SPECIAL SECTION ON ADVANCED COMMUNICATIONS AND NETWORKING TECHNIQUES FOR WIRELESS CONNECTED INTELLIGENT ROBOT SWARMS

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Performance Analysis of Routing Protocols for UAV Communication Networks

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ABSTRACT The design of routing protocol is an important and key problem in unmanned aerial vehicle (UAV) communication networks. In low altitude environment, UAV information transmission is a complex task. It is an important scientific challenge to design a routing protocol that can provide efficient and reliable node to node packet transmission. This paper develops a more realistic simulation environment based on OPNET 14.5, and performs performance tests and comparisons on four classic routing protocols: Ad Hoc on demand distance vector (AODV), dynamic source routing (DSR), optimized link state routing (OLSR), and geographic routing protocol (GRP). The performance parameters such as network delay, traffic received, data dropped and throughput are compared and analyzed. The experimental results indicate that different routing protocols can be adapted to different UAV communication network scenarios. Therefore, the quantitative results can provide pertinent reference for choosing the best routing protocol in different scenarios.

INDEX TERMS UAV communication networks, ad hoc, routing protocols, performance analysis.

I. INTRODUCTION

In recent years, with the rapid development of artificial intelligence, processor, communication module and other technologies, the performance of the communication equipment that can be carried on the UAV is getting better and better, the integrated chip is becoming more and more intelligent, and the performance of the UAV is increasing. The application of UAV is no longer limited to the original military field. In many fields, such as environmental monitoring, emergency relief, relay communication, target recognition, UAV is playing a core role [1]–[4].

Compared with single UAV or simple multi UAV system, UAV cluster has a huge advantage. It can avoid the collision of multiple UAVs in a limited space, and assign an overall task to the UAV cluster. The cluster will cooperate to complete the task. UAV cluster has the characteristics of dynamic self-healing, and has the ability of automatic recovery for unexpected interruption. It can realize the efficient information transmission of UAV without base station, share the information of other nodes in the network in real time, and improve the information collection ability and fault tolerance ability [5]–[8].

UAV communication network is an extended application of mobile Ad Hoc networks (MANET) in the field of UAV, but it has its own network characteristics. Different from the nodes in MANET which are limited by terrain factors, the UAV communication network nodes are not affected by terrain interference when they move in the air, and their speed is generally faster than the traditional MANET nodes, and the network topology changes more frequently [9]–[12].

UAV communication network nodes can complete communication with other nodes in the network without using existing facilities, and nodes that are not directly connected can perform multi-hop communication through forwarding of intermediate nodes. When a node in the network cannot work normally due to certain factors, other nodes will continue to work instead of its position. The UAV communication networks can be created independently and is highly robust [13]–[16]. In UAV communication networks, nodes communicate with each other by wireless way. Compared with wired channel, its bandwidth is limited and capacity is low. In communication, signal collision, noise interference and other factors are necessary considerations. Therefore, in the scenario where the UAV is actually flying,

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the communication bandwidth it can use will be much smaller than the bandwidth calculated by theory, and congestion will often occur in the network [17]–[20].

One of the core research points of UAV communication networks is the research of routing protocol. How to select the most suitable link for data transmission efficiently is the standard to measure whether a routing protocol is excellent. For the UAV communication networks, each node can be used as the sending node, receiving node and forwarding node at the same time. The transmission path is generally multi-hop path, and the routing determines the performance of the network to a large extent. In addition, nodes in the UAV communication networks enter and exit the network more frequently, making routing maintenance more difficult. Therefore, it is very important to design an excellent routing protocol for UAV communication networks [21]–[24].

Sarao *et al.* [25] analysed the routing protocols of Ad Hoc networks by considering several performance metrics like throughput, end-to-end delay, normalized routing load, received packets at various speeds and pause times. It provides ideas for the evaluation method of routing protocols. Jiang and Han [26] focus on the routes designed for UAVs, and aim to present a somewhat complete survey of the routing protocols. Moreover, the performance of existing routing protocols is compared in detail. Abbasi and Khan [27] provides the simulation based study of existing dynamic junction selection routing protocols and a static junction selection routing protocol. It provides a profound insight into the routing techniques suggested in this area. Sarkar [28] proposed reliable and energy-aware routing in mobile Ad Hoc networks. The proposed routing protocols ensure reliability and energy-awareness in MANET and avoid link failure due to node's low power in an established route. Prakasi and Varalakshmi [29] proposed a novel Decision Tree based Routing Protocol (DTRP), which is a data mining technique in route selection process from source to destination. The proposed DTRP protocol selects the one-hop neighbors based on the parameters such as speed, link expiration time, trip_time and node life time. Thus the performance of a route discovery mechanism is enhanced by selecting the stable one-hop neighbors along the path to reach the destination.

