Beam Tracking Using Monopulse Signal for UAV Communications With Doppler Shift

Dong-Hwee Kim*, Byungju Lim†, and Young-Chai Ko*
*School of Electrical Engineering, Korea University, Seoul, South Korea
†Department of Electronic Engineering, Pukyong National University, Busan, South Korea
Email: kdh605@korea.ac.kr, limbj@pknu.ac.kr, koyc@korea.ac.kr

***Abstract*—In UAV communications, beam tracking is essential for maintaining a reliable link, but it is challenging to acquire the specific AoA of a high-speed UAV due to Doppler shift. To handle this challenge, we propose an EKF-based beam tracking scheme that includes the state model based on geometric relationship and utilizes monopulse signal as a measurement model. We also propose a method to compute the Doppler shift from the estimated AoA, which can be used to compensate Doppler effect during data transmission. Simulation results show that the proposed scheme effectively estimates the AoA and Doppler shift in high-speed situations.**

***Index Terms*—Beam Tracking, Doppler shift, high-speed UAV communication, Kalman filter, Monopulse signal**

I. Introduction

As unmanned aerial vehicle (UAV) communications have attracted much attention for 5G and beyond-5G (B5G) networks, UAV communications hold potential advantages in disaster management, environmental monitoring, and communication infrastructure development [1]. However, the movement of a UAV poses challenges to beam alignment, which becomes critical in a high-speed scenario. Thus, beam tracking is essential to maintain a reliable link for UAV communications.

When the UAV moves with high-speed, wireless channel is changed more frequently, and thus beam alignment in a real-time incurs prohibitive high complexity. Moreover, the Doppler shift occurs due to high-speed of a UAV, which leads to significant performance degradation during data transmission. As such, it is important to perform the accurate beam tracking and the compensation of the Doppler shift. Hence, we consider two specific attributes arising from high-speed and complex flight path, and propose to establish beam tracking and Doppler shift calculation.

Beam tracking method has been studied for UAV communications [2]. In [2], Kalman filter (KF) based algorithm was proposed, which utilizes a nonlinear monopulse signal for a more reasonable measurement model. However, this work did not consider the Doppler effect for UAV communications, and thus we need to consider a new state model of KF in the high-speed movement of a UAV.

This work was supported by Institute of Information communications Technology Planning Evaluation (IITP) grant funded by the Korea government(MSIT) (2022-0-00704, Development of 3D-NET Core Technology for High-Mobility Vehicular Service).

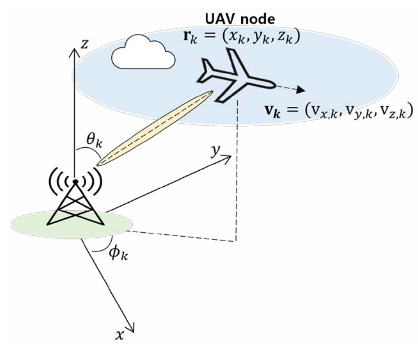

Fig. 1. System model of beam tracking for UAV communication with the movement of the UAV.

In this paper, we propose an Extended Kalman filter (EKF) based beam tracking scheme by analyzing the geometric relationship that takes into account the movement of the UAV. Specifically, we employ monopulse signal for beam tracking which offers a low complexity and less linearization loss. After obtaining the tracked AoA, we propose a method to compute the Doppler shift from the estimated AoA, which can be used to establish a reliable link by compensating the Doppler effect during data transmission.

II. System Model

We consider a mmWave uplink communication for beam tracking of a UAV as in Fig. 1 where a base station (BS) estimates the UAV's angle of arrival (AoA) information. Then, the BS utilizes the estimated AoA to communicate with the UAV moving along a specific path at a constant speed. Here, we assume that the BS knows the speed of UAV, but it does not know the flight path of UAV. The BS is equipped with $N = N_x \times N_y$ uniform planar array (UPA) and UAV has a single antenna. Then, the time-varying channel from the UAV to the BS at the kth frame is modeled as

$$\mathbf{h}_k = \alpha_k \mathbf{O}(f_{D,k}) \mathbf{a}_{BS}(\mathbf{x}_k), \tag{1}$$

where α_k denotes the channel gain. In (1), the array response vector of UPA $\mathbf{a}_{BS}(\mathbf{x}_k)$ is denoted as

$$\mathbf{a}_{BS}(\mathbf{x}_k) = \mathbf{a}_x(u_k) \otimes \mathbf{a}_y(v_k), \tag{2}$$

where $\otimes$ represents the kronecker product and the array response vector for the x-axis and the y-axis can be denoted as, respectively

$$\begin{aligned} \mathbf{a}_x(u_k) &= [1\ e^{ju_k}\ \cdots\ e^{j(N_x-1)u_k}]^T, \\ \mathbf{a}_y(v_k) &= [1\ e^{jv_k}\ \cdots\ e^{j(N_y-1)v_k}]^T. \end{aligned} \tag{3}$$

