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RESEARCH ARTICLE

Elastic Routing Mechanism for Flying Ad Hoc Network

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ABSTRACT Flying Ad-Hoc Network (FANET) is a hot topic in current research. The design of routing mechanism is challenging because when the scale of Unmanned Aerial Vehicle (UAV) nodes is large, vast amount of routing overhead may lead to network collapse. An elastic routing mechanism is proposed for large-scale small UAVs multitasking scenarios. Firstly, the New-Unifying Connected Dominating Set (N-UCDS) algorithm is proposed to construct a virtual backbone network based on the connected dominating set. The number of neighboring nodes, remaining energy and link duration are considered to influence the UAV network performance when electing backbone nodes. Secondly, by deploying and running the New Better Approach to Mobile Ad-Hoc Network-Advanced (NBATMAN-ADV) routing protocol on the backbone nodes, the link quality can be evaluated by using the received signal strength index and signal-to-noise ratio of the physical layer data. In this way, the change of the link can be quickly sensed while reducing the routing overhead. The simulation results show that the routing protocol proposed in this paper has significantly improved average packet delivery rate, end-to-end delay and received throughput compared with other traditional proactive routing protocols.

INDEX TERMS Flying ad-hoc network, elastic routing mechanism, virtual backbone, N-UCDS algorithm, NBATMAN-ADV routing protocol.

I. INTRODUCTION

In recent years, UAVs have become an important factor influencing the combat process due to their remarkable combat effectiveness, low cost, low casualties and easy to equip in large quantities. In particular, small UAV cluster systems have the advantages of good scalability, high resistance to destruction and high efficiency. Small UAV cluster system can play an important role in a variety of military operations such as battlefield reconnaissance, border patrol, communication relay and precision strike. However, reliable communication between UAVs is the basis and prerequisite for the mission collaboration of the cluster system.

UAV communication networks have the following characteristics [1]: ① high speed movement of nodes. Nodes can move at speeds of 30-460 km/h; ② large-scale sparse distribution. UAVs operate independently in widely distributed 3D space; ③ Multiple communication services coexist. UAVs usually need to transmit multiple types of services when performing multifunctional tasks, and different types of services have different Quality of Service (QoS) requirements, such as delay, transmission rate and throughput.

FANET [2], [3], [4] is the core technology for building UAV communication networks. There are differences among the three types of self-organizing networks: Mobile Ad-Hoc Network (MANET), Vehicular Ad-Hoc Network (VANET), and FANET [5]. FANET does not depend on a pre-built communication infrastructure and can transmit multiple messages between UAVs through wireless channels, thus forming a multi-hop, self-organized, distributed networks. In the large-scale small UAVs multitasking scenarios, UAVs cluster systems are characterized by large scale and high dynamic,

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leading to problems such as rapid changes in UAV network topology and frequent link failures. When MANET is applied in this scenario, due to the large scale of UAV nodes, problems such as reduced packet delivery rate, longer end-to-end delay, and increased routing overhead affect network performance seriously.

Nodes of on-demand routing protocols do not store real-time and accurate routing information but look for routes when they are needed. Such as Ad hoc On-demand Distance Vector (AODV) [6], Dynamic Source Routing (DSR) [7]. In a large-scale network system, the time of route establishment increase the delay due to route path finding, which is not suitable for high-speed moving UAV networks. Regardless of whether there is a communication requirement, each node of proactive routing protocols periodically broadcasts routing packets, thereby maintaining a routing table reaching other nodes, and periodically publish topology change messages. Such as Optimized Link State Routing (OLSR) [8] and Destination-Sequenced Distance Vector (DSDV) [9]. The node periodically updates the routing table. Compared with the on-demand routing protocol, the delay of the proactive routing protocol is significantly reduced. UAV cluster systems have the characteristics of high-speed movement and are sensitive to delay requirements, so the proactive routing protocol is more suitable for flying ad-hoc networks.

However, as the scale of UAV nodes expands, the routing overhead grows proportionally to the square of the number of nodes. If the overhead is reduced by decreasing the update frequency, the delay increases due to route switching. Therefore, the key to the flying ad-hoc network routing mechanism is how to use the lowest route maintenance overhead to achieve fast route update and ensure the normal operation of the network.

Constructing a virtual backbone network based on the connected dominating set in UAV cluster systems [10] is an effective means to reduce the routing overhead and message forwarding volume. A virtual backbone network is a backbone network formed by selecting some of the UAV nodes as backbone nodes among the UAV nodes. All non-backbone nodes have neighboring backbone nodes, and messages can be forwarded to the destination nodes by simply sending them to the neighboring backbone nodes. The virtual backbone network serves as a logical topology for the network and allows for performance optimization of the network.

This paper proposes an elastic routing mechanism. Firstly, a virtual backbone network is built in FANETs, and a part of nodes is elected as backbone nodes to constitute the backbone network. The aim is to reduce the node size. Secondly, when the virtual backbone network is introduced, only the routing protocols need to be deployed and run on the backbone nodes to achieve intercommunication of the entire network nodes. The use of lightweight active routing strategy can reduce the delay of route discovery and achieve fast routing. Therefore, this paper is divided into two parts: the construction of the virtual backbone network and the FANET routing protocol.

II. BACKGROUND

A. CONSTRUCTION OF VIRTUAL BACKBONE NETWORK

The concept of Unifying Connected Dominating Set (UCDS) was proposed in [11]. The UCDS algorithm is a distributed algorithm which each node only needs to obtain two-hop neighbor topology information to execute the algorithm correctly. Each node in UCDS supports the maintenance of routing information by playing an important role in relay forwarding and routing distribution. Maintenance of routing information can be done in UCDS. The virtual backbone nodes in UCDS algorithm are members of Dominating Set (DS) and Connected Set (CS). DS members are responsible for route distribution and relay forwarding of common nodes, and CS members are responsible for connecting the members of the dominating set. The election of DS members is mainly based on the domination factor, but the domination factor is only determined by the number of node neighbors without considering other factors of UAVs. The single metric makes the backbone nodes change too frequently, leading to instability of network topology. The CS membership election is performed by the node itself with CS rule and CS exception rule. Then the result of the judgment is broadcasted to the neighbor DS members and finally the DS members elect the CS members. This process makes the construction of the virtual backbone network inefficient and the topology convergence speed slow.

Therefore, this paper proposes an N-UCDS algorithm for electing backbone nodes to construct a virtual backbone network. In the large-scale small UAVs multitasking scenarios, the energy of small UAVs is limited, so the impact of energy consumption and link quality on the survival time and stability of the UAV network is fully considered in the DS member election process of the N-UCDS algorithm. The N-UCDS algorithm proposes that when a node is elected as a DS member, it automatically executes a new CS rule based on the two-hop neighbor node information to make a judgment and directly designate some Connected Set Candidate (CS') nodes as CS members. This saves an update cycle time and speeds up the topology convergence without affecting the correctness of the algorithm, making it more applicable to UAV networks.

