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RESEARCH ARTICLE

# On the Weighted Cluster S-UAV Scheme Using Latency-Oriented Trust

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**ABSTRACT** Drones, also known as unmanned aerial vehicles (UAVs), have become increasingly popular in the military and civil sectors. A swarm of UAVs (S-UAVs) is a group of UAVs that work together to complete a task. Because of the dynamic network topology of S-UAVs, routing schemes are complicated. Clustering is one of the most effective routing schemes for improving the performance of ad-hoc networks. The clustering scheme divides the network into groups known as clusters, each consisting of a cluster head (CH) and cluster members (CMs). The CH is a valuable element in the clustering scheme because it handles all inter- and intra-cluster communications. Proper selection of the CH is the key to enhancing the performance. Our study proposed a new clustering scheme for S-UAVs. Our scheme selects the CH and CMs based on a new weighted formula that consists of the following parameters: distance, speed, and reward index. The reward index is a newly calculated parameter based on latency. The weighted formula calculates the clustering index based on which CH and CMs are selected. This scheme was simulated using MATLAB to demonstrate its performance as a routing scheme. The simulation analyzed the latency due to the variation of the network's parameters. In addition, the rewarding index and cluster index were analyzed. Finally, the proposed scheme was compared with an existing scheme known as the adaptive enhanced weighted clustering algorithm for UAV swarm. The comparison demonstrates that the proposed protocol is promising due to its lower-generated delays. The obtained results are displayed and analyzed towards the end of this paper, along with some ideas for future work.

**INDEX TERMS** Cluster head, clustering scheme, clusters, cluster member, drone, latency, swarm, rewarding index, UAV.

## I. INTRODUCTION

A swarm of Unmanned Aerial Vehicles (UAVs) consists of aerial robots, known as drones. Drones with dedicated data collection and processing tasks fly to execute tasks in real-time [1]. A swarm of UAVs has advantages such as scalability, survivability, mission speed, and cost [2], [3]. In recent years, UAVs have overwhelmed several sectors of everyday life. Al-Naji et al. proposed using UAVs to find people in danger when disasters, such as floods, earthquakes, landslides,

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and snow slides, occur [4], [5]. Drones are also widely used in military tasks, such as weapons delivery, guided missiles, directing artillery, and spotting enemy positions [6].

A swarm of UAVs has two types of communication. The first type is UAV-to-UAV communication, in which UAVs can communicate directly or indirectly to form a multi-hop communication. The second type, UAV-to-infrastructure communication (U-T-I), is direct communication between UAVs and a fixed control center known as the base station [7], [8], [9]. A swarm of UAVs can have either centralized or decentralized communication. In centralized communication, a fixed central node represents the infrastructure and communicates with all UAVs via a one-to-one relationship. The action of neighboring nodes eliminates the communication range in a decentralized communication known as ad-hoc communication [10], [11]. Ad-hoc communication is the preferable type of communication because the network in a swarm of UAVs is highly vulnerable to disconnections. UAV communications are classified into either a single UAV, where the UAV relates to a ground station, or multi-UAVs, where several UAVs relate to different topologies, such as star, mesh, or cluster-based topologies [12], [13]. The International Telecommunication Union (ITU) dedicated specific segments for UAV communication. The L-band segments range from 960 to 977 MHz, while the C-band segments range from 5030 to 5091 MHz [14]. Cluster-based topologies are widely used in ad-hoc networks because they combine proactive and reactive routing schemes while taking advantage of both. Clustering schemes can also provide hierarchical network structures. A hierarchical network based on the clustering mechanism is commonly recommended in a dynamically changing environment with mobile nodes owing to its improved performance [15]. The clustering approach increases network scalability, decreases overhead, maximizes throughput and increases battery lifetime [16]. Each clustering scheme groups nodes differently based on unique parameters and algorithms. These parameters include residual energy, distance from the cluster centroid, node mobility, node velocity, node direction, node performance, and node concentration [17]. Each cluster is formed by one cluster head (CH), the leader node, and several cluster members (CM). The CH is responsible for inter-cluster and intra-cluster communication. Cluster formation and CH selection can significantly affect a network's communication performance; therefore, it is a continuous and challenging field of research.

This paper proposes a new clustering scheme that selects CH and CMs based on a weighted formula. The weighted formula used in the proposed scheme includes a newly added latency parameter. Latency is used to reflect the performance of nodes. Proactive nodes with a low latency index are more likely to be selected as a CH owing to the CH's responsibility for all intra-cluster communication. The two other parameters used in the weighted formula were distance and speed.

The third section covers the mathematical aspects of the proposed scheme, which were simulated using MATLAB. The simulation covered in the fourth section of this paper proves that the weighted formula used in CH and CMs selection has a high impact. Three weighted cases were studied, which resulted in different cluster formations. It is important to mention that the weights are to be defined depending on the network architecture; for example, in a highly dynamic network, the weight of the velocity will be higher; in highly disconnected networks, the index of the reward will be higher; and in high-density networks, the weight of the distance will be higher. The proposed scheme was also compared to a scheme known as the adaptive enhanced weighted clustering algorithm for UAV swarms. The two schemes were compared for the total delays generated for 100 packets. Our proposed scheme shows, on average, lower total delays than other schemes.

The clustering scheme in a swarm of UAVs is extremely challenging owing to its special features, such as the range of communication, velocity, collisions, dynamic topology, and external interference factors such as wind. Identifying the subgroup structures of clusters using CH and CMs selection is challenging. The authors in [18] proposed a network-integrated trajectory clustering algorithm (NIT) that achieves fast and accurate identification of a swarm of UAVs. The proposed algorithm can distinguish between trajectories and variations in their trends. In [19], Clustering Particle Swarm Optimization (CPSO) with an inertia weight factor and chaotic maps was proposed to improve performance. An optimized CPSO was also proposed in [20], which has an improved search mechanism that determines the best possible solution. The TCRP was proposed in [21], where the CH was chosen to have the minimum average distance from the rest of the vehicles. LEACH is a two-layered architecture in which sensors periodically elect themselves as a CH based on probability [22]. Other schemes, such as the SORI scheme, use reward concepts to encourage packet forwarding and discipline based on reputation systems. Another scheme that encourages truth-telling during CH selection is the Payment Punishment Scheme (PPS), in which the cluster collaborates with CMs to update reputation values [23], [24], [25]. Chunhua and Shouhong [26] proposed that UAVs cluster on the ground. Subsequently, based on the geographic information of the CH, it was selected to cover a defined zone. Zang et al. solved the cluster update problem using a tree structure, link failure time, and node movement [27]. In [28], the authors described a hierarchical swarm of drones as shown in Fig. In Fig. 1, a single-leader drone leads a cluster of subordinate worker drones denoted as Followers UAV. The leader drone, also known as the CH, uploads its collected data to the base station. The base station is connected to the internet; therefore, the data is uploaded to the operator. The mission's details are uploaded to the base station if the operator generates a mission. The leader UAV downloads the mission details from the base station and distributes them to the follower UAVs. The principle of Frequency Division (FD) is used to share the available spectrum for downlink (DL) transmission with several legitimate leader UAVs [29].

