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An Energy-Efficient Opportunistic Routing Protocol Based on Trajectory Prediction for FANETs

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ABSTRACT In recent years, with the emergence of UAVs(Unmanned Aerial Vehicles) in military and civil applications, the FANETs(Flying Ad-Hoc Networks) composed of multiple UAVs has attracted extensive attention from researchers. As a new type of airborne self-organizing network, the particularity in FANETs such as time-varying network topology and dynamic link makes it difficult to maintain continuous communication when performing tasks. Therefore, it is challenging to design a routing protocol for FANETs to guarantee the quality of data transmission and make communication more effective. In this article, we propose a new opportunistic routing protocol based on trajectory prediction, named EORB-TP. To be specific, we first predict the position of nodes in three-dimensional space and solve the problem of uncertainty of node contact in opportunistic communication. Secondly, we define the node's trajectory metric value to measure the node's trajectory characteristics and effectively avoid the excessive consumption of edge nodes. In addition, when choosing relay nodes, an energy-saving data forwarding strategy is designed to deal with the limited energy resources and storage space of UAVs. Simulation results show that compared with the state-of-the-art protocols, our protocol can increase the delivery rate by approximately 40% at best and can reduce the delay by approximately 80%.

INDEX TERMS Flying ad-hoc networks, data transmission, routing algorithm, opportunistic communication.

I. INTRODUCTION

In past few years, research on the application of unmanned aerial vehicles (UAVs) in the communication field has become a hot topic for a wide range of researchers. As an emerging kind of communication devices, UAVs have many outstanding advantages, such as strong survivability, good maneuverability, easy deployment and no risk of casualties. Therefore, UAV plays an extremely important role in the modern military and civil fields [1]–[3]. It can be wildly used in battlefield reconnaissance and surveillance, forest fire prevention, high altitude fire fighting, emergency communication, UAV logistics and many other applications [4]–[8]. In order to effectively connect the UAV system to the integrated information network, it is necessary to discuss the networking of the UAV system. Thus, a new paradigm, called flying ad-hoc networks (FANETs) came into being [9]. In some sensitive remote areas, there are usually no base station facilities, or base station facilities can only be established far from the target area to prevent from being damaged. In this case, the communication quality is poor and it will affect the task operation performance of the UAVs [10]. Therefore, a good strategy is to deploy a large number of UAVs in this area, which can form a completely autonomous network system to complete the collection and forwarding of the information data. Finally, the data is transmitted to the terminal command system to better complete tasks [11].

However, such network systems also present some challenges. In realistic mission scenarios, although UAVs are deployed in the air with large numbers, due to the relatively

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long distances, there is relatively sparse node density [12]. In addition, the UAVs fly very fast which cause dynamic topology changes in the network [13]. What needs more attention is that the flying environment of the UAV is three-dimensional, especially in a wide area. And as the flight distance increases, the signal strength of the UAV nodes decreases exponentially, then the transmission range gradually decreases [14]. All these characteristics can easily cause the network to be interrupted or split, and ultimately affects the successful delivery of data packets. What's more, the energy device carried by the UAV is mainly used to drive the flight of the UAVs, so the energy used for UAVs communication is very limited [15]. Under such circumstances, it is necessary to consider the multi-hop relay transmission to extend the network lifetime in FANETs.

For the particularity of the FANETs mentioned above, many researchers have proposed to introduce the working principle of the opportunistic network to deal with the network interruption and split in FANETs [16], that is, the UAVs nodes use the store-carry-forward mode to forward data. But the uncertainty of node contact in opportunistic communication seriously affects the quality of data transmission in FANETs. And to our knowledge, many researchers only regard FANETs as a two-dimensional planar network when designing routing protocols, but actually FANETs have three-dimensional topology structure in the air. Moreover, they just improve the protocols in the traditional self-organizing networks and directly apply them to the FANETs [17], [18], which can't satisfy our requirements for the quality of data transmission in real FANET communications [19], [20]. Therefore, in this work, we propose a new routing protocol that is more in line with practice for FANETs, named EORB-TP (Energy-Efficient Opportunistic Routing Protocol Based on Trajectory Prediction). In the selection of relay nodes, we adopt the method of trajectory prediction to change the uncertainty of node contact in opportunistic communication into certainty, and also consider the node energy and buffer size. The main features and contributions of this article are as follows:

- The network model we propose in this article is three-dimensional, which is different from the traditional two-dimensional environment of Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs). Because the UAVs have a certain altitude and variable speed when flying in the air, the position prediction is necessarily calculated in three-dimensional space.
- The Gaussian process is used to model the node's speed probability, so that the future speed probability of the node can be estimated based on the historical movement characteristics. Based on this, the future position and moving distance of the node can be calculated.
- We proposed a criterion for the trajectory metric value based on the predicted node location information, which considered three factors comprehensively: node moving distances, node direction and node density. The larger the trajectory metric value, the higher the probability that this node will be selected as the next hop relay node.
- When selecting the relay, we also take into account the own properties of the UAV nodes, that is, the node residual energy and buffer size, which is critical to the lifetime of the network. Ultimately the strategy we choose can effectively avoids problems such as data loss due to uneven load.

The rest of this article is organized as follows. Sec. II overviews the related works on routing protocols for FANETs. Sec. III shows the network model and assumptions. The method of trajectory prediction is introduced in Sec. IV. Sec. V presents our proposed protocol, named EORB-TP, and gives the algorithm for choosing the relay nodes. We present the simulation results in Sec. VI and concludes the paper in Sec. VII.

II. RELATED WORKS

Due to the advantages of FANETs, in recent years, researchers have gradually shifted the research hotspot from the traditional self-organization networks to the study of FANETs and proposed various routing protocols for data transmission [21]–[23]. According to the different problems that are mainly solved in the network, routing protocols are basically divided into the following categories [24]:

The first class is topology aware routing protocols, which mainly aim at the dynamic topology in FANET. For example, the author in [25] proposed a distributed priority tree-based routing protocol to solve the problems of topology construction. This protocol can support highly dynamic network such as FANETs [26]. Jie *et al.* proposed a routing selection scheme based on topology change awaring [27], which can help to monitor the topology changes in the network and make a routing decision. But the author don't consider the limited energy of FANET nodes. Peng *et al.* [28] proposed that the future topology information of UAVs can be obtained by GPS, and then the data information forwarding decision can be made based on the future topology state of UAVs, so as to transmit the message to the destination faster.