UAV information transmission is a complex task. It is important to design a routing protocol that can provide efficient and reliable node to node packet transmission. In this paper, according to the characteristics of the UAV communication networks, four classic routing protocols, AODV, DSR, OLSR and GRP, are selected for simulation testing. The performance parameters such as network delay, traffic received, data dropped and throughput are compared and analyzed. Simulation results show that different routing protocols have different performance under different node density and node moving speed.

The remaining sections of this paper are organized as follows. Section II describes the principle of routing protocols. Section III describes the simulation model. Section IV describes the performance analysis, compares and analyzes the performance of network delay, traffic received, data dropped and throughput in different scenarios. Finally, Section V summarizes the paper.

II. ROUTING PROTOCOLS

The routing protocols in UAV communication networks basically follow those in MANETs. They are mainly divided into two categories: topology-based and location-based. Proactive routing protocols (e.g. OLSR) and reactive routing protocols (e.g. AODV, DSR) are two main categories in topology-based routing protocols. GRP, as a proactive routing, is also a typical location-based routing protocol. Therefore, this paper analyzes the performance of AODV, DSR, OLSR and GRP.

A. THE AD HOC ON DEMAND DISTANCE VECTOR PROTOCOL

The AODV routing protocol supports dynamic, multi-hop, self-starting Ad hoc networks [30]. When the node has communication requirements, it will send a request to establish a communication link, and the node does not need to maintain the path to each node in the network all the time. The nodes only need to maintain the information of their neighbors through HELLO messages. In the communication process, the nodes that do not participate in the communication do not need to maintain communication routes, which will save a lot of energy overhead. The essence of the AODV routing algorithm is dynamic, which allows high-speed moving nodes to quickly create routes and find destinations [31]. When a node in the link is damaged, it can repair the link in time according to certain routing repair means to ensure the continuation of communication [32].

Fig. 1 and Fig. 2 are the packet formats of route request (RREQ) and route reply (RREP) in the AODV routing protocol, respectively. The path finding process of AODV mainly relies on the cooperation of RREQ and RREP, and the schematic diagram of path finding is shown in Fig. 3. Source node 1 wants to communicate with node 7 in the network. If it observes that there is no node 7 in the route it maintains, it will broadcast RREQ, turn on the routing request mechanism of AODV, and find the path that can communicate with node 7. The RREQ broadcast by node 1 contains the ID of the RREQ packet, the address and serial number of source node 1 and

Type	Flags	Reserved	Hop Count
RREQ Broadcast id			
Destination IP address			
Destination sequence number			
Source IP address			
Source sequence number			

FIGURE 1. The packet format of RREQ.

Type	Flags	Reserved	Hop Count
RREP Broadcast id			
Destination IP address			
Destination sequence number			
Source IP address			
Source sequence number			
Lifetime			

FIGURE 2. The packet format of RREP.

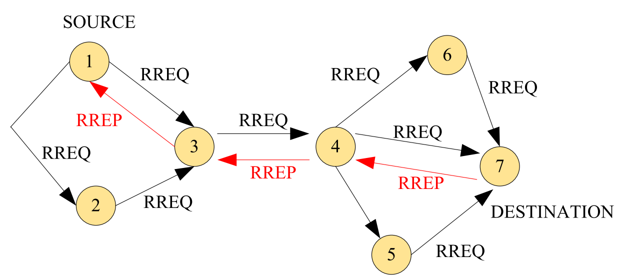

FIGURE 3. Schematic diagram of AODV path finding process.

the address and serial number of destination node 7. At the same time of broadcast, the packet ID and serial number of the RREQ will be increased by one. After receiving this RREQ, the intermediate node will first determine whether it is the destination node. If it is, it will return the RREP; if not, it will check its own routing table to determine whether there is a route to the destination node 7, if not, it will continue to forward until the destination node is found or the node that has a route to the destination node in the routing table is found. When node 1 receives the RREP packet returned from destination node 7, data transmission begins, and the AODV path finding process ends. The source node successfully finds the destination node.

AODV uses hops as criterion for path finding [33]. When a node receives a RREQ packet, it will read the number of hops in the packet. If the number of hops in the received packet is less than the number of hops in the existing reverse route, it will update the reverse route of the node, so as to ensure that the number of hops from the source node to the current node remains the minimum. Similarly, when a node sends or forwards a RREP packet, it will also determine whether it is the forward route with the smallest number of hops according to the number of hops in the RREP packet. This mechanism ensures that the route for communication is the route with the least number of hops. If the number of hops changes during the movement of the node, the path with the shorter number of hops will be selected for communication.

