ISSN 2706-655X Vol.5, Issue 3: 32-39, DOI: 10.25236/IJFET.2023.050306

Influence of UAV Jittering on Sensing Performance in ISAC System

Yipeng Zhang[1], Hao Xu[2]

[1]School of Communication and Information Engineering, Nanjing University of Postsand Communications, Nanjing, 210003, China
[2]School of Information and Electronic Engineering, Zhejiang Gongshang University, Hangzhou 310018, China

Abstract: *The integrated sensing and communication (ISAC) based on unmanned aerial vehicle (UAV) is considered to be an important candidate technology for future wireless communication, which can overcome the problem that the line-of-sight (LoS) path of ground communication in millimeter wave or terahertz band is easily blocked. However, recent studies have shown that due to the change of wind speed, the vibration of wing and other factors, UAV will appear jittering effect, which will seriously affect the communication performance. With the continuous research of ISAC, it is also necessary to explore the impact of UAV jittering on the sensing performance. This paper first proposes the UAV jittering model, then takes the target angle sensing scheme based on time-division wave scanning as an example, and explores the influence of UAV jittering on target sensing. This paper finds that UAV jittering has great influence on the accuracy and resolution of target sensing. Simulation results confirm this conclusion.*

Keywords: *ISAC, UAV jittering, sensing performance*

1. Introduction

Due to the limited radio spectrum resources, communication systems and radar systems are moving towards integration, which makes ISAC become the key candidate technology for the next generation of wireless communication. ISAC system has the potential to complete user communication and target sensing at the same time [1]. Once the BS system senses the various parameters of the physical environment, it can serve many intelligent scenarios, such as the Internet of Vehicles, smart hospitals, etc [2], [3].

Besides, the sixth generation mobile communication (6G) will use a higher frequency band, such as millimeter wave (mmWave) or terahertz band. However, the signal above millimeter-wave band will suffer serious free space propagation loss [4]. Fortunately, multiple input and multiple output (MIMO) array and beamforming technology can overcome the difficulty of path loss by transmitting the directional beams to improve the communication performance. However, the directional beam generated based on beamforming is easily blocked by buildings in urban ground communication, which makes it difficult to form a stable transmission link. Many scholars suggest to use UAV communication to alleviate this problem, in which the UAV can dynamically adjust its position in three-dimensional space to ensure the formation and stability of LoS path [5].

However, due to the air flow, gust, mechanical wing vibration and other factors, UAV will appear jittering effect, i.e., the actual position and attitude of the UAV generate random fluctuations near its expected position and attitude [6]. It has been confirmed that UAV jitter will have a negative impact on communication performance. For example, W. Wang deeply studied the UAV jittering effect on communication and adopted beam training design to compensate for the negative effect [7]. W. Yuan adopted learning-based predictive beamforming for UAV communications with jittering to achieve secure and reliable communication [8]. Y. Wen explored the influence of UAV jittering on communication confidentiality and put forward some measures to tackle it [9].

Nevertheless, the above studies are all aimed at exploring the influence of jittering on communication. In ISAC system, the influence of jittering on sensing performance also needs to be studied. This paper fills the research gap. We study the effect of UAV jittering on sensing performance in ISAC system. The contributions of this paper can be summarized as follows.

ISSN 2706-655X Vol.5, Issue 3: 32-39, DOI: 10.25236/IJFET.2023.050306

We first derive the echo channel model of ISAC system for target detection. Then we analyze the factors that cause the UAV jittering, and model the UAV jittering effect. We take the target angle sensing scheme based on time-division wave scanning as an example, and explore the influence of UAV jittering on target sensing. We find that UAV jittering has great influence on the accuracy and resolution of target sensing.

2. System model

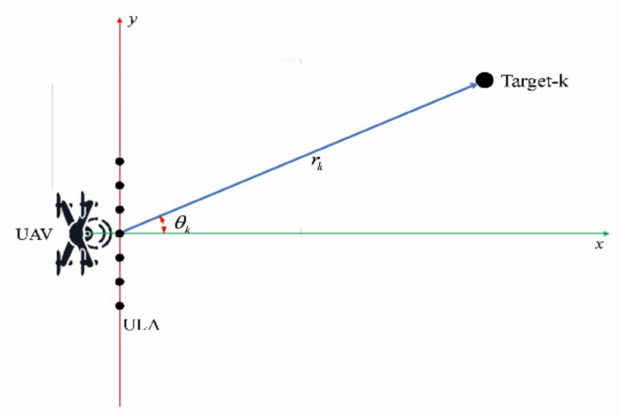

Figure 1: An illustration of UAV communication scenario.

