

## ORIGINAL ARTICLE

# Radiation pattern synthesis in conformal antenna arrays using modified convex optimization technique

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## Abstract

In this paper, a modified convex optimization technique is used for radiation pattern correction in a cylindrical-shaped conformal microstrip array antenna. The technique uses numerical simulations to optimize the amplitude and phase excitations, with the goal to decrease the Euclidean distance between the desired field pattern and the obtained (simulated/measured) field pattern while maintaining the main beam direction, null's location, and side lobe levels under control. Two prototypes of  $1 \times 4$  and  $2 \times 4$  conformal microstrip antenna array deformed from linear/planar structure to the prescribed cylindrical shape, with different radii of curvature, are studied to demonstrate the performance of the proposed technique. The proposed convex optimization model when applied to conformal antenna array possesses fast computing speed and high convergence accuracy for radiation pattern synthesis, which can be a valuable tool for engineering applications.

## KEYWORDS

conformal array antenna, convex optimization, least square optimization, mutual coupling compensation, radiation pattern correction

## 1 | INTRODUCTION

Conformal antenna arrays<sup>1</sup> with efficient beam forming capabilities are highly anticipated for future 5G technology in many applications such as avionics,<sup>2</sup> high-speed vehicles,<sup>3</sup> wearable body area networks,<sup>4</sup> conformal

antenna arrays,<sup>5</sup> conformal Ultra Wide Band (UWB) antennas,<sup>6</sup> and special purpose devices that require the antenna to operate on a curved surface.<sup>7</sup> A conformal array is designed to follow or conform to any prescribed shape, for example, circular, elliptical, cylindrical or spherical. When compared to linear or planar arrays, the

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conformal antenna arrays have several advantages, including: (i) flexibility of structural integration ability on an arbitrary non-flat surface, (ii) lower radar cross section (RCS), (iii) and wide angular coverage capabilities.<sup>8–10</sup>

However, antenna surface deformation seriously affects the radiation performance.<sup>11</sup> For example, it will lead to broadside beam deviation, null's depth and position transformation, reduced antenna gain and side lobe level (SSL) elevation. This surface deformation may occur due to intentional (static prescribed shape) and/or unintentional (vibrations, severe weather conditions, external mechanical load) forces that physically change the shape of antenna. Therefore, it is important that the conformal antenna arrays have an adaptive capability system for pattern correction with flexible controlled beams to mitigate the deterioration of the field pattern. This paper investigates the effect of cylindrical static deformations of various radii of curvature when curved from planar configuration. We describe a technique based on convex optimization for the compensation of mutual coupling and radiation pattern correction.

Array pattern synthesis requires electromagnetic (numerical or analytical or both) optimization with flexible controlled beams assisted by advanced signal processing systems, in order to restrain the parameters that satisfy a set of specifications to precisely control the beam pattern.<sup>12</sup> In the literature, various techniques and algorithms have been developed to achieve the desired radiation pattern characteristics in antenna arrays. Several probabilistic or evolutionary optimization techniques such as Particle Swarm Optimization (PSO),<sup>13</sup> Genetic Algorithm (GA),<sup>14</sup> Taguchi algorithm,<sup>15</sup> and Differential Evolution (DE) algorithm<sup>16</sup> have been used to control and correct the radiation pattern. These optimization methods iteratively search, evaluate and improve the parameters to determine the best-fitted results. In Reference 17, a hybrid evolutionary optimization algorithm using Improved Genetic Algorithm (IGA) along with Improved Particle Swarm Optimization (IPSO) is used for the pattern synthesis in conformal microstrip antenna array to minimize the side lobe levels by adjusting the amplitude and phase weights of the array elements. A comparative analysis of DE, PSO, and GA is evaluated to optimize the amplitude and phase excitations across the antenna elements for the design of scannable circular antenna arrays.<sup>18</sup> In Reference 19, the Differential Evolution (DE) algorithm is applied to aperiodic spherical arrays in order to achieve the optimum angular position of each element for attaining the maximum performance of array antenna in terms of radiation pattern, beam scanning and directivity. In Reference 20, the performance of several gradient based adaptive beam forming techniques such as traditional LMS (Least mean square),

NLMS, Hybrid LMS, VSS-LMS, and so forth have been investigated for beam-steering the main lobe and side lobes level suppression.

