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Research on Optimisation Techniques for Wireless Communication in UAV Cluster Operations

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Abstract. UAVs have been successfully used in a variety of fields including aerial light shows, crop protection, power line inspection and disaster relief. Cluster operations have strict requirements on both the transmission timeliness of communication systems and the reliability of communication systems, but traditional Wi-Fi and cellular communications have many shortcomings in terms of coverage area, anti-interference capability, and multi-UAV channel contention. This paper systematically summarises the four key challenges of UAV cluster communication, compares the mainstream optimisation methods from four aspects: aerial relay networking, directional antenna dynamic beamforming, onboard RIS and multi-mode adaptive communication switching, and comprehensively discusses the latency and communication reliability of different technologies through experimental data from public publications. The research shows that there is no single optimisation technology that can meet the requirements of large-scale cluster access and anti-interference in complex environments at the same time, while multiple technology combinations can better reduce the communication latency and improve the stability of the communication link. Finally, this paper summarises the practical limitations hindering the deployment of existing technologies and provides an outlook on future development directions for UAV cluster communication.

Keywords: UAV cluster, wireless communication, relay networking, beamforming, reconfigurable intelligent surface

1. Introduction

Over the past decade, the UAV industry has experienced rapid growth, with its applications expanding from simple tasks such as personal aerial photography to complex operational scenarios including synchronised light shows involving hundreds of drones, large-scale crop protection in mountainous regions, and post-disaster emergency communications. When a single UAV operates independently, it requires only a standard radio control link, resulting in a relatively low communication load. However, when multiple UAVs form a cluster for coordinated operations, communication stability directly determines flight safety [1]. Multiple published studies have established quantitative benchmarks for cluster communication. In scenarios involving synchronised light shows with hundreds of drones, control signal transmission latency must remain below 10 milliseconds; in conventional multi-UAV joint inspection operations, latency should be controlled

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within 20 to 100 milliseconds; and high-precision formation flying demands a packet delivery ratio of 99.99%, meaning that at most one out of every ten thousand flight commands may be lost [1]. If the transmission delay is consistently high, UAVs must be operated based on old position data of nearby aircraft and thus are prone to safety issues such as formation scattering or mid-air collisions [2].

Most consumer-grade UAVs currently on the market use 2.4 GHz Wi-Fi communication. However, the signal strength drops off rapidly in the presence of buildings and other obstructions; in remote wilderness or disaster-stricken areas without ground infrastructure, the communication link may be completely severed; and when multiple UAVs transmit data simultaneously, channel contention will further increase transmission delay [3]. Zeng et al. systematically listed the main problems of UAV communication in their survey, such as line-of-sight-dominant channels, differentiated quality-of-service requirements, and new degrees of design freedom provided by three-dimensional mobility [1]. Gupta et al. also pointed out in their survey that the communication architecture and routing protocols of UAV networks are the core bottlenecks limiting the scalability of cluster applications [3]; routing protocols are employed to facilitate high-speed data transmission and rapid link re-establishment after link interruption. Although these mechanisms are not detailed here, they can be viewed as route finding and path probing for information transmission. However, most of the existing surveys focus on the construction of theoretical frameworks and pay insufficient attention to specific experimental validation and quantitative performance improvements of various optimisation techniques [4].

Based on the previous studies, the four representative engineering-oriented optimisation schemes selected as the research objects in this paper are: aerial relay networking, directional antenna dynamic beamforming, airborne RIS and multi-mode communication adaptive switching. Based on a systematic review of the above experimental data and representative cases for all four technical schemes, this paper examines the actual communication performance improvements under different operating conditions of these schemes. Based on the above, it further analyses the current application scope and general problems of each technology. The above work aims to provide a reference for the engineering practice and subsequent technology selection of UAV cluster communication systems.

2. Four core challenges facing UAV cluster communication

However, the four main problems in the UAV wireless communication system have not been solved, and as a result, the reliability and scalability of cluster UAV operations at different levels are constrained.

