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RESEARCH ARTICLE

Distributed TDMA Scheduling for Autonomous Aerial Swarms: A Self-Organizing Approach

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ABSTRACT Self-organization is a key strategy for improving the performance of an aerial swarm ad hoc network. The proliferation of low-cost VTOL drones has broadened the application domain of aerial swarms, and the need for synchronized communication among network entities has become crucial. However, existing ad hoc approaches struggle to maintain multi-hop connections in contested environments characterized by frequent topology changes and intermittent links. To overcome these limitations, we introduced STDMA protocol, which enables the self-configuration of drones without reliance on a ground controller. In continuation of the earlier work, we conduct extensive experiments to evaluate the performance of the proposed protocol. Comparative simulation experiments cover various scenarios with different network sizes, frame lengths, and traffic loads. The STDMA protocol achieves optimal access delay in highly contested environments and reduces delay by approximately 19.181%. Moreover, it exhibits improved channel utilization compared to the E-ASAP/SM protocol, with a 4.5 times increase.

INDEX TERMS Ad hoc networks, autonomous control, decentralized control, distributed systems, reliable communication, self-organizing network management, swarm intelligence, UAV swarm.

I. INTRODUCTION

The revolutionary impact of wireless technology on mobility has transformed communication and access to information, making it an indispensable aspect of everyday life. This synergy has paved the way for innovative applications like UAVs and IoT devices, benefiting from wireless connectivity for their seamless operation [1]. Over the past few years, there have been notable advancements in the field of unmanned aerial vehicles. The design of UAVs aims to execute specific tasks that cannot be cost-effectively performed by other kinds of vehicles [2], [3]. These tasks include supporting search and rescue operations [4], capturing detailed aerial data for urban planning [5], construction [6], land surveying, and other mapping-related activities [7], as well as facilitating data collection for various industries and research purposes [8], [9].

The concept of aerial swarm networks has emerged to tackle even more complex tasks [3], [10], [11]. These networks consist of multiple UAVs collaborating in a synchronized manner. They often play a crucial role in carrying out critical tasks where the accuracy and timely delivery of information are important [12], [13]. However, swarm's dynamic is often subject to various environmental changes which can pose several challenges to its successful operation [14]. One significant challenge is the impact of the movement of obstacles or changes in terrain. For example, the sudden appearance of a new obstacle, such as a building or a tree, can cause a change in UAV altitude or position which results in disconnection to the transmission

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range of others. Another, changing environmental conditions, such as the presence of electromagnetic interference, can disrupt the UAVs' communication systems, leading to loss of control or loss of data transmission. Any disruptions or failures in data transmission can have significant consequences, including mission failure or insufficient situational awareness.

With the increasing adoption of aerial swarm networks across a wide range of applications, there is an increasing demand for effective management techniques, particularly in sustaining topological links in such networks. Employing a protocol that allows coordinated communication through a central unit may initially appear to be an efficient management strategy. However, the primary-secondary architecture, as mentioned in [15], is sensitive to topology and node failures, especially the failure of the primary node comes with a considerable cost. Relying solely on centralized control exposes the network to both cyber and physical attacks. Any malfunction on the central control node can have serious effects on network operations and compromise the reliability of data transmission. Another concern with a centralized control mechanism is scalability. As the number of UAVs in the swarm network increases, the centralized system may struggle to efficiently handle the growing volume of coordination overhead. Apart from single-point of failure, having a primary node to coordinate the network itself is a limiting factor in the scalability of the swarm [16]. The centralized entity becomes a bottleneck within the network itself, leading to longer delays, reduced responsiveness, and degraded overall network performance.

One prominent approach in this domain is the development of decentralized intelligence, which empowers the entire swarm to operate with distributed coordination while minimizing the risks associated with centralized control. Communication links between the nodes are established without the need for fixed infrastructure such as routers or wireless access points. Instead, the UAVs themselves act as communication nodes, forming autonomous aerial swarms that are suitable for scenarios where traditional infrastructure is unavailable or impractical to deploy. This enables the swarm to operate in an ad hoc manner, leveraging local information and interactions among the nodes to collectively achieve common goals.

In this study, the proposed protocol focuses significantly on the neighborhood aspect, empowering drones to adapt and collaborate effectively with other drones in close proximity. By constructing a comprehensive topological information database, each drone acquires the essential knowledge to make informed decisions and adjust its behavior accordingly. The protocol encompasses a range of time slot operations, including slot assignment, reuse, relinquishment, and release. By incorporating these mechanisms, the protocol greatly improves the network's responsiveness to topological changes, ensures seamless connectivity, and facilitates efficient collaboration among drones, thus successfully implementing a self-organizing strategy.

A. BACKGROUND AND MOTIVATION

UAVs introduce movement into the network by definition, resulting in constant changes in the organization of nodes. This inherent mobility makes maintaining reliable communication links between UAVs difficult. As highlighted by [17] and [18] developing a resilient communication protocol that covers the constantly dynamic nature of moving nodes and considers unexpected events is a challenging task that researchers and fellows from industry seek to solve. Ad hoc networks where packet collisions and hidden/exposed terminal problems usually require good management to keep Quality of Service (QoS) at a desired level. As a solution, several MAC layer algorithms are proposed to help the network for better management in lower layers in terms of network operability, and network reliability such as delivery ratio of packets, collision rates, and fair sharing of resources.

The main goal in developing MAC layer algorithms is to optimize the use of wireless channels. To achieve this, nodes exchange messages to inform each other. However, broadcasting control messages results in significant communication overhead. This leads to a wastage of network resources, including bandwidth.

These aforementioned problems can be mitigated by implementing a well-synchronized Time Division Multiple Access (TDMA) scheme, particularly for aerial swarm network setups. Because, compared to other access protocols, TDMA greatly reduces the occurrence of packet collisions. In [19], the authors highlight the effectiveness of TDMA protocols in mitigating the transmission conflict problems in UAV ad hoc networks. TDMA achieves this by employing clear time slot divisions for communication, making it more suitable for such scenarios. However, the paper also points out certain challenges associated with TDMA implementations. On one hand, TDMA protocols with fixed allocation tend to exhibit poor channel utilization. On the other hand, dynamic TDMA protocols can be challenging to implement.

1) CONTESTED ENVIRONMENT

This study specifically focuses on the challenges posed by contested environments. These environments, characterized by non-fixed network structures, can lead to unexpected outcomes that disrupt network operations, resulting in longer delays and potential failures. To address specific scenarios related to nodes' lifecycle in a network that has not been adequately covered in [20], it is crucial to design an optimized and efficient TDMA protocol that not only prevents collisions but also enables fast recovery from packet collisions.