Researchers have taken keen interest in calculating and mitigating the collective effect of the surface deformity and Mutual Coupling (MC) in conformal antenna arrays. Since MC affects the input impedance of antenna elements in the array, the concept of modeling the MC using impedance matrix in antenna arrays is used to reduce the effect of MC in a dipole array.<sup>21</sup> This MC Matrix is also used for adaptive nulling of interference in phased arrays<sup>22</sup> and for Direction of Arrival (DOA) estimation in dipole arrays.<sup>23</sup> An assimilation technique that uses port currents to model the MC is proposed in Reference 24 to compensate for the effect of MC in radiation pattern correction. In Reference 25, the redundant surface current that moves between the array elements is controlled for MC compensation and radiation pattern recovery, by employing the complementary split ring resonators (CSRR) in a four-element microstrip patch array for 5G beam forming application.

In radiation pattern synthesis of the conformal arrays, the major concern is to estimate the appropriate weights (amplitude and phase excitations) to compensate the mutual coupling and correct the desired radiation pattern without compromising the radiation characteristics of the array. In Reference 26, a projection method is described to compute accurate values of amplitude and phase excitations and providing low side lobe level patterns in a conformal array. Similar approach of using the projection method to correct the field pattern in conformal arrays has been used in References 24–26. In Reference 27, a pattern synthesizing technique based on Least Square Method (LSM) algorithm is developed to form the desired field pattern for Equally Spaced Linear Array (ESLA). A compensation technique<sup>28</sup> and iterative weight-correction method<sup>29</sup> based on Constraint Least-Squares Optimization are used to recompensate the mutual coupling effects and to control the side lobe level for phase correction of conformal arrays. In Reference 30, a novel approach using Hybrid Spatial Distance Reduction Algorithm (HSDRA) with particular null's placement, is used for radiation pattern correction in  $4 \times 4$  spherical-shaped conformal antenna array. To summarize, it is found that various optimization approaches along with appropriate signal processing techniques can be utilized for adjusting the amplitude and phase excitation of an individual element of the array in order to accurately restrain the radiation properties of conformal phased arrays.<sup>31–33</sup>

In this paper, convex optimization is modified for radiation pattern synthesis in order to mitigate the effect of antenna surface deformation by finding the correct weight excitation (amplitudes and phases) of array elements in cylindrically-shaped conformal array antenna.

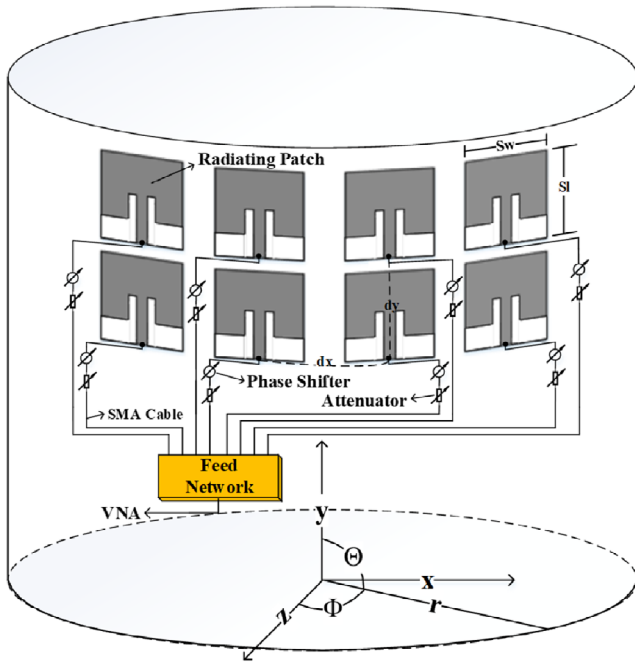


FIGURE 1 Compensation method for cylindrical deformation

The optimization technique is designed to decrease the Euclidean distance between the obtained (simulated/measured) field patterns and the desired field patterns while maintaining the main beam direction, null's location and side lobe levels (SSL) under control. The technique is also used to resolve the loss in radiation characteristics due to the surface change from desired linear/planar shape to prescribed cylindrical shape. In particular, two prototypes of a  $1 \times 4$  and a  $2 \times 4$  array are deformed from linear/planar structure to the prescribed cylindrical shape with various radii of curvature, and examined to demonstrate the performance of proposed optimization technique.

