Received September 16, 2018, accepted October 7, 2018, date of publication October 12, 2018, date of current version November 8, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2875739

Location-Aided Delay Tolerant Routing Protocol in UAV Networks for Post-Disaster Operation

MUHAMMAD YEASIR ARAFAT AND SANGMAN MOH, (Member, IEEE)
Department of Computer Engineering, Chosun University, Gwangju, 61452 South Korea

Corresponding author: Sangman Moh (smmoh@chosun.ac.kr)

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), Ministry of Education, under Grant NRF-2016R1D1A1A09918974.

ABSTRACT Wireless communication is essential for search and rescue operations in the aftermath of natural disasters. In post-disaster scenarios, unmanned aerial vehicles (UAVs) can be used to capture image and video data from the disaster area and transfer the data to a ground station, owing to their rapid mobility. However, packet forwarding is a challenge because of unstable links and intermittent connectivity in highly dynamic UAV networks. In this paper, we propose a location-aided delay tolerant routing (LADTR) protocol for UAV networks for use in post-disaster operations, which exploits location-aided forwarding combined with a store–carry–forward (SCF) technique. Ferrying UAVs are introduced to enable an efficient SCF, and this is the first attempt at introducing and using ferrying UAVs for routing in UAV networks, to the best of our knowledge. Ferrying UAVs improve the availability of connection paths between searching UAVs and the ground station, thus reducing end-to-end delays and increasing the packet delivery ratio. Future UAV locations are estimated based on the location and speed of UAVs equipped with a global positioning system. The forwarding UAV node predicts the position of the destination UAV node and then decides where to forward. The proposed LADTR ensures that the contact rate between UAV nodes remains high, which enables a high packet delivery ratio, and ensures single-copy data forwarding to avoid replication of each message. Our performance study shows that the proposed LADTR outperforms the four typical routing protocols reported in the literature in terms of packet delivery ratio, average delay, and routing overhead.

INDEX TERMS Unmanned aerial vehicle network, routing protocol, store-carry-forward, delay tolerant networking, data ferry, location awareness.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are promising as a new application area for military and civil use due to the rapid deployment of network technologies such as low-cost Wi-Fi radio interfaces, sensors, global positioning system (GPS), and micro-embedded computers [1]. In modern times, UAV devices have been used in several civilian applications; some examples include public protection, disaster search and rescue operations, post-disaster operation, relief operations, surveillance and reconnaissance, farming, goods transportations, filmmaking, managing wildfires, public safety, homeland security, remote sensing, traffic monitoring, and relaying in ad hoc networks. Mini-UAVs that weigh up to a few kilograms that contain server sensors, a small camera, a wireless communication system, embedded microcomputers, and GPS, are available for use in collecting information and transmitting mostly large-size data to a ground station [2]. In time-sensitive scenarios, data transmission delay is a key issue to consider [3].

There are two kinds of UAV systems: single-UAV and multi-UAV systems. In a single UAV system, a UAV device is linked with a ground base station. In the multi-UAV system, there will be several UAV nodes. All nodes can be variants with different topology, such as star, mesh, or cluster-based topology. All UAV devices can be linked with each other and with the ground base station. In a multi-UAV system, the UAV's device connection can take two patterns; the first is UAV to UAV (U2U), and the second is UAV to ground station (U2G). A multi-UAV network may provide coverage over a large area and high throughput by creating an ad hoc multi-hop flying wireless network [4]. The highly dynamic topology of UAV networks—because of their dynamic three-dimensional environments and highly fluctuating speeds—may impair the quality of wireless links [3]. Frequent changes in link quality and disconnection has impacts on end-to-end transmission. Another challenge is the range restriction between UAVs and a ground station. Therefore, high mobility, dynamic topology, and uneven UAV distributions make the development of a routing protocol ensuring reliable communication difficult in UAV networks. The unique features and characteristics of UAV networks are different from those of mobile ad hoc networks (MANET) and vehicular ad hoc networks (VANET).

UAV networks require highly accurate location data with small time intervals because of their high speeds and different mobility patterns in a multi-UAV environment. GPS provides position information at one-second intervals, which may not be adequate for UAV network protocols. For this case, an inertial measurement unit was designed, which can be calibrated from the GPS signal to provide the position of a UAV at a quicker rate [5]. For a range of corrections with an accuracy of about 10 m, some researchers proposed differential GPS (DGPS), or assisted GPS by using ground-based reference techniques [6]. The delay tolerant network (DTN) routing protocol was developed to deal with extreme network environments. Moreover, it supports communication scenarios where nodes are sparsely deployed and contacts are short-lived due to high mobility. Data in DTN protocols are transferred hop-by-hop with large buffer size in a store-carry-forward (SCF) fashion. A DTN routing protocol has a relatively large overhead because of the multi-copy routing modes, particularly in a dense network.

Packet forwarding in UAV networks may act as a communication relay and as a data forwarding ferry [7]. Communication ferry forwards the data physically to its destination or the next-hop relay. Communication relaying is a classical approach to extend the network by proper placement of relay nodes. Choosing a UAV network requires rethinking routing protocols for particular scenarios, such as disaster monitoring or search and rescue operations [8]. As GPS provides the location information of UAVs, geographic routing-based data forwarding to the nodes that are especially closer to the destination is a feasible approach [9]. Pure geographic routing is not feasible in UAV networks for data forwarding because of face intermittent connectivity. A well-known approach for UAV networks is DTN networking, allowing intermittent connectivity. However, stochastic knowledge of the moving nodes usually results in long disconnection times in a pure DTN network, primarily due to limited use of flooding. The concept of UAV ferrying may be used instead of traditional DTN schemes. The disconnection time for ferrying UAVs is significantly shorter than that in traditional DTN routing protocols [10]. Probabilistic DTN uses a multi-copy scheme, which is not suitable in UAV networks due to the consequential waste of network resources, particularly in a dense network. Movement-aware-forwarding schemes that borrow their basic disconnected operation from DTNs are rather promising. Hitherto, the DTN routing protocol has been reported for use in the UAV networks presented in [11] and [12].

In this paper, a location-aided delay tolerant routing (LADTR) UAV network protocol for application in post-disaster operations is proposed. Our contributions target the design and development of a location-aware and SCF-based delay tolerant routing protocol for UAV networks. The key contributions of the paper are as follows:

- The proposed LADTR protocol forwards data from the searching UAVs to a ground station with reduced delay. In this paper, ferrying UAVs are introduced for efficient routing and are effectively used in a SCF manner. To the best of the authors' knowledge, this is the first attempt to introduce and use ferrying UAVs for routing in UAV networks. Ferrying UAVs improve path connectivity between searching UAVs and a ground station, resulting in an increased packet delivery ratio and reduced end-to-end delay in UAV networks. In addition, LADTR can also be effectively used in multi-hop forwarding with no ferrying UAV.
- The location-aided forwarding is combined with the SCF technique in LADTR. Future UAV locations are estimated based on the location and speed of UAVs equipped with a GPS. The forwarding UAV node predicts the position of the destination UAV node and then makes a decision on where to forward. Link prediction significantly reduces data packet losses and average end-to-end delay. As a result, LADTR ensures high contact rate between UAV nodes, which enables high packet delivery ratio, and ensures single-copy data forwarding to avoid replication of each message.
- According to the performance study based on the NS-3 simulation, the proposed LADTR outperforms the existing AODV, GPSR, Spray-and-Wait, and Epidemic routing protocols in the same scenarios in terms of packet delivery ratio, average end-to-end delay, and normalized routing overhead.

The rest of this paper is organized as follows. Related research works are examined and summarized in the following section. Preliminaries including the motivating scenario, assumptions, message relaying, and location prediction are presented in Section III. The proposed LADTR protocol is presented with respect to system model, routing decision, and routing algorithms in Section IV. The performance of LADTR is evaluated via computer simulation and compared to the conventional protocols in Section V. Finally, the paper is concluded in Section VI.

II. RELATED WORKS

When the distance between a UAV and a ground station is longer than the communication range, another UAV may be used as a communication relay to maintain continuous path connectivity. Packet forwarding in UAV networks relates to routing protocols in MANETs. However, an unstable wireless link, frequent topology changes, and the high mobility of UAVs make MANET routing protocols impractical in UAV networks. A summary of the routing protocols for UAV networks is shown in Table 1.

TABLE 1. Summary of routing protocols for UAV networks.

Protocol	Routing type	Addressing mode
BATMAN [14]	Multi-hop based routing	Broadcast
GeoDTN+Nav [17]	Packet will convert the DTN mode when the next hop is not available	Unicast
LAROD [18]	SCF and geographic position based forwarding	Unicast
Epidemic [19]	SCF forwarding	Unicast
DTN+MANET [20]	Data is forwarded over an end-to-end path or SCF forwarding is used	Unicast
DTN+MANET [21]	Forward the packet when route is available or store otherwise	Unicast
DTN+ MANET [23]	Integration of a MANET node with DTN	Broadcast
Spray-and-wait [24]	SCF and single-copy direct transmission by each node	Unicast
Store-carry-cooperative [29]	Combination of SCF and Epidemic routing	Broadcast
Store-carry-forward [30]	SCF UAV node with vehicular ad hoc network (VANET)	Unicast

OLSR was evaluated in a network consisting of two UAVs and a ground station in [13]. According to the output, the authors conclude that OLSR cannot cope properly because of rapid topology changes in a UAV network. In [14], Asadpour *et al.* demonstrate that the B.A.T.M.A.N routing protocol has long route convergence time because of topology changes. Multi-copy based DTN routing may be avoided and single-copy based DTN routing can be employed in DTN networks [12]. Multi-copy based DTN routing requires huge overhead when transferring large amount of data [15].

Data ferrying is used to deliver data in disconnected networks. In [11], a hybrid DTN/geographical routing approach is proposed for the multi-UAV based network. The authors proposed estimating the future location of UAVs for data delivery. UAV speed and mobility direction were considered during estimation, and the authors assumed long-range communication between UAVs is required to observe each UAV in the network. A geographical routing protocol was proposed in [16], and the authors estimated the UAV link lifetime using mobility direction and velocity of UAVs. GeoDTN+Nav [17] was designed for ground vehicle navigation, and the SCF method is tied into this routing protocol. This approach may not work because of the nature of UAV mobility in free space. Another location-based routing algorithm for UAV network is LAROD [18]. Similar to our algorithm, LAROD combines geographic routing with the SCF method. LAROD performance is better than Epidemic routing in terms of data delivery ratio and routing overhead. Epidemic routing [19] is another SCF-based routing method, which performs well in terms of link losses and network disconnection. However, because of unnecessary buffer consumption and massive packet duplications, this routing requires large overhead. Ott *et al.* [20], Lakkakorpi *et al.* [21], Raffelsberger and Hellwagner [22], and Moon *et al.* [23] integrated SCF with the adaptive routing method. Nodes find end-to-end routing paths and forward the data accordingly. SCF-based forwarding is used when end-to-end networks break. The authors consider node velocity and node density to decide switching between multi-hop unicast forwarding and SCF forwarding. In [24], Spyropoulos *et al.* proposed a routing protocol called Spray-and-Wait based on the SCF scheme. Spray-and-Wait has been used to limit the number of copies made for a packet in order to control packet replications.

