Article

Position-Monitoring-Based Hybrid Routing Protocol for 3D UAV-Based Networks

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Abstract: Unmanned aerial vehicles (UAV) have emerged as prime technologies due to their compatible size and flexible architecture. UAV technology offers services in vast applications such as inter-UAV communication, wireless sensors, and the future Internet of Things (IoT) due to its compatible architecture. A UAV’s speed varies while roaming, which may increase the risk of a connection failure. Various routing schemes have provided solutions to address this essential issue for three-dimensional (3D) UAV-based networks. The main category of UAV routing schemes is position-based routing schemes, which choose the best route based on the UAV’s location. However, position-based routing has the drawback that it depends on exact positioning and tracking. An efficient routing scheme can resolve the significant issue associated with UAV mobility in a 3D environment. This paper aims to address these issues of static preloaded location values by presenting a hybrid routing scheme named the Position-Monitor-based Hybrid Routing Protocol (PMHRP), which takes advantage of both geographic and topology-based routing protocols. The PMHRP establishes the shortest possible route based on a UAV’s Global Positioning System (GPS). Moreover, the proposed protocol utilizes the links for data forwarding. Furthermore, a disaster-based UAV scenario is adopted to provide connections to IoT devices. A detailed comparison analysis shows the proposed scheme’s extreme performance and results in up to 65% to 73% better packet delivery ratio (PDR) than batch mark schemes under standard 3D UAV scenarios. Compared to earlier work, the proposed scheme reduces the average delay by up to 68% to 75%. Further proposed routing schemes offer 70% to 72% more throughput than the existing routing schemes, and NRL (%) is 42% to 49% lower than the existing routing schemes. This happens because of the global routing information available at each UAV which is provided by the position head coordinator (PHC) UAV in the proposed work.

Keywords: communication networks; centrality measure; routing protocols; 3D UAV networks

1. Introduction

Over time, Unmanned Aerial Vehicles (UAVs) emerged as a promising technology in many wireless communication applications. It is expected that by 2030, the economy of the UAV-based system will cross USD 90 billion [1]. Due to variations in size and the flexibility to fly everywhere, UAVs are deployed in military operations, goods delivery in
metropolitan cities, traffic monitoring in urban areas, natural disaster rescue operations, live streaming for events and many other critical applications. A UAV network is an infrastructure-less, self-organized, decentralized network, such as mobile ad-hoc networks (MANET) and vehicular ad-hoc networks (VANET), working in three-dimensional (3D) space. By employing the properties of MANETs and VANETs, UAVs can collect data from different places and transfer them to their destination by maintaining communication links [2].

Due to the presence of a 3D environment in UAV ad-hoc networks, it is essential to carefully consider UAVs’ position, movement, and direction [3]. Therefore, to achieve better performance of UAVs in specific applications, different mobility models have been considered. The mobility models utilize mathematical models and simulation environments to offer realistic results scenarios for complex networks. Moreover, UAV ad-hoc network mobility is highly dynamic due to its movement in the air; on the other hand, MANET/VANET nodes move on specific paths, such as vehicles on the roads and streets. Hence, choosing an appropriate mobility model for a particular UAV ad-hoc network scenario is essential. In the below taxonomy, Figure 1 describes the classifications of mobility models.

Figure 1. Mobility models taxonomy.

In contrast to the traditional MANET and VANET networks, the UAV-based network brings some new features and challenges, such as the fast movement of the UAVs in a sparse trajectory that makes maintaining communication links very challenging. One of the most challenging tasks is how UAVs can communicate while transmitting data. Therefore, high-speed mobility, stable connection, and 3D coordinates should be considered [4,5]. Since UAVs are responsible for data transfer from source to destination, this leads to a new network environment different from traditional MANETs/VANETs that require novel mobility models, 3D coverage areas, and other possible strategies. In this regard, UAVs create a 3D wireless network environment with a free space environment to move independently. The research community faces unique challenges while working with decentralized flying UAV-based networks, mainly the communication in a 3D environment due to the high mobility of UAVs [6]. To this end, packet routing is one of the open problems in the Inter-UAVs 3D environment [7].

The wireless routing protocol is an important aspect that directly affects multiple UAVs’ communication efficiency. The topology-based routing protocols maintain routing tables to perform routing [8]. The UAV nodes forward data packets to the destination via the shortest path hop by hop. In this case, where the hops are the UAVs, efficient path optimization
is essential. Due to the fast movement of UAVs, topology-based routing requires extra overhead to reinitiate route discovery. Therefore, typical topology-based routing protocols are not suitable to support the 3D nature of the UAV network [9]. To address the 3D issue when utilizing topology-based routing protocols, geographical, positioning, or location optimization throughout the network is necessary for determining the next hop toward the target [10,11]. Each UAV node forwards packets to the optimal neighboring UAV node that is within communication range and in the direction of the destination.

Position-based routing protocols offer many advantages over topology-based routing by utilizing additional geographical information about mobile UAVs available through global positioning systems (GPS) or other position-tracking services. A source UAV node sends signals to the destination UAV using position-based information [12,13]. Due to dynamic topological changes, UAVs often lose connection or are out of communication range. Hence, the UAV-based network requires position-based routing to maintain the network efficiently. However, position-based routing uses local information instead of the entire network information. Therefore, the chance of a high delay occurs when the source node does not find the proper coordination position of the destination node at one hop. Another reason is that nodes are not in the communication range because of the high mobility of UAVs; hence, packets cannot be forwarded, which decreases packet delivery of the whole network.

