

# A Velocity-Aware Hierarchical Communication Framework for Scalable and Resilient UAV Swarm Networks

Salini Kumari\*, Abhimanyu Yadav<sup>†</sup>, Divya Sharma<sup>‡</sup>

*Department of Electronics and Communication Engineering (Specialization in Artificial Intelligence and Machine Learning)  
Galgotias University, Greater Noida, Uttar Pradesh, India*

*Email: \*iamsalini962006@gmail.com, <sup>†</sup>abhimanyuy694@gmail.com,  
<sup>‡</sup>divyasharma@galgotiasuniversity.edu.in*

**Abstract**—The Unmanned Aerial Vehicle (UAV) swarm technology is becoming a crucial enabling solution for applications in Intelligent Transportation, Precision Agriculture, Disaster Management and Environmental Monitoring, as well as Next Generation Wireless Communications. The multi-dimensional mobility of UAV swarms in 3D space, however, brings several networking issues such as frequent topology changes, unstable communication links, excessive routing overhead, and limited energy resources. The available routing protocols for conventional flying ad-hoc network (FANET) and existing clustering approaches are mainly based on energy-centric or static decisions making, mechanisms that are flexible for reliable communication of thousands of nodes in a swarming environment. In order to overcome these drawbacks, the authors introduce this paper a Velocity-Aware Hierarchical Communication Framework (VAHCF) for scalable and resilient UAV swarms. The proposed framework classifies UAVs into these adaptive clusters and provides an energy residual velocity-aware leader election strategy that balances residual energy, mobility stability and local connectivity to form a secure communication backbone. The framework combines predictive mobility awareness and hierarchical multi-hop communication, which minimizes the number of unnecessary control signaling, enhances route stability and facilitates smooth cluster management for dynamic swarm operations. To provide practical aerial networking conditions, a three-dimensional mobility model and a realistic wireless propagation characteristics are added. The proposed approach is verified by conducting comprehensive validation using extensive simulations in the NS-3 environment for both varying node densities and mobility scenarios, to compare the approach with representative routing architectures and with the support of various performance metrics like packet delivery ratio, end-to-end delay, communication overhead, scalability and energy efficiency. The results acquired show that the velocity-aware hierarchical tactic could strikingly improve the reliability of communication and network resilience with efficient utilization of resources for dense and fast-changing airborne nests. The suggested framework can be used as a practical aid for the future autonomous aerial networks and presents the potential for seamless integration with edge intelligence, 5G/6G NTN and cooperative swarm applications with AI.

**Keywords**—UAV Swarm Networks, Flying Ad-hoc Networks (FANETs), Hierarchical Communication, Velocity-Aware Clustering, Multi-hop Routing, Network Resilience, NS-3, Scalable Aerial Networks, 5G/6G Communications.

## I. INTRODUCTION

In recent years, unmanned aerial vehicle (UAV) networks have developed into a significant paradigm for next generation autonomous systems, providing distributed sensing, the cooperative decision-making and large-scale aerial operations. In contrast, single-UAV configurations are used for missions

that can be completed by a single aircraft, whereas cohesive swarms of multiple individuals can be implemented to fulfill more advanced missions, such as the response to disasters, precision agriculture, surveillance missions at borders, surveillance missions in environmental monitoring units, military missions of surveillance and intelligent transportation systems. New sensor technologies, light-weight and compact platforms, AI algorithms, and wireless communication systems have dramatically catalyzed the implementation of UAV swarms into applications such as civilian or defense missions [1], [2]. As is the case with any military communication system that progresses towards full autonomy, sufficient communication is vital to the success of the mission in terms of efficiency, reliability, and survivability of the swarm.

### A. Evolution of UAV Swarm Networks

The evolution of the UAV communication architecture has experienced multiple transitions through technology as shown in Fig. 1, from early UAS to UAVs. The evolution of the UAV communication architecture has traced through several technology transitions from early UAS to UAVs as shown in Fig. 1. In the early days of UAV systems, the flight control was a direct teleoperation system, meaning that each flight unit would have its own ground control station. Centralized architectures were effective for isolated missions but were not as easily scalable and communicated highly. With the advent of Mobile Ad-hoc Networks (MANETs) and later Flying Ad-hoc Networks (FANETs) [3], [4], ad-hoc routing came into existence and enabled UAVs, even in the absence of any ground member, to create self-organising routing paths. The limitations of traditional terrestrial routing mechanisms were exposed by the highly dynamic three-dimensional mobility of UAV swarms, however.

Considering the scalability, the hierarchical routing and clustering strategies were presented whereby groups of UAVs communicate via cluster head. These architectures minimise the complexity involved in routing data and the overhead in network management by localising the tasks. However, static cluster formation and traditional cluster leader selection are still not adequate for environments exhibiting rapid environmental change in air systems. The recent research trends indicate that the use of mobility-aware and adaptive communication frameworks, which combine predictive networking techniques and the adoption of swarm intelligence to increase

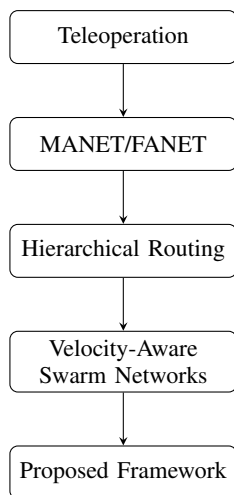


Fig. 1: Evolution of UAV communication architectures towards adaptive velocity-aware swarm networking.

the robustness of operations are promoted [5], [6]. Designed to support this development, the current contribution introduces a velocity-aware hierarchical communication approach that can flexibly cope with the dynamics of swarm mobility and ensure network stability.

As can be seen from Figure 1, there is a technological evolution from central operation of communication systems to intelligent, self-organizing, mobility-aware swarm communication systems.

### B. Challenges in UAV Swarm Communication

Although significant progress has been made, communication between the mobile UAV swarms is still a difficult problem to address. As opposed to terrestrial ad hoc networks, aerial nodes are in continuous motion in three dimensional space with variable velocities and trajectories and frequently change topology. This phenomenon is known as topological fluidity as it causes a substantial decrease of link lifetime and lends to route maintenance complications [1], [7].