After a disaster, information delivery is critical as disasters destroy the network infrastructure. In [25] the performance of an opportunistic routing protocol is analyzed in a disaster scenario. Fajardo *et al.* [26] proposed an aggregation technique to deliver data with minimum delays. In [27], Johnson and Maltz found that AODV was the routing protocol most suited to a disaster scenario. Many studies have proposed a mobility model to evaluate DTN routing. However, most of these studies are random waypoint mobility models [28]. Ye Aung *et al.* [29] proposed a data delivery solution for opportunistic networks using store-carry-cooperative forwarding (SCCF). In [30], Fawaz *et al.* explored the advantage of SCF nodes to enhance connectivity and reduce end-to-end delay. The ferrying based concept is well-suited to mitigate these limitations and the effects described in a related performance study [31].

III. PRELIMINARIES

UAV networks are a kind of wireless multi-hop networks. They need to ensure data communication between UAVs and a ground station. To provide an emergency communication system after natural disasters, we consider using a multi-UAV network. The availability of multi-hop paths in a UAV network depends mainly on the UAV density within the communication area. However, because the movement and action of UAVs are highly mission-driven, the behavior of nodes in a UAV network is quite different from that in MANETs and VANETs.

A. MOTIVATING SCENARIO

This paper adopts the typical network model shown in Figure 1 to demonstrate the benefits of using UAVs in a post-disaster scenario. UAVs are employed in post-disaster operation such as search and rescue as a demonstrative example scenario. That is, multiple UAVs search for objects and missing people, as well as monitor the disaster-affected area with a geo-tagged camera. Multiple searching UAVs can be sent to different areas to take images.

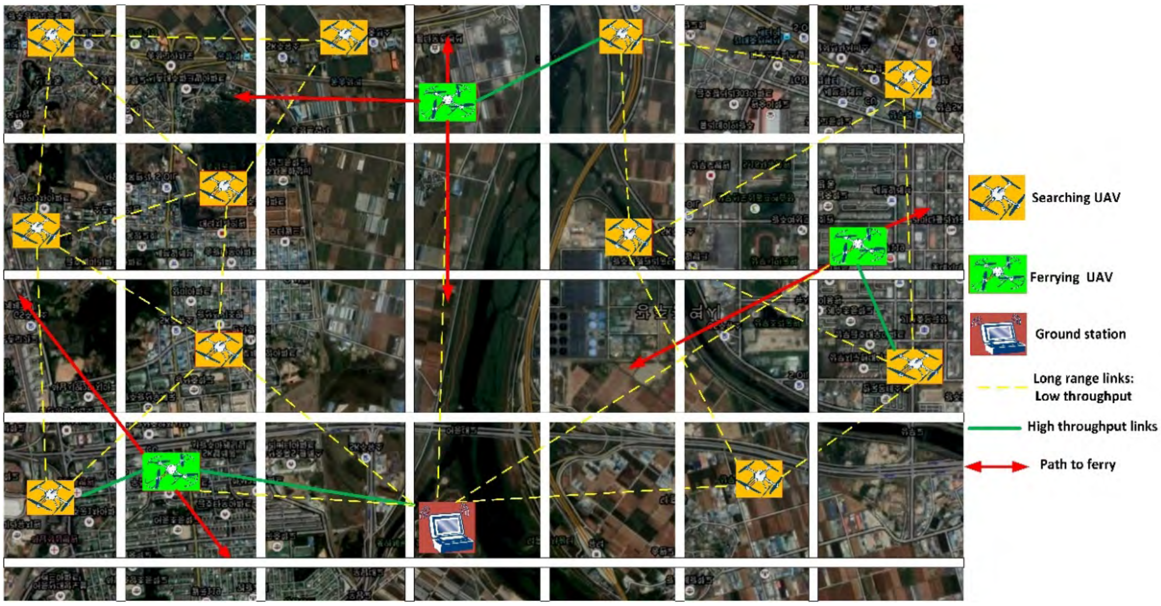

FIGURE 1. UAV-aided search and rescue operation: 11 UAVs are searching for an object and transfer images to a ground station using high-throughput links with limited range. Three ferrying UAVs establish high-throughput connectivity between the searching UAVs and the ground station. Furthermore, long-range links are leveraged for telemetry and control information.

Ferrying UAVs carry large-size images to a ground station via high-throughput links. UAVs and the ground station are aware of their own positions.

In case a UAV moves outside the communication range of the ground station, connectivity has to be re-established through a high throughput link. Data is sent back to the ground station through a long transmission range wireless link from the ground station. Dense deployment of UAVs is a possible solution for maintaining connectivity, but this solution may increase the implementation and operational cost of the network. By using ferrying UAVs, most of the UAVs may spend time searching for the object, while ferrying UAVs may become responsible for transferring data from the searching UAVs to a ground station. In the proposed network model, every UAV, including searching UAVs may also act as ferrying UAV to relay the data if needed.

B. ASSUMPTIONS

Geographic-based routing protocols rely on some location-aware components in the network. These location-aware components allow the routing protocol to operate more accurately and efficiently. Normally, location information can be obtained from another system; the most popular location information provider is GPS. In our proposed routing protocol, we assumed the availability of positioning and motion sensing provided by GPS and inertial measurement units (IMUs) in the UAV. Every UAV in the network knows the location of itself, its immediate neighbor, and the position of a ground station. For safety reasons, a majority of outdoor UAVs may operate in a flat area when monitoring a large area.

C. SCF MESSAGE RELAYING

SCF is realized by forwarding messages to the relay node. This process is known as a ''contact''. As shown in Figure 2, several factors may affect SCF performance. These factors are message generation rate, copy policy (single, multi-copy), buffer size, forwarding policy, drop policy, communication link properties, and mobility. A multi-copy policy wastes network resources. The buffer size and drop policy affect performance. For example, buffer message overflow may be deleted according to the drop policy. To create free space for a new message after time-to-live (TTL) expiration, the old message is dropped according to the drop policy. SCF also considers the data transfer rate and transmission range. The mobility model determines the contact time between a searching UAV and a ferrying UAV.

D. GUESS-MARKOV MODEL BASED LOCATION PREDICTION

The Guess-Markov mobility model [32] is widely used in ad hoc networks. In this model, nodes are placed randomly in the network area, and they move independently. In the proposed model, UAV node trajectory is assumed to be constant in a 2D area, where only the position between the (x, y) axis and z-axis changes. Initially, each node is given a mean speed and mean direction. For every constant time period, a node recalculates its speed and direction based on the values at the previous time step through Gaussian equations. The entire communication area is divided into some grid zone to establish the location prediction model, as shown in Figure 1.

Every grid zone Z is an $(m \times m)$ square. Searching UAVs may search for objects within their transmission range. At time t, a UAV node occupies a certain grid zone, and

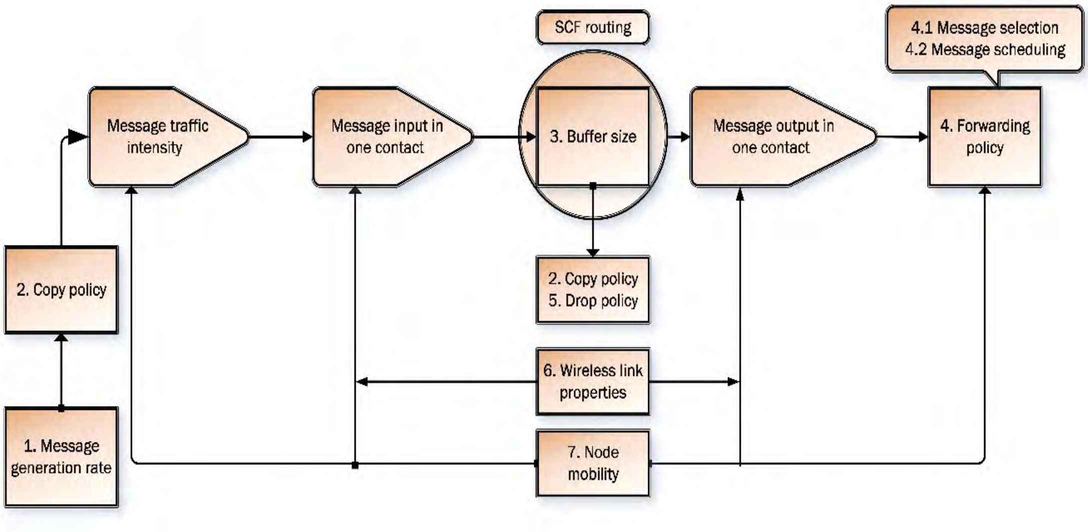

FIGURE 2. **SCF Routing Factors.**

the central point of the gird is regarded as the approximate position of the UAV. We assume there are N grid zones. Markov predictor assumes that location can be predicted from the current context that is the sequence of k most recent symbols in the location history $(a_{n-k+1}, \ldots, a_n)$. Let the location history of a moving UAV be $L = (a_1, a_2, a_3, \ldots, a_n)$, where n represents the number of historical positions sampled at a certain interval Δt, and location a_i is represented by coordinates (x_i, y_i) for $1 \leq i \leq n$. The location history from the i-th sample to j-th sample is denoted as $L(i, j) = (a_i, a_{i+1}, \ldots, a_j)$, where $1 \leq i \leq j \leq n$.