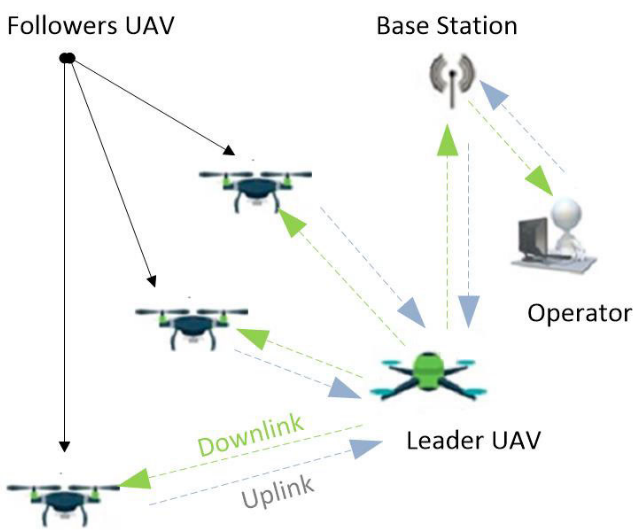


**FIGURE 1.** Hierarchical cluster for swarm of UAVs.

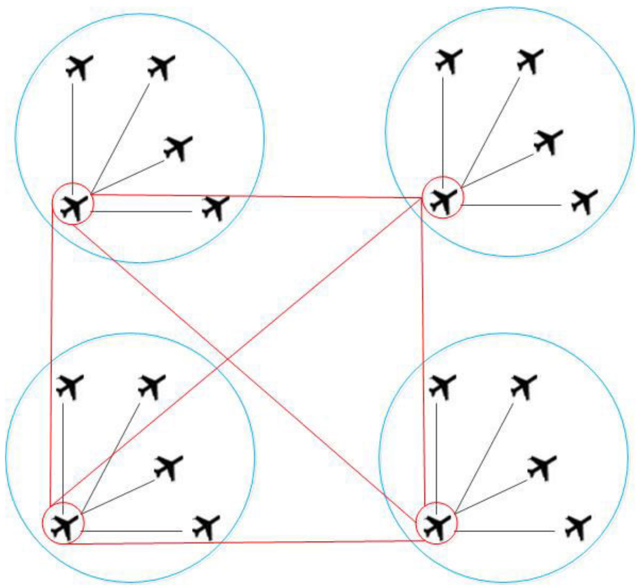

**FIGURE 2.** Complex hierarchical clusters for swarm of UAVs.

Hierarchy can become more complex when it consists of multiple clusters, as illustrated in Fig. 2. Each UAV in the cluster can directly communicate with other peers within the cluster, which is known as intra-cluster communication. Each member communicates with the immediate leader. The members had no access to anything outside the cluster. Only the CH or leader can communicate with people outside the cluster, referred to as inter-cluster communication. Inter-cluster communication may occur between the CH and another CH or between the CH and the base station [30].

## II. PAPER PROPOSAL

This study proposed a new clustering algorithm for swarms of UAVs. This study considered an ad-hoc network with single UAV-to-UAV communication. This scheme divides a swarm of UAVs into clusters based on the cluster index value. A cluster index was used to select the CH. The cluster index was calculated using a new weighted formula. The parameters considered in this formula are speed, distance, and reward index. The reward index is a new indirect method to determine the reward action of a node. It is rewarded when a node actively forwards packets with minimum latency.

Section three of this paper will discuss our proposed scheme using mathematical formulas and a detailed explanation of each step. Section four will cover the simulation results obtained using MATLAB and an analysis of the results obtained. The maximum delay was analyzed with the variation of initial packet time and the number of levels. The node's 1 delay, direct, indirect, and total trust were also analyzed. The cluster index variation was simulated with the variation of the weighted parameters. The last two figures compare the proposed protocol to other protocols regarding delay and the number of CH changes. Finally, this paper concludes with the outcomes and ideas for future research.

## III. WEIGHTED CLUSTER S-UAV SCHEME USING LATENCY-ORIENTED TRUST

This study considers a predefined network consisting of a swarm of UAVs. For this simulation, we consider a swarm consisting of 20 identical UAVs. The proposed scheme, the Weighted Cluster S-UAV, splits the 20 UAVs into clusters. This scheme calculates the cluster index based on which clusters are formed. In addition, this cluster index was used for CH and CM selection.

G(t), a time-varying graph, is used to represent a swarm of UAVs.

$$G(t) = \{U(t), E(t)\} \tag{1}$$

where:

- $U(t) = \{u_i | i = 1, 2, \ldots, n\}$ is a set of $n$ UAVs at time $t$
- $E(t) = \{e_{ij} | u_i \in U(t), u_j \in U(t)\}$ represents bi-directional broadband wireless links between UAVs at time $t$

As UAVs fly in the sky, each UAV will have a three-dimensional position consisting of the x, y, and z-axis positions. Therefore, the position of each UAV at time t should satisfy the following conditions.

$$q_i(t) \in R^3 \tag{2}$$

where:

- $q_i(t)$ represents the position of UAV $i$ at time $t$.

The distance between UAVs $i$ and $j$ at time $t$ can be calculated by using the variance between the two positions.

$$d_{ij}(t) = ||q_i(t) - q_j(t)|| \tag{3}$$

where:

- $d_{ij}(t)$ is the distance separating the two UAVs $i$ and $j$
- $q_i(t)$ and $q_j(t)$ are respectively the locations of nodes $i$ and $j$ at time $t$

As UAVs are generally equipped with a global positing system (GPS), the coordinate location of the UAV is available.

Based on the x, y, and z coordinate values, we can calculate $d_{ij}(t)$ as

$$d0_{ij}(t) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{4}$$

Due to the atmospheric layers' refractive effectiveness, the radio wave distance should be considered instead of the direct separation distance. In normal weather conditions, the radio wave extends the coverage radius by a factor of 4/3, resulting in the below radio wave formula [31]

$$d_{ij}(t) \approx 4.12\sqrt{d0_{ij}(t) - r} \tag{5}$$

where:

- r is the UAV's coverage radius

The UAVs constantly send HELLO packets separated by a constant interval of time. The HELLO packets are not forwarded by the UAVs, as doing so would deprive the UAVs of getting to know their neighbors. If a UAV receives two consecutive HELLO packets from the same sender UAV, then the sender UAV is a neighbor of the receiver UAV. The HELLO message includes the spatial location of the UAV, which is provided by the GPS [32], [33]. Therefore, the two UAVs are within communication range of each other, and they can forward the packets in a one-hop forwarding mechanism. In this case, the UAVs are denoted as neighbor nodes. Let $c_{ij}(t)$ be a boolean variable that represents whether $u_i$ and $u_j$ are neighbors. Therefore, the two UAVs are within communication range of each other, and they can forward the packets in a one-hop forwarding mechanism. In this case, the UAVs are denoted as neighbor nodes. Let $c_{ij}(t)$ be a boolean variable that represents whether $u_i$ and $u_j$ are neighbors.

$$c_{ij}(t) = \begin{cases} 1 & \text{if } e_{ij} \in E(t) \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where:

- $e_{ij}$ is the connection status between UAV $i$ and $j$ at time $t$
- E(t) represents all the edge connections between the UAV nodes at time $t$

