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A Course-Aware Opportunistic Routing Protocol for FANETs

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ABSTRACT In recent years, unmanned aerial vehicles (UAVs) have gained popularity in various applications and services in both the military and civilian domains. Compared with the single-UAV scenario, flying ad hoc networks (FANETs) consisting of ground stations (GSs) and UAVs have the advantages of flexible configuration and wide coverage. However, due to significant mobility and highly dynamic topology, designing reliable and efficient routing protocols for FANETs is a challenging task. In this paper, we consider a network that comprises multiple flying UAVs and GSs to transfer messages by multi-hop relaying. We propose a routing protocol, named course-aware opportunistic routing for FANETs (CORF). The UAVs cooperatively exchange aeronautical data with others. The source UAV node (SUN) calculates the transfer probabilities to different neighbors by jointly considering the positions of its neighbors and the destination node. Based on the direction information and the transfer probabilities, the SUN selects the next-hop relay nodes among the neighbor UAVs and GSs. This process continues until the destination node receives the message. The simulation results demonstrate that, the proposed CORF protocol achieves significant performance superiority as compared with the traditional protocols in terms of message delivery rate and network latency.

INDEX TERMS Course information, routing protocol, transfer probability, UAV.

I. INTRODUCTION

In recent years, the rapid development of sensors, embedded devices, and navigation systems such as GPS has enabled the wide application of unmanned aerial vehicles (UAVs) in military and civilian domains [1]–[2]. Examples include disaster relief, emergency communications [3], surveillance [4], reconnaissance [5], and air-ground integrated communication [6]. Moreover, multiple UAVs can share information and cooperate with each other, leading to the flying ad hoc networks (FANETs) [7]. Compared with the traditional mobile ad hoc networks (MANETs), the high mobility and wide range induce significant link quality changes in FANETs. Therefore, towards an efficient cooperation and information exchange among multiple UAVs, it is critical to design efficient routing protocols for message transfer over multiple hops in a FANET.

The FANETs generally comprise multiple Ground Stations (GSs) and UAVs in the sky. One UAV communicates with the GS and all the UAVs transfer messages with each other through single or multiple hops. In general, UAVs distribute sparsely in large a space and are separated by long distances. Meanwhile, the UAVs may move quickly, resulting in highly dynamic network topologies. In addition, since the power supply on UAVs is usually limited, the long-range transmission should be reduced because the signal strength decays exponentially with the increase of distance. As such, multi-hop relaying is quite preferable

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in extending the communication range in FANETs. In the past few decades, many research works have been devoted to routing protocols for MANETs and Vehicular Ad Hoc Networks (VANETs). However, due to the highly dynamic links and unstable wireless channels, those mechanisms that were specially designed for MANETs or VANETs may not be directly applicable in FANETs. Therefore, routing protocols for reliable and power/spectrum-efficient relaying in FANETs has been an important yet challenging issue.

In this paper, we consider a self-organized UAV networks that comprises multiple flying UAVs and GSs. The UAVs and GSs are the network nodes that transmit messages to each other by multi-hop relaying. Considering the characteristics of FANETs, utilizing the opportunistic communications by the movement of UAVs to forward data in a ''store-carry-forward'' manner is a promising approach. In addition, most prior approaches focus on the performance improvement in one single aspect, and do not consider the flying courses of UAVs and the opportunistic delivery of messages. Therefore, there is an urgent need for efficient routing design for FANETs while emphasizing their distinguished features.

Targeting at aforementioned issues for routing in FANETs, we in this paper consider to take advantage of the high mobility and cooperative aeronautical data sharing of UAVs and propose a new routing protocol, named course-aware opportunistic routing for FANETs (CORF). Specifically, the UAVs exchange aeronautical data such as flying courses with each other in a cooperative manner. The source UAV node (SUN) analyzes the flying directions of its neighbor UAV nodes (NUNs) with joint consideration of the destination. Meanwhile, the SUN calculates the transfer probabilities of each neighbor UAV and GS. Finally, the SUN selects the next-hop relay nodes among the neighbor UAVs and GSs by the course information and transfer probability. In this respect, CORF enables efficient message delivery and effectively limits the network overhead. Also, we have performed extensive simulations to evaluate the delivery ratio, routing overhead, and delivery delay.

Compared with the traditional routing protocols, the proposed CORF has several advantages as follows.

- The UAVs are cooperate with other and exchange their course information. In CORF, the SUN selects the next hop considering the courses of NUNs, then CORF can utilize the aeronautical data among UAVs and the mobility of UAVs to improve the performance of routing.
- Since the flying courses and transfer probabilities of NUNs are considered, the scheduled routes tend to traverse regions with high node density where more potential relay nodes are available. Thus, the message relaying reliability is improved.
- Because CORF uses only one-hop local topology information, the overhead for topology information is small. In addition, the computational complexity for route determination (including the flying course analysis, transfer probability calculation, and next-hop selection) is relatively low, which makes it feasible for UAVs with limited computational and energy resources.
- The network topologies of FANETs are 3-D instead of 2-D in territorial MANETs. The routing path is calculated in 3-D space in CORF, which is specially suitable for FANETs due to the different altitudes of UAVs and GSs.

The rest of the paper is organized as follows. Sec. II overviews the related works on routing protocols for FANETs. Sec. III presents the network model of the FANETs, discussing the features and requirements on routing. Sec. IV proposes the GORF scheme and presents the design of the underlying algorithms. Extensive simulations are performed in Sec. V to evaluate the performance. Sec. VI concludes the paper.

II. RELATED WORK

In recent years, UAVs have gained popularity for various applications and services in both the military and civilian domains. The routing is a key issue in FANETs and has drawn great attention.