Assuming that the current position of a UAV node is a random variable, the random variable sequence X_i establishes a Markov process, where i is the location after a certain time interval. We consider the location of a UAV to be a random variable X. Let $X(i, j) = (X_i, X_{i+1}, \ldots, X_j)$, where $1 \leq i \leq j \leq n$. Define the context $c = L(n - -k + 1, n)$, for the state k. Let the set of all possible locations represented by A. For all $a \in A$ and $i \in \{1, 2, \ldots, n\}$, the Markov assumption X behaves as follows:

$$\begin{aligned} P\{X_{n+1} = a|X(1, n)\} &= L \\ &= P\{(X_{n+1}) = a|X(n-k+1, n) = c\} \\ &= P\{(X_{i+k+1}) = a|X(i+1, i+k) = c\}, \end{aligned} \quad (1)$$

$$\begin{aligned} P\{X_{n+1} &= a|X(1, n)\} = L \\ &= P\{(X_{n+1})|X_n X_{n-1} = a_n a_{n-1}\}, \end{aligned} \quad (2)$$

and

$$\begin{aligned} P(X_{n+1} &= a|X_n X_{n-1} = a_n a_{n-1}) \\ &= P(X_{k+1}) = a|X_k X_{k-1} \\ &= a_n a_{n-1}\}, \end{aligned} \quad (3)$$

where $P(X_i = a_i| \ldots)$ is the probability that X_i takes a value of a_i. $P\{(X_{n+1}) = a|X(n-k+1, n) = c\}$ is the assumed probability, which depends on the most recent location value of k. $P\{(X_{i+k+1}) = a|X(i+1, i+k) = c\}$ is the stationary distribution probability, which is the same everywhere if the context is the same. The two probability equations $P\{(X_{n+1})$ and $P\{(X_{i+k+1})$ can be represent by a transition probability matrix $\mathscr{M}$. The Markov prediction model predicates the node location according to the current position (a_{current}) and previous position (a_{previous}). Both rows and columns of $\mathscr{M}$ are indexed by the string of length k from A^k. Hence,

$$\begin{aligned} P\{X_{n+1} &= a|X(1, n)\} = L(1, n) = \mathscr{M}(u, u') \\ &= P\{(X_{n+1})|X_n X_{n-1} \\ &= a_n a_{n-1}\}, \end{aligned} \quad (4)$$

where $u = L(n-k+1, n)$ is the current position and $u' = L(n-k+2, n)a$ is the next position. In this case, knowing $\mathscr{M}$ would immediately provide the probability for each possible symbol of L. K_{ij} is defined as the kernel function of Markov process as follows:

$$K_{ij} = P(L_{n+1} = j, T_{n+1} - T_n \leq t|L_n = i) = P_{ij} H_{ij}(t), \quad (5)$$

where $P_{ij} = P(L_{n+1} = j|L_n = i)$ is the transition probability from i to j, and H_{ij} presents the residence time distribution from state i to j and it is defined as follows:

$$H_{ij} = P(T_{n+1} - T_n \leq t|L_n = i, L_{n+1} = j), \quad (6)$$

where matrix $P = \{P_{ij}\}$ is used to donate the transition probability matrix of the random process. The second-order Markov location prediction model is a method for predicting the location of the node at the next moment, according to the current position (a_{current}) and previous position (a_{previous}).

The core prediction mode is based on the transition probability matrix formulated as follows:

$$\mathscr{M} = \begin{bmatrix} P_{11} & \cdots & P_{1j} & \cdots & P_{1n} \\ \vdots & & \vdots & & \vdots \\ & \ddots & & \iddots & \\ P_{il} & \cdots & P_{ij} & \cdots & P_{in} \\ \vdots & & \vdots & & \vdots \\ & \iddots & & \ddots & \\ P_{n1} & \cdots & P_{nj} & \cdots & P_{nn} \end{bmatrix} \quad (7)$$

The core of the prediction model is to establish the transition probability of matrix $\mathscr{M}$ in equation (7). In the above matrix, the row vectors provide the current location context $(a_{\text{previous}}, a_{\text{current}})$, and column vectors provide the next location context (a_{next}).

According to the average node speed, sampling interval Δt is calculated by $\Delta t = \frac{R}{\alpha v}$, where R is the shortest distance between two UAV nodes, v is the average speed of the node, and α is a factor of sampling accuracy. Here, Δt is related to the sampling frequency, and each node should measure the suitable interval and record the positions in equal time duration. Since we do not know $\mathscr{M}$, we can generate an estimation $\widehat{P}$ from the current history L by using current context c of length k. Each entry of the matrix provides the probability of node movement from a row to a column. The probability of transfer matrix for the next symbol a is

$$\widehat{P_k}\ (a) = X_{n+1} = a|L = \frac{N(ca, L)}{N(c, L)}, \quad (8)$$

where c is the previous and current position of node $(a_{n-1}a_n)$, ca is the previous, current and next position of nodes accordingly $(a_{n-1}\ a_n a)$, $N(c, L)$ is the number of c appearing in location L. The probability that a node moves to a, depending on the current situation, can be respesented as

$$\widehat{P_k}\ (a) = X_{n+1} = a|L. \quad (9)$$

Given this estimation, we can define the behavior of the Markov predictor. It predicts the symbol $a \in A$ with the maximum probability $\widehat{P}(X_{n+1} = a|L)$, which is the symbol that follows the current context c most frequently in the history.

IV. LOCATION-AIDED DELAY TOLERANT ROUTING

In this section, the system model of the proposed scenario, the working principle of searching and ferrying UAVs, single-copy data forwarding, and LADTR algorithms are presented in detail.

A. SYSTEM MODEL

In our system model, a set of all UAV nodes in a network is denoted as UAV_w, and two types of UAV nodes are assumed (searching UAVs and ferrying UAVs). The sets of searching and ferrying UAVs are denoted as UAV_s and UAV_f, respectively. That is, UAV_s are employed for searching objects and

Algorithm 1 The Algorithm Is Run by a Searching UAV in Order to Contact a Ferrying UAV

Input: Searching UAV (UAV_s), ferrying UAV (UAV_f), ground station (G_s), neighboring searching UAV (S_u), data packet (P_d)
Output: Data forwarding from UAV_s to UAV_f

for each contact of UAV_s and UAV_f // Data delivery process from searching UAV to ferrying UAV
    if (UAV_f is in range of UAV_s) **then** // Ferrying UAV is in range of searching UAV
        Deliver P_d to $UAV_f \rightarrow G_s$ // Receive data from searching UAV and transmit it to G_s
    else
        if (UAV_f is not in range of UAV_s) **then** // Ferrying UAV is out of range of searching UAV or no available ferrying UAV
            Store-carry-and-wait for UAV_f
        else
            Forward P_d to farthest S_u in range // Forwarding
        end if
    end if
end for

UAV_f are only working as data ferries. In addition, $UAV_s \subset UAV_w$ and $UAV_f \subset UAV_w$. Therefore,

$$\text{Total network elements} = \{(UAV_w \cup UAV_s) \cup (UAV_w \backslash UAV_s = UAV_f)\}. \quad (10)$$

In the considered scenario, each UAV is placed in a specific location, and location information is available to UAV_f. Ferrying UAV_f uses the controlled mobility, and mobility is controlled from the ground station. Ferrying UAV_f collects data (D_c) from the searching UAV_s and sends to the ground station through a high throughput link (HT). UAV_w may change the flight area and behavior when receiving a command message (C_m) through a long, low-throughput (LT) transmission link. Hence,

$$\text{Total data}(D_T) = D_c + C_m. \quad (11)$$

All UAV_w have the larger memory size in order to store data, so no buffer overflow should occur in the network. Algorithm 1 describes the process of data ferrying by actively engaging both searching and ferrying UAVs during contact.

In Algorithm 1, if any UAV_f is within the transmission range of UAV_s, then UAV_s transfers the data to UAV_f. Otherwise, the UAV_s stores the data until it meets any UAV_f. UAV_s transfers the data to UAV_f after the two UAVs meet. Finally, UAV_f forwards the data to ground station G_s. In the second attempt, if no available UAV_f is within the transmission range, UAV_s forwards the data to the farthest UAV in range, donated S_u. Note that, all UAVs in our proposed model

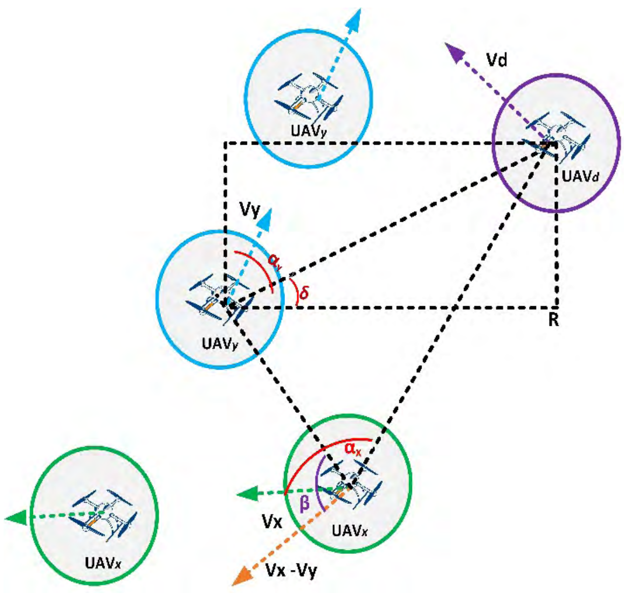

FIGURE 3. UAV position-based contact model.

can act as a UAV_f if needed. Then data will be transferred according to multi-hop UAVs to the ground station.

B. INCORPORATING GEOGRAPHIC INFORMATION INTO ROUTING DECISIONS

The time duration from connection to disconnection between two UAVs is called contact time. Location information is exchanged between searching and ferrying UAVs at the contact time. Contact time affects the maximum throughput and is related to some factors, such as UAV speed, direction, and transmission range.

We used geographic location information provided by GPS to make routing decisions in this model. Route request (*RREQ*) and route reply (*RREP*) packets are modified to include GPS location. Position information decreases the route setup time, which ultimately decreases the routing overhead. In place of flooding of RREQ during route discovery, we used the relative speed of a UAV node in the route discovery process.

Two connected UAVs or contact UAVs are shown in Figure 3. One is UAV_x and another is UAV_y, each with speeds V_x and V_y, respectively. The transmission ranges are R_x and R_y and the data transmission rates are T_x and T_y, respectively. The angle β formed between the two UAVs can be calculated as

$$\beta = arccos\frac{V_x.V_y}{|V_x|.|V_y|}, \tag{12}$$

where the angle $\beta \in [0, \pi]$. The UAV contact duration (C_d) can be calculated using

$$C_d = \frac{2\left(R_x + R_y\right)\cos\beta}{\left|V_x - V_y\right|} = \frac{2\left(R_x + R_y\right)(V_x.V_y)}{\left|V_x - V_y\right|\left|V_x\right|\left|V_y\right|} \tag{13}$$

The maximum throughput at contact is related to the movement speed, direction, and transmission range of UAV nodes. From (12) and (13), the maximum throughput (T_m) of the contact can be calculated as follows:

$$T_m = C_d \times T_s, \tag{14}$$

where T_s represents the transmission speed. After the contact begins, T_m decreases gradually. Assuming that the contact begins at time C_b, the remaining maximum throughput Tc_k at time C_k can be calculated as follows:

$$Tc_k = \{C_d - (C_k - C_b)\} \times T_s. \tag{15}$$

Location information is used by the ferrying UAV to estimate the time required to visit the searching UAV. Suppose the location information for UAV_x and UAV_y can be represented as $L_x(P_x, Q_x)$ and $L_y(P_y, Q_y)$, respectively, and the predicted location of the destination UAV_d is $L_d(P_d, Q_d)$. The vector distance between the two contact UAVs and the destination UAV are $\overrightarrow{XD} = (P_d - P_x, Q_d - G_y)$ and $\overrightarrow{YD} = (P_d - Q_x, Q_d - Q_y)$, respectively. The angles between the location and velocity vectors are

$$\alpha_{xd} = arccos\frac{\overrightarrow{XD}.V_x}{\left|\overrightarrow{XD}\right|.|V_x|} \text{ and } \alpha_{yd} = arccos\frac{\overrightarrow{YD}.V_y}{\left|\overrightarrow{YD}\right|.\left|V_y\right|} \tag{16}$$

Location estimation is used to estimate the time that the searching UAV needs before having contact with the ferrying UAV. The UAV contact time can be estimated as

$$C_{xd} = \frac{\sqrt{(P_x - P_d)^2 + (Q_x - Q_d)^2}}{V_x Cos\alpha_{xd}} \tag{17a}$$

and

$$C_{yd} = \frac{\sqrt{(P_y - P_d)^2 + (Q_y - Q_d)^2}}{V_y Cos\alpha_{yd}}, \tag{17b}$$

where C_{xd} and C_{yd} represent the estimation of the time needed for the two searching UAVs (UAV_x and UAV_y in Figure 3) to encounter the ferrying UAV (UAV_d in Figure 3), respectively. The decision to forward data from UAV_x and UAV_y is based on the comparison of C_{xd} and C_{yd}. If $C_{xd} > C_{yd}$, UAV_x will forward the data to UAV_y; otherwise, it will do nothing and process the next data. After successful forwarding, the data D_f will be marked by 1. However, if $C_{xd} < C_{yd}$, no data will be forwarded and D_f will be marked by 0.