At time t, N(t) represents the set of UAVs that are neighbors, thus having $c_{ij}(t) = 1$. Therefore:

$$N(t) = \{u_j | c_{ij} = 1\} \tag{7}$$

Since the UAVs are desired to stay within sight of each other at any moment, the line-of-sight relationship can be used to calculate the maximum separation distance depending on the coverage radius [34].

$$\frac{\pi d_{ij}}{9ln(10)r} + \frac{\eta LOSexp[-arctan(\frac{d_{ij}}{r}) - 1]}{[exxp(-arctan\frac{d_{ij}}{r})]^2} = 0 \tag{8}$$

The network can be represented by an n x n grid displaying the neighbor status based on N(t). Fig. 3 shows the neighbor status of ten nodes. The ten nodes considered were a subset of the 20 nodes used in the simulation. The nodes are represented identically in both rows and columns. Nodes

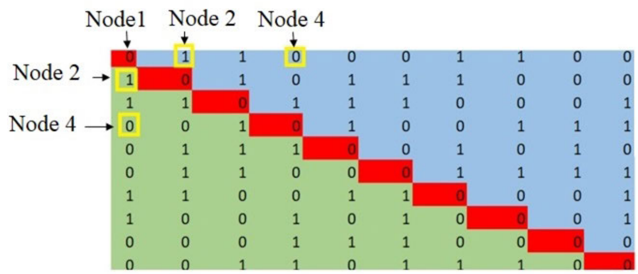


**FIGURE 3. Neighbor status of node 1 with nodes 2 and 4.**

$n$ and $m$ are neighbors when their intersection cell has a value of one. If their intersection cells have zero value, they are not neighbors. This n x n grid is a zero-diagonal symmetric matrix based on the nodes' neighboring relationships. As an example, let us examine the neighbor status of nodes 1 and 2. As shown in Fig. 3, the intersection cell of column 1 and row 2 is 1, which means that nodes 1 and 2 are neighbor nodes. The same can be deduced by examining the intersection of row 1 and column 2. Checking the neighbor status of nodes 1 and 4, represented by the intersection of column 1 and row 4, shows a value of 0, meaning that nodes 1 and 4 are not neighbors. As the grid is a zero-diagonal symmetric matrix, we can check the status of nodes 1 and 4 through the intersection of row 1 and column 4, which also has a value of 0, resulting in the fact that the two nodes are not neighbors.

A set of neighboring UAVs is denoted by S(t), representing a cluster. S(t) must follow the rules listed below to ensure that the set members are neighbors.

$$\begin{cases} S(t) \subseteq U(t) \\ S(t) \subseteq N(t) \\ \forall u_i \in S(t) \\ u_j \in S(t) \end{cases} \tag{9}$$

where:

- S(t) is the set of UAVs forming a cluster at time $t$
- U(t) is the set of UAVs at time $t$
- N(t) is the set of UAVs at time $t$ that are neighbors
- $u_i$ is any UAV at time $t$
- $u_j$ is any UAV at time $t$ such as $i \neq j$

The number of members within S(t) was limited to a maximum. $n_{max}$ is the maximum number of nodes within the cluster and is set based on the network constraints and size. Therefore, the number of members in S(t) is less than or equal to $n_{max}$.

A swarm of UAVs can be represented by a tree structure, as illustrated in Fig. 4. A tree structure is used to form the internal communication of our clusters based on the signal-to-noise ratio (SNR) [35].

$$SNR = \frac{P_{singal}}{P_{noise}} \tag{10}$$

The UAVs are classified into levels based on their highest SNR values. Thus, the UAVs at level 0 have the highest SNR value compared to those at level 1. The node at level 3 is the CH, also known as the leader. All the other nodes at levels 0,

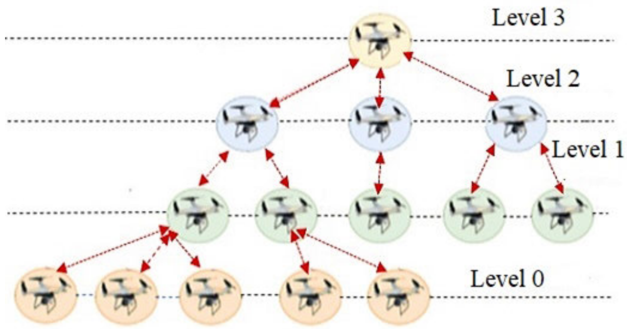


**FIGURE 4.** Tree hierarchy of Swarm of UAVs.

1, and 2 are CMs. Any node at level 0 should forward its packets to level 1, which forwards them to level 2. Packets at level 2 should finally be forwarded to level 3, the CH. The CH can communicate with the base station or other clusters' CH to upload the packets.

According to the authors of [36], a packet is formed with 48% overhead and 52% payload. In addition, only the payload is carried to the next packet, as the overhead is reduced. The identification and flags count for 4% of the original packet size, resulting in the addition of 56% of the original packet to the next forwarded packet. Therefore, as a generalized formula, the forwarded packet is:

$$Forwaded\ Packet\ Size = 0.56 * p \tag{11}$$

where:

- $p$ is the original packet size.

Therefore, as a generalized formula, the forwarded packet is:

$$Forwaded\ Packet\ Size = F_p * p \tag{12}$$

where:

- $F_p$ is the percentage of the packet forwarded to the next hop.
- $p$ is the original packet size.

In a tree-structure network, the transfer time $tt$ from one UAV to another is calculated as follows:

$$tt = nb_{maxn} * t \tag{13}$$

where:

- $nb_{maxn}$ is the maximum number of UAVs connected to the forwarded UAV
- $t$ is the transmission time of an original packet.

The total transfer time $TT$ is the sum of all the transfer times at each level, which can be calculated as follows:

$$TT = \sum_{i=0}^{n-1} tt_i \tag{14}$$

where:

- $tt_i$ is the transmission time at each level
- $n$ is the total number of levels within the tree

Based on the example considered in Fig. 4, the transfer time between UAVs from level 0 to UAVs at level 1, with a maximum of three UAVs sub-connected from level 1, is:

$$tt_0 = nb_{(max0)} * t = 3t \tag{15}$$

The transfer time between the UAVs at level 1 and the UAVs at level 2, with a maximum of two UAVs sub-connected from level 2, is 2t. Because 56% of the previous packet will be forwarded from level 0 to level 1, this will add up to 56% of the total number of packets forwarded, which is 5 in our example. Thus resulting in the following $tt_1$:

$$\begin{aligned} tt_1 &= 0.56t * nb_0 + nb_{(max1)} * t \\ &= 0.56 * 5t + 2t \\ &= 5.8t \end{aligned} \tag{16}$$

The same applies to the calculation of transfer time from level 2 to level 3

$$\begin{aligned} tt_2 &= 0.56t * (nb_0 + nb_1) + nb_{(max2)} * t \\ &= 0.56 * (5+5)t + 2t \\ &= 7.6t \end{aligned} \tag{17}$$

The same applies to the calculation of transfer time from level 3

$$\begin{aligned} tt_3 &= 0.56t * (nb_0 + nb_1 + nb_2) + nb_{(max3)} * t \\ &= 0.56 * (5+5+3)t + t \\ &= 8.28t \end{aligned} \tag{18}$$

