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Development of Software Package for Radiation Pattern and Beam Sensing with Conformal Array Analysis

Pinku Ranjan, Amit Sahu, Jayant Kumar Rai, and Rakesh Chowdhury

Abstract— **This paper presents a novel concept for creating a Graphical User Interface (GUI) tool for analyzing the beamforming behavior and sensing the radiation pattern of planar-phased array antennas. It incorporates built-in functionality to specify active elements and allows for importing radiation pattern data from external software. Additionally, the tool generates interactive 3-D plots of the radiation patterns and sensed beams. The main objective of this paper is to provide a comprehensive understanding of the tool's functionality and describe the methodology used to develop the software package for sensing the beam direction. The proposed software offers a user-friendly interface that simplifies the analysis of planar-phased array antennas for beam sensing. By leveraging the power of Python, the tool enables efficient sensing of antenna radiation patterns and beamforming.**

Keywords **—GUI, Phased array antennas, Python, 3-D radiation pattern**

I. INTRODUCTION

Antenna systems often require large apertures, high radiated power levels, sensitive reception capability, and rapid beam sensing. Phased array antenna systems, consisting of numerous discrete radiating sensing antenna elements, provide enhanced beam sensing agility and gradual signal decay compared to reflector antenna systems with single or multiple feeds. Typically, the radiating or receiving antenna elements that form the aperture of a phased array can be integrated onto a flat or curved surface, either planar or conformal [1]. Radar systems can meet their requirements for hemispheric coverage using spherical phased array antennas. However, they have certain shortcomings, such as the requirement for exact manufacture and alignment on a curved surface [2]. As an alternative, geodesic dome-phased array antennas are becoming more and more popular. They are easier to set up since they have planar subarrays and provide the same benefits for hemispherical coverage [3]. The design of these antennas overcomes the challenges associated with producing conformal arrays by leveraging tried-and-true planar array technology that is easy to build. For this reason, the geodesic dome phased array antenna is a practical and inexpensive solution [4-5]. More high-frequency radio frequency applications, including Wi-Fi,
Chirped radar and 5G communication utilize phased array sensing antennas. Therefore, there is an urgent need for extremely practical and adaptable tools to accurately analyze the beam sensing in these antennas [6]. To create a tool that can analyze the three-dimensional radiation pattern and beam sensing of phased array antennas while considering any random combination of active components and beam steering angles, this article presents the concepts and methods used in that process.

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II. MATHEMATICAL MODELLING

A. Sensing of Radiation Pattern

The sensing of antenna array configuration is shown in Fig.1.Let us consider two isotropic radiators of an arbitrary antenna array represented as R and S located at co-ordinates (0,0,0) and $(p,q,0)$ respectively and try to calculate the resulting electromagnetic field strength at the point M identified by the coordinates (l,m,n) in the far-field region of the antenna.

Represent the distance between points R and M as $\vec{\mathbf{r}}_{RM}$, between S and M as $\vec{\mathbf{r}}_{\mathbf{SM}}$ and that between R and S as $\vec{\mathbf{r}}_{RS}$.

$$\vec{\mathbf{r}}_{RM} = l\hat{x} + m\hat{y} + n\hat{z}, \tag{1}$$

$$\vec{\mathbf{r}}_{SM} = (l-p)\hat{x} + (m-q)\hat{y} + (n-0)\hat{z}, \tag{2}$$

$$\vec{\mathbf{r}}_{RS} = p\hat{x} + q\hat{y} + 0\hat{z}. \tag{3}$$

Let Δl be the path difference between the two vectors $\vec{\mathbf{r}}_{RM}$ and $\vec{\mathbf{r}}_{SM}$ and it is nothing but the projection of the vector $\vec{\mathbf{r}}_{RS}$ on the vector $\vec{\mathbf{r}}_{RM}$.