The second class is cluster-based routing protocols, which are designed to help UAVs save resources. Some cluster-based routing such as energy efficient routing algorithm [29] has been proposed to reduce the energy loss during each round of nodes clustering. Besides, Aadil *et al.* proposed an energy aware cluster based routing protocol [30], the transmission power of UAVs is adjusted by operation needs of UAVs. It enables the UAV to transmit data as far as possible to reduce the number of routing hops. And it uses k-means density clustering algorithm to choose cluster heads. The authors in [31] proposed mobility and location-aware stable clustering mechanism to help reduce the unnecessary overhead in the network, and used k-means clustering algorithm based on location to enhance the reliability of UAV networks. The disadvantage of this protocol is the lack of consideration for the high speed movement of nodes.

The last class is position aware routing protocols. This kind of protocol mainly uses the geographic location information of nodes to find optimal routing path. The author of the article [32] combined a set of cross-layer parameters to calculate the dynamic forwarding delay, including queue length, link quality, geographic location, and remaining energy so as to create and maintain reliable and continuous multi-hop routing. Pimentel *et al.* [33] proposed CABR, which considers the impact of different environmental information on dynamic forwarding delay, and adds location prediction to detect possible routing failures. Filho *et al.* proposed MOBIFANET [34], which considers mitigating the impact of UAV mobility and maintaining network connectivity. The author in [35] proposed a new geocast routing protocol namely geocast routing protocol for fleet of UAVs, the purpose of the protocol is to transmit information to a specific set of UAVs determined by their geographic location. The protocol greatly improves the transmission rate by taking into account the movement of UAV nodes.

From previous studies we can see that, the acquisition of the node location information is very necessary for the opportunity networks like FANETs [36]. However, in a large number of papers, the node location of UAVs is obtained through its own GPS device [37]. When the node wants to forward data, it only needs to know the location of the neighbor node and the destination node and then to calculate the most appropriate next-hop node. This approach does have many advantages over topology-based routing protocols, such as increasing network bandwidth utilization [38]. However, in the actual applications, the position of the UAVs can't be known in advance, and the UAVs are likely to change its direction according to the complex mission. Besides, most of the location-based routing protocols we know are designed in a two-dimensional environment, which is not consistent with the actual three-dimensional network environment of FANETs. What's more, existing work hardly pay attention to the importance of energy in the data packet transmission process. All these shortcomings of the existing work we have mentioned that prompt us to propose a new and efficient relay selection routing protocol for FANETs.

III. NETWORK BASIS AND ASSUMPTIONS

A. NETWORK BASIS

In this article, we consider a example scenario of applying UAVs to to perform reconnaissance missions on the battlefield. As show in FIGURE 1. In the data collection phase, UAVs are randomly distributed over the mission area to monitor the battlefield and search for suspected targets. When a UAV captures sensitive information, it enters into the data transmission phase. At this time, the UAV node carrying information becomes the source node and transmits the information to the far target node successfully through opportunistic communication. All nodes in the network may act as relay nodes to assist in the transmission of information.

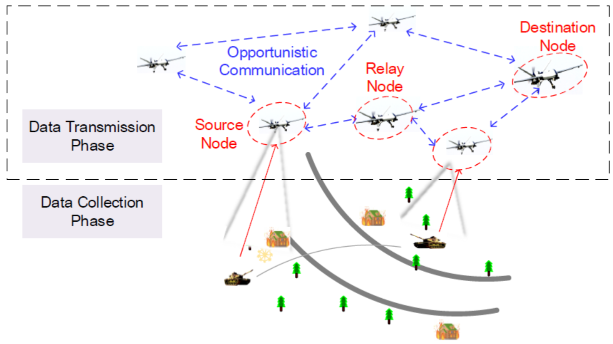

FIGURE 1. Network model of FANETs in military scenario.

B. ASSUMPTIONS

It's assumed that N UAVs are deployed in a military area to detect battlefield information. All UAVs are treated as network nodes, and each node has its own identity number ($i = 1, 2, \ldots, N$). Messages are transmitted through multi-hop relays between them. We regard these UAVs as a dynamic graph $G(V, E)$, where the V means the set of UAVs nodes, and the E means the set of edges. Each UAV is equipped with a camera, image encoder, radio transceiver, positioning system and limited energy supply and buffer space. It's assumed that all UAVs can be connected to the BeiDou Satellite, so the location, speed, buffering and energy information can be shared between all UAVs in real time through the short message function of BeiDou Satellite system. Supposing that the flying speed and direction of all UAVs are random and they are moving in three-dimensional space. Since the UAV has a very urgent need for energy when performing missions in the air, it's given that the energy consumption of the UAVs during the mission is mainly composed of the forwarding and receiving of data packets and the initial energy is equal. In addition, all UAVs have the same initial buffer size and are quantified by the total number of storable data packets.

IV. TRAJECTORY PREDICTION

In this section, we will introduce the method of node trajectory prediction, which includes two parts: the velocity prediction by using Gaussian Mixture Model(GMM) and calculation of position in three-dimensional space.

A. VELOCITY PREDICTION

Assuming that the position, speed, and direction of all the UAV nodes in the network can be obtained through the BeiDou satellite System. We can construct a suitable node movement model through analysis based on the position information carried by the nodes. In the first step, we need to get the average moving speed of the node, which can be analyzed by observing the moving speed of the node for a long time.

$$\bar{v} = \lim_{t \to \infty} \left(\frac{\sum_{t=0}^{\infty} v_i}{t} \right) \tag{1}$$

According to the characteristics of the FANETs, we assume that the movement of the UAV nodes presents a Gaussian distribution [39], and node's future movement state can be inferred from the historical movement circumstances of the nodes. The future movement state of the node can be described as

$$\delta = \frac{e^{-\frac{N^2}{2\pi^2}}}{\sqrt{2\pi}\lambda} \tag{2}$$

λ is a state factor ($0 \leq \lambda \leq 1$) which reflects the degree of change in node speed and represents the movement performance of the node itself. N represents the total number of nodes in network. When UAVs perform reconnaissance missions in the sensitive area, because environmental factors are uncontrollable, such as weather and terrain, the impact of environmental factors on the UAV's flying status is beyond our consideration [40]. Here we only analyze the movement of the UAV itself. The UAV's flight status is mainly affected by speed and direction. The moving speed of a node in the future is not only related to the average speed of the node's long-term movement, but also to the uncertain movement of nodes in the future. In addition, the moving state factor λ will also affect the speed change of the node. Then, we give the speed state model of the nodes:

$$v_{t+\Delta t} = [(\lambda - 1)v_t + (1-\lambda)\bar{v} + \sqrt{1-\lambda^2}\delta]\Delta t \tag{3}$$

where, Δt represents a period of time that a node moves. v_t represents the velocity of the node at time t and $v_{t+\Delta t}$ represents the velocity of the node at time $t + \Delta t$.