Based on the above issues mentioned in this paper, we research the 3D UAV scenario, especially for routing information. We propose a new, state-of-the-art routing protocol based on a position-monitoring-based hybrid routing protocol (PMHRPs) in a 3D UAV network, aiming to establish more appropriate routing services during the high mobility of wireless UAV nodes for better routing performance. The PMHRP combines proactive topology-based routing and position-based routing and introduces the PHC, which is responsible for updating and coordinating the routing information of all responsible UAVs based on their geographic position. The topology-based routing property of PMHRP establishes the shortest paths among the network nodes. In this way, all nodes receive routing information as well as the geographic position of other UAVs before data forwarding. To the best of our knowledge, no one has used our proposed methods in any published work to select the PHC node in a UAV-based system. Moreover, PMHRP not only reduces the delay but also maintains the packet delivery ratio in the UAV-based network. We compare our results with existing position-based and topology-based routing protocols. Table 1 shows the abbreviations and notations, with descriptions, that are used in this study.

Table 1. Abbreviations.

| Abbreviations | Definitions |
|---------------|-------------|
| UAV           | Unmanned aerial vehicle |
| PMHRP         | Position monitoring-based hybrid routing protocol |
| GPS           | Global positioning system |
| MANET         | Mobile ad-hoc networks |
| VANET         | Vehicular ad-hoc networks |
| PHC           | Position head coordinator |
| LADTR         | Location-aided delay-tolerant routing |
| LCG           | Linear congruential generator |
| SCF           | Store-carry-forward |
| Geo-cast      | Geographic casting |
| GEOED         | Geographic distance |
| GEOMF         | Geographic most forward |
| GEOC          | Geographic compass |
| PDR           | Packet delivery ratio |
| Pr_UAV        | Receiving power of UAV |
| Pt_UAV        | Transmitting power of UAV |
| Gt_UAV        | Transmitting gain of UAV |
Table 1. Cont.

| Abbreviations | Definitions                        |
|---------------|------------------------------------|
| $D_n$         | UAV distance                       |
| $D_C$         | Centroid distance                  |
| CB            | Betweeness centrality              |
| NS2           | Network simulator                  |
| TCL           | Tool command language              |
| 3D            | Three dimensional                  |
| CBR           | Constant bit rate                  |
| UDP           | User datagram protocol             |

1.1. Contributions of This Study

(1) We proposed a novel Position-Monitor-based Hybrid Routing Protocol (PMHRP), which possesses topology and geographic routing protocol features. Furthermore, the PMHRP establishes the shortest path based on the locations of UAVs.

(2) The proposed scheme introduces the PHC-UAV which limits the message exchange and avoids message flooding across the network. Furthermore, we have considered the position of UAV as the main parameter based on three different approaches: (a) centroid approach, (b) static approach, and (c) random approach based on linear congruential generator (LCG) according to the network environment.

(3) The PHC-UAV only shares the geographic information of all UAVs in the network and is not responsible for calculating the shortest path for each UAV; therefore, the packet overhead and load on the PHC-UAV decrease. Unlike other clustering routing schemes where the cluster head forwards the data across the network as result, the load on cluster head increases, which results in the degradation of the whole network’s performance.

(4) Moreover, for the centroid approach of PHC-UAV selection, centrality and degree of betweenness are considered to have a stable and efficient path from source to destination.

(5) To justify the efficiency of the proposed scheme in comparison with benchmark schemes under different network scenarios and various mobility speeds considered. The results show the efficiency of our proposed scheme in complex network conditions.

1.2. Organization of This Article

Section 2 comprehensively reviews the literature on the routing protocols for UAV networks. Section 3 explains the methodology of the novel routing protocol scheme for a 3D UAV network. Section 4 describes the results based on performance evaluation parameters and experimental results. Finally, Section 5 concludes the article with future work, followed by references.

2. Related Works

Increasingly significant challenges always exist in wireless communication due to the rapid growth of new emerging applications and service requirements, particularly in the development of fifth-generation (5G) or the emergence of sixth-generation (6G) network architectures, with their improved coverage enhancement and reliable communication [14]. In this case, to support reliable data forwarding in an infrastructure-less wireless network, several studies on the routing protocols have been conducted because routing protocols are the backbone of infrastructure-less wireless communication. Efficient routing protocols play an important role in obtaining the desired outcome of UAV ad-hoc networks. Therefore, researchers have tried to investigate the unique features of UAVs. Recently, many researchers studied routing protocols for UAV ad-hoc networks in different [15–17] categories, such as topology-based and geographic-based networks. The traditional routing schemes have been deployed in inter-UAV communication or UAV-to-ground user communication scenarios. UAVs integrated with traditional routing schemes offer challenges...
due to 3D communication distance, high mobility and unstable link quality; a number of traditional routing protocols have been investigated in [18].

As for routing information, the author in [19] discussed a routing scheme where all UAVs perform operations using topology-based routing protocols through a predetermined path. Authors adopted a military scenario where UAVs perform critical operations to have secure communication between UAVs [20,21]. Similarly, in [22], a single UAV is utilized as a relay node to forward data; usually, this type of network is suitable for delay-tolerant networks. Moreover, a swarm of UAVs is considered in [23], where a proactive routing algorithm is used to maintain the efficiency of the UAV network having less packet delay. To optimize the path of a topology-based network, authors in [24] proposed a Q-learning-based routing scheme, where each UAV can only have a table of two next hops. Another topology-based routing scheme in [25] is Optimized link state routing—extended (OLSR-EXT), which is an enhanced version of optimized link state routing (OLSR). OLSR-EXT utilizes the dynamic network topology and maintains reliable communication. Another wireless routing scheme is a hybrid routing protocol that is the combination of multiple algorithms, such as the Zone Routing Protocol (ZRP) [26], which takes features of both proactive and reactive routing protocols. Though UAVs have high mobility, the network’s topology changes often; therefore, it is necessary to update network information rapidly. The quick update in the routing information causes overhead due to the frequent transfer of control messages, particularly in large networks, as well as increases the size of the routing table. Thus, topological routing protocols are not recommended for large networks and networks with mobile nodes.