According to simple vector algebra the projection of a vector $\vec{\mathbf{A}}$ on another vector $\vec{\mathbf{B}}$ is given by the formula:

$$Projection\ of\ \vec{\mathbf{A}}\ on\ \vec{\mathbf{B}} = \frac{\vec{\mathbf{A}}\cdot\vec{\mathbf{B}}}{|\mathbf{B}|}\ or\ \frac{\vec{\mathbf{A}}\cdot\vec{\mathbf{B}}}{\vec{\mathbf{A}}\cdot\vec{\mathbf{B}}}. \tag{4}$$

Assuming the angle that the vector $\vec{\mathbf{r}}_{RM}$ makes with the *z*-axis be θ and the angle that the projection of $\vec{\mathbf{r}}_{RM}$ on *x*-*y* plane makes with *x*-axis be φ. Then, the unit vector $\hat{\mathbf{r}}_{RM}$ is given by:

$$\hat{\mathbf{r}}_{RM} = \sin\theta\cos\varphi\,\hat{x} + \sin\theta\sin\varphi\,\hat{y} + \cos\theta\,\hat{z}\,. \tag{5}$$

From equations (3), (4) and (5)

$$\Delta l = p\sin\theta\cos\varphi\,\hat{x} + q\sin\theta\sin\varphi\,\hat{y}. \tag{6}$$

The phase difference between the two waves is given by the formula:

$$\Delta\varphi = \frac{2\Pi}{\lambda} \times \Delta l\ or\ k\Delta l, \tag{7}$$

where, $k = 2\pi/\lambda$ is the angular wavenumber of the electromagnetic wave.
So, from equations (6) and (7)

$$\Delta\varphi = k(p\sin\theta\cos\varphi\,\hat{x} + q\sin\theta\sin\varphi\,\hat{y}). \tag{8}$$

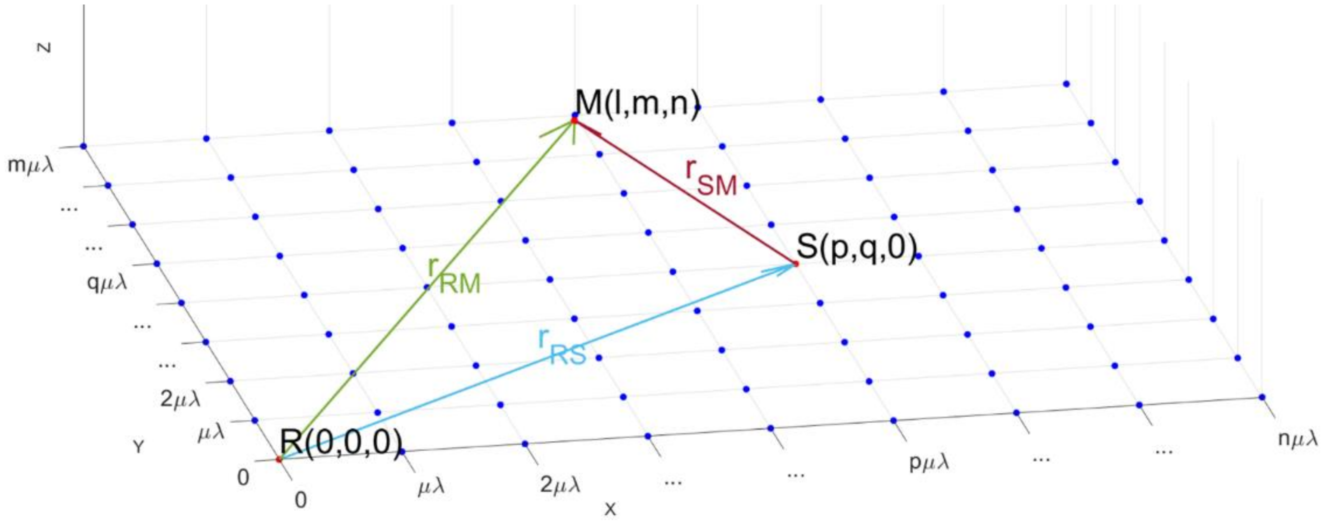

Fig. 1. Antenna array configuration

Let the magnitude of EM wave at point M due to the radiator at R be:

$$M_R(t) = m(t)\cos \omega_\circ t, \quad (9)$$

where, $m(t)$ represents the modulating signal and $\cos \omega_\circ t$ represents the carrier signal.