As shown in Fig. 1, we consider an UAV carrying the MIMO array to form a BS system for communication and sensing. For the convenience of discussion, it is considered that the BS is configured with a uniform linear array (ULA) of *N* antennas. The distance between antenna units is $d=\frac{\lambda}{2}$, where λ is the wavelength. We take the center of the ULA as the origin of the coordinate system, and denote the position of the *n*-th antenna as $(0, nd)$, where $n=-\frac{N-1}{2},...,\frac{N-1}{2}$. It is premised that BS operates in the millimeter wave band with narrow band orthogonal frequency division multiplexing (OFDM) signal, and the center carrier frequency is f_0.

Suppose that the BS needs to sense a total of *K* targets, and the location of the *k*-th target in the coordinate system mentioned above is (x_k, y_k), which can also be expressed as (r_k, θ_k) in planar polar coordinate system. We assume that all the targets are located in the far-field area of the BS. When the BS needs to sense the target, the BS first transmits the pilot signal to detect the target. The single-way channel of the pilot signal from the BS array to the *k*-th target through the LoS path is

$$\boldsymbol{h}_k=\alpha_k \boldsymbol{a}_k=\alpha_k[e^{j\frac{2\pi f_0 d\sin\theta_k}{c}(-\frac{N-1}{2})},...,e^{j\frac{2\pi f_0 d\sin\theta_k}{c}(\frac{N-1}{2})}]^T, \tag{1}$$

Where $\boldsymbol{a}_k$ is the steering vector of BS antenna array and α_k is the attenuation coefficient of the signal in this single-way channel.

Different from communication, BS needs to transmit the detection signals and receive the echo of targets to realize the sensing process. Based on (1), the double-way echo channel for all the targets can be expressed as

$$\mathbf{H}=\sum_{k=1}^{K}\mathbf{H}_k=\sum_{k=1}^{K}\beta_k \boldsymbol{a}(\theta_k)\boldsymbol{a}^H(\theta_k), \tag{2}$$

Where β_k is the attenuation coefficient of the *k*-th target's echo channel.

3. Influence of UAV jittering on sensing

3.1 Sensing Scheme Based on Beamforming

In ISAC systems, MIMO arrays always adopt beamforming technology to achieve high directional channel to reduce high path loss attenuation. Here we assume that BS adopts the beamforming based on phase shifters to realize target sensing. Supposing that the phase shift corresponding to the *n*-th phase shifter is ϕ_n, and then the beamforming vector $\boldsymbol{w}$ is

$$\boldsymbol{w} = \frac{1}{\sqrt{N}}[e^{-j2\pi\phi_1},...,e^{-j2\pi\phi_n}]^T. \tag{3}$$

When BS needs to sense the potential targets in the direction of θ_s, where $\boldsymbol{a}(\theta_s)$ is the steering vector, the single-way channel transmission power gain of BS with the adoption of beamforming can be expressed as

$$p = |\boldsymbol{w}^H \boldsymbol{a}(\theta_s)| = |\frac{1}{\sqrt{N}} \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} e^{j2\pi\phi_n} e^{j\frac{2\pi f_0 nd \sin\theta_s}{c}}|. \tag{4}$$

Obviously, p is maximized when the phase changed by each phase shifter satisfies

$$\phi_n = -\frac{f_0 nd \sin\theta_s}{c}. \tag{5}$$

Therefore, we find a strategy for phase shifters that can achieve the effect of beamforming. It can be presented as

$$\boldsymbol{w}(\theta_s) = \frac{1}{\sqrt{N}}[e^{j\frac{2\pi f_0 d \sin\theta_s}{c}(-\frac{N-1}{2})},...,e^{j\frac{2\pi f_0 d \sin\theta_s}{c}(\frac{N-1}{2})}]^T, \tag{6}$$

which can maximize the power of transmitted signal in the direction of θ_s.