Consider that UAV_y is flying with a turning radius R and prediction time of $\mathcal{P}$. The real position of UAV_y is (P_r, Q_r), and the predicted position of UAV_y is (P_p, Q_p). The predicted position of a UAV node for a given prediction time is calculated by liner extrapolation as follows:

$$(P_p, Q_p) = (R, \nu \times \mathcal{P}), \nu \quad \text{is UAV velocity.} \tag{18}$$

The resultant angle is $\delta = \frac{\nu \times \mathcal{P}}{R}$, with $0 \le \delta \le 2\pi$. The real position of UAV_y is $(P_r, Q_r) = \{Cos(\delta) \times R, Sin(\delta) \times R\}$. The UAV position prediction error is calculated as follows:

$$P_e = \sqrt{(P_r - P_p)^2 + (Q_r - Q_p)^2}. \tag{19}$$

Algorithm 2 Single-Copy Data Forwarding

Input: Data transmission queue (Q_d), maximum throughput (T_m), the number of data copies (N_c)
Output: Number of copies of data to be forwarded (D_f)

```
Q_d ← data transmission queue in UAV_x
T_m ← maximum throughput
N_c ← number of data copies
S_d ← size of data
for each contact of UAV_x (Algorithm 1)
    while Q_d != null then
        update T_m; // By (14)
        if (T_m > S_d)
            while N_c == 1
                Use UAV destination node prediction
 model L_d(P_d, Q_d)
                Measure C_xd and C_yd; // By (17)
                If (C_xd > C_yd) then D_f = 1;
                else D_f = 0;
                end if
            end while
        else
            remove data from queue Q_d;
        end if
    end while
end for
return D_f;
```

In Algorithm 2, when two UAVs meet for forwarding data, they exchange location and speed information. Suppose UAV_x is the searching UAV, UAV_y is the ferrying UAV, and UAV_x wants to transfer data to UAV_y. After transferring data successfully, the searching UAV_x removes the old data from the queue and start saving new data. Detailed procedures are given in Algorithm 2.

C. ON-THE-FLY DECISION OF THE NEXT UAV

A score value is calculated in the ferrying UAV for each searching UAV_s in the network. Based on the score value, the ferrying UAV decides to visit a particular searching UAV. The maximum value may take priority. The score function is

$$\text{Score}(UAV_z) = \frac{fb_o\,(UAV_z) + Ivt(z)}{D(UAV_c, UAV_z)}, \tag{20}$$

where $D(UAV_c, UAV_z)$ is the Euclidean distance between the current UAV(UAV_c) and next candidate UAV (UAV_z), and $fb_o\,(UAV_z)$ is a function which returns a value from the next candidate UAV. The value of $fb_o\,(UAV_z)$ is calculated for UAV node z as follows:

$$fb_o\,(UAV_z) = \frac{|\cup^{i\in N}\, D\,(i, UAV_z)\,|}{\max\,(\{\left|D_{i,j}\right|\, i, j\epsilon N\})}, \tag{21}$$

where i and j are the UAV node index, N is the network notation, and $D_{i,j}$ is the subset of data symbol. $Ivt(z)$ is the normalized value for UAV node z. The value is based on the

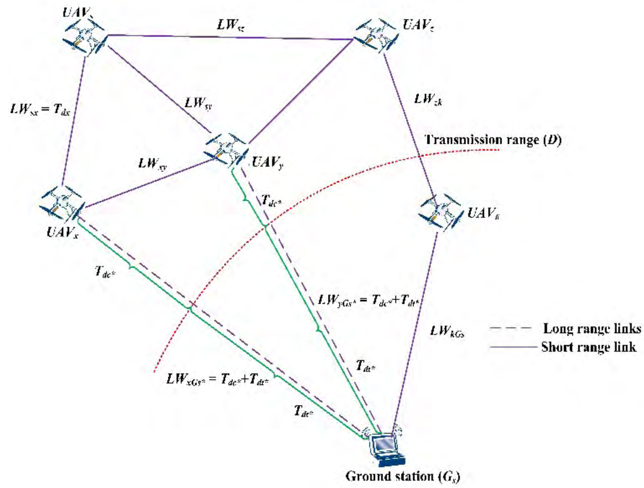

FIGURE 4. UAVs link weight calculation model.

amount of time that the searching UAV has been visited by a ferrying UAV. $Ivt\ (z)$ is calculated as follows:

$$Ivt(UAV_z) = 1 - \frac{vt(z)}{time}, \tag{22}$$

where $time$ is noted as a current time, and $vt(z)$ is the returns the time for the last visit to the UAV node z.

D. UAV NETWORK MODEL

Here, we evaluate the UAV delivery latency. The UAVs are moving within the network area, and every UAV gets its geographic position and predicts its velocity, making it possible to predict further movement. A searching UAV transmits data to a ferrying UAV or the ground station. If neither a ferrying UAV nor the ground station is within the transmission range of a searching UAV, then the searching UAV stores the data and forwards it to the nearest UAV according to the forwarding algorithm. As shown in Figure 4, the transmission delay of data on a single hop is calculated as the sum of the data carried duration (T_{dc}) and the packet transmission time to the ground station (T_{dt}). The end-to-end transmission delay is

$$\Sigma Delay\,(D) = \Sigma T_{dc} + \Sigma T_{dt}. \tag{23}$$

A short-range link occurs when two UAVs are within communication range. In contrast, a long-range link occurs when UAVs are outside the communication range. Two searching UAVs are marked as UAV_x and UAV_y with a geographic distance of d, and $d \le D$ defines the condition for a short range link. Here, D is the transmission range of a UAV node. In our network model, we consider a link weight value. As shown in Figure 4, UAV_s transfer the data through multi-hop DTN forwarding. The source UAV is denoted UAV_s its one hop neighbor UAV is denoted UAV_x, and the link weight between them is

$$LW_{sx} = T_{dc} = \frac{T_{data}}{P(UAV_s, UAV_x)}, \tag{24}$$

where T_{data} is the transmitted data from UAV_s to the neighbor UAV. P (UAV_s, UAV_x) is the throughput between UAV_s and UAV_x. If no short links exists between UAV_x and the ground station (G_s) then UAV_x must carry the data from the present position to the nearest hop or to the ground station. The weight of a long range link from UAV_x to the ground station (G_s) is denoted LW_{xGs*}.

$$LW_{xGs^*} = \Sigma T_{dc^*} + \Sigma T_{dt^*} \quad \text{and } T_{dc^*} = \frac{T_{data}}{P(UAV_x, G_s)} \tag{25}$$

The transmission delay ΣT_{dc^*} depends on the distance between a UAV node positon and the ground station transmission range (D). In (25), P (UAV_x, G_s) is the distance between UAV_x and the ground station (G_s).

E. FORWARDING ALGORITHM

The proposed LADTR protocol is a location-aware packet forwarding approach with DTN support. In this approach, all UAVs are aware of their own position. All UAVs maintain the topology table, which is periodically updated by a transmitted UAV status message. The topology table maintains the UAV ID, position, link weight value for short and long-range links. In our routing protocol, we employ single-copy data forwarding, i.e., only one copy of the data will be forwarded.

In Algorithm 3, a searching UAV first tries to find a ferrying UAV to transfer data to the ground station. A ferrying UAV contacts a searching UAV in order to share its position and speed information. Afterwards, searching UAVs forward their data to ferrying UAVs. The job of a ferrying UAV is to forward data to the ground station. The ferrying UAV, which holds the data to be forwarded, forwards the data to a searching UAV which has the highest score value defined in (20). If no ferrying UAV is available, the searching UAVs try to find the shortest path or neighboring UAVs. If the shortest path is available, the searching UAVs carry and forward the data to neighboring UAVs, and the neighboring UAVs then forward the data to the ground station via end-to-end delay-tolerant routing. If the shortest path does not exist, the searching UAVs forward the data to the neighboring UAVs with the smallest link weight, or they store the data in case a UAV's own weight is less than or equal to the neighboring UAV's link weight.

V. PERFORMANCE EVALUATION

In this section, the performance of the proposed LADTR is evaluated via simulation using NS-3.27 [33], and it is then compared to the conventional protocols of AODV, GPSR, Spray-and-Wait, and Epidemic routing. In our simulation, the geographic class of NS-3 is used to obtain the GPS information for UAV nodes in the network. To calculate and measure the performance metrics, we use NS-3 trace files and flow-monitor output.