## 2 | ARRAY FACTOR FORMULATION

The system model of a  $i \times j$  microstrip patches fixed at half wavelength placed on a cylindrical surface of radius  $r$  with broadside beam along  $z$ -axis, is shown in Figure 1. Each microstrip patch is fabricated on a “Lossy Roger RT-6002” substrate having a relative dielectric value  $\epsilon_r = 2.95$ , and the substrate thickness is 1.52 mm having width  $Sw = 37$  mm and length  $Sl = 41$  mm. The conformal array is designed for 2.50 GHz and inter-element spacing between patches is kept at  $0.5\lambda$ .

The design and measurements of a single fabricated microstrip patch in the  $i \times j$  conformal array are given in Figure 2 and Table 1, respectively.

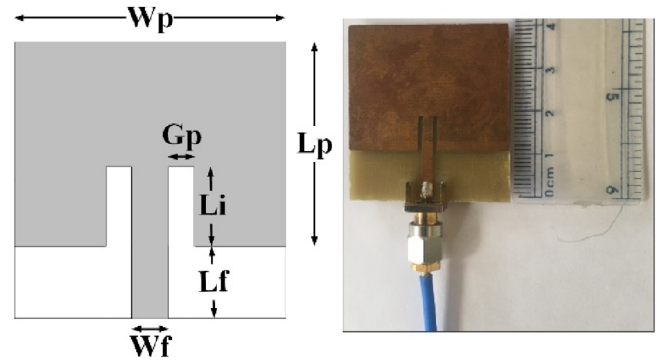


FIGURE 2 Prototype of single patch

TABLE 1 Dimension of a single microstrip patch

Parameter	Length (mm)	Description
$W_p$	37	Width of the patch
$L_p$	30	Length of the patch
$W_f$	2.5	Width of the feed line
$L_i$	8	Length of the inset feed
$L_f$	11	Length of the feed line
$G_p$	1	Gap between the patch and feedline

The position of each antenna element in an array is determined by the following equation

$$CP_n(d, r) = r \left[ \sin \left( -(N-1) \frac{d}{2r} + \frac{d}{r}(n-1) \right) \right], \quad (1)$$

where,  $N$  represents the number of radiating elements in the array,  $d$  is the inter-element spacing in terms of  $\lambda$  (lambda) and  $r$  is the radius of the cylinder. To analytically calculate the compensated radiation field pattern and verify it with the simulation results, based on the location of the radiating patches, the following array factor (AF) is used

$$AF = \sum_{n=1}^N w_n |E_0(\theta, \varphi)| e^{jk[i_n \sin \theta + j_n \cos \varphi]}, \quad (2)$$

where,  $|E_0(\theta, \varphi)|$  is the electrical field pattern of the individual element,  $k$  is the free space wave number, the vector  $w_n = I_n e^{j\Delta\phi}$  represents the complex weighting function need to guide  $n$ th element at the  $(i_n, j_n)$  location of the conformal array,  $\Delta\phi$  represents progressive phase shifts between adjacent antenna elements, while  $\theta$  and  $\varphi$  are the elevation and azimuthal angles, respectively.

The Array Pattern  $AP(\theta, \varphi)$  is calculated by the Kronecker product of  $AF(\theta_{i_n}, \varphi_{j_n})$  and a matrix  $K$ , which is

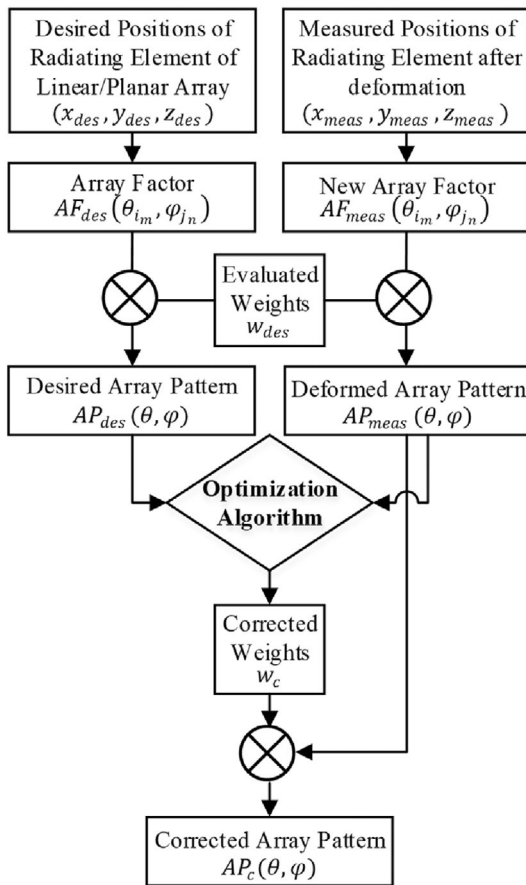


FIGURE 3 Proposed technique for the pattern correction of cylindrical deformation

compiled by concatenating the individual element pattern vectors. It is given by

$$AP(\theta, \varphi) = AF(\theta_{in}, \varphi_{jn}) \otimes K. \quad (3)$$

For the analysis of the algorithm, the azimuthal angle  $\varphi$  is assumed to be fixed and the results are taken for the elevation angle  $\theta$  only.