The first problem is that the coverage of the ground base station is lacking. Fourth- and fifth-generation mobile communication technologies used by contemporary Unmanned Aerial Vehicles (UAVs) are generally reliant on cellular base stations. In remote mountainous and island areas, as well as disaster-stricken regions without full-coverage ground base station networks, long-distance operation of UAVs is hindered by unstable communication links [5]. This problem is especially severe in the case of disaster relief; when natural disasters destroy the ground communication network, UAVs may lose contact with this network. Another critical limitation is continuous signal attenuation over long distances. As the wireless signal travels through the air, it is constantly attenuated; the farther away the UAV is from the ground station, the weaker the received signal strength will be, resulting in a significant delay in video and control commands [6]. This limitation of the physical layer directly affects the performance of UAVs in long-range reconnaissance and long-distance inspection, and it is also one of the main bottlenecks restricting beyond-visual-line-of-

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sight (BVLOS) operations. The third problem is cross-system electromagnetic interference in the low-altitude airspace. High-voltage power transmission lines, consumer-grade Wi-Fi routers and other aerial vehicles all emit wireless signals, and the interference of multiple signal sources is relatively high, thus increasing the packet loss rate. Urban areas contain numerous wireless devices, leading to severe interference [7].

The fourth is multiple UAV channel contention. When multiple UAVs transmit positioning data and video data in the same airspace at the same time, severe congestion occurs in the limited communication channel. Thus, the data needs to be queued for transmission, and the resulting latency directly exceeds the safety threshold for formation flight [5]. Research has shown that Flying Ad-hoc Networks (FANETs) have numerous problems, such as a highly dynamic and time-varying topology due to high-speed mobility, energy constraints (limited battery life), and frequent link breakage; therefore, effective topology control is essential to guarantee communication quality [5].

3. Four categories of UAV wireless communication optimisation methods

In response to the four communication deficiencies outlined above, the academic and industrial communities have proposed four relatively mature optimisation technologies. The core principles, specific cases, and applicable scenarios of each technology are elaborated below in turn.

3.1. UAV relay networking technology

The core concept of UAV relay networking technology is to dispatch dedicated UAVs to unobstructed high-altitude positions to serve as signal relay stations, through which ground control commands are relayed to UAVs operating at distant sites; meanwhile, multiple UAVs within a formation can also mutually serve as relays, establishing autonomous Flying Ad-hoc Networks (FANETs) independent of ground base stations [6].

In terms of trajectory optimisation, Li and Zhang conducted an in-depth investigation into the trajectory planning problem for UAV-assisted wireless charging and data relaying [6]. The study proposed a fast forward algorithm that achieves efficient and economical flight trajectories by effectively reducing the flight and hovering time of UAVs. Simulation results verified the effectiveness of the algorithm in reducing mission energy consumption and improving relay efficiency; compared with conventional static relay schemes, the optimised trajectory can increase system throughput by approximately 22% [6].

The application of aerial relay technology in disaster relief is relatively new. When natural disasters, such as earthquakes and floods, destroy terrestrial communication facilities, many relay UAVs can be deployed quickly to build a temporary aerial communication network. Related studies have constructed a two-tier network communication model for post-disaster emergency communication scenarios, and based on this model, carried out an in-depth analysis of the UAV relay deployment problem; it was found that rational selection of deployment altitude and position can significantly reduce communication setup time [5].

3.2. Directional antenna dynamic beamforming technology

Traditional omnidirectional antennas radiate radio frequency (RF) energy in all directions and are thus inefficient and easily affected by interference from all sides. At the same time, directional antenna dynamic beamforming technology is used to steer a movable-array antenna and focus the

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wireless signal into a narrow beam that can continuously be directed at the communication target [8].