In (3), the spatial angle u_k and v_k are denoted as $\frac{2\pi d}{\lambda}\cos\phi_k \sin\theta_k$ and $\frac{2\pi d}{\lambda}\sin\phi_k \sin\theta_k$, respectively, with the azimuth angle ϕ_k, the elevation angle θ_k, and the antenna spacing d. From these spatial angle informations, the vector $\mathbf{x}_k = \begin{bmatrix} u_k, v_k \end{bmatrix}^T$ can be constructed. In addition, $\mathbf{O}(f_{D,k})$ represents the relative Doppler frequency offset (DFO) matrix, which is expressed as $\mathbf{O}(f_{D,k}) = \mathrm{diag}(\mathbf{O}_x(f_{D,k}) \otimes \mathbf{O}_y(f_{D,k}))$, and each relative DFO vector for the x-axis and the y-axis can be modeled as, respectively

$$\mathbf{O}_x(f_{D,k}) = [1\ e^{j\frac{\lambda}{c} f_{D,k} u_k}\ \cdots\ e^{j\frac{\lambda}{c} f_{D,k}(N_x-1)u_k}]^T, \tag{4}$$

$$\mathbf{O}_y(f_{D,k}) = [1\ e^{j\frac{\lambda}{c} f_{D,k} v_k}\ \cdots\ e^{j\frac{\lambda}{c} f_{D,k}(N_y-1)v_k}]^T. \tag{5}$$

Here, $f_{D,k}$ is the Doppler shift at the kth frame given by

$$f_{D,k} = \frac{\langle \mathbf{v}_k,\ \mathbf{r}_k \rangle}{\lambda \|\mathbf{r}_k\|}, \tag{6}$$

where $\langle\cdot\rangle$ and $\|\cdot\|$ represents the inner-product and l_2-norm. λ is the wavelength of the signal, and $\mathbf{v}_k = (\mathsf{v}_{x,k}, \mathsf{v}_{y,k}, \mathsf{v}_{z,k})$ and $\mathbf{r}_k = (x_k, y_k, z_k)$ denote the velocity and position vector of the UAV. Note that the distance between the BS and the UAV can be calculated by the TDOA [3].

The received pilot signal at the kth frame from the UAV is written as

$$\mathbf{y}_k = \mathbf{h}_k s_k + \mathbf{n}_k, \tag{7}$$

where s_k is the transmitted pilot signal, and $\mathbf{n}_k$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2. After estimating the AoA using the received pilot signal, the received signal during data transmission phase is combined using the beamforming vector obtained from the estimated AoA. The estimated AoA is essential to enable the data transmission. However, due to the movement of a UAV, it keeps changing and is difficult to obtain the AoA in a real-time. Thus, we propose a beam tracking method to track the AoA of a UAV.

III. BEAM TRACKING

In this section, we propose the AoA tracking method using a KF while minimizing angle mismatch error and the estimated AoA is used for establishing a reliable link between a BS and a UAV. Assuming that the initial AoA is perfectly obtained through initial channel estimation phase, we will focus solely on the beam tracking process, which is proposed as follows.

Algorithm 1 EKF Beam tracking Algorithm

Initial estimation of u_0, v_0
while at each frame **do**
  Prediction step
  $\hat{\mathbf{x}}_k^- = \mathbf{F}\hat{\mathbf{x}}_{k-1} + \mathbf{b}_k$
  $\mathbf{P}_k^- = \mathbf{F}\mathbf{P}_{k-1}\mathbf{F}^T + \mathbf{Q}_{p,k}$
  Get Innovation value by Measurement
  $\tilde{\mathbf{r}}_k = \mathbf{r}_k - g(\hat{\mathbf{x}}_k^-) = g(\mathbf{x}_k) + \mathbf{n}_{m,k} - g(\hat{\mathbf{x}}_k^-) \simeq \mathbf{G}\mathbf{x}_k + \mathbf{n}_{m,k} - \mathbf{G}\hat{\mathbf{x}}_k^-$
  Calculate Innovation Covariance and Kalman gain
  $\mathbf{S}_k = \mathbf{G}\mathbf{P}_k^-\mathbf{G}^T + \mathbf{Q}_{n,k}$
  $\mathbf{K}_k = \mathbf{P}_k^-\mathbf{G}^T\mathbf{S}_k^{-1}$
  Output
  $\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k\tilde{\mathbf{r}}_k$
  $\mathbf{P}_k = \mathbf{P}_k^- - \mathbf{K}_k\mathbf{S}_k\mathbf{K}_k^T$
end while

