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Research on Ground Wide-Area Network Communication Coverage Method Based on Multi-UAV Swarm

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ABSTRACT

With the rapid development of 5G/6G, smart cities, and emergency communications, traditional ground communication infrastructure has exposed bottlenecks such as long deployment cycles and poor adaptability in rapid response, wide-area coverage, and dynamic scheduling. Due to their high mobility, flexible networking, and rapid deployment capabilities, multi-UAV swarms are regarded as a key technology to enhance ground wide-area network communication coverage. However, shortcomings remain in multi-dimensional environment perception, swarm adaptive control and self-healing, and edge intelligence collaboration and proactive resource scheduling capabilities. This paper proposes a comprehensive method integrating multi-source heterogeneous perception—edge computing—multi-agent reinforcement learning (MARL)—and user intention prediction, aiming to achieve wide-area communication coverage and resilience enhancement in complex dynamic environments. It also proposes a simulation – physical system integrated verification approach. The core ideas include: constructing a swarm self-organizing/self-healing model driven by multi-dimensional perception, designing edge intelligence collaboration and global consistency mechanisms, establishing a user-intention-driven proactive resource scheduling system, and building an evaluation framework based on NS-3/OMNeT++ and physical platforms. The proposed solution is oriented toward scenarios such as emergency communication, smart cities, and coverage in remote areas, demonstrating significant potential for engineering application.

KEYWORDS

Multi-UAV swarm; Wide-area communication coverage; Multi-source perception; Edge computing; Multi-agent reinforcement learning; Resource scheduling

1 Introduction

In scenarios such as smart cities, emergency rescue, coverage in remote areas, and support for large-scale events, communication systems face increasing demands for wide-area coverage and low latency. However, traditional ground base stations face limitations in construction cycles and scalability, making it difficult to provide stable coverage in complex and dynamic contexts. Multi-UAV swarms, with their mobility, rapid deployment, and flexible networking capabilities, have become an important approach to enhance ground wide-area communication coverage. The main challenges are: (1) insufficient multi-source heterogeneous perception and adaptive swarm reconfiguration; (2) lack of scalable edge collaboration and global consistency assurance; (3) resource scheduling remains passive and struggles to adapt to high concurrency and hotspot migration; (4) lack of a simulation – physical system integrated engineering verification loop. To address these issues, this paper proposes a systematic method and evaluation platform centered on multi-source perception fusion, edge intelligence and MARL collaboration, and user-intention-driven proactive scheduling, aiming to achieve comprehensive improvement in coverage, latency, and robustness under complex scenarios.

Contributions of this paper include:

• Self-organization/self-healing enabled by multi-source heterogeneous perception: constructing a fusion model based on key information including environment, user distribution, and channel state to drive adaptive formation adjustment and self-healing.

• Edge intelligence and distributed consistency: deploying edge capabilities on core UAVs to form local processing and task offloading mechanisms, with distributed consistency to ensure global service quality.

• User-intention-driven proactive resource scheduling: introducing big data/AI behavioral analysis to predict regional demand and allocate resources in advance, mitigating hotspot competition and enhancing fairness.

• Simulation – physical system integrated verification: building joint evaluation based on NS-3/OMNeT++ and physical platforms, supporting engineering implementation from algorithm to system.

2 Related work review

2.1 Multi-uav cooperative networking and air-ground integration

FANETs describe UAV communication as highly dynamic self-organizing networks, with key challenges including rapid topology changes, link reliability, and energy management. Dynamic routing and time-slot resource allocation are critical directions. Studies show application potential in emergency and inspection scenarios, but for large-scale heterogeneous nodes and complex urban environments, networking protocols still require higher adaptability and flexible switching capabilities.

2.2 Applications of reinforcement learning and intelligent optimization in swarm communication

Multi-agent reinforcement learning (e. g., DDQN, MAPPO) has been applied in joint trajectory and communication design, dynamic resource optimization, and load balancing. Its advantage lies in mapping high-dimensional states and nonlinear dynamics into policy updates. However, challenges remain in training sample diversity, generalization to real environments, and convergence stability in large-scale systems, requiring integration with task priors, hierarchical collaboration, and edge training.