B. FANET ROUTING PROTOCOL

The BATMAN-ADV [12], [13] routing protocol is a proactive routing protocol that works at the second layer of the OSI model, the data link layer. Each node only needs to know the best next-hop neighbor node to the destination node and does not have to worry about global topology changes. This makes the overall architecture of the protocol small and can quickly adapt to changes in the network topology, which is very suitable for UAV networks. Each node periodically broadcasts OGM packets for informing other nodes of its own existence. After receiving OGM packets from other nodes, the node forwards them according to the policy, enabling the OGM packets to spread to the whole network.

Therefore, this paper proposes a NBATMAN-ADV routing protocol that needs to be deployed and run only on the backbone nodes elected by the N-UCDS algorithm. In this protocol, DS member nodes periodically send out Originator Message (OGM) packets and Connected Dominating Set (CDS) member nodes forward the OGM packets. The link quality is evaluated using the received signal strength indicator and signal-to-noise ratio of physical layer data, which reduces the routing overhead while enabling fast sensing of link changes.

The main contributions of this paper are as follows:

1. With the expansion of UAV node size, the overhead of a proactive routing protocol grows proportionally to the square of the number of nodes. So, an elastic routing mechanism is proposed to construct a FANET virtual back-bone using the N-UCDS algorithm. Then run the NBATMAN-ADV routing protocol on the backbone nodes. Routing messages are broadcast by backbone nodes, which greatly reduces routing overhead.

2. Compared with the UCDS algorithm, by using the N-UCDS algorithm to construct a virtual backbone network, the election method of the connected dominating set members and the calculation method of the dominating factor are improved considering the remaining energy of the UAV and the link duration. This greatly improves the robustness of the algorithm, reduces the time for constructing a virtual backbone network by one update cycle, and increases the network lifetime by 5%.

3. Compared with the BATMAN-ADV routing protocol, running the NBATMAN-ADV routing protocol on the backbone node changes the routing metric criteria. Using the received signal strength index and signal-to-noise ratio of physical layer data to evaluate link quality, it can quickly and accurately perceive changes in the link. At the same time, only OGM packets are broadcast on DS members of the backbone node. OGM packets are forwarded on CDS members, and neighbor node information is added to the OGM packets. This greatly reduces the number of OGM packets and the total amount of data flooded in the network.

The rest of this paper is organized as follows: part 2 introduces the research background; part 3 introduces the related research work; part 4 presents the system model; part 5 describes the FANET virtual backbone construction method based on the N-UCDS algorithm; part 6 introduces the NBATMAN-ADV routing protocol; part 7 performs simulation and experimental analysis; part 8 concludes the full paper and proposes subsequent research directions.

III. RELATED WORKS

A. CONSTRUCTION OF VIRTUAL BACKBONE NETWORK

Currently, the connected dominating set-based approach to build virtual backbone networks is widely used in MANETs, VANETs and FANETs, but finding minimum connected dominating set (MCDS) has proven to be an NP-hard problem [14].

Chowdhury [15] studied the problem of efficient data dissemination between mobile nodes in wireless networks, MCDS is commonly used to reduce redundant transmissions in broadcasts. The problem of constructing MCDS is discussed, using MCDS as a starting point for constructing contention aware connected dominating set (CACDS) algorithm to optimize the network competition problem with large node size. Qi *et al.* [16] proposed to construct CDS in FANET to solve the joint optimization problem of node transmission power and location. It proposed a topology control mechanism based on CDS and a time-discretized topology construction maintenance algorithm, which outperforms the general particle swarm optimization (PSO) algorithm in terms of network overhead and network stability in UAV cluster systems. Wang *et al.* [17] proposed that a swarm of UAVs can build a virtual backbone network (VBN) based on graph-theoretical d-hop DS, where each UAV outside the VBN can send the collected data within distance to the VBN. an adaptive ADMS algorithm was proposed to maintain a stable VBN, which can achieve a better trade-off between routing overhead, response time, and maintenance cost.

Liang *et al.* [18] used CDSs as the virtual backbone of WSNs, but due to the actual environmental factors, the transmission radius of nodes in the network is unstable, so the robustness of VBs in WSNs is considered, and the corresponding algorithm is proposed to construct d-robust CDSs in WSNs with unstable transmission range. But the paper does not consider the construction of virtual backbone networks for 3D scenarios, which can be extended to 3D spatial FANET scenario. Mao *et al.* [19] proposed an efficient distributed routing algorithm based on connected dominating sets to build a virtual backbone network can effectively mitigate the broadcast storm problem in mobile self-assembly networks, which is more applicable to dynamic self-assembly networks. By broadcasting only through selected network nodes, the same effect as flooding can be achieved and the broadcast storm problem is avoided. Considering the transmission range, residual energy and mobility of nodes, this algorithm can significantly reduce the network construction overhead, ensure network connectivity, improve energy efficiency, and prolong network survival time.

Guanghui Li and Huan Ma of Beijing Jiaotong University applied the UCDS algorithm to WNW tactical waveform networks [20] and tactical Internet [21]. Xu *et al.* of Zhejiang University applied the UCDS algorithm to construct a virtual backbone network for OLSR routing protocol [22].

B. FANET ROUTING PROTOCOL

In recent years, many researchers have studied routing in FANETs because traditional mobile self-assembled network routing protocols are not suitable for application in FANETs, and rapid topology changes can cause dramatic degradation of performance indicators such as packet delivery rate, end-to-end delay, throughput, and overhead. FANETs routing protocols still faces many challenges [23]: dynamic topology, high mobility, low latency, QoS requirements, energy efficiency, communication standards and various links.

Usually, FANETs routing protocols can be divided into two categories: topology-based and position-based routing protocols. Furthermore, the first category consists of three specific types of protocols: proactive routing protocols, reactive routing protocols, and hybrid routing protocols. This paper focuses on proactive routing protocols. Wheeb [23] summarized some proactive routing protocols improved on OLSR protocol: OLSR-Expected Transmission Count (OLSR-ETX) [24], Trajectory-OLSR (T-OLSR) [25], Mobility and Load Aware OLSR (ML-OLSR) [26], Predictive-OLSR (P-OLSR) [27].

T-OLSR's process basically follows the classical OLSR. The nodes update their MPR nodes upon receiving the hello message from neighbors and update the routing table upon receiving the TC message from MPR nodes. Each node periodically sends out a hello message, and the nodes that are selected as MPR nodes send TC messages when they sense topology changes. Each node shares its pre-planned short-term trajectory in the hello message and TC message, resulting in a slight increase in overhead. T-OLSR is specifically designed to accomplish collaborative operation in FANETs. The performance of T-OLSR is shown to be superior to traditional methods, especially in sparsely distributed networks.