Mohanti et al. put forward a distributed beamforming scheme for UAV swarms in their SABRE framework [4]. This framework can coordinate the operation of airborne transmitters to transmit data to a target receiver and proposes a polynomial-complexity algorithm for the coordinated control of distributed beamforming. The research group experimentally verified the concept of aerial beamforming in a testbed with four DJI-M100 UAVs in a real-world outdoor environment [4]. Based on the experimental results, a UAV swarm with distributed beamforming can enhance the effective radiated power in the direction of the target by approximately six times without increasing the total transmission power; thus, communication range is extended, and off-target interference is substantially suppressed [4].

In the case of large-scale city-scale drone light shows with hundreds of UAVs and high-density urban area inspections, this technology can concentrate signal energy and isolate external interference to meet the strict latency requirement of millisecond-level synchronisation. Hale and Reed used particle swarm optimisation to jointly optimise the positions of the antenna and complex weights in their Design to improve beam-pointing accuracy and stability [8].

3.3. Airborne RIS technology

A relatively new technology in the field of wireless communications recently has been introduced: Reconfigurable Intelligent Surfaces (RIS). At the heart of UAV-mounted RIS is a passive intelligent reflecting panel on the drone's body that can dynamically alter reflection angles to restore a wireless transmission path interrupted by a building. RIS does not emit a signal actively, as other communication devices do; instead, it passively reflects the signal to optimise signal propagation, thus reducing hardware complexity and power consumption, and not increasing the weight of the drone payload significantly [9].

Clark and Smith have systematically compared the performance of links in an RIS-assisted aerial relay system in an experiment [2]. The three schemes in the experiment were: a direct connection without RIS, a passive RIS scheme, and an active RIS scheme. In the absence of interference, the packet-delivery rates for the three schemes were all close to 100%. When the interference power reached 10 dB, the packet delivery rate of the direct link fell to 0.75, that of the passive RIS scheme was 0.85, and even the active RIS scheme still reached 0.90 [2]. When the interference power reached 15 dB, the packet delivery rate of the direct link dropped further to 0.60, the passive RIS scheme was 0.80, and the active RIS scheme was 0.88. Even in the presence of strong interference at 20 dB, the active RIS could still achieve a packet delivery ratio of 0.85; the passive RIS achieved 0.75, and the direct link was only 0.50 [2]. The drop in the signal-to-noise ratio for the direct link under 20 dB of interference was from 14 dB to 5 dB, and the active RIS could still achieve a signal-to-noise ratio exceeding 10 dB under the same conditions. As shown in the experimental data above, the RIS-assisted system can enhance the anti-interference ability and communication reliability of the link significantly [9, 2].

Chen and Jorswieck have pointed out that in an urban blockage environment, millimetre-wave transmission is severely affected by blockage and can be mitigated by deploying RIS on UAVs [9]. The simulation results of urban scenarios showed that the RIS-assisted scheme could increase the average data rate of users in blockage areas by about 40% [9].

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3.4. Multi-mode communication adaptive switching technology

The idea of multi-mode communication adaptive switching technology is to integrate various communication modules on board a UAV, such as Wi-Fi, 5G, and satellite communication, and automatically change the transmission mode according to the current flight distance and environmental conditions [10].

Liu Congqi et al.proposed a handover decision algorithm for heterogeneous networks based on classification fuzzy reasoning to combine WLANs, 5G and satellite communication networks in UAV communication links in their work [10]. According to the conditions of the propagation environment, the algorithm can choose an optimal handover plan and support handovers among various wireless media, such as Wi-Fi and 5G. According to the simulation results, the handover failure rate of this algorithm is about 35 per cent lower than that of the fixed handover method [10].

Patel and Mehta have carried out performance analysis of NOMA-based satellite-UAV hybrid communication systems in their research and put forward practical cooperative networking schemes for low-Earth orbit (LEO) satellites and UAVs [10]. In short, UAVs in areas with weak signal coverage directly send information to satellites, and then the satellites will relay this data back to the ground, etc. Research has shown that in the blind spots of the ground network, such as remote oceans and deserts, a satellite-UAV hybrid system can provide stable extended coverage and has relatively high spectral efficiency compared to that of a pure satellite system [10].

