

Anti-jamming Technology for Integrated Communication and Sensing of Unmanned Aerial Vehicles under Obstacle Factors

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Abstract

The obstacle factors will deteriorate communication links and sensing performance when the unmanned aerial vehicles (UAVs) are working in an environment like a urban canyon, which limit the applications of them. However, Integrated Communication and Sensing (ISAC), one of the key enabling technologies for 6G, provides new approaches for reducing occlusion interference. This paper reviews the research on Anti-jamming Technology for ISAC of UAVs under Obstacle Factors in recent years by analyzing the characteristics of occlusion and sorting out the existing technologies from three aspects: communication, sensing and cross-domain collaboration. In the future, constructing a high-fidelity dataset for urban canyon, developing lightweight intelligent anti-jamming architectures and exploring Integrated Communication, Sensing and Computing Collaboration (ISCC) will be an important research direction, which can provide technical support for the large-scale application of scenarios like urban air traffic, emergency response and Wide-Area Internet.

Keywords

UAV, ISAC, occlusion effect, anti-jamming technology

1. Introduction

The Unity Nations predicts that 68% of the world population will live in cities, which promote the rapid growth of the application of UAVs in logistics, inspection, emergency response and other fields. However, when UAVs are carrying out tasks in a multi-occlusion environment, their functions of communication and sensing functions will face severe challenges.

Certain development has been achieved in the field of anti-jamming for UAV communication, but there are still obvious deficiencies. In terms of visual perception, most studies focus on ensuring the reliability of communication links but ignore the impact of occlusion on sensing[1]; In terms of methods, anti-jamming technologies are often confined to a single part like physical layer or network layer, which are lack of sorting out of communication, sensing and Cross-domain Collaboration; In terms of scenarios, although existing channel models have considered the impact of large-scale fading, they fail to fully characterize the

complexity of high-frequency dynamic occlusion in urban canyon[2]. These deficiencies constrain the robustness of the task. ISAC, one of the key enabling technologies of 6G, provides a new idea for solving the above-mentioned difficult problem.

To systematically sort out the progress in improving the anti-occlusion capability of UAVs, this paper focus on the obstacle factors, analyzes from three aspects: communication, sensing and cross-domain collaboration, and looks forward to the future challenges and development directions, so as to provide theoretical references for the accumulation of measured data, algorithm iteration and large-scale application of low-altitude economy.

2. Analysis of Occlusion Interference Characteristics

2.1 Static Occlusion

Static occlusion refers to the blocking of line-of-sight links by fixed buildings, which is directly manifested as shadow fading. Shadow fading refers to the slow fading of the received power and its random fluctuations and characteristics when the signal passes through the shadow area formed by the occlusion of buildings.

In the ISAC system, shadow fading not only affects the communication link but also reduces the signal-to-noise ratio of the perceived echo. The fading of signal strength directly leads to a shortened detection distance and an increased ranging error. In severe cases, it may cause blind spots in sensing. Therefore, static occlusion and shadow fading are among the core channel characteristics that subsequent anti-jamming technologies need to address.

2.2 Dynamic Occlusion

Dynamic occlusion refers to the instantaneous signal blockage introduced by moving objects such as vehicles, pedestrians, and other UAVs. It has transience, randomness and time-variance. When an occlusion passes through the communication links rapidly, the signal strength will drop sharply and then recover. In the low-altitude airspace of cities, the high-frequency operation of UAV swarms significantly increases the complexity of dynamic occlusion [3].

The impact of occlusion on the UAV ISAC system is reflected in two aspects. In terms of communication, the intermittent link disruption leads to data retransmission and increased end-to-end delay. In terms of sensing, moving objects generate noise in radar or visual sensors, which may lead to false alarms or target loss. In addition, interference factors such as dynamic occlusion and static occlusion superimpose on each other causes the channel state to be simultaneously affected by both spatial fixed loss and random temporal fading, posing a severe challenge to the real-time performance and robustness of the system [4].

2.3 Multipath Effect

Multipath effect refers to the communication signal reaching the receiving end through multiple paths, resulting in changes in phase and amplitude. In urban canyon, obstacles such as buildings, grounds and vehicles form a complex reflection environment, causing signals to propagate in a way that coexists along the direct paths and multiple reflection paths. Channel fading refers to random variation of the signal strength, which is more significantly in urban canyon.

Multipath effect and channel fading will seriously affect the quality and reliability of communication signals and increase the error rate of data transmission [4].

3. The Current Situation of Anti-jamming Technology for ISAC of UAVs under Obstacle Factors

3.1 Anti-jamming Technology for the Communication Layer

3.1.1 Adaptive Modulation and Coding (AMC) Diversity Techniques

AMC dynamically adjusts the modulation order and coding rate based on the real-time channel quality. When the channel conditions deteriorate, it switches to a lower-order modulation to enhance link robustness. AMC can effectively handle channel quality fluctuations [5]. Its advantage lies in its simple implementation, but the response speed is limited by the channel feedback delay and may lag behind the channel changes in high-speed mobile scenarios.

