Radiation Pattern Synthesis and Mutual Coupling Compensation in Spherical Conformal Array Antennas

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Abstract **─** This paper presents a novel technique based on Hybrid Spatial Distance Reduction Algorithm (HSDRA), to compensate the effects of deformity and mutual coupling occurred due to surface change in conformal arrays. This antenna surface deformation shifts the position of null points and loss of the main beam resulting in reduced antenna gain along with substantial undesirable effects on the antenna performance. The proposed algorithm, which cumulatively incorporates the Linearly Constraint Least Square Optimization (LCLSO) and Quadratically Constraint Least Square Optimization (QCLSO) techniques, is formulated to minimize/reduce the absolute distance between the actual (simulated/measured) radiation pattern and the desired radiation pattern while keeping the direction of mainbeam and nulls position under control. In particular, a 4x4 conformal microstrip phased array from planar surface is deformed to prescribe spherical-shape surface with various radii of curvature, is validated. For the enhancement of Gain of the conformal array antenna, Gain Maximization Algorithm is also proposed, the simulated results of which is compared to the traditional Phase compensation technique and unconstraint least squares optimization. The analytical results for both planar and spherical deformed configurations are first evaluated in MATLAB and then validated through Computer Simulation Technology (CST).

Index Terms **─** Conformal array antenna, least square optimization, mutual coupling compensation, radiation pattern correction.

I. INTRODUCTION

In future 5G networks, antenna integration is intended to be less disturbing, volume saving and less visible to the human eye. Conformal array antennas with improved adaptive beamforming capabilities and robust signal processing are expected to replace the linear array antennas because of its mechanical design which makes them suitable to be mounted on unique curved surfaces. A conformal array antenna adapts to prescribed curved surface (non-flat surface) forging new shape which are not necessarily limited to the planar or linear array configurations, e.g., circular, cylindrical, parabolic, spherical etc. [1]. Hence it is used in several types of applications such as wearable wireless networks [2], special electronic devices for load-bearing purposes [3], Aerospace designs [4], spacesuit [5] etc.

The conformal array antenna when deformed from the original shape to the prescribe shape it will seriously affect the radiation response of the array. This antenna surface deformation will change the relative position and angle of antenna elements, changing the antenna impedance, steering vector, relative gain, mutual coupling and radiation pattern [6]. The resulting distorted pattern may shift the positions of null points and loss of the main beam which will results in reduced antenna gain along with substantial undesirable effects on the antenna performance. It is therefore; contended that researchers are focusing on decoupling methods in conformal arrays to mitigate the problem associated with mutual coupling, and compensation techniques to control the shape of radiation pattern through precise positioning of the nulls and pointing the broadside beam to any desired direction regardless of the extent of deformation in the conformal surface.

Adaptive beamforming in conformal phased arrays is a powerful technique that adjusts the excitation (gain and phase) of the signals to generate radiation pattern in order to emphasize signal-of-interest (SOI), tuning out the signal-not-of-interest (SNOI) signals [7]. In literature, various compensation methods have been proposed to compensate and correct the field patterns of the conformal phased array antennas. In mechanical calibration methods, the compensation algorithms correct and reconfigure the field patterns by adaptively altering the shape of the

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antenna surface and positions of antenna elements using driving mechanisms [8], or mechanical beam steering [9], smart materials employing shaped memory alloys [10], magnetically-actuated antenna tuning [11], and using electro-active polymers in deformable smart antennas [12]. However, these methods require sophisticated control techniques, extra installation space and have limited radiation correction accuracy with the slow response time. Compared to the mechanical calibration methods, the electrical calibration methods have a faster response time to compensate the effect of deformation occurred in conformal array without the requirement of mechanical adjustments. One of the most precise beam steering techniques is the phased array antennas which give the possibility to reconfigure and correct the radiation pattern in both elevation and azimuth planes by adjusting the amplitudes and phases of each element in the array. Several methods including the traditional mathematical methods and optimization algorithms for mutual coupling reduction and radiation pattern correction for conformal phased arrays were proposed in the past. For example: particle swarm optimization (PSO) [13], quasi-analytical method [14], gain maximization algorithm [15], [16], convex optimization technique [17], active element pattern technique [18], Recursive Least Squares method [19], Linear Constrained Minimum Variance (LCMV) algorithm [7], genetic algorithm [20], array interpolation technique [21], Element Pattern Reconstruction [22], Phase compensation [23], and method based on rotating-element electric-field vector (REV) [24].

In [25], a projection method is used to find analytically the amplitude and phase distribution, which provides low sidelobe level for spherical arrays. Similar approach of using projection method has been followed in [26], [27] and [28] to correct the main beam direction for conformal arrays. To study the gain limitation of phase compensated conformal array, the same projection method is used in [29]. To validate the results two prototypes of spherical shapes of radius $r = 20.32$cm and $r = 27.94$cm are used in which six microstrip element array is used with an inter element spacing of 0.5λ. The results obtained are compared with flat array that reveals that as the radius of the sphere is reduced, the gain also decreases in phase compensated array.