B. THE DYNAMIC SOURCE ROUTING PROTOCOL

DSR is a typical on-demand routing protocol. It is also the earliest ad hoc network routing protocol designed with on-demand routing idea. At the same time, DSR is also an on-demand adaptive routing protocol based on the concept of source routing [34]. Each node in the network needs to store the complete routing information that the node knows to reach other nodes. When the topology of the whole network changes, the locally maintained routing table will also be updated [35]. Its main feature is the use of the source routing design, each control message header records the entire path information from the source node to the destination node. The DSR protocol uses the mechanism of source routing and relies on buffer to store routes to other nodes. The intermediate nodes do not need to store routes required for forwarding message, so the overhead is relatively small and there is no expired routing information [36]. The DSR protocol provides fast reactive services to ensure the correct transmission of messages, even when the topology of the whole network changes.

The DSR protocol is composed of the following two main mechanisms. These two mechanisms work together on the mobile Ad Hoc network to complete the search and maintenance of source routes [37].

1) ROUTE DISCOVERY MECHANISM

When node S has a request to send a service message to destination node D, it will actively initiate the route discovery process to find a path to destination node D. The route discovery mechanism is initiated only when the source node S needs to send a service message to the destination node D, and there is no local route to the destination node D. The detailed process of route discovery is shown in Fig. 4.

2) ROUTE MAINTENANCE MECHANISM

When the source node S is using a route to the destination node D, the source node S can use the route maintenance mechanism to detect the following problems: if the network topology of the whole network has changed, then the source node S cannot continue to use the route to send service messages, because the route information has expired. When the route maintenance process indicates that a source route has been invalidated and can no longer be used, in order to continue to send service messages to the destination node D, the source node S will query whether there are other routes to the destination node D in the local buffer, or re-execute the route discovery mechanism to maintain a new route to the destination node. And only when the source node S is using a source route to send service messages to the destination node D, the source node S uses the route maintenance mechanism to maintain the source route. A complete flow chart of the route maintenance process is shown in Fig. 5.

C. THE OPTIMIZED LINK STATE ROUTING PROTOCOL

The OLSR protocol is one of the most classical protocols in table driven routing protocol, which is obtained by improving the classical link state algorithm [38]. The protocol continuously updates and maintains a routing information table to other network nodes. Before data exchange, each

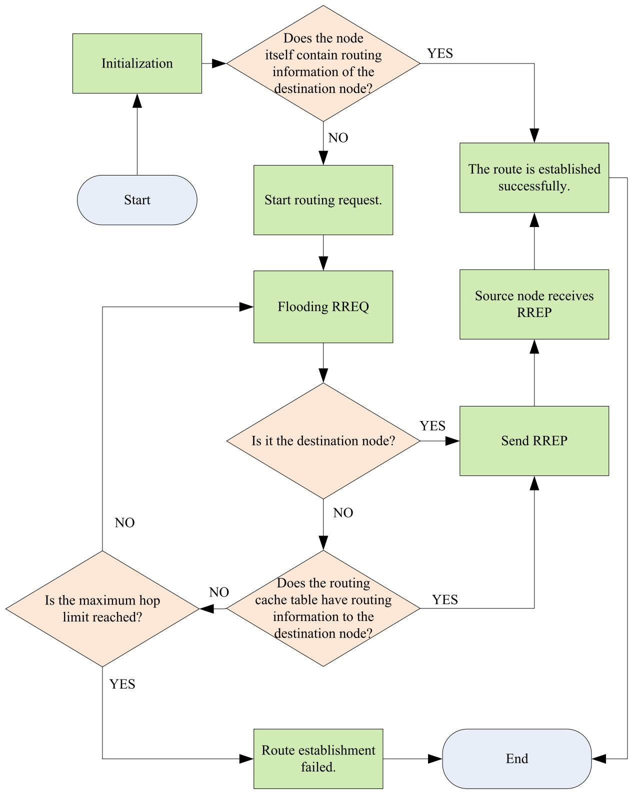

FIGURE 4. The flow chart of DSR route discovery.

node in the network has a path to its own destination node. The communication process is to complete packet forwarding along this path [39]. Compared with link state routing algorithm, there are two main improvements in OLSR protocol.

First, it has a serial number that can distinguish the old and new routing information. There is a data field in the topology control (TC) group to store this serial number. The benefit brought by this is to realize the update of routing information and the non-sequential transmission of TC packets. The TC packets with this serial number interact continuously in the network, so each node establishes one-hop and two-hop neighbor node information, and maintains the topology of the whole wireless ad hoc network, so that each node has a single hop or multi-hop path to the destination node. The communication process is to forward packets along this path, which reduces the end-to-end delay of communication.