Arafat and Moh [28] proposed topology-aware routing based on Q-learning, where UAV nodes adaptively adjust their routing strategies based on obtaining information about their two-hop neighbor nodes, but it brings certain computational consumption and instability as the environment changes. Costa *et al.* [29] proposed an improved Q-Learning algorithm to reduce network delay in scenarios with high-mobility, called Q-FANET. The experiments provide evidence that the Q-FANET presents lower delay, a minor increase in packet delivery ratio, and significant lower jitter compared with other reinforcement learning-based routing protocols. In the study of SDN-based FANETs, Silva *et al.* [30] proposed a topology management algorithm for SDN with the aim of constructing and maintaining a FANET topology. It provides stable and continuous links between UAV nodes operating in clusters. Wu *et al.* [31] proposed to apply the Extended Kalman Kilter (EKF) for accurate mobility estimation and prediction of UAVs, to represent the routing problem in SDN-based heterogeneous FANETs as a graph decision problem, and to propose a Directed Particle Swarm Optimization (DPSO) routing protocol with superior performance.

Wu and Sun of the University of Electronic Science and Technology extended the BATMAN-ADV routing protocol by designing a routing fast-aware algorithm, an adaptive multi-interface multipath routing protocol, and a routing protocol applicable to temporary network outages [32] and proposed a broadcast flood suppression algorithm based on domain combination selection and a layer 2 routing metric based on link state [33]. By comparing the BATMAN-ADV routing protocol with the BATMAN routing protocol [34] and the HWMN routing protocol [35], it is demonstrated that the BATMAN-ADV routing protocol has better performance.

IV. SYSTEM MODEL

Fig.1 shows the large-scale small UAVs multitasking scenarios. The ground is divided into multiple areas. The UAV cluster system operates in the air and needs to perform various tasks. The trajectory of a single UAV can be represented by the set $\{(\mathbf{X}_0, \mathbf{X}_1, S_1), \cdots, (\mathbf{X}_{n-1}, \mathbf{X}_n, S_n)\}$, where $S_n \sim N(\mu_s, \sigma_s^2)$ denotes the hovering time of the UAV performing the mission at the path point $\mathbf{X}_n$. Assuming that the displacement length l_n of the projection of the path points $\mathbf{X}_{n-1}$ and $\mathbf{X}_n$ on the $x-y$ plane conforms to the Rayleigh distribution [36], when $\sigma = \sqrt{\frac{1}{2\pi\lambda}}$, the distribution function and the probability density function can be expressed as follows:

$$F_{L_n}(l_n) = P(L_n \le l_n) = 1 - \exp\left(-\lambda\pi l_n^2\right) \tag{1}$$

$$f_{L_n}(l_n) = \frac{\partial F_{L_n}(l_n)}{\partial l_n} = 2\pi\lambda l_n \exp(-\pi\lambda l_n^2) \tag{2}$$

where $\mu(l_n) = \sigma\sqrt{\frac{\pi}{2}} = \sqrt{\frac{1}{4\lambda}}$ and $D(l_n) = \frac{4-\pi}{2}\sigma^2 = \frac{4-\pi}{4\pi\lambda}$.

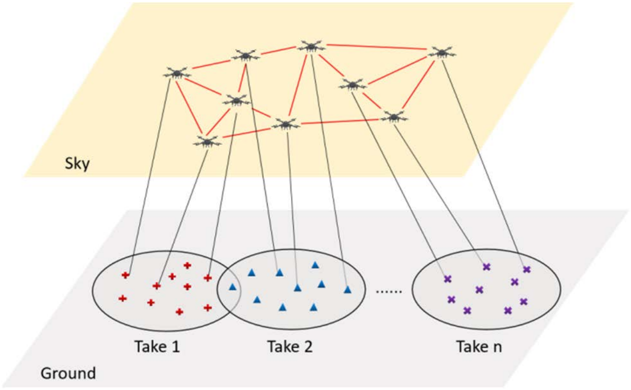

FIGURE 1. Large-scale small UAVs multitasking scenarios.

The angles of the projected displacements of path points $\mathbf{X}_{n-1}$ and $\mathbf{X}_n$ in the $x-y$ plane, $f_\Theta(\theta) \sim U(0, 2\pi)$ conform to the uniform distribution [31], and the altitude of each path point $f_H(h) \sim N(\mu_h, \sigma_h^2)$ conforms to the Gaussian distribution $\mu_h = (H_{high} + H_{low})/2$ and $\sigma_h = (H_{high} - H_{low})/6$. The lengths of the displacements projected by the UAV on the $x-y$ plane and the flight altitude are independent of each other, so the joint probability density of both can be expressed as [37]:

$$f_{L,H}(l_n, h) = \begin{cases} \dfrac{6\sqrt{2\pi}\lambda l_n}{(H_{high} - H_{low})} \\ \times \exp\left(-\dfrac{18(h - \frac{H_{high}-H_{low}}{2})^2}{(H_{high} - H_{low})^2} - \pi\lambda l_n^2\right) \end{cases} \tag{3}$$

To simplify the analysis, it is assumed that all UAVs have the same communication capability and all use omnidirectional antenna. $d_{\max}$ indicates the maximum communication

TABLE 1. N-UCDS algorithm rules.

Rules	Description
DS Rule	The node i assigns the node i with the highest dominance factor d_{ij} among all its neighboring nodes j as DS members.
Not-CS Rule	If node i is a non-DS member and any two neighboring nodes j and k can be connected to each other, then node i is a normal node.
CS Rule	For DS member node j , the nodes whose neighbors are CS' members i are sorted according to the high or low dominance factor d_{ji} , and for node i there exists a neighbor node k ($j \neq k$ and if node k has been recorded, the next node k is judged directly). **Case 1.** if node k is a DS member and nodes j and k have a CS member in their common neighborhood, the next node k is judged. **Case 2.** if the node k is a non-DS member and the node i has a common DS neighbor node with this node k , then the next node k is judged. If the DS neighbor sets of node j and k do not intersect, then node j designates the node i as a CS member and records the node k then determines the next node.

distance, it is considered that the UAV nodes i and j can communicate with each other when $d(i,j) < d_{\max}$ is satisfied. Assume that the active space of the UAV is $[-L, L] \times [-L, L] \times [H_{low}, H_{high}]$. According to the Euclidean distance formula, the real-time distance between the UAV nodes i and j can be expressed as:

$$d(i,j) = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + \left(h_i - h_j\right)^2} \tag{4}$$

V. N-UCDS ALGORITHM

The N-UCDS algorithm is improved from the UCDS algorithm. The impact of energy consumption and link quality on the survival time and stability of the UAV network is fully considered in the DS member election process. During the selection process of CS members, new CS rule is executed automatically, which saves one update cycle time and speeds up the topology convergence without affecting the correctness of the algorithm. The operation flow of the algorithm is: DS rule→ Not-CS rule→ CS rule. The specific N-UCDS algorithm rules are shown in Table 1.