Secondly, we assume that each v_i can be obtained by the deformation of λ_i, formula is

$$v_i = \Lambda\lambda_i + \mu \tag{4}$$

where Λ is the information matrix of the Gaussian process, μ is the mean value of Gaussian process. It's known that he historical trajectory information obtained from positioning system usually concludes noise terms and the Gaussian white noise process is an independent random process, which is expressed as $\eta \sim N(0, \psi)$, ψ is variance. So our predicted data is expressed as $\Lambda\lambda + \mu + \eta$. The velocity probability model can be obtained by the following equation:

$$p(V|\lambda) = \prod_{i=1}^{k}\sum_{i=1}^{k}\sigma_i\varphi(v_i|\mu_i + \Lambda\lambda_i, \psi_i) \tag{5}$$

where k is the number of Gaussian processes, ψ_i represents the Gaussian process weight of node i, $\varphi(v_i|\mu_i + \Lambda\lambda_i, \psi_i)$ is Gaussian probability density function. Then we introduce a Gaussian Mixture Model(GMM) [41] to estimate parameters. Generally, if we need to estimate the parameter values of the GMM, it's commonly to choose the expectation maximum algorithm [42], which is used to find the maximum likelihood estimation in incomplete data. After we get the estimated value of $\sigma, \mu, \Lambda, \varphi$,we can predict the speed probability of the node in the future.

B. POSITION PREDICTION

As long as we obtain the speed of the node at the next moment, we can predict the future position of the node. We use (x_t, y_t, z_t) represents the position coordinates of the node at time t. At a certain time in the future $t+\Delta t$, the position of the node can be obtained based on the speed, position, direction (speed vector change angle) of the node at time t and the speed of the node at time $t+\Delta t$. As shown in the FIGURE 2, a node moves at any speed v at time t, and $\theta_x, \theta_y, \theta_z$ are respectively the inclined angle between the direction of node speed v and the x, y and z axes. The coordinate position after Δt time shift is calculated as:

$$(x_{t+\Delta t}, y_{t+\Delta t}, z_{t+\Delta t}) = \begin{cases} x_{t+\Delta t} = x_t + v_{t+\Delta t}\Delta t\cos\theta_x \\ y_{t+\Delta t} = y_t + v_{t+\Delta t}\Delta t\cos\theta_y \\ z_{t+\Delta t} = z_t + v_{t+\Delta t}\Delta t\sin\theta_z \end{cases} \tag{6}$$

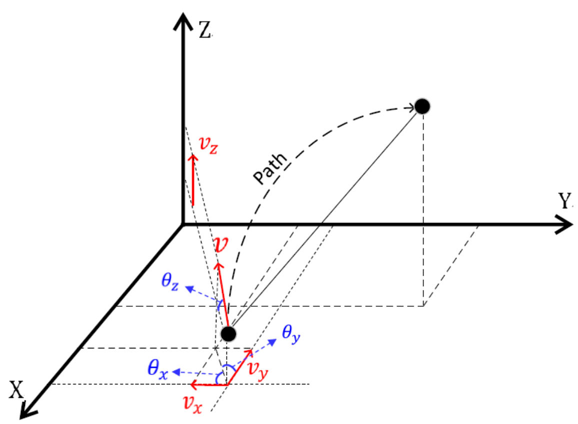

FIGURE 2. Nodes movement in three-dimensional space.

After the position coordinates of the node at the next moment are obtained, the moving distance of the node in a certain period of time can be calculated. We define the length of the node moving from time t to time $t + \Delta t$ as the node moving distance, which is represented by ΔD.

$$\begin{aligned} \Delta D &= \sqrt{(x_{t+\Delta t} - x_t)^2 + (y_{t+\Delta t} - y_t)^2 + (z_{t+\Delta t} - z_t)^2} \\ &= 3(v_{t+\Delta t}\Delta t) + \cos^2\theta_x + \cos^2\theta_y + \sin^2\theta_z \end{aligned} \tag{7}$$

where $(x_{t+\Delta t}, y_{t+\Delta t}, z_{t+\Delta t})$ is the coordinates of the node at time $t+\Delta t$, (x_t, y_t, z_t) is the coordinates of the node at time t.

From the above discussion we can get the predicted position of the node.

V. INTRODUCTION OF EORB-TP

In this section, we present the EORB-TP protocol in detail. The core of this protocol is to select the best next hop relay node for data forwarding. From a practical point of view, we have considered three factors when selecting relay nodes: the node trajectory metric value, the residual energy and buffer space.

Here, we define the trajectory metric as an indicator of the trajectory properties of a node, and the greater the value, the more likely the node will successfully reach the destination node.

A. CALCULATION OF TRAJECTORY METRIC VALUE

The value of the node trajectory metric can be measured by the prediction of the node trajectory, and its value can be used as the basis for our determination of candidate nodes. As show in FIGURE 3, supposing that A is the current source node with data packets and node D is the destination node. Node A' is the predicted position of node A in the next time. The angle deflection between node A' and node A is calculated as:

$$\phi_A = \arcsin \frac{d_{A'-AD}}{d_{AA'}} \tag{8}$$

where, $\phi_A \in [0, \frac{\pi}{4}]$. $d_{A'-AD}$ represents the vertical distance between node A' and the line AD. $d_{AA'}$ represents the moving distance between node A and node A', which can be calculated by equation (7).

