Beamforming a circular-polarized radiation pattern on volumetric random arrays with deliberately aligned array antennas

Shihyuan Yeh¹,a) and Zhong Chen¹

¹Department of Electrical and Computer Engineering, Texas A&M University
301 Wisenbaker Engineering Building, College Station, TX 77843-3128, United States of America

a) steven.yeh66@gmail.com

Abstract: This letter proposes a circularly polarized beamforming technique on volumetric random arrays with each antenna aligned deliberately. This technique seeks to advance the capabilities of spatially distributed antenna systems on mobile platforms. Sixteen microstrip patch antennas grouped as the tested array are adopted to investigate the fidelity of the developed beamforming technique. Each array element is distributed randomly and rotated freely to emulate the real mobile environment. Detailed and systematic beamforming procedures are provided and illustrated. Measured radiation patterns of the volumetric random array are compared to the simulated ones to benchmark their performance.

Keywords: Beamforming, circular polarization, mobile platforms, phased array, random array, volumetric array

Classification: Antennas and Propagation

References

[1] D. C. Jenn, J. H. Ryu, T. Yen-Chang and R. Broadston, “Adaptive phase synchronization in distributed digital arrays,” 2010 NASA/ESA Conference on Adaptive Hardware and Systems, Anaheim, USA, pp. 199-204, June 2010. DOI: 10.1109/AHS.2010.5546258

[2] S. Yeh, “A Phased Array Pattern Prediction Technique Based on the Pattern Multiplication Method,” 2018 Asia-Pacific Microwave Conference (APMC), Kyoto, Japan, pp. 1531-1533, November 2018. DOI:10.23919/APMC.2018.8617194

[3] S. Yeh, Z. Chen, and Y. Wu, “Developing Circular-Polarized Beamforming Techniques on Volumetric Random Arrays with Arbitrarily Oriented Array Elements,” 2019 International Symposium on Antennas and Propagation (ISAP), Xi’an, China, pp. 1-3, October 2019.

[4] S. Yeh, J. Chamberland and G. H. Huff, “An investigation of geolocation-aware beamforming algorithms for swarming UAVs,” 2017 IEEE International
1 Introduction

Phased arrays scan beams electronically with the speed of the microprocessor and have been used on high-performance applications for years. Leveraging mobile platforms to extend array capabilities is an emerging topic. To realize mobile phased arrays applications, three challenges need to be overcome: wireless phase synchronizations [1], positions and orientations awareness [2], and mobile beamforming and beamshaping techniques [3, 4]. The contribution of this work is limited and primarily focuses on developments of mobile beamforming techniques. In fact, a circularly polarized (CP) beamforming technique, specifically designed for volumetric random arrays, is established to fulfill the idea of mobile arrays. For the sake of simplicity, the mutual coupling between antennas is assumed to be trivial and is thus ignored.

A simplified diagram in Fig. 1(a) along with the experimental array in Fig. 1(b) depict wireless phased arrays on mobile platforms, and array elements are possibly carried out by drones. Considering the mobile environment, the antenna’s position and orientation change over time, and a uniform current distribution along the array aperture is impractical. The orientation variation causing the antenna’s polarization changes accordingly. Therefore, a CP radiation pattern is advisable to avoid cross-polarization, and the detailed step-by-step procedures are elaborated in the following section.
The photograph of the volumetric random phased array placed in the anechoic chamber; a camera is employed to acquire the XYZ positions of the antennas.

Fig. 1. Phased arrays on mobile platforms.

2 Circular-Polarized beamforming techniques

As illustrated in Fig. 1(a), the blue arrow symbolizes the antenna polarization vector, the cyan arrow is the cross-polarized vector parallel to the antenna aperture (yellow surface), and the purple arrow is the antenna’s normal vector. Positions of the array antennas are denoted as \( P_n(x_n, y_n, z_n) \), where \( n = 1, 2, 3, \ldots, N \). An observer is located at \( R(r_s, \theta_s, \phi_s) \), which is in the direction of the array scan angle \((\theta_s, \phi_s)\).