Position-based routing reduces the traffic overhead by avoiding the collection and maintenance of unwanted topology information in the routing table. The position routing protocols are based on the exact GPS coordinates of the UAVs in the network. The authors in [27] introduced a location-aided, delay-tolerant routing (LADTR) scheme for disaster post-network scenarios. This routing scheme offers a mechanism to predict the position of each UAV node. If the source and destination have no direct connection, this scheme utilizes the traditional store-carry-forward (SCF) mechanism. Moreover, an adaptive hello interval [28] process is proposed in order to save the energy of UAVs. Geo-cast-based [29] routing is proposed, which takes into account 3D movement and forwards data toward the destination location. In [30], authors proposed an ant-colony-based location optimization problem scheme that considers the location of each UAV and assigns scores according to locations. A Geographic-Spray and wait routing scheme is introduced in [31] for rescue scenarios, where UAVs move along predefined locations; therefore, it is easy to predict the path. To enhance the efficiency of position-based routing protocols, clustering techniques have been adopted by [32–34], where UAVs transfer data through cluster heads. GEO-D [35] is a class of position-based routing algorithms in which the source node forwards the message to its neighboring node within the communication range. During the high-speed movement of UAVs, the selected node might not be within the communication range or can have some signal issues; therefore, the message can experience a high delay or be dropped. Similarly, another position-based routing protocol known as the GEO Most Forward (GEOF) routing algorithm [36] is similar to GEO greedy, but uses the projection technique on the 3D surface to choose the shortest path from source to destination. MF may fail when the neighboring nodes are not on the projection plane. Another scheme is GEO Compass [37], which forwards the messages in a particular direction or angle towards the nearest node. The compass scheme also suffers when there is no neighboring node in a specific direction. In addition, the calculated direction can be a long path to the destination place. In other words, the compass routing scheme may suffer from the never-ending loop; therefore, the network can suffer from high delays and a lower packet delivery ratio (PDR).

The above literature review justifies that the different routing schemes and their combination provide a better solution for an infrastructure-less wireless multi-hop network, especially in terms of link stability during communication. The topology of the infrastructure-less network changes dynamically due to the high speed of nodes. It is
challenging to have a stable routing protocol to meet the requirement of the high mobility speed of UAVs in a 3D infrastructure-less network. Furthermore, position-based routing protocols have two drawbacks: (1) higher delay because there is no predefined path from source to destination and (2) communication range, i.e., if the source UAV node does not have any neighbor in its communication range, data cannot be forwarded. At the same time, topology-based routing schemes suffer due to the high mobility of UAVs and have extra overhead. Therefore, to overcome these issues, a novel hybrid routing is proposed in this paper. In the below Table 2, the comparative literature of previous routing protocols is highlighted.

Table 2. Limitations of Existing Work.

| References | Routing Type    | Limitations                                      |
|------------|-----------------|--------------------------------------------------|
| [38]       | Topology based  | High overhead, link risk, and high normalized load |
| [20]       | Topology based  | High overhead, link breakage, and loop routing    |
| [39]       | Topology based  | High overhead, higher bandwidth                  |
| [10]       | Topology based  | High delay and higher risk of link breakage       |
| [18]       | Topology based  | High overhead, high bandwidth consumption        |
| [31]       | Geographic based| High energy, high normalized load, and loop routing|
| [24]       | Geographic based| High normalized load, high delay, and high energy consumption |
| [40]       | Geographic based| Loop routing, high energy, and flooding route    |
| [32]       | Geographic based| Loop routing, high energy consumption            |
| [41]       | Geographic based| Loop routing, high energy, and flooding route    |
| Proposed Scheme | Unsuitable for ultra-dense networks, PHC vulnerable to attackers, and limited routing between UAVs if all PHCs are dead. |

3. Methods

The proposed Position-Monitor-based Hybrid Routing Protocol (PMHRP) is a combination of the position and topology routing schemes. The proposed scheme tried to decrease the flooding messages exchange across the network by introducing the concept of PHC, unlike cluster-based routing schemes, where the cluster head is a superindentor for calculating the short paths of the whole network. As a result, the traffic load increases on the cluster head. When the PHC does not managing to find the shortest path, it just shares the geographic information of each UAV, hence decreasing the packet overhead as well as the traffic load on PHC due to the presence of significant z-axis modifications in the PMHRP 3D Free Space Model and considering the gain on receiving and the transmitting side. Furthermore, this section consists of three main parts. In the first part, a 3D Free-space model is created, and the second part describes the PHC selection mechanism. The third part describes the working mechanism of the proposed scheme.

3.1. 3D Free Space Model for PMHRP

Generally, UAVs operate in an outdoor environment; therefore, a 3D free-space propagation model is considered, where each UAV transmits and receives data information without any hurdles [42], which creates an actual 3D environment and free-space propagation. For a stable communication link, it is necessary that the neighboring UAVs are in communication range of each other; therefore, transmitting power and receiving power are calculated using Equation (1):

\[
\frac{P_{r_{UAV}}}{P_{t_{UAV}}} = \frac{A_{t_{UAV}} * A_{r_{UAV}}}{d^2 \lambda^2}
\]

where \( P_{r_{UAV}} \) is the receiving antenna signal power, \( P_{t_{UAV}} \) is the transmitting antenna signal power, and \( A_{t_{UAV}} \) and \( A_{r_{UAV}} \) are the effective areas of the antenna at both sides. \( \lambda \) is the wavelength of the signal, and \( d \) is the distance between the receiving UAV and transmitting UAV antennas, accordingly. An isotropic antenna is adopted in a 3D free-space
model; therefore, an effective area of the antenna is \( \lambda/4\pi \), and adding in Equation (1) gives us Equation (2):

\[
\frac{P_{r_{UAV}}}{P_{t_{UAV}}} = \frac{\lambda^2}{(4\pi d)^2}
\]