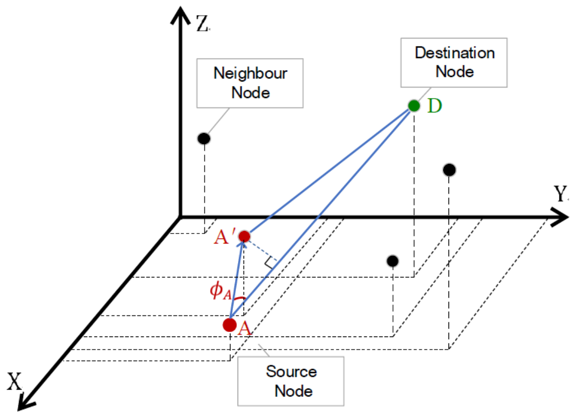

FIGURE 3. **Nodes in the network.**

Then, we give the expression of the node's trajectory metric value as:

$$\Omega = \frac{1}{\tau_a \frac{d}{d_0} + \tau_b \frac{4\phi(A)}{\pi} + \tau_c (1 - \frac{n}{N})} \tag{9}$$

where τ_a is the distance factor, τ_b is the angle factor, and τ_c is the neighbor node factor. d represents the Euclid distance between the neighbour node and the destination node, and d_0 represents the Euclid distance between the current node and the destination node. n represents the number of neighbor nodes owned by current node, and N is the total number of all nodes in the network. The greater the value of Ω, the more suitable the node is to be selected as the next hop relay node. According to the calculation formula of the metric value, the relay node we have selected has the following advantages:

1. From the perspective of distance, we can choose the next hop node closer to the destination node to reduce the number of routing hops.

2. From the perspective of direction, we choose the next hop node with the smallest deflection angle to prevent the appearance of boundary effect.

3. From the perspective of node density, it can avoid that the relay nodes we choosing have no next hop for transmission, so as to reduce the probability of routing void in data transmission.

From the above discussion, we can know that the value of Ω represents the degree of appropriateness of the candidate nodes trajectory, and following we can use this value as a part of the utility function that we choose the relay node.

B. NODE ENERGY

The impact of UAV's energy on the performance of FANETs is critical, since each UAV is equipped with limited energy resources. However, the behavior of nodes is also consuming energy. In practice, the energy of UAV is mainly used to support the movement and communication in the air. However, the propulsion energy required by UAV's movement accounts for the main part, which is closely related to aircraft weight, wing area, air density and other factors, and is not in the scope of this article. We only consider the energy consumed by UAV to transmit data in communication. If the UAV node is depleted of energy, the node will not be able to support the transmission of data packets, and the data packets it carries will also be lost. These nodes are considered invalid nodes and exit the network. It can be seen that in the routing design process, considering the energy balance between UAV nodes is very important to extend the life of the network.

To simplify the problem, we assume that the UAV node energy consumption mainly includes two parts: data receiving and forwarding, ignoring the energy consumed by storing data packets and collecting neighbor information. Suppose the initial energy of each UAV is E_0, receiving and forwarding each data packet consumes equal energy, we can calculate the residual energy of each node based on the total number of packets that the node has forwarded and received.

$$E_{res} = E_0 - E_c \times P_n \tag{10}$$

where, E_c represents the energy consumed when forwarding or receiving each data packet, and P_n represents the total number of data packets sent and received by the node.

C. NODE BUFFER

The size of the buffer determines the number of packets that a node can actually store. In practical application scenarios, the buffer of UAV nodes are usually limited. If a node no longer receives data packets because the buffer is full, it will cause waste of network resources and reduce network performance. If a node receives data packets frequently, that will lead to a high buffer occupancy rate. At this time, if it wants to receive new packets again, it will cause the loss of the original packets and reduce the transmission quality of packets delivery. Therefore, the effect of the state of the node buffer on the performance of the routing cannot be ignored. Assume that each flying node has equal initial buffer space and is limited in the network, expressed as B_0. When receiving a data packet m, the remaining buffer occupancy space of the node will decrease by B_m. On the contrary, when a data packet n is dropped, The remaining buffer occupancy space of the node will increase by B_n. Then, the residual buffer space of the node can be expressed as:

$$B_{res} = B_0 - B_m + B_n \tag{11}$$

Through the above equation, we can obtain the remaining space of node buffer.When the node carrying the packet encounters other nodes, the remaining buffer can be used to determine whether the data can be exchanged.

D. UTILITY FUNCTION

There are two very important factors related to the selection of relay nodes: the trajectory metric and its own attributes. According to the neighbor node information table, the trajectory metric value of each node can be calculated. The larger this value is, the more likely the node is to be a candidate node for next hop relay forwarding. In addition, the attributes of the node itself (remaining energy and buffer space) also must be considered. Specifically, selecting the node with the most suitable trajectory can not only effectively reduce the boundary packet loss rate, avoid excessive consumption of the boundary nodes, but also reduce the probability of routing holes. What's more, if the node has sufficient remaining energy, it has the ability to process more data packets, and the task efficiency will be improved. If the remaining energy of the node is 0, it will lose the ability to perform tasks, and will have no value to the network and therefore cannot be selected as a relay node.As for the buffer, if the node has enough buffer, which means it will carry more data.

However, if a UAV is continuously selected as a relay node to help other nodes transmit data packets, then it is likely to run out of power prematurely and lose its function, finally it will exit the network. Therefore, in our routing design, we fully consider these three factors to balance the performance of a node. We quantified and integrated the three attributes of each node:

$$X = \lg(\alpha\Omega + 1) * \lg(\beta E + 1) * (\gamma B_{res} + 1) \tag{12}$$

where Ω is the trajectory metric value, E and B are respectively the residual energy of nodes and the residual buffer space. α, β and γ are weighting factors of these three metrics which respectively assigned to the trajectory metric, the remaining energy, and the available buffer size of the current node, and are used to adjust the weights of different weighting factors in the selection of the relay node when performing routing. We can know from this function that if any of these factors are 0, the whole utility function is going to be 0. According to our routing scheme, when nodes meet, the node with higher utility value will be selected as the next hop relay node to complete the data forwarding.