### 3 | PROPOSED SOLUTION

The approach adopted for the correction of the radiation field pattern in cylindrical configuration is presented as a flow chart in Figure 3.

The convex optimization model is chosen as the basic method for radiation pattern synthesis, the electric field pattern of the conformal array is selected as an objective function, and a model is transformed into convex optimization problem. The algorithm aims to iteratively update the complex weights (amplitude and phase excitations) while searching for the maximum likelihood between the

obtained field pattern in the deformed cylindrical array  $E_{meas}$  and desired field  $E_{des}$  of a linear/planar array. MATLAB and Computer Simulation Technology (CST) are integrated together in a loop for the algorithm implementation and verification, respectively.

The process is divided in the following steps:

- The individual array pattern is imported from CST software for particular radius  $r$  and a correction matrix  $K$  is found by Least Square Estimation (LSE) method. Using the correction matrix, the desired corrected weights  $w_c$  for deformed array are found from

$$\text{Arg minimize}_K \sum_{\theta, \varphi} |AP_{meas}K - AP_{des}|^2. \quad (4)$$

Solving the above equation for  $K$

$$K = F_{des}(F_{meas})^\dagger = F_{des}F_{meas}^H(F_{meas}F_{meas}^H)^{-1}. \quad (5)$$

The compensated/corrected weights  $w_c$  are found by multiplying correction matrix  $K$  with desired weights  $w_{des}$  as follows

$$w_c = K \cdot w_i. \quad (6)$$

In (5) the symbol  $\dagger$  indicates the pseudo inverse and  $F_{meas} \in \mathbb{C}^{i \times j}$  is the matrix that contains the simulated/measured field pattern of an individual element of the array that contains the initial weights  $w_i = w_{des}$ , which shape the desired array pattern.

- The goal is to decrease the Euclidean distance between the obtained (simulated/measured) field pattern and the desired field pattern while not disturbing the main beam direction, null's location and side lobe levels (SLL). Therefore, constraints are taken first at those positions (null's location, side lobe positions, the peak and  $-3$  dB points of the main beam) on the pattern that must be accurately recovered to estimate the compensated weights  $w_c$  as shown in Equation (1). The performance of the optimizing algorithm is improved with increasing number of constraints applied evenly over the radiation pattern at the extremum points. However, the maximum number of constraint points has an upper limit ( $q \leq N$ ). Therefore, in Equation (1), Convex Optimization is introduced within the loops after constraining the pattern in order to allow the corrected/measured field to track the desired field pattern. This more closely ensures that the desired null's location, direction of main beam and side lobe levels are accurately achieved.



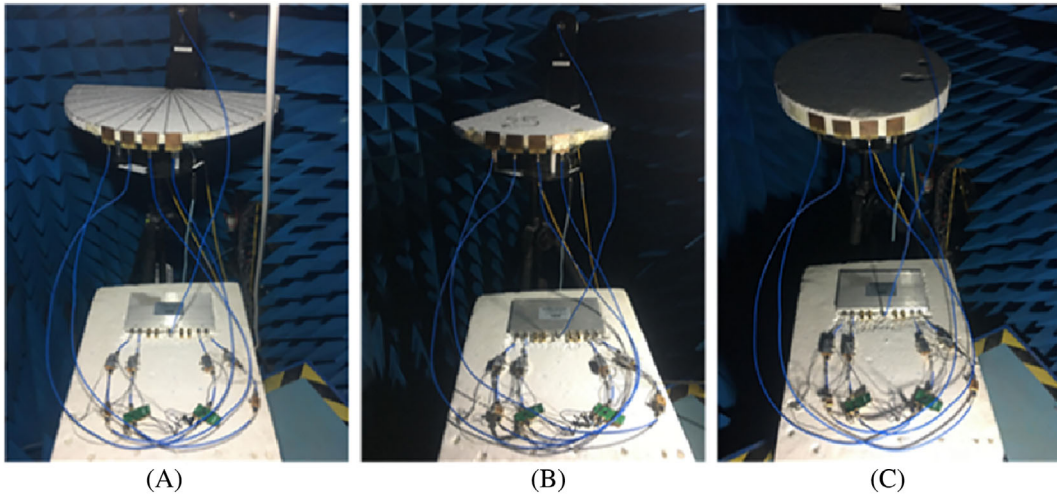


FIGURE 4  $1 \times 4$  conformal array mounted on a cylindrical configuration with radius (A) 30 cm, (B) 25 cm, and (C) 20 cm