Now we consider a sensing scheme of targets' angles based on time-division beam searching. It is assumed that the range of angle sensing required by BS is $[\theta_{\min}, \theta_{\max}]$, and M times beam detections are adopted by BS to realize the searching coverage of the whole space. The angle interval of two adjacent beam searching is $\frac{\theta_{\max} - \theta_{\min}}{M}$. Suppose that the *m*-th detection of BS focus on the direction of θ_m. According to (6), the corresponding beamforming vector is $\boldsymbol{w}(\theta_m)$. Then the power of echo signal during the *m*-th beam searching can be expressed as

$$p(\theta_m) = |y(\theta_m)| = |\boldsymbol{w}^{\mathrm{H}}(\theta_m)\mathbf{H}\boldsymbol{w}(\theta_m) + n_m|, \tag{7}$$

where $y(\theta_m)$ is the echo signal and n_m is the noise, which obeys the complex Gaussian distribution.

After M times detections, BS can piece the echo signal power of each detection into a vector $\boldsymbol{p}$, which is called as the *echo power vector* and can be represented as

$$\boldsymbol{p} = [p(\theta_1),...,p(\theta_M)]^T. \tag{8}$$

Then we can estimate the number and angles of the targets by monitoring the peaks in $\boldsymbol{p}$, in which each target will correspond to one peak.

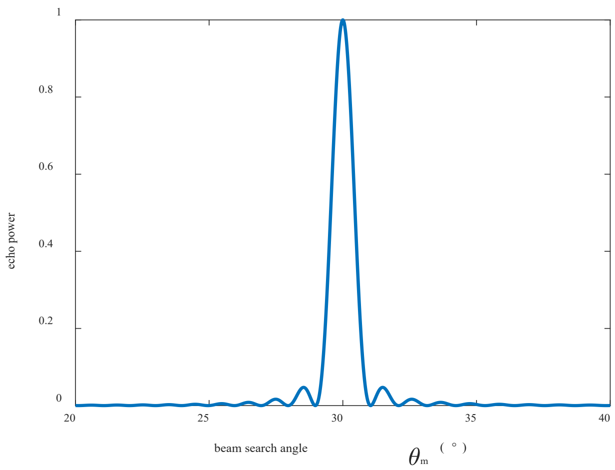

Figure 2: An example of target sensing based on time-division beam searching.

Fig. 2 shows an example of target sensing based on time-division beam searching, where only one target is located at (100*m*,30°). The parameter is $N = 128$, $f_0 = 60\text{GHz}$, and $[\theta_{\min}, \theta_{\max}] = [20°, 40°]$. After the visualization of $\boldsymbol{p}$, we can clearly find that there is a peak in the figure, and its corresponding angle θ_m = 30° just is equal to the angle of the target θ_k = 30°. This example shows that we can estimate the angle of the target by the sensing scheme based on beamforming.

3.2 UAV Jittering Model

Since the UAV does not tie to any fixed object, coupled with the influence of air pressure, gusts of wind, and airflow, the UAV will appear *jittering effect*. Here, jittering is defined as the short-term deviation of UAV parameters from their ideal position at each instant. It has confirmed that the UAV jittering will have a significant negative impact on LoS path communication in millimeter wave or terahertz frequency band [10], [11]. Here we want to explore whether the UAV jittering will affect the sensing process.

By analyzing the above sensing model, it is obvious that UAV jittering will also have a direct impact on some sensing parameters, thus affecting the process and performance of sensing. Specifically, since we simplify the target sensing of UAV to two-dimensional situation, the UAV jittering will have a jittering effect on the angle of each detection. When jittering is not considered, the focusing angle of the *m*-th detection beam is θ_m . When the UAV jitters, the direction of the sensing beam will generate the following jittering, which will focus on the direction of $\theta_m + \Delta\theta_m$. Thus we can model the UAV jittering as

$$\theta'_m = \theta_m + \Delta\theta_m, \tag{9}$$

where θ'_m is the angle of actual direction in the presence of jittering and $\Delta\theta_m$ is considered the angle away from the designated angle θ_m , which is modeled as a zero mean Gaussian distributed variable with variance σ_θ^2 . The value of σ_θ can represent the jittering intensity, which depends on the influencing factors of UAV jittering. And σ_θ is typically in the range of [0.01, 0.1] rad.

