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A Review of Integrated Sensing and Communication of Unmanned Aerial Vehicle Swarms

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Abstract: Integrated sensing and communication (ISAC) for unmanned aerial vehicle (UAV) swarms, as a core technology of 6G space-air-ground integrated networks, significantly enhances the system efficiency of low-altitude economic and military applications by integrating sensing and communication functions. This paper studies the current status and future challenges of ISAC for UAV swarms from three aspects: physical layer transmission, beamforming and networking, and multi-task joint scheduling. In the future, it is necessary to deeply integrate estimation theory, optimization algorithms, and AI methods to break through the bottlenecks of physical layer dynamic modeling, intelligent networking, and joint sensing and communication scheduling for swarm ISAC, and promote the systematic implementation of low-altitude economic and defense applications.

Keywords: Integrated sensing and communication; unmanned aerial vehicle swarms

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1. Review of ISAC Physical Layer transmission in UAV Swarms

6G wireless communication and wireless sensing show more and more similarities in system design, signal processing and data processing. The development of technologies such as massive antennas, high bandwidth and artificial intelligence further promotes the integration of sensing and communication, making ISAC one of the dominant trends in 6G. Many studies have conducted preliminary research on the physical layer design of ISAC, and many domestic and foreign institutions have also released white papers on 6G and the integration of sensing and communication. The China Academy of Information and Communications Technology studied the vision, requirements, application scenarios and technical challenges of ISAC, while Huawei studied the driving forces and development trends of ISAC [1-3]. References [4,5] pointed out that sensing introduces different performance metrics from traditional communication and requires the design of new physical layer transport technologies to explore the optimal performance boundaries and trade-offs between sensing and communication functions. For radar sensing and communication integration, reference [6] presented a waveform design and performance analysis method for sensing and communication integration, using the waiting time slot of pulsed radar to transmit communication signals, using full-duplex transmission to increase communication rate, and designing indicators such as detection probability and fuzzy function to analyze system performance. Reference [7] presented a 6D parameter estimation method for single-base station sensing and communication integration, which uses a high-resolution estimation algorithm to achieve precise estimation of sensing parameters. In addition, some scholars conducted research on joint signal models of radar sensing and communication based on fixed base stations, theoretical evaluation criteria and performance limits of integrated communication sensing, joint communication sensing beamforming, integrated waveforms and resource allocation, etc [8-12].

UAVs are an important platform for the realization of 6G sensing and communication integration technology and an important part of the future low-altitude economy. However, ISAC for UAV swarms is still in the exploratory stage, and there is currently a lack of literature on integrating UAV swarm platform ISAC design. In terms of the overall design of ISAC for UAV swarms, reference [13] pointed out that UAVs fit integrated sensing and communication applications, and explores the challenges and future development directions of ISAC for UAV swarms. In terms of physical layer design, reference [14] presented a frame structure for the fusion transmission of UAV sensing and communication signals to improve the efficiency of UAV sensing and communication information transmission. Reference [15] presented a joint design method for UAV sensing and communication, which improves radar target sensing accuracy by extending Kalman filtering. To address the complexity of obtaining ISAC channel information for UAV, reference [16] presented a conditional channel estimation and sensing method for massive millimeter-wave antenna arrays of UAVs, using compressive sensing technology to reduce pilot overhead under ISAC. Reference [17] further analyzed the impact of UAV attitude changes on the integrated sensing and communication channel. Meanwhile, with the rapid development of artificial intelligence, literature [18] investigated the application of large language models in UAV swarm communication and proposed a UAV sensing and communication method based on multi-objective evolutionary algorithms. The applicant also conducted a preliminary study on the ISAC of UAV and proposed a method for estimating target parameters under interference conditions to improve the spectral efficiency of the system through sensing and communication joint design.

As can be seen from the above, the current research mainly focuses on the design of single ISAC for UAV swarms, and the physical layer design of ISAC for UAV swarms is still in the initial exploration stage. At present, most studies have not fully considered the impact of the dynamics of UAV on sensing and communication, and have not fully exploited the characteristics of UAV platforms such as flexible deployment and a wide variety of sensors to assist system design. The implementation of ISAC for UAV swarms is based on the establishment of smooth sensing and communication links, and research on the physical layer technology faces technical challenges from multiple aspects and levels.

To this end, it is necessary to fit the characteristics of ISAC for UAV swarms, further integrate various sensor information of the ISAC for UAV swarms platform in a more intensive and efficient manner, and design ISAC transmission signals, channel modeling methods, parameter estimation methods, and cooperative transmission methods, etc., to achieve deep integration of UAV swarm sensing and communication.

2. Review of research on beamforming and networking of ISAC for UAV swarms

The key to achieving the ISAC platform for UAV swarms is the efficient networking and coverage of UAVs. For this reason, scholars at home and abroad have conducted research on beamforming, networking, etc. Reference [19] optimized the beamforming design with the average mutual interference and communication capacity of the system as the optimization objective and developed a cooperative networking method for unmanned aerial vehicles. However, this method fails to take into account the fusion design of sensing and communication functions, thus failing to leverage the advantages of ISAC. Reference [20] evaluated the probability of interruption at the communication end and the probability of discovery at the sensing end by using communication base stations in conjunction with radar sensing networking. Reference [21] presented a new integrated sensing and communication air division multiple access networking technology and designs a new sensing and communication transmission signal. Reference [22] presented an ISAC networking mode for unmanned aerial vehicles based on periodic functions, sensing and communicating in time slots, reducing system overhead and complexity. Reference [23] presented an integrated method for UAV sensing and communication in eavesdropping scenarios, which improves communication rate by optimizing UAV position, power, and user association.

