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Leaderless Adaptive Coordination for Fault-Tolerant UAV Swarm Communication: A Simulation Study

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***Abstract* - Unmanned Aerial Vehicle (UAV) swarms rely on reliable communication and coordination mechanisms to perform cooperative tasks such as surveillance, search and rescue, and environmental monitoring. Traditional swarm architectures often depend on a centralized leader node to coordinate communication and decision-making among swarm members. However, such architectures suffer from significant reliability limitations, as the failure of the leader node can disrupt the entire swarm network. This paper proposes a leaderless adaptive coordination mechanism for improving fault tolerance in UAV swarm communication networks. In the proposed approach, coordinator nodes are dynamically elected based on a score computed from node connectivity and battery level, enabling decentralized decision-making and rapid recovery from node failures. A simulation-based study is conducted to evaluate the robustness of the proposed architecture. Results demonstrate that the leaderless adaptive coordination strategy significantly improves network resilience and maintains higher connectivity after coordinator failure compared to traditional leader-based swarm architectures. The proposed method provides a lightweight and scalable framework for improving reliability in UAV swarm communication systems.**

Keywords* - *UAV swarms, swarm communication, fault tolerance, distributed coordination, multi-agent systems

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV) swarms have gained significant attention in recent years due to their ability to perform complex cooperative missions through distributed coordination. Applications of UAV swarms include environmental monitoring, disaster response, precision agriculture, and surveillance operations. These systems rely on distributed communication and coordination mechanisms to maintain cooperative behavior among multiple autonomous agents.

The concept of swarm intelligence originates from the study of collective behavior in biological systems such as bird flocks, fish schools, and insect colonies. Early models demonstrated that complex group behaviors can emerge from simple local interaction rules among agents [1], [2]. These principles have been widely adopted in swarm robotics and multi-agent systems to enable decentralized coordination among large numbers of autonomous agents [3]–[7].

Recent research has explored the use of UAV swarms for communication networks, sensing applications, and distributed monitoring tasks. UAV-based communication networks have been studied extensively due to their flexibility and ability to provide rapid deployment in dynamic environments [8]–[14]. Such networks often rely on distributed communication architectures where nodes interact with neighboring agents to maintain network connectivity.

Distributed coordination algorithms have also been widely investigated in multi-agent systems. Techniques such as consensus-based coordination and distributed control enable agents to cooperate without centralized supervision [15]–[18]. These approaches improve system scalability and robustness in large-scale distributed environments.

Despite these advances, many swarm architectures still rely on leader-based coordination models in which a designated leader node manages communication and decision-making processes. While this approach simplifies coordination, it introduces a significant limitation: the leader node becomes a single point of failure. If the leader node becomes unavailable due to hardware failure, communication disruption, or energy depletion, the entire swarm network may lose coordination.

To address this limitation, decentralized coordination mechanisms have been proposed in which leadership roles can be dynamically assigned among swarm members [30]–[34]. Such systems improve fault tolerance by enabling the swarm to continue functioning even when individual nodes fail.

In this work, a leaderless adaptive coordination mechanism for UAV swarm communication networks is proposed. The proposed approach dynamically elects coordinator nodes based on node connectivity and battery level. A simulation-based evaluation is conducted to analyze the robustness of the proposed architecture under node failure conditions.

The main contributions of this work are summarized as follows:

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- A leaderless adaptive coordination architecture for UAV swarm communication networks

- A coordinator election mechanism based on node connectivity and battery level

- A simulation-based performance evaluation demonstrating improved fault tolerance compared to conventional leader-based swarm architectures

II. RELATED WORK

Research in swarm robotics and multi-agent systems has significantly advanced in recent years, particularly in the context of distributed coordination and communication among autonomous agents. Swarm intelligence techniques inspired by natural systems such as ant colonies, bird flocks, and fish schools have provided effective strategies for decentralized coordination and collective behavior in large groups of agents [1]–[4]. These approaches demonstrate that complex group behavior can emerge from relatively simple local interaction rules among agents.

Several studies have investigated communication architectures for UAV swarms. Early research focused on centralized coordination models where a leader node or base station managed swarm operations and communication flow [5]–[8]. While such approaches simplify coordination and control, they introduce a critical limitation: the leader node becomes a single point of failure. If the leader becomes unavailable due to hardware malfunction, communication loss, or energy depletion, the entire swarm may lose coordination and operational capability.