3.3 Jittering Effect on the Sensing Scheme

Under the influence of jittering, the power of echo signal during the *m*-th beam searching can be represented as

$$\tilde{p}(\theta'_m) = | y'(\theta'_m) | = | \boldsymbol{w}^{\text{H}}(\theta_m + \Delta\theta_m)\mathbf{H}\boldsymbol{w}(\theta_m + \Delta\theta_m) + n'_m |, \tag{10}$$

where $y'(\theta'_m)$ is the echo signal in the presence of jittering and n'_m is the noise under this circumstance, which also obeys the complex Gaussian distribution. Similarly, in this situation, BS can also piece the echo signal power of each detection into a vector $\tilde{\boldsymbol{p}}$, which can be represented as

$$\tilde{\boldsymbol{p}} = [\tilde{p}(\theta'_1), \ldots, \tilde{p}(\theta'_M)]^T . \tag{11}$$

We consider the jittering effect on sensing performance on two aspects below. On the one hand, the effect of jittering on sensing is reflected in the deviation between the target angle and the angle found in vector $\tilde{\boldsymbol{p}}$ by BS. In fact, the effect of jittering will not be taken into account by the search system, and the maximum power obtained by the search with noise and jittering will be biased to a certain extent.

Fig. 3 shows an example of target sensing based on the jittering model, where we take σ_θ as 0.05 and only one target located at (100*m*,30°). It can be seen from the figure that in the case of UAV jitter, even without the influence of noise factors, it is difficult to directly determine the angle of the target from the peak value in $\tilde{\boldsymbol{p}}$. Besides, from the comparison between Fig. 2 and Fig. 3, we can find that there is a certain deviation between the angle corresponding to the maximum value in the two scans. In practice, this will cause errors in sensing the angle of the target.

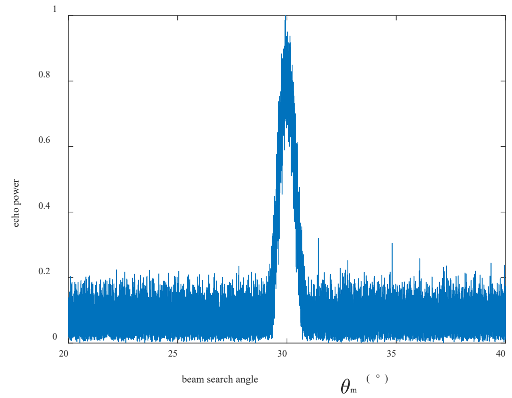

Figure 3: An example of UAV jittering effect on target sensing accuracy.

On the other hand, when BS needs to sensing multiple targets, *angular resolution* is an important parameter. Here, angular resolution is defined as the ability to differentiate between two adjacent crests, which can also be expressed as the angle between two minimal discernible crests. The effect of jittering on sensing is also reflected on the angular resolution. In practice, when BS needs to sense several extremely close targets, the detected peaks will also be very close, and it will become difficult to distinguish the two peaks clearly in the presence of jittering.

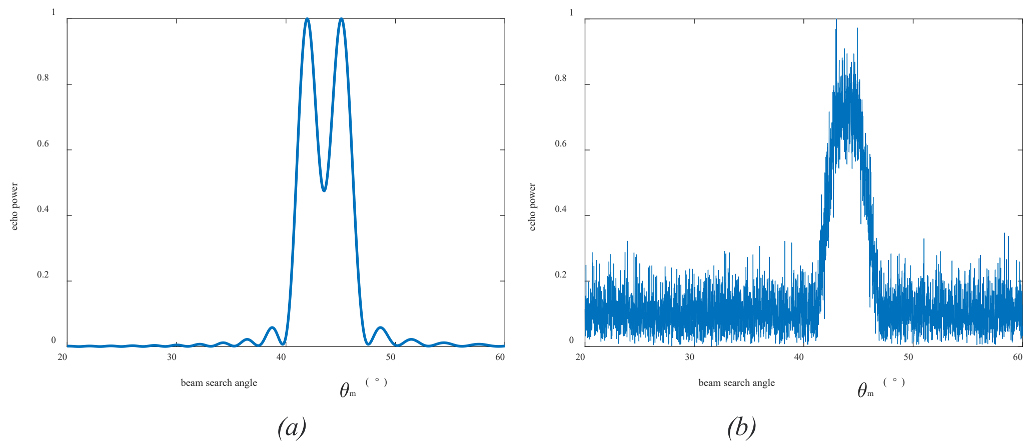

Figure 4: (a) Multiple targets scene without noise and UAV jittering. (b) Multiple targets scene with UAV jittering.