Secondly, the multipoint relay (MPR) mechanism is adopted. In the link state routing algorithm, all one-hop neighbor nodes are selected as relay nodes, while in the OLSR protocol, among all one-hop neighbor nodes owned by the node, the nodes that can form a symmetric link with all two-hop neighbor nodes are selected as multipoint relay nodes. In this way, the node only needs to send the link state information connected to the multipoint relay node, so the number of TC packets in the network will be significantly reduced. Each one-hop neighbor node will not forward the broadcast packet after receiving it, just like the link state algorithm. Instead, it needs to determine whether it is the

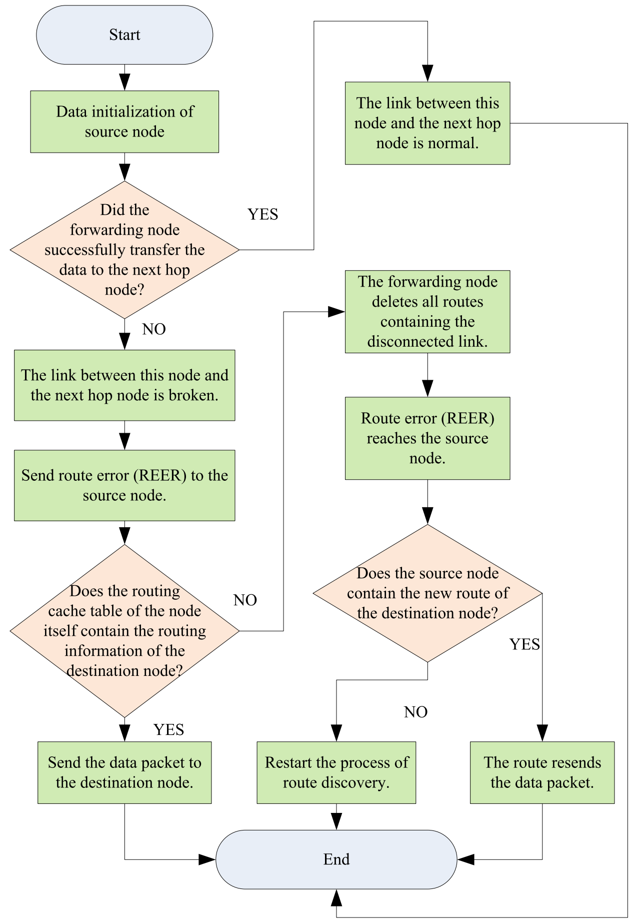

FIGURE 5. The flow chart of DSR route maintenance.

MPR node of the node. If it is the MPR node, it can forward the broadcast packet. By using the above method, the number of links for forwarding control packets is reduced, and then the length of control packets is shortened.

The core idea of OLSR protocol is multipoint relay mechanism. The number of broadcast packets in wireless ad hoc networks is obviously controlled. The number of flooding object nodes is controlled by selective flooding, which greatly reduces the number of TC packets forwarded [40]. Fig. 6 shows the comparison between the common flooding

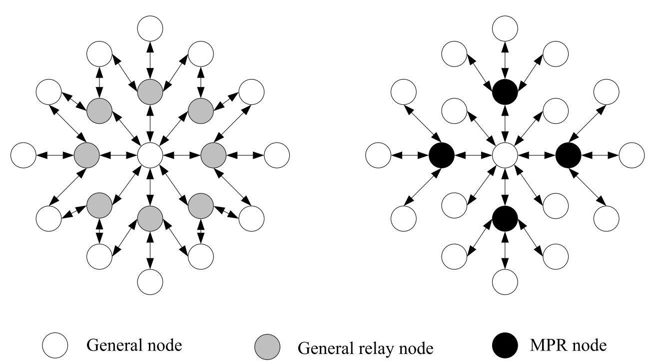

FIGURE 6. The comparison between the common flooding mechanism and the MPR mechanism.

mechanism and the MPR mechanism. It can be seen from the figure that flooding with MPR strategy can significantly reduce the number of TC packet forwarding, and this advantage will be more obvious with the expansion of wireless ad hoc network scale.

The OLSR protocol establishes the local link information database and the adjacent area information database through periodic HELLO packet interaction. The format of HELLO packet is shown in Fig. 7.

Reserved		Htime	Willingness
Link Code	Time	Link Message Size	
Neighbor Interface Address			
Neighbor Interface Address			
…………			
Neighbor Interface Address			

FIGURE 7. The format of HELLO packet.

Generally speaking, the communication nodes using OLSR protocol realize link detection and neighbor discovery by interacting with HELLO packets. Finally, based on the entire network topology established by the TC packet, the MPR-based route calculation and maintenance are performed [41]. The basic flow of the routing protocol is described in the following 7 steps.

Step1: The nodes in the network periodically broadcast HELLO packets.

Step2: After receiving the HELLO packet, the node maintains its one-hop and two-hop neighbor tables.

Step3: Through the information in HELLO packets obtained by each node, the MPR sets of each node are calculated, and the MPR sets of the node are informed through HELLO broadcast.

Step4: According to the information of HELLO packets, the MPR node establishes its own MPR selector table.

Step5: Each node periodically sends TC packets, which are flooded into the whole network.

