Performance Analysis of UAV-based Array Antenna Arrangement for Target Detection

Ji-Hyeon Kim
Dept. of Electronics Engineering
Pusan National University
Busan, Republic of Korea
kjihyeon@pusan.ac.kr

Soon-Young Kwon
Dept. of Electronics Engineering
Pusan National University
Busan, Republic of Korea
ysk1680@pusan.ac.kr

Hyoung-Nam Kim
Dept. of Electronics Engineering
Pusan National University
Busan, Republic of Korea
hnkim@pusan.ac.kr

Abstract—UAV-based array antennas can autonomously make the shapes of UAV array to provide an optimized placement to achieve a specific goal. In this paper, three representative antenna arrays are considered as a candidate for the optimized placement and their detection performance is analyzed in terms of target detection performance. Through the simulation results, we present the most suitable antenna arrangement for the given environment.

Keywords—UAV, array antenna, target detection

I. INTRODUCTION

As the use of unmanned aerial vehicles (UAVs), popularly known as drones, is growing rapidly, research on the operation and application of UAV has been actively conducted in various fields. In the military field, UAVs have been used for reconnaissance and surveillance, electronic warfare, attack missions using UAVs. Private sector UAVs are used in many domains such as performances and home delivery [1-5]. In particular, UAVs can play a key role in enabling wireless connectivity in various scenarios such as public safety and Internet of Things (IoT) scenarios [1-3]. Effective use of UAVs in such scenarios requires array signal processing technology that provides optimal UAV antenna arrangement.

Whereas conventional array antennas have a specific type of fixed antenna structure to achieve their purpose, UAV-based array antennas can autonomously transform the shapes of UAV array to provide an optimized placement to achieve a specific goal. For example, if it is necessary to acquire a low-frequency signal in the battlefield area, it may be changed to a linear array antenna having an appropriate interval for a search frequency. It can be also changed to an array with high directivity to improve search and jamming performance for specific areas [4-7].

In this paper, we try to find an optimal antenna array when implementing a target detection system using a UAV array antenna. For the study of UAV array antenna arrangement for target detection, the detection performance of three representative antenna arrays is analyzed. The types of arrays use linear, circular, and rectangular arrays, and an antenna array suitable for a fixed target is obtained through comparison of beamforming gains of each array antenna.

This paper organized as follows: Section II briefly describes the UAV system model and antenna arrays. Through simulation, the target detection performance of the UAV array antenna is analyzed in Section III. Finally, we conclude this paper in Section IV.
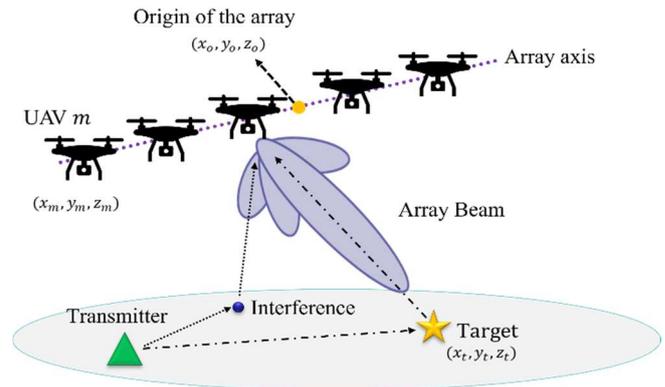

Fig. 1. UAV-based antenna array.

II. SYSTEM MODEL AND ANTENNA ARRAY ARRANGEMENT

A. System Model

Consider a target located within a given geographic area. In this area, a set $\mathcal{M}$ of M UAVs are used as flying objects to detect targets on the ground. The M UAVs forms an antenna array where each element is a single antenna UAV, as shown in Fig. 1. For tractability, we consider a linear antenna array whose elements are symmetrically located to the origin of the array. The three-dimensional (3D) locations of UAV $m \in \mathcal{M}$ and target are given by (x_m, y_m, z_m) and (x_t, y_t, z_t). To avoid collisions between UAVs, we assume that adjacent UAVs in the array are separated by at least D_{min} [7].

For this UAV array system, a transmitter is employed to send narrowband signals, and the echo signals reflected from far-field targets are then received by the each UAV. There are also interference signal. Assume that there are K narrowband signals $s_{m,k}(t), \ k = 1, 2, \cdots, \ K$, observed at the m-th array element. And we use $\mathbf{x}_m(t)$ to represent the observed signal vector, and the narrowband array output model is given by

$$\mathbf{x}_m(t) = \mathbf{A}(\boldsymbol{\theta}_m, t)\mathbf{s}_m(t) + \bar{\mathbf{n}}_m(t) \tag{1}$$