E. RELAY SELECTION

The EORB-TP protocol proposed in this article is a relay node selection scheme based on trajectory prediction. In this scheme, each node knows its own position, and all UAV nodes have an information table containing their own ID, predicted trajectory metric value, residual energy and buffer. When the reconnaissance mission starts to execute, once the source node has collected the sensitive information, it starts to consider the optimal path to transmit the information to the target node. The key problem is to choose the best relay forwarding node to achieve higher packets delivery rate. The scheme proposed in this article is shown in algorithm 1. Assuming a situation where node i carries data to be transmitted and encounters node j. First, node i needs to determine whether node j is the destination receiving node. If so, perform the forwarding operation directly to complete the data delivery. On the contrary, if node j is not the destination node, then we need to use the formula (12) to calculate the utility function value of both the node i and j, and select the node with the larger utility function value to complete the successful transmission of the data packet. The transmission of the packet is not completed until the packet is successfully sent to the target node.

Algorithm 1 EORB-TP Routing Algorithm

Input: The ID of all nodes in the network,$i = 1, 2, \ldots N$.;
Information table of all nodes;
Output: Optimal path;

node i carrying data packets and encounters node j, D is the target destination node;
if node $j = D$ **then**
  forward packet to j;
  update residual energy, buffer and utility function value X for node i, j;
end
else
compare utility function value of i and j using (12);
  if $X_i < X_j$ **then**
  forward packet to j;
  update residual energy, buffer and utility function value X for node i, j;
  end
end

VI. PERFORMANCE EVALUATION

In this section we perform a simulation evaluation using *IntelliJIDEA*2020.2 of our proposed routing algorithm (EORB-TP) and discuss the experimental results. First, we will simply introduce our simulation settings. Secondly, the routing strategies to be compared with are listed and we will give the performance evaluation metrics. Finally we will analyze the simulation results and make extensive comparative studies.

A. SIMULATION ENVIRONMENT SETUP

In order to obtain the most realistic UAV movement data, we choose to use RWP model to generate data sets. We import the JAVA code of the RWP model into *IntelliJIDEA*2020.2

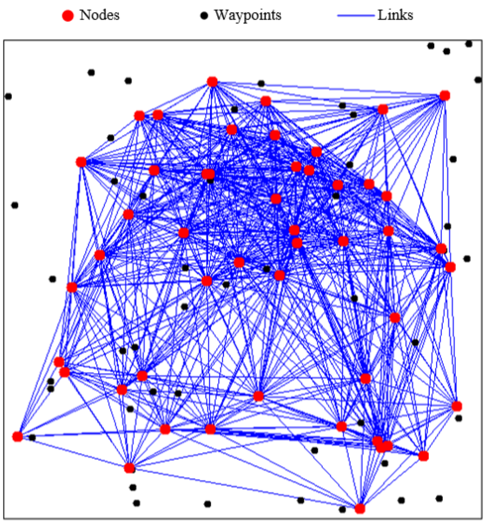

FIGURE 4. Nodes' movement in RWP Model.

and set the moving parameters to simulate the moving track of the UAV nodes. As shown in FIGURE 4. In this model, the node speed can be customized, including three levels of low speed (10-40 km/h), normal speed (40-70 km/h) and high speed (70-100 km/h). Finally, we export the data sets, which contain the real-time location information of the nodes. The simulation parameters are exhibited in TABLE 1.

TABLE 1. Simulation parameters.

Parameter	Value
MAC type	IEEE 802.11g
Simulation area	$2000m \times 2000m$
Simulation time	100 min
Number of UAV nodes	50
UAV Transmission range	300 m
UAV speed	10-100 Km/h
Message size	500 KB- 1 MB
Message TTL	30 min
Message producing interval	30 s
Mobility model	Random Waypoint Model

Our simulation includes 50 UAV nodes, each UAV is equipped with IEEE 802.11g wireless devices to communicate with other UAVs. During the process of data transmission, the source nodes and destination nodes are selected randomly from datasets. The size of messages generated by source nodes is randomly between 500KB to 1 MB and the packet lifetime is 30 minutes. During each simulation, the simulator will generate a data packet when reading a set of node location information. We set to read a new set of node location information every 30 seconds, and defined a total of 200 data packets. All nodes have the same initial energy and buffer size, and the nodes consume energy and buffer when receiving or sending packets. Here, we used a constant height value for simulation, and we respectively simulated the UAVs' trajectory at three moving speeds.

B. PROTOCOLS TO BE COMPARED WITH

In order to accurately evaluate the performance of our proposed protocol, the following three routing protocols are selected for simulation and comparative analysis. It should be mentioned that all protocols have the same energy and buffering limits during simulation.

- LADTR [43] is a location-aided delay tolerant routing for UAV networks. It introduced a ferrying UAV to improve connectivity between searching UAV and the ground station. The location information is used to estimate the time of contact between the neighbor nodes and the target nodes. During the story-carry-forward forwarding process, it used single copy strategy to forward packets. As the increasing number of nodes in network, the number of hello packets in the network will also increase, which will cause high routing cost.
- GEOSAW [44] is a location-aware waypoint-based routing protocol for FANET. This protocol exploits UAV's geographical information to predict the future location of the nodes and then choose the best forwarding node to the destination. In this protocol, when a node discovers that a packet is available, this node will first check all of its neighbors to see if there are any neighboring nodes that will arrive at the destination. But it dosen't compare the nodes' TTA(Time To Arrival) and there is only one copy of the message on the network, so the transmission latency is high.
- LEPR [45] is also a preemptive routing protocol based on link stability estimation in FANET. This protocol aims to find an alternative path which can replace the disconnect link. In this protocol, the routing table has been modified and adds the control of hop counts. It has relatively low routing cost and hop counts.

C. PERFORMANCE METRIC

In our simulation, the following metrics are used to evaluate the routing performance between our proposed routing protocol and the others.

- Delivery Ratio: the ratio between the total number of packets successfully received by the destination node and the total number sent by the source node. It indicates the successful transmission rate of data packets.

$$Delivery\ ratio = \frac{packets_{sended}}{packets_{recieved}} \tag{13}$$

where $packets_{sended}$ represents the number of data packets sended by the source node and $packets_{recieved}$ represents the number of data packets successfully recieved by the destination node.

- Average End to End Delay: the average time taken for data packets to be transmitted from the source node to the destination node.

$$Average\ end\ to\ end\ delay = \sum_{m=1}^{M} T_m/M \quad (14)$$

where M is the total number of packets generated by the source node and T_m is time taken by the m_{th} packet to transmit from the source node to the destination node.