Step6: By obtaining the information in the TC packets, the node maintains its own topology table.

Step7: Each node calculates the route according to its own topology table, and finally obtains the routing table.

D. THE GEOGRAPHIC ROUTING PROTOCOL

GRP is a proactive routing protocol based on geographic location information [42]. GRP realizes the next hop forwarding of data packets through the geographic location information and the routing table maintained by nodes, using the strategy of dividing neighborhoods and hierarchies [43].

In GRP, the whole network is divided into different neighborhood to optimize flooding and forwarding data. The size of neighborhood can be defined as a specified value according to the scale of network topology and actual demand. All neighborhoods are organized in a hierarchical way [44]. Each high-level neighborhood is divided into four sub-level neighborhoods. Fig. 8 shows the method of neighborhood division and hierarchies. Assuming that the first layer network has two neighborhoods A and B, A and B are divided into four lower level neighborhoods (second layer). A_a, A_b, A_c, and A_d constitute the upper neighborhood A. B_a, B_b, B_c, and B_d constitute the upper neighborhood B. Similarly, A_a is further divided into four low-level neighborhoods (third layer), namely A_{a1}, A_{a2}, A_{a3}, and A_{a4}. In the same way, other second-layer neighborhoods are also divided into four low-level neighborhoods. Although there can be four or more layers of neighborhoods, in most cases three levels are sufficient.

When the system is initialized, flooding information is in the whole network. When a node moves beyond a specified distance or crosses the border of a neighborhood, the node will immediately flood the relevant information about the geographic location [45]. If the node moves in a neighborhood, the flooding message will only be received by the node in the current neighborhood. If the node crosses the boundaries of different neighborhoods, flooding information will be sent to each node in the high-level neighborhood where the two neighborhoods are co-located. For example, in Fig. 8, if the node crosses the boundary of the neighborhood from A_{a1} to A_{a2}, flooding information will be sent throughout the neighborhood of A_a. If the node crosses the border of the neighborhood from A_{a1} to A_{b3}, flooding information will be sent in the neighborhood of A, not the entire network. By dividing the neighborhood to limit the flooding range, it will avoid unnecessary flooding to save network resources.

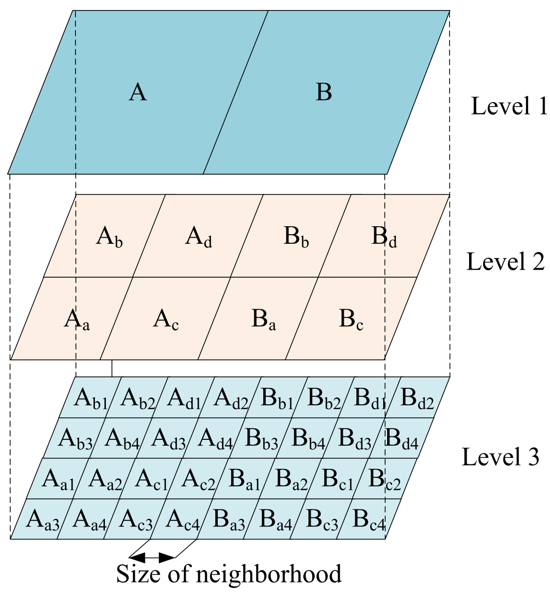

FIGURE 8. Neighborhood division and hierarchies.

III. SIMULATION MODEL

In this section, it mainly analyzes the structure of UAV communication network simulation system, OPNET-based UAV communication network simulation model, and evaluates the performance metrics of UAV communication network routing protocol.

A. UAV COMMUNICATION NETWORK SIMULATION SYSTEM

The UAV communication network simulation system is mainly used to study wireless network communication protocols suitable for different mobile self-organizing network application scenarios. The functions provided mainly include network simulation scenario configuration, protocol development, simulation control, and protocol simulation performance evaluation. The structure of the UAV communication network simulation system is shown in Fig. 9.

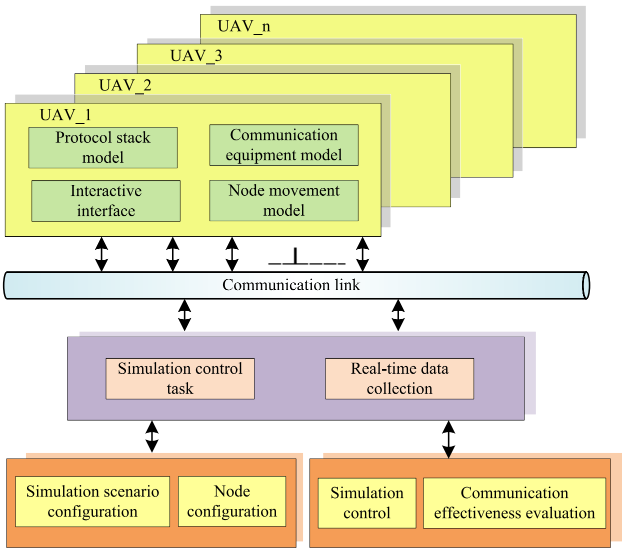

FIGURE 9. The structure of the UAV communication network simulation system.