Then, if τ_{RS} is the time difference between the arrival time of the signals from the radiators at R and S, the signal strength due to radiator at S can be calculated as:

$$M_S(t) = m(t+\tau_{RS})\cos(\omega_\circ(t+\tau_{RS})). \quad (10)$$

Assuming the rate of change of modulating signal is very low when compared to carrier signal, the above equation reduces to:

$$M_S(t) = m(t)\, cos(\omega_\circ t + \omega_\circ \tau_{RS}). \quad (11)$$

Simplifying further, we obtain:

$$\omega_\circ \tau_{RS} = \frac{2\Pi c}{\lambda} \times \tau_{RS} = k\Delta l = \Delta\varphi. \quad (12)$$

From equations (11) and (12)

$$M_S(t) = m(t)\cos(\omega_\circ t + \Delta\varphi). \quad (13)$$

The total strength of electromagnetic field at M is given by:

$$M(t) = M_R(t) + M_S(t), \quad (14)$$

$$M(t) = m(t)(\cos\omega_\circ t + \cos(\omega_\circ t + \Delta\varphi)), \quad (15)$$

$$M(t) = \mathrm{Re}[m(t)\cdot(\mathrm{e}^{\mathrm{j}\omega_\circ t} + \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot \mathrm{e}^{\mathrm{j}\Delta\varphi})], \quad (16)$$

$$M(t) = \mathrm{Re}[m(t)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}(1+\mathrm{e}^{\mathrm{j}\Delta\varphi})]. \quad (17)$$

The equation (14), (15) (16), and (17) can be generalized for an arbitrary N element array as

$$M(t) = \mathrm{Re}[m(t)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot(\textstyle\sum_{i=1}^{N} e^{j\Delta\varphi_i})], \quad (18)$$

where, $\Delta\varphi_i$ is the phase difference between the signals originating from the i^{th} element and the element located at origin.

The radiation pattern for the antenna array in terms of the elevation angle (θ) and azimuthal angle(φ) can be written as:

$$M(\theta,\varphi) = \left|m(t)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot \left(\textstyle\sum_{i=1}^{N} \mathrm{e}^{\mathrm{j}k(p_i \sin\theta\cos\varphi\hat{x} + q_i\sin\theta\sin\varphi\hat{y})}\right)\right|, \quad (19)$$

where, p_i and q_i denote the x and y co-ordinate of the i^{th} element, θ and φ represent the elevation and the azimuthal angle of the point M.

Let us assume, $u = \sin\theta\cos\varphi$ and $v = \sin\theta\sin\varphi$, then the equation (19) is given by:

$$M(\theta,\varphi) = \left|m(t)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot\left(\textstyle\sum_{i=1}^{N} \mathrm{e}^{\mathrm{j}k(p_i u\hat{x} + q_i v\hat{y})}\right)\right| . \quad (20)$$

In case of different element excitations, the equation is modified as:

$$M(\theta,\varphi) = \left|m(t)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot\left(\textstyle\sum_{i=1}^{N} w_i \mathrm{e}^{\mathrm{j}k(p_i u\hat{x} + q_i v\hat{y})}\right)\right|, \quad (21)$$

where w_i, represents the complex weight associated with i^{th} element.

According to the Principle of Pattern Multiplication [7], the radiation pattern $P(\theta,\varphi)$, of an array of N identical antennas is given by

$$P(\theta,\varphi) = P_e(\theta,\varphi) \times AF, \quad (22)$$

where, $P_e(\theta,\varphi)$ represents the pattern of one of the antennas and AF represents the array factor.

Using the equations (21) and (22)

$$M(\theta,\varphi) = \left|m(t)\cdot S_e(\theta,\varphi)\cdot \mathrm{e}^{\mathrm{j}\omega_\circ t}\cdot\left(\textstyle\sum_{i=1}^{N} w_i \mathrm{e}^{\mathrm{j}k(p_i u\hat{x} + q_i v\hat{y})}\right)\right|, \quad (23)$$

where, $S_e(\theta,\varphi)$ represents the radiation pattern of the custom antenna, and $\sum_{i=1}^{N} w_i \mathrm{e}^{\mathrm{j}k(p_i u\hat{x} + q_i v\hat{y})}$ represents the Array Factor of the antenna array.