In [30] Chopra et al. investigated the performance on the basis of steering of main beam, interferers nullifying capability and side lobe level suppression, of several beamforming algorithms such as LMS, NLMS, Hybrid LMS, VSS-LMS etc. In [31], Linear Pattern Correction Method (LPCM) has been used in a 6 elements patch array to reduce the effects of mutual coupling. The same technique is also implemented to compensate the pattern of 4 elements linear DRA array antenna and it was shown that pattern correction through LSE is very promising as compare to conventional OCVM [32]. A new method based upon LSE and electromechanical coupling analysis is presented in [33], in which Network theory model is employed to model the Mutual Coupling effects and constraints are taken on desired points for original pattern recovery. In summary, it is found that different calibration techniques together with various signal processing algorithms can be used to adjust phases and amplitudes of each element in array to precisely control the radiation pattern of conformal array antennas.

In this paper, the 4x4 planar microstrip array antenna is spherically deformed to a conformal surface of radius r=20cm and r=30cm and the results are compared for each case to show the performance of the proposed optimization technique. The HSDRA algorithm cumulatively uses the Linearly Constraint Least Square Optimization (LCLSO) and Quadratically Constraint Least Square Optimization (QCLSO) techniques to calculate the correct excitation of the amplitudes and phases to attain the preferred main beam and Side-Lobe Level SLL reduction with particular null placement to achieve the desired radiation pattern for 4x4 spherical conformal microstrip array antenna. Gain maximization algorithm based on maximizing the distance between minimum and maximum points in the pattern while constraining the output power is used to increase the overall gain of the spherical array, which is compared with traditional phase compensation methodology in which phases of excitation were changed so that the all the patterns of element reach at certain reference plane in constructive manner. The results are further compared with unconstrained least squares estimation technique, which is based on reducing the Mean Square Error (MSE) between desired and measured patterns. The results reveal that for the gain enhancement of spherical array structure, the Gain maximization algorithm has better results as compared to unconstraint least square optimization and conventional phase compensation method where as in terms of radiation pattern correction, the Quadratic Constraint Least Square Optimization technique is very efficient and reliable technique to compensate the effects of deformity and mutual coupling occurred due to surface change in conformal arrays.

II. PROBLEM FORMULATION

The physical layout of a ixj microstrip patch conformal array antenna when curved to a spherical surface with a radius r with broadside radiation pattern along $z - axis$ is shown in Fig. 1.

The 4x4 planar array designed for $2.50GHz$ is spherically deformed at a radius of 30cm and 20cm. The dimension of the microstrip patch in proposed 4x4 array design is depicted in Fig. 2. Each miniaturized microstrip patch has been created on a “Roger RT-6002 (lossy)” substrate having relative dielectric constant $\varepsilon_r = 2.94$ with substrate thickness of $1.50mm$ having length and width of $51mm$ and $25mm$ respectively. The dimensions of a single patch in the ixj array are given below in the Table 1.

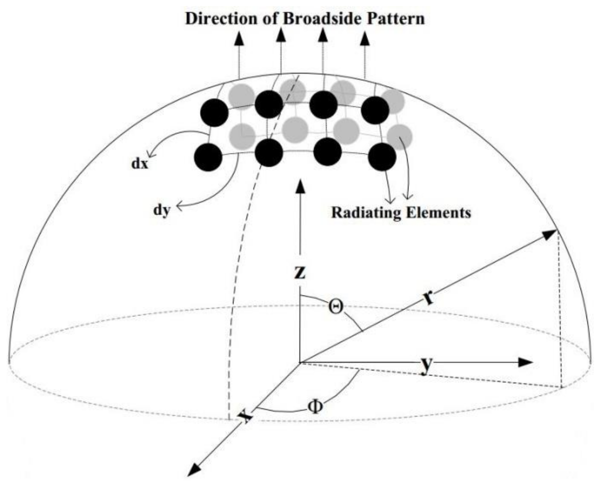


Fig. 1. Illustration of the ixj Array on spherical surface of radius r.

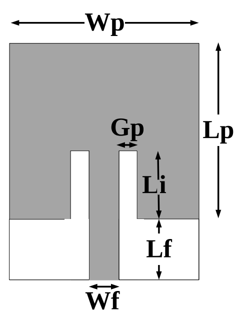


Fig. 2. Single patch antenna.

Table 1: Dimensions of a single patch

Parameter	Description	Length (mm)
Lp	Length of patch	37
Wp	Width of patch	25
Lf	Length of feed line	14
Li	Length of inset feed	14
Wf	Width of feed line	4
Gp	Gap between the feed line and patch	2

Two cases are investigated in this research. In the first case the inter element separation dx and dy along $x-axis$ and $y-axis$ between the antenna elements was kept same at 0.5λ respectively, whereas in the second one the inter element separation was changed so that antenna elements are compact to increase gain in which the spacing in $x-axis$ is kept at $dx = 0.4\lambda$ and spacing in $y-axis$ at $dy = 0.6\lambda$. The positions of each radiating element in the array along x, y and z directions are determined by the following equations respectively:

$$x = rsin\theta cos\varphi$$
$$y = rsin\theta sin\varphi \quad (1)$$
$$z = rcos\theta,$$

where r represents the radius of the spherical structure and $\theta$and φ are adjusted according to inter element spacing dx and dy along $x-axis$ and $y-axis$ respectively. Based on the position of radiating elements in ixj array, the Array Factor $\boldsymbol{AF}(\theta_i, \varphi_j)$ is given by:

$$AF(\theta_i, \varphi_j) = \left\{\frac{1}{I}\frac{sin\left(I\frac{\psi_x}{2}\right)}{sin\left(\frac{\psi_x}{2}\right)}\right\}\left\{\frac{1}{J}\frac{sin\left(J\frac{\psi y}{2}\right)}{sin\left(\frac{\psi y}{2}\right)}\right\}, \quad (2)$$

where $\psi_x = kdxsin\theta cos\varphi + \beta_x$ and $\psi_y = kdysin\theta sin\varphi + \beta_y$, k is the propagation constant, β_x and β_y are the progressive phase shifts succeeded by each element and can be represented as matrix to invoke in algorithm to control the Array Factor as,

$$\beta_{i,j} = \begin{bmatrix}\beta_{1,1} & \cdots & \beta_{1,j}\\ \vdots & \ddots & \vdots \\ \beta_{i,1} & \cdots & \beta_{i,j}\end{bmatrix}. \quad (3)$$

The variables i and j represents the position of array elements in $x-axis$ and $y-axis$ respectively, λ is the wavelength, θ and φ is the elevation steering angle and azimuth steering angle respectively.

The Array Pattern $\boldsymbol{F}(\theta, \varphi)$ is evaluated by the Hadamard product of $\boldsymbol{AF}(\theta_i, \varphi_j)$ and a matrix **M,** which is set up by concatenating the individual pattern vectors of radiating patches, $\boldsymbol{F}(\theta, \varphi) = \boldsymbol{AF}(\theta_i, \varphi_j)\circ\boldsymbol{M}$. The Gain Pattern $\boldsymbol{G}(\theta, \varphi)$ at any arbitrary angle θ and φ can be calculated as:

$$\boldsymbol{G}(\theta, \varphi) = \boldsymbol{F}(\theta, \varphi).\boldsymbol{w}, \quad (4)$$

where vector $\boldsymbol{w} = \boldsymbol{I}_{(i,j)}e^{j\Delta\phi}$represents the complex weighting function need to guide the ixj^{th} element in 4x4 array. For subsequent analysis, the azimuth angle φ has been taken fixed and the results are presented for the elevation angle θ only.

When 4x4 planar array shape changes to the prescribe spherical shape of radius r, the whole radiation array pattern distorts due to change in $\boldsymbol{AF}(\theta_i, \varphi_j)$ for each element in the array. The problem is to calculate the correct weights $\boldsymbol{w_c}(\theta_i, \varphi_j)$ in 4x4 spherical conformal microstrip array to compensate for any radiation pattern errors occurred due to change in the shape.

III. PROPOSED SOLUTION

The approach adopted for mutual coupling reduction and deformity compensation is presented as a flowchart in Fig. 3.

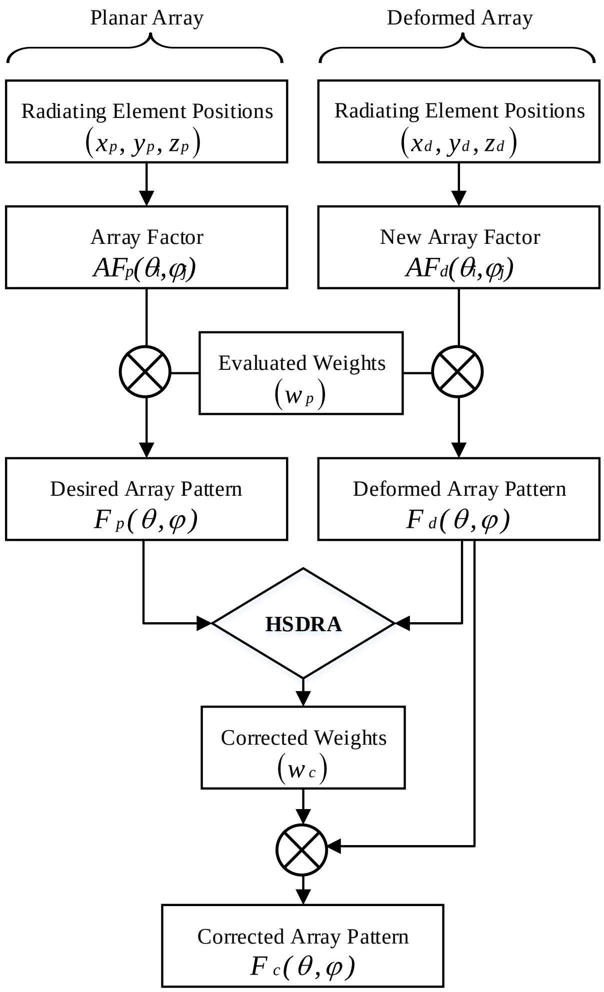


Fig. 3. Compensation technique for spherical deformation.

The 4x4 array antenna is designed and simulated in Computer Simulation Technology (CST) for the center frequency of $2.5GHz$. The initial weights w_p assigned to each element of the array are used to obtain the desired radiation pattern by optimizing the field patterns to get the desired mainlobe direction and nulls at the specific positions. In particular, unity weights are assigned to the elements of planar array to show the performance of proposed compensation algorithm. The original positions of array element in planar and spherically deformed structure were found in CST and the Array Factor is calculated on the basis of their position vectors, then the element patterns are concatenated with the Array Factor to from the Array pattern of desired and deformed structure respectively.