To address these challenges, researchers have explored distributed communication frameworks for UAV swarms. Distributed approaches allow swarm nodes to coordinate using local communication with neighboring nodes instead of relying on a centralized controller [9]–[13]. These systems improve scalability and flexibility while reducing dependence on any single node within the swarm network. However, maintaining reliable coordination in such distributed environments remains an open challenge, particularly under node failure scenarios.

Recent studies have also investigated leader election and dynamic coordination mechanisms in multi-agent systems [14]–[18]. These methods enable nodes to dynamically assume leadership roles based on predefined metrics such as node connectivity, energy availability, or communication reliability. Dynamic leadership selection can improve system resilience and allow swarm networks to maintain operational functionality even when individual nodes fail.

Fault tolerance has become an increasingly important consideration in UAV swarm research. Various fault-tolerant swarm architectures have been proposed to ensure that swarm systems remain functional despite communication disruptions or node failures [19]–[24]. These approaches include redundant communication links, distributed decision-making frameworks, and adaptive network restructuring techniques. While these strategies improve system robustness, many existing implementations still rely on partially centralized coordination models.

In recent years, several works have explored fully decentralized coordination mechanisms in swarm systems [25]–[30]. These methods eliminate permanent leader nodes and instead rely on distributed consensus or adaptive coordination mechanisms to maintain swarm organization. Such approaches are particularly promising for UAV swarm applications where communication environments may be dynamic and unpredictable.

Despite these advances, designing lightweight coordination mechanisms that maintain network robustness while minimizing communication overhead remains an ongoing challenge. In particular, efficient mechanisms for dynamically selecting temporary coordinators in response to node failures are still an active area of research.

To address this gap, this work proposes a leaderless adaptive coordination mechanism for UAV swarm communication networks. The proposed approach dynamically elects coordinator nodes based on a composite score derived from node connectivity and battery level. By enabling dynamic coordinator selection and rapid recovery from node failures, the proposed method improves swarm network resilience while maintaining decentralized communication among UAV nodes.

III. PROPOSED LEADERLESS ADAPTIVE COORDINATION METHOD

Swarm communication networks are typically modeled as distributed multi-agent systems in which agents interact through local communication with neighboring nodes. Distributed coordination mechanisms have been widely used in multi-agent systems and robotic networks to enable cooperative behavior without centralized control [15]–[18], [21]. These approaches improve scalability and robustness in large-scale distributed environments.

This section presents the proposed leaderless adaptive coordination mechanism designed to improve fault tolerance in UAV swarm communication networks. The proposed approach eliminates reliance on a permanent leader node by dynamically selecting temporary coordinators based on network connectivity and energy availability.

A. Swarm Communication Model

The swarm is modeled as a distributed network of autonomous UAV nodes that communicate with neighboring nodes within a predefined communication range. Each node

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represents an individual UAV, and communication links are established when two nodes are within communication distance of each other. This communication structure forms a dynamic network graph G = (V, E), where V represents the set of swarm nodes and E represents communication links between neighboring nodes.

In the proposed model, swarm nodes operate using local communication with their immediate neighbors rather than relying on centralized coordination. Each node maintains information regarding its neighboring nodes and its current energy level. This distributed communication model improves system scalability and reduces dependency on a single control node.

B. Coordinator Election Mechanism

To enable decentralized coordination, the proposed system dynamically elects a temporary coordinator node. The coordinator facilitates information dissemination and coordination among swarm members during operation. Instead of assigning a permanent leader, the coordinator role is determined through a scoring mechanism that evaluates the suitability of each node.

The coordinator score is computed using two key parameters: node connectivity and remaining battery level. Node connectivity represents the number of neighboring nodes within communication range, while battery level represents the available energy of the UAV.

The coordinator score is calculated as

$$\text{Coordinator Score} = \text{Connectivity} + \text{Battery Level} \quad (1)$$

Nodes with higher connectivity values have better communication links within the swarm network, making them suitable candidates for coordination. Similarly, nodes with higher battery levels are more reliable for temporary leadership roles. The node with the highest coordinator score is selected as the swarm coordinator.

The coordinator election procedure can be summarized as follows:

1. Each node determines the number of neighboring nodes within communication range.
2. Each node obtains its current battery level.
3. The coordinator score is computed using the defined scoring function.
4. The node with the highest score is selected as the coordinator.

This adaptive selection mechanism ensures that coordination responsibilities are assigned to nodes with favorable network and energy characteristics.

C. Failure Detection and Recovery

In swarm systems relying on centralized leadership, failure of the leader node can disrupt communication and coordination. To address this limitation, the proposed architecture incorporates a dynamic failure recovery mechanism.