where $s_{m,k}(t) = \left[s_{m,1}(t), s_{m,2}(t), \cdots, s_{m,K}(t) \right]^T$ is the signal vector consisting of all reflected signals, and $\{\cdot\}^T$ denotes the transpose operation. $\bar{n}_m(t)$ represents the noise vector of the m-th array UAV. And the steering matrix $\mathbf{A}(\boldsymbol{\theta}_m, t) = \left[\mathbf{a}(\theta_{m,1}, t), \ldots, \mathbf{a}(\theta_{m,K}, t) \right]$, with its k-th column vector $\mathbf{a}(\theta_{m,K}, t)$ being the steering vector corresponding to the k-th source signal.
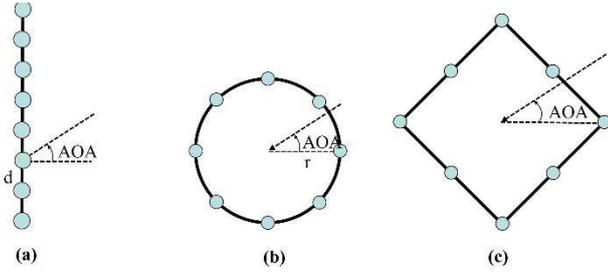
Fig. 2. Antenna array configurations: (a) ULA, (b) UCA, (c) URA.

B. Antenna Array Arrangement

In this paper, three representative antenna types including ULA, UCA, and URA are chosen to analyze target detection performance. The spatial structure of these three antenna arrays are illustrated in Fig. 2.

1) Uniform Linear Array (ULA)

Uniform linear array (ULA) is a collection of sensor elements equally spaced along a straight line. The property means that the array accepts a signal from a particular direction and rejects the signal from another direction [10]. The expression of the steering vector of ULA at each angle of arrival (AoA) is defined as follows:

$$\mathbf{a}(\phi) = \left[1, \cdots, e^{jkd \sin \phi}\right]^{T} \quad (2)$$

with d is distance between the antennas, and $k = 2\pi/\lambda$ is the wave number.

2) Uniform Circular Array (UCA)

Uniform circular array (UCA) is formed from identical sensor elements equally spaced around a circle. As a type of planar array, it provides a more symmetrical pattern with lower side lobes and much higher directivity [10]. The steering vector of UCA at each AoA can be obtained as follows:

$$\mathbf{a}(\phi) = \left[e^{jkr \cos(\phi-\phi_1)}, \cdots, e^{jkr \cos(\phi-\phi_M)}\right]^{T} \quad (3)$$

with r being the radius of the circular array, and ϕ_M the angle of the m-th array element with respect to horizontal axis.

3) Uniform Rectangular Array (URA)

Uniform rectangular array (URA) refers to an antenna in which sensors are arranged at equal intervals on a square plane.

Parameters	Values or variables	
	Signal 1 (SOI)	Signal 2 (interference)
Carrier frequency f_c	150 MHz	
Angle of arrival (AoA) (azimuth, elevation)	(-37° , 10°)	(17° , 10°)
# of sensor elements M	16	
Signal to noise ratio (SNR)	-20 dB	

It has the characteristics of a planar array like UCA and can be used to scan the main beam towards any point in space. The steering vector of URA at each AoA is expressed as follows:

$$(\phi) = \begin{bmatrix} 1 \\ e^{-j\chi} \\ \vdots \\ e^{-j(Q-1)\chi} \\ e^{-j\gamma} \\ e^{j(\chi+\gamma)} \\ \vdots \\ e^{-j((Q-1)\chi+(P-1)\gamma)} \end{bmatrix} \quad (4)$$

$$\chi \triangleq 2\pi \left(\frac{d}{\lambda}\right) \sin \theta \cos \phi, \quad \gamma \triangleq 2\pi \left(\frac{d}{\lambda}\right) \sin \theta \sin \phi \quad (5)$$

In Equations (4) and (5), θ and ϕ represent the elevation angle and azimuth angle of the signal, Q and P are the rows and columns of the array [9].