The HSDRA algorithm for radiation pattern correction is based on Constraint Least Squares Optimization modified with particular nulls placement. It is given to the deformed array to evaluate the corrected weights which compensate the effects of deformity and mutual coupling occurred due to surface deformation. Although the compensation technique can be implemented for several geometrical deformations but here only spherical deformation is considered on the planar array. The algorithm is formulated to minimize/ reduce the absolute distance between the field pattern of the deformed array and the desired field pattern of planar array while ensuring that the null positions are precisely defined, and are of sufficient depth and the main beam direction is at the desired location. For this, first Linearly Constraint Least Squares Optimization (LCLSO) is used and then Quadratically Constraint Least Squares Optimization (QCLSO) is used on the results obtained from LCLSO to calculate the correct excitation of the amplitude and phase to synthesize the preferred main beam and nulls direction to achieve the desired radiation pattern for 4x4 spherical conformal microstrip array antenna and the results are shown separately for the comparison.

For the enhancement of Gain of the conformal array antenna, the Gain Maximization Algorithm is proposed, the simulated results of which is compared to the traditional phase compensation technique and basic form of least squares optimization. Gain maximization algorithm is based on maximizing the distance between minimum and maximum points in the pattern while constraining the input and output power to unity to increase the overall gain and performance.

A. Computation for radiation pattern correction

The HSDRA algorithm for radiation pattern correction is based on Constraints Least Squares Optimization which iteratively updates the weights of conformal array while searching for the point of minimum sum of squared errors between the actual field in deformed array E_d and targeted field E_p of planar array. The basic form of Least Square Optimization includes some excitation amplitude distribution weights for maximizing the gain while minimizing the sidelobes to a certain level. It aims to decrease the Mean Square Error (MSE) between the field patterns of deformed spherical array and targeted planar array as shown in equation:

$$\text{minimize } \mathrm{w_d} \sum_{\theta,\varphi} \left|\mathrm{F_d w_d} - \mathrm{F_p w_p}\right|^2. \quad (5)$$

The individual antenna pattern has been imported from CST for specific radius r whereas the distorted array pattern is compensated by a matrix P obtained as:

$$\begin{aligned} P &= (F_d)^{\dagger} F_p \\ w_c &= P \cdot w_i \\ E_p &= F_d w_c, \end{aligned} \quad (6)$$

where † indicates the pseudo inverse and is defined as $(F_d)^{\dagger} = F_d^H (F_d F_d^H)^{-1}$. Here $F_d \in \mathbb{C}^{i \times j}$ is the matrix containing measured/simulated gain pattern of the vector contain the initial weights $w_{i=}w_p$ which shape the desired array pattern (in this paper, unity weights are assigned to the elements of planar array to show the performance of proposed algorithm), and w_c contains the recovered corrected weights which correct the radiation pattern errors occurred due to deformity.

The Least Squares Optimization (LSO) method in its basic form generates a solution that is for unknown (guessed) excitation values. This solution contains error distribution either in the main-lobe or sidelobes or both because it does not control the level of individual peaks, rather than it only controls and measures the level of general lobes by reducing the Mean Square Error (MSE) between the resulting field pattern and the desired one. Unfortunately using LSO only without modification for the pattern correction gives guessed values which may not be optimal for the final design. Therefore for recovering precisely some of the points on the pattern the optimization problem need to be constraint. In order to accurately control nulls positions and the direction of main beam, LSO is modified by introducing constraints at those points on the pattern that needs to be recovered and controlled precisely.

The goal in Constraint LSO approach is minimizing the Euclidean distance between simulated/measured and desired pattern while constraining some points (either peak of main lobe, null points or sidelobe points) to find the corrected weights. In Linearly Constraint Least Squares Optimization (LCLSO) method, the Euclidean distance between the measured pattern in deformed array E_d and desired pattern of planar array E_p is minimized while constraining the pattern at some points (either null points or the peak side lobe points) to find the compensated weights w_c. The optimization problem is written as:

$$\text{minimize}_{\,\mathrm{w_c}} \sum_{\theta,\varphi} \left| \mathrm{F_d w_c} - \mathrm{F_p w_p} \right|^2 \quad (7)$$
$$\text{subject to } \mathrm{F_d w_c} = \mathrm{b},$$

$$\mathrm{F}_c = [F_d(\theta_1, \varphi_1), F_d(\theta_1, \varphi_2) \cdots F_d(\theta_4, \varphi_4)]^T,$$
$$\mathrm{b} = \left[E_p(\theta_1, \varphi_1), E_p(\theta_2, \varphi_2) \cdots E_p(\theta_4, \varphi_4)\right]^T. \quad (8)$$

Here $\mathrm{F_c} \in \mathbb{C}^{q\times(ixj)}$ is a matrix containing the q constraint vectors at ixj positions of 4x4 array at the desired constrained angles in the measured individual element pattern matrix of deformed structure and $b \in \mathbb{C}^{q\times(N)}$ is a vector of q constraint points on the planar array pattern and N represent the ixj^{th} location of radiating elements on the array.