In the context of aerial swarm networks, the movement of drones introduces topological changes that potentially cause nodes to move out of the range of their one-hop neighbors. When nodes rejoin the network after being out of range, it disrupts network operations and requires additional control packet transmissions. The transmission of these control packets consumes bandwidth, introduces latency, and requires synchronization efforts from other nodes. For that, possible scenarios are considered and further explained in Section IV. The impact of these scenarios on network performance can be assessed by analyzing the overhead introduced by control packets, which can affect throughput, delay, and packet loss further given in Section V.

B. SCOPE OF THE PAPER AND CONTRIBUTIONS

This study contributes significantly to the field of aerial swarm communication in several ways:

- Self-Organizing Strategy: We propose a self-organizing TDMA strategy specifically designed to improve connectivity in contested environments with faulty or disrupted links. This strategy not only ensures proper configuration but also includes critical recovery and maintenance policies to ensure the continuous functioning of the aerial swarm. Our approach enhances the overall performance of the communication system by sending appropriate control messages and mitigating transmission losses.
- Autonomous Network Management: We introduce an autonomous and decentralized network management system capable of supporting fully distributed time-slot operations, including slot assignment and slot migration. This enables seamless entry and exit of nodes or drones into the network without requiring prior configuration. The system can readjust slot distribution between nodes without the need for manual intervention from any network manager. Our solution is scalable, robust, and efficient to the dynamic nature of the network organization.
- Implementation and Testing: We have implemented our protocol using OMNET++ and the INET4 library modules, ensuring a comprehensive testing process. Additionally, we conducted a proof-of-concept implementation on a small-scale test-bed using commercially available off-the-shelf (COTS) entities. These practical validations demonstrate the value and efficacy of our proposed solution in real-world scenarios.

This study presents a self-organizing protocol that addresses the challenges associated with entry, active-migration, and exit sequences of drones in aerial swarm communication. Our protocol is among the first attempts to develop a comprehensive solution capable of handling the complexities and varied scenarios encountered in aerial swarm communication.

The structure of this paper is as follows: Section II provides a comprehensive review of the relevant literature. The system model employed in this study is outlined in Section III. The details of the proposed protocol can be found in Section IV. Section V offers an analysis of simulation results for performance evaluation. Finally, Section VI concludes the paper and provides insights into future directions.

II. RELATED WORKS

Several studies have been conducted on distributed and dynamic slot assignment protocols in the domains of wireless sensor networks and ad hoc networks. However, there is a scarcity of research focusing on self-organization in UAV networking. This research builds upon and extends the work presented in [21], aiming to address the unique challenges and requirements of UAV networks.

In the design problem of MAC protocol which considers energy, delay, and collision issues, detailed work is done in [22]. The authors propose a schedule for a wireless sensor network with non-uniform node density, using an average two-hop neighbor count for slot allocation, which can be done quickly and less collision-less, considering region-specific variations in sensor node density.

In [23], authors emphasized the necessity of dynamic behavior in the context of adaptive communication of quadcopter swarms. To effectively use the system resources, the slot allocation algorithm works only for the nodes that generate new information. In each time slot, the proposed method updates the set of potential senders. With that modification, the bandwidth allocated to inactive nodes is eliminated, as the same problem is defined in [24] which states that the amount of energy loss and the cost are directly related to inactive nodes and non-wake-up nodes. Reference [25] aims to prevent the aerial swarm network, managed by a central control unit, from facing additional costs and energy consumption.

In [26], the authors highlight the suitability of contention-free deterministic scheduling for low-power devices. In [27], the authors propose a distributed communication scheme for UAVs that assigns diverse roles to each UAV to ensure coordinated control.

The paper [28] investigates the time slot reservation problem and presents a novel priority-based solution that takes into account the two-hop range. In [29], the authors emphasize the significance of understanding the two-hop neighbors and their corresponding transmission times to effectively tackle the hidden terminal problem in multi-hop wireless networking.

The paper [30] identifies basic weaknesses of TDMA: negotiation overhead and inefficient resource utilization. Their proposed channel access mechanism focuses on the dynamic nature of vehicular ad hoc networks and employs traffic prediction models and cluster-based structures to minimize collisions and channel access delay. During a new node's entry process, it listens to the channel for a specified duration. This protocol allocates time slots based on centralized control and ignores individual node demands. Nevertheless, [31] focuses on the energy demands of nodes within an IoT network, proposing an architecture where a UAV swarm satisfies the energy demand. The authors in [15] inspect similar problems: reducing communication overhead caused by designing an effective and adaptive algorithm for self-organizing networks. It differentiates from our work by using only a part of neighboring information with the help of a machine learning method and only evaluating the achievement of synchronization.

A similar approach is taken in [32] where collision-free slot allocation and effective bandwidth usage are considered. Slot allocation in a time-divided frame structure is done via using Multi-Armed Bandit Learning and effective bandwidth utilization is provided by the idea of frame size reduction. However, in this work, the authors do not conduct detailed experiments on frame size adjustments.

There are also several more suggestions on frame design in TDMA-based protocols. In the study by [33], a superframe structure is proposed which consists of control, exchange, and data frames. Within the control frame, time slots are allocated for reservation and reply purposes. Additionally, the purpose of defining an exchange frame is to facilitate the migration of time slots between nodes. However, it is important to note that this superframe structure, along with similar studies [28], has a notable disadvantage. The predefined and reserved frames may suffer from underutilization if no control packets are being transmitted or if there are no requests for slot exchange from the nodes. This underutilization can result in inefficient resource allocation and reduced transmission time for data packets.

Despite notable research, there are still some unresolved issues that need to be addressed. One significant concern is the inefficiency observed during node join or leave events, as it can significantly impact the overall system performance. Another area of concern is the computational overhead involved in configuring the network at the start of each time slot or frame, which results in unnecessary time consumption. Besides, the design complexities of the frame structure pose challenges in rapid recovery from synchronization losses, which could potentially impact the node's ability to allocate slots. Existing protocols often lack flexibility and scalability due to centralized control and overlook individual node requirements. Moreover, certain frame structures and similar methods may remain underutilized if control packets are not sent frequently enough, while excessive control packet transmissions can lead to subsequent packet collisions. Further research is needed to develop efficient protocols that handle network dynamics, address individual node demands, and optimize packet transmission.

III. SYSTEM MODEL

In this section, we present a comprehensive description of the proposed network management system. The system encompasses various elements, including neighborhood discovery, a simplified yet effective frame structure, and an initial discussion on the drawbacks of centralized control mechanisms.