When a coordinator node becomes unavailable due to failure or energy depletion, the swarm network detects the absence of coordination and initiates a new coordinator election process. Using the previously defined scoring mechanism, swarm nodes recompute their coordinator scores and select a new temporary coordinator.

This leaderless adaptive coordination mechanism allows the swarm network to recover rapidly from node failures without requiring external control. By enabling dynamic reassignment of coordination roles, the proposed method improves the resilience and reliability of UAV swarm communication systems.

IV. SIMULATION SETUP

To evaluate the effectiveness of the proposed leaderless adaptive coordination mechanism, a simulation-based experiment was conducted to analyze swarm network robustness under node failure conditions. The simulation models a UAV swarm communication network where nodes represent individual UAV agents capable of communicating with neighboring nodes within a predefined communication range.

A. Simulation Environment

The swarm network consists of 25 UAV nodes randomly distributed within a two-dimensional simulation space. Each node represents an autonomous UAV capable of establishing communication links with neighboring nodes located within a specified communication radius. The communication network is represented as an undirected graph where nodes represent UAVs and edges represent communication links between nodes located within the communication range.

In the simulation, each UAV node is assigned a simulated battery level representing its remaining energy. This battery value is used in the coordinator election process to ensure that nodes with sufficient energy resources are prioritized for temporary coordination roles.

B. Communication Model

Communication between UAV nodes is based on distance constraints. Two nodes establish a communication link if the Euclidean distance between them is less than the predefined communication range. This mechanism produces a dynamic swarm communication topology where nodes maintain

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connections only with nearby neighbors. The resulting network topology represents the communication structure of the swarm.

C. Failure Scenario

To evaluate fault tolerance, a node failure scenario is introduced during the simulation. In the leader-based swarm model, a designated leader node initially coordinates swarm communication. At time step 20, the leader node is assumed to fail, simulating potential real-world scenarios such as hardware malfunction, communication loss, or energy depletion.

For the proposed leaderless coordination approach, the failure of the current coordinator triggers a dynamic coordinator re-election process based on the scoring mechanism described in Section III. This enables the swarm network to continue functioning without relying on a permanent leader node.

D. Evaluation Metrics

The performance of the swarm communication system is evaluated using several metrics related to network robustness and coordination efficiency.

The primary evaluation metric is network connectivity, which represents the proportion of swarm nodes that remain connected within the communication network over time. This metric provides insight into how well the swarm maintains communication after a coordinator failure.

In addition, the simulation analyzes the coordinator election score distribution across swarm nodes. This distribution illustrates how node connectivity and battery level influence coordinator selection within the leaderless coordination framework.

These metrics allow a comparative analysis between the traditional leader-based coordination model and the proposed leaderless adaptive coordination method.

V. RESULTS AND DISCUSSION

This section presents the results obtained from the simulation experiments and evaluates the performance of the proposed leaderless adaptive coordination mechanism. The analysis focuses on the robustness of the swarm communication network under node failure conditions and the effectiveness of the coordinator election mechanism.

A. Network Robustness Analysis

To evaluate the resilience of the swarm communication architecture, a comparison was performed between a traditional leader-based coordination model and the proposed leaderless adaptive coordination method. In the leader-based model, a designated leader node is responsible for coordinating the

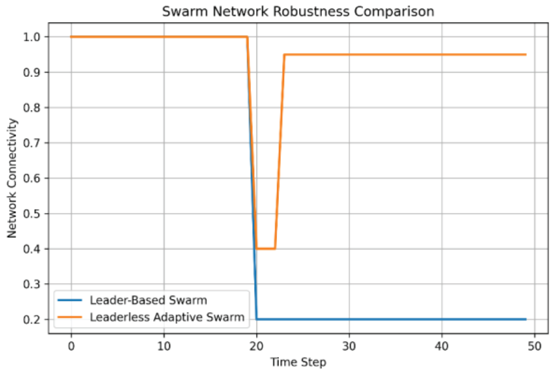

Fig. 1. Swarm network robustness comparison between leader-based and leaderless coordination approaches.

communication among swarm members. In contrast, the proposed approach dynamically elects temporary coordinators based on node connectivity and battery level.

The simulation introduces a failure scenario at time step 20, where the leader node becomes unavailable. The effect of this failure on swarm network connectivity is illustrated in Fig. 1.