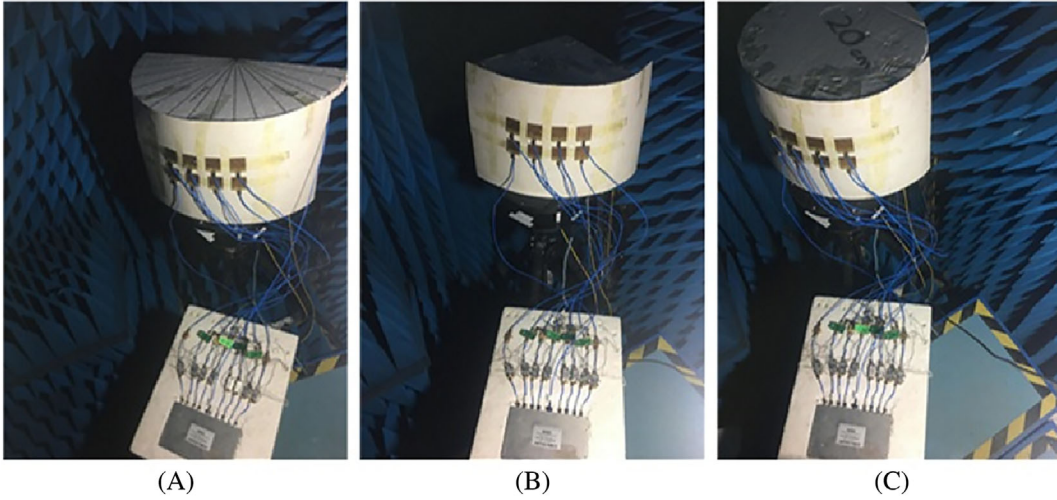


FIGURE 5  $2 \times 4$  conformal array mounted on a cylindrical configuration with radius (A) 30 cm, (B) 25 cm, and (C) 20 cm

$$\begin{aligned} & \text{minimize}_{w_c} \sum_{\theta} |AP_{meas} w_c - AP_{des} w_i|^2 \\ & \text{(i) subject to } R_{q \times N} K w_c = b_{q \times 1} \\ & \text{(ii) subject to } |R_{q \times N} w_c - b_{q \times 1}|^2 \leq \beta \end{aligned} \quad (7)$$

