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Near-field Beamforming Technique Based on 3-D Cylindrical Array: Enlarging Region and Improving Spectral Efficiency

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***Abstract*- For large incidence/emergence angles in uniform linear arrays, the near-field region shrinks sharply. In this paper, we present Uniform 3D Cylindrical Array (UCA-3D), which can enlarge the near-field region and improve the spectral efficiency. Specifically, using the rotational symmetry of UCA-3D, we can obtain near-field regions that are uniformly enlarged at all angles. As UCA-3D can generate orthogonal near-field beams along the same direction, we can improve the spectral efficiency. The simulation results prove that the theory is valid, and the UCA-3D is feasible.**

I. INTRODUCTION

Wireless communications demand for data transmission has increased dramatically, and spectral efficiency has become a key performance indicator. To satisfy the spectral efficiency requirements for 6G, the Extremely Large-scale Antenna Array (ELAA) has become the key research object [1]. In 5G-oriented multiple-input multiple-output systems, the antenna array for base stations is small enough that the near-field spherical model can be simplified to a far-field plane-wave model. However, in ELAA system, the phase difference between the plane wave model and the spherical wave model cannot be neglected due to the significant increase in the array aperture. Thus, the ELAA system requires more accurate near-field spherical wave model, while the widely used far-field plane wave model cannot be applied [2].

Compared to mitigating the performance decrease caused by the near-field effect, we prefer to utilize the near-field effect to improve the system performance. Near-field communication can utilize distance information to increase multi-user communication capacity. The reason is that the focusing properties of the near-field beam are enhanced and users at different distances can be served. Unfortunately, the effective array aperture shrinks at large angle for Uniform Linear Arrays (ULA), leading to a smaller phase difference between the plane and spherical wave models [3]. This phenomenon seriously hinders the improvement of ELAA performance. Thus, the investigation of alternatives to ULA in near-field communication has become a key issue. To solve this problem, we design Uniform 3D Cylindrical Array (UCA-3D), which enlarges the near-field region and improves the spectral efficiency.

We provide available code, which can be downloaded at **https://github.com/WangYeeng/Near-field_UCA_master**.

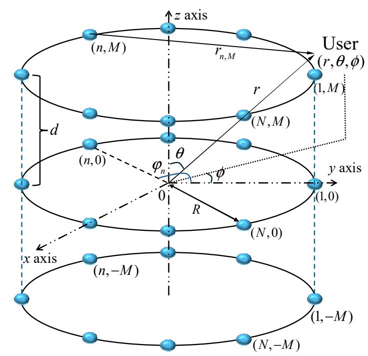

Figure 1. The geometrical structure for UCA-3D.

II. MODEL & ANALYZE

The UCA-3D ensures that both azimuthal and elevation planes have coverage areas. In this paper, we assume that all antennas contribute to beamforming, which is widely used in theoretical analysis. UCA-3D can be regarded as $2M+1$ concentric circular arrays composition. And the circular arrays are uniformly distributed in the z - axis direction with spacing d . Fig. 1 shows the geometrical structure of UCA-3D.

To guarantee the symmetry of the array structure, we locate the origin at the center of the middle circular array. If each circular array contains N antenna elements, then UCA-3D contains a total of $N\tilde{M}$ antenna elements, with $\tilde{M}=2M+1$. If r , θ and ϕ denote the distance to the origin, elevation and azimuth, respectively, then the 3D coordinates $\psi=(r,\theta,\phi)$ denote the user's position. According to the geometric location, the distance between user and the (n,m) th antenna can be expressed as

$$r_{n,m}=\sqrt{r^2+R^2-\xi_1-\xi_2+m^2d^2} \tag{1}$$

Where variables $\xi_{\{1,2\}}$ are defined as

$$\begin{aligned}\xi_1&=2rR\sin(\theta)\cos(\phi-\varphi_n)\\ \xi_2&=2mdr\cos(\theta)\end{aligned} \tag{2}$$

Thereby, the near-field beamforming vector can be written as

$$\mathbf{b}(\psi)=\frac{1}{\sqrt{N\tilde{M}}}\left[e^{-j\frac{2\pi}{\lambda}\left(r_{1,-M}-r\right)},\cdots,e^{-j\frac{2\pi}{\lambda}\left(r_{N,M}-r\right)}\right]^T \tag{3}$$

Where λ is the wavelength. The beamforming gain can be calculated as

$$g(\psi_1,\psi_2)=\frac{1}{N\tilde{M}}\left|\mathbf{b}^H(\psi_1)\mathbf{b}(\psi_2)\right| \tag{4}$$

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Note that Eq. (4) applies to any user location and any UCA-3D array setting. Now, we only consider the beamforming gain in the distance domain, i.e., $\theta_1 = \theta_2$, $\phi_1 = \phi_2$. Eq. (4) can be simplified as

$$g\left(\hat{\psi}_1, \hat{\psi}_2\right) = \frac{1}{N\tilde{M}} \left| \sum_{m=-M}^{M} \sum_{n=1}^{N} e^{j\frac{2\pi}{\lambda}\left(\frac{1}{r1}-\frac{1}{r2}\right)(\zeta_1+\zeta_2+\zeta_3)} \right| \tag{5}$$