The linear weights reduce the search space so that the solution satisfying the constraint is the only possible solution. Consequently, the compensated pattern performs well at the mainlobe peak and null points (constraint points) but does not care for the rest of the radiation pattern. As a result, higher side-lobe level at the edges, away from the constraint points can be observed. The error performance of LCLSO, however, improves with increasing the number of constraints chosen at the extremal point evenly spread over the radiation pattern. However, there is an upper limit on the maximum number of constraint points $q < N$.

The problem in LCLSO with controlling the side lobes level is therefore further modified by quadratically constraints, which is given as:

$$\text{minimize}_{\,\mathrm{w_c}} \sum_{\theta,\varphi} \left| \mathrm{F_d\, w_c} - \mathrm{F_p\, w_p} \right|^2 \quad (9)$$
$$\text{Subject to } |\mathrm{F_c w_c} - \mathrm{b}|^2 \le \beta,$$

where $0 \le \beta \le 1$ is a constraining factor, lower the value of β smaller is the search space. This technique provides alternative to the Linearly Constraint LSO because it allows a good compromise, enabling the corrected pattern to follow the desired pattern more closely. The QCLSO compensates the weighting function not only in the main lobe but also on the peaks of the side lobes while at the same time ensuring that the desired null depths are achieved. Since exact solution of QCLSO does not exist, therefore numerical approach using Newton-Raphson method has been used to solve the above optimization problem.

The algorithm is programmed and analyzed for the spherical structure of $r = 20cm$ (maximum deformation) deformed from planar structure. The algorithm uses 12 number/level of iterations for finding the correct excitation of the amplitudes and phases. The average computation time between each iteration is 0.23 seconds and the Total CPU time is approximately 2.74 seconds. A computer of Intel Core i7 (6th Generation) processor with 3.40 GHz CPU speed and 8 GB of RAM was used and the algorithm was programmed and verified in MATLAB 2018a version and CST Studio Suite 2019 version respectively.

B. Computation for gain optimization

To compensate the loss in gain when the array is deformed, an approach using Gain maximization algorithm is introduced which minimizes the Euclidean distance between measured Gain in deformed array $G_d(\theta, \varphi)$ and target Gain in planar array $G_p(\theta, \varphi)$ while minimizing the gain loss to find the compensated weights. The weights are generated for the desired gain pattern which is estimated using the Gain maximization algorithm based on maximizing the distance between minimum and maximum points in the pattern while constraining the input power and output power to unity. So, the problem formulation for this technique is:

$$minimize \sum_{\theta,\varphi} \left| \mathrm{F_d w_c} - \mathrm{F_p w_p} \right|^2 \quad (10)$$
$$\text{Subject to: } \mathrm{w_c}^{\mathrm{H}} \mathrm{w_c} \le \gamma,$$

where γ represents the output power of compensated weights. The input power of weight vectors is kept unity to find all the patterns. In minimizing the gain loss approach the error was minimized while keeping power of weights unity. Hence loss in gain is also minimized. Newton-Raphson method has been used to evaluate the solution of w_c for the above optimization problem.

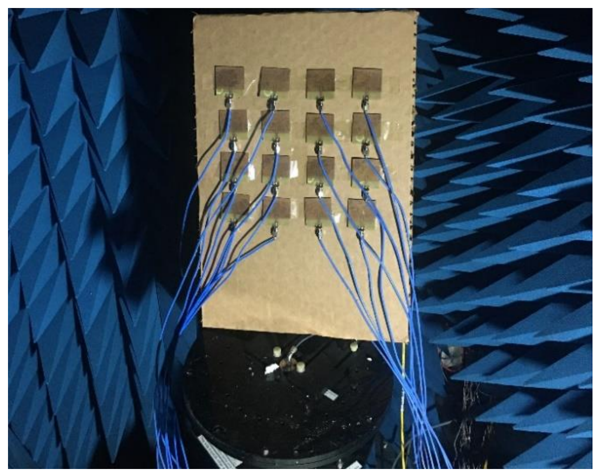
The concept of Phase compensation technique used in [23] is implemented here to generate a broadside radiation pattern along a tangent reference plane, for gain enhancement. The results obtained with this technique are compared with the proposed method using Least Square Optimization and Gain Maximization Algorithm. A tangent reference plane is considered to the center of the array and the E-fields from each of the radiating elements on the 4x4 spherical array are assured to reach the tangent plane with the matching phase to create constructive interference for gain enhancement. For this, each radiating element on the spherical surface is specified with correct weighting function of amplitudes and phases for the creation of broadside radiation pattern along z-axis. The location of each element on a sphere is determine by the following expressions in terms of angle "θ" measured from z-axis,