Diversity techniques transmit the same information through multiple independent fading paths and combine them at the receiving end to combat multipath fading. Dynamic shadowing effect is one of the main challenges faced by UAV systems. For this reason, C.Xu et al. proposed an adaptive spatial modulation scheme [6]. This scheme can achieve multi-antenna diversity gain under a single radio frequency chain condition, effectively enhancing the link reliability under dynamic shadowing effect. Spatial diversity requires the use of multiple antennas. Although it is limited by size, weight and power consumption constraints, the improvement in link reliability it brings is particularly important for resource-constrained UAV platforms. However, the complexity of the diversity combining algorithm is high, and a balance must be struck between performance and processing overhead.

3.1.2 Beamforming and RIS-Aided Communication

Beamforming focuses the signal energy in a specific direction on the target UAV through a multi-antenna array. This technology can effectively compensate for the path loss caused by occlusions and is one of the core methods for enhancing the air interface link gain [7]. Through cooperative beamforming, this technology can significantly enhance communication performance, and it has unique advantages in high-dynamic occlusion scenarios. However, in a dynamic occlusion environment, the rapidly changing channels may cause beam pointing deviation. Therefore, beam tracking technology needs to be combined [8].

IRS is composed of a large number of tunable passive reflecting elements. By adjusting the phase and amplitude of the incident signal, it intelligently changes the signal propagation path to reconstruct the originally blocked link. Lu W D et al. solved the problem of wireless channel being blocked by obstacles by jointly optimizing the position of UAVs, the beamforming of base stations, and the phase shift of IRS [9]. This algorithm can effectively enhance the minimum secrecy rate of the system and has excellent convergence properties. The advantages of IRS lie in its low energy consumption and flexible deployment, which can improve the channel environment without increasing the radio frequency link. However, the real-time optimization calculational complexity of IRS phase shifting is relatively high, so a balance between performance and cost needs to be achieved.

3.2 Anti-jamming Technology for the Sensing Layer

3.2.1 Robust Target Detection and Ranging (RTDR)

Robust target detection refers to the ability of the detection algorithm to maintain a high detection probability and a low false alarm rate even under non-ideal conditions such as target signal being obscured or attenuated, background clutter interference, multipath pollution, or a sudden drop in signal-to-noise ratio. In a multi-target environment, the traditional cell-averaging constant false alarm rate algorithm is prone to the target occlusion effect. when there are interfering targets within the reference window, the detection threshold will be raised, resulting in the main target being "occluded" and thus being missed [10].

Therefore, researching robust target detection technologies for occluded environments is an essential guarantee for the reliable operation of the perception function of the UAV ISAC system.

For the problem of target detection under low signal-to-noise ratio and partial occlusion, Guo W et.al proposed various improvement methods from perspectives such as feature enhancement, multi-frame association, and clutter suppression [11]. The research focused on the problem that UAVs are prone to be affected by changes in viewing angle, partial occlusion and background clutter when tracking targets, and proposed a target tracking algorithm with dual response anomaly constraints. Although this research focuses on the tracking stage, if the response anomaly detection mechanism can be transferred to the detection stage,

it will be able to maintain the confidence judgment of the target's existence using temporal information even when the target is occluded and a single-frame detection fails.

3.2.2 Multi-sensor Fusion (MSF)

Multi-sensor fusion integrates data from heterogeneous sensors such as visible light, infrared, and radar. By leveraging the complementary advantages of each modality, it can maintain perception capabilities even when a single sensor fails due to occlusion or changes in lighting conditions. Among them, the multimodal fusion technology that integrates sensors based on different physical principles is an important approach to enhancing the perception robustness in occluded environments. Sun X Y et.al proposed a multimodal target detection method for multi-UAV collaboration. They achieved the deep fusion of visible light and infrared images through a convolutional fusion network and introduced a visual perception enhancement module to eliminate the influence of adverse lighting conditions. Moreover, the effectiveness of the algorithm was verified [12]. Multi-sensor fusion belongs to typical multimodal information fusion. It can significantly improve the detection accuracy in occluded environments but still necessary to balance the temporal-spatial alignment accuracy of heterogeneous data with the computational cost.

3.2.3 Robust Simultaneous Localization and Mapping (SLAM)

The anti-occlusion SLAM algorithm can address scenarios where visual features are lost due to occlusion. It maintains the positioning and mapping capabilities of the UAV through prior information or temporal prediction methods. Chen et al. proposed an anti-occlusion target tracking algorithm based on Kalman filtering. When abnormal high-confidence detections occur, they introduced Kalman filtering to predict the target's motion trajectories, generate candidate regions, and associate them with historical templates to achieve repositioning [13]. This idea can also be applied to the feature loss and recovery problem in SLAM.

The anti-occlusion method assisted by prior maps can utilize the highly precise map of laser radar (LiDAR) points collected in advance to provide prior environmental information when real-time perception is occluded. R. J. A. A. Nathan et al. addressed the issue that UAVs have difficulty detecting ground targets when obstructed by objects. They utilized pre-recorded LiDAR point clouds to calculate the visibility of ground interest points for potential UAVs positions in the air, thereby guiding the UAVs to the optimal observation position. Prior information can effectively make up for the disadvantages of real-time perception, but the timeliness of the map and its adaptability to dynamic environments still require further research.