In the literature, most of the existing works suggest that the routing protocols of FANETs need to adapt to the frequent changes of the network topology. In FANETs where the communication nodes are sparsely distributed, the delivery ratio of information will be greatly reduced, and the delivery latency will increase. For the above situation, cooperative communication mechanisms [8]–[15] or highly accurate localization technologies [16]–[19] are usually adopted to improve performance. Recently, there have also emerged the research works that consider the geographic information in FANETs [20]–[23], [40]–[43]. We have summarized these works in Table 1. For these research efforts, most of them have been devoted to study the positional relationship between UAVs. In contrast, in our work, we fully consider the cooperation among UAVs in a flying, the UAV mobility, and the assistance of GSs for routing path scheduling, which, to the best of our knowledge, have not been studied in the previous works. By the making full use of the features of course information, the proposed scheme achieves better performance than the traditional routing protocols in FANETs.

III. SYSTEM MODEL

In this section we present the network model and graphic model of FANETs.

A. NETWORK MODEL

In this paper, we consider a UAV network that comprise multiple flying UAVs and ground stations (GSs), as shown in Fig. 1. The UAVs and GSs are referred as the network nodes and they transmit messages to each other by multi-hop relaying. The source and destination nodes are in the network. The key issue is to determine the optimal path from a source node (a UAV or GS) to a destination node (a UAV or GS), where the other UAVs and GSs can serve as relay nodes.

TABLE 1. Summary of key contributions and drawbacks of existing works on routing protocols for FANETs.

Reference	Key contributions	Limits
[20]	This study presented a cluster-based routing protocol to ensure the system performance such as throughput, end-to-end delay, and energy efficiency.	These routing protocols adapt to the high-speed topology of FANETs by considering star networks. The star architecture restricts the operative area of groups of UAVs, because the nodes are not allowed to fly out of the communication range of the control center.
[21]	This topology-based flow-oriented adaptive network coding-aware routing scheme for FANETs was presented achieving higher throughput with minimum possible packet transmissions.	
[22]	This authors studied the characteristics of Lora technology and proposed the route searching time that depended on the number of nodes in the network was estimated.	These routing protocols improve network performance by grouping, while not considering the links between UAVs and GSs.
[23]	This work focused on the state-of-the-art, stateless geographic packet routing protocols conceived or adapted for 3-D network scenarios.	
[40]	A jamming-resilient multipath routing protocol for flying Ad Hoc networks was presented.	These routing protocols do not consider that the transmission of messages in FANETs can be opportunistic, and can increase the FANETs performance by carrying the message.
[41]	This authors designed a dynamic routing for flying Ad Hoc networks, and evaluated the link performance and communication range, as well as routing performance through experiments.	
[42]	This authors combined the link prediction with the greedy approach to determine the next hop forwarder to the destination.	These routing protocols use greedy algorithms in the process of data forwarding, resulting significant overhead and complexity.
[43]	This authors presented link stability estimation-based preemptive routing protocol for FANETs.	

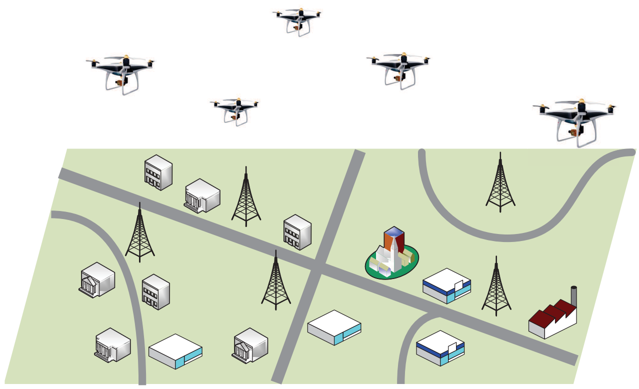

FIGURE 1. Network model of FANETs.

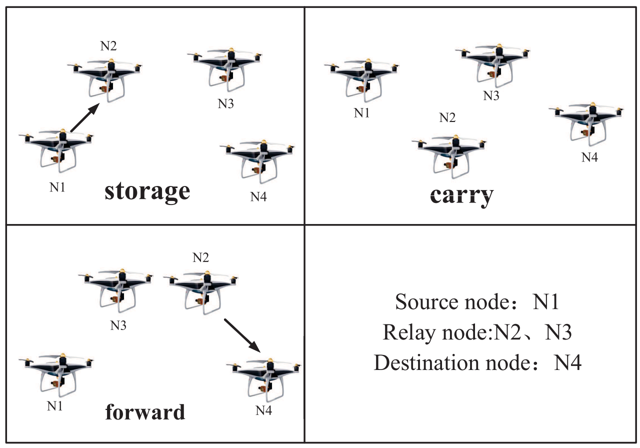

FIGURE 2. "Storage-Carry-Forward" method.

B. GRAPHIC MODEL

To effectively model and analyze the network, we employ the undirected graph. The model consists mainly of node sets and link sets that can be defined as

$$G = \{V, E\}, \tag{1}$$

where V is the communication node set, and E is the communication link set.

When a message is transmitted from the source node $V1$ ($V1 \in V$) to the destination node $V2$ ($V2 \in V$), it needs to find a path set from $V1$ to $V2$ of the link set. The path set can be defined by

$$\text{path}\{V1, V2\} = \{V1, l_0, l_1, \ldots, l_n, V2\}, \tag{2}$$

where l_n is the relay node ($l_0, l_1, \ldots, l_n \in V$), and the line between two adjacent nodes, corresponding to the communication link, is the edge, i.e., $\{l_{n-1}, l_n\}, \in E$.

For the FANETs considered in our work, they have the following two distinguished features. First, as the UAVs fly or hover, the communication links become dynamic and change over time. As such, the network graph is time-varying, defined as

$$G(t) = \{V(t), E(t)\}, \tag{3}$$

where t denotes the time. Second, because UAVs usually move faster than typical territorial MANET nodes, the lifetime of end-to-end transmission paths in FANETs is even shorter, but the movement of UAVs can be utilized to carry and forward messages. Therefore, FANETs may use the "storage-carry-forward" method for information transmission. In addition, UAVs usually have line of sight (LOS) paths to each other and to GSs without the being blocked by terrain artifacts. The communication mode is shown in Fig. 2.