As shown in Fig. 1, the leader-based swarm experiences a significant drop in network connectivity immediately after the leader failure. Because coordination depends on the central leader node, the network becomes fragmented and communication efficiency is significantly reduced. In contrast, the proposed leaderless coordination mechanism rapidly elects a new coordinator and restores network functionality. After a brief recovery period, the swarm maintains a connectivity level close to its original state.

These results demonstrate that eliminating reliance on a permanent leader node significantly improves swarm resilience and enables rapid recovery from coordinator failures. The adaptive coordinator election mechanism enables the swarm to maintain communication even when individual nodes fail. This improvement highlights the effectiveness of adaptive coordinator election in maintaining communication stability within decentralized UAV swarm networks.

The simulation results indicate that the leaderless coordination mechanism maintains approximately 95% network connectivity after coordinator failure, whereas the leader-based model experiences a sharp connectivity drop.

B. Swarm Communication Topology

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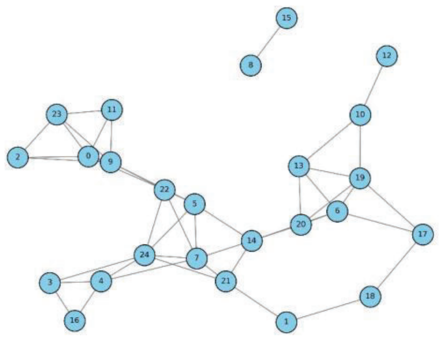

Fig. 2. Communication topology of the simulated UAV swarm network.

The communication structure of the simulated swarm network is represented as a graph where nodes correspond to UAV agents and edges represent communication links between neighboring nodes. The topology of this network depends on the spatial distribution of nodes and the defined communication range.

An example communication topology generated during the simulation is illustrated in Fig. 2.

The topology demonstrates the distributed nature of the swarm communication system. Nodes form communication links with neighboring UAVs located within the communication range, resulting in a decentralized network structure. Several nodes act as bridge nodes that connect different clusters within the swarm, helping maintain overall network connectivity. This distributed topology supports the implementation of leaderless coordination by allowing nodes to exchange information locally without requiring centralized control.

C. Coordinator Election Analysis

The effectiveness of the proposed coordinator election mechanism was further analyzed by evaluating the distribution of coordinator scores across swarm nodes. The coordinator score combines two parameters: node connectivity and battery level. Nodes with higher scores are more suitable candidates for temporary coordination roles.

The distribution of coordinator scores obtained from the simulation is shown in Fig. 3.

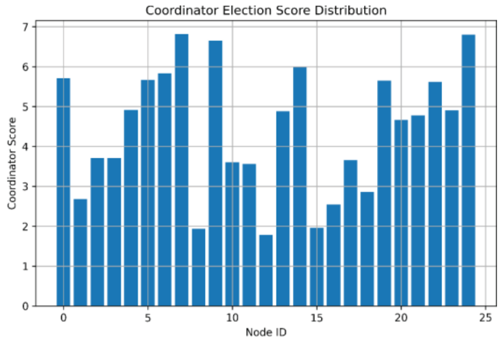

Fig. 3. Coordinator election score distribution across swarm nodes.

VI. CONCLUSION

This paper presented a leaderless adaptive coordination mechanism designed to improve the fault tolerance of UAV swarm communication networks. Traditional leader-based swarm architectures rely on a single coordinator node, which introduces a critical single point of failure. To address this limitation, the proposed approach dynamically elects temporary coordinators based on node connectivity and battery level, enabling decentralized coordination and rapid recovery from node failures.

A simulation-based evaluation was conducted using a swarm network consisting of 25 nodes operating within a distance-based communication model. The results demonstrated that the leaderless coordination mechanism significantly improves swarm resilience compared to conventional leader-based systems. When a coordinator failure was introduced during the simulation, the leader-based architecture experienced a sharp decline in network connectivity, whereas the proposed method successfully elected a new coordinator and restored communication within a short time.

The findings indicate that adaptive coordinator election can effectively enhance the robustness and reliability of distributed swarm communication systems. By eliminating dependence on a permanent leader node, the proposed architecture enables more resilient swarm operation in dynamic and uncertain environments. However, the current study is limited to simulation-based evaluation and assumes static node mobility during the communication analysis.

Future work will focus on extending the proposed framework to larger swarm sizes and evaluating its performance under more complex communication conditions, including dynamic mobility and real-world UAV networking constraints. Additionally, future research may explore the integration of machine learning techniques to further optimize coordinator selection and network stability in large-scale swarm systems. Experimental validation using real UAV platforms could also provide deeper insights into the practical feasibility and scalability of the proposed coordination approach.

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