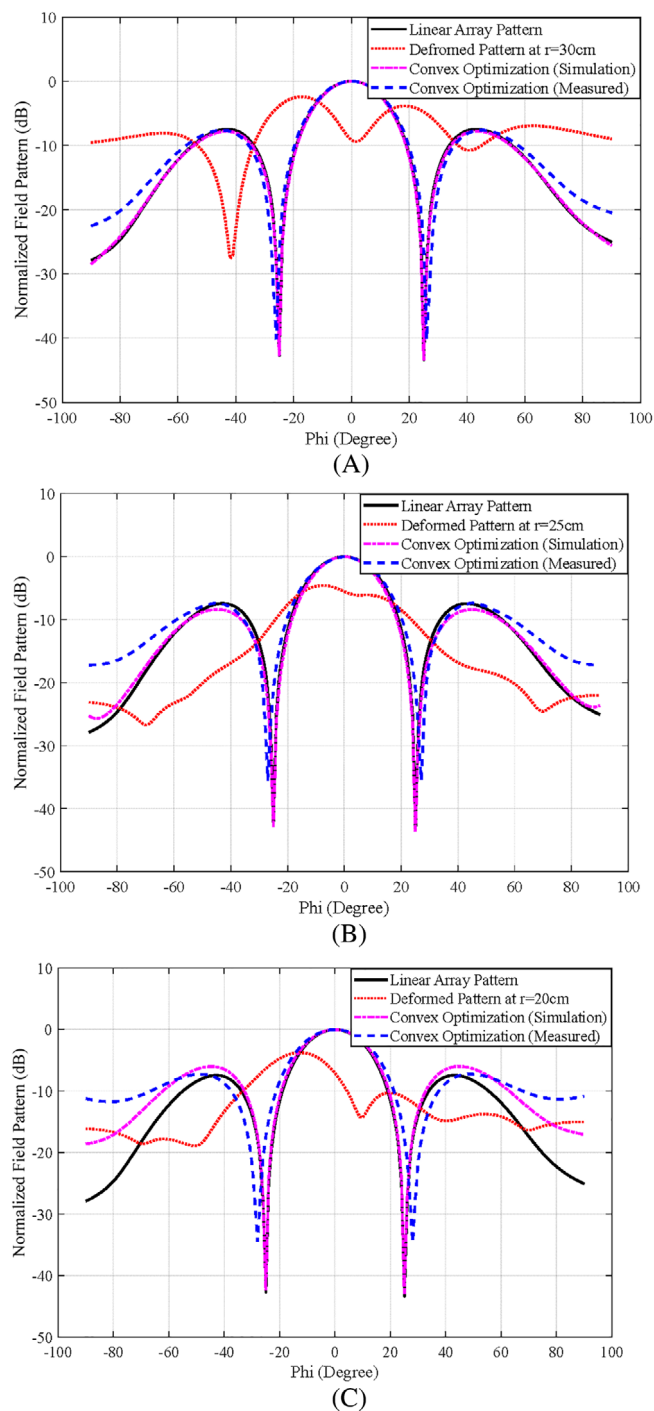
$$\begin{aligned} R_{q \times N} &= [AP_{meas}(\theta_1) AP_{meas}(\theta_1) \cdots AP_{meas}(\theta_t)]^T \\ b_{q \times 1} &= [F_{des}(\theta_1) F_{des}(\theta_2) \cdots F_{des}(\theta_t)]^T \\ w_c &= \text{pinv}(R \times K) b \\ \beta &= 20 \text{ dBs} \end{aligned} \quad (8)$$

Here  $R_{q \times N} \in \mathbb{C}^{q \times (N)}$  is a matrix containing the  $q$  constraint points of the deformed array at desired constrained angles, whereas  $b \in \mathbb{C}^{q \times (N)}$  is the vector of  $q$  constraint positions on the array pattern of linear/planar-structure. The value of  $\beta$  defines the constraining factor

of the search space and an iterative approach is adopted for the convergence to evaluate the minimum value of the objective function. The method descends in each step until the minimum is achieved, and the measured pattern follows the desired pattern more closely. The analytical approximation for the above-mentioned optimization problem has been solved using the Newton–Raphson method and the value of  $w_c$  is found using the Karush–Kuhn–Tucker (KKT) conditions.

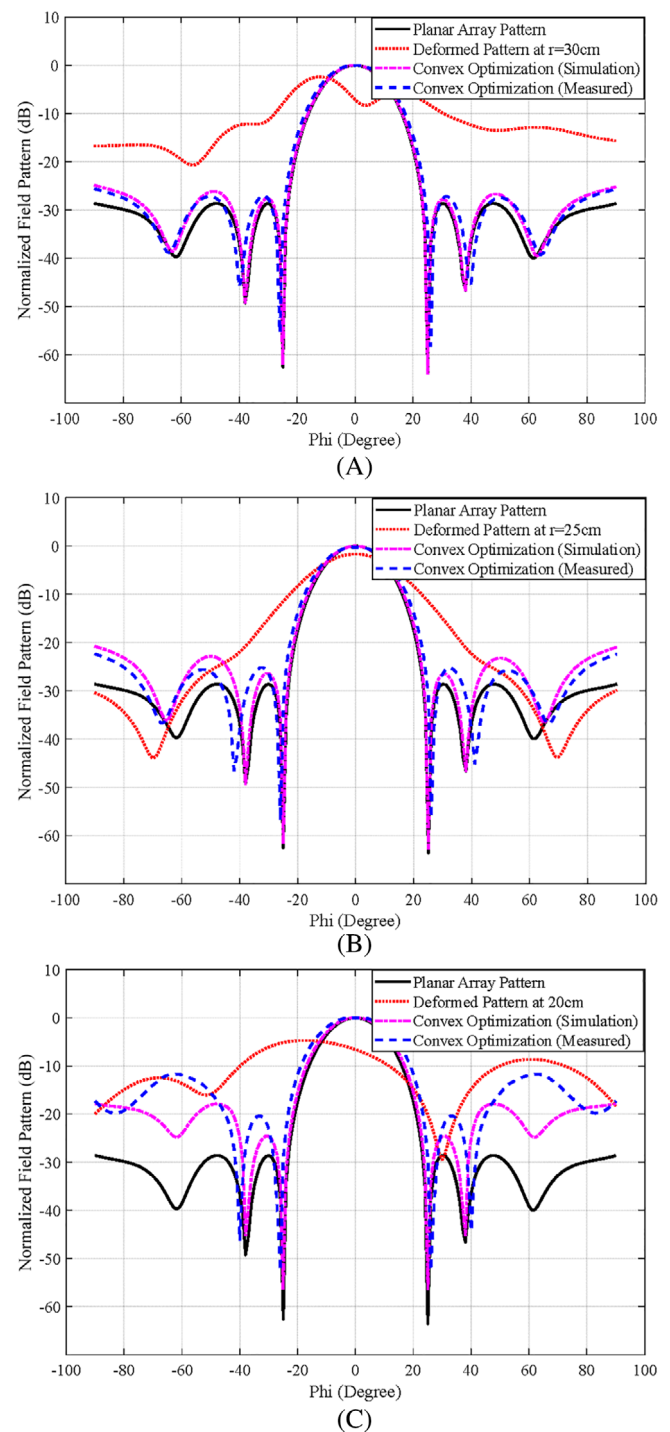
### 3.1 | Computational cost of the algorithm