Our simulation computes the maximum latency of packets sent from sender node $UAV_n$ to destination node $UAV_m$ at time $t$. As Equation (9) relies on the number of levels and a maximum number of sub-nodes, our simulation considers the case shown in Fig. 4 with four maximum levels and five maximum sub-nodes. Considering all levels to have five maximum sub-nodes will result in the worst-case scenario, which should be considered to have the maximum latency value.

$$\begin{aligned} t_{max(n,m)} &= \sum_{i=0}^{3} tt_i = tt_0 + tt_1 + tt_2 + tt_3 \\ &= nb_{(max0)}t \\ &\quad + (0.56t * nb_0 + nb_{(max1)}t) \\ &\quad + (0.56t * (nb_0 + nb_1) + nb_{(max2)}t) \\ &\quad + (0.56t * (nb_0 + nb_1 + nb_2) + nb_{(max3)}t) \\ &= 5t \\ &\quad + (0.56t * 5 + 5t) \\ &\quad + (0.56t(5+5) + 5t) \\ &\quad + (0.56t(5+5+5) + 5t) \\ &= 5t + 7.8t + 10.6t + 13.4t \\ &= 36.8t \end{aligned} \tag{19}$$

To assess the performance of each UAV, our scheme checks the packet latency. For each UAV in the network, we compared the latency of the packets forwarded from it to the maximum latency calculated using Equation (15). Therefore, as the data lifespan is critical, any packet with a latency greater than the maximum latency calculated in Equation (15) will be considered outdated and no longer useful. Therefore, comparing the latency of each packet to the maximum latency determines whether the packet is forwarded or dropped.

$$\begin{cases} t(n, m) \leq t_{\max(n,m)} \times \beta, & \textit{the packet is forwarded} \\ \textit{otherwise}, & \textit{the packet is dropped} \end{cases} \tag{20}$$

where:

- t(n, m) is the latency of a packet sent from $UAV_n$ to $UAV_m$.
- $t_{max\,(n,m)}$ is the maximum latency of packets sent from $UAV_n$ to $UAV_m$ based on Equation (15).
- $\beta$ is the threshold constant that varies between 0 and 1

$\beta$ is added to inequality (16) for the data lifespan, and it varies depending on the content of the data. For example, temperature information has a longer lifespan than location information because it requires a longer time to vary. Therefore, to reflect the data sensitivity of location, $\beta$ should be less than that used in the temperature-related packets. The lower the $\beta$ value, the more sensitive the data is and the shorter its lifespan. At time $t$, the total number of packets sent by all UAVs in the swarm is represented by:

$$y(t) = \sum_{i=1}^{G(t)} \sum_{j=1}^{G(t)} P \tag{21}$$

where:

- $i$ denotes the sender UAV
- $j$ denotes the receiver UAV such that $i \neq j$
- *G(t)* is the set of nodes in the network that are not necessarily neighboring nodes
- $P = 1$ to represent a packet sent from source $i$ to destination $j$

Based on Equations (16) and (17), we can deduce the number of packets being forwarded and the number of packets being dropped. The number of packets sent from UAV $i$ to UAV $j$ is considered forwarded, as represented in $f_{ij}$

$$f_{ij}(t) = \sum_{i=1}^{G(t)} \sum_{j=1}^{G(t)} P \tag{22}$$

such that

$$t_p(i, j) \leq t_{max}(i, j) * \beta \tag{23}$$

Based on the above forwarding or dropping decision, a new ratio value denoted as Direct Trust can be calculated [37]. Direct Trust represents the ratio of packets forwarded from the total number of packets sent from source $i$ to destination $j$.

$$Direct\ Trust_{(i,j)}(t) = \frac{f_{(i,j)}(t)}{y_{(i,j)}(t)} \tag{24}$$

A rewarding mechanism is a well-known procedure followed by several schemes to differentiate between the activities of the nodes as responsive or unresponsive, respectively. Several studies have proposed that cooperative nodes should be rewarded with a positive reputation for dealing with such behavior. In contrast, noncooperative nodes should have a negative reputation similar to the one proposed in the SORI scheme. Similarly, in our scheme, the nodes that forward packets within the maximum latency are rewarded, whereas the nodes that delay the packets and are thus considered to be dropped are not rewarded. The UAV's reward can be calculated as follows

$$R_i(t) = \sum_{i=1}^{G(t)} Direct\ Trust_{(i,j)} \tag{25}$$

such that

$$i \neq j \tag{26}$$

As the interference reward is set to have a certain level of impact depending on the network specifications, the total reward can be denoted as [38]

$$R_{Ti}(t) = \alpha R_{(i)}(t) \tag{27}$$

where:

- $\alpha$ is the reward weight that varies between 0 and 1.

As $\alpha$ approaches zero, it indicates that the reward mechanism does not have a significant impact on network decisions. Otherwise, when $\alpha$ tends toward 1, the reward mechanism significantly affects the network's decisions. There are better solutions than basing the reward on direct trust, as UAVs might act selfishly to increase their reward without being active and fair network members. Therefore, indirect trust is required to represent the trustworthiness of UAV $i$ concerning all the nodes within the network. Indirect trust is calculated based on the following:

$$Indirect\ Trust_{(i,j)} = \frac{\sum_{j=1}^{G(t)} Direct\ Trust_{(i,j)}}{Count\ G(t)} \tag{28}$$

where:

- $i$ is the trustor node (UAV calculating the trust)
- $j$ is the trustee.
- *G(t)* is the set of nodes in the network that are not necessarily neighboring nodes

To compensate for direct and indirect trust, their sum results in total trust.

$$Totalt\ Trust_{(i,j)} = \lambda * Direct\ Trust_{(i,j)} + (1 - \lambda) * Indirect\ Trust_{(i,j)} \tag{29}$$

where:

- The constant threshold, $\lambda$, varies between 0 and 1 to represent the weighted values of direct and indirect trust.

As $\lambda$ approaches zero, the reward mechanism is based on indirect trust rather than direct yrust. Otherwise, it is based more on direct trust. Based on Equation (25), Equation (23) can also be updated to reflect indirect trust, resulting in:

$$R_{Ti}(t) = \alpha(\lambda * Direct\ Trust_{(i,j)} + (1 - \lambda) * Indirect\ Trust_{(i,j)}) \tag{30}$$

Dividing a swarm of UAVs into clusters requires selection criteria for CMs and CHs. The proposed scheme considers a weighted formula to select the CH and CMs. The weighted formula results in a cluster index denoted as I. The parameters considered in this weighted formula are as follows:

- Distance: The closer the two nodes are, the higher the index of being in the same cluster.
- Reward index: The higher the reward index of the node, the higher the cluster index; thus, this node will be selected as the CH. The CH should have the best performance among the nodes to effectively handle inter-cluster communication.
- Velocity: The velocity has a negative impact because the faster the node, the faster its location varies. With a faster change in location, the node loses its connection with the CMs faster, resulting in disconnected CMs.