A. DOMINANCE FACTOR

The selection of DS members is mainly based on the dominance factor. In the UCDS algorithm, the dominance factor is only determined by the number of node neighbors. However, in the large-scale small UAVs multitasking scenarios, the impact of energy consumption on UAV network survival time and the impact of link quality on UAV network stability should be fully considered in the DS member selection process because of the energy limitation of small UAVs. Therefore, the N-UCDS algorithm redefines the dominance factor:

$$\begin{aligned} d_{ij} = \theta_A \times \frac{N_i}{N} + \theta_B \times \frac{E_r}{E_t} + \theta_C \\ \times \frac{T_{ij}}{T_{\max}} (\theta_A + \theta_B + \theta_C = 1) \end{aligned} \tag{5}$$

where for node i, the dominance factor d_{ij} of its neighbor node j is determined by the combination of the number of one-hop neighbors N_i of node j, the remaining energy E_r and the link duration T_{ij} between nodes i and j, where $\theta_A, \theta_B, \theta_C$ is the normalization factor of each item,Ndenotes the total number of UAV clusters,$E_t$denotes the total energy of individual UAVs, and$T_{\max}$denotes the maximum duration of the link.

The steady state of the network within the two-hop neighborhood of the node i can be expressed as:

$$W_i = 1 - \frac{N_{CDS}^i + V_{CDS\_change}^i}{2N} \tag{6}$$

where N_{CDS}^i denotes the number of backbone nodes in the two-hop neighborhood of node i and $V_{CDS\_change}^i$ denotes the rate of node attribute change in the two-hop neighborhood of node i. The node attribute change refers to the transition between backbone node state and non-backbone node state.

The coefficients $\theta_A, \theta_B, \theta_C$ are calculated using the multivariate gradient descent method in machine learning. The calculation is shown in Algorithm 1 and where α is the learning rate.

Algorithm 1 $\theta_A, \theta_B, \theta_C$ Selection Algorithm

```
Hypothesis:
$W_i(x) = h_\theta = \theta^T x = \theta_0 x_0 + \theta_A x_A + \theta_B x_B + \theta_C x_C$
Parameters: $\theta_0, \theta_A, \theta_B, \theta_C$
Cost function:
$J(\theta_0, \theta_A, \theta_B, \theta_C) = \frac{1}{2m} \sum_{i=1}^{m} \left(h_\theta\left(x^{(i)}\right) - y^{(i)}\right)^2$
Gradient descent:
Repeat $\left\{\theta_j := \theta_j - \alpha \frac{\partial}{\partial \theta_j} J(\theta_0, \theta_A, \theta_B, \theta_C)\right\}$
Output:
$\theta_j := \theta_j - \alpha \frac{1}{m} \sum_{i=1}^{m} \left(h_\theta\left(x^{(i)}\right) - y^{(i)}\right) x_j^{(i)} \ (j = 0, A, B, C)$
```

As shown in Fig.2, the network reaches the most stable state when $\theta_A = 0.3, \theta_B = 0.5, \theta_C = 0.2$ and $W_i$takes the maximum value.

B. ENERGY CONSUMPTION

Small UAVs energy consumption includes propulsion and hovering energy consumption and UAVs communication energy consumption. This paper assumes that 75% of the energy is used for propulsion and hovering and 25% of the energy is used for communication. All UAVs have 100% energy at the initial moment. Whether the UAV node is a

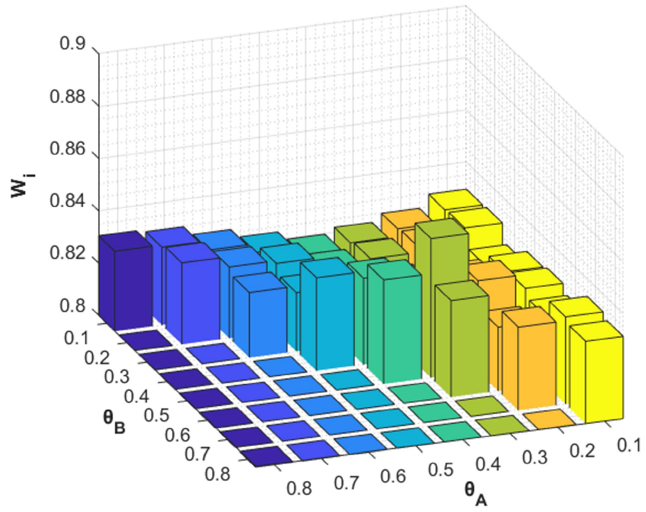

FIGURE 2. **Choice of dominance factor coefficients.**

backbone node and whether the UAV is in a mobile state can make a difference in the rate of energy consumption.

The energy consumption rate of UAV is discussed in the following four cases: ① The UAV node is a DS member and is in the mobile state. The energy consumption rate is δ_1. ② The UAV node is a DS member in the hovering state. The energy consumption rate is δ_2. ③ The UAV node is not a DS member and is in the mobile state. The energy consumption rate is δ_3. ④ The UAV node is not a DS member and is in the hovering state. The energy consumption rate is δ_4. In this paper, $\delta_1 = 0.1$, $\delta_2 = 0.06$, $\delta_3 = 0.07$, $\delta_4 = 0.03$.

C. LINK DURATION

The amount of change in speed of the two UAVs in the direction of x, y, h can be expressed as [38]:

$$k_x = \bar{v}_i \sin\theta_i \cos\varphi_i - \bar{v}_j \sin\theta_j \cos\varphi_j \tag{7}$$

$$k_y = \bar{v}_i \sin\theta_i \sin\varphi_i - \bar{v}_j \sin\theta_j \sin\varphi_j \tag{8}$$

$$k_h = \bar{v}_i \cos\varphi_i - \bar{v}_j \cos\varphi_j \tag{9}$$

where $\bar{v}_i, \bar{v}_j$ indicates the average speed of flight of the UAV nodes i and j, θ_i, θ_j indicates the angle in the plane of $x - y$, and φ_i, φ_j indicates the angle in the axis of z.

The duration of the communication link T_{ij} between the UAV nodes i and j is calculated as shown in Algorithm 2.