Furthermore, the "storage-carry-forward" model is used for data transmission and aims to find an opportunistic path

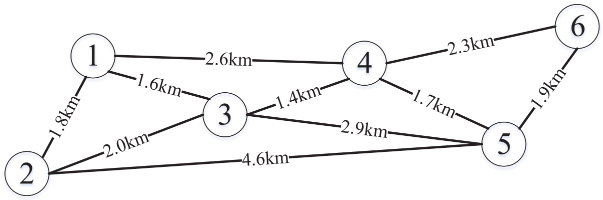

FIGURE 3. Dijkstra's Algorithm.

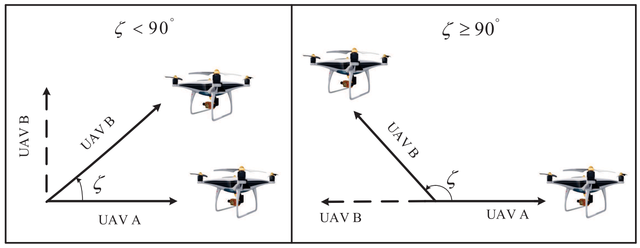

FIGURE 4. A demo of the flying courses of two UAVs.

to transmit information. The opportunistic path is defined as

$$\text{path}\{V1, V2\} = \{(t_1, V1, l_0), \ldots, (t_{n+1}, l_n, V2)\}, \tag{4}$$

where t_n is the time for the n-th hop. According to (4), when the communication node in the network cannot find the next hop for information forwarding, it can cache the message locally and choose an appropriate opportunity later for information transfer. In addition, to facilitate the analysis, we ignore the time for establishing a communication connection between a pair of network nodes, and assume that the information of each node (UAV or GS) can be obtained through GPS.

IV. COURSE-AWARE OPPORTUNISTIC ROUTING FOR FANETS

In this section, we describe the CORF protocol, which mainly includes two steps: a source UAV (having a message to send) calculates the relative flying direction between the communication nodes (UAV or GS), and then utilizes the transfer probabilities as auxiliary information to select relay node adaptively.

A. COURSE INFORMATION

In general, because the UAV's endurance is limited, it prefers the shortest path. The shortest path can be calculated based on the Dijkstra's Algorithm. In addition, in order to prevent collision between the two UAVs, the UAV can only fly along the prescribed route.

Consider the case with 6 UAVs in the network, where Node 1 is the source node and Node 6 is the destination node. The flight route and UAV location are shown in Fig. 3. Node 1 can successfully find one path to send data packets towards destination node by Dijkstra's Algorithm. The shortest path is expressed as

$$L = \min(D_1, \ldots, D_n), \tag{5}$$

where n is the number of paths, and D_n is the path length.

In FANETs, in order to improve the message delivery ratio, nodes usually based on the Epidemic method adopt to send message [31]. The number of network copies is

$$C = C_{source} + C_{relay}, \tag{6}$$

where C_{source} is the number of copies produced by the source node, and C_{relay} is the number of copies produced by relay nodes. However, this way results in a large number of redundant copies in the network, consuming network resources. As such, we propose to control the number of network copies. We define the $PublicInformation(PI)$ and the $Acknowledgement(ACK)$ as follows.

- PI is the message that contains five parts, the vector, position, source, time to live (TTL), and payload. The vector contains information of the direction and speed of the UAV. Position information is acquired from GPS. TTL is the remaining survival time of the PI. Payload corresponds to useful data to be transmitted.
- ACK contains three parts, vector, position, and number. The vector and position are the same as defined in PI. Number is denotes the times that the ACK was received.

B. DIRECTION CALCULATION

In CORF, the node with PI broadcasts to its surroundings in a fixed time interval, and decides whether to forward according to the received ACK. CORF makes decisions through a two-step strategy, including direction calculation and transfer probability calculation.

CORF uses only one-hop local topology information to select the relay node. The basis for the selection is to calculate the direction in which the UAV is flying. Direction calculation is mainly divided into the following two aspects.

1) THE RELATIVE FLYING DIRECTION BETWEEN TWO COMMUNICATING UAVS

Suppose that UAV A needs to transfer a message, and UAV B is the destination node or the next-hop relay node. According to their course information, the relative flying direction between the two UAVs is calculated by

$$\begin{aligned} \zeta &= \cos^{-1}\frac{\vec{V_A}\,\vec{V_B}}{|\vec{V_A}||\vec{V_B}|} \\ &= \cos^{-1}\frac{A_{VX}B_{VX} + A_{VY}B_{VY}}{\sqrt{(A_{VX}{}^2 + A_{VY}{}^2) + (B_{VX}{}^2 + B_{VY}{}^2)}}, \end{aligned} \tag{7}$$

where $\vec{V_A}$ and $\vec{V_B}$ are the velocity vectors in the 3-D space of UAVs A and B respectively, and ζ is the angle between the courses of the two UAVs. If $|\zeta| < \pi/2$, the UAVs A and B are flying in the same direction, and if $|\zeta| \geq \pi/2$, they are flying in the opposite direction, as shown in Fig. 4.

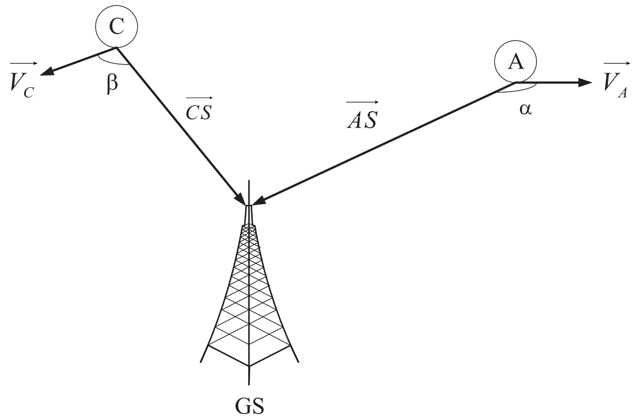

FIGURE 5. Diagram of the node *A* and the node *C*.

2) THE RELATIVE FLYING DIRECTION OF UAVS AND A GS

As shown in the network model in Sec. III, there are GSs in the FANET and they can be the source, relay, or designation nodes. As an illustration, we consider the scenario that a GS serves as a relay node for two UAVs, and this model can be conveniently extended to other cases. CORF defines two relative states of the UAV and the GS: flying toward the GS and flying away from the GS. CORF can obtain the directions by calculating the UAVs' velocity vector and angle relation.