The maximum cylindrical deformation of  $r = 20$  cm for  $2 \times 4$  array bent from linear/planar configuration, is analyzed to find the computational complexity of



**FIGURE 6** Results for  $1 \times 4$  conformal array mounted on a cylindrical configuration with radius (A) 30 cm, (B) 25 cm, and (C) 20 cm

optimization algorithm. The optimization algorithm uses 10 levels of iterations to satisfy the accurate weight excitations for the individual array element. The total computational time of the algorithm for the pattern synthesis is 2.74 s, whereas the average execution time between each iteration is approximately



**FIGURE 7** Results for  $2 \times 4$  conformal array mounted on a cylindrical configuration with radius (A) 30 cm, (B) 25 cm, and (C) 20 cm

0.19 s. A 6th Generation Intel Core i7-6700 Processor having 3.40 GHz Processor Base Frequency and 8 GB of RAM is used for the simulation. MATLAB 2018a version is used for the algorithm simulation whereas the 3D EM analysis software (CST Studio Suite 2019) is used for the validation of results.

## 4 | MEASUREMENT RESULTS

Two prototypes of  $1 \times 4$  and  $2 \times 4$  conformal microstrip antenna arrays with inter-element spacing equal to  $0.5\lambda$  have been used in order to show the performance of optimization algorithm. Both structures are deformed from linear/planar configuration to the prescribed cylindrical configuration with radiuses equal to  $r = 30$  cm,  $r = 25$  cm, and  $r = 20$  cm. A broadside radiation pattern having first nulls at  $25^\circ$  and  $-25^\circ$  has been taken for the analysis. To validate the simulation results, the test platform of  $1 \times 4$  and  $2 \times 4$  array configuration is fabricated for both planar array and cylindrical array with  $r = 30$  cm,  $r = 25$  cm, and  $r = 20$  cm as depicted in Figures 4 and 5.

The proposed experimental setup consists of a high gain power amplifier (PE15A4018) connected to  $8 \times 1$  power combiner/splitter (ZN8PD1-63W+) feed network. The feeding network is further connected to 8 RF Variable Attenuators (ZX73-2500+), each coupled with voltage controlled phase shifters (DBVCPS02000400A). The amplitude and phase values are given to the phase shifter and attenuators through variable power supplies. First, the position vector of each individual array unit is obtained. Thereafter, the array factor is computed using the method discussed in section III.

Preliminary simulations are done in CST to achieve the electric field intensity for all the units. Second, MATLAB-based optimization algorithm as described in Equation (7), is used to find the weight excitation (amplitudes and phases) for each array element in deformed configuration. After receiving the required weight calculation and phase results, the data are sent to CST again to obtain the final simulated radiation pattern of the optimized array antenna.

Finally, the simulation model of corrected radiation pattern of the deformed array is measured in a fully calibrated Anechoic Chamber.