A. NEIGHBORHOOD

The network model is represented as a connectivity graph, with each drone in the network roles as a vertex. Edges are drawn between vertices in the drone network graph only when two drones are within transmission range of each other and can communicate. A connectivity graph is a useful tool for illustrating a drone network as it simplifies the network's structure for better comprehension.

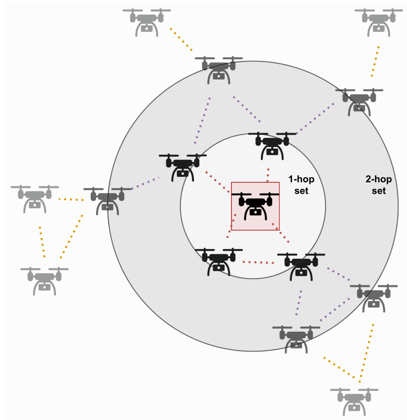


FIGURE 1. One-hop and two-hop neighboring sets from a single drone's perspective in an ad hoc network, ignoring others.

The protocol must be adaptable to changes in the network size and the number of nearby nodes. The recommended protocol addresses this by using time slots to be flexibly allocated to drones when needed. This allows the network to manage changing traffic loads and adjust to shifting traffic demands effectively. Moreover, the topology information base stores information about a drone's one-hop and two-hop neighbors, which is defined by (1) and (2). The variables v_i' and v_i'' denote the sets of neighboring drones that are one-hop and two-hop away from *Drone i*, respectively.

$$v_i' = \{v_j| < v_i, v_j > \in E\} \tag{1}$$

$$v_i'' = [\bigcup_{v_j \in v_i'} v_j'] - v_i' \tag{2}$$

Knowing beyond 2-hop neighbors may extend network coverage, but it comes at a cost in terms of information exchange and memory requirements. Drones can still effectively coordinate communication timings by focusing on one-hop and two-hop neighbors, avoiding interference with other drones' broadcasts. This approach avoids hidden or exposed terminal situations, and the benefits of only considering 1 and 2-hop neighbors compensate for the associated complexity and resource consumption.

The ad hoc network depicted in Fig. 1 showcases the concept of neighboring sets from the viewpoint of a single drone to better understand the neighboring sets. Analyzing these neighboring sets is essential for various network operations, such as resource allocation and collision estimation on shared time slots. By understanding the neighboring sets, nodes can make informed decisions and effectively direct their future actions in the network's contested environment.

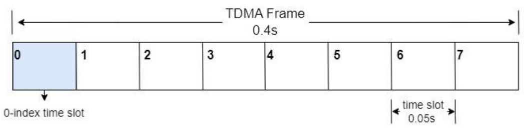


FIGURE 2. Frame structure with size 8.

B. FRAME STRUCTURE

The frame structure design of this proposed protocol is characterized as being multifaceted but also flexible. Fig. 2 illustrates the structure of an 8-sized frame. As shown in this figure, the time slots are uniform in size, and no distinction is made according to packet types. Additionally, each time slot has the same duration. Nevertheless, the 0-index time slot has a unique characteristic that restricts active nodes from transmitting, allowing new nodes to join the network without causing a collision on active node's transmissions. The primary objective of this special slot is to serve as an introduction mechanism for new nodes.

The protocol's frame structure also offers an adaptable mechanism for responding to variations in network demand. When network resources are insufficient to fulfill the request, a single drone can double the frame size, incurring additional time slots as detailed explained in Section IV-E. The information provided in each received packet will notify all drones in the immediate area about the new frame size. As a result, frame sizes across the network can vary regionally depending on the network's setup.

C. CONTROL MECHANISM

In order to show how centralized control mechanisms degrade system performance in ad hoc networks, we examine the entry sequence of a new node since it is the case where the largest flow of control packets is involved. Section IV-A offers insights into the packet traffic within a collision-free entry sequence. In a centralized control mechanism, new node is required to communicate exclusively with a central node for all its requests. Other active units in the network lack the authorization to respond to new node's requests and can only navigate the packets if new node and central node are not in direct communication range. As a result, the distance between new node and central node plays a significant role in determining the total number of control packets transmitted and the time required for the successful entry of new node. As the hop distance between new node and central node increases ($d > 1$), the total number of control packets transmitted is given by (3):

$$P = (P_n + P_c) \times d \tag{3}$$

where P indicates the total number of transmitted packets, P_n, transmitted packets by new node, P_c, by central node and d is hop distance between central node and new node.

In order to compare the control mechanism differences, we come up with an example test scenario given in Fig. 3. In this line topology, we assume that the relative distance between central node and new node is at most 5. To analyze the impact of hop distances on the control mechanism, we can construct a connectivity graph with 6 drones arranged in a line, and central node can be any of these 5 nodes.

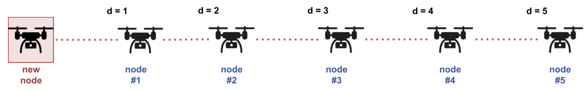


FIGURE 3. Hop distance between swarm nodes.

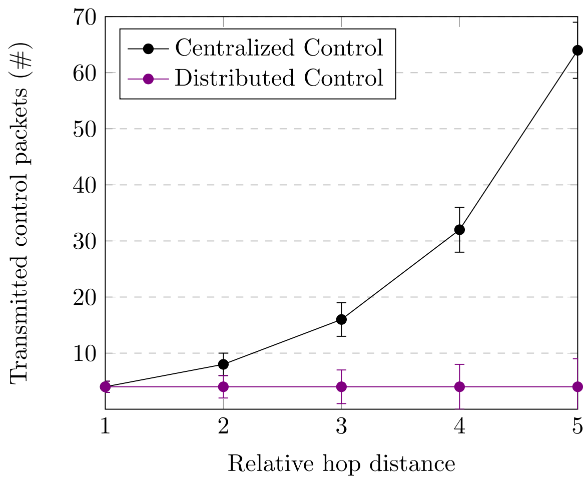


FIGURE 4. Number of transmitted packets measurement under two different control strategies.

During the entry sequence of a single drone, in other words, until a new node becomes an active member of this network system with an increasing number of hop distances between, the comparison between centralized and decentralized network structures in terms of (i) the number of transmitted packets, (ii) time spent are plotted in Fig. 4 and Fig. 5. Frame size was set to its maximum value, ensuring that no negative acknowledgment (N-REP) packets are sent. Additionally, the distance between hops is set to 120 m. However, as the hop distance between new node and central node increases, it highlights one of the drawbacks of the centralized control mechanism. Nodes located at a greater number of hop distances from central node may face limitations in their ability to directly send reply messages to new node. Therefore, the distance between new node and central node directly influences the number of control packets transmitted in total. Therefore, central control mechanisms introduce additional packet transmissions and result in computational complexity. This highlights the importance of distributed communication in this network architecture when designing MAC layer protocol.