The next important issue is the “broadcast storm” issue. Traditional reactive routing protocols broadcast route discovered packets throughout the network if the communication paths breaks. At high densities, because of the amount of control traffic competing with mission-critical data, latency can be higher, and throughput can lower. Likewise, frequent and consistent failure of the links due to rapid mobility leads to frequent path reconstruction process, reducing network reliability and communication overhead [8].

To overcome these issues, hierarchical communication architectures have been developed that establish leaders for each cluster which coordinate local matters and communicate amongst clusters. However, lack of a solid leadership structure is a serious issue. A cluster leader, chosen on the basis of the battery energy that is left after installation may quickly become out of communication range, causing cluster fragmentation and further reconfiguration overhead. Thus, a

TABLE I: Comparison of Existing Routing Architectures

Protocol	Mobility	Complexity	Weakness
AODV	High	$O(N^2)$	Route flooding
OLSR	Moderate	$O(N)$	Control overhead
GPSR	High	$O(1)$	GPS dependency
LEACH	Moderate	$O(k)$	Static clustering
HEED	Moderate	$O(k)$	Energy-only leader selection
Proposed	High	$O(k)$	Adaptive velocity management

balance between energy efficiency, mobility adaptation and reliable communication is an open research challenge.

### C. Research Gap

A number of routing approaches, which can enhance the performance of UAV communication, have been proposed. Reactive protocols like AODV constantly do not create routes, but only in case they are needed, therefore creating fewer updates (at the expense of high latency during route discovery). When complete routing table is maintained through periodic routing table exchanges, it is defined as a proactive protocol and results in faster forwarding with higher overhead of control messages. Geographic routing techniques (like GPSR) make use of node localization schemes to route packets, and are not only robust to localization errors [9], [10] but also need a fair degree of accuracy in the localization information.

Hierarchical clustering protocols such as LEACH, HEED, etc., decreases the communication complexity by forming clusters with their cluster heads. Yet most proposed solutions are based on either a fixed clustering policy or a battery-centric leader election that fail to incorporate the dynamic mobility features of UAV swarms. Moreover, current clustering methods are mostly unable to incorporate the predictive velocity information into the clustering leader selection, leading to the unstable backbone and the small-scale deployments. Additionally, there are many clustering techniques which do not incorporate the velocity prediction information in the clustering leader selection, which results in unstable cluster communication backbone in dense deployment conditions.

In general, Table I compares representative routing architectures with their main restriction, in a qualitative manner.

As shown in Table I, some existing protocols focus on one specific aspect such as routing efficiency, some others consider topology awareness, and others even deal with the issue of energy conservation, but each of them considers only one of the three issues we raised, such as high mobility, leader stability and large size of swarms. This limitation inspires the design of a velocity-aware hierarchical communication design that is resilient and scalable to serve as a networking backbone.

### D. Research Contributions

This work aims at addressing the aforementioned challenges, by introducing a hierarchical communication scheme that considers the velocity of each UAV in the swarm. The main contributions of this work can be summarized as follows:-

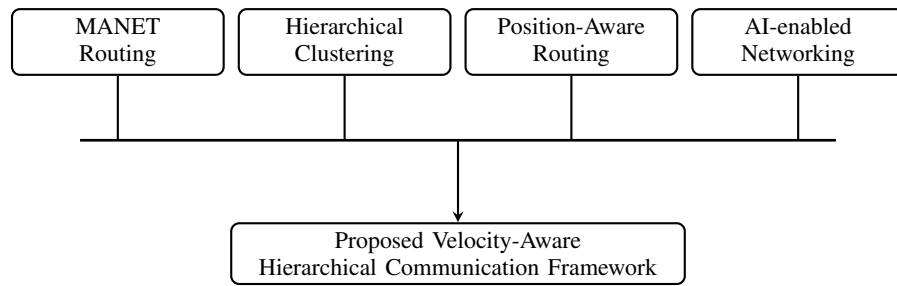


Fig. 2: Research pillars supporting the proposed UAV swarm communication framework.

- A scalable hierarchical communication architecture is designed to decrease the control overhead and enhance the scalability of swarms with high-density UAVs.
- Energy efficiency is further improved by incorporating neighboring node loading and mobility stability of clusters, which results in a velocity-aware cluster leader election mechanism to increase leader reliability.
- A predictive multi-hop communication mechanism is introduced to assist stable inter-cluster communication and adaptive topology management in fast changing network environment.
- This is done by simulating the proposed framework using NS-3 assuming different Mob, $N$  configurations and computing the packet delivery ratio, latency, overhead of communication, scalability, and energy consumption as metrics.

In the rest of this paper, we proceed as follows. In Section II, the existing literature on the communication and clustering mechanisms of UAV swarms is reviewed. The proposed velocity-aware hierarchical communication scheme and the mathematical expressions of the proposed scheme are demonstrated in Section III. The setup and simulation methodology are described in Section IV. The obtained results and comparative performances are discussed in Section V and finally, the paper is concluded and future research directions are outlined in Section VI.

## II. RELATED WORK

With the fast progress of Unmanned Aerial Vehicles (UAV) swarm technologies, a large amount of researches are currently conducted on communication architectures that enable distributed aerial operations. There are significant differences between the operation of conventional wireless networks and the UAV swarms, as the latter missions take place in highly dynamic 3-D networks where topology changes occur frequently, connectivity is intermittent, and energy is extremely limited. All the existing studies can be summarized in four groups: MANET-based routing, hierarchical clustering mechanisms, position-aware routing strategies, and artificial intelligence (AI)-based networking solutions. The evolution of these different research directions and their connection with the velocity-aware hierarchical communication framework are summarized in figure 2.

In contrast, the current UAV networking solutions are shown in Figure 2 as a mixture of several communication paradigms. However, the addition of mobility aware algorithm, adaptive clustering framework and scalable communication routing still remains an emerging research problem.