The results show that the proposed optimization technique computes appropriate values of complex weights, which restore the field pattern in the conformal array with cylindrical deformation up to a radius of 20 cm. It can be observed that when  $1 \times 4$  and  $2 \times 4$  arrays are deformed from the linear/planar geometry to the prescribed cylindrical deformation, a significant distortion is observed in the radiation pattern. The null's location and side lobe level are completely removed and a remarkable decrease in the gain of the main beam is noticed. However, after applying the optimization algorithm to the deformed array, the distorted pattern is recovered successfully with a main lobe nearly at the same position as

TABLE 2 Measured excitation weights of  $1 \times 4$  cylindrical array

No.	Desired pattern		Measured pattern for cylindrical configuration of $1 \times 4$ array					
	Linear structure		$r = 30$ cm		$r = 25$ cm		$r = 20$ cm	
$i \times j$	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
$1 \times 1$	0.6614	7.4412	0.7200	9.0579	0.7140	-169.75	0.6696	4.8333
$1 \times 2$	0.3576	-25.643	0.3830	137.2300	0.4047	139.166	0.2927	22.3877
$1 \times 3$	0.3681	-24.876	0.3971	138.3013	0.4163	140.607	0.2901	25.0516
$1 \times 4$	0.6479	6.2514	0.7059	-171.74	0.6998	-170.86	0.6678	176.803

TABLE 3 Measured excitation weights of  $2 \times 4$  cylindrical array

No.	Desired pattern		Measured pattern for cylindrical configuration of $2 \times 4$ array					
	Planar structure		$r = 30$ cm		$r = 25$ cm		$r = 20$ cm	
$i \times j$	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
$1 \times 1$	0.1208	173.2463	0.1474	-150.099	0.1958	107.394	0.6971	167.184
$2 \times 1$	0.2505	79.5654	0.2690	86.4104	0.2440	-41.169	0.5150	-137.69
$1 \times 2$	0.4615	16.2119	0.5008	23.1285	0.4806	-147.38	0.1465	-19.790
$2 \times 2$	0.6232	-9.5821	0.6608	165.858	0.6662	171.688	0.2102	148.620
$1 \times 3$	0.6193	-10.0388	0.6609	165.5638	0.6672	171.574	0.2103	148.956
$2 \times 3$	0.4599	15.1888	0.5013	-157.57	0.4795	-148.05	0.1484	161.728
$1 \times 4$	0.2533	78.8695	0.2676	-95.258	0.2433	-40.950	0.5157	42.227
$2 \times 4$	0.1239	170.0651	0.1499	27.806	0.1998	105.668	0.6968	-13.032



that of the linear array. At the same time, the desired nulls and sidelobe levels are achieved. After deformation of the array to the particular cylindrical configuration, the optimization algorithm calculates the optimum weights to overcome the mutual coupling effect and deterioration of the radiation pattern. Figures 6 and 7 show the comparison between the electric field pattern of the flat array and the electric field pattern of the deformed configuration for  $1 \times 4$  array and  $2 \times 4$  array, respectively. The complex weights given to each array element of the  $1 \times 4$  and  $2 \times 4$  array to obtain the optimized radiation pattern for various radii of curvature are tabulated in Tables 2 and 3.

The optimization model produces suitable results in terms of main lobe reconstruction, at the nulls' locations, and has side lobe levels approximating the desired ones. However, it is obvious that the optimization model fairly recovers the radiation pattern for more deformation ( $r = 20$  cm). On the other hand, when the radii of curvatures of cylindrical array decreases that is the conformal array is less deformed ( $r = 30$  cm), the optimization algorithm gives a good agreement, allowing the measured radiation pattern to more closely follow the desired radiation pattern.

## 5 | CONCLUSION

In this paper, a convex optimization model is proposed for radiation pattern correction on a cylindrically shaped conformal microstrip antenna array. The optimization model is developed to compute the appropriate amplitude and phase excitations in order to decrease the Euclidean distance between the simulated/ measured field patterns and the desired field patterns. Two prototypes of  $1 \times 4$  and  $2 \times 4$  cylindrical arrays with various radii of curvature are studied, and the results are compared to those of linear/planar antenna arrays. The analytical investigation and simulation/ measurement findings are in good agreement in terms of main lobe reconstruction, side lobe levels and nulls' position recovery. The proposed convex optimization model when applied to conformal antenna arrays has fast computational speed and high convergence accuracy for radiation pattern synthesis, which can be a valuable tool for engineering applications.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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