IV. PROPOSED METHOD

This self-organizing protocol enables appropriate time slot reuse by considering neighborhood relations. In situations where the available slots are insufficient to meet the demands, frame size can be doubled. Besides, the suggested

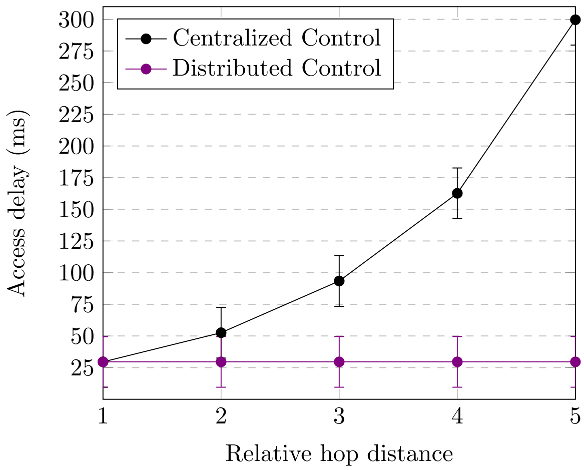


FIGURE 5. **Access delay measurement under two different control strategies.**

protocol makes use of a topology information base in each node to store topological information, such as current frame length, slot assignments, MAC addresses, the type of neighborhood (one-hop, two-hop), the most recent slot status (available, requested), and the time at which the packet was most recently received. By keeping track of these details, scheduling choices may be made and network resources can be managed more effectively. We provide further elaboration on these aspects in the subsequent sections.

A. ENTRY SEQUENCE

As given the details in previous work [21], the entrance of a new node in our proposed method follows a well-defined packet traffic sequence, ensuring a smooth joining process. Each packet serves a specific purpose and can be simply explained as follows:

1) New node initiates the entry sequence by sending a Request (REQ) packet. This packet serves as a request to join the network, indicating new node's intention to become an active member.
2) The surrounding nodes respond by sending an Information (INF) packet. INF packet contains important details and instructions that new node needs to understand the network's structure and operation.
3) Equipped with the information provided by INF packets, new node formulates a proposal for its frame length and slot selection. This information is then encapsulated in a Suggestion (SUG) packet, which includes the new node's preferred settings.
4) After one frame length has passed and no negative acknowledgment (N-REP) packets are received, during the specific time slot assigned to new node within the SUG packet, new node seizes the opportunity to broadcast an Information (INF) packet. This INF packet confirms its entry into the network and signals its readiness to participate actively.
5) With the successful transmission of INF packet, new node officially becomes a member of the network. It gains the ability to actively transmit its data packets and engage in communication with other network nodes.

Building upon the work presented in [21] and taking it a step further, the proposed method takes into account various entry scenarios that were previously discussed but not extensively explained and evaluated in terms of performance. In this work, we aim to provide a comprehensive understanding of the entry sequence for new nodes by addressing three main scenarios in detail:

- *Collision-Free Entry Sequence:* In this scenario, a new node initiates its entry by sending a request (REQ) packet after the extended waiting period. It actively receives and analyzes packets from drones in its coverage area, gathering information about the network topology and available slots. Once new node selects a time slot, it marks it as requested and broadcasts a Suggestion (SUG) packet to inform other nodes of its frame length and slot selection. If there are no conflicting requests from nearby nodes, new node can successfully join the network. However, if there are conflicting slot requests or overlapping assignments, the surrounding nodes within one hop send negative acknowledgment (N-REP) packets. These N-REP packets inform new node about the unacceptable slot request.
  Upon receiving the N-REP packets, new node updates its local network topology database. Based on this information, it can decide whether to send an additional packet to request another available slot. By utilizing N-REP packets instead of positive acknowledgment (REP) packets, the total number of reply packets transmitted is minimized.
- *Concurrent Entry Sequence:* In scenarios where multiple drones attempt to enter the network simultaneously, a contention state occurs. Each drone waits for the beginning of a frame and then transmits its request (REQ) packet in the same slot. If multiple drones transmit their requests in the same slot, a collision may occur, resulting in the loss of those packets. After transmitting their request, drones monitor the network for corresponding control packets (INF). If both drones do not receive any packet within one frame length, it assumes that a collision has occurred and initiates a retransmission of SUG packet with a slotted ALOHA approach. This process continues until a drone successfully receives any acknowledgment or until the timer reaches its maximum time limit. To handle contention, a slotted ALOHA approach is followed.
- *Delayed Entry Sequence:* This entry sequence addresses situations where a new drone senses that another drone is in the entry sequence and will become active soon. Instead of immediately sending its packets, the new drone employs a back-off algorithm. This helps prevent

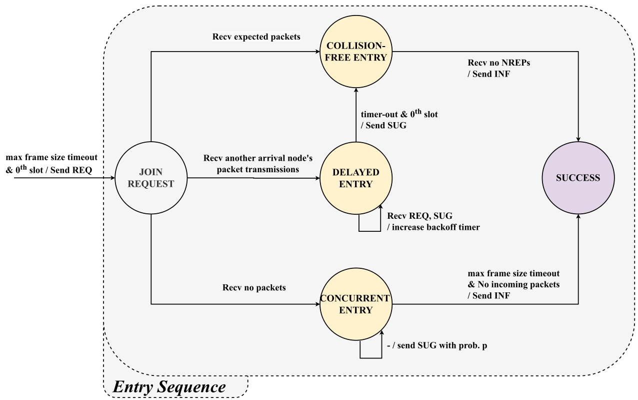


FIGURE 6. Finite State Machine (FSM) illustrating entry sequences.

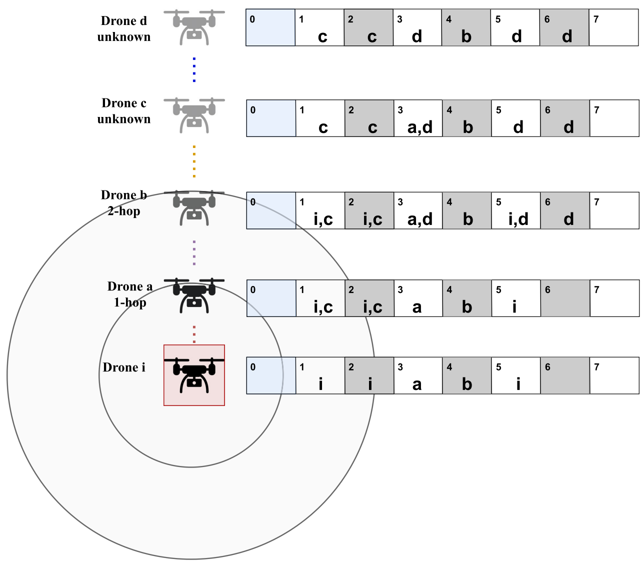


FIGURE 7. Illustration of slot reuse in a line topology.