### A. MANET-Based Routing

The first UAV Communications Systems were based on routing approaches of Mobile Ad-hoc Networks (MANETs). Reactive routing protocols like AODV and Dynamic Source Routing (DSR) are built when they are needed and take a lot of time when a route is being discovered, but they minimize the overhead overhead of periodic control [11], [12]. If the UAV swarm system is very dynamic, the topology evolves several times, leading to continuous route reconstruction which results in gaps in the system's communication and high signalling response rates.

Optimized Link State Routing (OLSR) and Destination-Sequenced Distance Vector (DSDV) are both proactive routing methods which use periodic topology exchange [13]. These protocols have the advantages of decreasing the delay of forwarding, but the constant sending of control packets causes a lot of loss of bandwidth and battery resources. In large aerial deployments, the global routing information can not be maintained well as the number of the swarms grow in size.

Thus, existing MANET protocols offer valuable building blocks but are not well suited for the special characteristics of mobility and interactions of UAV-swarms.

### B. Hierarchical Clustering

One prominent approach that has been used to cope with dense wireless networks is hierarchical clustering, which has been proven to be a viable tool for decreasing the complexity of communication. Cluster-based protocols group nodes together in logical clusters and have cluster heads for local coordination and inter-cluster communication. FieldBenedetti and Proakis [14] introduced the concept of rotation of cluster heads in a randomized fashion in order to distribute the energy usage among the sensor nodes. Later, HEED enhanced its cluster grouping capability by taking into account the residual energy and communication cost in the call to cluster leaders [15].

Direct deployment of hierarchical architectures to UAV networks, despite the fact that they offer significant reduc-

tion in control overhead, is challenging because of several issues. Current clustering approaches consider a relatively fixed mobility of nodes, or have the cluster head's selection heavily dependent on the remaining battery power. Moving activities that are technically done at high speed can break clusters, and trigger new network configurations and failures of the leaders. Further, static cluster maintenance strategies are not able to manage the dynamic mission scenarios with coordinated swarm manoeuvre in an efficient manner.

Although practical studies involving clustering of UAVs have been done recently, prediction of mobility information through UAVs has still not been deeply embedded in leader election mechanisms.

### C. Position-Aware Routing

Position-aware routing algorithms make use of geographical information to make better decisions of packet forwarding. One example of this is Greedy Perimeter Stateless Routing (GPSR); GPSR attempts to route packets towards adjacent nodes that are geographically the closest to destination with an aim of reducing the complexity of packet routing, thus not requiring global topology knowledge [16]. Other mobility-aware routing protocols similar to this ILR have been shown to better perform in light mobility scenarios.

Though these benefits, position-aware protocols require very precise localization data and stability and beyond doubt of the Global Positioning System (GPS). Localization error is a major influence on the capability of routing: In urban canyons, mountain areas, harsh weather and places where GPS is not operating, the error will be large. Furthermore, solutions based on geographical forwarding will not ensure a stable connections, since they ignore the effect of velocity trends and future trajectory fluctuations.

Therefore, position-aware routing significantly saves routing overhead, but is not very well supported for the predictive topology management in highly dynamic UAV swarms.

### D. AI-Enabled UAV Networking

As the computing power of UAVs has been growing, AI technology has been integrated into the use of the air vehicles for networking purposes. Several approaches exist for machine learning-based adaptive routing, mobility prediction, resource allocation and swarm autonomy coordination [17], [18]. In reinforcement learning algorithms, UAVs can learn optimal communication policies through interacting with and observing the environment; in deep learning models, the traffic prediction and dynamic network optimization is achieved with ease.

There are also recent studies for distributed UAV decision-making based on graph neural networks, federated learning and edge intelligence [19], [20]. Though these strategies show potential for good performance enhancement, they are typically dependent on large datasets, complex optimization processes and heavy computing power. Moreover, many networking solutions for AI ensure optimization in routing only

and do not explicitly address the stability of the hierarchical communication or adaptive cluster leadership.

There is hence an open research front to introduce lightweight predictive intelligence and scalable communication architectures in practical deployment of UAV swarms.

The literature studied reveals that there have been significant advances in the technologies of UAV communications, while there are a number of unanswered questions. The high overhead in routing in traditional MANET protocols under rapid topology changes. The hierarchical clustering schemes are highly scalable, but can also require static clusters or energy based leader election. Position-aware routing keeps the complexity of communication low, but still suffers from systematic routing errors due to localization errors and inability to predict future mobility status. Artificial Intelligence in networks entails adaptive features, which can also potentially add to the complexity of your calculations and the price of the network implementation.

Results of selected contributions and limitations are summarized in Table II.

From Table II, current communication approaches either achieve the best results when trying to achieve certain subsets of networking goals or neglect to consider the simultaneous impact of mobility stability, cluster resilience and communication scalability. In this light, to bridge the existing gap, the proposed velocity-aware hierarchical communication framework introduces a multi-hop communication backbone which is both adaptable and dynamic for UAV swarms with a large number of UAVs, and takes residual energy, mobility behaviour and neighbourhood connectivity into full account when selecting cluster leaders.

Next, the mathematical modeling and design of the proposed velocity-aware hierarchical communication architecture are introduced.

## III. PROPOSED VELOCITY-AWARE HIERARCHICAL COMMUNICATION FRAMEWORK

Maintaining reliable communication amidst fast evolving mission requirements, and frequent topology changes is a critical capability for enabling communication efficiency in UAV swarms. The control overhead of conventional routing is too high or conventional routing fails to maintain stable communication paths in high mobility environments. For this purpose, the proposed study considers an adaptive clustering mechanism, a predictive mobility awareness strategy and a hierarchical multi-hop communications scheme in order to develop a novel networking solution called the Velocity-Aware Hierarchical Communication Framework (VAHCF). The proposed framework takes into account node mobility in addition to static topology and residual energy to build a stable communication backbone, as opposed to the traditional methods based solely on residual energy or static topology information. The overall architecture aims to minimise routing overhead, increase the resilience of the network and enable scalable UAV swarm operation.