3.3 Cross-domain Collaborative Anti-jamming Architecture

3.3.1 IRS-assisted ISAC Cooperative Beamforming

The IRS reflection signal can be used simultaneously for communication and sensing. Li F et.al proposed a dual-IRS-assisted ISAC system design that combines beamforming and reflection for complex low-altitude scenarios. This research jointly optimizes the base station beamforming and the dual IRS reflection coefficient matrix under the constraints of base station transmission power and sensing performance, significantly enhancing the communication and sensing collaboration performance in low-altitude complex scenarios [14]. The dual IRS architecture can further expand the coverage range, but the phase coupling among multiple IRSs increases the non-convexity of the optimization problem, and requires the use of tools such as continuous convex approximation and alternating direction method of multipliers.

3.3.2 Joint Resource Allocation

Joint resource allocation is one of the core methods for cross-domain collaborative anti-jamming. This method achieves the balance between communication rate and sensing accuracy by dynamically allocating limited resources such as power, spectrum, and beams. In the UAV swarm ISAC system, the resource allocation problem is usually modeled as a multi-objective optimization problem.

In response to this issue, Wang M et.al introduced the reinforcement learning framework, incorporating resources such as beams, spectrum and power into a unified optimization model. They achieved better performance than traditional algorithms in complex environments [15]. R. Wang et al. utilized the optimal transmission theory and joint optimization of cell association and power allocation to achieve a coordinated improvement in communication rate and positioning accuracy [16]. The above research indicates that

intelligent optimization algorithms have significant potential in solving the ISAC resource allocation problem. However, further reducing the complexity of the algorithm to meet the real-time requirements of UAV platforms remains the focus of future research.

3.3.3 Distributed Cooperation

Distributed collaboration is the core advantage of UAV swarms compared to individual UAV. Through information sharing and task coordination among multiple nodes, it can overcome the blind spots of individual node sensing and the computational limitations, achieving swarm-level anti-occlusion capabilities.

Multi-UAV cooperative perception enables sensing-limited UAVs to obtain observation data from other perspectives through cross-viewpoint information sharing, thereby completing the information of occluded targets. H. Zhou et al. proposed a multi-UAV collaborative detection network, which mitigates the impact of projection errors through a secondary matching method and a hybrid fusion strategy [17]. Multi-UAV collaborative perception is an effective way to solve the occlusion problem, but it still needs to balance the accuracy of projection transformation, communication overhead and real-time performance.

Distributed optimization and consensus mechanism are designed to address the distributed characteristics of UAV swarms. Z. Zhai et al. proposed an optimization framework based on decentralized consensus, enabling UAVs to make concurrent decisions on their respective positions and reach a consensus on the global optimal swarm geometric configuration [18]. This algorithm decomposes the global objective into local projection updates, proxy-assisted consensus coordination, and lightweight dual updates, ensuring the scalability and consistency of the swarms. The simulation results show that this algorithm converges rapidly, and the UAV swarm outperforms the fixed array baseline scheme in both communication and sensing capabilities.

4. Challenges and Development

Although ISAC provides new ideas for improving the anti-jamming capability of UAVs under occlusion factors, current research still faces several challenges. First, the measured data of the urban canyon environment is lacking. Most of the existing channel models are constructed based on suburban or open scenarios, lacking the characterization of the complex propagation characteristics in urban canyons, which restricts the verification and optimization of algorithms. Second, the coupled modeling of occlusion and mobility is difficult, most existing research handles several occlusion factors separately, which lacks a unified coupled model. Third, there is a contradiction between computing power constraints and intelligent algorithms. The complexity of the intelligent algorithm conflicts with the computing resources of UAV platforms.

In response to the above challenges, future research can be carried out from the following aspects. First, construct a high-fidelity dataset for urban canyon, integrate 3D building maps, ray tracing and measured data, and establish dedicated datasets for occlusion interference to provide an effective foundation for algorithm training and performance evaluation. Second, develop a lightweight intelligent anti-jamming architecture to reduce the burden of computing power. Third, explore a new paradigm of ISCC to build an environmentally adaptive and task-driven intelligent anti-jamming closed-loop system.

5. Conclusion

This paper systematically reviews the research progress of ISAC anti-jamming technology for UAVs under occlusion factors, comments on some existing key technologies from three aspects: communication, sensing and cross-domain collaboration, and points out the current challenges, including the scarcity of available field measurement data, difficulties in coupled modeling, and constraints on airborne computing power. This work can provide theoretical references for the design of highly reliable communication and perception systems for UAVs in urban canyons.

In the future, with the large-scale development of the low-altitude economy, constructing a high-fidelity dataset for urban canyon, developing a lightweight intelligent anti-jamming architecture and promoting collaborative ISCC will be important research directions. In addition, integrating physical layer security with

anti-jamming technologies and constructing a collaborative framework for ISAC anti-jamming and secure transmission are also fields worth exploring.

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Conflicts of Interest

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