The weighted cluster index formula is shown in Equation (27).

$$I_{(i,j)} = (\mu D_{(i,j)} + \phi R_{(i,j)} - \psi V_{(i,j)}) * C_{(i,j)} \tag{31}$$

where:

- I(i, j) is the cluster index of node i with respect to node j such that $i \neq j$
- $\mu$, $\phi$ and $\psi$ are predefined constant values based on system requirements, such that

$$\mu + \phi + \psi = 1 \tag{32}$$

- D(i, j) represents the distance between the two UAVs *i* and *j*
- R(i, j) represents the reward index of UAV *i* with respect to UAV *j*
- V(i, j) represents the velocity of UAV *i* with respect to UAV *j*
- C(i, j) represents the neighbor index of UAV *i* with respect to UAV *j*

Let us break down the calculation of the elements in Equation (27). The distance is calculated using the previously discussed formula presented in Equation (4). The reward index is calculated based on the formula presented in Equation (26). The missing element is the velocity calculation. V(i, j) represents the relative velocity of UAV i with respect to UAV j and is calculated as follows [39].

$$V(t+1)_{(i,j)} = v(t)_{\ (i,j)} * \omega + a(t+1)_{(i,j)} \tag{33}$$

where:

- $V(t+1)_{(i,j)}$ is the new speed of UAV *i* with respect to UAV *j*
- $v(t)_{(i,j)}$ is the current speed of UAV *i* with respect to UAV *j*
- $\omega$ is the inertia factor
- $a\,(t+1)_{(i,j)}$ is the acceleration of UAV *i* with respect to UAV *j*

As the UAV moves in 3D space, as shown in Fig. 5, the velocity and acceleration are calculated based on the x, y, and z perspectives.

Based on the 3D geometry, the velocity of the UAV is split into three sub-vectors along x, y, and z. Therefore, $V_{UAV}$ can

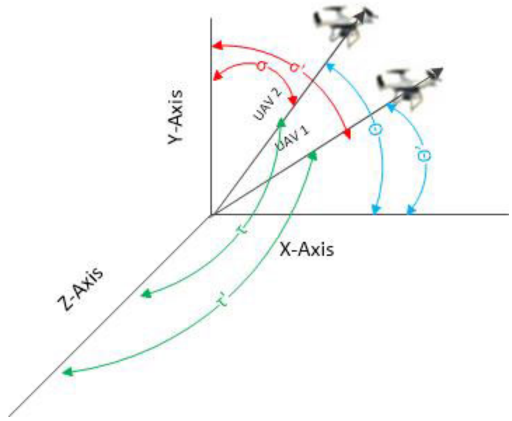


**FIGURE 5.** **UAV 3D velocity calculation.**

be represented as:

$$\overrightarrow{V_{UAV}} = \begin{cases} V_x \\ V_y \\ V_z \end{cases} \tag{34}$$

Based on Fig. 5

$$\overrightarrow{V_{UAV1}} = \begin{cases} V_{x1} \\ V_{y1} \\ V_{z1} \end{cases} \tag{35}$$

and

$$\overrightarrow{V_{UAV2}} = \begin{cases} V_{x2} \\ V_{y2} \\ V_{z2} \end{cases} \tag{36}$$

where:

- $V_{x1} = V_{UAV1} * \cos\theta'$ and $V_{x2} = V_{UAV2} * \cos\theta$
- $V_{y1} = V_{UAV1} * \cos\sigma'$ and $V_{y2} = V_{UAV2} * \cos\sigma$
- $V_{z1} = V_{UAV1} * \cos\tau'$ and $V_{z2} = V_{UAV2} * \cos\tau$

Based on the 3D geometry, the velocity of the UAV is split into three sub-vectors along x, y, and z. Therefore, $V_{UAV}$ can be represented as:

$$V(t)_{i,j} = \begin{cases} V_{xi} - V_{xj} \\ V_{yi} - V_{yj} \\ V_{zi} - V_{zj} \end{cases} = \begin{cases} V_{UAVi} * cos\theta' - V_{UAVj} * cos\theta \\ V_{UAVi} * cos\sigma' - V_{UAVj} * cos\sigma \\ V_{UAVi} * cos\tau' - V_{UAVj} * cos\tau \end{cases} \tag{37}$$

The absolute magnitude of the variance velocity, used in Equation (29), is calculated as follows:

$$\begin{aligned} V(t)_{(i,j)} &= \sqrt{(v_{xi} - v_{xj})^2 + (v_{yi} - v_{yj})^2 + (v_{zi} - v_{zj})^2} \\ &= \sqrt{\begin{aligned} &(V_{UAVi} * cos\theta' - V_{UAVj} * cos\theta)^2 \\ &+ (V_{UAVi} * cos\sigma' - V_{UAVj} * cos\sigma)^2 \\ &+ (V_{UAVi} * cos\tau' - V_{UAVj} * cos\tau)^2 \end{aligned}} \end{aligned} \tag{38}$$

in such a way that $i \neq j$.

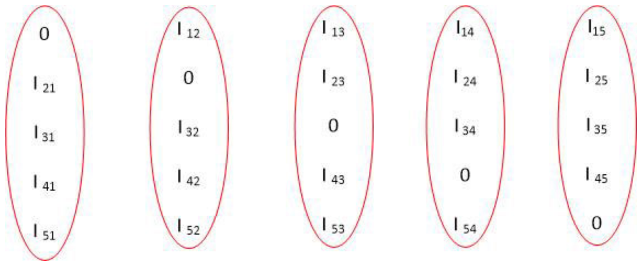


**FIGURE 6.** Cluster index routing table.

Equation (29) was used in the simulation to update UAV velocities. At time $t$, the equation presented in Equation (34) is used to calculate the relative velocity, which is used in Equation (27). Following the calculation of the cluster index, the UAVs broadcast their calculated cluster index to the neighboring nodes, represented by the nodes of set N(t). Every node tracks the cluster indices in a cluster routing table.

Fig. 6 shows an example of a 5 × 5 grid network. It is important to note that this table is not symmetric like the grid in Fig. 2 because node 1's cluster index with respect to node 2 is not equal to node 2's cluster index with respect to node 1. Each column represents the cluster routing table populated by one UAV; for example, the first column represents the cluster indices saved by UAV 1.

The columns represent the cluster index considered when calculating the average cluster index of each node.

$$C_{(i)} = Average \sum_{n=1}^{n} C_{(i,j)} \tag{39}$$

where:

- $C_i$ is the average calculated cluster index of UAV $i$
- $C_{ij}$ is the cluster index of UAV i with respect to UAV $j$
- $n$ is the total number of UAVs in the network

The node with the highest average cluster index is selected as the CH node. CMs were then selected in decreasing order of the average cluster index. Each cluster consisted of a predefined number of CMs, defined as $C_{max}$. If the CM count reaches the $C_{max}$, the next UAV is selected as the CH for the second cluster. This process continues until all the UAVs are selected as either CHs or CMs. This scheme is restarted after a certain amount of time, $T_{loop}$, to reflect any network changes, such as UAV disconnection, location, or velocity changes. The available bandwidth is split into subchannels in frequency-division multiple access (FDMA). Because a base station can only support a limited number of clusters due to bandwidth constraints, the bandwidth (BW) is divided into K sub-channels (SC) [40]. Each SC will have a BW split based on

$$B_{SC} = \frac{BW}{K} \tag{40}$$

Based on the above equation, we can deduce the maximum number of clusters served by the base station, depending on the communication technology adopted in the network.