Algorithm 2 Communication Link Duration Algorithm

```
Input: $\bar{v}_i, \theta_i, \varphi_i, \bar{v}_j, \theta_j, \varphi_j, d_{\max}$
$d_{\max}^2 = (x_i - x_j + k_x T_{ij})^2 + (y_i - y_j + k_y T_{ij})^2 + (h_i - h_j + k_h T_{ij})^2$
$\begin{cases} a = k_x^2 + k_y^2 + k_h^2 \\ b = 2\left[k_x(x_i - x_j) + k_y(y_i - y_j) + k_h(h_i - h_j)\right] \\ c = (x_i - x_j)^2 + (y_i - y_j)^2 + (h_i - h_j)^2 - d_{\max}^2 \end{cases}$
Output: $T_{ij} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$
```

VI. NBATMAN-ADV ROUTING PROTOCOL

A. ROUTING METRIC

When the virtual backbone network is introduced, the routing mechanism can obtain many benefits. Deploying and running a lightweight active routing protocol on backbone nodes can achieve a better balance between routing overhead and route discovery delay. In the BATMAN-ADV routing protocol, the routing metric criterion mainly depends on the TQ value. The TQ value is divided into two parts: PTQ (Path Transmit Quality) represents the global link quality value after multiple hops through a path; LTQ (Link Transmit Quality) represents the local link quality value with neighboring nodes. The protocol uses the sliding window mechanism for OGM packet statistics and the average TQ value as the routing criterion. When the link quality changes significantly, the change rate of the average TQ value is slow and does not reflect the rapid change of the link well, resulting in poor convergence of the protocol. After the network topology changes, the protocol has poor ability to sense network fluctuations.

NBATMAN-ADV routing protocol evaluates link quality using received signal strength metrics and signal-to-noise ratio of physical layer data. Each network node is very easy to obtain physical layer data. This paper believes that the link quality with high signal-to-noise ratio and strong received signal strength should be better. $metric$ and $metric_{\min}$ are two routing metrics in the NBATMAN-ADV routing protocol. $metric$ is the link quality value after multiple hops, and $metric_{\min}$ is the link quality value of the worst path quality among multiple hops. To reduce the impact of temporary fluctuations in the network, the link metric is smoothed with the data from the previous time. The initial values of both $metric$ and $metric_{\min}$ are 1. The values of $metric$ and $metric_{\min}$ are updated when the node receives OGM packets. In the NBATMAN-ADV routing protocol, the factors affecting the optimal next-hop node selection are changed from TQ to $metric$ and $metric_{\min}$, and the neighbor node with the maximum $metric$ is selected as the next-hop forwarding node subject to $metric_{\min} > \tau_{\min}$. $\tau_{\min}$ is the minimum threshold of $metric_{\min}$. The value of $\tau_{\min}$ can be adjusted according to the network type and network environment.

The received signal strength of the node can be expressed as:

$$RSS = \frac{G_d^2 P}{(4\pi d/\lambda)^2} \tag{10}$$

where G_d denotes the antenna gain, P is the maximum transmit power of the node, d is the distance between the UAV nodes, λ denotes the wavelength of the signal, R is the coverage radius of the antenna, and the received signal strength is the minimum threshold when $d = 0.905R$ [39]:

$$\psi_{RSS} = \frac{G_d^2 P}{(3.62\pi R/\lambda)^2} \tag{11}$$

The node received signal strength indicator can be expressed as:

$$RSSI = 1 - \frac{\psi_{RSS}}{RSS} \tag{12}$$

The signal-to-noise ratio of the signal transmitted by the UAV node from i to j can be expressed as:

$$SNR = \frac{Hd^{-\alpha}(i,j)G_d P}{N_0 + U} \tag{13}$$

where P denotes the maximum transmit power of the UAV node, H denotes the power gain of the channel, α denotes the average path loss index of the transmission link, $N_0 \sim (0, N)$ denotes the Gaussian white noise in the channel, and U denotes the average signal interference brought by the remaining UAV nodes, which can be expressed as:

$$U = \frac{3n\left(R^{3-\alpha} - \varepsilon^{3-\alpha}\right)}{2R^3(3-\alpha)} \tag{14}$$

where ε denotes the minimum safe distance between UAVs and n denotes the average number of UAVs in a sphere of radius R with the UAV node as the center of the sphere, which can be expressed as:

$$n = \frac{N\pi\left(8L^2 + (H_{high} - H_{low})^2\right)^{\frac{3}{2}}}{3L^2(H_{high} - H_{low})} \tag{15}$$

This paper proposes a new method for calculating link metric values, which can be expressed as follows:

$$metric = \begin{cases} \omega\left[\alpha_1 RSSI_{t-1} + (1-\alpha_1)RSSI_{\mathrm{t}}\right] + \\ (1-\omega)\dfrac{\alpha_2 SNR_{t-1} + (1-\alpha_2)SNR_{\mathrm{t}}}{SNR_{\max}} \end{cases} \tag{16}$$

where $RSSI_{\mathrm{t}}$ is the received signal strength indicator at the current moment, $RSSI_{\mathrm{t-1}}$ is the received signal strength indicator at the previous moment, SNR_{t} is the signal-to-noise ratio at the current moment, SNR_{t-1} is the signal-to-noise ratio at the previous moment, $SNR_{\max}$ is the maximum signal-to-noise ratio, α_1 is the smoothing factor of the received signal strength indicator, α_2 is the smoothing factor of the signal-to-noise ratio, ω is the routing metric of the received signal strength, and $1-\omega$ is the routing metric of the signal-to-noise ratio. $\alpha_1, \alpha_2, \omega, 1-\omega$ is between 0 to 1. Assuming that the transmission path of an OGM packet is the node $1 \to 2 \to \ldots\ldots \to n \to n+1$, then *metric* and $metric_{\min}$ can be represented as:

$$metric_{1,n+1} = \begin{cases} (1-HP)^{n-1} \times metric_{1,2} \\ \times metric_{2,3} \times \cdots \times metric_{n,n+1} \end{cases} \tag{17}$$

$$metric_{\min} = \min\{metric_{1,2}, metric_{2,3}, \cdots, metric_{n,n+1}\} \tag{18}$$

where HP indicates the penalty factor for each hop passed by the OGM packet, HP is between 0 to 1.

B. ROUTING OVERHEAD

In the NBATMAN-ADV routing protocol, DS member nodes send OGM packets out periodically and CDS member nodes forward OGM packets. It significantly reduces the OGM packets flooding in the network. But it need add neighbor node information in HELLO packets and OGM packets. This slightly increase the total length of HELLO packets and OGM packets.

In the BATMAN-ADV routing protocol, each node needs to broadcast OGM packets periodically. While all nodes need to forward OGM packets sent by other nodes. Assuming that the broadcast period is $T_{interval}$ and the OGM packet size is $Size_{OGM}$. The number of OGM packets generated by the network in the time $(0, t)$ is $\frac{N^2 t}{T_{interval}}$ and the total data volume is $\frac{N^2 Size_{OGM} t}{T_{interval}}$.