TABLE 1. Topology information table of proposed system model.

Slot Id	Mac Address	type of neighborhood	status of slot	time
0	-	-	contention	-
1	XX:XX:XX:XX:XX:X1	one hop	occupied	4 ms
2	XX:XX:XX:XX:XX:X2	-	owned	-
3	-	-	available	-

persistent collisions. Besides, this prioritization mechanism ensures that both the delayed node and another new node will eventually become active members of the network, which promotes a balanced network entry process for all participants.

Fig. 6 provides a simple representation of entry sequences in a wireless network using a Finite State Machine (FSM). It depicts the different stages and transitions involved in the joining process of nodes. The states in the FSM represent the various states that a node can be in during the entry sequence, while the transitions illustrate the events or conditions that trigger the node to move from one state to another. This visual representation helps in understanding the sequential flow of actions and decisions involved in the entry process, providing insights into the dynamics of node's successful integration into the network.

Unlike previous work at [21], we not only consider these scenarios but also provide an in-depth analysis of their impact on the overall performance of the network. In Section V, we present a comprehensive analysis that sheds light on the effects of these scenarios, offering valuable insights into the performance dynamics of the network.

B. TOPOLOGY MANAGEMENT

As [34] states ad hoc network's key characteristic is decentralized coordination. The proposed protocol takes this into consideration, and further builds a local information base in each node, which is then utilized to store and transmit topological information to other nodes via packets. This implies that drones are aware of their local topology, use a connectivity graph to represent the network, and operate in a distributed manner. As a result, the network becomes self-organizing [4].

Table 1 provides valuable insights into the topological structure of the proposed system model from the perspective of a single drone. It includes essential information such as slot assignments, corresponding MAC addresses, neighborhood type (e.g., one hop), frame size, and slot status. In this example, the table indicates that Slot 1 is occupied by a node with the MAC address XX:XX:XX:XX:XX:X1, and the latest packet from that MAC address was received 4ms from the beginning of the simulation. Slot 2 is owned by a node with the MAC address XX:XX:XX:XX:XX:X2. The remaining slot, Slot 3, is available for assignment. Keeping track of this information is crucial for analyzing slot assignments and identifying unassigned slots, allowing for efficient resource allocation in the network.

C. TIME SLOT ASSIGNMENT

In this proposed method in order to optimize bandwidth utilization, time slots can be exclusively assigned within a two-hop range, allowing the other nodes beyond this range to reuse the time slots. This approach ensures conflict-free usage of time slots and efficient allocation of system resources, ultimately optimizing resource utilization.

The selection of a time slot for an assignment is performed randomly from the set of available time slots, denoted as $\{s \mid s \text{ is not assigned to any drone } j \in v_i' \cup v_i''\}$. This definition ensures that each drone selects a time slot that is not used by any drone within its two-hop neighborhood. By avoiding time slots overlapping with nearby drones, the network achieves collision-free communication within the two-hop range.

Fig. 7 illustrates an instance of slot assignments in a line topology, where the same slots are assigned to multiple nodes that are not within a 2-hop range.

D. TIME SLOT RELINQUISHMENT

Slot exchange or migration between nodes refers to the process in which nodes in a network transfer their assigned time slots to other nodes. This operation allows for the redistribution of time slots to optimize resource utilization. The slot migration process involves the following steps:

1) Node Selection: A node that needs more slot(s) first selects available nodes to negotiate with. Unlike the approach proposed by Kanzaki et al. [20], this protocol incorporates a more comprehensive network connectivity criteria for candidate selection. The candidate set for slot migration is formed by defining two groups of neighboring nodes. The first group consists of one-hop neighbors that have multiple slot assignments, denoted as $v'_{i(multi)}$. These are the immediate neighboring nodes of the active node i that possess multiple slots. The second group comprises two-hop neighbors, denoted as v''_i, which are the neighbors of the immediate neighboring nodes. These two-hop neighbors do not reuse the same slots as the active node i.

$$v_{i(cand)} = \{v'_{i(multi)} - v''_i\} \tag{4}$$

Equation 4 represents the formation of the candidate set, where $v_{i(cand)}$ is obtained by subtracting the set of two-hop neighbors v''_i from the set of one-hop neighbors with multiple slots $v'_{i(multi)}$. This mathematical representation ensures that the candidate set includes nodes that will not be left without any slots and also avoids collisions with nodes within a two-hop range, thereby it addresses the hidden terminal problem.
2) Negotiation: The node initiates a negotiation with the selected node to request the exchange of time slot(s). This negotiation involves exchanging positive and negative acknowledgment control messages to ensure that both nodes agree on slot exchange.
3) Time Slot Transfer: Once the negotiation is successful, nodes proceed with the actual transfer of time slot(s). The node releasing the slot(s) updates its local information base to remove the transferred slot(s), while the demanding node updates its own table to reflect the newly acquired slot(s).
4) Synchronization: After the slot transfer, both nodes involved in the exchange synchronize their operations to align with the new time slot allocations. This ensures that subsequent transmissions include the latest information according to the updated slot assignments.

Slot migration can help address various network dynamics, such as node mobility, changing network topologies, or varying traffic patterns. By allowing nodes to adapt their slot allocations based on network conditions, slot exchange enhances the efficiency and performance of ad hoc networks.

E. FRAME SIZE INCREASE

The protocol incorporates a dynamic mechanism for adjusting the time slot size, allowing for the doubling of the frame size when necessary. Frame doubling provides a solution to address the limitations of a fixed-size frame in ad hoc networks. To ensure that the system operates within its capacity limits and avoids unnecessary changes in frame size, the protocol keeps a maximum limit in frame size and also only authorizes nodes with additional slot requests to double the frame size when there are no available time slots. Fig. 8 gives a general perspective on how to manage excessive frame-doubling operations in this work.