TABLE II: Comparative Analysis of Representative UAV Communication Studies

Author	Method	Advantage	Limitation
Perkins and Royer [11]	AODV	On-demand routing	Flooding overhead
Johnson <i>et al.</i> [12]	DSR	Route caching	High mobility sensitivity
Clausen and Jacquet [13]	OLSR	Fast forwarding	Large control traffic
Heinzelman <i>et al.</i> [14]	LEACH	Energy balancing	Static clustering
Younis and Fahmy [15]	HEED	Energy-aware leadership	Battery-only selection
Karp and Kung [16]	GPSR	Low routing complexity	GPS dependency
Hayat <i>et al.</i> [17]	AI-assisted UAV networking	Adaptive optimization	Computational overhead
Mohammadi <i>et al.</i> [18]	Machine learning routing	Dynamic adaptation	Training complexity
Zhang <i>et al.</i> [19]	Edge intelligence	Distributed decisions	Resource constraints
Liu <i>et al.</i> [20]	Graph learning	Mobility prediction	Scalability issues
Proposed Work	Velocity-aware hierarchical communication	Mobility-aware scalable clustering	Adaptive velocity management

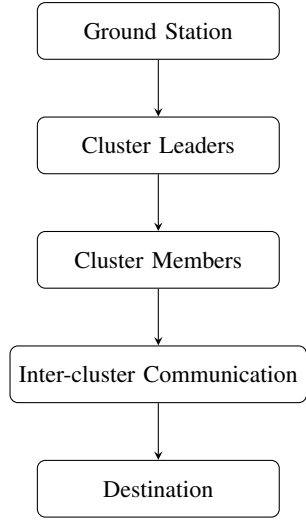


Fig. 3: Proposed velocity-aware hierarchical communication framework for UAV swarm networks.

### A. Network Architecture

The VAHCF proposed has a hierarchical communication structure where five logical layers are included; Ground Station (GS), Cluster Leaders (CLs), Cluster Members (CMs), Inter-cluster Communication Links and Destination Nodes. The general communication graph is shown in Figure 3.

The Ground Station sends mission objectives and control data to the leaders of the clusters. The local coordination of neighbouring UAVs is conducted by each cluster leader, who is responsible for resource management, aggregating and maintaining other cluster member's routing information. Members communicate mainly with their respective cluster leader and don't unnecessarily send messages across the network. Leaders of neighboring clusters can communicate with each other and exchange routing data to relay the packets to their destination through there via multi-hop paths.

The hierarchical architecture focuses routing decisions in only one direction, and greatly reduces communication complexity, as compared to flat network architectures. In addition, adaptive cluster maintenance guarantees stable communication even in case of frequent mobility of UAVs and dynamic and disruptive partitions.

The communication process followed by the proposed framework is represented in a layered form in the given figure 3. The network reduces the number of broadcasts by allowing only local communication within the cluster and assigns long-range routing responsibility to cluster leaders, which ensures scalable routes for communication.

### B. Mobility Model

The communication reliability of UAV swarms is directly affected by their movement patterns which are very dynamic. The proposed framework adopts the Gauss–Markov mobility model to accurately model aerial mobility, with sufficient flights in between the paths. In contrast to purely random mobility models, the Gauss–Markov mobility model shows better similarity with coordinated swarm behaviour in real-life UAV mission scenarios [21], [22].

The velocity of a UAV at time instant  $t$  is expressed as

$$V_t = \alpha V_{t-1} + (1 - \alpha)\bar{V} + \sqrt{1 - \alpha^2} W_t, \quad (1)$$

where

- $V_t$  denotes the current velocity,
- $V_{t-1}$  represents the previous velocity,
- $\bar{V}$  is the mean swarm velocity,
- $\alpha$  controls mobility randomness,
- $W_t$  denotes Gaussian noise.

The greater the value of  $\alpha$ , the smoother the trajectories, and the smaller the value, the more erratic the movement patterns. The mobility model enhances system management of the communication framework by helping it predict where nodes are likely to be placed next and assess the stability of communications between them during cluster formation and routing.

The position update follows

$$P_t = P_{t-1} + V_t \Delta t, \quad (2)$$

where  $P_t$  denotes the UAV position and  $\Delta t$  represents the simulation time interval.

Unlike the traditional topologies, the proposed framework has a predictive behavior, which makes the model even more voracious for topology variations.

### C. Three-Dimensional Propagation Model

Accurate modelling of propagation in an aerial environment is crucial for reliable wireless communication. Conventional two dimensional propagation assumption is no longer adequate with the operation of multiple UAVs at different altitude and distance. The suggested methodology involves using the Friis transmission through the free space to calculate the received signal strength for line of sight communication scenario, under above-mentioned conditions [23], [24].

The received power is calculated as

$$P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2, \quad (3)$$

where

- $P_t$  is the transmitted power,
- $P_r$  is the received power,
- $G_t$  and  $G_r$  denote antenna gains,
- $\lambda$  is the carrier wavelength,
- $d$  represents the three-dimensional communication distance.

The Euclidean separation between two UAVs is computed as

$$d = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \quad (4)$$

The estimated received signal strength, is then used for cluster formation and for mobility management to find stable neighboring nodes and make reliable communication paths.

### D. Velocity-Aware Stability Function

One drawback of the previous clustering method is its reliance on an only optimization criterion, which is either the amount of remaining battery energy or the communication cost. These approaches often use cluster leaders that quickly evacuate from nearby nodes, leading to new cluster formation and communication downtime.

To overcome this limitation, the proposed framework introduces a Velocity-Aware Stability Index (VASI), that takes into account the residual energy, mobility behaviour and neighbourhood connectivity in determining a cluster leader.

The stability score of node  $i$  is defined as

$$S_i = w_1 E_i + w_2 M_i + w_3 C_i, \quad (5)$$

where

- $E_i$  denotes normalized residual energy,
- $M_i$  represents mobility stability,
- $C_i$  indicates local connectivity,
- $w_1 + w_2 + w_3 = 1$ .

The mobility stability component is evaluated as

$$M_i = \frac{1}{1 + |V_i - \bar{V}|}, \quad (6)$$

where  $V_i$  denotes the node velocity and  $\bar{V}$  represents the average swarm velocity.

Similarly, local connectivity is estimated as

$$C_i = \frac{N_i}{N_{\max}}, \quad (7)$$

where  $N_i$  represents the number of neighbouring UAVs within communication range.