The “position phase \( e^{jk\psi_p} \)” is the phase contributed from the antenna’s relative position in the array, and it is expressed as
\[
e^{jk\psi_p} = e^{jk(x_n\sin\theta\cos\phi+y_n\sin\theta\sin\phi+z_n\cos\theta)}.
\] (1)

Supposing that a wavefront arrives on the array, the “distance phase \( e^{-jk\psi_d} \)” is the progressive phase delay to each array element and depends on the array scan angle. A matrix multiplication method is developed to calculate the offset distance of the phase delay. First, the \( T \) matrix is used to transform the far-field observer, \( R(r_s, \theta_s, \phi_s) \), from the spherical coordinate to the Cartesian coordinate system. The \( P \) matrix is the locations of the array antenna in the Cartesian coordinate. The \( D \) matrix is the product of the \( P \) and \( T \) matrices and represents the offset distances.

Casting these in matrix form gives
\[
D = P \cdot T,
\] (2)

where \( P = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \vdots \\ x_n & y_n & z_n \end{bmatrix} \), \( T = \begin{bmatrix} R_s\sin\theta_s\cos\phi_s \\ R_s\sin\theta_s\sin\phi_s \\ R_s\cos\theta_s \end{bmatrix} \), and
$$D = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{bmatrix} = \begin{bmatrix} x_1 \cdot R \sin \theta_x \cos \phi_z + y_1 \cdot R \sin \theta_z \sin \phi_y + z_1 \cdot R \cos \theta_x \\ x_2 \cdot R \sin \theta_x \cos \phi_z + y_2 \cdot R \sin \theta_z \sin \phi_y + z_2 \cdot R \cos \theta_x \\ \vdots \\ x_n \cdot R \sin \theta_x \cos \phi_z + y_n \cdot R \sin \theta_z \sin \phi_y + z_n \cdot R \cos \theta_x \end{bmatrix}.$$  

Once $D$ is calculated, the distance phase of the $n^{th}$ array antenna is derived by Eq. (3) and is given as

$$e^{-jk\psi d_n} = e^{-jk\phi n},$$  

where $k$ is the propagation constant of the free space, and $D_n = x_n \cdot R \sin \theta_x \cos \phi_z + y_n \cdot R \sin \theta_z \sin \phi_y + z_n \cdot R \cos \theta_x$.

To make the array have CP characteristics, each array element has to apply a rotational phase delay based on the antenna’s polarization. The delayed phase is named the “rotation phase ($e^{jk\psi r}$)” and depends not only on the antenna’s polarizations but also on the array scan angle. A succinct leveraged projection approach method (as shown in Fig. 2) is established, and the evaluated rotation phases are decent enough for antennas with simple geometry, such as dipole or patch antennas.

As depicted in Fig. 2, each antenna’s polarization is represented by an antenna polarization vector ($\vec{I}_n$), where $n$ is the antenna number and $n = 1, 2, 3, \ldots, N$. From the array’s steering direction ($\theta_s, \phi_s$), the array scan angle vector ($\vec{S}$) is created by $\vec{S} = \hat{x} R \sin \theta_s \cos \phi_z + \hat{y} R \sin \theta_s \sin \phi_y + \hat{z} R \cos \theta_s$; accordingly, a scan angle plane ($S'$), which is orthogonal to the $\vec{S}$, is established. Next, projecting all the $\vec{I}_n$ onto $S'$ as the projected polarization vectors ($\vec{I}_n'$), $\vec{I}_n'$ is derived by vector operations of $\vec{I}_n' = \vec{I}_n - (\vec{I}_n \cdot \vec{S})\vec{S}$.

To this end, all the $\vec{I}_n'$ are on the $S'$ for rotation phase ($e^{jk\psi r}$) estimation, and the rotation phase is proportional to the relative angle ($\angle \psi_{RHCP}$) between projected
polarization vectors. As a result, a reference vector \(\vec{u}\) on \(S'\) is necessary to create by \(\vec{u}(x, y, z) = (\cos \theta_x \cos \phi_z, \cos \theta_z \sin \phi_z, -\sin \theta_z)\), and \(\vec{u}\) is defined as the starting direction with an initial angle of \(\angle \psi = 0^\circ\). For right-hand circularly polarized (RHCP) cases, the \(\angle \psi_{\text{RHCP}}\) is the angle rotated counterclockwise from \(\vec{u}\) to \(\vec{I}'_n\). After obtaining \(\angle \psi_{\text{RHCP}}\), \(\psi_{r_n}\) is derived accordingly. For example, if \(\angle \psi_{\text{RHCP}} = 120^\circ\), then the \(\psi_{r_n} = -120^\circ\). Note that the physical meaning of the minus sign in \(-120^\circ\) is the phase delay. Contrarily, for left-hand circularly polarized (LHCP) cases, the \(\angle \psi_{\text{RHCP}}\) is the angle rotated clockwise from \(\vec{u}\) to \(\vec{I}'_n\).