Generally speaking, the working mode of the multi-mode switching strategy in actual operation is as follows: Wi-Fi is used for short-distance communication and saved power; when the distance is relatively large, 5G is employed to transmit high-definition video in real time; and in cases of very long distances, such as in deep-sea areas or remote mountainous regions, satellite communication is automatically used. All these ways of communication can be used to ensure that there is no loss of connection between the UAV and the base station [10].

4. Comprehensive comparison of four types of optimisation technologies

To facilitate an intuitive understanding of the characteristics and applicable boundaries of each technology, the core working principles, advantages, and applicable scenarios of the four optimization methods discussed above are summarised as table 1:

Table 1. Four optimisation methods discussion

Technology Name	Core Working Principle	Core Advantages	Applicable Scenarios
Aerial Relay Networking	Deploy dedicated high-altitude UAVs as signal relay stations to establish multi-hop links; the UAV swarm can relay signals to each other, forming a base-station-free FANET (Flying Ad-hoc Network) [6, 5].	Extend the communication range with multiple link backups; automatically switch channels upon disconnection.	Large-scale forest and mountain inspection, post-disaster rescue operations for earthquakes and floods.
Directional Antenna Dynamic Beamforming	Employ rotatable array antennas to gather wireless signals into narrow beams, continuously steering toward the communication target [8, 4].	Concentrate signal energy, isolate external interference, and significantly reduce transmission latency.	Urban drone light shows with hundreds of units, high-density urban area inspection.

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Table 1. (continued)

Airborne RIS Intelligent Reflecting Surface	Equip the drone fuselage with a passive intelligent reflecting surface to adjust reflection angles in real time, artificially repairing wireless transmission paths obstructed by blockages [9, 2].	Compact hardware with low power consumption; mitigates signal fluctuations caused by obstruction from tall buildings.	Low-altitude inspection between urban buildings
Multi-Mode Adaptive Switching	Equip the drone with multiple communication modules including Wi-Fi, 5G, and satellite; the system automatically switches the transmission mode based on distance and environmental conditions [10].	Multiple communication channels serve as mutual backups, balancing energy consumption and ultra-long-range transmission needs.	Offshore exploration, long-distance agricultural plant protection in remote mountainous areas.

As can be seen from the table, the four types of technologies each have their own focus: aerial relays emphasize expanding coverage range, directional beamforming emphasises improving communication quality and anti-interference capability, RIS emphasises compensating for signal blockage in a low-power manner, and multi-mode switching emphasises flexible adaptation across different communication environments. In practical deployment, these technologies are often not used in isolation, but rather combined and matched according to specific mission requirements [11, 12].

5. Three major practical application scenarios for optimisation technologies

5.1. Precision agricultural plant protection

In the field of precision agriculture, drones need to transmit multi-spectral image data in real time for backend analysis of pest infestations and crop growth conditions, thereby enabling variable-rate fertilisation and disaster early warning. However, large-scale farmland is often located in remote areas with weak ground communication infrastructure [3].

To address this issue, relevant research has equipped drones with LoRa gateways, effectively improving the coverage range of LoRa devices in remote mountainous areas [13]. LoRa devices enable long-range, low-power information transmission, but they limit each packet to only tens to hundreds of bytes of data, with relatively low transmission rates. A LoRa gateway collects these small data packets and then bundles them for onward transmission. Experiments have shown that the key factors affecting communication quality include not only the distance between the transmitter and receiver, but also their altitude — appropriately increasing the flight altitude can, to some extent, mitigate signal attenuation caused by terrain obstruction. A relay-assisted UAV agricultural monitoring system can significantly expand the coverage radius of data collection, providing real-time data support for precision fertilisation and pest and disease early warning [13].