- Average Hop Count: the average number of hops used for packets to be transmitted from the source node to the destination node.

$$Average\ hop\ count = \sum_{m=1}^{M} Hop_m/M \quad (15)$$

where Hop_m represents the hop numbers of m_{th} packet.

- Routing Cost: the ratio of the total number of packets produced by the source node to the total number of packets forwarded by all nodes.

$$Routing\ cost = M/packets_{forwarded} \quad (16)$$

where $packets_{forwarded}$ indicates the number of packets that have been successfully forwarded.

D. PERFORMANCE COMPARISON AND ANALYSIS

To provide a better performance comparison, we have run our routing strategy EORB-TP and the three other routing strategies listed above at different speed levels. In our simulation, the node speeds are set in low ($20Km/h$), normal($50Km/h$) and high speed ($80Km/h$) respectively. In the paragraphs below, we will give detailed simulation results and discussions.

1) POSITION PREDICTION ERROR IN EORB-TP

First, in order to evaluate the effectiveness of position prediction in our algorithm, we calculated the difference value between the predicted position and the actual position of the UAV nodes. As shown in the following formula, the smaller the *Prediction error* value, the more accurate the position we have predicted for nodes.

$$Prediction\ error = \frac{\sum_{i=1}^{I} \sqrt{(pred_i - actu_i)^2}}{I} \quad (17)$$

where $pred_i$ is the predicted position (x_{pred}, y_{pred}), $actu_i$ represents the actually position (x_{actu}, y_{actu}). I is the number of predicted nodes' trajectory points.

In the process of trajectory prediction in section IV, in order to obtain more stable movement data of nodes, we set the value of the movement state factor λ to 0.75 [46]. Then, we run the position prediction algorithm at three levels of speed respectively, and the error values obtained are shown in the FIGURE 5. From this figure we can see that the higher moving speed of the node, the smaller position error we predicted. The reason is that the higher speed of the UAV, the smaller the instantaneous value of its flight angle change. In this way, our estimation of velocity is less susceptible to suffer external environment interference, so the prediction of position is more accurate. Therefore, our routing strategy

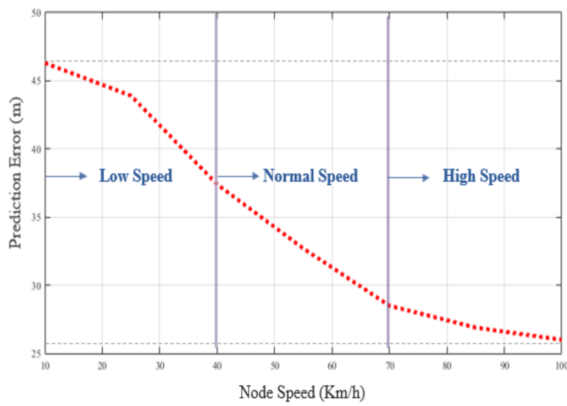

FIGURE 5. Prediction error with varying velocity of nodes.

is more suitable to be applied in high-speed node mobility network, such as FANET.

2) DELIVERY RATIO

The comparison of the delivery rates among the four protocols at different speed levels is shown in FIGURE 6. From these pictures we can get the following information. First, the delivery rate of our EORB-TP protocol is the worst at low node speed. The reason is that at low speed, the efficiency of nodes' position prediction is reduced. As for normal speed and high speed levels of nodes, our EORB-TP protocol has achieved the relatively best performance in the aspect of delivery ratio. The second one is that LADTR protocol achieves the highest delivery rate at low speed because the UAV has a more stable communication link at low speed, and the SCF(store-carry-forward) mechanism ensures that packets will be transmitted to the base station in the shortest path. Last, (a) and (b) show that LEPR has the lowest performance in terms of delivery ratio. The main reason is that when choosing relay nodes, LEPR only considers link stability without considering the buffer and energy of nodes. It is easy for a node to be frequently selected as a relay node and run out of power prematurely.

3) AVERAGE HOP COUNT

The average hop counts of four routing strategies based different velocity of nodes are shown in FIGURE 7. To make the comparison of this metric more meaningful, we calculated the average number of packets which are successfully transmitted. As we can see from these pictures, the all protocols show the similar trend as simulation time increases. The most prominent of changes in these figures is our EORB-TP protocol. From the sequence of (a), (b), and (c), we can see that the number of hops of the EORB-TP protocol increases slightly as the speed increases, the direct reason is that the low speed affects the accuracy of our position prediction. But in diagrams (a) and (b), the number of hops of the EORB-TP protocol remains relatively low compared to other three protocols. The reason is that in our EORB-TP protocol,