A. SIMULATION ENVIRONMENT

The simulation area is 1000 $m\times$ 1000 m, and the duration of simulation is 12000 s. It is assumed that UAVs are moving

Algorithm 3 End-to-End Data Forwarding From a Searching UAV to a Ground Station

Input: Searching UAV (UAV_s), ferrying UAV (UAV_f), ground station (G_s), nearest searching UAV (S_u), data transmission queue in UAV (Q_d), number of data copies (N_c), Link weight value (LW), transmitted data ($Tdata$)
Output: Successful data forwarding from searching UAVs to the ground station

// Ferrying UAV receives new route from ground station
Ferrying UAV starts moving toward the destination searching UAV
if ferrying UAV arrived
    Ferrying UAV stops moving
end if
Ferrying UAV (UAV_f) starts contact with searching UAV (UAV_s) // **Algorithm 1**
for each contact **do** exchange the routing information, position, and speed of UAV
    if $\exists$ UAV_f in rage of UAV_s
        Established message transmit queue with $UAVs \rightarrow Q_d$
        Calculated the node speed: $\beta = arccos \frac{Vs.Vf}{|Vs|.|Vf|}$
        Go to the single-copy data forwarding // **Algorithm 2** (for checking duplicate data)
        Deliver data from the searching UAV to the ferrying UAV, $Tdata \rightarrow UAV_f \rightarrow G_s$
    else
        $\nexists$ No available UAV_f in range of UAV_s
        Store-carry-wait data in searching UAV_s
    end if
end for
// LADTR (Source UAV, neighbor UAV, $Tdata$) // Sending $Tdata$ from source to destination
if $\exists$ shortest link ($UAV_s \in S_u$) // Deliver data to short-range neighboring searching UAV
    Forward data to nearest hop ($S_u \leftarrow Tdata$) // Route
else
    Calculated the link weight value: $\{LW^* \leftarrow$ $Get\ link\ weight\ for\ source(Src)\ to\ destination(Dst)\}$
    $R \leftarrow Src$
    for ($S_u \in UAV_s$) **do**
        if link weight value (S_u, Dst) $< LW^*$ **then**
            $LW^* \leftarrow$ get link weight value for (S_u, Dst)
            $R \leftarrow S_u$ and $S_u \rightarrow G_s$ // Data reaches ground station
        end if
    end for
    if ($R \neq Src$) **then**
        Forward the data to $R \leftarrow Tdata$ // Transmit
    else
        Store and carry in the searching UAV queue // Carry
    end if
end if

TABLE 2. Simulation parameters.

Parameter	Value
Network simulator	NS-3.27
Simulation time	12000 *s*
Simulation area	1000 *m* × 1000 *m* × 250 *m*
MAC protocol and frequency	IEEE 802.11b (2.4 GHz) Searching UAVs, IEEE 802.11n (5 GHz) Ferrying UAVs
Number of searching UAVs/number of ferrying UAVs	8/2, 12/3, 16/4 (default setup), 20/5, 24/6
Number of ground station	1
Routing protocol	LADTR, AODV, GPSR, Spray-and-Wait, and Epidemic
Transmission range	250 *m*
Propagating model	Two-ray ground reflection model (for searching UAVs) Long distance propagation loss model (for ferrying UAVs)
Traffic type	CBR
CBR rate	2 Mbps
Speed	10-30 *m/s* (default velocity is 20 *m/s*)
Mobility model	Gauss-Markov mobility model and predefined mobility
Traffic load	5 messages/s
Message Size	20-100 kB (default size is 20 kB)
Transport protocol	UDP
Data bundle time-to-live TTL	1200 to 8400 *s*
Bandwidth	11 Mbps (between UAVs) 600 Mbps (between ferrying UAVs and the ground station)

around at an altitude of 250 m. In the first set of simulations, we use 10 UAVs, where two UAVs work as ferrying UAVs with the ground station and the remaining eight UAVs work as searching UAVs. It is assumed that the searching UAVs are situated beyond radio transmission range of the ground station. The two ferrying UAVs communicate with the ground station as well as the searching UAVs. Each searching UAV is assigned a coverage area of 150 $m \times 150\ m$, and images and data are gathered from within this area.

We test the output by increasing the number of searching and ferrying UAVs. In the simulation, searching UAVs move according to the Guess-Markov mobility model [32] with speeds ranging from 10 to 30 m/s. We use predefined mobility for ferrying UAVs. That is, a ferrying UAVs trajectory is controlled from the ground station, and a ferrying UAV trajectory is defined in a mobility trace file.

We use IEEE 802.11b and IEEE 802.11n radio standards for wireless communication. The searching UAVs use IEEE 802.11b. IEEE 802.11b operating in the 2.4 GHz frequency band, which allows every searching UAV to connect with each other. IEEE 802.11b provides a maximum transmission speed of 11 Mbps and with 200-250 m outdoor coverage. The ferrying UAVs used IEEE 802.11n for high throughput communication, which is well suited for transferring large amounts of data. To avoid interference with IEEE 802.11b, we configure IEEE 802.11n in the 5 GHz radio frequency band. Its outdoor coverage range is around 250-350 m with 150-175 Mbps data transfer speed.

To evaluate the performance of the LADTR routing protocol and compare it with that of AODV, GPSR, Spray-and-Wait, and Epidemic routing, the following three performance metrics are used in our simulation study.

Packet delivery ratio(PDR): The PDR is defined as the fraction of the messages that are successfully delivered to the destination out of the messages that were been generated. A higher value of PDR indicates a more reliable routing protocol.

Average end-to-end delay: Average end-to-end delay is equal to the average time taken by the messages to reach the destination. The average end-to-end delay is calculated for each message successfully received at the destination. Delay is calculated with (23); it contains carry time and the transmission time of messages. A lower delay value reflects the speed with which messages pass through the routing protocol.

Normalized routing overhead(NRO): NRO is defined as the number of routing control packets required to transmit a packet to the destination node. NRO is the ratio of extra packet transmission for packets being delivered from the source node to the destination node. Transmission of duplicate packets would be considered as routing overhead in a multi-copy routing protocol like Epidemic and Spray-and-Wait.

B. SIMULATION RESULTS AND DISCUSSION

In this subsection, the simulation results are summarized and comparatively discussed for various parameters.

1) VARYING THE NUMBER OF UAVS

In this simulation, we evaluate the performance of routing protocols LADTR, AODV, GPSR, Spray-and-Wait, and Epidemic while the varying number of UAV nodes. The UAV average velocity is 20 m/s, message size is 20 kB, buffer size is 20 MB, and transmission range is 250 m.

The simulation output in Figure 5 shows a comparison of packet delivery ratio, average delay, and routing overhead as a function of the number of UAVs in the network for the AODV, GPSR, Spray-and-Wait, and Epidemic routing protocols. The number of UAV, including both searching and ferrying UAVs, increased from 10 to 30. Figure 5(a) clearly shows that the LADTR and Spray-and-Wait protocols demonstrate their effectiveness in delivering more than 85% of the data. When the number of UAVs increases, LADTR shows the best performance compared with other routing protocols thanks to SCF with geographic position. Initially, the packet delivery ratio of LADTR is around 65%. The PDR value for LADTR increases as the UAV node density increases. LADTR performs better in comparison to other routing protocols due to the use of ferrying UAVs and multi-hop forwarding. Spray-and-Wait exhibits a higher PDR compared to Epidemic routing. Epidemic routing exhibits a lower PDR compared to LADTR and Spray-and-Wait because Epidemic routing uses flooding-based forwarding and does not have any packet recovery method in case of route failure. More UAV nodes are connected and more packets are delivered in AODV as the UAV node density increases.

Figure 5(b) shows the average end-to-end delay as the number of UAV nodes varies. As the number of UAV nodes increases, the average end-to-end delay using AODV is shorter than the other protocols thanks to its better network connectivity. The average end-to-end delay in LADTR is lower compared to Spray-and-Wait and Epidemic routing. The end-to-end delay is significantly reduced in LADTR due to the use of ferrying UAVs. The connectivity between UAVs increases as the number of nodes increases, thus, the average end-to-end delay decreases in LADTR. In GPSR, the average end-to-end delay increases when the number of UAV nodes increases. This is due to the non-uniform distribution of UAV nodes and the highly dynamic network topology. Spray-and-Wait has longer delay compared to LADTR. Spray-and-Wait routing works on two phases of spray and wait. In the spray phase, the protocol needs to wait for successful data delivery, which causes further delay.

The normalized routing overload is shown in Figure 5(c). In our study, a duplicated copy of data is also considered as routing overhead. GPSR and AODV have less routing overhead because AODV never replicates packets and GPSR has the light overhead due to the use of beacon packets.

The routing overhead of LADTR is less than that of Spray-and-Wait and Epidemic routing. This occurs because LADTR uses single-copy data forwarding. Epidemic routing forwards many copies of each message. In Spray-and-Wait, the routing overhead depends on the limit placed on the number of data copies rather than the node density. The single-copy method is used for Spray-and-Wait routing in this simulation.

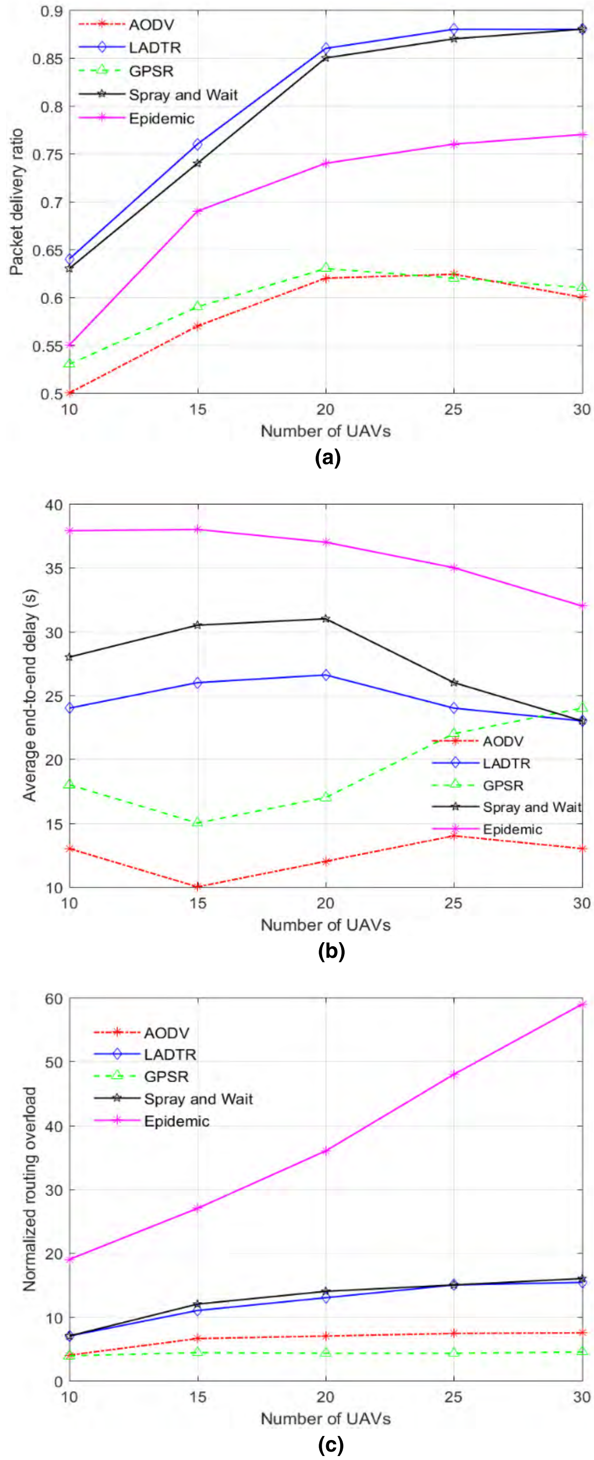

FIGURE 5. Performance metrics as a function of the number of UAVS: (a) packet delivery ratio, (b) average end-to-end delay, and (c) normalized routing overhead.