We define two relative states between a UAV and a GS: flying toward the GS and opposite to the GS. We can determine the state based on the UAVs' velocity vector with respect to the GS. As shown in Fig. 5, the source UAV, denoted as node A, flies at a speed of $\vec{V_A}$, the destination UAV, denoted as node C, flies at a speed of $\vec{V_C}$. Let S represent the GS. And we define $\vec{AS}$ is the distance vector from the node A to the GS, and $\vec{CS}$ is the vector from C to the GS. In addition, α is the angle between $\vec{AS}$ and $\vec{V_A}$, and β is the angle between $\vec{CS}$ and $\vec{V_C}$. The locations of A and C can be acquired through the GPS, $\vec{AS}$ and $\vec{CS}$ can be acquired from the flying course information.

For the network model in Fig. 5, the angles α and β can be calculated by

$$\alpha = \tan^{-1}(AS_Y/AS_X) - \tan^{-1}(\overrightarrow{V_{AY}}/\overrightarrow{V_{AX}}), \quad (8)$$
$$\beta = \tan^{-1}(CS_Y/CS_X) - \tan^{-1}(\overrightarrow{V_{CY}}/\overrightarrow{V_{CX}}), \quad (9)$$

where $\alpha, \beta \in (0, \pi)$. We can further obtain the results for the following four cases:

- Case 1: if $\alpha < \pi/2$, the source UAV node flies toward the GS;
- Case 2: if $\alpha \geq \pi/2$, the source UAV node flies away from the GS;
- Case 3: if $\beta < \pi/2$, the destination UAV node flies toward the GS;
- Case 4: if $\beta \geq \pi/2$, the destination UAV node flies away from the GS.

C. TRANSFER PROBABILITY

It was shown in [27] that the way nodes move in a network is not random, but they are very likely to move in a repetitive manner. Therefore, the future movement trajectory of a node in such a movement mode can be somehow predicted. For example, when a node passes a position at a certain moment, the possibility for the node to pass the same position again is higher. Thus, we adopt this method to predict whether messages can be successfully transmitted based on the probability theory.

When the nodes A and B (two UAVs or a UAV and a GS) enter the communication range, the predicted transfer probability can be calculated by

$$P_{A,B}{=}P_{A,B_{old}} + (1 - P_{A,B_{old}})P_{init}, \quad (10)$$

where $P_{init} \in (0, 1)$ is a constant, $P_{A,B_{old}}$ is the previous predicted transfer probability. Based on the predicted transfer probability, we know that if the nodes A and B fail to meet in a period, $P_{A,B}$ will decrease and the probability is updated according to

$$P_{A,B}{=}P_{A,B_{old}}\xi^k, \quad (11)$$

where $\xi \in (0, 1)$ is a constant, k is the period that the nodes A and B fail to meet, and $P_{A,B}$ represents the transfer probability of indirectly transfer probability.

D. RELAY SELECTION

According to the FANET model in Sec. III and considering the flying course information and the transfer probabilities of the communication nodes, a source node can adaptively select a neighbor UAV or GS as the next-hop relay based on the direction information and transfer probability. Specifically, there are four cases to be detailed as follows.

- Case 1: When $|\zeta| < \pi/2$, $\alpha \geq \pi/2$, and $\beta \geq \pi/2$, or $|\zeta| < \pi/2$, $\alpha < \pi/2$, and $\beta \geq \pi/2$, we choose the UAV as the relay node. Thus, the source UAV sends *PI* to the relay UAV and receives *ACK* from it.
- Case 2: When $|\zeta| \geq \pi/2$, $\alpha < \pi/2$, and $\beta < \pi/2$, we choose the GS as the relay node. The source UAV sends *PI* to the relay GS and receives *ACK* from the relay GS.
- Case 3: When $|\zeta| < \pi/2$, $\alpha < \pi/2$, and $\beta < \pi/2$, or $|\zeta| < \pi/2$, $\alpha \geq \pi/2$, and $\beta < \pi/2$, the relay node of the next hop needs to be selected according to the transfer probability.
  - Subcase 3-a: If $P_{GS,B} \geq P_{A,B}$, according to (12), we choose the GS as the relay node. The source UAV sends *PI* to the relay GS and receives *ACK* from the relay GS. In this case, the destination UAV is more likely to get information from the GS. When the destination UAV flies into the communication range of the GS, the GS sends *PI* to the destination UAV.
  - Subcase 3-b: If $P_{GS,B} < P_{A,B}$, according to (10), we choose the UAV as the relay node. The source

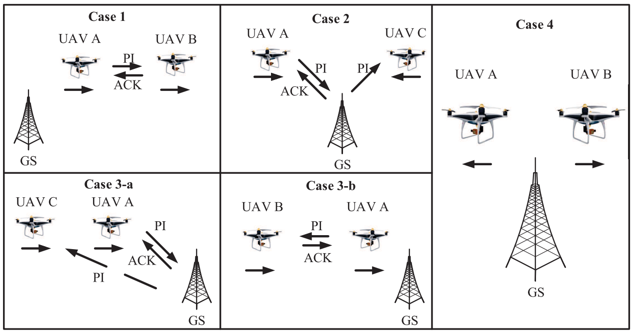

FIGURE 6. Relay selection cases.

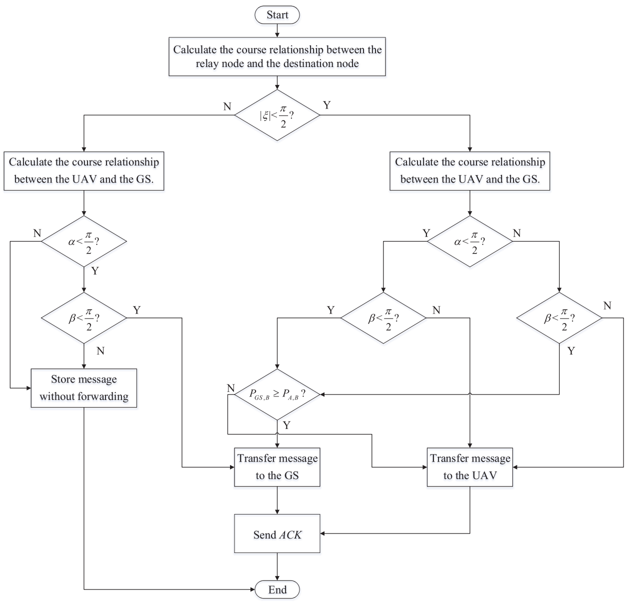

FIGURE 7. Flowchart for the proposed relay selection case of the CORF protocol.