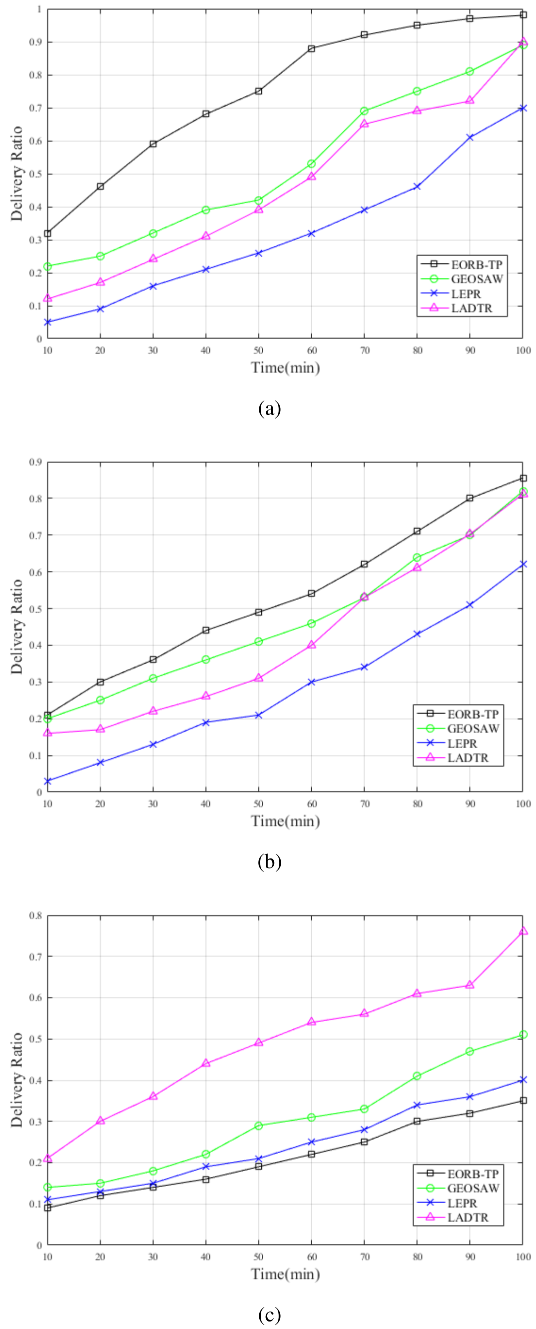

FIGURE 6. **Comparison of delivery ratio with varying velocity of nodes: (a) High speed (80Km/h), (b) Normal speed (50Km/h), (c) Low speed (20Km/h).**

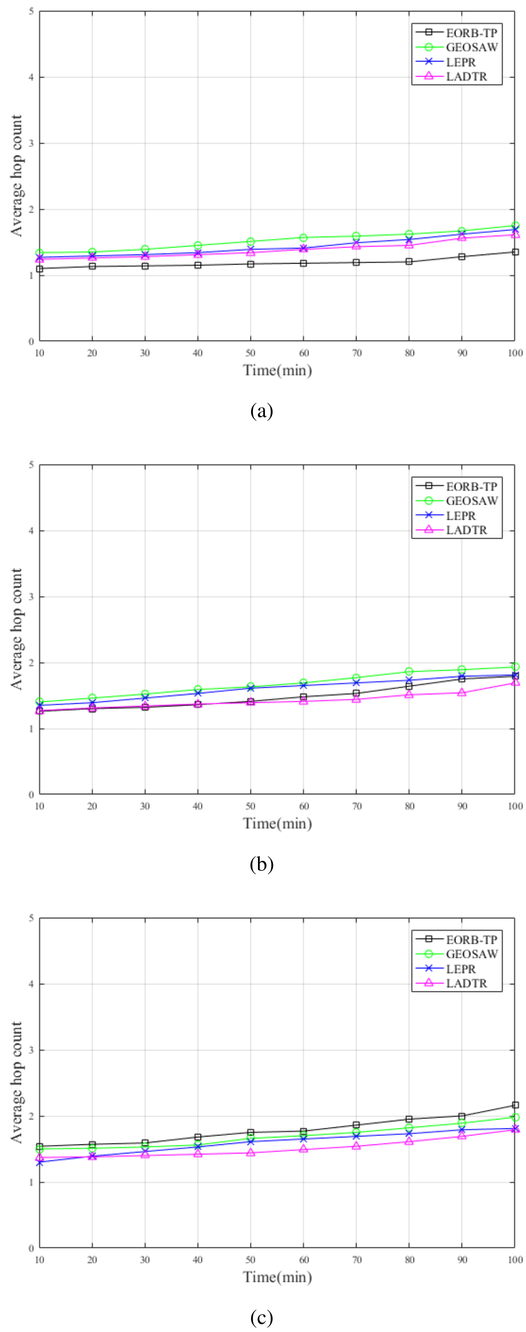

FIGURE 7. **Comparison of with average hop count varying velocity of nodes: (a) High speed (80Km/h), (b) Normal speed (50Km/h), (c) Low speed (20Km/h).**

the trajectory metric of the node is taken into account when the packets choose the optimal path, and the relay node with sufficient energy and buffer is selected for data transmission. Although the GEOSAW protocol predicts the future path of neighboring nodes, it does not consider the problem of limited buffer of nodes. Hence lots of packets will be discarded before they reach the destination node because the buffer is full. So GEOSAW shows the highest number of hops. In addition, LEPR and LADTR both estimate the link quality and make use of control messages in network to reduce the number of packet hops, but the same problem with GEOSAW that is they ignore nodes' energy and buffer, which cause packet loss. Therefore, the number of hops in these protocols is relatively higher than our EORB-TP protocol.

4) AVERAGE END TO END DELAY

FIGURE 8 gives the performance comparison of average end to end delay of these four protocols at different node speeds, respectively. Obviously, the average end to end delay

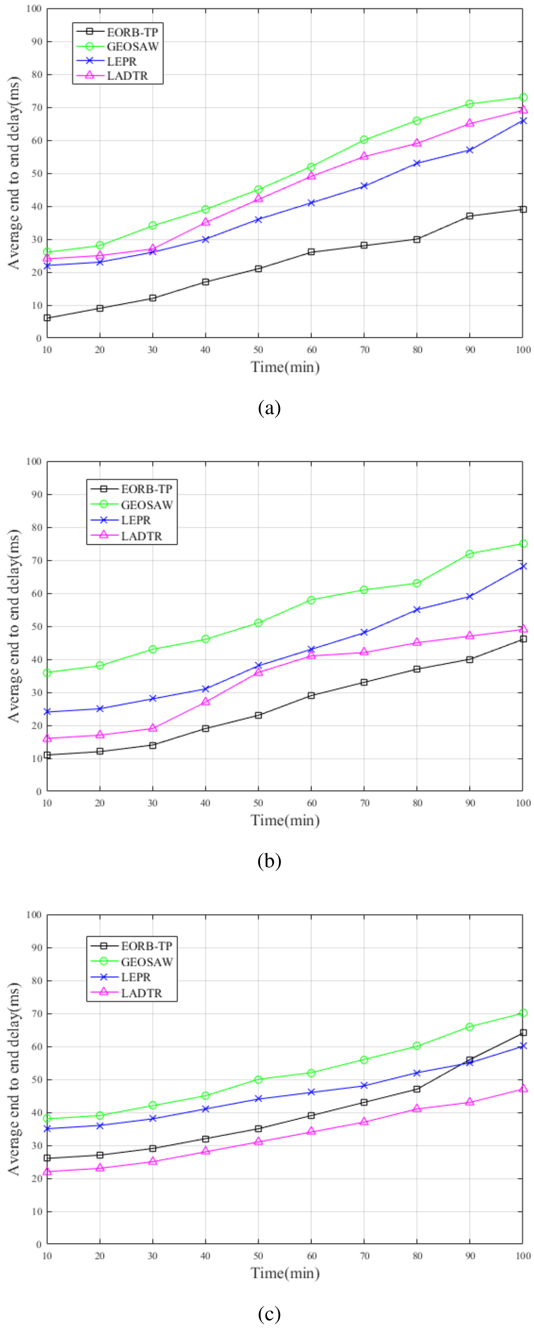

FIGURE 8. Comparison of with average end to end delay varying velocity of nodes: (a) High speed (80Km/h), (b) Normal speed (50Km/h), (c) Low speed (20Km/h).