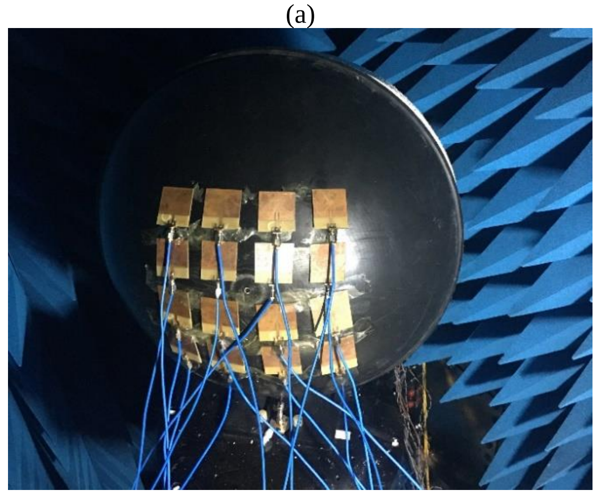
$$\theta_{i,j} = \frac{1}{r}\sqrt{\left(id_y + d_y/2\right)^2 + (jd_x + d_x/2)^2}, \quad (11)$$

and the phases of each element required for correction of radiation pattern is computed as $\Delta\phi_e = -jk\Delta z_e$, where $\Delta z_p = r(1 - sin\ \theta_{re})$ represents the distance from the radiating element on the spherical surface to the reference plane and θ_{re} is the corresponding angle from the origin along z-axis.

IV. RESULTS AND DISCUSSIONS

Sixteen elements patch antenna in 4x4 spherical configurations have been used for simulation and analysis purposes. Two spherical deformations were investigated where planar array is deformed at $30cm$ and $20cm$ radius. Further these two deformations are investigated for equally and unequally inter-element spaced arrays and the results of these deformations are compared with the desired results achieved in planar array configuration. One is equally spaced on both side, that is $dx = dy = 0.5\lambda$, and the other one has $dx < dy$. In unequally spaced case dx is kept at 0.4λ and dy at 0.6λ. 3D electromagnetic simulation and analysis software (CST) is used for the verification of the results. All the radiation patterns, such as desired in planar array, deformed and the corrected one in spherical array, are first evaluated in MATLAB and then validated through CST. To verify the results, the antenna test platform for equally spaced 4x4 array structure is constructed for planar and spherical configurations of $\mathrm{r} = 30\mathrm{cm}$ and $\mathrm{r} = 20\mathrm{cm}$ as shown in Fig. 4. Similar test platform is also used for unequal spaced array configuration. The experimental setup includes sixteen numbers of Phase Shifters (DBVCPS02000400A) and variable voltage controlled attenuators (ZX73-2500+), which are connected with two numbers of 1x8 power Splitter/Combiner (ZN8PD1-63W+) feed network connected with high gain power amplifier (PE15A4018) as discussed in Section II of the paper. This test platform is developed to validate the results for QCLSO technique because this method gives most optimum results in term of radiation pattern correction. Phases and Array Factors are calculated using the methodology mentioned in Section III and the position vectors of antenna elements in spherical surface is obtained in CST. A broadside radiation pattern possessing nulls at 30° and -30° has been chosen for analysis. The HSDRA algorithm calculates the weights (amplitudes and phases) for each element of the array, which are provided to attenuators and phase shifter with help of variable power supplies. After receiving the required phase shift and amplitude attenuation/ amplification at the individual patch of the conformal array, the corrected radiation pattern measurements were carried out in a fully calibrated Anechoic Chamber.


(a)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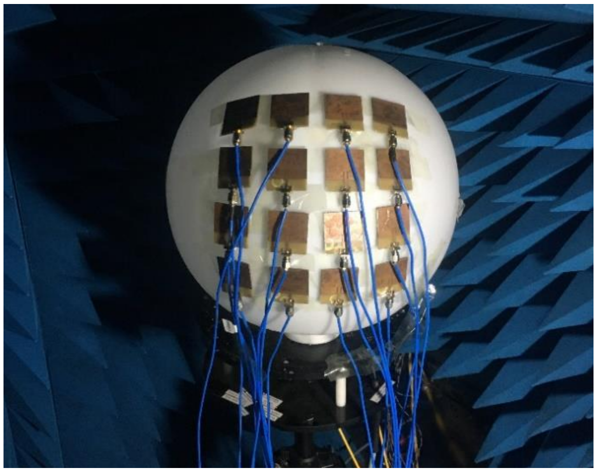
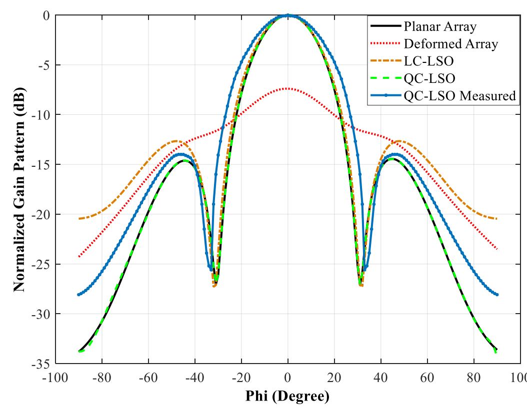


(c)

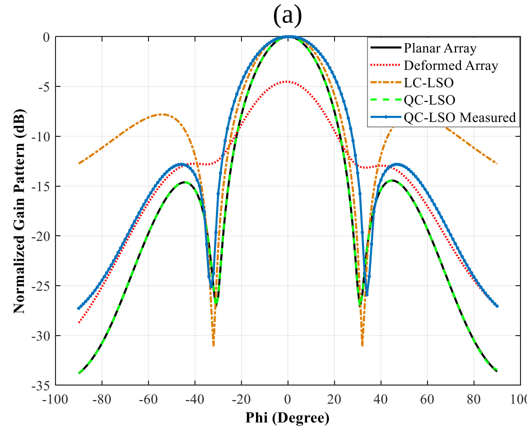
Fig. 4. 4x4 array configuration of: (a) planar array, (b) spherical configuration of $30cm$, and (c) spherical configuration of $20cm$.