B. OPNET NETWORK SIMULATION

OPNET is a good software for network simulation. It has a friendly graphical interface, good visualization effect, and can also be used for animation demonstration. In terms of software function, OPNET is relatively perfect, which can set the packet arrival time distribution, packet length distribution, network node type and link type in detail, and it can design its own simulation environment through the network equipment and application scenarios provided by different manufacturers. Users can also conveniently select the existing network topology in the library. The choice of NS2 and NS3 in this aspect is not as rich as OPNET. They can only build a logical network structure through scripts according to the actual simulation environment, and the results need the assistance of other software. In terms of ease of operation, there is no doubt about the advantages of OPNET, because it

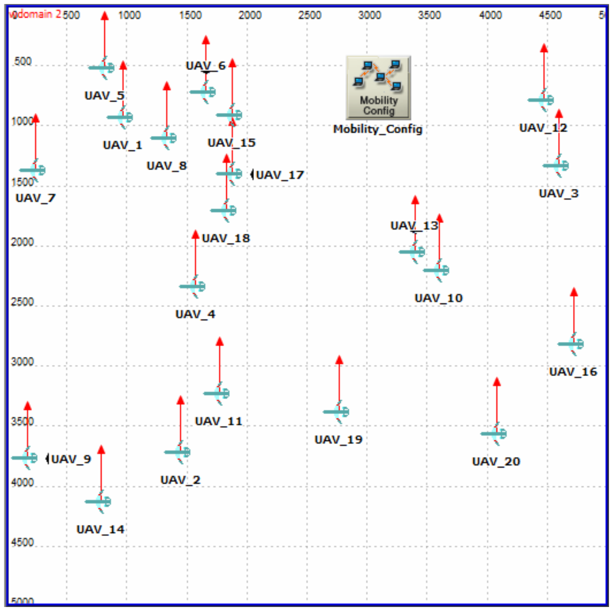

FIGURE 10. The network model of UAVs.

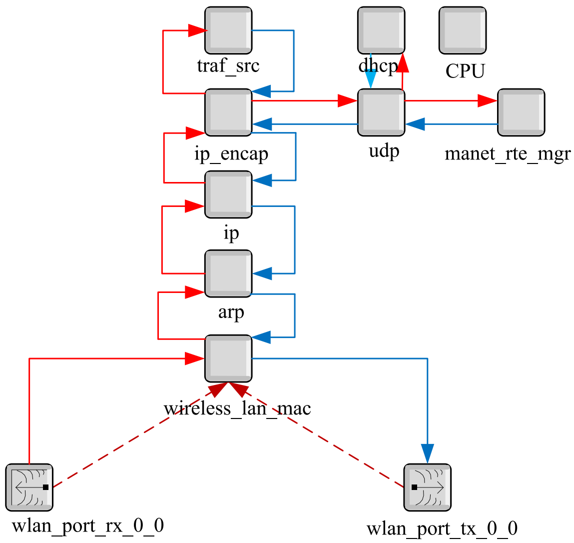

FIGURE 11. The node model of UAV.

can use less operation to get more detailed and real simulation results. NS2 and NS3 need to write script and C++ code to realize network simulation, and it is very difficult to build complex network structure in this way. Therefore, OPNET 14.5 is chosen as the simulation tool in this paper.

Fig. 10 shows the network model of UAVs. The network model describes the layout and resources of the physical network. The network model of UAVs shown in Fig. 10 is composed of 20 mobile nodes, which are UAV_1, UAV_2, …, UAV_20. These UAV nodes are randomly distributed in a rectangular area of 5000m × 5000m and communicate through wireless links.

Fig. 11 shows the node model of UAV. The model is used to define the behavior of each node. A node is usually composed of multiple modules, and each module completes a part of the behavior of the node. Each node in the UAV communication network is uniquely identified by its IP address. In Fig. 11, the wlan_port_rx_0_0 is a wireless receiving module, and the wlan_port_tx_0_0 is a wireless transmitting module. The wireless_lan_mac is a MAC protocol module, 802.11b protocol is adopted in this paper. The ip and ip_encap are modules corresponding to the network layer. The ip module is responsible for sending IP data packets to the corresponding UAV node, reading the routing information table, and completing the correct forwarding of the data. The ip_encap module is responsible for encapsulating IP packet headers of UDP packets. The remaining modules in the node are the process models of OPNET. In this paper, all UAV nodes use the same node model.