Generally, the gain at both sides (transmitting and receiving) is not equal to 1; therefore, it is necessary to consider the gain at the receiving and transmitting antenna using Equation (3):

\[
\frac{P_{r_{UAV}}}{P_{t_{UAV}}} = G_{t_{UAV}} G_{r_{UAV}} \frac{\lambda^2}{(4\pi d)^2}
\]

Here, \( G_{t_{UAV}}, G_{r_{UAV}} \) are the gain at the transmitting and receiving antenna, respectively. Several UAVs move across the wireless network to form a 3D environmental network by taking into account three coordinate mechanisms. Suppose there is a set of \( N = \{u_1, u_2, \ldots, u_n\} \), where \( u_i \) represents the UAV. The proposed work utilizes the 3D coordinates to find the position of each UAV by utilizing the Euclidean distance (Equation (4)):

\[
D_n = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}
\]

In Equation (4), distance \( D_n \) is the distance of each UAV, and it can be calculated by subtracting the three coordinates \( (x_j, y_j, z_j) \) with respect to the coordinates of the initial reference point \( (x_i, y_i, z_i) \). After the formation of the 3D free-space model, the next step is to generate a mobility scenario for UAV movement. We have adopted the random waypoint mobility model to create a 3D network environment. The main reason behind choosing the random waypoint mobility model is that it supports 3D environment and offers a ad-hoc network environment where UAVs can select the next position independently.

### 3.2. Random Waypoint UAV Mobility Model

The random waypoint mobility model is widely adopted in simulation environments due to its simple approach and easy accessibility. This model employs two main parameters, pause time and velocity; both are inversely proportional to each other.

Let us suppose that the starting \( I_{th} - UAV \) has a constant velocity chosen value from \( [0, V_{max}] \), and the velocity and direction of the UAV vary until it travels from location \( L_0 \) to \( L_1 \). After reaching \( L_1 \), the UAV has some pause time, \( T_{p_{=1}} \); as mentioned above, the velocity and pause time have an inverse relationship. Therefore, different mobility scenarios are generated by changing the velocity of UAVs accordingly [43]. The waypoints or stop locations can be drawn from the uniform density function as below:

\[
UAV(I_{th}) = \begin{cases} 
1 & a \in A \\
0 & \text{otherwise}
\end{cases}
\]

Here, \( A \) is area of the network, and \( a \) is an area of location where the UAV exists; hence, \( a \) is the location vector drawn from the uniform distribution belonging to \( = U(A) \). The location vector is evaluated as:

\[
a = \Delta x + \Delta y + \Delta z
\]

Here, \( \Delta x, \Delta y, \text{and} \Delta z \) represent the change in each coordinate that occurs in the position of the UAV. Moreover, the movement of UAVs consists of range \( [V_{min}, V_{max}] \) and can be calculated from a discrete distribution as:

\[
f(V) = [V_{min}, V_{max}]
\]

The UAVs are moving with different velocities; therefore, it is necessary to calculate velocity variation, which is described as a change in distance per unit of time:

\[
V_x = \frac{\Delta x}{\Delta t}, \quad V_y = \frac{\Delta y}{\Delta t}, \quad V_z = \frac{\Delta z}{\Delta t}
\]
Based on the above equation, total velocity change can be calculated by simply adopting the Euclidean formula:

$$\Delta V = \sqrt{V_x^2 + V_y^2 + V_z^2}$$  \hspace{1cm} (9)

The relative speed between two UAVs can be captured by utilizing the basic equation of random waypoint mobility [44]:

$$RS(UAV_A, UAV_B) = |V(t)_A - V(t)_B|$$  \hspace{1cm} (10)

Here, $V(t)_A$ and $V(t)_B$ are relative velocities of both UAVs with respect to time. Finally, the relative speed of all UAVs present in the network is evaluated in the mobility metric, which describes the speeds of UAVs as follows:

$$MM = \frac{1}{|UAV_A| \cdot UAV_B|} \sum_{A=1}^{N} \sum_{B=A+1}^{N} \frac{1}{T} \int_0^T RS(UAV_A, UAV_B) dt$$  \hspace{1cm} (11)

Figure 2 shows the mobility movement of a UAV in a 3D network at different locations at different time intervals. After generating the mobility model in the UAV ad-hoc network, the next step is the selection of PHC-UAVs, explained in the following section. PHC-UAV

![Figure 2. Three-Dimensional UAV Mobility Model.](image)

### 3.3. Selection of PHC

PMHRP selects one PHC responsible for sharing the geographic position information across the network. Unlike geographic-based routing protocols, which use the flooding mechanism that increases the normalized load of the network, PMHRP implements three methods suitable for different network conditions and the UAV’s speed (i.e., static, random, and centroid).

#### 3.3.1. Static PHC Selection

This method is suitable for a scenario where UAVs have fixed positions (hovering UAVs) and can particularly be deployed in cellular-assisted UAVs and regions where UAVs are in a static position. Since UAVs have fixed geographic positions, a UAV having a middle position in the network is selected as a PHC node. Equation (12) calculates the middle of all nodes as a PHC-UAV. Here, we have considered absolute value to obtain an exact integer:

$$PHC = \text{Abs}(\text{total number of UAVs} / 2)$$  \hspace{1cm} (12)

#### 3.3.2. Random PHC Selection

The random method randomly selects a PHC node by utilizing the linear congruential generator (LCG) method, which considers the connections of each UAV with other UAVs in the network. LGS [45] is widely used due to its low memory allocation and very fast speed,
particularly in computer hardware technology. Random PHC selection is the best choice, where UAVs have less resources. Random PHC can be calculated from Equation (13) for random LCG number generation:

\[ F(X_i) = (a \times X_{i-1} + c) \mod m, \text{ for } i > 0 \] (13)

where \( m \) is the modulus, \( a \) is a constant multiplier, \( c \) is a constant increment value, and \( X_i \) is a seed number.