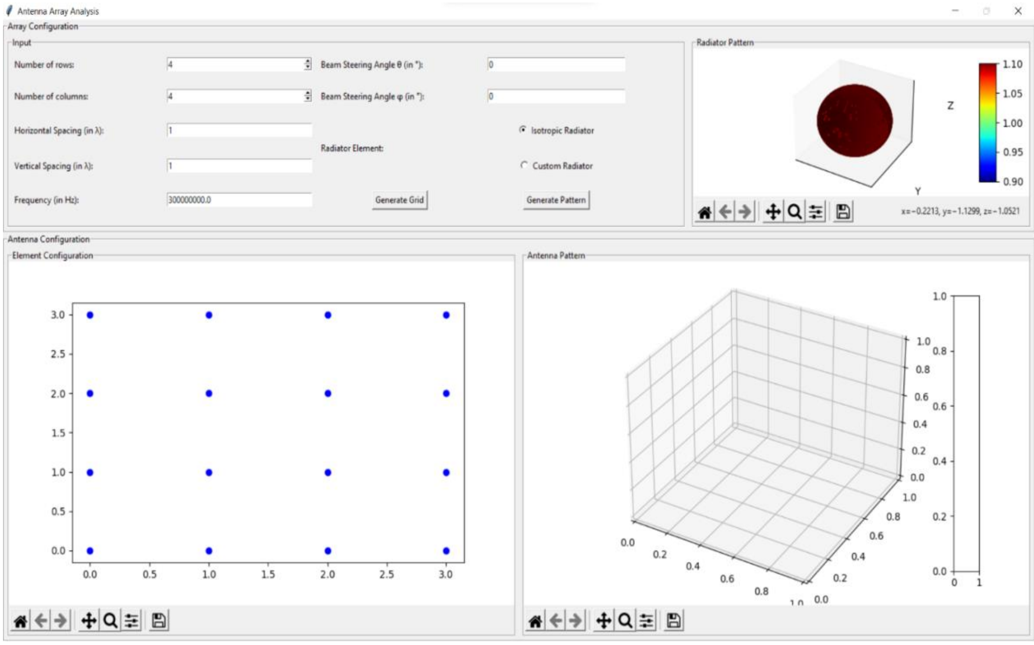

Fig.2. GUI interface

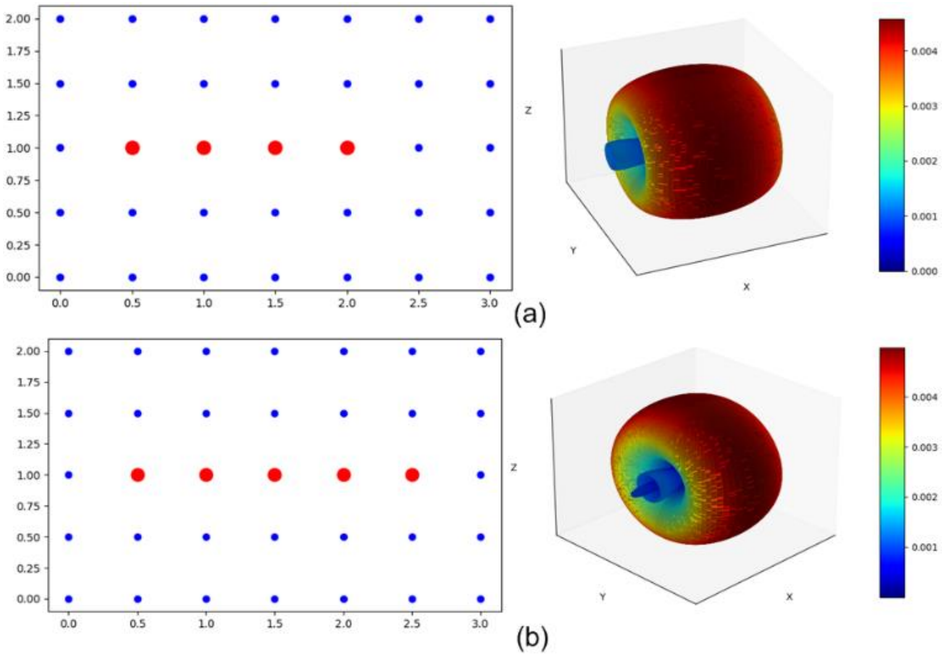

Fig.3. Array Configuration and 3-D Radiation Patterns for N element linear array: (a) N = 4, (b) N = 5