A. State Model for KF

First, we set up a state model based on the movement of the UAV. To account for the movement of the UAV in the x, y, and z-axis simultaneously, it is necessary to check the angular change through the geometric relationship. Given the simplest case, when UAV is moving in 2D environment, the angular change is modeled as

$$\cos\theta_{k+1} = \frac{a_k}{a_{k+1}}\cos\theta_k + \frac{\mathsf{v}_{x,k}}{a_{k+1}}t, \tag{8}$$

where t is the time duration of one frame, a_k and a_{k+1} are the distance between the BS and the UAV at kth and $k+1$th frame, respectively. By extending this model to 3D environment, u_k and v_k can be written as

$$\begin{aligned} u_k &= \pi\cos\phi_k\sin\theta_k = \frac{\pi x_k}{\sqrt{x_k^2 + y_k^2 + z_k^2}} \\ v_k &= \pi\sin\phi_k\sin\theta_k = \frac{\pi y_k}{\sqrt{x_k^2 + y_k^2 + z_k^2}}, \end{aligned} \tag{9}$$

where $d = \frac{\lambda}{2}$. (9) represents the ratio of coordinates in 3D when the position of the UAV is projected onto the x, y axis. Based on (8) and (9), we can establish the state model at the kth frame as

$$\begin{aligned} \mathbf{x}_{k+1} = \begin{bmatrix} u_{k+1} \\ v_{k+1} \end{bmatrix} &= \begin{bmatrix} \frac{r_{xz,k}}{\hat{r}_{xz,k}} & 0 \\ 0 & \frac{r_{yz,k}}{\hat{r}_{yz,k}} \end{bmatrix} \begin{bmatrix} u_k \\ v_k \end{bmatrix} + \begin{bmatrix} \frac{\mathsf{v}_{x,k}}{\hat{r}_{xz,k}}t \\ \frac{\mathsf{v}_{y,k}}{\hat{r}_{yz,k}}t \end{bmatrix} + \begin{bmatrix} \omega_{u,k} \\ \omega_{v,k} \end{bmatrix} \\ &= \mathbf{F}\mathbf{x}_k + \mathbf{b}_k + \mathbf{n}_{p,k}, \end{aligned} \tag{10}$$

where $r_{xz,k}$ and $r_{yz,k}$ are the projection distance onto the xz-plane and the yz-plane. $\hat{r}_{xz,k}$ represents the estimated projection distance at the $(k+1)$th frame which is calculated as $\sqrt{(x_k + v_{x,k}t)^2 + (z_k + v_{z,k}t)^2}$.

B. Measurement Model for KF

Most existing works related to the AoA tracking using KF exploit the beamformed signal as the measurement model [4]-[5]. Due to the nonlinearity of the beamformed signal, an EKF is widely used for tracking the AoA, but brings high computational complexity and high estimation error. To tackle this challenge, we adopt a monopulse signal as the measurement model, which has the benefits such as less linearization loss and low complexity [2]. The measurement model with monopulse signal can be represented as

$$\mathbf{r}_k = \begin{bmatrix} \tan\left(\frac{u_k}{2}\right) \\ \tan\left(\frac{v_k}{2}\right) \end{bmatrix} + \begin{bmatrix} n_{u,k} \\ n_{v,k} \end{bmatrix} = g(\mathbf{x}_k) + \mathbf{n}_{m,k}, \tag{11}$$

where $n_{u,k}$ and $n_{v,k}$ are the measurement noise with variance σ_m^2.

Our proposed EKF Beam tracking method, based on the (10) and (11), is outlined in Algorithm 1. First, the predicted state $\hat{\mathbf{x}}_k^-$ is calculated using the previous estimated state $\hat{\mathbf{x}}_{k-1}$, and the predicted error covariance matrix $\mathbf{P}_k^-$ is performed in the same way. In the next step, we obtain the innovation value by using the measurement model in (11), where the Jacobian matrix is $\mathbf{G} \simeq 0.5\mathbf{I}$. Then, we can get the innovation covariance and Kalman gain as $\mathbf{S}_k$ and $\mathbf{K}_k$ respectively, and then the updated state and error covariance can be finally obtained. These procedures are repeated at each frame to estimate AoA.