3.3.3. Centroid PHC Selection

The centroid approach selects a PHC-UAV based on the densities of all UAVs and the average paths of the whole network [46]. As demonstrated by the flowchart in Figure 1, this approach is used to find the center point of all UAVs in the network. We have calculated the centroid coordinates accordingly from Equation (14):

\[ X_c = \frac{\sum_{n=0}^{n} x_n}{n}, \quad Y_c = \frac{\sum_{n=0}^{n} y_n}{n}, \quad Z_c = \frac{\sum_{n=0}^{n} z_n}{n} \] (14)

The next step is to find the minimum distance from the centroid coordinates point and the nearest UAV from the minimum value function:

\[ f(X_{PHC}, Y_{PHC}, Z_{PHC}) = \sum_{m=1}^{n} d_m \] (15)

Here, \( dm \) is a minimum distance of the PHC-UAV from the centroid point coordinates, and \( n \) is the maximum number of nearest UAVs. The above can be simplified as:

\[ f(X_{PHC}, Y_{PHC}, Z_{PHC}) = \sqrt{(X_m - X_C) + (Y_m - Y_C) + (Z_m - Z_C)} \] (16)

From Equation (16), the nearest UAVs to the centroid point are selected as candidates for the PHC-UAV of the network. The two potential candidate UAVs having the closest distance to the centroid distance are selected. The next step is to choose the PHC-UAV that is nearest to \((D_C)\) point as the PHC-UAV node contains the highest power in terms of shortest paths and having connections across the network. Therefore, centrality measures are adopted to find the UAV closest to the \(D_C\) point. The two key preferences utilize the degree of centrality of each UAV and the betweenness centrality of the UAVs to select the optimal PHC. The degree of centrality determines the number of neighboring UAVs connected to the PHC. An increase in connection makes the location information of all UAVs more accurate and can be calculated by Equation (17):

\[ \text{Deg}(I_{th}(UAV)) = \frac{\sum_{i=1}^{N} uav_{i,n-i}}{N - i} \] (17)

Here, \( \text{Deg} \) is the degree, the \( I_{th} \) UAV is the summation of all connections that are connected minus the total number of UAVs present in the network. The degree of centrality plays an important role in finding more connections and optimal paths. The other preference is betweenness centrality; as we know, the UAVs are distributed in a sparse nature; therefore, it is very important that PHC-UAV must be well connected with all UAVs. Equation (10) calculates the betweenness centrality, which is all shortest paths from \(I_{th}\) UAV divided by all paths across the network:

\[ \text{CB}(I_{th}(UAV)) = \sum_{i > n-1}^{n} \frac{P_i}{P_{N-i}} \] (18)

After finding two key measures, we have formulated the maximum utility function based on two key preferences. Based on Equation (19), the UAV attaining the highest utility value is selected, as primarily shown in Figure 3, which shows the PHC and neighboring
UAVs, PHC-UAV contains the highest degree of centrality, and PHC-UAV has the shortest paths of all other UAVs. The maximum utility can be evaluated as:

\[
U(I_{th(UAV)}) = \sqrt{\text{Deg}(I_{th(UAV)})} \times \text{CB}(I_{th(UAV)})
\]

(19)

where, \(U(I_{th(UAV)}) > U(n - I_{th(UAV)})\).

From the maximum value of the utility function, UAV is selected as the primary PHC-UAV, and the second highest maximum value can work as a secondary PHC. In case the primary PHC loses connection or is dead, the secondary UAV acts as a substitute PHC for the network. Figure 3 shows the PHC-UAV and other UAV nodes moving in a 3D environment.

Algorithm 1 presents the pseudo-code of the selection of PHC in a UAV environment using the centroid approach. It starts from line 1, using the centroid function that takes N number of UAV nodes. Lines 2–4 execute a loop, where each UAV node updates its 3D positions according to 3 coordinator points (x,y,z) of the GPS. Line 5 calculates the centroid point (D\(_C\)) based on Equations (7) and (8). Line 6 adds the ID of each UAV node with its calculated distance (dist) in the NL vector. Line 7 shows that if the NL vector is empty, it goes back to Line 5 for recalculation of the D\(_C\) point. Lines 9 to 11 calculate the degree of all neighboring UAVs and save values in vector dl in descending order. The next step is to choose two maximum values, Max1 and Max2, as described in line 12. The betweenness centrality values of Max1 and Max2 are calculated, and the utility function is formed, which takes the values of degree and centrality and betweenness centrality in line 13. Furthermore, based on utility function values, if the value of U1 is greater than U2, Max1 will be PHC, otherwise, Max2 will be considered as PHC., as can be observed from lines 14 to 22. Finally, the centroid algorithm ends at line 23.
Algorithm 1: The pseudo-code of the Centroid PHC-UAV.

Input: Number of Nodes deployed = N; NodeList=NL
Output: Get PHC Node

1. Centroid (N) start
2. for each node(i) do
3. Update Local position x_i,y_i,z_i
4. End foreach
5. To find Dc point in network via Eq(7) and Eq(8)
6. Add all neighbor nodes of D.C. point in vector (NL)
7. if (is vector (N.L.) is empty)
8. Go to line 5
9. Else
10. Measure the degree and betweenness of all neighbor nodes using Eq 9 and store in vector (dL)
11. Sort vector(dL) in descending order
12. Set Max1= dL [0]=8, set Max2=dL [1] =8, set a=-1
13. If(betweenness (Max1,Max2)==Max1) //using Eq 11
14. A = Max1
15. Else
16. a = Max2
17. Set U1 = Max1 * a
18. Set U2 = Max2 * a
19. If(U1 > U2)
20. return PHC = U1
21. Else
22. return PHC = U2
23. End Centroid

Figure 4a shows the flow of three different methods to select the PHC. In the first step, one of the three methods must be selected to run the PMHRP routing protocol in a 3D environment. In Figure 4b, the routing data forwarding mechanism is described.