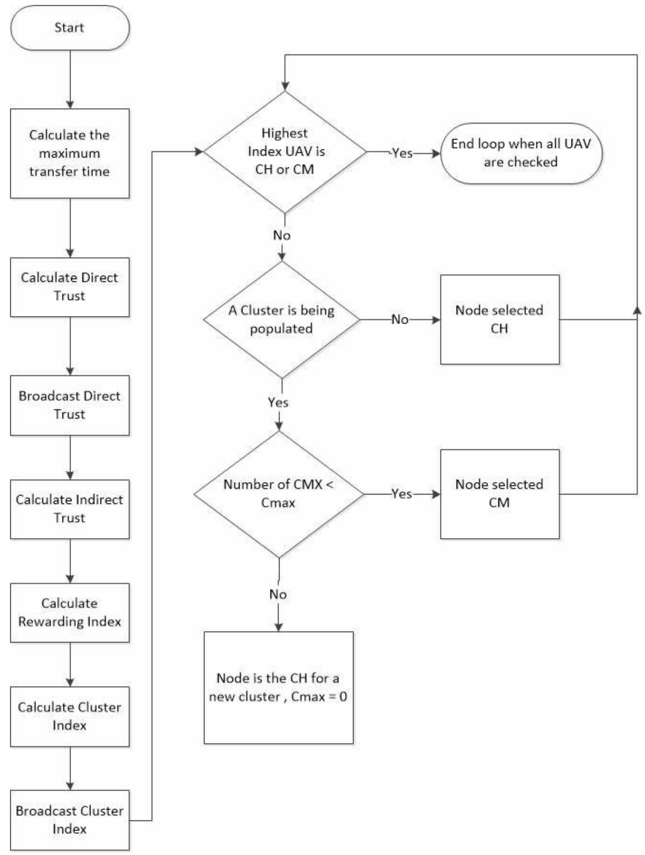


**FIGURE 7.** Flowchart of weighted cluster S-UAV.

**TABLE 1.** Technologies available in a swarm of UAVs.

| Technology | LTE | WiFi | ZigBee |
|---|---|---|---|
| IEEE | LTE | 8021.11n | 802.15.4 |
| Outdoor Range | 100 km | 250 m | 10-20m |
| Transfer Rate | 300 Mbps | 600 Mbps | 200 Kbps |
| Latency | 10 ms | less than 5ms | less than 70ms |
| Topology | Plan | Ad Hoc, Star, Mesh, Hybrid | Ad Hoc, Star, Mesh, Hybrid |

Fig. 7 displays the flowchart of our scheme for one iteration at a time $T_{loop}$. After the incorporation of $T_{loop}$ the clustering algorithm restarted to reflect changes in the network.

## IV. SIMULATION AND RESULTS

A simulation of the proposed clustering scheme for a swarm of UAVs, the weighted cluster S-UAV routing scheme, was performed using MATLAB.

The simulation considers a network of 20 identical UAVs represented in Fig. 8 flying within a predefined geometric zone. Based on the technologies listed in Table 1, our simulation considered Wi-Fi communication because of its outdoor range. The outdoor communication range is a fundamental requirement for communication between the CH and the base station and intra-cellular communication between the CHs.


**FIGURE 8.** UAV specification considered in the simulation.

**TABLE 2.** Simulation assumptions.

| | |
|---|---|
| UAV Dimensions | Length : 35 cm<br>Width : 35 cm<br>Height : 9.3 cm |
| Communication Range | 294 m |
| Transfer Rate | 300 Mbps |
| Number of UAVs | 20 |
| Flying Speed | 10 km/h-45 km/h |
| Packet Size | 4 Kbits |
| Number of simulated packets | 100 |

Specifying the type of drone used in the simulation will limit the distance separating the drones to avoid collisions and limit their speed. Both distance and speed are of interest in our scheme because they are the parameters used in the cluster index calculation. The outdoor communication range is a fundamental requirement for communication between the CH and the base station and intra-cellular communication between the CHs. Because the drone has a width and length of 35 cm, we will consider the distance between any two UAVs to vary from 100 cm to 250 m. The minimum separation distance was set to 100 cm to avoid collisions. The maximum separation distance was set to 250 m to ensure continuous communication by overlapping the UAVs' coverage.

Table 2 summarizes assumptions considered for the simulation parameters.

Fig. 9 shows a simulation of Equation (10), which calculates the maximum latency of packets depending on the number of sub-nodes at each level. The simulation considered four levels with varying numbers of maximum sub-nodes, from two to five. Fig. 9 shows that the maximum latency time increases proportionally with an increase in the number of sub-nodes. The proportional relationship between the number of sub-nodes and the maximum latency is due to more packets received by higher-level nodes, increasing the queuing time for packets to be processed and forwarded to the next level.

Fig. 10 shows the maximum latency of the packets as a function of the number of levels and sub-nodes based on Equation (14). The figure shows a sharp increase in the fourth level. The difference between the two sub-nodes and the five

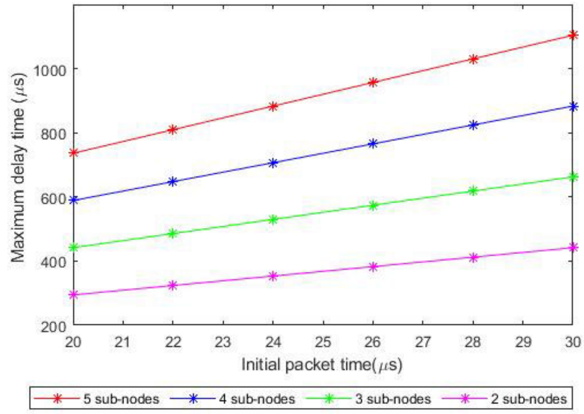


**FIGURE 9.** Maximum latency versus the number of sub-nodes.

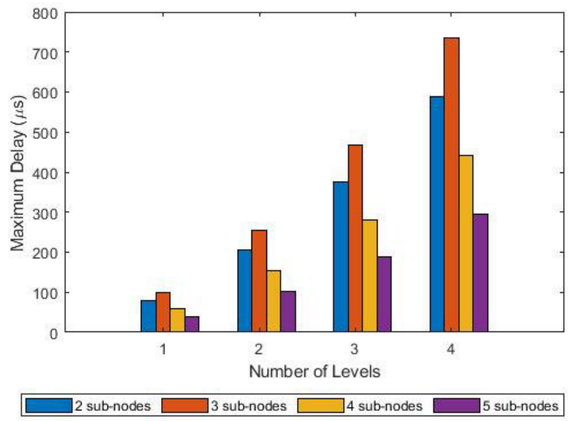


**FIGURE 10.** Maximum latency as function of the number of levels and sub-nodes.

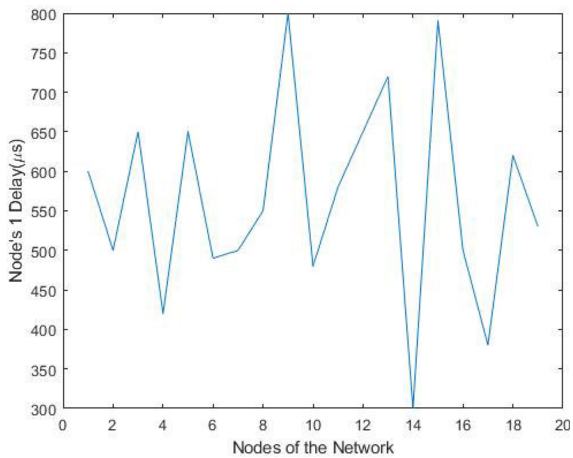


**FIGURE 11.** Average latency of 100 packets sent from node 1 to 20 different destination.

sub-nodes with one level is 60 *mu*, *butitis*441.6 mu with four levels. Based on the results shown in Fig. 11, using 4 or more levels in the considered network is not recommended owing to the sharp increase in latency.