Table 1 shows the simulation parameters setting of the UAV communication network based on OPNET. In this paper, the UAV communication network is arranged in a geographical range of 5000m × 5000m. The movement of the UAV uses the random waypoint model and the data rate of communication is set to 1Mbps. The MAC protocol uses 802.11b protocol. The number of UAVs is set to 20 and 40 respectively, the moving speed of UAVs is set to 20 m / s and 40 m / s respectively, and the routing protocols are set to AODV, DSR, OLSR and GRP respectively.

TABLE 1. Simulation parameters setting.

Parameter	Value
Moving range	5000m*5000m
Mobility model	Random waypoint
Number of UAVs	20, 40
UAV speed	20 m/s, 40m/s
UAV altitude	200 m
Node transmission power	0.005 W
MAC protocol	802.11b
Data rate	1 Mbps
Routing protocol	AODV, DSR, OLSR, GRP
Simulation time	1800s

C. PERFORMANCE METRICS

The paper mainly considers the parameters of network delay, traffic received, data dropped and throughput to evaluate the performance of routing protocol.

1) NETWORK DELAY

Network delay represents the end to end delay of all the packets received by the wireless LAN MACs of all WLAN nodes in the network and forwarded to the higher layer. This delay includes medium access delay at the source MAC, reception of all the fragments individually, and transfer of the frames via AP, if access point functionality is enabled. Network delay reflects the effectiveness of routing, if network delay is too large, it will seriously affect the quality of communication.

2) TRAFFIC RECEIVED

Traffic received represents the total number of traffic received in bits per second by all traffic destinations in the entire network.

3) DATA DROPPED

Data dropped represents total higher layer data traffic (in bits/sec) dropped by the all the WLAN MACs in the network as a result of consistently failing retransmissions. It reports the number of the higher layer packets that are dropped because the MAC couldn't receive any ACKs for the (re)transmissions of those packets or their fragments, and the packets' short or long retry counts reached the MAC's short retry limit or long retry limit, respectively. A lower value of data dropped means a better capability and stability of transmission path.

4) THROUGHPUT

Throughput represents the total number of bits (in bits/sec) forwarded from wireless LAN layers to higher layers in all WLAN nodes of the network.

IV. PERFORMANCE ANALYSIS

In this paper, we mainly study the performance of various routing protocols, and test their performance quantitatively. The performance parameter metrics used in this work are run from OPNET 14.5. The paper considers the following parameters to evaluate the performance of routing protocols.

A. NETWORK DELAY PERFORMANCE ANALYSIS

Fig. 12 shows the comparison of the average network delays of AODV, DSR, OLSR, and GRP under different number of nodes and UAV speed. Fig. 12(a) shows the average network delay performance when the number of nodes is 20 and the UAV speed is 10 m/s. Fig. 12(b) shows the average network delay performance when the number of nodes is 20 and the UAV speed is 20 m/s. Fig. 12(c) shows the average network delay performance when the number of nodes is 40 and the UAV speed is 10 m/s. Fig. 12(d) shows the average network delay performance when the number of nodes is 40 and the UAV speed is 20 m/s. From the comparison between Fig. 12(a) and Fig. 12(b), it can be seen that when the node density is low, the network delay performance based on the routing protocols of GRP and OLSR is little affected by the UAV speed. However, the network delay based on the routing protocols of AODV and DSR increases significantly with the acceleration of the UAV speed. From the comparison between Fig. 12(c) and Fig. 12(d), it can be seen that when the node density is high, the network delay performance is little affected by the UAV speed. From the comparison between Fig. 12(a) and Fig. 12(c), it can be seen that when the UAV speed is low, the network delay performance based on the routing protocols of GRP and OLSR is little affected by the node density, while the network delay based on the