The result of HSDRA algorithm for the radiation pattern correction is shown separately as LCLSO and QCLSO. The results of radiation pattern correction for equally spaced array with geometric spacing of 0.5λx0.5λ and unequally spaced array with geometric spacing of 0.4λx0.6λ are discussed in Fig. 5 and Fig. 6 respectively. The choice of different inter element separation is considered to render the effect of mutual coupling and deformity on the radiation pattern of the spherical array. It is observed that when pattern is compensated with Linearly Constrained Least Squares Optimization (LCLSO), the mainlobe direction is well achieved whereas the sidelobe level increases which is obvious because when the locations are linearly constrained it does not care about the rest of the pattern as it only tries to satisfy the constrained points. Similarly, when the deformation is increased that is that radius of curvature of conformal spherical array is $20cm$, the sidelobe level further increases while satisfying the mainlobe direction and losing the nulls points. Whereas the Quadratic Constrained Least Squares Optimization (QCLSO) gives some relaxation in search space of output. This compensation technique gives better fit results at the nulls, at the edges of the mainlobe and has low side lobe level almost approaching to the desired one. This method computes appropriate amplitude and phase excitation that recovers the radiation pattern of the spherical array set up on a conformal structure up to a radius of $20cm$.

It is shown that when the planar array undergo spherical deformation, the radiation pattern has been distorted severely, i.e., significant reduction up to 80% is noticed in the mainlobe gain, no sidelobes are formed and the nulls are completely lost; however, the QCLSO compensation algorithm accurately recovers the radiation pattern to the desired one. So, the HSDRA algorithm combines the linearly constraint and quadratically constraint Least Squares optimization to calculate the corrected complex weights to synthesize the preferred mainlobe, sidelobes and nulls direction to attain the desired radiation pattern in the planar array which compensate the effects of deformity and mutual coupling occurred due to surface deformation. After compensation algorithm, the distorted pattern recovers successfully which is similar to the planar (desired) array pattern with sidelobe levels and nulls locations nearly in the same position as that of the planar array as shown in the Figs. 5 and 6.

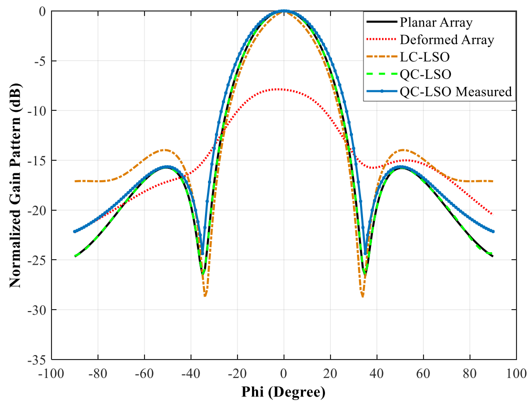


(a)

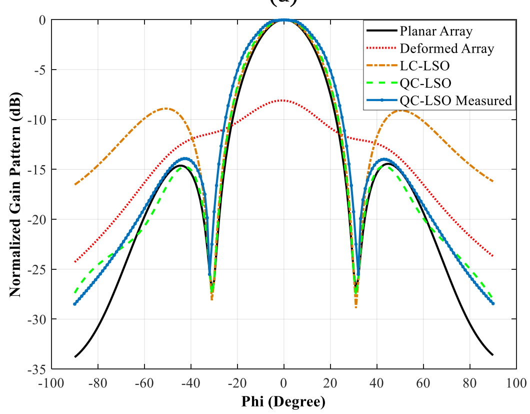


(b)

Fig. 5. Results for 4x4 spherical array with equal element spacing ($dx = dy = 0.5\lambda$) with a radius of (a) $30cm$ and (b) $20cm$.



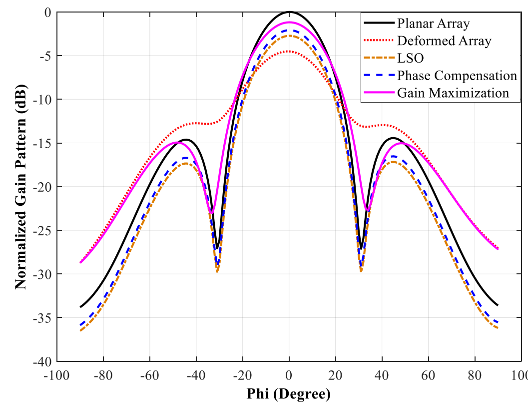
(a)



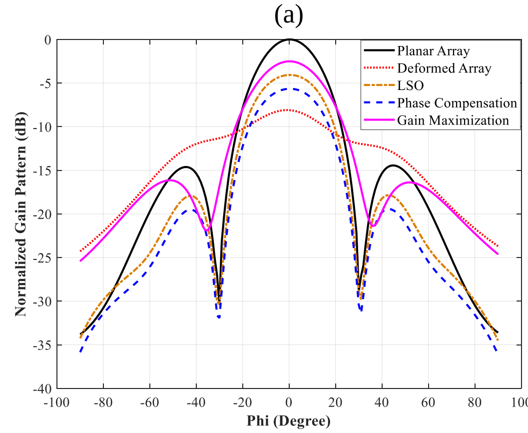
(b)

Fig. 6. Results for 4x4 spherical array with unequal element spacing ($dx = 0.4\lambda, dy = 0.6\lambda$) with a radius of (a) $30cm$ and (b) $20cm$.