UAV sends *PI* to the relay UAV and receives *ACK* from the relay UAV. In this case, the destination node is more likely to get information from the relay UAV.

- Case 4: In other conditions, the source UAV will continue to hold the *PI* without forwarding.

The relay selection cases are shown in Fig. 6.

The detailed flowchart for the proposed relay selection case of the CORF protocol is shown in Fig. 7. This process continues until the destination node receives the message.

V. SIMULATION RESULTS

In this section, we use the Opportunistic Network Environment (ONE) simulator to evaluate the performance of our proposed routing algorithm (CORF). In our simulations, we use the INFOCOM05 [34] dataset to simulate the message generation and transmission process. The INFOCOM05 dataset contains 30 GSs and 0 to 600 UAVs equipped with IEEE 802.11g wireless devices to collect the connection information in a period of 5 hours. Besides, the source and destination nodes are randomly selected from the dataset. The source node generates message at a rate of 25.0 to 35.0 packet/sec, and the message size is between randomly 500 KB and 1 MB.

The UAV uses Shortest Path Map Based Movement (SPMBM) to plan the course, and the speed of the UAVs are 40 km/h-70 km/h. The GSs are uniformly distributed in the simulation area. The transmission range and buffer size of each UAV are 300 m and 30 MB, respectively. While 1000 m and 100 MB, respectively, for the GS. The area is of 20 km×20 km. The simulation settings are summarized in Table 2. In this paper, to obtain steady state performance, we have performed 1000 simulation trails and showed the averaged results as follows.

TABLE 2. Simulation parameters.

Category	Parameter	Value
Node	Transfer Method	Wi-Fi
	UAV Transmit Range	300 m
	GS Transmit Range	1000 m
	UAV Speed	40 km/h-70 km/h
	UAV/GS Buffer	30/100 MB
Message	Message Size	500 KB-1 MB
	TTL	5 h
	Message Interval	25 s-35 s

A. METRICS

We compare our proposed routing algorithm with some classical ones, including First Contact [29], Direct Delivery [30], Epidemic [31], Spray and Wait [32], Prophet [27] and Max-Prop [33]. Moreover, we consider the following three different metrics to demonstrate the performance.

1) Delivery Ratio: The ratio of number of messages that have been successfully delivered to the destination nodes to the number of generated messages from the source nodes. The delivery ratio is defined as

$$\text{Delivery Ratio} = \frac{m}{n}, \tag{12}$$

where m is the number of packets received, and n is the number of packets sent.

2) Delivery Latency: The average time duration from message generation unto the successful message reception. It is defined as

$$\text{Delivery Latency} = \sum_{i=1}^{m} T_i, \tag{13}$$

where T_i is information transmission delay.

3) Overhead Ratio: The ratio of the total number of messages created by source nodes to the total number of messages forwarded by all nodes. It is calculated by

$$\text{Overhead Ratio} = \left(h - \sum_{i=1}^{m} F_i\right) \Big/ \sum_{i=1}^{m} F_i, \tag{14}$$

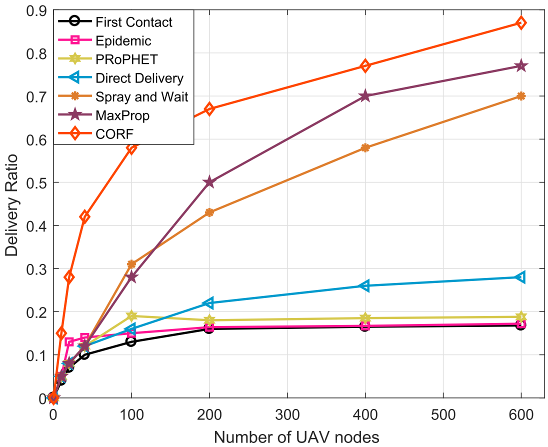

FIGURE 8. Delivery ratio vs. number of UAV nodes.

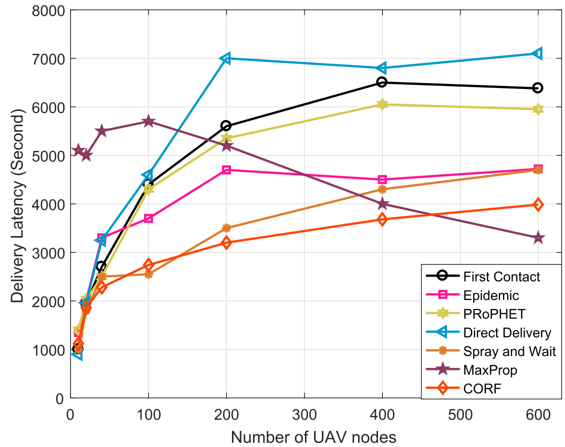

FIGURE 9. Delivery latency vs. number of UAV nodes.

where h is the number of packets, and F_i is the number of successfully packets.

B. IMPACT OF DIFFERENT NUMBER OF COMMUNICATION NODES ON ROUTING PERFORMANCE

In this section, we compare the CORF protocol with some classical routing algorithms with different numbers of UAVs.

Fig. 8 shows that the delivery ratio of all algorithms increases with an increasing number of UAV nodes, because with the more the UAV nodes, the more chances for messages to be transferred. Specifically, relay nodes cannot be adaptively selected in the proposals of First Contact, Direct Delivery, Epidemic, Spray and Wait, Prophet and MaxProp, hence their delivery ratio increases slower than CORF. The delivery ratio of CORF increases can be achieved 86.9%, when UAV communication nodes increase from 0 to 600. Obviously, in terms of delivery ratio, CORF is observed with evident advantages as compared with the other six routing algorithms. In CORF, we use the UAV course information and transfer probability to select the relay nodes adaptively. As a result, CORF is more effective in selecting relay nodes and has a higher delivery ratio.

