can be done by allowing the amplitude weights to be zero as well. Population size is selected to be 4. Then each matrix in multidimensional matrix is input to the cost function. For each population matrix, a cost is generated. Hence cost generated has the same size as the population size. The best population matrix giving the lowest cost is arranged in the first matrix in the multidimensional population matrix, and the corresponding lowest cost is arranged in first row. The



(a) Optimized Planar Array.



(b) Uniform Planar Array.

Fig.2: *3D Radiation Pattern.*

matrices whose cost is less than or equal to the mean cost are selected while the rest are rejected. For the mating, the selection of parent population matrix is done by tournament selection of size 2, from the selected matrices based on fitness, with the hope to get better offsprings.

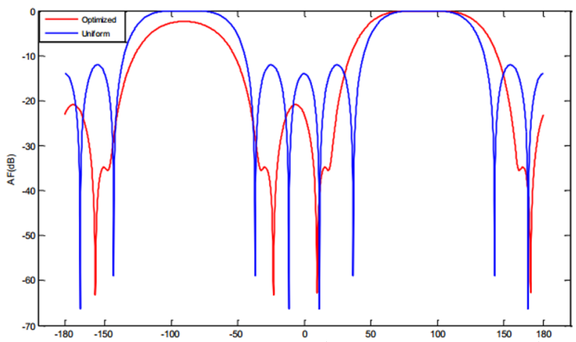
Uniform crossover is done in between the selected population matrices. After crossover, offspring is generated. The first matrix with the lowest cost is unchanged or considered elite population matrix. Elitism is used to save the best chromosomes in population matrix giving lowest cost. Then mutation is carried in the all of the matrices except the first elite matrix. Mutation results in random change in the population matrix, according to mutation rate. Mutation rate is selected as 0.05. During mutation, a one is changed to a zero or a zero is changed to a one. Mutation is important in order to avoid being stuck in local minima. Hence new multidimensional population is formed. The cost is recalculated for the matrices and the process continues until the maximum number of generations is reached.

4. RESULTS AND DISCUSSIONS

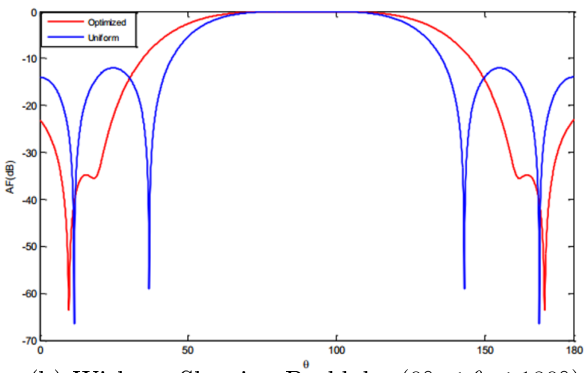
Optimized amplitude weights for 5×5 planar array are obtained using BGA, under backlobe reduction

Table 1: *Comparison Between Uniform and Optimized* 5×5 *Planar Array.*

	Optimized	Unifrom
I_{mn}	0.3047 0.4805 0.4531 0.2773 0.1133	1 1 1 1 1
	0.6445 0.8086 0.8164 0.6445 0.3008	1 1 1 1 1
	0.9531 0.8906 0.9609 0.8750 0.5508	1 1 1 1 1
	0.6133 0.4141 0.5508 0.5859 0.5859	1 1 1 1 1
	0.3477 0.0156 0.3359 0.0625 0.5273	1 1 1 1 1
β_x (radian)	-2.8274	0
β_y	0	0
d_x	0.45λ	0.5λ
d_y	0.45λ	0.5λ
PSL (dB)	-20.89	-12.04
BLL (dB)	-2.37	0



(a) Showing Backlobe ($-180° \leq \theta \leq 180°$).



(b) Without Showing Backlobe ($0° \leq \theta \leq 180°$).

Fig.3: *Normalized* AF_{XY} *(dB) for Optimized and Uniform Planar Array vs.*θ *at* $\phi = 0°$.

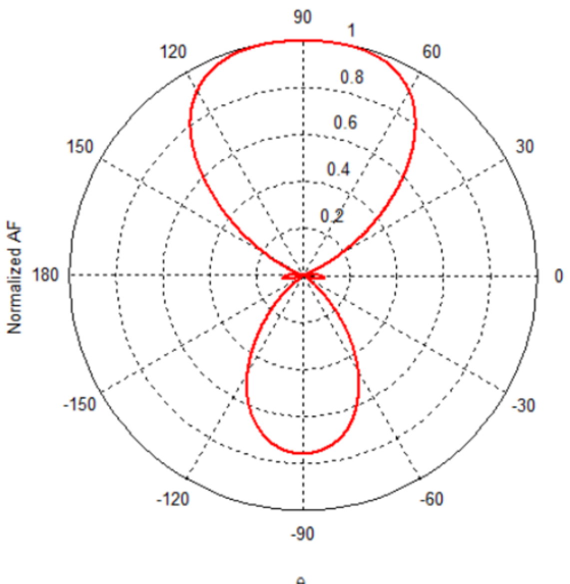
condition, with 3D-beamforming.