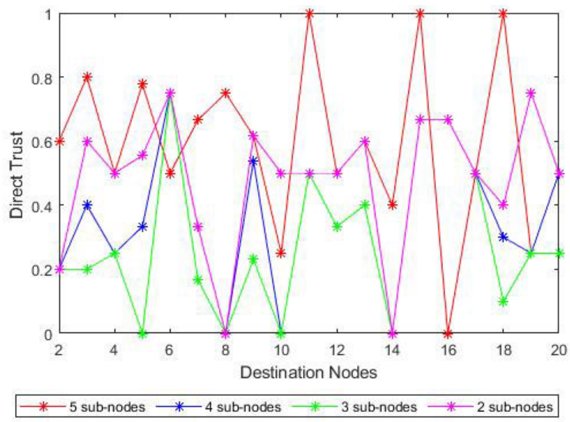


**FIGURE 12.** Node's 1 direct trust with respect to all other nodes with variable number of sub-nodes.

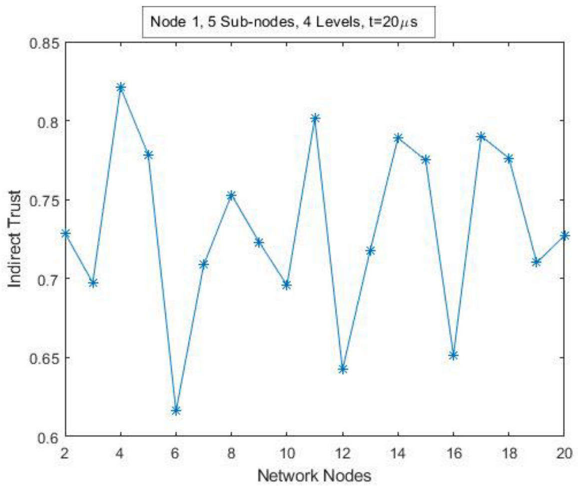


**FIGURE 13.** Indirect Trust of node 1 with respect to all other nodes.

Fig. 11 shows the average latency of 100 packets sent from node 1 to various destinations, that is, nodes 2 to 20. The latencies of these packets were used to generate the direct trust, indirect trust, and total reward indices. In the considered network, the latencies vary from 300$\mu$s to 800 $\mu$s, with some nodes having higher latencies than others because of the queuing of the packets received and their processing time. The figure shows that our network has almost average latency for all UAVs.

Fig. 12 shows the direct trust calculated based on 100 packets sent from node 1 to all the other nodes within the network. Because direct trust is related to latency, the peaks observed at each sub-node level are due to the high latency induced by that node. For example, nodes 6 and 9 have increased latency in sub-nodes 2, 3, and 4. Fig. 12 also shows various direct trust values with various sub-nodes due to the latency calculation change. Direct trust with 2, 3, and 4 sub-nodes is conformant. However, the results for the 5 sub-nodes vary

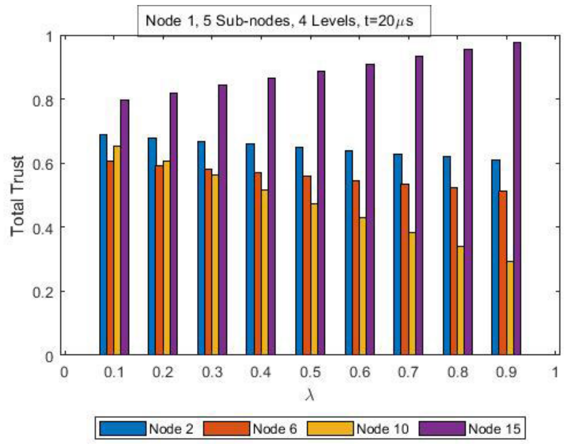


**FIGURE 14.** Total trust of node 1 with respect to $\lambda$.

compared to the others, as the latency variances increase significantly with 5 sub-nodes, as shown in Fig. 10.

Fig. 13 shows the indirect trust of node 1 calculated based on all the nodes' direct broadcast trust. Fig. 13 shows a network with 5 sub-nodes, 4 levels, and a 20 $\mu$s initial packet transfer time. These criteria were used to generate the results. As indirect trust is an average calculation of all broadcast direct trust, the indirect trust value should vary between 0 and 1. Based on the simulation, Fig. 13 shows an increase in indirect trust from 0.6 to 0.83. Fig. 13 also shows that some nodes have higher indirect trust than others, which in turn refers to the latency of the nodes in forwarding the packets.

Fig. 14 shows the total trust of node 1 for nodes 2, 6, 10, and 15 with varying $\lambda$. As $\lambda$ tends towards 0, total trust is based more on indirect trust than on direct trust, and when $\lambda$ tends towards 1, total trust relies more on direct trust. Fig. 14 depicts three different scenarios for total trust in relation to $\lambda$. For node 15, as $\lambda$ tends towards 1, the total trust increases, which means that the direct trust of node 15 is much higher than its indirect trust. Nodes 2 and 6 slightly differ with the variance in $\lambda$ which means that their indirect and direct trust are almost equal. Node 10 shows a decrease in total trust with an increase in $\lambda$, which means that this node's indirect trust is higher than its direct trust.

Fig. 15 shows the clustering index of node 1 with three different sets of weights. We can see that, for the case represented in yellow, nodes 4 and 8, for example, have a peak compared to the other two cases. In addition, node 7 exhibited a severe drop in the case represented in yellow compared to the other two cases. From this variation, we can conclude that the weights affect the cluster index calculation, which changes CH selection, CM selection, and cluster formation.