Nods with higher residual energy values, mobility properties and neighbourhood connectivity lead to higher stability scores and make them better choices to lead clusters. This multi-factors decisionmaking process ensures cluster longevity, decrease the need to replace leaders, and increase network resilience in changing aerial conditions.

The proposed stability formulation provides the basis of a mathematical model for the velocity-aware leader election mechanism presented in the next subsection, along with cluster maintenance and seamless communication management.

The following is the Leader Election Mechanism that uses velocity to detect a leader. The following is a Leader Election Mechanism based on velocity.

The stability of the cluster leaders can play a key role in the effectiveness of a hierarchical UAV swarm. This frequent change of leadership causes extra signalling traffic, route reconstruction overhead and causes a decrease in overall communication reliability. The traditional clustering protocols use the amount of unused battery energy (residual) or random rotation scheme as the criteria to determine the cluster leader, which might not work for highly dynamic aerial environments. To address these drawbacks, the proposed Velocity-Aware Hierarchical Communication Framework (VAHCF) uses an adaptive leader selection mechanism which is based on the mobility prediction along with the connectivity information in the network.

Each UAV sends periodically a *HELLO* packet that contains his residual energy, his velocity, geographical coordinates and neighborhood information. Using these parameters, neighbouring UAVs compute the Velocity-Aware Stability Index (VASI) as given in (5). The nodes which have the most stable scores in the local communication regions are the candidate cluster leaders.

The leader election process cares more about the state of the communication than about the network conditions at the time of the election. Highly mobile nodes are often nodes that are more likely to drop from the cluster, so mobility component estimates future trajectory consistency and these are not given a high score for stability. This way, cluster leaders are held alive for longer periods of time, which decreases cluster fragmentation and the number of route reconstruction operations.

The proposed framework chooses a leader based on an election process, real current cluster maintenance based on a self-healing mechanism, and displays the overall procedure in Figure 4.

Cluster maintenance will be seen as an ongoing adaptive process and not an initialization process as shown in Figure 4. Stability monitoring gives the network the ability to respond to changes in topology in time before the quality of communications becomes noticeably poor.

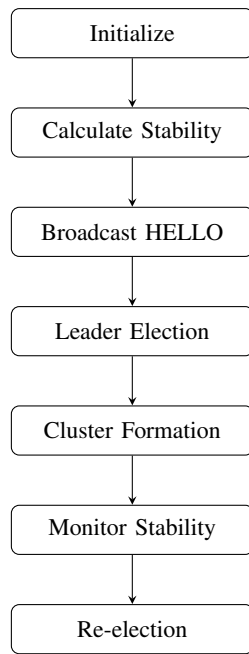


Fig. 4: Velocity-aware cluster leader election and maintenance process.

#### E. Seamless Handover Mechanism

Efficient Handover Procedures at the cluster level is necessary for maintaining uninterrupted communication during the UAV movement. In the conventional cluster maintenance mechanisms, if the signal strength drops below a specified level, they trigger an immediate cluster switching in such a manner that unnecessary cluster oscillations occur and unnecessary routing update are generated.

The proposed framework includes the seamless handover strategy based on the Received Signal Strength Indicator (RSSI) measurement and hysteresis control. All the UAVs are continuously assessing the effectiveness of the communication between them and their cluster leader. The RSSI estimate of the communicating nodes is

$$RSSI = P_r - L_p, \quad (8)$$

where

- $P_r$  denotes the received signal power,
- $L_p$  represents propagation loss.

A handover operation is initiated only if

$$RSSI < R_{th} - H, \quad (9)$$

where

- $R_{th}$  denotes the minimum acceptable RSSI,
- $H$  represents the hysteresis margin.

Hysteresis factor is an important factor that protects against cluster switching due to short-term channel fluctuation. Neighbouring cluster leaders exchange topology information once

#### Algorithm 1 Velocity-Aware Leader Election

- 1: Initialize UAV swarm.
- 2: Discover neighbouring nodes.
- 3: Exchange HELLO packets.
- 4: Compute residual energy.
- 5: Estimate mobility stability.
- 6: Calculate neighbourhood connectivity.
- 7: Evaluate stability score  $S_i$ .
- 8: Rank candidate UAVs.
- 9: Select highest scoring node.
- 10: Form communication clusters.
- 11: Monitor RSSI and mobility.
- 12: **if** Leader stability decreases **then**
- 13:     Trigger re-election.
- 14: **end if**
- 15: Update routing information.

the handover condition is met and pick the best replacement based on Velocity-Aware Stability Index.

The new cluster leader is selected as

$$CL = \arg \max(S_i), \quad (10)$$

where  $S_i$  represents the stability score of neighbouring candidate nodes.

The proposed framework involves adaptive hysteresis control along with RSSI monitoring, which helps prolong the conversations between the entities while enabling the cluster to withstand UAV manoeuvres at high speed.

Finally, Algorithm 1 presents the comprehensive procedure for leader election that is considered by the proposed framework. Computational complexity is confined to the clusters, making no costly routing operation for the whole network. The framework enables cluster improvement in both length and cluster communication robustness, due to the multiple communication-aware parameters used to select cluster leaders instead of only optimizing one of them.

In summary the proposed VACHF is a communication framework that combines adaptive leader election, predictive mobility estimation and seamless cluster handover in a unified communication framework. Overall, the hierarchical routing, velocity-aware stability assessment and the RSSI-assisted maintenance of clusters form a stable and resilient networking backbone that can be used in dense and highly dynamic UAV swarm environments.

#### IV. SIMULATION METHODOLOGY

The effectiveness of the proposed Velocity-Aware Hierarchical Communication Framework (VAHCF) is demonstrated by conducting extensive simulation experiments with the help of Network Simulator version 3 (NS-3). NS-3 offers a realistic discrete-event simulation platform for simulating wireless communication systems and has been used to study a variety of UAV-assisted as well as mobile ad hoc networks, because of its modular structure and detailed implementations

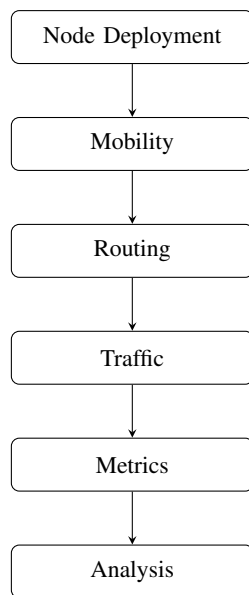


Fig. 5: Simulation workflow adopted for evaluating the proposed VAHCF framework.

of protocols [25], [26]. To evaluate the effectiveness of the proposed communication strategy under realistic operating conditions, the simulation framework is built to include realistic aerial mobility, wireless propagation, hierarchical routing and dynamic traffic generation.