Uniform array has the uniform inter-element separation of 0.5λ and each antenna element is fed with unit amplitude. For the optimized case, the uniform inter-element spacing is 0.45λ as obtained by using the BLL reduction condition in inter-element spacing as given in (3) and (4). Antenna elements are fed with amplitudes as obtained from optimization process as shown in Table. 1. For the uniform planar array, the backlobe has the same magnitude as the main lobe and PSL is -12.04 dB. For the optimized case, the PSL is reduced by 8.84 dB from the uniform case. Backlobe is significantly reduced from 0 dB to -2.37 dB. 3D beamforming is done along $\phi_0 = 0°$ and $\theta_0 = 90°$. However there is an increase in beamwidth as observed in Fig. 2-5.

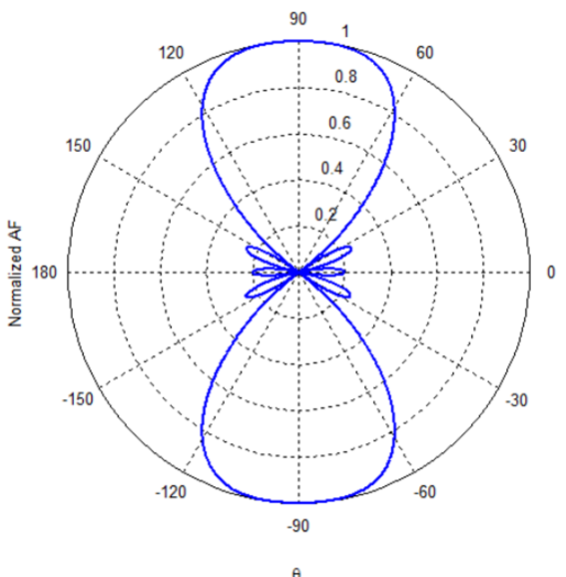
In Fig. 2, the main lobe and backlobe beamfomed by uniform planar array is perpendicular to yz plane towards positive x and negative x directions respectively. The magnitude of the backlobe in the case of uniform planar array is the same as that of the mainlobe. For the optimized case, PSL and backlobe level are reduced as mentioned in Table. 1. Main beam is directed towards 0° azimuth and 90° elevation in both optimized and uniform planar array cases.

Fig. 3 is a dB plot of Fig. 2. Such plots are useful for showing minor lobes as sidelobes and backlobe. The reduction of PSL and BLL is clearly illustrated in Fig. 3. In order to analyse the 3D radiation pattern of the planar array, the 3D plot is evaluated at $\phi = 0°$ or xz plane. Direction of mainlobe with normalized magnitude of 0 dB is $\theta_0 = 90°$ The plots are symmetric. From the plots, it can be observed that PSL and BLL are reduced as shown in Table. 1. The halfpower beamwidth (HPBW) is measured at normalized AF_{XY} equal to 0.707 level. HPBW is increased when there is reduction of backlobe and sidelobes. HPBW is represented by θ_{HP} when evaluated in the ϕ direction. When evaluated at $\phi = 0°$, HPBW for uniform planar array,$\theta_{HP\ UNIFORM} = 70.2°$ and for optimized case, $\theta_{HP\ OPTIMIZED} = 82.8°$. In the optimized case, PSL is reduced by 8.84 dB and BLL is reduced by 2.37 dB. However there is an increase in HPBW; θ_{HP} is increased by 12.6°.

In Fig. 4, 2D polar plot of normalized array factor for optimized and uniform planar array as a function of θ is evaluated at main beam azimuth direction $\phi = 0°$ or xz plane. It is distinctly observed that there is significant improvement in reduced PSL and BLL, with the main beam directed to the desired azimuth $\phi_0 = 0°$ and elevation direction $\theta_0 = 90°$. For the uniform case, backlobe level has normalized AF of unit magnitude, same as the main lobe, whereas after applying optimized amplitude weights, the backlobe is significantly reduced to -2.37 dB. PSL is reduced



(a) Optimized Planar Array



(b) Uniform Planar Array

Fig.4: *2D Polar Plot of Normalized* AF_{XY} *vs.* θ *at* $\phi = 0^\circ$ *Showing Backlobe* $(-180^\circ \leq \theta \leq 180^\circ)$.

too; uniform planar has PSL -12.04 dB, whereas after optimization the PSL of the optimized planar array is -20.89 dB.

In Fig. 5, 2D polar plot of normalized array factor for optimized and uniform planar array vs. ϕ is evaluated at main beam elevation direction, $\theta = 90^\circ$ or xy plane. The reduction in PSL and BLL are observed as shown in Table. 1. HPBW is represented by ϕ_{HP} when evaluated in the θ direction. When evaluated at $\theta = 90^\circ$ or xy plane, ϕ_{HP} for uniform planar array, $\phi_{HP\,UNIFORM} = 21.08^\circ$ and for optimized case, $\phi_{HP\,OPTIMIZED} = 24.26^\circ$. Hence with the reduction of PSL and BLL, there is an increase in ϕ_{HP} by 3.18°.