However, references [19-23] did not take into account the impact of high dynamics of UAV swarms on beamforming and networking. Existing information transmission, beamforming and tracking methods based on pure communication protocols have high time-frequency resource overhead, high delay, low robustness, high probability of sensing failure and communication interruption, and cannot meet the requirements of high-precision sensing and high-rate communication for ISAC systems of unmanned aerial vehicle swarms. And most of the existing ISAC systems for UAV swarms are based on traditional communication networking methods and do not consider networking designs suitable for dynamic applications of UAV swarms. In the future 6G air-space-ground integrated network, the ISAC platform for UAV swarms is an important complement to the ground fixed ISAC base stations, especially in hotspots and areas affected by natural disasters, where the support of UAV base stations is playing an increasingly strong role. The combined networking of UAV base station swarms and ground base stations will significantly enhance sensing and communication performance.

To this end, in the ISAC for UAV swarms scenario, the impact of UAV swarm navigation, attitude changes, formation topology, etc. on sensing and communication needs to be considered, and the beamforming design needs to be optimized to improve sensing and communication efficiency. On this basis, design sensing-assisted communication signal processing methods, utilize the rich sensing information of the on-board sensors of the UAV swarm, the huge spatial gain of the high-frequency large-scale antenna array, and the flexible deployment of the UAV swarms design Angle domain beamforming and networking methods, perceive the properties and state changes of the environment in real time, and improve the robustness of the ISAC networking of the UAV swarm.

3. Review of multi-task joint scheduling of ISAC for UAV swarms

The multi-task scheduling of sensing and communication for the ISAC system of UAV swarm can provide reference value for actual deployment. On this basis, efficient resource allocation can improve the sensing and communication performance while meeting the requirements of communication or sensing. For this purpose, some scholars have studied the sensing and communication multi-task scheduling and resource allocation of ISAC for UAV swarms. In response to the coupling problem of UAV motion state and beamforming, reference [24] proposed a joint optimization design method of motion state and beam for the integrated sensing and communication system of a single UAV, decomposing the transmitted signal into two parts: information transmission and target sensing, and improving task efficiency by optimizing resources such as position and transmission power. To enhance the sensing and communication performance of the ISAC system simultaneously, reference [25] designed a resource allocation algorithm that maximizes the throughput at the communication end while ensuring the signal-to-interference-to-noise ratio of radar reception. For the problem of resource allocation in single-task scenarios, reference [26] presents a method for resource allocation and performance evaluation of 5G millimeter-wave unmanned systems, jointly designing dynamic frame structures to reduce transmission delay, and reference [27] presented a method for power allocation and performance analysis of integrated sensing and communication systems, improving the spectral efficiency of unmanned aircraft through non-orthogonal multiple access transmission. System performance is evaluated using performance index functions such as detection probability and system capacity. Reference [28] presented a resource allocation scheme for UAV swarms based on multi-agent reinforcement learning. The UAV swarm is equipped with a single antenna to complete the sensing and communication function, and the sensing efficiency and communication rate are improved by optimizing the resource allocation.

However, most of the above-mentioned literature only studied the ISAC communication or sensing resource allocation of single-order unmanned aerial vehicles in a single scenario, without considering the joint design of sensing and communication multi-task planning and resource allocation in the case of unmanned aerial vehicle swarm collaboration. Moreover, in the ISAC network of UAV swarms, various sensing and communication tasks coexist, and multiple users and multiple targets are present simultaneously, which increases the difficulty of joint design and scheduling of ISAC for UAV swarms. How to achieve optimal joint scheduling of sensing and communication tasks under multi-user and multi-target sensing and communication interference is an urgent problem to be studied [29-31].

To this end, a collaborative sensing and communication task planning and resource scheduling method for ISAC for UAV swarms should be designed, taking into account factors such as system energy efficiency, spectral efficiency, communication transmission rate, and sensing detection accuracy, in response to the sensing and communication task requirements of ISAC for UAV swarms.

4. Conclusion

To sum up, the research on ISAC technology for UAV swarms is still in the exploratory stage, and many issues remain to be further studied. The integration of “high frequency bands, large bandwidth, massive antenna arrays, and multi-source sensors” in UAV swarms, which leverages their respective advantages through ISAC architecture integration and swarm collaboration, also brings many challenges. To this end, there is an urgent need to explore key technologies such as ISAC physical layer design, collaborative networking, and joint sensing and communication task scheduling for UAV swarms, to reveal the essence of ISAC for UAV swarms, and to achieve mutual benefit of sensing and communication functions under the UAV swarm platform.

The modern signal processing methods such as estimation theory, optimization theory, control theory and artificial intelligence can be comprehensively exploited to solve the theoretical problems of ISAC for UAV swarms, and promote the development of ISAC for UAV swarms and military and civilian applications such as low-altitude economy and swarm combat.

Disclosure statement

The author declares no conflict of interest.

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