Fig. 4 gives an example of target sensing on the multiple targets, where the first target's direction is 43° and the second target's direction is 45°. From the comparison between Fig. 4(a) and Fig. 4(b), BS can easily and clearly determine targets' angles in (a). However, it's nearly impossible for BS to separate the first target and the second target through (b). This means that UAV jittering will seriously influence the sensing performance in multiple targets scene.

4. Simulation result

In this section, we will explore the influence of jittering on sensing performance through simulation trials. Here we consider the UAV to have $N = 128$ antennas. In addition, the carrier frequency is set as $f_0 = 60\text{GHz}$, and the location of UE in polar coordinate is $(100m, 30°)$. In order to reduce the waste of calculating resources, the scanning range of scheme A is set as $[20°, 40°]$ with the searching accuracy 0.001°.

Root mean square error (RMSE) can measure the difference between the predicted value and the true value, and is sensitive to outliers in the data. Here the RMSE represents the difference between the detected angle and the target angle, which can be expressed as

$$RMSE = \sqrt{\frac{1}{X}\sum_{i=1}^{X}(\hat{\theta}_{k,i} - \theta_k)^2}\ , \tag{12}$$

where X is the number of repeated experiments and $\hat{\theta}_{k,i}$ is the i-th detected angle when detecting k-th target.

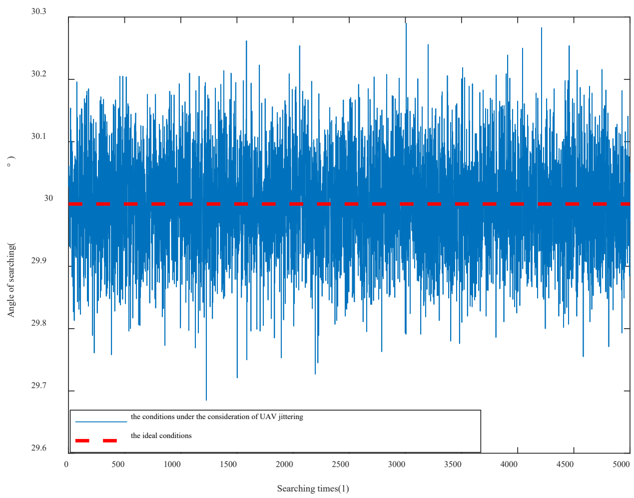

Figure 5: Detection angle distribution generated by Monte Carlo simulation.

Fig. 5 shows the results of Monte Carlo simulation experiment for target sensing under ideal conditions and under the UAV jittering. Obviously, a search for the maximum value of a single scan shown in Fig. 3 will achieve an angle that is more or less away from the correct angle. Therefore, in order to make it clearer to explore the influence of jittering on the angle of searching results, we repeated the scan-search operation on a large scale for X = 5000 times. We take SNR=5dB as the initial signal-to-noise ratio under each trial. It shows that the angles obtained by large-scale search are clustered around the target angle and have a certain deviation, which indicates the jittering effect on the sensing performance.

Then we explore the impact of UAV jittering on sensing performance under different jittering levels. Fig. 6 shows the variation curve of sensing RMSE with SNR under different jittering levels. Firstly, it can be seen from the figure that RMSE decreases with the increase of SNR. Besides, the curves of RMSE with SNR showed different decreasing trends at different jittering levels. In particular, jittering introduces a new lower bound on the RMSE of angle estimation compared to the conditions in the absence of jittering. And we find that the lower bound of RMSE increases with the increase of jitter

ISSN 2706-655X Vol.5, Issue 3: 32-39, DOI: 10.25236/IJFET.2023.050306

intensity.