2.3 Edge computing and intelligent perception integration

Edge computing enables pre-processing and rapid decision-making near the data source, reducing latency and core network load. In UAV swarms connected via cellular networks, edge collaboration enhances system scalability and low-latency assurance. However, challenges persist in multi-dimensional perception fusion, protocol overhead of consistency, and heterogeneous UAV management.

2.4 Commentary

Overall, existing work still falls short in deep fusion of multi-modal perception, scalable collaboration of edge intelligence, user-intention-driven proactive resource scheduling, and system-level engineering validation. This paper's solution addresses these gaps, emphasizing a closed-loop of "perception–decision–execution", distributed collaboration, and intention prediction, forming a platform-based path bridging algorithm and engineering.

3 System model and problem definition

3.1 System composition

The system consists of UAV swarms, ground users/nodes, edge nodes (selected core UAVs), and a central coordination module. UAVs are equipped with sensing modules for environment/network status/user distribution and link equipment. Edge nodes possess local computing and caching capabilities. The central module aggregates strategies and coordinates globally. Links include air-to-air (A2A) and air-to-ground (A2G) types.

3.2 Objectives and constraints

• Objectives: under multi-scenario, multi-topology, and dynamic demands, achieve high connectivity, fairness, low latency, and low energy consumption for wide-area coverage, with self-healing and robustness under node/link failures.

• Constraints: flight safety (collision avoidance/regulations), energy budget, latency threshold, limitations of edge/central processing capabilities, and spectrum resource constraints.

4 Methodology

4.1 Overall architecture

The proposed solution consists of five modules:

(1) Multi-dimensional sensing and data acquisition;

(2) Perception fusion and adaptive swarm reconfiguration;

(3) Edge computing collaboration and distributed communication;

(4) User intention prediction and proactive resource scheduling;

(5) System integration verification and iterative optimization.

4.2 Multi-source heterogeneous sensing and fusion

• Sensing objects: geographic environment (including buildings/terrain), user distribution (density/migration trends), channel state (link quality/interference).

• Fusion methods: using clustering analysis, principal component analysis, etc., to reduce dimensions and select features, compressing multi-modal data into key state variables for policy decisions; lightweight preprocessing is performed on edge nodes to ensure timeliness and robustness.

4.3 Adaptive swarm reconfiguration (MARL)

• Policy learning: multi-agent reinforcement learning drives formation and trajectory coupling, with a reward function integrating coverage, link robustness, energy consumption, and safety (collision avoidance).

• Self-organization/self-healing: upon node failure or link interruption, local observations and edge consistency enable rapid reconfiguration of topology and formation. The proposed distributed collision avoidance and self-healing method integrates "inter-UAV distance penalty and recursive repair logic" into the decision process, aiming for automatic repair within 2 seconds and formation deformation rate $\leqslant$ 5% under extreme splits (as a reference for experimental goals).

4.4 Edge computing collaboration and consistency

• Edge selection and task offloading: edge modules are deployed on a few core UAVs for local data preprocessing, model inference, and real-time decision-making; dynamic offloading and layered communication reduce core network load and end-to-end latency.

• Consistency assurance: via distributed consistency protocols (lightweight maintenance of key global variables such as hotspot locations and task allocation summaries), balancing local adaptability and global stability in large-scale collaboration.

4.5 User intention prediction and proactive resource scheduling

• Demand modeling: modeling user distribution and traffic demand based on historical and real-time data to capture hotspot migration and burst traffic.

• Proactive scheduling: guided by prediction results, bandwidth, links, and energy are proactively allocated, enabling elastic provisioning and fairness enhancement in hotspot scenarios. This module forms a closed loop with MARL/edge (prediction → resource allocation → policy update).

4.6 Multi-modal, human-machine collaboration and trajectory generation (optional extension)

As an extension, OpenPose+YOLO for human/target detection and MINCO-optimized trajectory generation can be integrated for specific human-machine collaboration scenarios, emphasizing advantages in energy efficiency and misdetection/omission rates (as a pluggable module, whether to activate depends on the scenario).