3.4. PMHRP Working Principle

The data forwarding mechanism aims to establish communication among the UAVs. After selecting the PHC-UAV node in a UAV-based network, the PMHRP routing protocol exchanges the number of routing packets to introduce PHC with all active UAVs. The PHRMP uses GPS positions and establishes the shortest path. Figure 5 shows the working environment of PHRMP with adjacency matrix, root update, and root response messages. The selected PHC node maintains the routing information in 6 steps for the whole network: (1) The PHC-UAV broadcasts a root update message which contains an empty adjacency matrix to normal UAVs. (2) On receiving the root update message, each UAV updates the adjacency matrix with its GPS location coordinates accordingly and forwards it to neighboring UAVs. (3) UAVs send root response messages to the PHC-UAV with a filled adjacency matrix. (4) After receiving the filled adjacency matrix of all UAVs, the PHC stores that information. This is the method through which PHC stores the locations of all UAVs. (5) PHC fills binary information into a new adjacency matrix with the help of locations of all UAVs and broadcasts it to all UAVs. (6) Every UAV performs the Dijkstra algorithm on the binary adjacency matrix to find the shortest path between sources to destination. In this way, all UAVs have routing information for the entire network, which overcomes the problem of position-based routing protocol because position-based routing protocols have only local routing information instead of the whole network.
Figure 4a shows the flow of three different methods to select the PHC. In the first step, one of the three methods must be selected to run the PMHRP routing protocol in a 3D environment. In Figure 4b, the routing data forwarding mechanism is described.

Figure 4. Flowchart of PMHRP: (a) PHC Selection; (b) Data Forwarding.
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4. Experimental Evaluation

4.1. Experimental Setup

We have implemented and simulated PMHRP in discrete-event network simulator 2 (NS2) [47]. Generally, NS2 and its default routing protocols do not support 3D space propagation models. Therefore, we patched the space propagation model and also the GEO routing protocol [48] in NS2 version 2.35 running on ubuntu16 to support the 3D UAV network environment. The seven routing-protocol-based experiments are conducted with the simulation parameters given in Table 3, and the results gathered include the three methods of the proposed PMHRP, three variants of the existing GEO, and one famous topology-based AODV routing protocol. All routing protocols are executed with the same parameters to compare the performance of routing protocols in a 3D UAV network. Different scenarios have been simulated based on the varying average speeds of 20, 40, and 60 m/s by utilizing the random waypoint mobility model. The 2D RWP supports planner structure has only two coordinates: x and y regions. On the other hand, the 3D RWP mobility model tries to imitate unmanned aerial vehicle movement and position as closely as possible because it creates a 3D environment by utilizing three coordinates (x, y, z) instead of a planner structure. Therefore, the 2D RWP mobility model or other 2D mobility models are not as close as the 3D RWP mobility model for UAV networks. The 3D RWP mobility model improves the performance of the routing protocols, which supports the UAV environment. To the best of our knowledge, the traditional AODV routing protocol works better only for planner network environments; therefore, its performance may slightly
decrease in a UAV environment. In the following Section 4.3, we will analyze benchmark routing protocols in more detail. Furthermore, in order to check the stability of routing protocols, the different data flows are configured for different communication connections via the NS2 traffic generator. This traffic generator is a reliable software based on the Pascal language and is used in multiple studies, such as [49,50]. This software generates TCL traffic patterns compatible with NS2 end-user code.

### Table 3. Simulation Parameters.

| Parameters                        | Values                                      |
|-----------------------------------|---------------------------------------------|
| MAC Standard                      | 802.11 g                                    |
| Frequency                         | 2.4 Ghz                                     |
| Propagation Model                 | 3D Free Space Model                         |
| Mobility Model                    | Random waypoint                             |
| Antenna Model                     | Omnidirectional Antenna                     |
| Transmitted Signal Power          | 0.2818 W                                    |
| Carrier Sense Threshold           | $1.559 \times 10^{-11}$ W                   |
| Receive Power Threshold           | $3.652 \times 10^{-10}$ W                   |
| System Loss Factor                | 1.0                                         |
| Network Coverage Area             | $1000 \times 1000 \times 500$ (m$^3$)       |
| Communication Range               | 250 m                                       |
| Max number of UAVs                | 50                                          |
| The transport protocol and traffic| UDP and CBR traffic                         |
| Packet Rate/Data flow             | 24 Packet/s                                 |
| Packet size                       | 512 kb                                      |
| Number Nodes in Movement          | 10, 20, 30, 40, 50                          |
| Pause time                        | Dynamic                                     |
| Mobility speeds                   | 20, 40, 60 (m/s)                            |
| Connections                       | 20                                          |
| Simulation time                   | 60 s                                        |

### 4.2. Quality of Services

Generally, the quality of service (QoS) is a set of techniques that identifies the network behavior and intelligence of routing protocols under a limited network capacity. This paper uses four primary QoS techniques, namely, packet delivery ratio (%), delay(s), throughput(kbps), and normalized routing load(%).

1. **Packet delivery ratio (PDR %):** PDR (%) is the best QoS technique for determining a routing protocol’s operational capability. It shows the percentage (%) of packets those successfully arrive at the destination UAV node over packets originating from the source. Equation (20) shows the calculation of the PDR:

   \[
   PDR = \frac{\sum \text{Total number of packets received}}{\sum \text{Total number of packets originated}} \tag{20}
   \]

2. **Average Delay:** Delay indicates the total taken time taken by received data packets take to reach the destination UAV. It is in seconds. Equation (21) shows the average delay. To determine the average delay ($D_T$), the total time of the received data packet ($R_T$) is subtracted from the total time of sent data packets ($S_T$). The remaining value is divided by the total number of packets received:

   \[
   D_T = \frac{\sum R_T - \sum S_T}{\sum R} \tag{21}
   \]