The resultant clusters, based on the different weights in Fig. 15, are listed in Table 3. The CM table shows the ranking of all nodes in the network based on the cluster index, in decreasing order. Therefore, node 7 has the highest cluster index in all three cases. The node with the lowest cluster index varies between nodes 4 and 12, depending on the weights

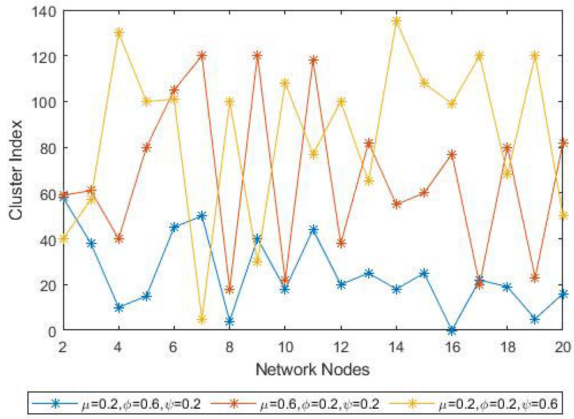


**FIGURE 15.** Cluster index of node 1.

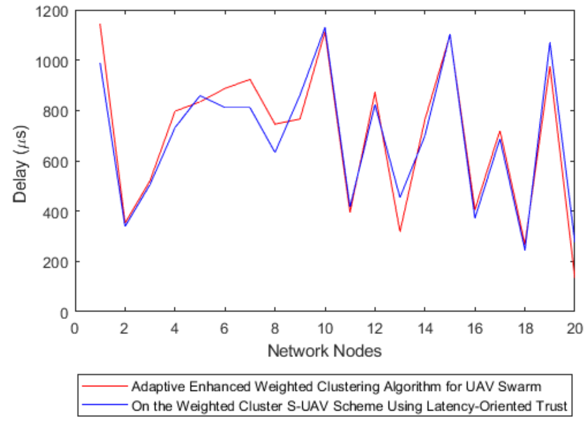


**FIGURE 16.** Comparison between our proposed scheme and Adaptive Enhanced Weighted Clustering Algorithm for UAV Swarm.

**TABLE 3.** Cluster index.

| Case 1 | Case 2 | Case 3 |
|---|---|---|
| 7 | 7 | 7 |
| 15 | 15 | 15 |
| 3 | 3 | 13 |
| 13 | 13 | 18 |
| 18 | 18 | 3 |
| 16 | 16 | 6 |
| 6 | 6 | 16 |
| 9 | 9 | 11 |
| 11 | 11 | 9 |
| 10 | 10 | 10 |
| 20 | 20 | 8 |
| 8 | 8 | 20 |
| 5 | 5 | 5 |
| 2 | 1 | 2 |
| 1 | 2 | 19 |
| 19 | 19 | 1 |
| 17 | 17 | 17 |
| 14 | 4 | 12 |
| 12 | 14 | 14 |
| 4 | 12 | 4 |

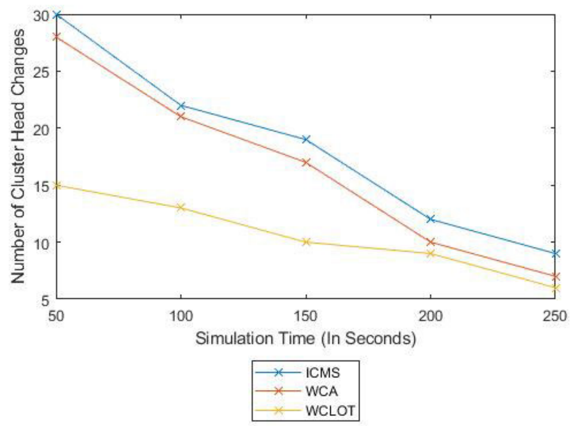


**FIGURE 17.** Comparison between our proposed scheme and Adaptive Enhanced Weighted Clustering Algorithm for UAV Swarm.

**TABLE 4.** UAV clusters.

| | | | | |
|---|---|---|---|---|
| Case 1 | **7**,15,3,13,18 | **16**,6,9,11,10 | **20**,8,5,2,1 | **19**, 17,14,12,4 |
| Case 2 | **7**,15,3,13,18 | **16**,6,9,11,10 | **20**,8,5,1,2 | **19**, 17,4,14,12 |
| Case 3 | **7**,15,13,8,3 | **6**,16,11,9,10 | **8**,20,5 2,19 | **1**, 17,12,14,4 |

considered. If the highest weight is for distance, then the lowest cluster index is for node 12. Otherwise, it is for node 4.

The splitting of UAVs into clusters depends on $C_{max}$. Our simulation considered 20 UAV nodes and $C_{max}$ of 5. This resulted in four clusters, as listed in Table 4. Table 4 lists the four clusters obtained based on the proposed weighted cluster S-UAV routing scheme, with the nodes in bold as the CH.

Table 4 shows the effects of the weights on the CH and CM selections. For example, the third cluster has different CMs when Cases 1 and 2 are compared. In addition, we can detect different CH selections in Case 3. Case 3 had the highest weight on the velocity, which explains the detected variation. Cases 1 and 2 had the highest weights for distance and trust, which are indirectly related. This explains why we obtained almost the same results, except for a few variations in the CM selection.

Fig. 16 compares the proposed scheme and an existing scheme known as the adaptive enhanced weighted clustering algorithm for UAV swarm. These two schemes are based on a weighted formula for cluster formation. The Adaptive Enhanced Weighted Clustering Algorithm for a UAV Swarm uses a weighted formula consisting of the optimal node degree, distance, and link retention rate [39]. The comparison focused on the delays generated by the transmission of 100 packets. The proposed protocol exhibited a decreased delay at nodes 1, 4, 6, 7, 8, 14, and 16. However, there was an increased delay at nodes 5, 9, 13, and 20. On average, our proposed scheme resulted in lower total latency than the other schemes.

Fig. 17 compares our proposed scheme (WCLOT) to A Weighted Clustering Algorithm for Mobile Ad Hoc Networks (WCA) and Intelligent condition monitoring system (ICMS) for unmanned air vehicles (UAVs), unmanned surface vehicle (USV) and autonomous underwater vehicle

(AUV), robots: a feasibility study (ICMS). The figure compares the number of CH changes while the simulation time varies from 50 to 250 seconds. After 100 seconds of running the simulation, Fig. 17 shows that our proposed protocol decreases by 38% the number of CH changes as compared to WCA and by 40% as compared to ICMS. After 250 seconds of running the simulation, a decrease in CH changes is still detected. A decrease of 14% as compared to WCA and of 33% as compared to ICMS are detected. Therefore, the number of CH changes in our proposed scheme, WCLOT, is less than the other two schemes, which results in a more stable network.

## V. CONCLUSION

This study proposes a new routing scheme called the weighted cluster S-UAV routing scheme. This scheme is based on the clustering concept because it is one of the most reliable routing concepts in ad-hoc networks. In cluster formation, a swarm of UAVs is divided into groups known as clusters. Each cluster has one CH, also known as the leader. Each cluster has several CMs. The CH is responsible for all inter- and intra-cluster communications. The CH can communicate with other CMs or outside their clusters with other CHs.

Our scheme divides UAVs into clusters, with the selection of CH and CMs based on a new cluster index. The cluster index was calculated using a weighted formula. The parameters of this formula are distance, velocity, and reward index. The reward index is based on direct and indirect trust and represents the level at which the UAV cooperates in forwarding packets with minimal latencies.

Different clusters were formed by varying the weights of the parameters in the cluster index calculation. The weights impact CH and CMs selection, resulting in a unique clustered network. The weights used in the cluster index calculation depend on network requirements and constraints. Depending on the network, the cluster index can be calculated with the highest impact on the reward index, the velocity, or the distance. The MATLAB simulation results show that our proposed scheme is promising because it has a lower total latency than other existing schemes.

In the future, we would like to simulate our scheme and analyze different network-performance metrics. The metric that has a high impact on routing schemes is throughput.

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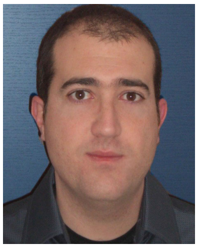

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