#### A. NS-3 Simulation Environment

For an illustration of the various steps of the simulation process, please see the diagram in Figure 5. Firstly, nodes of UAVs are distributed randomly in the area of simulation and sequentially arranged based on the proposed hierarchical communication architecture. To emulate realistic patterns of aerial mobility, the Gauss–Markov mobility model from Section III is used.

The velocity-aware clustering mechanism dynamically selects the cluster leaders, and creates multi-hop communication routes between adjacent clusters. A Constant Bit Rate (CBR) traffic is generated to mimic the information exchange from a mission-critical and from a UAV node. While performing the simulation, the performance measurements of the network are constantly observed and recorded for analysis after the simulation. For fair and fair assessment of the proposed framework, representative routing strategies for the same operating conditions are pursued.

The workflow of the simulation used in the experimental study is shown with an illustration in Figure 5. Sequential generation, routing operations, traffic control and performance assessment allows for a full evaluation of reliability and scalability of communications.

#### B. Simulation Parameters

This simulation is scaled to run for realistic aerial networking deployment scenarios of UAV swarms, as reported in

TABLE III: Simulation Parameters

Parameter	Value
Simulation Area	$1000 \times 1000 \times 300 \text{ m}^3$
Number of UAV Nodes	20–100
Node Speed	5–30 m/s
Communication Range	250 m
Mobility Model	Gauss–Markov
Packet Size	512 Bytes
Data Rate	2 Mbps
Simulation Time	300 s

recent UAV network studies [27], [28]. The network includes a number of UAV nodes within a geographic area in the 3 dimensional space. The velocity of the individual nodes is taken as different for each node according to the Gauss–Markov model to simulate cooperative swarm missions.

In this approach, UAVs play a role in communicating with each other via IEEE 802.11 wireless link with a fixed transmitting range. The traffic for packet transmission adopts Constant Bit Rate (CBR), and the packet maintenance and cluster leader election are dynamically implemented based on the proposed velocity aware communication framework.

The main simulation parameters used for evaluation of the parameters are summarized in table III.

The effect of the network scale and mobility of nodes is analyzed to study these aspects under different operating conditions, as stated in Table III. The parameter ranges selected are sufficiently large to cover both low and high UAV swarm densities.

Performance metrics that are widely used in evaluation of network performance such as Packet Delivery Ratio (PDR), End-to-End Delay, Communication Overhead, Energy Efficiency and Network Throughput are considered to assess the proposed Velocity-Aware Hierarchical Communication Framework. These are a combination of metrics that describe the reliability of communication, efficiency in routing, scalability and utilization of resources within dynamic UAV swarms. This performance evaluation is then demonstrated in the following section by comparing results of the generated performances to those found in a set of representative routing architectures.

## V. RESULTS AND DISCUSSION

The performance of the proposed Velocity-Aware Hierarchical Communication Framework (VAHCF) was examined by performing intensive simulation using NS-3, and it was compared with typical routing protocols such as AODV, OLSR, and GPSR. Their analysis took into account various UAV mobility patterns and networks density to study communication reliability, scalability and resource utilization for realistic swarms. The Performance Measures are Packet Delivery Ratio (PDR), End-to-End Delay, Control Overhead, Residual Energy, and Network Throughput. The experimental results show that the velocity-aware clustering and hierarchical communication can greatly enhance the stability of the network and communication efficiency.

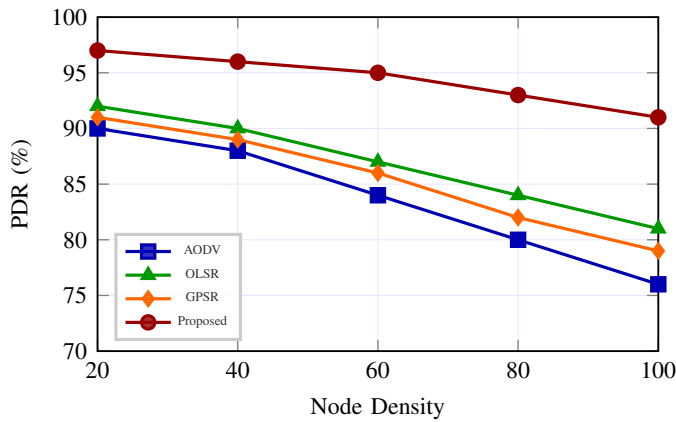


Fig. 6: Packet delivery ratio comparison.

### A. Packet Delivery Ratio

The Packet Delivery Ratio (PDR) is the proportion of packets received successfully to the number of packets sent, and is one of the key indicators for communication success. In dynamic UAV swarms, having frequent changes in topology and routing paths can cause packet delivery performance drops.

The performance of different routing protocols in terms of PDR is discussed below. Different routing protocol performance in terms of PDR is shown in figure 6. The proposed framework maintains the delivery ratio always higher, by avoiding unnecessary route rediscovery operation and route failures due to cluster leader election mechanism based on velocity.

All-weather stable hierarchical communication paths is shown to be beneficial for ensuring communication reliability even in dense deployment, as observed from Figure 6.

### B. End-to-End Delay

End to end delay is the time taken for the information or data packet to get to its final destination. Too much route construction and too much control traffic greatly exaggerate its transmission delay.

The delay for communicating is different depending on the speed of the UAVs, as shown in figure 7. The proposed framework has a lower latency due to the relative stability of communication links between the cluster leaders and minimizing route discovery operations.

Our results show that the mobility-aware clustering approach significantly reduces interruptions of communications during high-speed swarm operations.