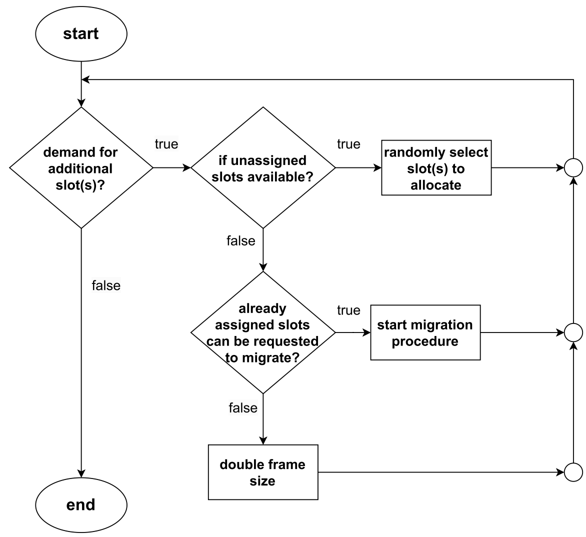


FIGURE 8. Additional slot allocation procedure based on node's demand.

While it offers advantages in terms of increased capacity and scalability, it also introduces a longer frame duration and complexity of keeping up with the latest information about network's overall status. Moreover, there is an issue when accessing slot 0 again if the frame size is very large, as it would require a significant amount of time to reach slot 0 again. As the number of slots in a frame increases from 4 to 128, the waiting time for Slot 0 gradually increases, indicating a potential increase in the delay of new nodes' network entrance. Longer frame sizes result in a longer wait to access slot 0, yet the benefits to the new nodes' entry sequence outweigh this drawback. Defining a maximum frame length can help mitigate this effect too.

V. RESULTS

In this section, we provide a thorough performance analysis of the proposed protocol, examining critical factors like access delay, frame utilization, control packet traffic, and network operability. Table 2 provides an overview of simulation parameters used during the evaluation process. These parameters define several features of the simulation environment as well as the communication system's characteristics. The simulation area is a 1000 m x 1000 m square space. Both the transmission and interference ranges are set to 120 m, indicating the maximum communication distance and potential interference range between nodes. The number

TABLE 2. Simulation parameters.

Parameter	Value
Simulation Area	1000 m × 1000 m
Transmission Range	120 m
Interference Range	120 m
Frame Length (min)	4 × 0.05 s
Frame Length (max)	128 × 0.05 s
Slot Duration	0.05 s
Bitrate	19200 bps
Data Flow Rate	Exp(λ) (12 ms)
Message Length	10 Bytes
Transmitter Preamble Duration	0.0001 s
UAV transmit power (Ptr)	0.8 W

of drones in the coverage region fluctuates based on how frequently they leave and enter the network. Data flow rates have an exponential distribution with a mean inter-arrival duration of 12 ms, indicating variability in data packet arrival.

The implementation comprises several modules responsible for packet transmission, reception, and channel access. These modules interact with each other to simulate the behavior of the protocol. Each node is created with the AdhocHost module provided by INET4. The nodes utilize the UnitDiskRadio radio type, while the default MAC protocol is substituted with our custom protocol.

A. CHANNEL ACCESS DELAY

The channel access delay refers to the time it takes for a new node to successfully join the network and start actively participating in the communication. In the proposed system, three entry sequences are considered: collision-free entry sequence, concurrent entry sequence, and delayed entry sequence. Each entry sequence has different characteristics and time requirements, as explained in detail in Section IV-A. Collision-Free Entry Sequence involves a new node requesting a slot, receiving INF packets, and sending SUG packets. If there are no conflicts, new node can join the network relatively quickly. However, if there are conflicts, additional packet exchanges are needed to resolve the conflicts, leading to increased access delay. In concurrent entry sequence, multiple nodes attempt to enter the network simultaneously, resulting in contention. Incoming nodes have to employ a slotted ALOHA approach. Delayed entry sequence introduces a back-off algorithm to prevent collisions when multiple nodes are in the entry sequence. This prioritization mechanism ensures a balanced entry process for all participants. Although delayed entry sequence may introduce a bit longer waiting time, it helps avoid persistent collisions and promotes fairness in network access.

Fig. 9 illustrates access delay for different entry scenarios based on the number of slots in a frame. As the frame size increases, access delay also increases for all entry sequences. Collision-Free Entry Sequence has the lowest access delay, followed by concurrent entry sequence. Delayed entry sequence has the highest access delay due to the backoff timer.

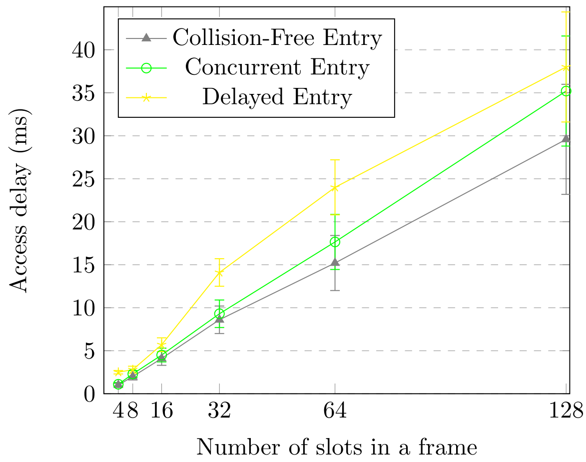


FIGURE 9. Access delay for different entry scenarios.

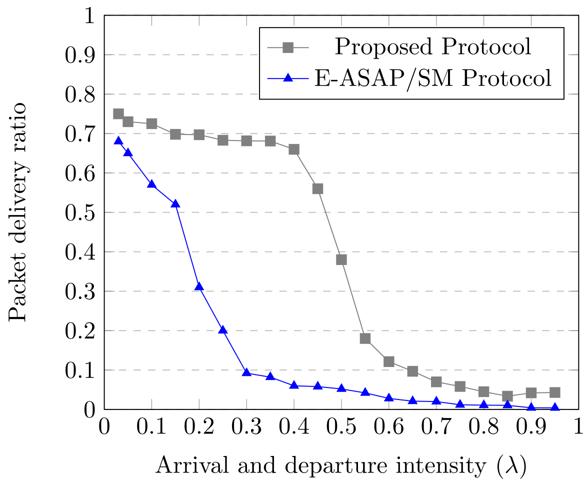


FIGURE 10. Packet delivery ratio performance under varying arrival/departure intensities [21].