3. **Throughput:** It is the amount of data delivered to the receiver in a unit average time over the number of nodes [51], usually calculated in bits per second (bps) or kilobits per second (kbps). Equation (22) shows the calculation of throughput:
Throughput (kbps) = \( \frac{\sum \text{packets (kbps) successfully Delivered}}{T} \) (22)

(4) Normalized Routing Load (NRL): NRL is defined as the number routing packets transmitted divided by data packets from the source. NRL is calculated from Equation (23):

\[
NRL = \frac{\sum \text{routing control packets}}{\sum \text{data packets received}}
\] (23)

4.3. Results and Discussion

This section explains the results of all routing protocols. We compare the proposed PMHRP (Static-PHCS, Random-PHCR, and Centroid-PHCC) schemes with GEO (Greedy-GEOD, Compass-GEOC, Most Forward-GEOMF) and AODV for performance evolution. We have generated results of four basic parameters, i.e., packet delivery ratio, delay, throughput, and normalized routing load, by varying the mobility speed of UAVs (20, 40, and 60 m/s). Furthermore, each QoS result generates 20 connection stress, which is a medium traffic load scenario. The graphs evaluate the impact of mobility and stress on the PDR, delay, throughput, and normalized routing load QoS metrics for data transfer.

4.3.1. Packet Delivery Ratio (PDR %)

Figure 6 shows the packet delivery ratio (PDR %) results of the three different mobility scenarios, 20, 40, and 60 m/s, versus 50 simultaneously moveable UAV nodes. The PDR of the proposed routing schemes offers better performance in all scenarios under different mobility. The benchmark routing protocols suffer and have low PDR; hence, their performance decreases due to the dynamic nature of nodes and unstable links during simulation time. In the 20 m/s mobility speed, the PDR of the proposed scheme PHCC is at 95%, whereas the GEO-D routing protocol has a 60% PDR, though it offers better results in all benchmark schemes. In the comparison, at the start, AODV has a 70% PDR but its performance gradually decreases as the mobility increases due to the fact at high mobility, the topology of the UAV ad-hoc network is highly dynamic (unpredictable). Moreover, among our proposed techniques, PHCC gives 3.5% better PDR with static and 2% better PDR with random schemes. Our three proposed schemes offer better results in comparison with benchmark schemes. At 40 m/s, UAVs move at higher speeds; all routing protocols try to maintain the route. As the number of moving UAV nodes increases, the communication links between UAVs across the network change dynamically; as a result, the performance of other protocols decreases. At the start, GEOD tries to have 58%; as the number of moving UAVs increases, its performance decreases, just like other benchmark schemes. On the other hand, PHC-Static’s performance also decreases due to mobility. At 60 m/s, which is the highest speed (suitable for military UAVs), the performance of all our proposed schemes is better than that of all other four-benchmark routing protocols. The GEO benchmark is for the 3D environment, but its PDR is less in our scenario due to the high-speed mobility under the different network environments. GEO cannot maintain the routes quickly; therefore, its PDR decreases. Moreover, the AODV topology scheme’s performance is the worst because there is no stable path across the network. The proposed schemes store the position of each UAV in the routing table (unlike AODV, the UAVs have addresses); therefore, the source UAV knows the position of destination UAV and intermediate UAVs and, hence, can find the shortest path efficiently. Meanwhile, the benchmark schemes’ performances degrade because of their unstable topology (AODV) and no information from UAVs out of communication range (position-based routing).
4.3.2. Delay(s)

Figure 7 shows the average delay(s) results of the 20, 40, and 60 (m/s) speed scenarios. At 20 m/s, all proposed routing protocols initially perform well with little difference, while GEOD has less delay as compared to other benchmark schemes. The average delays of other versions of GEO (GOEC and GEOMF) and AODV linearly increase as compared to all versions of the proposed routing protocol in the case of connection-10. The centroid version (PHCC) of the proposed routing protocol has about 1% to 70%, 6% to 75%, 7% to 80%, and 2% to 60% lower delay than the AODV, GEOC, GEOMF, and GEOD routing protocols, respectively, as shown in Figure 6. In the 40 m/s case, we further increase the number of moving UAVs in the network for analysis. The GEOC version of the position-based GEO routing protocol generates more delay than other routing protocols in its class of routing. The AODV has about 5% more delay than the GOEC routing protocol, and it has about 3% to 12% higher delay than GEOMF and GEOD, respectively, at 50 moveable nodes. When we compare GEOC with the proposed routing protocol, it has about 50% to 55% higher delay than all variants of the proposed routing protocols. Similarly, we also compare all routing protocols when a speed of 60 m/s is used. Initially, the proposed routing protocol consists of a lower delay. However, as the number of moveable UAV nodes increases, the proposed routing protocol’s network delay(s) also increases. However, all proposed variants of PMHRP have low network delay(s) compared to benchmark routing protocols. The PHCS has a higher delay in proposed schemes due to the fact its PHC is selected by the static approach (not considering the position and other aspects for selection). Furthermore, the PHCC routing protocol shows up to 68% to 75% lower delay than all variants of GEO and 74% lower than AODV routing protocols. The reason behind the lower delay of the proposed variants of the PMHRP is that they have a lower network delay since they contain global routing information. On the other hand, all variants of the GEO routing protocols include local routing information; therefore, they do not control delay efficiently. The centroid variant of the PMHRP has an excellent ability to maintain the network delay, even in high call load scenarios because of its centroid position, and it provides complete routing information to all UAVs by considering the centrality measure values.
4.3.5. Discussion

Connections. As we know, the position of the PHC is essential in UAV networks. The performance of the PHCC remains almost stable, even when the mobility of the network changes. However, the position-based routing protocols do not have global information of routing paths and only consider local routing paths and directions. Therefore, control packets are forwarded to the whole network. However, in the proposed routing scheme, each UAV node has global information of all routes and connectivity, so it can control the routing process. At 20 m/s, the proposed schemes PHCC and PHCR both maintain their throughput in different mobilities, which is more than double than benchmark schemes. PHCS decreases as the mobility speed of UAVs increases, though it offers better performance than position-based and topology (AODV)-based schemes. The PHCC’s outer performance is due to the PHC selection process. As we know, the position of the PHC is essential in UAV networks. The performance of the PHCC remains almost stable, even when the mobility of the network changes.