The routing overhead in the NBATMAN-ADV routing protocol is divided into: ① the implementation of the N-UCDS algorithm requires UAV nodes to broadcast HELLO packets periodically, and HELLO packets need to contain information about themselves and neighboring nodes; ② DS member nodes in the virtual backbone nodes broadcast OGM packets periodically, and CDS member nodes forward OGM packets, and OGM packets need to contain information about themselves and neighboring nodes information. Then the number of routing packets generated by the network in time $(0, t)$ is $\frac{t}{T_{interval}}(N + N_{DS} \times N_{CDS})$ and the total data volume can be expressed as:

$$\frac{t}{T_{interval}}\begin{bmatrix} N \times Size_{HELLO} + N_{DS} \times N_{CDS} \times Size_{OGM} \\ + \dfrac{N\pi d_{\max}^3}{3L^2(H_{high} - H_{low})} \times (N \times Size_{HELLO\_neighbor} \\ + N_{DS} \times N_{CDS} \times Size_{OGM\_neighbor}) \end{bmatrix} \tag{19}$$

where $\frac{N\pi d_{\max}^3}{3L^2(H_{high} - H_{low})}$ denotes the average number of neighbors of the UAV node, $Size_{HELLO}$ denotes the size of the node's own information in the HELLO packet, $Size_{HELLO\_neighbor}$ denotes the size of one neighbor node's information in the HELLO packet, N_{DS} denotes the number of DS members in the network, N_{CDS} denotes the number of CDS members in the network, and $Size_{OGM\_neighbor}$ denotes the size of one neighbor node's information in the OGM packet. As the maximum communication distance $d_{\max}$ varies, the ratio between the number of routing packets and the total data volume of routing packets for NBATMAN-ADV routing protocol and BATMAN-ADV routing protocol is shown in Fig.3. When the maximum communication distance is 1600 m, the average number of backbone nodes for 100 UAV nodes to build a virtual backbone network through the N-UCDS algorithm is 28.3157 within 1000s of simulation time. Compared with the BATMAN-ADV routing protocol, the NBATMAN-ADV routing protocol generates 4.85% of the routing packets and 65.43% of the total data volume, so there is a significant reduction in routing overhead.

VII. PERFORMANCE EVALUATION

The simulation software in this paper uses MATLAB and QualNet. MATLAB is used for algorithm and numerical simulation with better performance, but it cannot simulate the real network environment, so QualNet is used for network system simulation. In QualNet each network node is

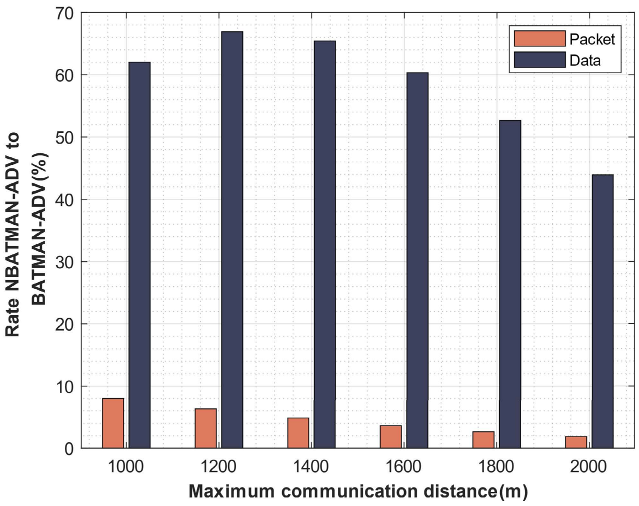

FIGURE 3. Rate NBATMAN-ADV to BATMAN-ADV at different maximum communication distances.

operated independently, which matches with the real situation and truly realizes parallel simulation. By simulating the real network environment, the required network performance data is derived in a statistical way and the obtained data is more convincing.

A. PARAMETER SETTING

Every result in the figures is the average value of 100 simulations. The simulation parameters are shown in Table 2 [23].

TABLE 2. Simulation parameters.

Parameter	VALUE
Simulator	MATLAB and QualNet
Coverage area	5km×5km
Number of UAVs	100
Simulation time	1000s
Speed	10-40m/s
Traffic type	CBR
Number of CBR	10
CBR interval	0.2s
CBR rate	2Mbps
Packet size	512Bytes
$d_{\max}$	1000-2000m
T_{interval}	1s

B. SIMULATION RESULTS AND ANALYSIS

Fig.4 represents the changes in the number of members of DS, CS, and CDS after the system network reaches stability for different maximum communication distances of the UAV nodes. The simulation results show that the number of members of each set decreases as the maximum communication distance of the UAV nodes increases. The number of backbone nodes produced by the N-UCDS algorithm and the UCDS algorithm are approximately equal, but the N-UCDS algorithm produces significantly fewer DS members and significantly more CS members than the UCDS algorithm. Fewer DS members and more CS members can make the network more robust and can effectively cope with the effects of network fluctuations.

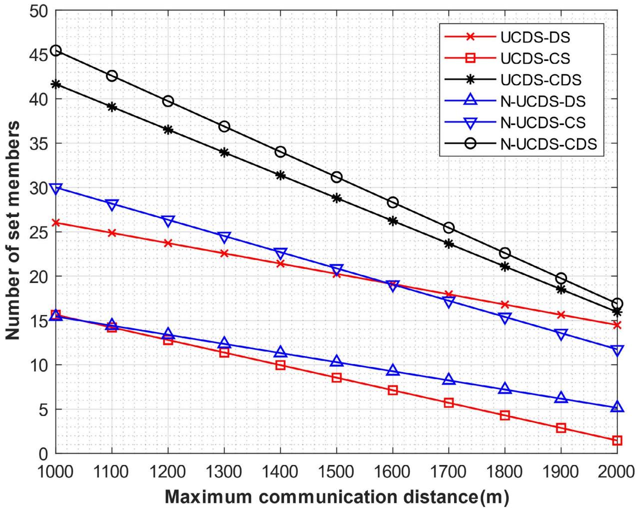

FIGURE 4. Number of set members at different maximum communication distances.

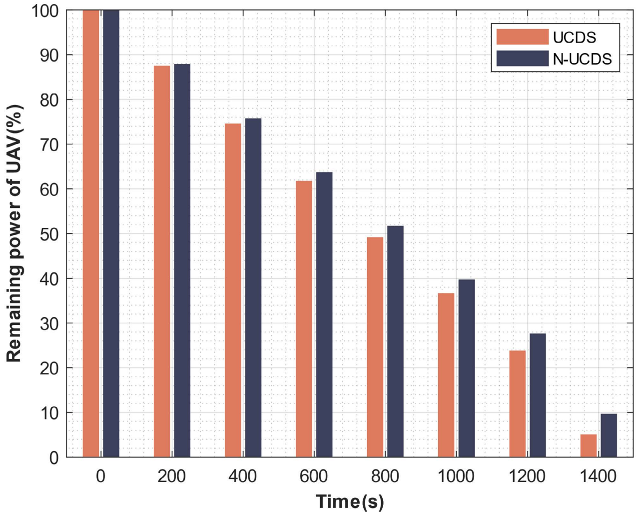

FIGURE 5. Average value of remaining power of UAVs.