5 Experimental design and simulation platform

5.1 Design principles

Adhering to the principles of "reproducibility, scalability, and engineering applicability": using NS-3/OMNeT++ to build simulation environments with multiple scenarios, topologies, and dynamic elements; setting up physical platforms with multiple rotor UAVs; enabling comparison and evaluation from algorithm to system through a unified metric system.

5.2 Simulation experiments

Platform and scenarios: NS-3, OMNeT++ (or self-developed environment); urban dense areas (obstruction/hotspot migration), mountainous/remote regions (terrain/coverage blind spots), disasters/emergency (base station failure/ temporary high concurrency).

Comparisons and ablation studies:

(1) Compare with static networking/centralized scheduling to observe the effects of dynamic self-organization and edge collaboration;

(2) Ablation of edge offloading (central processing only), intention prediction (passive response), adaptive reconfiguration (fixed formation).

(3) Metrics: network connectivity, throughput, end-to-end latency, energy consumption, coverage, resource utilization, fairness (e. g., equivalent measure presentation), robustness/self-healing performance. All metrics are based on the evaluation requirements in the document.

5.3 Physical experiments

• Platform and modules: multiple rotor UAVs, onboard sensing and A2A/A2G communication modules, pluggable edge nodes.

• Typical scenarios: emergency/temporary high-density areas; recording coverage capability, swarm robustness, edge processing delay, and service quality under high-density user conditions.

• Procedure: step-by-step integration → field testing → parameter feedback and policy fine-tuning → fault/congestion reproduction and self-healing observation.

6 Results presentation and analysis template

(1) Coverage and connectivity: presenting coverage heatmaps/connectivity rate curves for different scenarios, user distributions, and swarm strategies; observing coverage maintenance and blind spot changes during hotspot migration.

(2) Latency and throughput: under increased load and edge offloading on/off conditions, observing changes in end-to-end latency and throughput; analyzing distributed consistency overhead and benefits.

(3) Energy consumption and fairness: comparing energy consumption and resource utilization across strategies; evaluating the positive effect of intention prediction on fairness under hotspot/high concurrency.

(4) Robustness and self-healing: recording recovery timelines and formation stability indicators (targeting automatic recovery within 2 seconds and deformation ⩽ 5%) after node/link failures, compared with fixed formations or non-self-healing mechanisms. Note: The above presentation formats and conclusion descriptions are part of the pre-experiment analysis plan and indicator framework; no quantitative conclusions beyond the document are introduced. Final values are based on simulation/real-world results.

7 Summary of innovations

• Intelligent swarm reconfiguration enabled by multi-source heterogeneous perception: integrating geographic, channel, and user distribution information to enhance environmental adaptability and support dynamic self-healing and self-organization.

• Deep integration of edge intelligence and distributed decision-making: through localized task processing and parallel global/local optimization, reducing latency and communication load, overcoming centralized bottlenecks.

• User-intention-driven proactive scheduling: introducing behavioral modeling and big data analysis to enhance resource utilization and fairness in high-concurrency scenarios.

• Simulation–physical integrated verification: platform-based approach bridging algorithm and system applications to ensure deployability and scalability.

• Self-healing and collision avoidance mechanism: applying inter-UAV distance penalty and recursive repair logic to pursue system robustness indicators such as recovery within 2 seconds and ⩽5% formation deformation in extreme cases.

• Multi-modal, hierarchical, recursive self-optimization: integrating OpenPose/YOLO with MINCO trajectory generation in human-machine collaboration scenarios to control energy consumption and detection accuracy.

8 Conclusion and outlook

This paper addresses key challenges in wide-area communication coverage with multi-UAV swarms by proposing a human–machine–network integration solution based on multi-source perception, edge intelligence, and MARL. It further improves resource utilization and fairness through user-intention-driven proactive scheduling and ensures end-to-end engineering implementation via a simulation – physical integrated route. Future work will focus on convergence and stability of large-scale systems, interoperability of heterogeneous devices, higher-fidelity real-world experiments, and engineering promotion in typical urban/emergency applications.

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