B. Sensing of Beam Steering:

Let θ_s and φ_s be the elevation and azimuthal sensing of beam steering angles, then we calculate the steering parameters u_s and v_s as:

$$u_s = \sin\theta_s \cos\varphi_s, \quad (24)$$

$$v_s = \sin\theta_s \sin\varphi_s, \quad (25)$$

the individual element weights for all the elements can now be calculated as:

$$w_i = \mathrm{e}^{-\mathrm{j}k(p_i u_s \hat{x} + q_i v_s \hat{y})}, \quad (26)$$

where, p_i and q_i denote the x and y co-ordinate of the i^{th} element, θ_s and φ_s represent the beam steering angles.

$$M(\theta,\varphi) = \left| m(t)\cdot S_e(\theta,\varphi)\cdot \mathrm{e}^{\mathrm{j}\omega_o t}\cdot \left(\sum_{i=1}^{N} \mathrm{e}^{\mathrm{j}k(p_i(u-u_s)\hat{x}+q_i(v-v_s)\hat{y})}\right)\right|. \quad (27)$$

III. Result and Discussion

The main concept behind the GUI-based simulation tool is the analytical approach mentioned in the preceding section. The proposed tool is demonstrated in Fig.2, which features an easy-to-use, and reliable design, highly interactive plots, the generation of uniformly spaced 2-D grids with different horizontal and vertical spacing, a selection of active elements, and the simplicity of importing the radiation pattern of the array elements ($-180 \leq \theta \leq 180$ and $-180 \leq \emptyset \leq 180$) from third-party apps. The Fig.3. shows the simulation results generated by the proposed tool for a linear array of isotropic antennas with inter-element spacing 0.5λ, and number of elements (a) N=4, and (b) N=5, respectively. The Fig. 4. shows the comparison of the simulation results generated by the proposed tool with MATLAB Sensor Array Analyzer for rectangular antenna arrays, with inter-element spacing 0.5λ in both the directions and having the dimension (a) N=5×5, and (b) N=6×6, respectively. Overall, the results are well within the acceptable range, and it has an advantage over other currently available tools. It has additional features like active element selection, radiation pattern imports from third-party apps, interactive visual plots, and the ability to generate nearly any geometry.

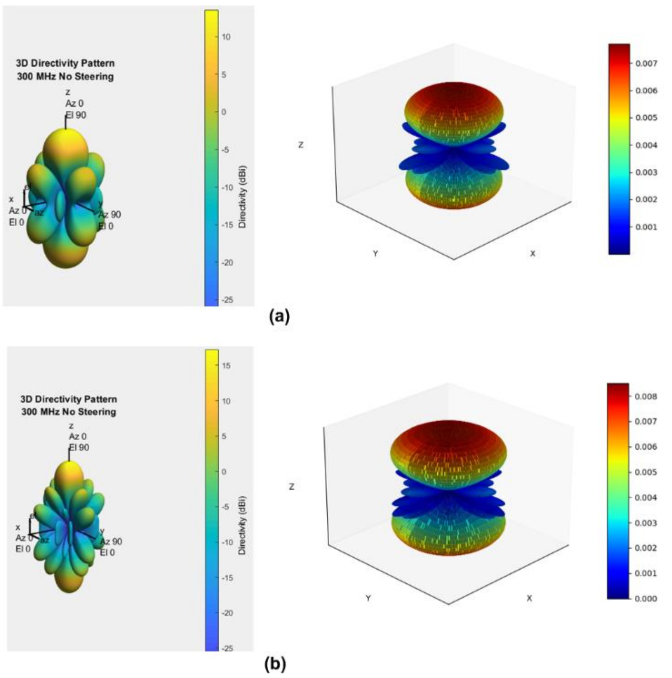

Fig.4. Comparing simulation result with MATLAB generated output for N×N rectangular array: (a) N=5, (b) N=6.

IV. Conclusion

This tool presents a cost-effective and straightforward yet highly efficient method for analyzing the sensing of radiation patterns and beamforming behavior of planar-phased array antennas, eliminating the need for advanced equipment. It offers unparalleled flexibility in terms of selecting active elements, importing radiation patterns, sensing individual elements from third-party software, and specifying array configuration parameters such as inter-element spacing, steering angles, and the number of rows and columns. Additionally, it incorporates interactive 3-D pattern plots that deliver an accurate visual representation of the resultant radiation pattern of the antenna array.

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