Fig. 9 shows the results in terms of average latency. We can see that when the number of UAV nodes are more than 200 and lower than 400, CORF has the lowest delay. The MaxProp is an overhead based routing algorithm, when the number of network nodes is higher than 500, MaxProp has the lowest average delay, because MaxProp can transmit information based on message priority. But when the number of nodes is lower than 100, MaxProp has the highest average delay. In Prophet and Spray and Wait routing algorithms, the message carriers must wait for a cooperative node to forward messages, which introduces a long delay.

Fig. 10 shows the overhead ratio. As expected, the overhead ratio of Epidemic and Spray and Wait rapidly increases with the number of UAV nodes, because the schemes are based on flooding. In Spray and Wait, each message has a fixed number of copies, and hence the overhead ratio is

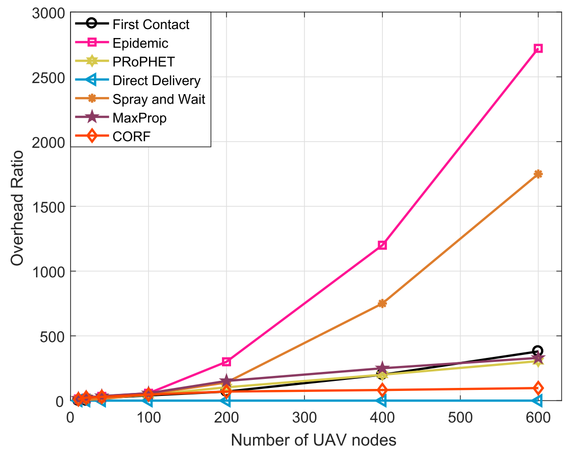

FIGURE 10. Overhead ratio vs. number of UAV nodes.

lower than that of Epidemic. In addition, CORF, MaxProp, and Prophet have a relatively overhead ratio. Compared with other three algorithms, Direct Delivery has the lowest overhead ratio, because it cannot find a relay node, as shown in Fig. 10, so its delivery ratio is the lowest. For CORF, in the process of message forwarding, the source node can choose a suitable relay node according to the flying course information and transfer probabilities, which not only improves the delivery ratio but also keeps a low overhead ratio.

C. IMPACT OF BUFFER SIZE

In this subsection, we consider the impact of buffer size on delivery ratio, average latency, and overhead ratio. In the simulations, we consider the buffer size of the UAV nodes varying from 0 MB to 100 MB and set the number of UAV nodes to 600. All other parameters remain the same with those in the previous simulations.

From Fig. 11, we can see that with the increase of buffer size, the delivery ratio of the baseline algorithms, except Direct Delivery, increases accordingly. When the buffer size is small, more copies of the message will be discarded, so the delivery ratio is very low. In CORF, when the buffer size

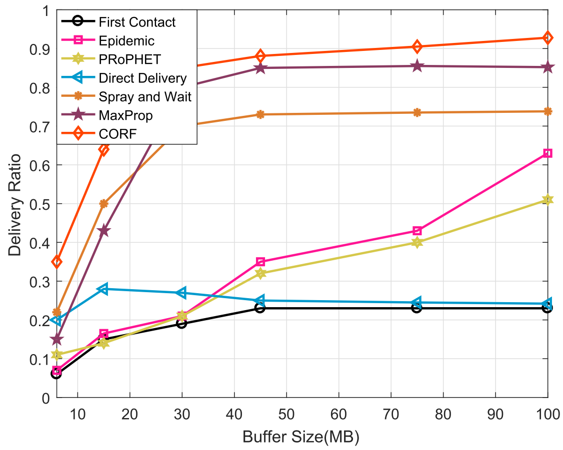

FIGURE 11. Delivery ratio vs. buffer size of UAV nodes.

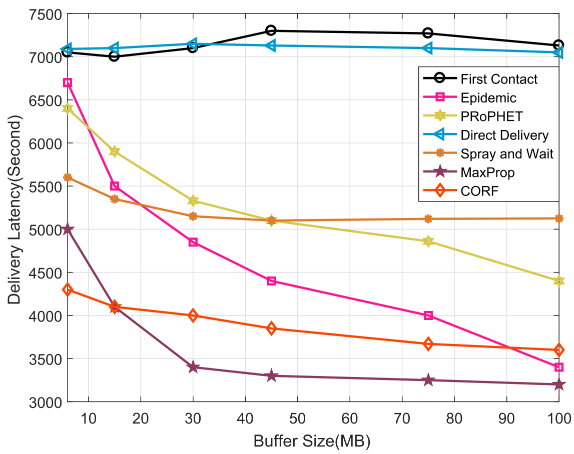

FIGURE 12. Delivery latency vs. buffer size of UAV nodes.

is limited, we adaptively select the appropriate relay nodes based on direction information and transfer probability, so the delivery ratio of CORF is highest. Compared with PRGT, the other five routing algorithms do not have the assistance from the relay nodes (except Direct Delivery). Therefore, the delivery ratio is relatively low.

Fig. 12 shows the comparison in terms of average latency with respect to different buffer sizes. Although the average latency of all five routing algorithms (except First Contact and Direct Delivery) gradually decreases when the buffer size of nodes increases, CORF has the least average latency. For any node in the network, the larger the buffer size, the more copies of different messages can be retained. In Direct Delivery, the source node must wait for the destination node for message forwarding, so the average latency is the highest. Similarly, in Epidemic and Spray and Wait, the source node also needs to wait for a cooperative relay node, which increases the latency of message forwarding.