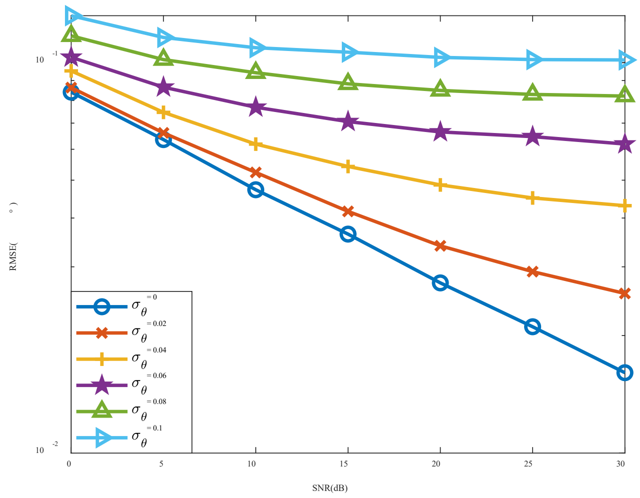

Figure 6: The fitting accuracy of different jittering intensities.

5. Conclusion

The ISAC based on UAV is considered to be an important candidate technology for future wireless communication, which can overcome the problem that the LoS path of ground communication in millimeter wave or terahertz band is easily blocked. However, recent studies have shown that UAV will appear jittering effect, which will seriously affect the communication performance. With the continuous research of ISAC, it is also necessary to explore the impact of UAV jittering on the sensing performance. In this paper, we first propose the UAV jittering model. Then we take the target angle sensing scheme based on time-division wave scanning as an example, and explore the influence of UAV jittering on target sensing. We find that UAV jittering has great influence on the accuracy and resolution of target sensing. Simulation results confirm this conclusion.

References

[1] K. Kim, J. Kim and J. Joung, "A survey on system configurations of integrated sensing and communication (ISAC) systems," in Proc. 13th International Conference on Information and Communication Technology Convergence (ICTC), Jeju Island, Korea, Republic of, Oct. 2022, pp. 1176-1178.
[2] X. Wang et al., "Optimizing content dissemination for Real-Time traffic management in Large-Scale internet of vehicle systems," IEEE Transactions on Vehicular Technology, vol. 68, pp. 1093-1105, Feb. 2019.
[3] S. Jing, R. Xiao, T. Shan, Z. Wang and Y. Liu, "Application practice of smart hospital based on IoT cloud platform," in Proc. IEEE International Conference on Consumer Electronics - Taiwan (ICCE-Taiwan), Taoyuan, Taiwan, Sep. 2020, pp. 1-2.
[4] T. Kebede, Y. Wondie, J. Steinbrunn, H. B. Kassa and K. T. Kornegay, "Precoding and beamforming techniques in mmWave-Massive MIMO: Performance assessment," IEEE Access, vol. 10, pp. 16365-16387, Feb. 2022.
[5] L. Cao and H. Wang, "Research on UAV network communication application based on 5G technology," in Proc. 3rd International Conference on Electronic Communication and Artificial Intelligence (IWECAI), Zhuhai, China, Jan. 2022, pp. 125-129.
[6] B. Yang and W. Zhang, "Analysis of propagation characteristics for MIMO Air-to-Air communications with UAV jitter," in Proc. 13th International Symposium on Antennas, Propagation and EM Theory (ISAPE), Zhuhai, China, Feb. 2021, pp. 1-4.
[7] W. Wang and W. Zhang, "Jittering effects analysis and beam training design for UAV millimeter wave communications," IEEE Transactions on Wireless Communications, vol. 21, pp. 3131-3146, May. 2022.
[8] W. Yuan, C. Liu, F. Liu, S. Li and D. W. K. Ng, "Learning-Based predictive beamforming for UAV

ISSN 2706-655X Vol.5, Issue 3: 32-39, DOI: 10.25236/IJFET.2023.050306

communications with jittering," IEEE Wireless Communications Letters, vol. 9, pp. 1970-1974, Nov. 2020.

[9] Y. Wen, H. Wu, H. Li and X. Tao, "Robust AN-Aided secure beamforming design for A2G communication networks with UAV jitter," in Proc. 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Seoul, Korea (South), Apr. 2020, pp. 1-6.

[10] K. Liu, Y. Liu, T. Mao, Z. Xiao and X. -G. Xia, "Robust hybrid beamforming for jittering UAV with mmWave antenna array," in Proc. IEEE/CIC International Conference on Communications in China (ICCC), Sanshui, Foshan, China, Aug. 2022, pp. 244-249.

[11] H. Wu, Y. Wen, J. Zhang, Z. Wei, N. Zhang and X. Tao, "Energy-Efficient and secure Air-to-Ground communication with jittering UAV," IEEE Transactions on Vehicular Technology, vol. 69, pp. 3954-3967, April 2020.