Where $\hat{\psi}_1 = (r_1, \theta, \phi)$, $\hat{\psi}_2 = (r_2, \theta, \phi)$. The variables $\zeta_{\{1,2,3\}}$ are defined as

$$\begin{aligned} \zeta_1 &= \tfrac{R^2}{2}\left(1-\sin^2(\theta)\cos^2(\phi-\varphi_n)\right) \\ \zeta_2 &= \tfrac{m^2 d^2}{2}\sin^2(\theta) \\ \zeta_3 &= Rmd\sin(\theta)\cos(\theta)\cos(\phi-\varphi_n) \end{aligned} \tag{6}$$

To characterize the beamforming performance more accurately, we use the Effective Rayleigh Distance (ERD) as a metric. With ULA and UCA-3D sharing the same array aperture ($D_L = D_C = 2R$), according to the conclusion in [4], the ERDs can be expressed as

$$r_{\text{ERD}}^{ULA}\left(\phi\right) = \frac{0.734 D_L^2 \cos^2(\phi)}{\lambda} \tag{7}$$

$$r_{\text{ERD}}^{UCA_{3D}}\left(\phi\right) = \frac{2\pi D_C^2}{16\lambda I_0^{-1}(1-\delta)} \tag{8}$$

Where δ is the beamforming loss threshold and $I_0^{-1}(\cdot)$ the inverse function of the zero-order Bessel function. Due to direct analysis UCA-3D is more complex, generally we can first investigate the $z=0$ plane, i.e., $\theta = \frac{\pi}{2}$, and then, increase the number of M . Thereby, the performance of UCA-3D is analyzed.

III. Numerical Results

To prove the validity of the analysis, we perform numerical analysis. Table I shows the simulation parameters.

TABLE I
SIMULATION PARAMETERS

Carrier frequency f_c	30GHz
Antenna element number N	512
Array aperture $2R$	1.28m
Antenna spacing d	0.5m
Beamforming loss threshold δ	0.05

We first evaluate the beamforming gain in the angular domain. Fig. 2(a) shows the beamforming gain against spatial angle. We can observe that the beamforming gain varies very small with the propagation distance. This proves that the beamforming gain achieved by adopting the near-field beamforming vector $\mathbf{b}$ can approximate that of the far-field. Secondly, we research the beamforming gain in the distance domain. If the beamforming vector $\mathbf{b}\left(20, \pi/2, 0\right)$ is applied, then Fig. 2(b) shows the beamforming gain versus spatial distance. When the zero location is unchanged, we can sufficiently suppress the sidelobe height by increasing M .Thirdly, we consider the ERD. Fig. 2(c) shows the edges of the ERD. Over all angles of the same array aperture, we can observe that the ERD of the UCA-3D outperforms that of the ULA. Finally, we analyze the achievable rate, defined as

$$\text{R} = \log_2\left(1 + \frac{P\left|\mathbf{h}^H \mathbf{c}\right|}{\sigma_n^2}\right) \tag{9}$$

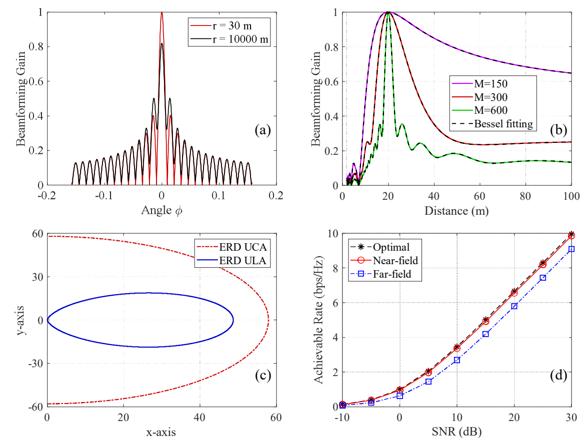

Figure 2. Summary of UCA-3D performance.

Where P and σ_n denote the transmitted power and noise power, respectively. $\mathbf{c}$ is the codebook vector that maximizes the beamforming gain. $\mathbf{h}$ is defined as

$$\mathbf{h} = \sqrt{\tfrac{N}{L}} \sum_{l=1}^{L} \eta_l \mathbf{b}\left(r_l, \theta_l, \phi_l\right) \tag{10}$$

Where η_l denotes the fading coefficient of the l th path. Assuming that the propagation distance of each path is uniformly distributed within the range [5m, 20m], Fig. 2(d) shows the achievable rates for the far-field and near-field. Compared to the far field, the performance of the near field is improved by about 12.8%. Note that with increasing communication distance, the performance of the near-field achievable rate decreases to the far-field performance.

IV. Conclusion

In this paper, we propose an antenna array with three-dimensional extension of concentric circular arrays. By extending the 2D circular array with strict symmetry to 3D space, UCA-3D can retain rotational symmetry and generate orthogonal near-field beams. Simulation results show that the array greatly improves the ERD in the near-field region and increases the achievable rate by about 12.8%. However, the blockage problem of UCA-3D, which is not all antennas contribute to beamforming, needs to be further investigated.

Acknowledgment

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