B. NETWORK DYNAMICS

In this work, we highlight the network dynamics in Section I-A1. The arrival-departure intensity is defined as the number of nodes arriving or departing divided by the time duration as shown in (5). As the number of drones arriving or leaving the network grows, the arrival-departure intensity approaches 1.

$$\lambda = \frac{\text{Number of Nodes Arriving and Departing}}{\text{Time Duration}} \tag{5}$$

Packet delivery ratio for the proposed protocol and E-ASAP/SM protocol is examined for a range of arrival and departure intensity in [21]. As shown in Fig. 10, across all intensity values, the proposed protocol outperformed the E-ASAP/SM protocol in terms of robustness. Moreover, the packet delivery ratio of the proposed protocol saw a noticeable fall at an arrival and departure intensity of 0.4, but the E-ASAP/SM protocol see a substantial decline at an intensity of 0.1. This indicates that the proposed protocol is successful in minimizing the negative impacts of increasing

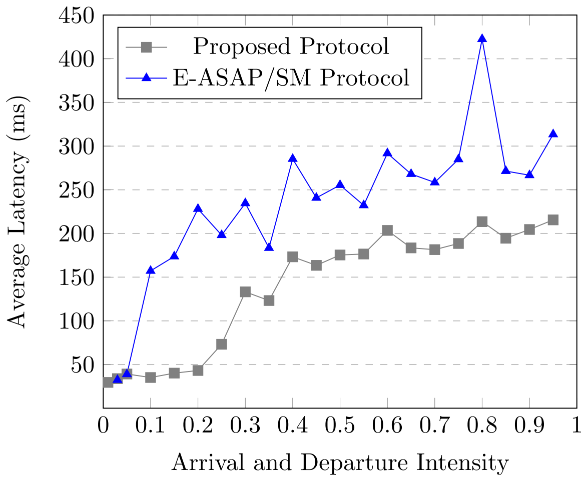


FIGURE 11. **Average Latency under varying arrival/departure intensity.**

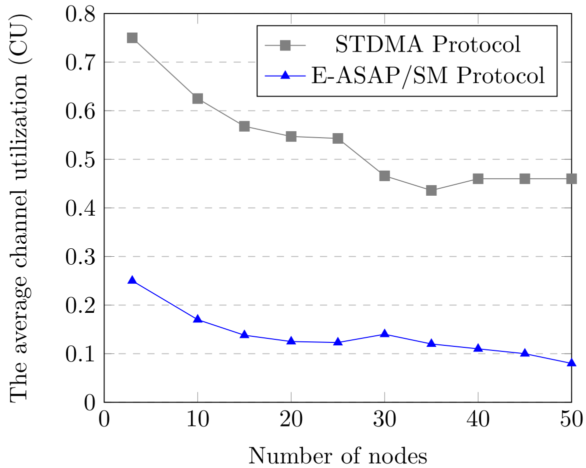


FIGURE 12. **Comparison of average channel utilization achieved by E-ASAP protocol/SM and proposed protocol (STDMA) as the number of drones increases.**

traffic loads and ensuring successful message delivery in dynamic aerial swarm situations. The outcomes show how the proposed protocol can maintain communication in an extremely hectic aerial swarm network.

In addition to building upon previous work, we extend the analysis by incorporating the evaluation of average latency as the arrival-departure intensity increases. This allows us to gain insights into the network's responsiveness and efficiency under varying levels of network traffic.

The obtained results are presented in Fig. 11 and show that our proposed protocol has reduced latency compared to the E-ASAP/SM protocol in every arrival/departure intensity value. The average delay in our protocol is measured at 189.511 ms, whereas the E-ASAP/SM protocol exhibits a higher average latency of approximately 234.541 ms. This signifies a significant reduction in delay of approximately 19.181%. Furthermore, with increasing intensity levels, E-ASAP/SM protocol experiences a rapid increase in latency, resulting in a steep upward trend. In contrast, our protocol exhibits a more gradual line, indicating a more controlled and consistent latency performance since our protocol takes into account multiple entry sequences, allowing for a more optimized handling of network dynamics and node interactions. By considering these different entry sequences, our protocol effectively mitigates sudden spikes in latency and ensures a more stable performance throughout varying intensity levels.

C. CHANNEL UTILIZATION

To compute the channel utilization, the total number of occupied time slots is divided by the total number of time slots in a frame. However, since slot 0 is treated differently in the protocol, it is excluded from the equation. Therefore, the channel utilization is defined as (6):

$$CU = \frac{\text{Total occupied time slots}}{\text{Total number of time slots in a frame} - 1} \tag{6}$$

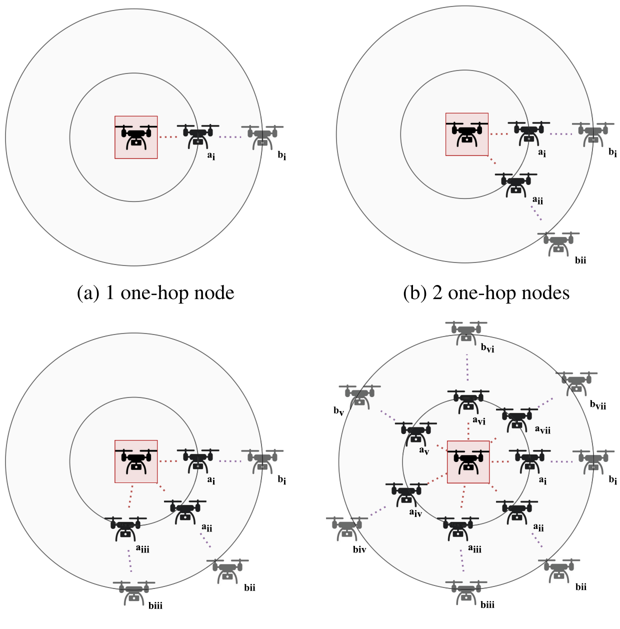
From Fig. 12, it can be observed that both protocols exhibit a decrease in average channel utilization as the number of nodes increases. However, the proposed protocol shows a significant improvement in channel utilization compared to the E-ASAP/SM protocol. The average channel utilization for the E-ASAP/SM protocol is 0.12, while the average channel utilization for the proposed protocol is 0.54.

These findings indicate that the proposed protocol, which enables active nodes to transmit SUG packets for allocating empty slots, effectively enhances overall channel utilization at the end. It demonstrates a significant advantage, with a 4.5 times improvement, over the previously proposed E-ASAP protocol. On the other hand, the E-ASAP/SM protocol relies on node migration from neighboring nodes to address slot demand, resulting in lower channel utilization. The results clearly demonstrate the superiority of the proposed protocol, offering better resource utilization and capacity management compared to the E-ASAP/SM protocol.

D. PACKET OVERHEAD

The proposed protocol aims to reduce unnecessary transmissions, thereby preventing the network from being overloaded with control traffic. To achieve this objective, an optimized procedure for sending reply packets is implemented. Unlike the approach described in [20], where positive reply packets are sent by every one-hop node, our protocol involves sending negative reply packets only from one-hop nodes that identify potential slot conflicts. In complex networks, more and more control packet transmission may be required to manage or coordinate network activities. Non-complex topologies, as shown in Fig. 13, are preferred for evaluating the impact of this strategy.