2) VARYING THE UAV VELOCITY

In this simulation, we evaluate the performance of AODV, LADTR, GPSR, Spray-and-Wait, and Epidemic routing for different UAV velocities. There are 16 searching UAVs with four ferrying UAVs, the message size is 20 kB, buffer size is 20 MB, and transmission range is 250 *m*.

Figure 6(a) shows that LADTR maintains PDR of almost 90% due to the high contact rate between searching and ferrying UAVs. For GPSR and AODV, PDR decreases as UAV velocity increases. The network topology changes frequently due to high mobility, which has an effect on network performance.

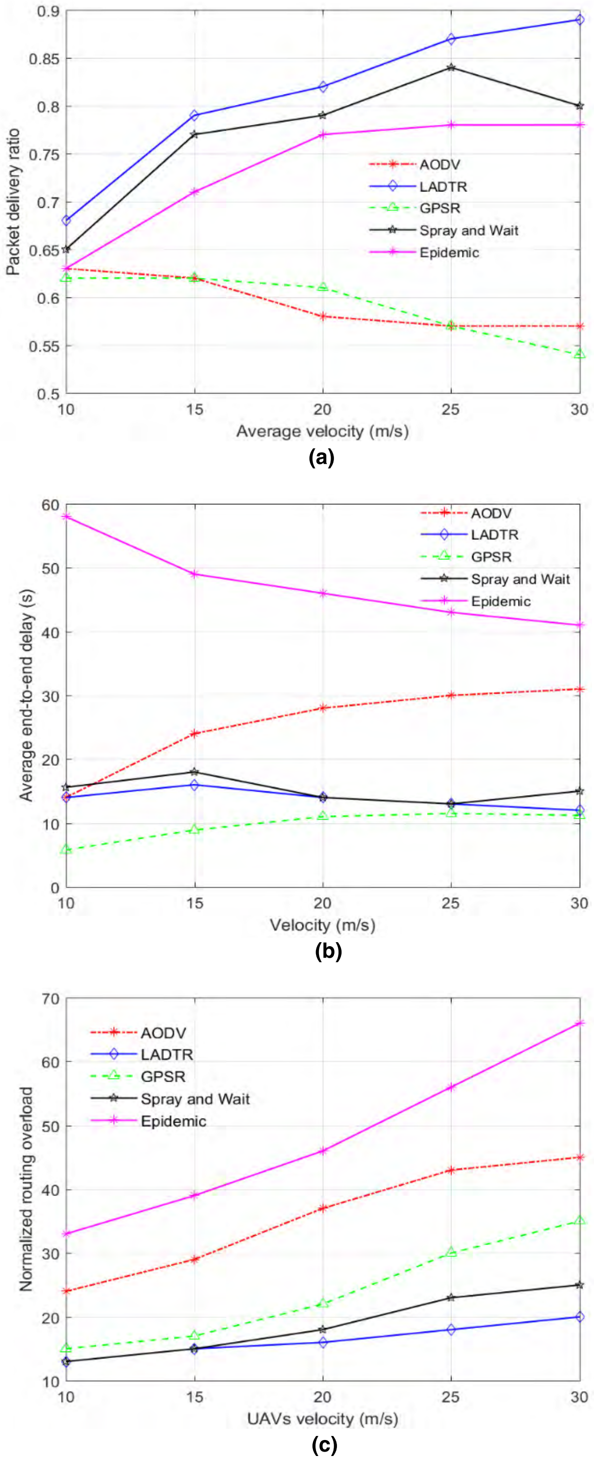

FIGURE 6. **Performance metrics as a function of UAV velocity: (a) packet delivery ratio, (b) average end-to-end delay, and (c) normalized routing overhead.**

Figure 6(b) shows the average end-to-end delay for various UAV velocities. The average end-to-end delay in GPSR is lower than in the other routing protocols. The average end-to-end delay of AODV increases with increased UAV velocity because a routing path is discovered on demand. LADTR shows lower end-to-end delay compared with Spray-and-Wait. This is because the forwarding algorithm ensures lower waiting time and higher contact rate between the searching UAVs and ferrying UAVs. The average end-to-end delay in Epidemic routing decreases when the node velocity increases. This is mainly due to the increased of node velocity, which ensures a higher contact rate. Higher contact rate reduces the end-to-end delay. We also observe that a low contact rate between the UAV nodes greatly increases the waiting time. The long waiting time is the reason for the higher end-to-end delay. In Figure (c), Epidemic routing shows a higher NRO for all velocities. The AODV routing overhead increases because a large amount of time is required to find a path in the high-speed network. The LADTR shows comparatively lower NRO.

3) VARYING THE MESSAGE SIZE

Message size is an important factor to measure performance in DTN environments. The performance of the UAV network is highly affected by traffic load. Larger messages requires more packets. Delivery delay may be large when the network traffic load is heavy. 16 searching UAVs with four ferrying UAVs are used to investigate the performance with various message sizes. The average UAV velocity is 20 m/s, buffer size is 20 MB, and transmission range is 250 m. The message size is varied from 20 kB to 100 kB. Each searching UAV generates 5 messages per second. Each searching UAV generates 20 kB messages at 100 kB/s.

The five routing protocols are compared in terms of different message size in Figure 7. This figure clearly shows that PDR decreases and end-to-end delay increases as the message size increases. Message size has several impacts on routing protocols. For example, a message may be dropped because of lifetime expiry before reaching the ground station, large messages occupy more buffer space, and the number of contacts can decrease due to the large message size. The average end-to-end delay increases in Epidemic routing because of its flooding nature. Figure 7(c) shows that LADTR has a lower NRO compared to the Spray-and-Wait protocol. However, NRO decreases when the traffic load is heavy in Epidemic routing.

4) VARYING THE TTL VALUE

Figure 8 shows how time-to-live (TTL) impacts PDR, average end-to-end delay, and NRO. LADTR and Spray-and-Wait perform better than Epidemic routing. Epidemic routing performs poorly because of the flooding situation in terms of the buffer overflow and bundle drop rate. LADTR forwarding has a lower end-to-end delay because the geographic position-based approach aids in locating a node within a short time period. The single-copy based data forwarding reduces unnecessary data transmission. For this reason, fewer data drops occur during transmission.

The use of geographic information and the single-copy based data forwarding algorithm increases the number of data deliveries and ensures that LADTR can offer a lower delivery delay compared to other routing protocols. Figure 8(c) shows

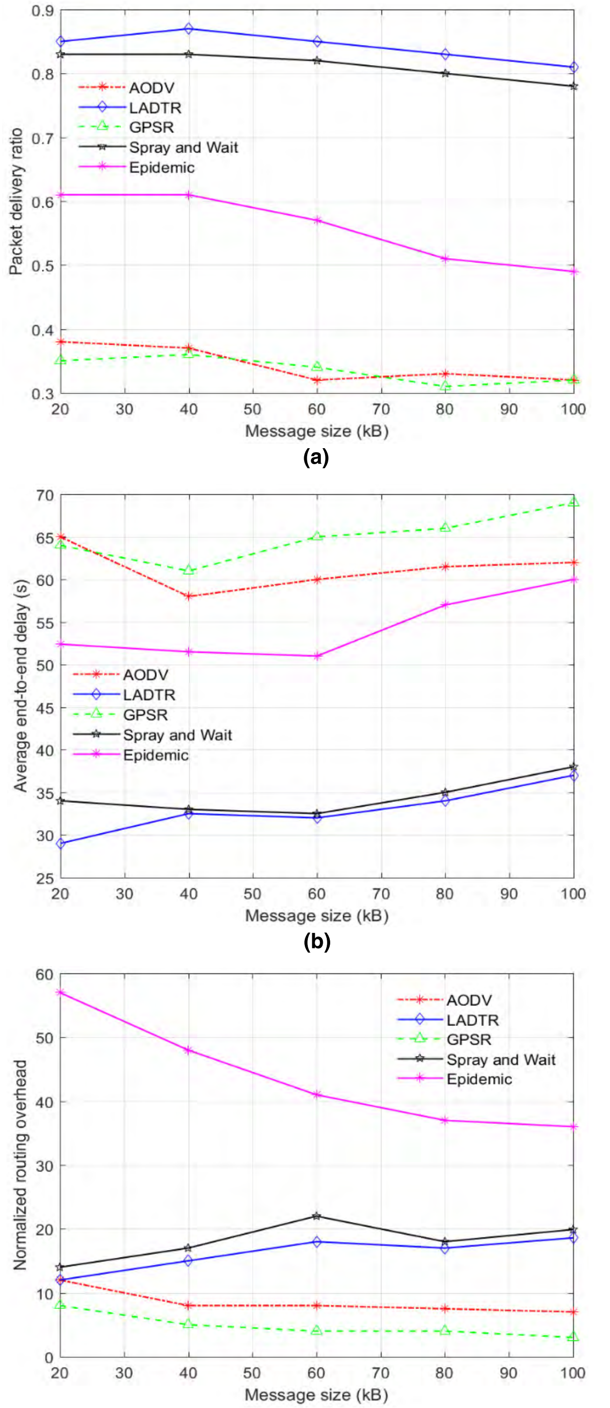

FIGURE 7. **Performance metrics as a function of message size: (a) packet delivery ratio, (b) average end-to-end delay, and (c) normalized routing overhead.**