After obtaining the AoA at each frame, the estimated AoA information would be used for data transmission. However, Doppler shift should be considered during data transmission due to the movement of a UAV. Therefore, the obtained AoA through beam tracking are used to calculate the Doppler shift during data transmission at the kth frame. By using the estimated AoA and the distance information, we can calculate the position vector of the UAV as

$$\hat{\mathbf{r}}_k = (\hat{x}_k, \hat{y}_k, \hat{z}_k) = \|\mathbf{r}_k\| \Big(\frac{\hat{u}_k}{\pi}, \frac{\hat{v}_k}{\pi}, \sqrt{1 - ((\frac{\hat{u}_k}{\pi})^2 + (\frac{\hat{v}_k}{\pi})^2)} \Big). \tag{12}$$

From (12), we can obtain the Doppler shift in (6) which would be compensated for data transmission.

IV. Simulation Results

In this section, we verify the effectiveness of the proposed beam tracking scheme through numerical simulations. We choose N_x, $N_y = 8$, $f_c = 28$GHz, and σ_u^2, $\sigma_v^2 = 0.05$, and the UAV is moving along the specific path at the constant speed 240km/h.

Fig. 2 shows the beam tracking performance in a real-time. Here, we adopt the auxiliary beam pair (ABP) method as a benchmark [4]. The proposed scheme exhibits that both the spatial angles are being well tracked, and shows the stable beam tracking performance. While the ABP scheme also provides good tracking performance, there is occasional discrepancies between the estimated angle and the actual beam direction, especially in the v, which introduces a high beam-tracking error compared to the proposed scheme. Therefore, it demonstrates that the propsed method provides a lower estimation error despite the fast movement of the UAV.

Fig. 3 shows the Doppler shift estimation error which is obtained from the estimated AoA. Compared to the ABP scheme, the proposed scheme shows a lower Doppler shift estimation error due to more accurate AoA estimation as shown in Fig. 2.

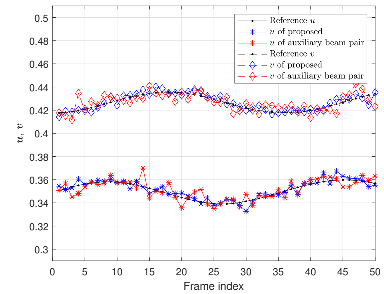

Fig. 2. Illustration of the spatial angle when UAV is moving with 240km/h velocity.

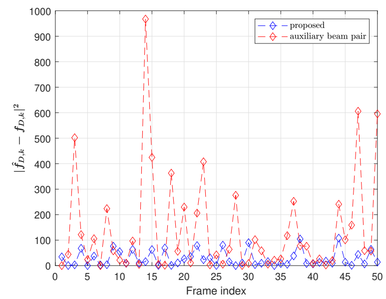

Fig. 3. Comparison of Doppler shift estimation error which is obtained from the estimated AoA.

V. Conclusions

In this paper, we propose the EKF based beam tracking scheme for high-speed UAV scenarios in a real-time. First, the geometric relationship, accounting for the complicated path, is analyzed to construct the state model for the EKF. Specifically, we utilize monopulse signal as a measurement model, which offers some benefits such as a low complexity and less linearization loss. Then, we exploit the estimated AoA to calculate Doppler shift. The simulation results show that the proposed scheme can accurately estimate both the AoA and Doppler shift even in a high-speed scenario.

References

[1] Z. Xiao, P. Xia, and X.-g. Xia, "Enabling UAV cellular with millimeter-wave communication: potentials and approaches," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 66–73, May. 2016.

[2] H.-L. Song and Y.-C. Ko, "Robust and Low Complexity Beam Tracking With Monopulse Signal for UAV Communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 4, pp. 3505–3513, April. 2021.

[3] J. Talvitie, T. Levanen, M. Koivisto, T. Ihalainen, K. Pajukoski, M. Renfors, and M. Valkama, "Positioning and Location-Based Beamforming for High Speed Trains in 5G NR Networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1–7.

[4] S. Kim, H. Han, N. Kim, and H. Park, "Robust Beam Tracking Algorithm for mmwave MIMO Systems in Mobile Environments," in *Proc. IEEE Vehicular Technology Conference (VTC-Fall)*, 2019, pp. 1–5.

[5] V. Va, H. Vikalo, and R. W. Heath, "Beam tracking for mobile millimeter wave communication systems," in *Proc. IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, 2016, pp. 743–747.