In Fig 13a, new drone communicates with only one neighboring one-hop drone. This active drone is connected to only one additional node, creating a two-hop distance for the new drone. Similarly, in Fig 13b, the new drone



(a) 1 one-hop node (b) 2 one-hop nodes

(c) 3 one-hop nodes (d) 7 one-hop nodes

FIGURE 13. Line topology illustration for the test of packet overhead analysis.

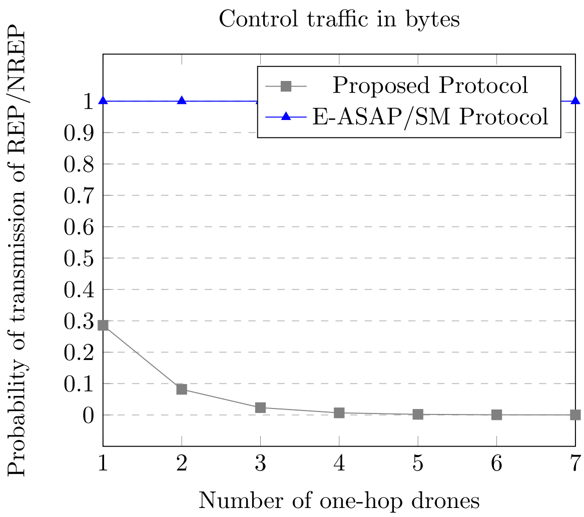


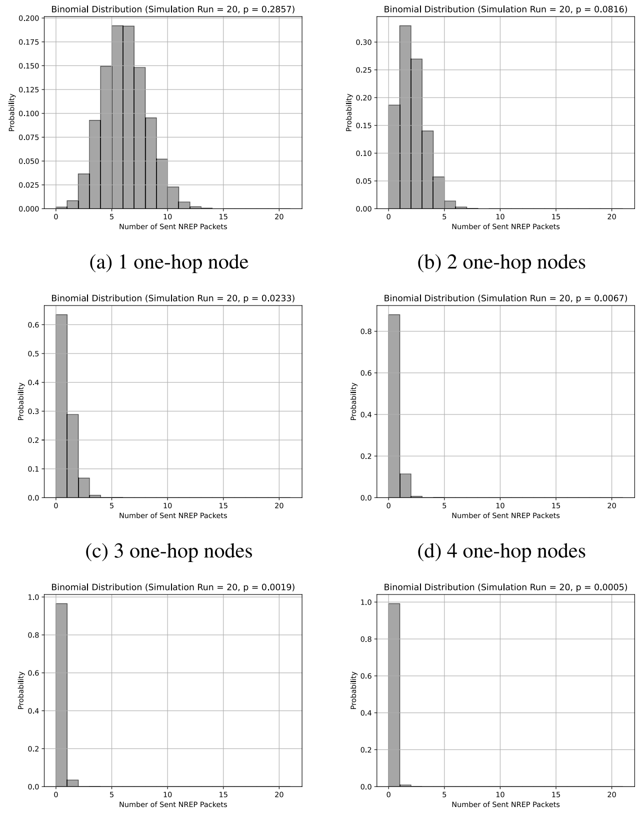
FIGURE 14. Comparison of Reply Packet (REP/NREP) transmission probabilities for the Proposed Protocol and the E-ASAP/SM Protocol during a single drone's entry sequence. The frame size is configured to eight slots, with each one-hop drone connecting to only one further node and each node taking only one slot.

communicates with two neighboring one-hop drones, and this procedure continues until the number of available time slots, in this case, is 7, as drawn in Fig 13d.

First, probability values are obtained using binomial distribution calculations as in (7), considering the network setup and protocols' reply packet transmission rules.

$$P(X = k) = C(n, k) \cdot p^k \cdot (1 - p)^{n-k} \quad (7)$$

In this formula, $P(X = k)$ represents the probability of sending k reply packets, n represents the number of nodes, p represents the probability of sending a reply packet



(a) 1 one-hop node (b) 2 one-hop nodes

(c) 3 one-hop nodes (d) 4 one-hop nodes

(e) 5 one-hop nodes (f) 6 one-hop nodes

FIGURE 15. Test results for packet overhead analysis by considering line topologies represented in Figure 13.

from a single node, and $C(n, k)$ represents the number of combinations of selecting k reply packets from n nodes.

Fig 14 compares the likelihood of sending reply packets between protocols. As depicted in Fig 13, the probability of transmitting reply packets decreases with changing network topology. However, regardless of network size, the E-ASAP/SM protocol has a constant probability of 1 for reply packet transmission. This constant probability results in more packet overhead.

Furthermore, the analysis of packet overhead for different line topologies is depicted in Fig. 15. It provides valuable insights into the distributions observed in each test case during a 20-run simulation. Each plot in the figure represents the distribution of NREP (Negative Reply) packet transmissions across the simulation runs.

VI. CONCLUSION

In conclusion, this work has focused on the development of a distributed intelligence approach for unmanned aerial swarm networks. By leveraging the inherent capabilities of individual drones, such networks can operate autonomously while minimizing the risks associated with centralized control. The protocol proposed in this study places a strong emphasis on neighborhood interactions and adaptability, enabling drones to collaborate effectively and respond to topological changes. The implementation of comprehensive topological information databases in each drone equips them with the necessary knowledge to make informed decisions and adjust their behavior accordingly. Despite the protocol's simplicity in decision-making using a finite state machine (FSM), the time complexity of finding and checking specific slot information can reach $\mathcal{O}(n)$, where n represents the frame size. As the network topology becomes more complex, the local topology base of individual drones grows, potentially straining their computational resources. Therefore, the protocol is constrained to operate within frame lengths ranging from 4 to 128 to mitigate this challenge. By incorporating these mechanisms, the protocol enhances each drone's ability to maintain connectivity, respond to dynamic changes, and achieve efficient collaboration among others. This self-organizing strategy enables the swarm to effectively carry out complex tasks and achieve common goals. Moreover, this work highlights the importance of considering unexpected events that may occur in aerial swarm networks, such as the simultaneous entry of multiple nodes or a sudden increase in node demand. The development of proactive strategies for detecting and mitigating such unforeseen problems is crucial to improving the flexibility and adaptability of the network while minimizing their impact. However, this protocol lacks packet re-transmission mechanisms in collision scenarios. As collisions increase, the intended packet may not be delivered within the expected time interval, potentially resulting in performance degradation and latency in data delivery.

Looking ahead, future work should focus on evaluating the stability and performance of the network over an extended period of time. This can be achieved through a combination of real-world testing and controlled experiments, considering different scenarios, including but not limited to entry sequences, and conditions such as varying traffic loads, node densities, and mobility patterns.

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