3 Experiments
Considering the attributes of mobile platforms, volumetric random arrays become a proper candidate to demonstrate the mobile beamforming methodology. To verify the proposed CP beamforming technique, a reconfigurable phased array developed in [5] was adopted as the test array, as shown in Fig. 1(b). One special feature of the reconfigurable array is that the positions and orientations are reconfigurable for each array element. Sixteen microstrip patch antennas acted as the mobile elements, and each antenna was randomly displaced and rotated in a volume. Each patch antenna has a degree of freedom to rotate along the coordinate axis. The rotation capability is used to replicate the real mobile platform dynamic environment. The array was designed to provide a RHCP radiation pattern to alleviate the polarization loss from the mobile platforms, and the whole experiment was evaluated at 2.4 GHz.

4 Results
The microstrip patch antenna acting as the array element has linearly polarized attributes. The linearity simplifies the follow-on derivation of the rotation phases (each patch has random orientation). The patch was well designed to operate at 2.4 GHz with approximately 50 \(\Omega\) input impedance; therefore, no additional impedance matching network is added, which significantly reduces the complexity and cost of the antenna. These antennas were fabricated on 62-mil-thick (1.57 mm) FR4 (\(\varepsilon_r = 4.4\)) and had a width of \(w = 38\) mm and a resonant length of \(L = 28\) mm. The FR4 is the common material used in the printed circuit board (PCB) manufacturing, and there are other electronic components that need to be embedded with the antenna. Thus, the FR4 is chosen as the antenna substrate, and the antenna gain is acceptable for this application. The SMA probe feed was placed at a distance of 6 mm from the patch edge. Fig. 3(a) shows the measured VSWR and input impedance of the patch antenna from 2 GHz to 3 GHz. The antenna has a 2:1 VSWR bandwidth of 60 MHz (from 2.365 GHz to 2.425 GHz) centered at 2.395 GHz. Fig. 3(b) shows the measured radiation pattern at 2.4 GHz for the two-elevation cut planes. The antenna has a maximum gain of 2.97 dBi and a HPBW of HPBW\(_\theta\) = 75°.

The experiment was evaluated by beamforming the main beam and by providing a RHCP characteristic at the array broadside, as shown in Fig. 3(c). For this reason, the first step is to drive the main beam to the designated scan angle \((\theta_s, \phi_s) = (0^\circ,\)
0°) with linear-polarized characteristics. The second step is to impose a rotation phase ($e^{j\psi r}$) on each array element to generate a RHCP radiation pattern. Fig. 3(c) shows the $G_{RHCP}$ of the measured and simulated results for $\theta$ from $-180^\circ$ to $180^\circ$ and $\phi = 0^\circ$. The measured RHCP gains are normalized and combined with the simulated ones for comparison. Both results have normalized maximum $G_{RHCP}$ of 17.1 dBi at $\theta = \phi = 0^\circ$, and the measured and simulated sidelobe levels (SLLs) are close to −8.2 dB. Meanwhile, the Fig. 3(d) shows the $G_{LHCP}$ of the measured and simulated results for $\theta$ from $-180^\circ$ to $180^\circ$ and $\phi = 0^\circ$. The measured and simulated LHCP gains are −8.7 dBi and −2.6 dBi at $\theta = \phi = 0^\circ$, respectively.

![Measured VSWR and Smith Chart](image1)
![Measured radiation patterns (dBi)](image2)

![Measured and simulated $G_{RHCP}$ Patterns](image3)
![Measured and simulated $G_{LHCP}$ Patterns](image4)

5 Conclusion

This letter elaborates on CP beamforming techniques for mobile arrays by using sixteen microstrip patch antennas randomly distributed in a volumetric, with each array element arbitrarily oriented. The procedures on how to estimate the rotation angles and convert them into rotation phases for each tilted antenna are explained. Simulated and measured radiation patterns for the experimental array are provided, and comparisons between them are made. There are no grating lobes observed within the visible region, and the result is in accordance with expectations.