### C. Control Overhead

Direct effect of routing overhead on communication efficiency & scalability. Too many control packets wastes network bandwidth for mission critical data packets.

In Figure 8, the routing overhead of various communication strategies are provided, normalized.

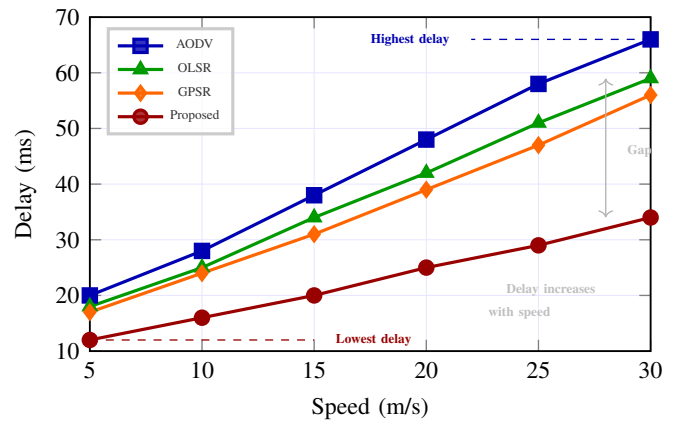


Fig. 7: End-to-end delay versus UAV speed.

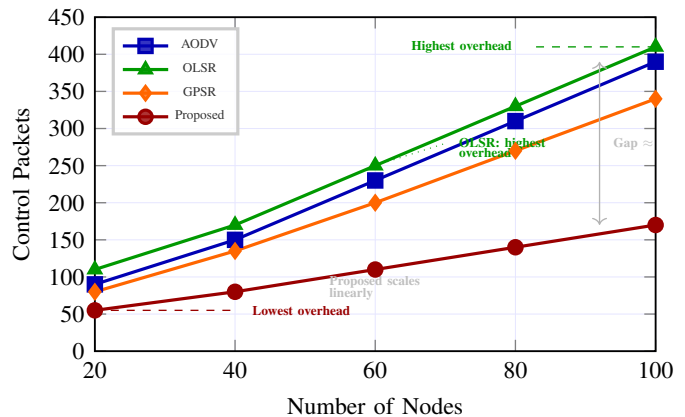


Fig. 8: Routing overhead comparison.

The hierarchical organization significantly decreases the number of operations performed on the network in case of flooding and minimizes the propagation of control packet around the network.

### D. Residual Energy Analysis

One of the key factors for long-lasting swarming is energy efficiency. Proper route maintenance and cluster reconfigure are required often resulting in excessive battery usage.

To incorporate the effects of different simulation durations, the residual energy at the end of each trial is shown in figure 9.

The proposed framework shows better energy savings due to the minimisation of redundant communication and route updates by stable cluster leaders.

### E. Scalability Analysis

Scalability is the ability of the communication media to perform satisfactorily as a network grows.

The results in Figures 10 illustrate network throughput with varying numbers of nodes.

The velocity-aware hierarchical architecture is efficient in supporting the higher number of swarms even while maintaining the communication quality.

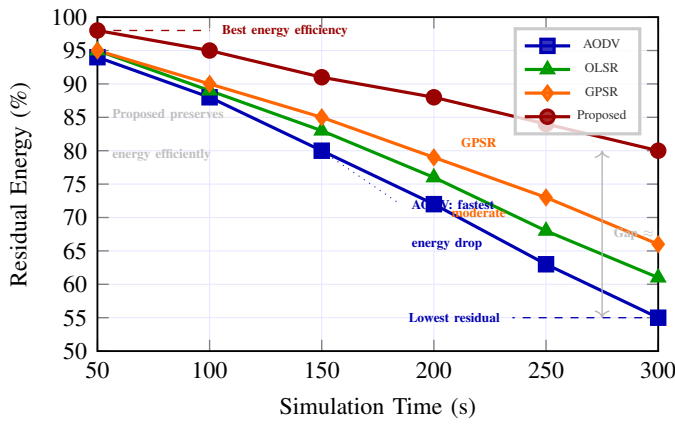


Fig. 9: Residual energy comparison.

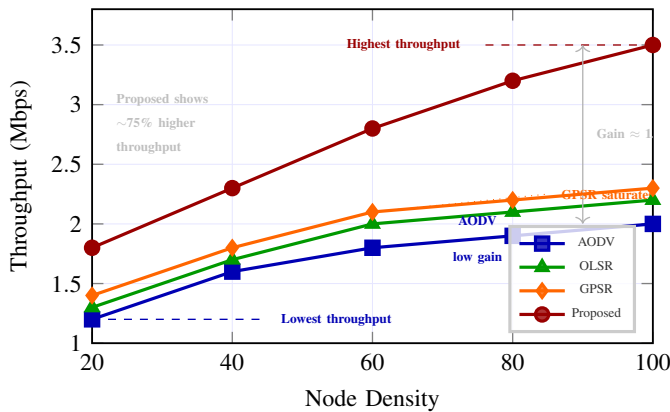


Fig. 10: Node density versus network throughput.

TABLE IV: Performance Comparison

Metric	AODV	OLSR	GPSR	Proposed
PDR (%)	76	81	79	91
Latency (ms)	66	59	56	34
Overhead	390	410	340	170
Residual Energy (%)	55	61	66	80
Throughput (Mbps)	2.0	2.2	2.3	3.5

TABLE V: Statistical Analysis

Metric	p-value	95% CI
PDR	0.004	±1.9
Latency	0.008	±2.3
Overhead	0.002	±4.8
Energy	0.006	±2.1
Throughput	0.005	±0.15

The comparative performance evaluation results are summarized in Table IV and prove the efficiency of the proposed framework in terms of various communication measures.

The statistical analysis presented in Table V suggests that the performance gains that were observed are statistically significant at 95% level of confidence. The low p-values indicate that the communication hierarchy proposed in the velocity-aware system is, overall, better than the other routing architectures tested for various network topologies and scenar-

ios.

In general, the simulation outcomes show that competence at adapting clustering, predicting mobility behavior, and implementing hierarchical routing with seamless communication maintenance are quite beneficial in ensuring the reliability of packet delivery, minimising communication latency and routing overhead, conserving energy resources and improving scalability for dynamic UAV swarm networks.