Further BLL reduction for same PSL level, -20.89 dB is possible by applying the obtained optimized amplitude weights and by reducing d_x and d_y as per BLL reduction conditions (3) and (4). However with the reduction in d_x and d_y, BLL can be reduced at the cost of increased HPBW. For instance, BGA is used to find the optimized distance for 5×5 planar array, such that $0.3\lambda \leq d_x, d_y \leq 0.45\lambda$, with the step size of 0.0078λ, to achieve lowest possible BLL, for the same PSL, using the optimized amplitude weights obtained previously. Lowest possible BLL is obtained when $d_x = d_y = 0.31562\lambda$. In this case when evaluated at $\phi = 0^\circ$, achieved BLL is -48.83 dB and PSL is -20.89 dB however HPBW is increased tremendously. When evaluated at $\phi = 0^\circ, _{HP\,UNIFORM} = 70.2^\circ$ and $\theta_{HP\,OPTIMIZED} = 99.72^\circ$; and when evaluated at $\theta = 90^\circ, \phi_{HP\,UNIFORM} = 21.08^\circ$ and $\phi_{HP\,OPTIMIZED} = 35^\circ$. Hence θ_{HP} is increased by 29.52° and ϕ_{HP} is increased by 13.92°.

5. CONCLUSION

It is the first time that BGA is used to obtain the PSL minimizing amplitude weights for planar array, with 3D beamforming under the BLL reduction condition. 3D beamforming condition is applied in progressive phase shifts and BLL condition is applied in inter-element distance between the antenna elements lying on xy plane. With this technique, both PSL and BLL are found significantly reduced. Simulation results for the 5×5 planar array shows 8.84 dB reduction in PSL compared to the uniform planar array, and 2.37 dB reduction in BLL compared to existing research works [12-13]. However there is an increase in HPBW, θ_{HP} is increased by 12.6° and ϕ_{HP} by 3.18°.

Further work can be done in 3D beamforming. 3D beamforming in a particular azimuth and elevation direction can be extended by beamforming in multiple desired azimuth and elevation directions. Additionally further investigation can be performed on the reduction of BLL and PSL while trying to maintain HPBW as much as possible.

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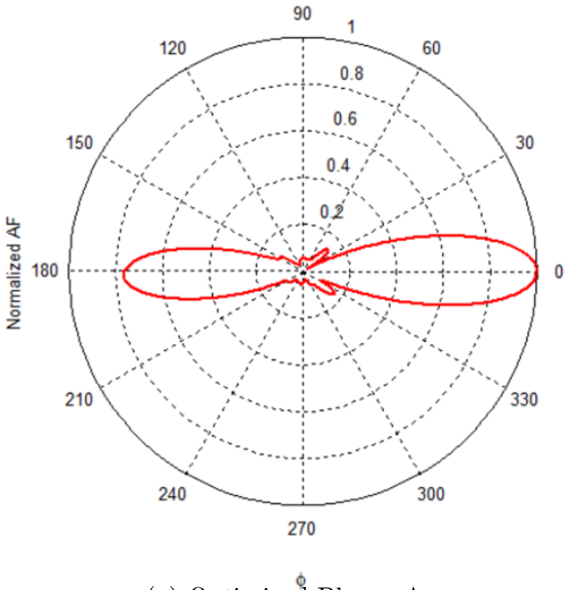
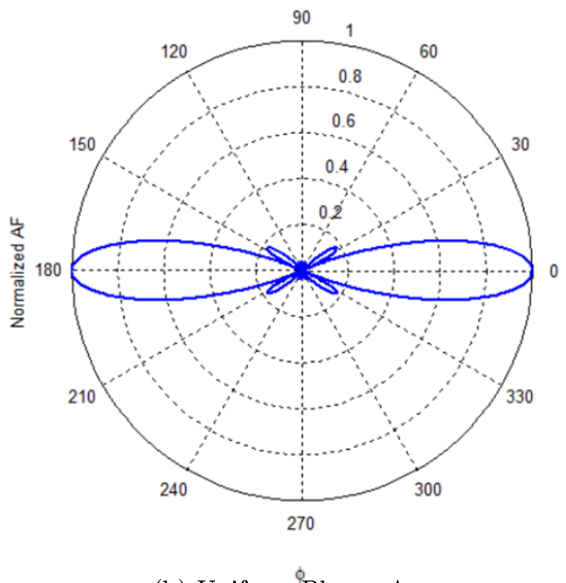


(a) Optimized Planar Array



(b) Uniform Planar Array

Fig.5: *2D Polar Plot of Normalized AF_{XY} vs. ϕ at $\theta = 90°$ Showing Backlobe* $(-180° \leq \theta \leq 180°)$

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