In Fig. 13, we can see that the overhead ratio of the CORF protocol is similar to that of MaxProp and Prophet, which is much lower than Epidemic and Spray and Wait. In First

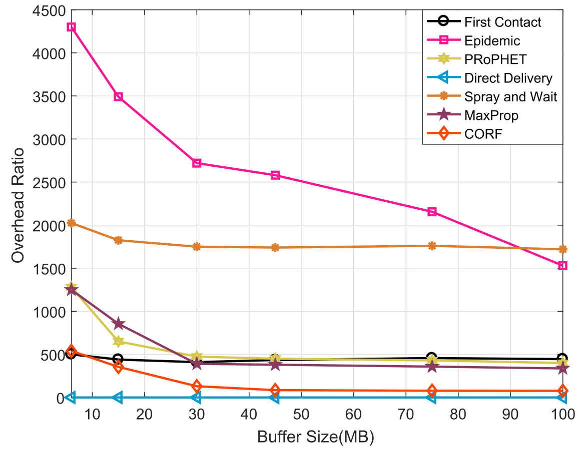

FIGURE 13. Overhead ratio vs. buffer size of UAV nodes.

Contact and Direct Delivery, the copies of messages are zero, so the overhead ratio is also zero. Since Epidemic is a routing scheme based on flooding, the overhead ratio is highest among these routing algorithms.

In summary, the simulation results show that the CORF protocol achieves better performance than the other protocols, owing to the improvement in routing decision making. By calculating the course directions between the communication nodes and the transfer probability, CORF can adaptively select a UAV or GS as the relay node of the next hop. Owing to the evident performance enhancement brought by the proposed CORF protocal, it can be widely used in emergency rescue, smart city and Internet of Things (IoT) domains. For example, in the event of a disaster with base station being damaged and communication blocked, we can quickly deploy the UAVs and establish the communication employing the CORF protocol, helping the rescue and reconstruction.

VI. CONCLUSION

In FANETs, routing plays a key role in cooperative and collaborative network operations. In this paper, we have designed a course-aware opportunistic routing protocol. In the process of message forwarding, based on the flying course information and transfer probabilities, the source UAV can choose a suitable relay UAV or GS that is most likely to forward the information to the destination node. Simulation results show that the proposed CORF protocol has achieved evident performance superiority in delivery ratio, average latency, and overhead ratio, compared with the traditional routing protocols. Therefore, when the number of nodes and node buffer are limited, the CORF protocol can significantly improve network performance without introducing extra communication resource, which indicates a viable routing approach in FANETs.

REFERENCES

[1] M. Y. Arafat and S. Moh, "Routing protocols for unmanned aerial vehicle networks: A survey," *IEEE Access*, vol. 7, pp. 99694–99720, 2019.