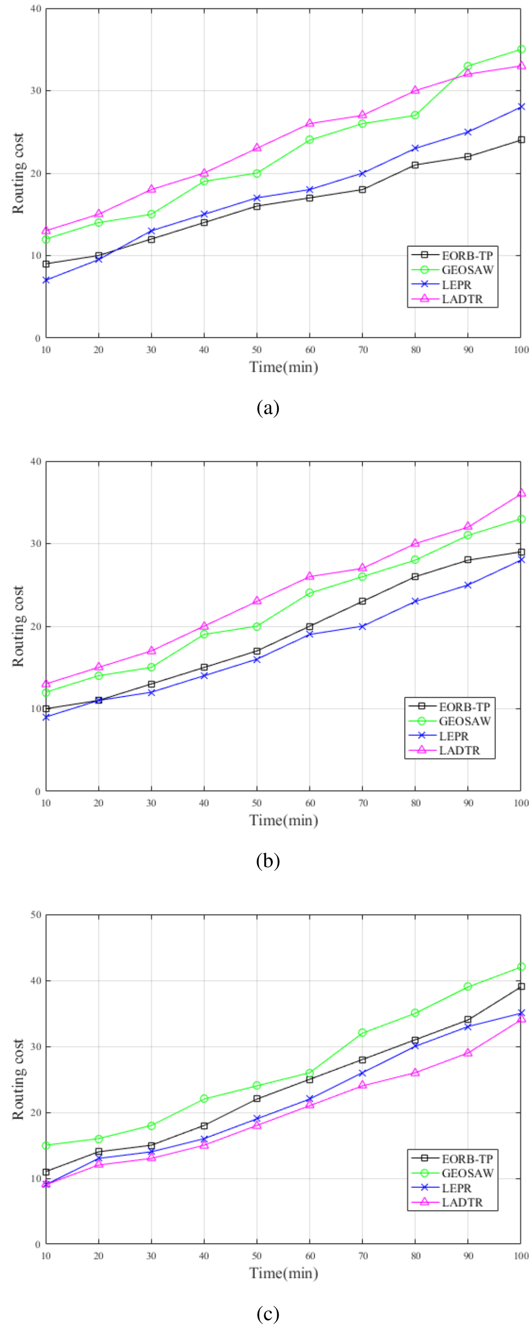

FIGURE 9. Comparison of with routing cost varying velocity of nodes: (a) High speed (80Km/h), (b) Normal speed (50Km/h), (c) Low speed (20Km/h).

fo GEOSAW is higher than the other three protocols at high, normal and low speeds. The reason is that although GEOSAW can predict the future path of nodes, it cannot predict the link state of nodes when transmitting data packets in the future, and it lacks consideration of the buffer space and energy of nodes. Secondly we can see that LADTR has the lowest delay at low speed, because the LADTR introduces the ferry UAVs which play the prat of relay node in the network. The forwarding mechanism based on link prediction ensures the connection time between the ferry UAVs and the search UAVs, so decreasing the delay to a large extent. Furthermore, we can see from these pictures that the delay of LEPR is always higher than EORB-TP, because LEPR is on-demand routing and the reaction time during packets transmission can cause an increase in latency. Finally we can see that the average end to end delay shows a decrease trend with the increase of speed in our EORB-TP protocol. The reason is that when we design the utility function of the relay node, we not only consider the future path of the node, but also consider the energy and buffer of the node itself.

5) ROUTING COST

In order to highlight the effectiveness of our EORB-TP protocols, we also provide a comparison of routing cost among four routing strategies based on different node speeds. As shown in FIGURE 9, we can see that LADTR has the highest routing overhead at high and normal speed but exhibits the lowest routing overhead at low speed. This is because the encounter time between nodes is longer when the UAV nodes are moving at a low speed. By the way, the single-copy forwarding strategy is also beneficial to reduce overhead. However, with the increase of node speed, the control messages in the network will increase correspondingly, which leads to high overhead. What's more, we can see that the routing cost of LEPR and GEOSAW are all increasing as the speed increases. The common reason is that the high speed movement of nodes leads to the drastic change of network topology, so the communication link is prone to interrupt. Under such circumstances, the number of copies of packets will increase in the process of looking for an effective transmission path. Finally, our EORB-TP protocol exhibits the lowest routing overhead at high node speed. Because at high speed, our relay selection strategy is more effective in selecting suitable relay forwarding nodes.

VII. CONCLUSION

In this article, an opportunistic routing protocol based on trajectory prediction is proposed to deal with the dynamic topology and unstable links of the FANET, named EORB-TP. First, we adopt the Gaussian mixture model to analyze the possibility of the node's future time moving speed. Secondly, according to the predicted node location information, the trajectory metric value of the node can be obtained, which can avoid the boundary effect and routing void. Most importantly, the limited energy and buffer of nodes are also taken into account when selecting the relay nodes. In order to evaluate the performance of our protocol, we have done extensive comparative simulations based on the variation of UAV movement speed. The results show that our proposed EORB-TP protocol has advantages over the other three protocols in terms of delivery rate, end to end hops, latency and routing overhead. This results indicates that our EORB-TP protocol is more suitable to be applied in FANET with dynamic network topology changes.

In the future, we hope to improve the applicability of this protocol by considering the height variation of UAVs when predicting the location of UAVs. Secondly, we want to consider an algorithm based on copy control stategy to control the number of copies of data packets in the network so as to reduce the network load.

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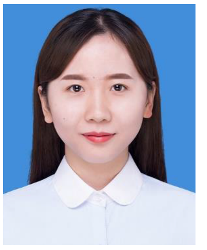

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