When maximum communication distance is 1500 m, Fig.5 represents the average value of the remaining energy for 100 UAVs over time. The topology of the ad-hoc network is constantly changing, so the backbone nodes are also changing. Therefore, the energy consumed by each UAV is almost balanced. The simulation results show that the UAV cluster system using the N-UCDS algorithm has a reduced energy consumption rate, increased network survival time and improved the duration of the UAV cluster system performing the mission.

100 UAV nodes are deployed in QualNet, the motion model of UAV has been described in the third part of the article, the

activity space is 5 km × 5 km. 10 CBR services are randomly launched between nodes with a rate of 2 Mbps, interval of 0.2 s, packet size of 512 Byte, and simulation time is 1000 s. The simulation scenario is shown in Fig.6. In this paper, three performance indicators are considered to evaluate the routing protocol of FANET:

(1) Packet delivery ratio (PDR): the ratio of the number of packets successfully delivered to the destination node to the number of packets sent by the source node.
(2) Average end-to-end delay (E2E): the average of the time required to successfully transmit a packet from source node to destination node.
(3) Average received throughput (Throughput): the average rate of data received by the destination node.

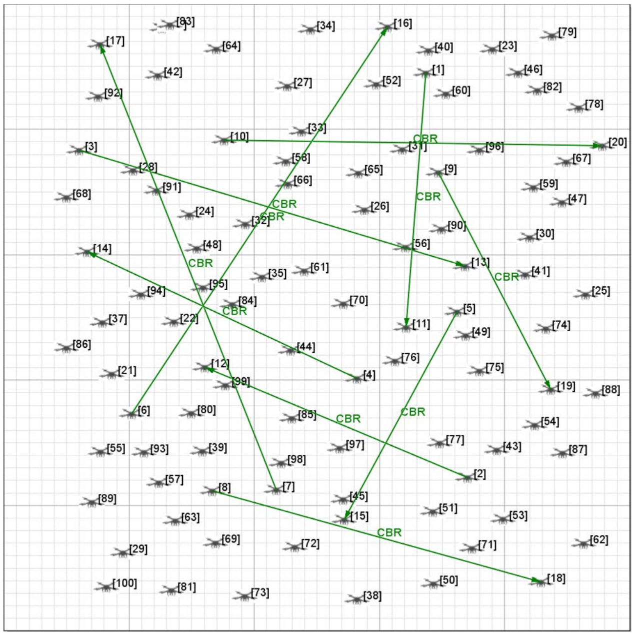

FIGURE 6. Simulation scene diagram.

OSLR is a routing protocol that is widely used in ad hoc networks. The most critical factors affecting the performance of OLSR are contained within multipoint relay (MPR) nodes. The sender node's function is to select the MPR node, covering two-hop neighbors. MPR node is used to forward broadcast messages during flooding. MPR is a critical feature in OLSR for reducing control messages.

DSDV routing protocol is a hop-by-hop distance vector routing protocol, widely used in Ad hoc mobile wireless Ad hoc LAN. It is a table-driven algorithm based on traditional Bellman-Ford routing selection mechanism.

The performance of NBATMAN-ADV routing protocol is analyzed and compared with OLSR routing protocol and DSDV routing protocol in proactive routing protocol. When the flight speed of the UAV is 20 m/s and the maximum communication distance of the node is 1000 m-2000 m, Fig.7 shows the change of PDR, Fig.8 shows the change of E2E and Fig.9 shows the change of Throughput. The black line indicates the performance of the NBATMAN-ADV routing protocol. The blue line indicates the performance of the OLSR routing protocol. The grey line indicates the performance of the T-OLSR routing protocol, and the red line indicates the performance of the DSDV routing protocol. As the maximum communication distance increases and the UAV nodes have more information about neighboring nodes. The simulation results show that the performance indicators of all four routing protocols increase. But the performance of the NBATMAN-ADV routing protocol has a significant advantage over the other routing protocol.

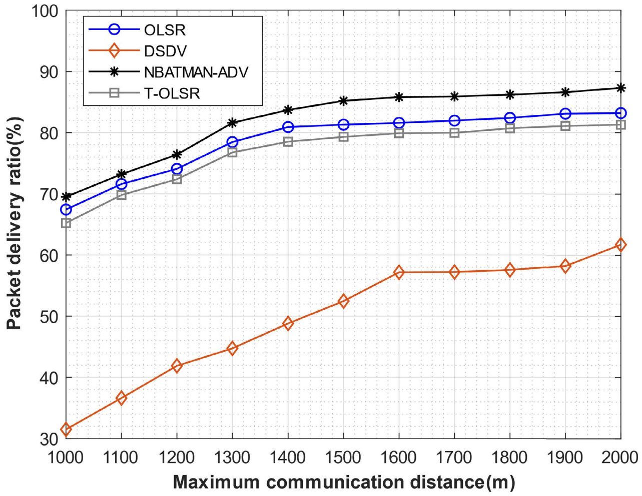

FIGURE 7. PDR of nodes at different maximum communication distances.

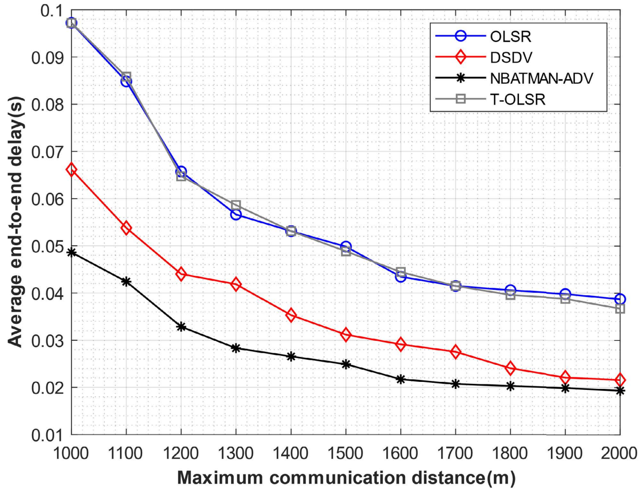

FIGURE 8. E2E of nodes at different maximum communication distances.