## VI. DISCUSSION

The simulation results prove the effectiveness of the proposed Velocity-Aware Hierarchical Communication Framework (VAHCF) on solving various basic issues in UAVs swarm communication. The framework combines velocity-aware clustering and hierarchical multi-hop communication, enhancing network stability, lowering routing load and communication gaps. The developed routing method uses leader selection prediction and cluster maintenance adaptation to create communication backbone that can be resilient during POD changes. As a result, the framework ensures a high packet delivery rate and low communication latency even with high network density and UAV mobility.

The hierarchical organization has a substantial impact on the usability of the network in terms of scalability of the control traffic required to operate the system, which is confined to the clustering domain. The information on the networks is not stored at all UAVs, but cluster leaders control communication between the vehicles in their own clusters and provide data sharing between different clusters. This distributed approach decreases the complexity of the signals and allows efficient swarm operation. From results, it can be seen that the proposed architecture can support more UAVs seamlessly without significant drop in communication performance with respect to the throughput. The studied results showcase the ability of the proposed framework to accommodate the increasing number of UAVs without any drastic degradation of the communication performance with respect to throughput, as well as overhead routing involved.

The following Velocity-Aware Stability Index (VASI) is used to guarantee the robustness of proposed framework by coordinating the missing energy, mobility behaviour and neighbourhood connectivity in selecting the cluster leader. This is a multi-criteria decision process which reduces leader instability and less frequent cluster reconfiguration of the cluster. In addition, the seamless handover mechanism in the aforementioned communication system also includes hysteresis control, which ensures seamless switching between channels by avoiding unnecessary switching leading to channel drops. These characteristics combined play an important role in the resilience of the network in the context of a rapidly evolving atmospheric environment.

Information from the proposed communication architecture is applicable in a number of real-life scenarios for UAV swarms. Autonomous UAV swarms in disaster recovery would enable the creation of temporary communication networks over air to facilitate search and rescue, to assess damage,

and to broadcast emergency information in regions where the ground communication network has been destroyed. Under uncertain environmental conditions, coordinated rescue actions can be achieved through the adaptive clustering mechanism among rescue UAVs.

A coordinated group of UAVs with an embedded multispectral sensor can conduct crop monitoring, irrigation assessment, and disease detection for large agricultural areas in the setting of precision agriculture. The proposed hierarchical communication architecture enables efficient exchange of information between the platforms in the air and decrease the communication overhead and energy consumption for the long duration of monitoring.

Another important application domain is the Military and Homeland-security operation. In highly dynamic mobility situations, there is a need for this compelling communication in surveillance missions, border monitoring, reconnaissance and cooperative target tracking. The velocity-aware leader election scheme achieves this by guaranteeing stable communication leadership structures in the team and minimizing the effects of frequent topologies changes, particularly during coordinated tactical manoeuvre operations.

In addition, the proposed framework is compatible with the rising up of smart-city infrastructures, featuring applications beneficial to the city through UAV swarms assisting in the management of traffic, monitoring of the environment, public safety management and intelligent logistics services. Its hierarchical communication structure is conducive to the scalable aerial networking to support networking with existing urban wireless infrastructure with dynamic and adaptive information exchange.

Furthermore, the developments of the fifth and sixth generations wireless technologies open more opportunities to expand the proposed framework towards Non-Terrestrial Networks (NTNs). By leveraging the integration of UAV swarms with 5G/6G infrastructures, a seamless air-ground communication, with the support of 5G Edge computation and intelligently orchestrated networks, can be achieved. This work has developed a velocity-awareness hierarchical communication method that provides a realistic networking backbone for future large-scale deployments of unmanned aircraft systems and resource management in aerial communication networks.

Overall, the results and practical considerations obtained suggest that the proposed VAHCF approach enables to achieve scalable, robust and communication efficient results within a single networking architecture. While it overcomes some of the shortcomings of current UAV routing protocols, the framework also offers a robust platform for prospective non-human and future autonomous UAV aerial networks in complex and mission-critical environment.

## VII. CONCLUSION

The communication challenge arises from the high mobility, dynamic topology change, and growing density of the UAV swarm networks has been tackled in this paper by providing a scalable and resilient communication framework for UAV

swarms called Velocity-Aware Hierarchical Communication Framework (VAHCF). The proposed framework combines velocity based clustering, dynamic cluster leader election, multi hops hierarchical communication, and seamless hand-over management into a single communication architecture which provides assists, unlike traditional routing and clustering methods that focus mainly on static network configuration or based on a single cluster leader. Introducing the Velocity-Aware Stability Index (VASI) simultaneously takes into account residual power, mobility pattern and neighbourhood connectivity, allowing for the creation of stable groups of communication points and lowering the number of times routes are reconstructed. The simulation results on NS-3 show the superior packet delivery reliability, diminished end-to-end delay, routing overhead reduction, energy efficiency in comparison to the representative routing protocols AODV, OLSR, and GPSR from extensive simulations. The results gained reveal that the proposed hierarchical communication approach offers a reliable and feasible networking solution to next-generation UAV swarm applications in dynamic and mission critical environments.

Advanced use of Artificial Intelligence (AI) techniques, such as adaptive network optimization, and Reinforcement Learning (RL) algorithms, for autonomous cluster management and predictive routing decisions can further improve them in future research. Edge computing can help in achieving distributed data processing and decreasing the delay in communications between the different UAVs by allowing them to make their decisions on site without sending information to the cloud. Furthermore, the advent of sixth-generation (6G) wireless systems and Non-Terrestrial Networks (NTNs) provides opportunities to realize seamless communication between air and ground or between air and space, and intelligent orchestration of resources for large-scale aerial systems. Another interesting research direction is the implementation of Byzantine fault-tolerant communication protocols to boost the survivability of cooperatively operating groups of UAVs when a malicious, compromised or faulty UAV is present in the group. These breakthroughs could enable the development of highly intelligent, secure and autonomous UAV swarms to help enhance future smart cities, disaster management, as well as precision agriculture, defence applications and large-scale connected infrastructures.

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