[2] M. Y. Arafat and S. Moh, "Location-Aided delay tolerant routing protocol in UAV networks for post-disaster operation," *IEEE Access*, vol. 6, pp. 59891–59906, 2018.
[3] S. Chowdhury, A. Emelogu, M. Marufuzzaman, S. G. Nurre, and L. Bian, "Drones for disaster response and relief operations: A continuous approximation model," *Int. J. Prod. Econ.*, vol. 188, pp. 167–184, Jun. 2017.
[4] J. Guo, Y. Luo, and K. Li, "Robust gain-scheduling automatic steering control of unmanned ground vehicles under velocity-varying motion," *Vehicle Syst. Dyn.*, vol. 57, no. 4, pp. 595–616, Apr. 2019.
[5] T. Kopfstedt, M. Mukai, M. Fujita, and C. Ament, "Control of formations of UAVs for surveillance and reconnaissance missions," *IFAC Proc. Volumes*, vol. 41, no. 2, pp. 5161–5166, 2008.
[6] R. R. Pitre, X. R. Li, and R. Delbalzo, "UAV route planning for joint search and track missions—An information-value approach," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 48, no. 3, pp. 2551–2565, Jul. 2012.
[7] S. Zhang, W. Quan, J. Li, W. Shi, P. Yang, and X. Shen, "Air-ground integrated vehicular network slicing with content pushing and caching," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 2114–2127, Sep. 2018.
[8] J. Wang, R. Zhang, J. Yuan, and X. Du, "A 3-D energy-harvesting-aware routing scheme for space nanosatellite networks," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2729–2740, Aug. 2018.
[9] P. Lottes, R. Khanna, J. Pfeifer, R. Siegwart, and C. Stachniss, "UAV-based crop and weed classification for smart farming," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, May 2017, pp. 3024–3031.
[10] Z. Xue, J. Wang, G. Ding, H. Zhou, and Q. Wu, "Maximization of data dissemination in UAV-supported Internet of Things," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 185–188, Feb. 2019.
[11] A. Bujari, M. Furini, F. Mandreoli, R. Martoglia, M. Montangero, and D. Ronzani, "Standards, security and business models: Key challenges for the IoT scenario," *Mobile Netw. Appl*, vol. 23, no. 1, pp. 147–154, Feb. 2018.
[12] A. H. Iche and M. R. Dhage, "Location-based routing protocols: A survey," *Int. J. Comput. Appl.*, vol. 975, p. 8887, Jan. 2015.
[13] Y. Yu, L. Ru, and K. Fang, "Bio-inspired mobility prediction clustering algorithm for ad hoc UAV networks," *Eng. Lett.*, vol. 24, no. 3, pp. 83–92, 2016.
[14] F. Aadil, A. Raza, M. F. Khan, M. Maqsood, I. Mehmood, and S. Rho, "Energy aware cluster-based routing in flying ad-hoc networks," *Sensors*, vol. 18, no. 5, p. 1413, 2018.
[15] L. Chen, J. Liang, Z. Hu, and B. Wu, "Movement control algorithm of fault-tolerant UAVs Ad Hoc networks," *J. Nat. Univ. Defense Technol.*, vol. 33, no. 1, pp. 58–62, Feb. 2012.
[16] Z. Guan, Y. Zhang, L. Zhu, L. Wu, and S. Yu, "EFFECT: An efficient flexible privacy-preserving data aggregation scheme with authentication in smart grid," *Sci. China Inf. Sci.*, vol. 62, no. 3, pp. 1–14, Mar. 2019.
[17] 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.
[18] A. K.-S. Wong, T. K. Woo, A. T.-L. Lee, X. Xiao, V. W.-H. Luk, and K. W. Cheng, "An AGPS-based elderly tracking system," in *Proc. 1st Int. Conf. Ubiquitous Future Netw.*, Jun. 2009, pp. 100–105.
[19] S. Uluskan, M. Gökçe, and T. Fılık, "RSS based localization of an emitter using a single mini UAV," *Proc. Signal Process. Commun. Appl. Conf. (SIU)*, pp. 1–4, May 2017.
[20] J.-J. Wang, C.-X. Jiang, Z. Han, Y. Ren, R. G. Maunder, and L. Hanzo, "Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones," *IEEE Veh. Technol. Mag.*, vol. 12, no. 3, pp. 73–82, Sep. 2017.
[21] V. Pham, T. Dinh, and K. Ruslan, "Method for organizing mesh topology based on LoRa technology," in *Proc. Int. Congr. Mod. Telecommun. Control Syst. Workshops (ICUMT)*, Moscow, Russia, Nov. 2018, pp. 1–6.
[22] M. Azhar, D. Islam, and M. Arshad, "Topology-based flow-oriented adaptive network coding-aware routing scheme for VANETs," *KSII Trans. Int. Inf. Syst.*, vol. 12, no. 5, pp. 2044–2062, Jun. 2018.
[23] A. Bujari, C. E. Palazzi, and D. Ronzani, "A comparison of stateless position-based packet routing algorithms for FANETs," *IEEE Trans. Mobile Comput.*, vol. 17, no. 11, pp. 2468–2482, Nov. 2018.
[24] K. Zhuo and H. Zhang, "Progress of UAV ad hoc network: A survey," *Telecommun. Sci.*, vol. 4, no. 1, pp. 28–32, Nov. 2015.
[25] C. Sun, "Develop on mobile ad hoc network," *Sci. Technol. Vis.*, vol. 6, no. 2, pp. 57–58, Sep. 2018.
[26] I. Bekmezci, O. K. Sahingoz, and, Ş. Temel, "Flying Ad-Hoc networks (FANETs): A survey," *Ad Hoc Netw.*, vol. 11, no. 3, pp. 1254–1270, May 2013.
[27] T.-K. Huang, C.-K. Lee, and L.-J. Chen, "PRoPHET+: An adaptive PRoPHET-based routing protocol for opportunistic network," in *Proc. AINA*, Apr. 2010, pp. 112–119.
[28] D. Becker and A. Vahdat, "Epidemic routing for partially connected ad hoc networks," Duke Univ., Durham, NC, Tech. Rep. CS-200006, 2000.
[29] A. Jindal and K. Psounis, "Performance analysis of epidemic routing under contention," in *Proc. Int. Conf. Wireless Commun. Mobile Comput.*, New York, NY, USA, Jul. 2006, pp. 539–544.
[30] M. Conti and M. Kumar, "Opportunities in opportunistic computing," *Computer*, vol. 43, no. 1, pp. 42–50, Jan. 2010.
[31] S. Han and Y. Chung, "An improved PRoPHET routing protocol in delay tolerant network," *Sci. World J.*, vol. 2015, no. 12, pp. 1–7, Oct. 2015.
[32] Y. Lin, X. Wang, F. Hao, L. Wang, L. Zhang, and R. Zhao, "An on-demand coverage based self-deployment algorithm for big data perception in mobile sensing networks," *Future Gener. Comput. Syst.*, vol. 82, pp. 220–234, May 2018.
[33] S. Al-Saif, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular Ad Hoc network," *J. Netw. Comput. Appl.*, vol. 37, pp. 380–392, Jan. 2014.
[34] K. Xiong, P. Fan, S. Yi, M. Lei, and Z. Zhong, "Cooperative opportunistic network-coded transmission strategy for wireless mesh networks," *Int. J. Ad Hoc Ubiquitous Comput.*, vol. 20, no. 2, pp. 78–90, 2015.
[35] D. Pan, H. Zhang, W. Chen, and K. Lu, "Transmission of multimedia contents in opportunistic networks with social selfish nodes," *Multimedia Syst.*, vol. 21, no. 3, pp. 277–288, Jun. 2015.
[36] X. Qin, X. Wang, L. Wang, Y. Lin, and X. Wang, "An efficient probabilistic routing scheme based on game theory in opportunistic networks," *Comput. Netw.*, vol. 149, pp. 144–153, Feb. 2019.
[37] Y. Feng, S. Yan, C. Liu, Z. Yang, and N. Yang, "Two-stage relay selection for enhancing physical layer security in non-orthogonal multiple access," *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 6, pp. 1670–1683, Jun. 2019.
[38] R. Zhang, J. Pan, D. Xie, and F. Wang, "NDCMC: A hybrid data collection approach for large-scale WSNs using mobile element and hierarchical clustering," *IEEE Internet Things J.*, vol. 3, no. 4, pp. 533–543, Aug. 2016.
[39] S. K. Lakshmanaprabu, K. Shankar, S. S. Rani, E. Abdulhay, N. Arunkumar, G. Ramirez, and J. Uthayakumar, "An effect of big data technology with ant colony optimization based routing in vehicular ad hoc networks: Towards smart cities," *J. Cleaner Prod.*, vol. 217, pp. 584–593, Apr. 2019.
[40] C. Pu, "Jamming-resilient multipath routing protocol for flying ad hoc networks," *IEEE Access*, vol. 6, pp. 68472–68486, 2018.
[41] X. Li and J. Yan, "LEPR: Link stability estimation-based preemptive routing protocol for flying ad hoc networks," in *Proc. IEEE Symp. Comput. Commun. (ISCC)*, Jul. 2017, pp. 1079–1084.
[42] S. Rosati, K. Krużelecki, G. Heitz, D. Floreano, and B. Rimoldi, "Dynamic routing for flying ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1690–1700, Mar. 2016.
[43] S.-C. Choi, H. R. Hussen, J.-H. Park, and J. Kim, "Geolocation-based routing protocol for flying ad hoc networks (FANETs)," in *Proc. 10th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2018, pp. 50–52.

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