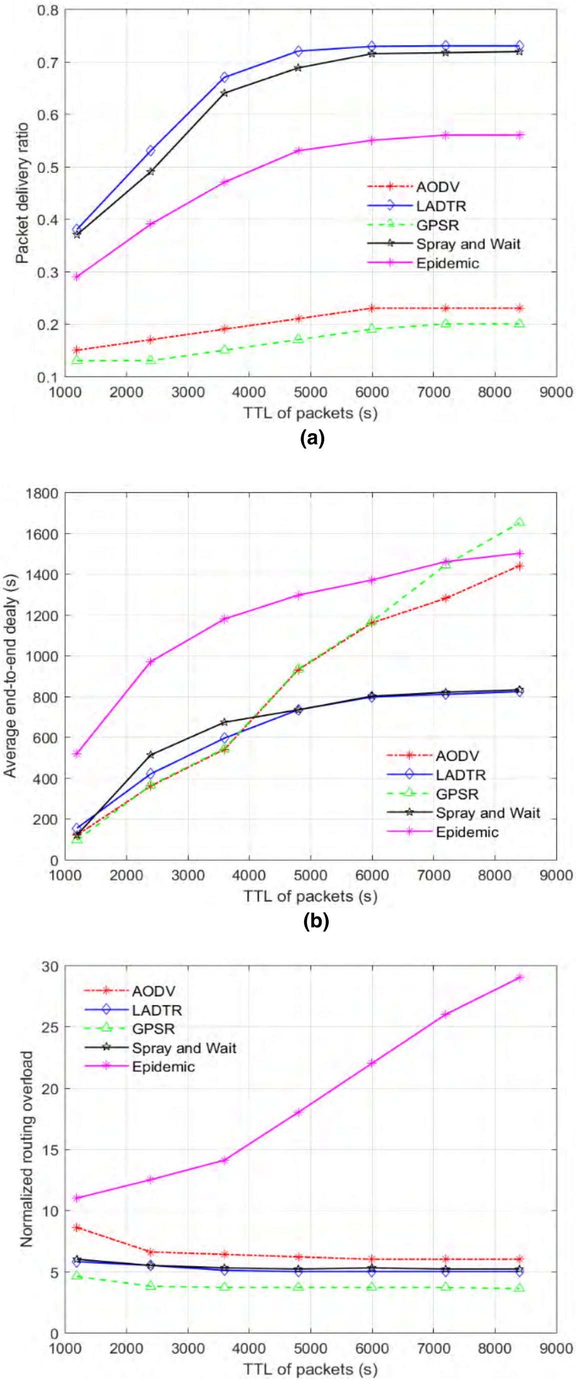

FIGURE 8. **Performance metrics as a function of TTL value: (a) packet delivery ratio, (b) average end-to-end delay, (c) normalized routing overhead.**

that LADTR and Spray-and-Wait have lower overhead ratio due to the advantage of the single-copy forwarding algorithm. However, because of the flooding method, Epidemic routing shows worse NRO performance.

5) VARYING THE BUFFER SIZE

Figure 9 shows how buffer size impacts PDR, average end-to-end delay, and NRO performance. The simulation results show that LADTR performs better in terms of PDR compared with AODV, GPSR, Spray-and-Wait, and Epidemic routing. For Spray-and-Wait, PDR becomes stable when the buffer size is greater than 20 MB. PDR increases as the UAV node buffer size increases in LADTR. LADTR binds the number of copies to a fixed value for this buffer space, and which has less impact on the results.

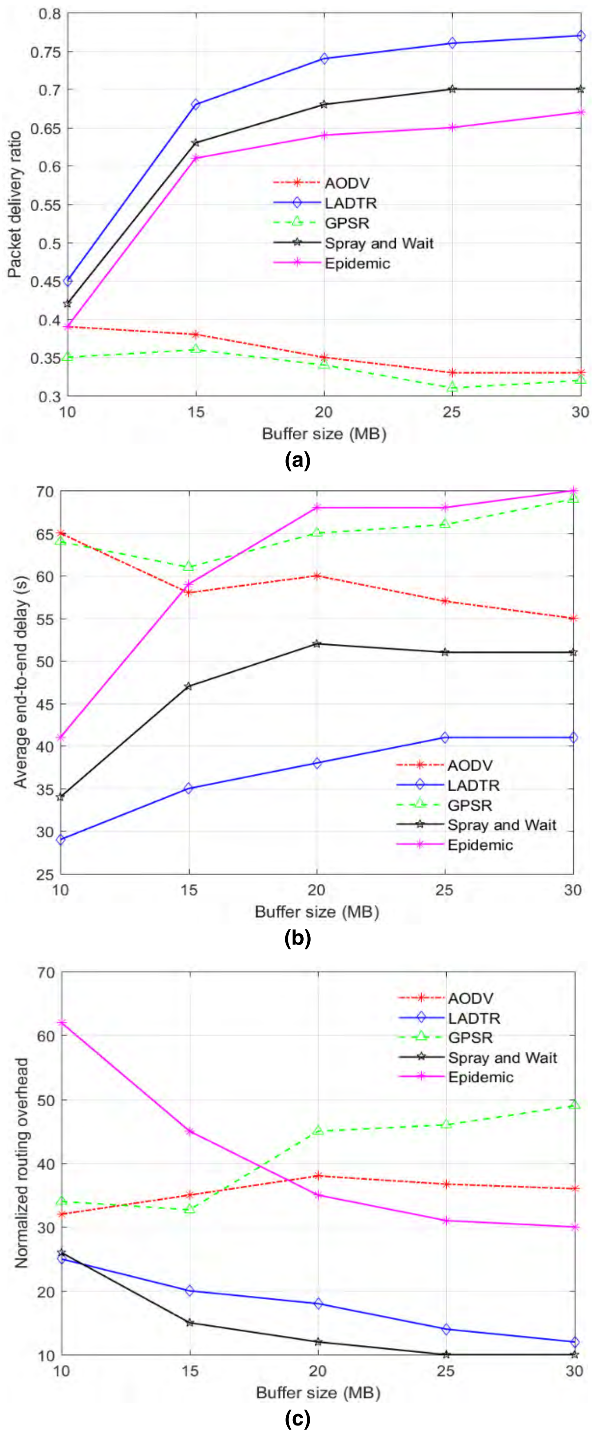

FIGURE 9. **Performance metrics as a function of buffer sizes: (a) packet delivery ratio, (b) average end-to-end delay, and (c) normalized routing overhead.**

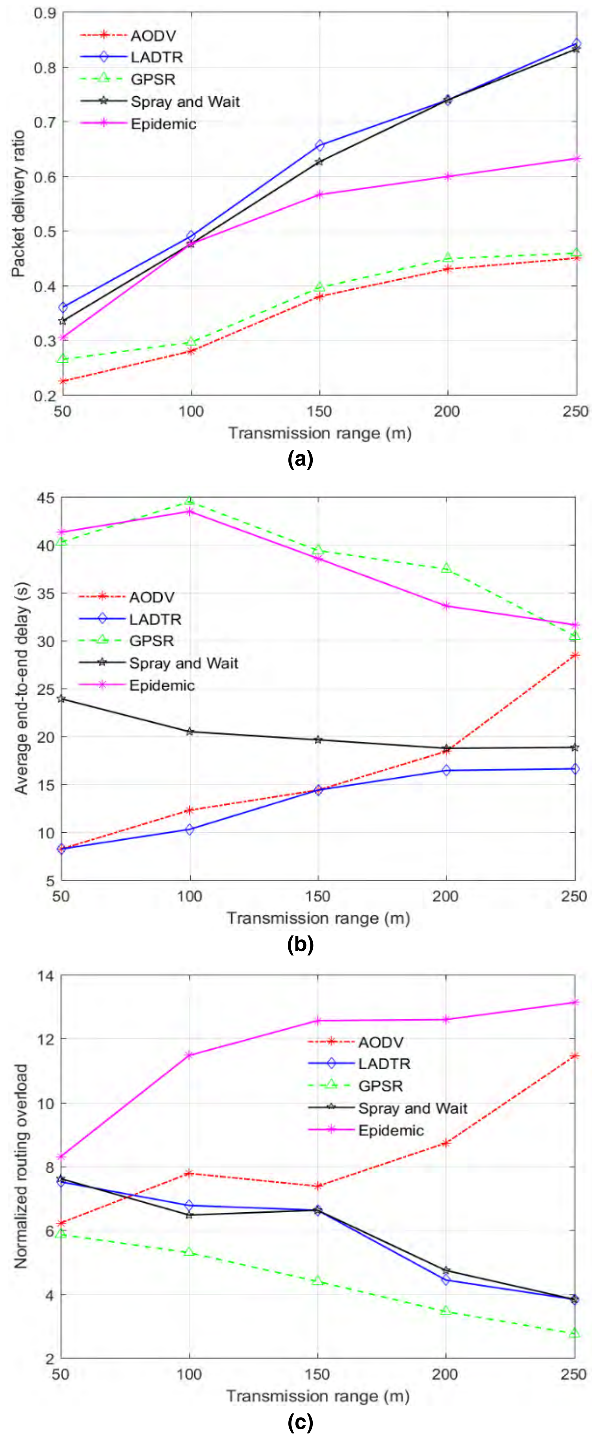

FIGURE 10. **Performance metrics as a function of transmission range: (a) packet delivery ratio, (b) average end-to-end delay, and (c) normalized routing overhead.**

As shown in Figure 9(b), LADTR maintains lower end-to-end delay compared with other routing protocols. After increasing the buffer size, Epidemic routing exhibits higher end-to-end delay due to transmission of multi-copy data. The average end-to-end delay increases slightly when the buffer size is greater than 20 MB for both Spray-and-Wait and LADTR. The location-aided and single-copy data forwarding methods exhibit lower end-to-end delay for LADTR. Figure 9(c) shows a comparison of NRO among the AODV, GPSR, LADTR, Spray and Wait, and Epidemic routing. Spray-and-Wait performs better than LADTR because Spray-and-Wait only sprays the data to the destination node whereas LADTR needs to forwards data to the nearest UAV nodes.

6) ARYING THE TRANSMISSION RANGE

Figure 10 shows the impacts of transmission range. It clearly shows that all routing protocols perform well with a large transmission range. Large transmission range creates more contact opportunities, which increases PDR. Figure 10(a) and (b) show that the PDR increases and the average end-to-end delay decreases as the transmission range increases. Beyond 200 *m* transmission range, AODV shows increased end-to-end delay. Figure 10(c) also shows that AODV exhibits increased NRO because AODV broadcasts more route request (*RREQ*) packets. Epidemic routing shows a higher overhead because of the flooding method. The LADTR exhibits a lower NRO due to the use of GPS and, moreover, because it controls packet forwarding with the LADTR routing approach.

VI. CONCLUSION

UAV networks have unique features and characteristics, such as rapid mobility and highly dynamic topology, which make the design of routing protocols challenging. In such challenging scenarios, compared with other traditional DTN routing protocols, location-aided routing has proven itself to be more realistic and suitable for highly dynamic environments. In this paper, we have proposed a novel routing protocol named LADTR for UAV networks for use in disaster areas, which is a location-aided delay-tolerant routing method combined with node location and SCF schemes. In LADTR, by introducing ferrying UAVs, the searching UAVs enhance network performance compared to other routing protocols. A ferrying-based forwarding path improves the problem of frequent link disconnection. Moreover, single-copy data forwarding ensures high PDR with reduced end-to-end delay and low overhead.

Our extensive performance study show that the proposed LADTR achieves higher PDR, lower end-to-end delay, and lower routing overhead compared to the well-known DTN routing protocols, such as Spray-and-Wait and Epidemic routing. LADTR also outperforms AODV and GPSR routing protocols in terms of PDR, end-to-end delay, and routing overhead. As a result, it can be easily inferred that LADTR is suitable for post-disaster operations.

In the future, we will improve the robustness of location estimation systems by finding the optimal values of the Gauss-Markov model parameters and semi-Markov process model parameters. We also aim to refine the proposed routing scheme for use in different network environments, such as traffic monitoring in vehicular networks.