4.3.3. Throughput (kbps)

The throughput is an important parameter to measure the performance of the network; it measures how many messages reach from source to destination in a given time. As UAV ad-hoc networks are sensitive to forwarding data in the required time, it is therefore necessary to have high throughput. The results in Figure 8 show that as the number of moving UAVs increases, the throughput decreases gradually. We examine our results in three scenarios: at 20, 40, and 60 m/s at different numbers of nodes. PHCC (a centroid-based scheme) maintains its throughput because it utilizes position and best links across the network. We can observe that position-based routing schemes have unstable throughput in a zigzag manner; the reason for this is that they forward messages to the UAVs present in the communication range if the destination UAV is in range or if it finds an appropriate route; otherwise, the message cannot reach. Moreover, from Figure 8, it can be observed that the proposed schemes PHCC and PHCR both maintain their throughput in different mobilities, which is more than double than benchmark schemes. PHCS decreases as the mobility speed of UAVs increases, though it offers better performance than position-based and topology (AODV)-based schemes. The PHCC’s outer performance is due to the PHC selection process, such as the geographical position and number of connections. As we know, the position of the PHC is essential in UAV networks. The performance of the PHCC remains almost stable, even when the mobility of the network changes.

Figure 7. Delay versus Number of UAV nodes at different speeds (20, 40, and 60 m/s).

Figure 8. Throughput versus number of UAV nodes at different speeds (20, 40, and 60 m/s).
4.3.4. Normalized Routing Load (NRL %)

In this scenario, Figure 9, the UAVs move at an average speed of 20, 40, and 60 m/s. Normalized routing describes the number of control packets generated to the number of packets delivered. We can observe from Figure 9 that the normalized routing load of all benchmark schemes is higher, and AODV in particular offers a very high load value. While other position-based schemes’ normalized loads also increase as the mobility of the UAVs increases, because of the rapid movement of the UAVs, the network topology changes dynamically. There are two main reasons for being out of communication range: invalid signal direction and low power signal. However, our proposed schemes have lower normalized load, and PHCC has better results in all mobility scenarios due to utilizing centrality measures: it can choose the best routes and ignore the weak routes. Furthermore, the position-based routing protocols do not have global information of routing paths and only consider local routing paths and directions. Therefore, control packets are forwarded to the whole network. However, in the proposed routing scheme, each UAV node has global information of all routes and connectivity, so it can control the routing packets more easily than the existing routing protocols.

Figure 9. Normalize routing load versus number of UAV nodes at different speeds (20, 40, and 60 m/s).

4.3.5. Discussion

The proposed scheme is particularly designed for search, rescue, and special operations where UAVs are responsible for sensing and tracking things on the ground. Due to 3D coverage, where UAVs are flying at different heights and high mobility, the position information of UAVs in a particular region is required to have reliable communication. Considering these practical scenarios, we have proposed the PMPHR scheme, which utilizes the PHC to share the position information of all UAVs in the network. The position information helps the UAVs to find the shortest path across the network. Moreover, UAVs have different speeds in different scenarios. Let us assume that UAVs are assigned in a forest rescue scenario, where they are responsible for controlling the fire and sharing ground information. Initially, the PHC-UAV (which has access to all UAVs’ positions) collects the information of the whole network and shares to all UAVs. Based on the shared information, the UAVs easily communicate with each other and ground users. Recently, a fire accident happened in Chongqing city of China, where trees on the mountain caught fire. It was difficult for humans to perform rescue operations due to there being no roads on the mountain [52]. Therefore, UAVs were deployed to perform rescue operations, efficiently control the fire, and save valuable things. During rescue operations on mountains, it is very difficult for UAVs to maintain direct communication links and stable topology due to the high mobility and the mountain’s structure. Hence, topology-based and position-based schemes suffer from having unreliable communication, whereas the proposed scheme has
the advantage of a hybrid nature (contains the location information of all UAVs in the routing table), where the PHC can maintain an appropriate location from where it can share the location of all UAVs in the network. Furthermore, UAVs can find the shortest path based on the position information of other UAVs in the network.

5. Conclusions

UAV-based wireless networks require scalable routing, which is a challenging and complex task due to the 3D environment. Due to UAVs’ dynamic nature, topology-based routing suffers as UAVs change their position quickly, whereas position-based routing suffers due to a lack of global routing information. In this regard, this paper proposes the Position-Monitor-based Hybrid Routing Protocol (PMHRP) for 3D UAVs. In addition, three novel methods to select the position-head coordinator under PMHRP are introduced. The three techniques are compared with well-known routing protocols in a 3D UAV network environment. Different mobility scenarios are developed with multiple connection loads to evaluate the efficiency of the proposed scheme. Our simulation analysis shows that the proposed PMHRP with centroid PHC performed better than the GEOC, GEOD, GEOMF, and AODV routing schemes. Even the static variant of the proposed PMHRP has a higher network delay than the proposed random and centroid variants of the PMHRP. The detailed results from a number of experimentations clearly justify that the proposed routing strategies out-perform in terms of delay, packet delivery ratio, throughput, and normalized routing load. The proposed protocol is intended to support UAV architectures’ network coverage and enables air-base stations to connect multiple UAVs. Future research can focus on its applications in this area. For future work, the impact of each UAV’s weight and size on the performance of the proposed scheme can be considered. Moreover, implementing different clustering schemes can bring more improvements. Since PHC has its drawbacks, this work may be extended to include the use of an alternative method (such as the Election Protocol) for choosing the PHC-UAV node before and during simulation.

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