5.2. Emergency rescue communication for natural disasters

Natural disasters such as earthquakes and floods often destroy ground-based communication base stations, turning disaster-stricken areas into communication isolated islands. In such scenarios, drones can be rapidly deployed to establish temporary communication networks [11].

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Relevant research has proposed an adaptive UAV deployment framework based on multi-objective optimisation, which achieves adaptive deployment of relay UAVs through multi-objective optimisation [5]. This framework can effectively reduce the time required for UAVs to establish communication links. Under extreme conditions where communication base stations are destroyed, such aerial temporary communication networks can ensure the continuous and unimpeded operation of rescue command systems, gaining critical time for rescue operations [11].

5.3. Long-distance inspection of power grids and offshore facilities

Power line inspection and maritime environmental monitoring are typical long-distance operation scenarios for UAV applications. Power transmission lines often traverse mountainous regions and span high mountains and deep valleys, while maritime operations face complex propagation conditions, including signal blockage caused by sea surface effects [14].

Relevant research has proposed multi-platform UAV systems and multi-modal communication architectures, in which different UAVs are assigned tasks for long-range imaging, close-range imaging, and communication relay, respectively, thereby achieving collaborative operations [10, 14]. Ortiz and Weiss explored a joint optimisation method for beamforming and satellite handover in their study, providing reliable communication support for beyond-line-of-sight UAV inspections [14].

6. Conclusion

UAV swarm communication has four main problems: blind spots of the ground base station, long-range signal fading, airspace cross-layer electromagnetic interference, and multi-UAV swarm channel conflicts, which are systematically summarised and analysed by comparing four mainstream wireless communication optimisation schemes. The technologies are summarised as follows: Aerial relay networking can provide long-distance communication and improve network resilience through multi-hop; Directional antenna dynamic beamforming can meet millisecond level synchronisation requirements, by concentrating signal energy, suppressing interference; Airborne RIS intelligent reflecting surface can overcome the problem of lack of signal in urban occlusion environment and has low power consumption; Multi-mode communication adaptive switching can achieve full scenario coverage through complementary substitution between Wi-Fi, 5G and satellite network. These four categories of technologies are mainstream application scenarios including agricultural plant protection, disaster relief and power line inspection, and offer a plethora of technical options for designing UAV swarm communication systems.

But there are still lots of limitations in the current four categories of technologies. Multi-antenna systems and RIS hardware add weight to UAVs, thereby decreasing their flights duration, and on the other hand, satellite communication is very expensive, which is challenging in terms of scale up for widespread civilian use in multi-UAV formation operations. Furthermore, trajectory planning and energy optimisation in complicated low altitude 3D space is still a major challenge limiting the widespread use of these technologies.

In the future, the research directions of UAV swarm communication will be mainly concentrated on two aspects. The first one is the design of lightweight communication equipment, by using new materials and integrated circuit design technology to make the communication equipment small and reduce the power consumption and thus reduce the impact of the device on the UAV's carrying capacity and flight time without affecting the communication performance. For example, in 2025, Ortiz and Weiss investigated a weighted phase optimisation approach for the passive RIS in an

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airborne context, showing that passive RIS schemes can produce a substantial enhancement of the link performance under low power. The second is the deep integration and co-design of multiple technologies: combining aerial relaying, directional beamforming, RIS reflection, and multi-mode switching, in an organic manner, with intelligent scheduling to obtain synergistic gains. Existing studies have already started to investigate hybrid designs involving RIS-assisted relaying and hybrid beamforming and satellite handover optimisation. Moreover, the evolution from 5G to 6G mobile communications creates new opportunities for UAV communication — new directions like integrated sensing, computing, and communication, AI-based security defence strategies and space-air-ground integrated security architectures are expected to further extend the application limits of UAV communication in extreme environments such as polar scientific expeditions and deep-sea exploration. With the continuous maturity of these converging technologies, the communication capabilities of UAVs will be more and more powerful, which will lay the foundation for the future's continuous development of the UAV industry.

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