III. SIMULATION RESULTS

In this section, simulations are performed to compare the target detection performance according to the arrangement of the UAV array antenna. The simulation results show the beamforming gain of the signal of interest (SOI) and interference that obtained according to the three antenna arrays. Specific simulation parameters are summarized in Table 1. The number of sensors is 16, in the case of URA, it has a 4×4 arrangement. For convenience, the elevation angle of the SOI and the interference signal were set to be the same. A narrowband minimum-variance distortionless-response (MVDR) was used as the beamforming algorithm [11].
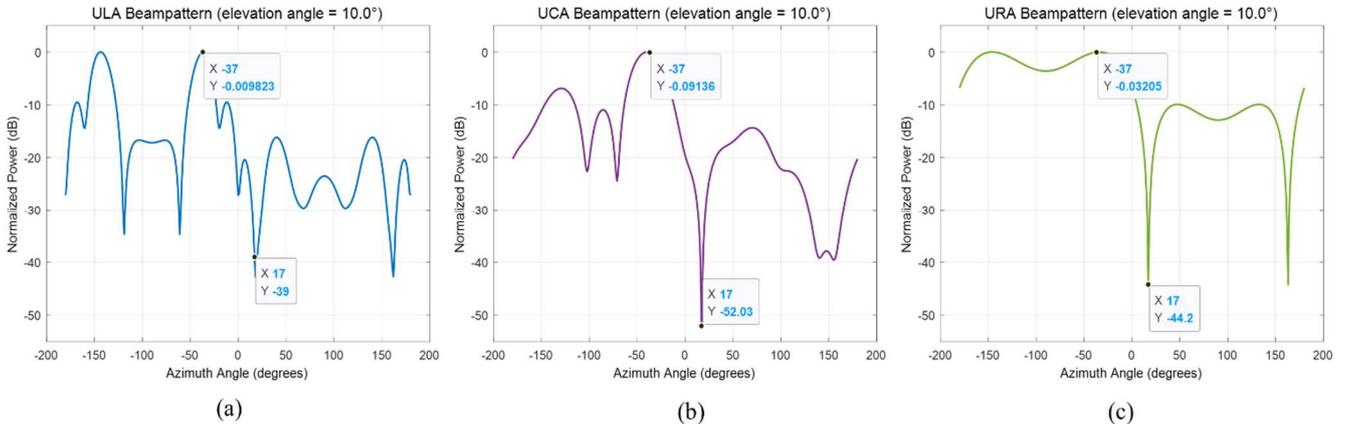

Fig. 3. Beampattern obtained with different antenna arrays: (a) ULA, (b) UCA, (c) URA.

Fig. 3 shows the beamforming gain obtained with three antenna arrays. All array antennas have the largest beam gain at -37 °, which is the direction of the SOI, and it can be confirmed that a deep null is formed at direction of the interference, 17 °. Comparing the target detection performance of these arrays, UCA has the largest gain difference between the direction of the SOI and the interference signal by about 52 dB.

IV. Conclusions

For the study of UAV array antenna arrangement to detect the target, we analyzed detection performance using three representative antenna arrays such as ULA, UCA, and URA. Simulation results show that all three antenna arrays can extract the target signal and remove the interference signal. In particular, UCA has better performance than the other two arrays. A study to find an optimal antenna arrangement for various signals and operating environments will be conducted in the future works.

References

[1] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Transactions on Wireless Communications*, vol. 15, no. 6, pp. 3949–3963, June 2016.

[2] M. Alzenad, A. El-Keyi, and H. Yanikomeroglu, "3D placement of an unmanned aerial vehicle base station for maximum coverage of users with different QoS requirements," *IEEE Wireless Communications Letters, Early access,* 2017.

[3] Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for UAV-enabled multiple access," *IEEE Transactions on Wireless Communications, Early access,* 2017.

[4] Ho Young Jeong, Byung Duk Song, Seokcheon Lee, "The Flying Warehouse Delivery System: A Quantitative Approach for the Optimal Operation Policy of Airborne Fulfillment Center," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1-10, July 2020.

[5] Y. Zhou, C. Pan, P. L. Yeoh, K. Wang, M. Elkashlan, B. Vucetic, Y. Li, "Communication-and-Computing Latency Minimization for UAV-Enabled Virtual Reality Delivery Systems," *IEEE Transactions on Communications*, Nov. 2020.

[6] P. S. Bithas, V. Nikolaidis, A. G. Kanatas, G. K. Karagiannidis, "UAV-to-Ground Communications: Channel Modeling and UAV Selection," *IEEE Transactions on Communications*, Vol. 68, Issue. 8, Aug. 2020.

[7] M. Mozaffari, W. Saad, M. Bennis and M. Debbah, "Drone-Based Antenna Array for Service Time Minimization in Wireless Networks," *2018 IEEE International Conference on Communications (ICC)*, pp. 1-6, May 2018.

[8] Garza Jesus, Panduro Marco A., Reyna Alberto, Romero Gerardo, and del Rio Carlos. "Design of UAVs-Based 3D Antenna Arrays for a Maximum Performance in Terms of Directivity and SLL," *International Journal of Antennas and Propagation*, Aug. 2016.

[9] Ji-Youn Mun and Suk-Seung Hwang, "Performance Analysis of Adaptive Beamforming System Based on Planar Array Antenna," *Journal of the KIECS*. pp. 1207-1212, vol. 13, no. 6, Dec. 31 2018.

[10] Antonio Forenza, David J. Love, and Robert W. Heath Jr, "Simplified Spatial Correlation Models for Clustered MIMO Channels With Different Array Configurations," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 4, Aug. 2007.

[11] Van Trees, H. "*Optimum Array Processing*," New York: Wiley-Interscience, 2002.