The results of gain analysis is shown in Figs. 7 and 8. It reveals that the 4x4 planar array with equally spaced array has a simulated gain of $16dB$ and for unequally spaced it is $17.5dB$. After deformation the gain loss is more than $26dB$ for each case. It is observed that after the transformation of the planar array onto the spherical surface the radiation pattern changes significantly, hence phase correction is required to correct the gain and recover the pattern. The unconstrained least squares optimization yields unfeasible excitations for antenna elements, which causes a significant decrease of gain (up to $3dB$) in each case whereas, the location of nulls are slightly compromised for both equally and unequally spaced arrays. The distorted pattern obtained with Phase Compensation technique in which the radiation pattern is targeted on a reference tangent plane, the nulls are well recovered however the gain is decreased by$2dB$ for $30cm$ radius and $3.5dBs$ for $20cm$ radius respectively. Furthermore, Gain Maximization Algorithm is employed to maximize the gain of array. It shows a good increase (up to $2-4dBs$) in gain as compared to phase compensation and LSO technique however, the nulls are not recovered properly. In general, the results reveal that gain is recovered very efficiently for unequally spaced spherical patch antenna array, whereas it shows less recovery for equally spaced spherical antenna array.

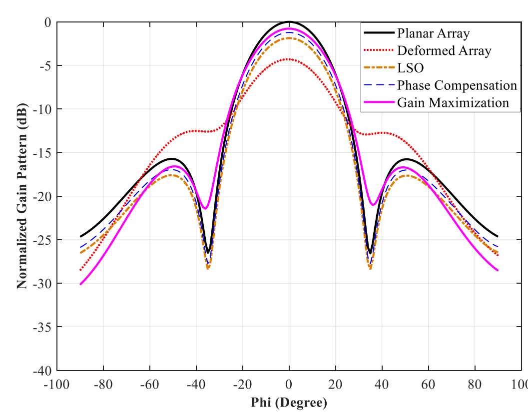


(a)

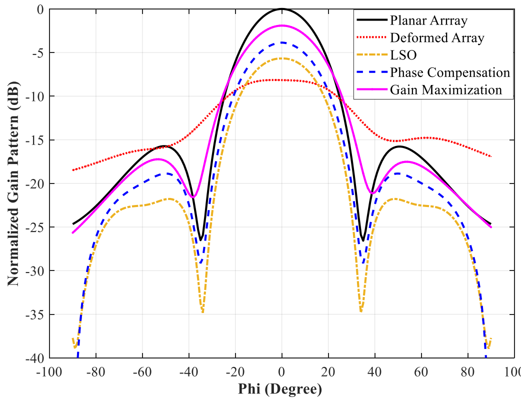


(b)

Fig. 7. Comparison of least squares optimization, gain maximization and phase compensation technique for 4x4 spherical array with equal element spacing ($dx = dy = 0.5\lambda$) with a radius of (a) $30cm$ (b) $20cm$.



(a)



(b)

Fig. 8. Comparison of least squares optimization, gain maximization and phase compensation technique for 4x4 spherical array with unequal element spacing ($dx = 0.4\lambda$, $dy = 0.6\lambda$) with a radius of (a) $30cm$ and (b) $20cm$.

V. CONCLUSION

In this Paper, a radiation pattern correction technique based on Hybrid Spatial Distance Reduction Algorithm (HSDRA) is used to reduce the effects of antenna surface deformity and mutual coupling for 4x4 conformal array antenna. The algorithm put together LCLSO and QCLSO techniques to calculate the corrected complex weights to synthesize the radiation pattern. The algorithm is formulated to minimize/reduce the absolute distance between the simulated radiation pattern and the desired radiation pattern while keeping the direction of mainbeam, sidelobe levels, and the nulls position under control to overcome these changes. The results for LCLSO are shown separately. However, with this technique, higher sidelobes levels are observed. The inadequate results obtained with LCLSO are therefore further modified by QCLSO technique. This method gives adequate results at the nulls, at the peak and edges of the mainlobe and has low side lobe level almost approaching to the desired one. This method computes appropriate amplitude and phase excitation that restores the radiation pattern of spherical conformal microstrip array up to a radius of $20cm$ spherical deformation.

The simulated results for gain analysis between the unconstraint least squares optimization, Phase compensation and Gain Maximization Algorithm is also presented. All the three techniques follow the same approach to optimize the pattern with slight changes in gain. The distorted pattern obtained with Phase Compensation technique and unconstrained least squares optimization yields unfeasible excitations for antenna elements, which causes a significant decrease of gain in each case. The Gain Maximization Algorithm shows a good increase in gain as compared to unconstraint least squares optimization and phase compensation technique however the nulls are not recovered properly in this method. Furthermore, this algorithm recovers the gain very efficiently for unequally inter-element spacing, whereas it shows less recovery for equally spaced spherical array.

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