ACKNOWLEDGMENT

The authors wish to thank the editor and anonymous referees for their helpful comments in improving the quality of this paper.

REFERENCES

[1] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, Nov. 2016, doi: 10.1109/COMST.2015.2495297.

[2] T. Andre *et al.*, "Application-driven design of aerial communication networks," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 129–137, May 2014, doi: 10.1109/MCOM.2014.6815903.

[3] M. Asadpour, D. Giustiniano, K. A. Hummel, S. Heimlicher, and S. Egli, "Now or later?: Delaying data transfer in time-critical aerial communication," in *Proc. 9th ACM Int. Conf. Emerg. Netw. Exp. Technol. (CoNEXT)*, 2013, pp. 127–132, doi: 10.1145/2535372.2535409.

[4] Y. Zhou, N. Cheng, N. Lu, and X. S. Shen, "Multi-UAV-aided networks: Aerial-ground cooperative vehicular networking architecture," *IEEE Veh. Technol. Mag.*, vol. 10, no. 4, pp. 36–44, Dec. 2015, doi: 10.1109/MVT.2015.2481560.

[5] H.-S. Ahn and C.-H. Won, "DGPS/IMU integration-based geolocation system: Airborne experimental test results," *Aerosp. Sci. Technol.*, vol. 13, no. 6, pp. 316–324, 2009, doi: 10.1016/j.ast.2009.06.003.

[6] A. K.-S. Wong, T. K. Woo, A. T.-L. Lee, X. Xiao, V. Luk, and K. W. Cheng, "An AGPS-based elderly tracking system," in *Proc. 1st Int. Conf. Ubiquitous Future Netw.*, Jun. 2009, pp. 100–105, doi: 10.1109/ICUFN.2009.5174293.

[7] M. Harounabadi and A. Mitschele-Thiel, "Applying message forwarding and replication to multi-UAV message ferry networks," *Mobile Netw. Appl.*, vol. 23, pp. 1–10, Mar. 2018, doi: 10.1007/s11036-018-1038-7.

[8] G. Tuna, B. Nefzi, and G. Conte, "Unmanned aerial vehicle-aided communications system for disaster recovery," *J. Netw. Comput. Appl.*, vol. 41, pp. 27–36, May 2014, doi: 10.1016/j.jnca.2013.10.002.

[9] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016, doi: 10.1109/TWC.2016.2531652.

[10] M. Asadpour, K. A. Hummel, D. Giustiniano, and S. Draskovic, "Route or carry: Motion-driven packet forwarding in micro aerial vehicle networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 3, pp. 843–856, Mar. 2017, doi: 10.1109/TMC.2016.2561291.

[11] H. Guo, X. Wang, H. Cheng, and M. Huang, "A location aided controlled spraying routing algorithm for delay tolerant networks," *Ad Hoc Netw.*, vol. 66, pp. 16–25, Nov. 2017, doi: 10.1016/j.adhoc.2017.08.005.

[12] R. Shirani, M. St-Hilaire, T. Kunz, Y. Zhou, J. Li, and L. Lamont, "The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks," in *Proc. 9th IEEE Annu. Commun. Netw. Services Res. Conf. (CNSR)*, May 2011, pp. 161–166, doi: 10.1109/CNSR.2011.31.

[13] A. Jimenez-Pacheco, D. Bouhired, Y. Gasser, J.-C. Zufferey, D. Floreano, and B. Rimoldi, "Implementation of a wireless mesh network of ultra light MAVs with dynamic routing," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 1591–1596, doi: 10.1109/GLOCOMW.2012.6477823.

[14] M. Asadpour, S. Egli, K. A. Hummel, and D. Giustiniano, "Routing in a fleet of micro aerial vehicles: First experimental insights," in *Proc. 3rd ACM MobiHoc Workshop Airborne Netw. Commun.*, 2014, pp. 9–10, doi: 10.1145/2636582.2636832.

[15] A. Balasubramanian, B. N. Levine, and A. Venkataramani, "Replication routing in DTNs: A resource allocation approach," *IEEE/ACM Trans. Netw.*, vol. 18, no. 2, pp. 596–609, Apr. 2010, doi: 10.1109/TNET.2009.2036365.

[16] M. Harounabadi, A. Puschmann, O. Artemenko, and A. Mitschele-Thiel, "TAG: Trajectory aware geographical routing in cognitive radio ad hoc networks with UAV nodes," in *Ad Hoc Networks*. Cham, Switzerland: Springer, 2015, pp. 111–122, doi: 10.1007/978-3-319-25067-0_9.

[17] P.-C. Cheng, K. C. Lee, M. Gerla, and J. Härri, "GeoDTN+Nav: Geographic DTN routing with navigator prediction for urban vehicular environments," *Mobile Netw. Appl.*, vol. 15, no. 1, pp. 61–82, 2010, doi: 10.1007/s11036-009-0181-6.

[18] E. Kuiper and S. Nadjm-Tehrani, "Geographical routing in intermittently connected ad hoc networks," in *Proc. IEEE 22nd Int. Conf. Adv. Inf. Netw. Appl. Workshops (AINAW)*, Mar. 2008, pp. 1690–1695, doi: 10.1109/WAINA.2008.132.

[19] A. Vahdat and D. Becker, "Epidemic routing for partially-connected ad hoc networks," Dept. Comput. Sci., Duke Univ., Durham, NC, USA, Tech. Rep. CS-200006, 2000, doi: 10.1.1.34.6151.

[20] J. Ott, D. Kutscher, and C. Dwertmann, "Integrating DTN and MANET routing," in *Proc. SIGCOMM Workshop Challenged Netw. (CHANTS)*, 2006, pp. 221–228, doi: 10.1145/1162654.1162659.

[21] J. Lakkakorpi, M. Pitkänen, and J. Ott, "Adaptive routing in mobile opportunistic networks," in *Proc. 13th ACM Int. Conf. Modeling, Anal., Simulation Wireless Mobile Syst. (MSWIM)*, 2010, pp. 101–109, doi: 10.1145/1868521.1868539.

[22] C. Raffelsberger and H. Hellwagner, "A hybrid MANET-DTN routing scheme for emergency response scenarios," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops*, Mar. 2013, pp. 505–510, doi: 10.1109/PerComW.2013.6529549.
[23] C. Moon, Y. Kim, D. Kim, H. Yoon, and I. Yeom, "Efficient packet routing in highly mobile wireless networks," *Wireless Pers. Commun.*, vol. 84, no. 2, pp. 1265–1284, 2015.
[24] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait," in *Proc. ACM SIGCOMM Workshop Delay-Tolerant Netw. (WDTN)*, 2005, pp. 252–259, doi: 10.1145/1080139.1080143.
[25] A. Martín-Campillo, J. Crowcroft, E. Yoneki, and R. Martí, "Evaluating opportunistic networks in disaster scenarios," *J. Netw. Comput. Appl.*, vol. 36, no. 2, pp. 870–880, 2013, doi: 10.1016/j.jnca.2012.11.001.
[26] J. T. B. Fajardo, K. Yasumoto, N. Shibata, W. Sun, and M. Ito, "Disaster information collection with opportunistic communication and message aggregation," *J. Inf. Process.*, vol. 22, no. 2, pp. 106–117, 2014, doi: 10.2197/ipsjjip.22.106.
[27] D. G. Reina, S. L. Toral, F. Barrero, N. Bessis, and E. Asimakopoulou, "Modelling and assessing ad hoc networks in disaster scenarios," *J. Ambient Intell. Humanized Comput.*, vol. 4, no. 5, pp. 571–579, 2012, doi: 10.1007/s12652-012-0113-3.
[28] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing* (The Kluwer International Series in Engineering and Computer Science). Boston, MA, USA: Springer, 1996, pp. 153–181, doi: 10.1007/978-0-585-29603-6_5.
[29] C. Ye Aung, I. W.-H. Ho, and P. H. J. Chong, "Store-carry-cooperative forward routing with information epidemics control for data delivery in opportunistic networks," *IEEE Access*, vol. 5, pp. 6608–6625, 2017, doi: 10.1109/ACCESS.2017.2690341.
[30] W. Fawaz, R. Atallah, C. Assi, and M. Khabbaz, "Unmanned aerial vehicles as store-carry-forward nodes for vehicular networks," *IEEE Access*, vol. 5, pp. 23710–23718, 2017, doi: 10.1109/ACCESS.2017.2765498.
[31] M. M. Bin Tariq, M. Ammar, and E. Zegura, "Message ferry route design for sparse ad hoc networks with mobile nodes," in *Proc. 7th ACM Int. Symp. Mobile Ad Hoc Netw. Comput. (MobiHoc)*, 2006, pp. 37–48, doi: 10.1145/1132905.1132910.
[32] J.-D. M. Me Biomo, T. Kunz, M. St-Hilaire, and Y. Zhou, "Unmanned aerial ad hoc networks: Simulation-based evaluation of entity mobility models' impact on routing performance," *Aerospace*, vol. 2, no. 3, pp. 392–422, 2015, doi: 10.3390/aerospace2030392.
[33] (2018). *The Network Simulator ns-3*. Accessed: Apr. 1, 2018. [Online]. Available: https://www.nsnam.org/

MUHAMMAD YEASIR ARAFAT received the B.Sc. degree in electronics and telecommunication engineering and the M.Sc. degree in computer networks and communication from Independent University, Bangladesh, in 2011 and 2014, respectively. He is currently pursuing the Ph.D. degree with the Mobile Computing Laboratory, Chosun University, South Korea. From 2011 to 2016, he was with Amber IT Limited, Bangladesh, as a Systems Manager. His current research interests include ad hoc networks, unmanned aerial networks, and cognitive radio sensor networks, with a focus on network architectures and protocols. He is a Korean Government Scholarship Program Grantee.

SANGMAN MOH (M'91) received the M.S. degree in computer science from Yonsei University, South Korea, in 1991, and the Ph.D. degree in computer engineering from the Korea Advanced Institute of Science and Technology, South Korea, in 2002. Since 2002, he has been a Professor with the Department of Computer Engineering, Chosun University, South Korea. From 2006 to 2007, he was on leave at Cleveland State University, USA. Until 2002, he was with the Electronics and Telecommunications Research Institute, South Korea, where he served as a Project Leader. He has published more than 200 papers in international and domestic journals and conference proceedings and has held more than 40 overseas and domestic patents. His research interests include mobile computing and networking, ad hoc and sensor networks, cognitive radio networks, and parallel and distributed computing systems. He serves on the program committees of international conferences and workshops in his areas of interest as the Chair or a member. He is a member of the ACM, IEICE, KIISE, IEIE, KIPS, KICS, KMMS, IEMEK, KISM, and KPEA.