Due to the high dynamic nature of UAV nodes, it leads to frequent link failures, resulting in lower PDR. In the NBATMAN-ADV routing protocol, the nodes use the number of neighboring nodes, remaining energy, and link duration as a combined factor to calculate the dominance factor to select the backbone nodes. This reduces the rate of change of the backbone nodes, increases the effectiveness of the forwarding nodes and increases the connectivity of the network. Therefore, PDR is improved. In the NBATMAN-ADV

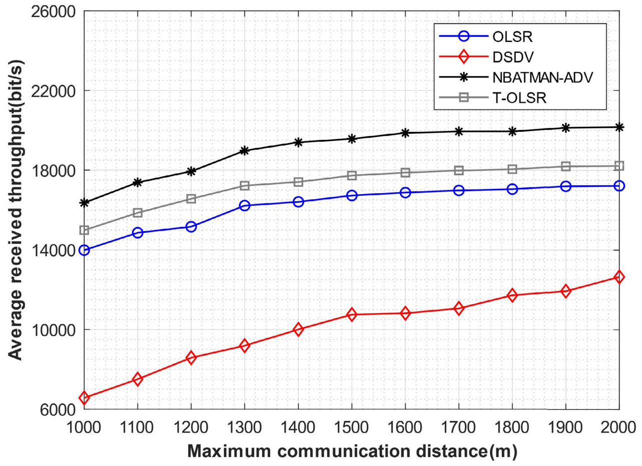

FIGURE 9. Throughput of nodes at different maximum communication distances.

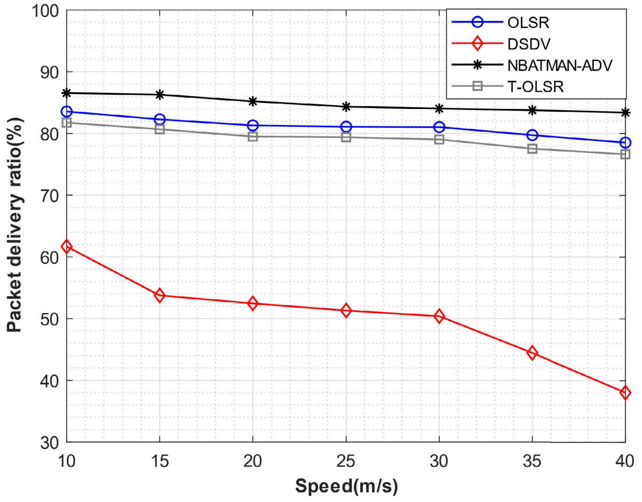

FIGURE 10. PDR of nodes at different speeds.

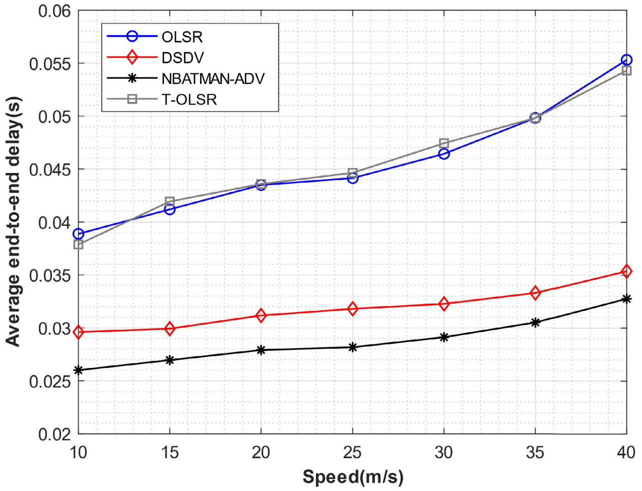

FIGURE 11. E2E of nodes at different speeds.

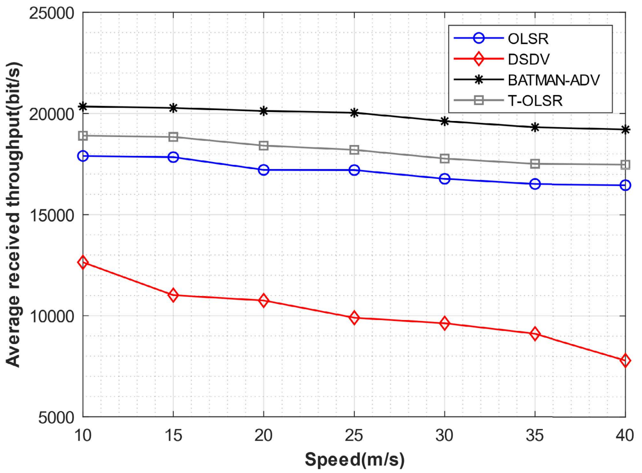

FIGURE 12. Throughput of nodes at different speeds.

routing protocol, each normal node has neighboring backbone nodes because of the construction of a virtual backbone network. The source node only needs to send the packets to the backbone node and the packets can reach the destination node, so the E2E is reduced. In this paper, the received signal strength index and signal-to-noise ratio of physical layer data are used to evaluate the link quality and optimize the path quality from the source node to the destination node, and the improvement of PDR makes the Throughput of the destination node increase accordingly. Compared with the OLSR routing protocol, the Throughput of the destination node is improved by about 17% for the NBATMAN-ADV routing protocol.

When the maximum communication distance of every UAV node is 1500 m and the flight speed is 10-40 m/s, Fig.10 shows the change of PDR, Fig.11 shows the change of E2E, and Fig.12 shows the change of Throughput. As the UAV flight speed increases and the link failures become more frequent. The simulation results show that the performance indicators of all four protocols degrade. But the performance of the NBATMAN-ADV routing protocol has a significant advantage over the other routing protocol. With the acceleration of the flying speed of the UAV, the network topology changes more drastically while the structure of the backbone network is constantly changing. However, in the NBATMAN-ADV routing protocol, the rate of change of backbone nodes has decreased since the comprehensive factors are considered in the selection of the backbone nodes.

Meanwhile, the UAV nodes do not need to worry about the global topology change. The packets from the source nodes only need to be delivered to the backbone nodes to reach the destination nodes. This makes the architecture of the protocol small and can quickly adapt to the network topology change. Therefore, with the increase flight speed of UAV, the performance of NBATMAN-ADV routing protocol has significant advantages over other routing protocol.

VIII. CONCLUSION

This paper proposes an elastic routing mechanism for the routing problem of large-scale small UAVs multitasking scenarios. First of all, N-UCDS algorithm is proposed to construct a virtual backbone network based on the connected dominating set. When electing backbone nodes, consider the influence of the number of neighbor nodes, energy consumption and link duration on the performance of the UAV network. Second, NBATMAN-ADV routing protocol is deployed and ran on the backbone nodes. By using the received signal strength index and signal-to-noise ratio of the physical layer data to evaluate the link quality, it can quickly sense the change of the link while reducing the routing overhead. The simulation results show that, compared with the traditional proactive routing protocol, the routing protocol proposed in this paper has better performance indicators in terms of PDR, E2E and Throughput.

However, due to the highly dynamic nature of the UAV nodes, the elected backbone nodes have a certain rate of turnover. This brings some overhead and takes time to reconstruct the backbone network. This is the short-coming of the paper and the research direction for the next work.

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