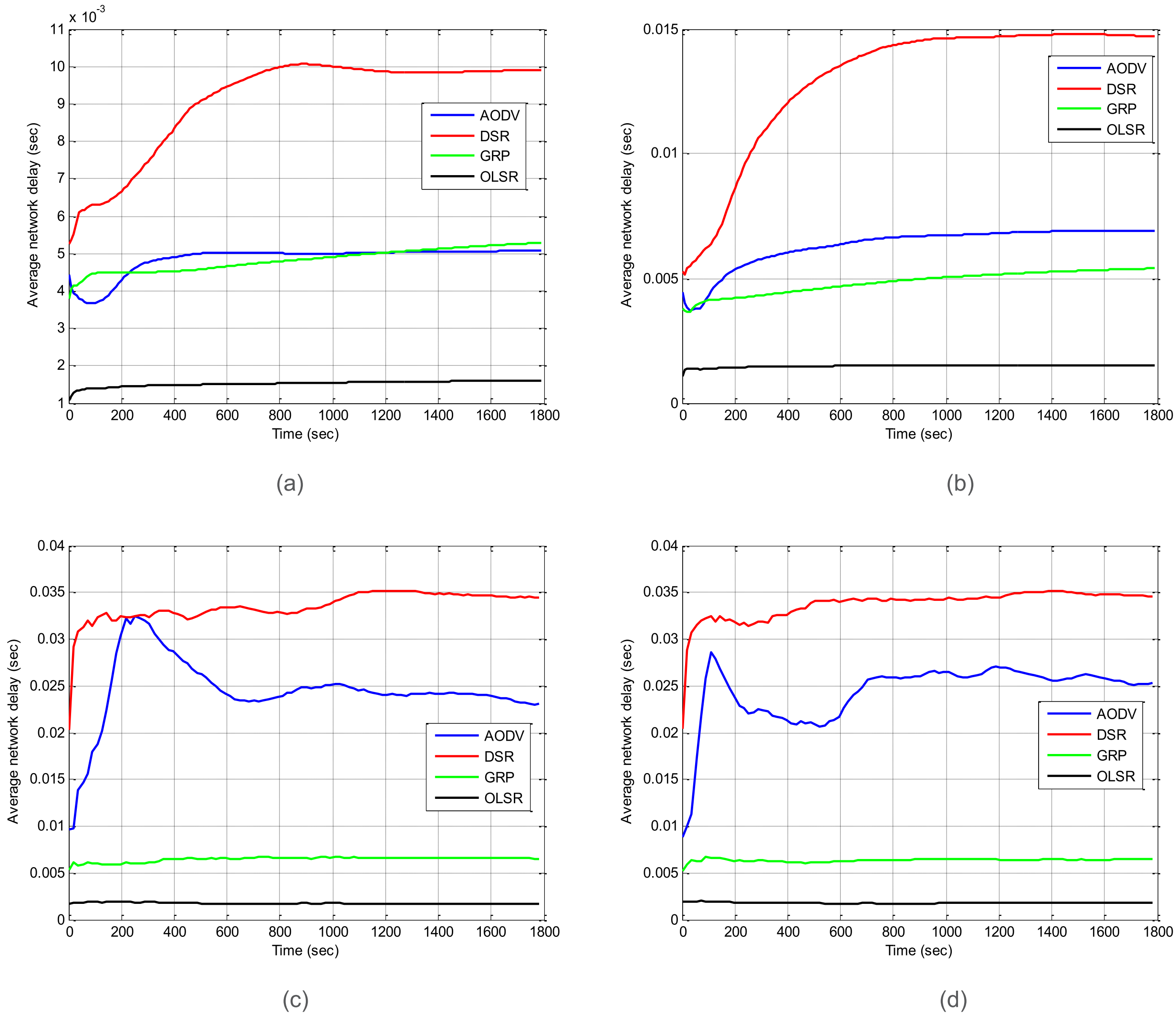

FIGURE 12. Average network delay for different routing protocols. (a) The number of nodes is 20, the UAV speed is 10m/s. (b) The number of nodes is 20, the UAV speed is 20m/s. (c) The number of nodes is 40, the UAV speed is 10m/s. (d) The number of nodes is 40, the UAV speed is 20m/s.

routing protocols of AODV and DSR increases significantly with the increase of the node density. From the comparison between Fig. 12(b) and Fig. 12(d), it can be seen that when the UAV speed is high, the network delay performance based on the routing protocols of GRP and OLSR is little affected by the node density, while the network delay based on the routing protocols of AODV and DSR increases significantly with the increase of node density. Comparing four different routing protocols, it can be seen that the UAV communication network based on the routing protocol of OLSR has the best network delay performance.

B. TRAFFIC RECEIVED PERFORMANCE ANALYSIS

Fig. 13 shows the comparison of the average traffic received of AODV, DSR, OLSR, and GRP under different number of nodes and UAV speed. Fig. 13(a) shows the average traffic received performance when the number of nodes is 20 and the UAV speed is 10 m/s. Fig. 13(b) shows the average traffic received performance when the number of nodes is 20 and the UAV speed is 20 m/s. Fig. 13(c) shows the average traffic received performance when the number of nodes is 40 and the UAV speed is 10 m/s. Fig. 13(d) shows the average traffic received performance when the number of nodes is 40 and the UAV speed is 20 m/s. From the comparison between Fig. 13(a) and Fig. 13(b), it can be seen that when the node density is low, the traffic received performance based on the routing protocols of AODV and GRP is little affected by the UAV speed. However, the traffic received based on the routing protocols of DSR and OLSR decreases significantly with the acceleration of the UAV speed. From the comparison between Fig. 13(c) and Fig. 13(d), it can be seen that when the node density is high, the traffic received decreases significantly with the acceleration of the UAV speed. From the comparison between Fig. 13(a) and Fig. 13(c), it can be seen that when the UAV speed is low, the traffic received increases significantly with the increase of the node density.

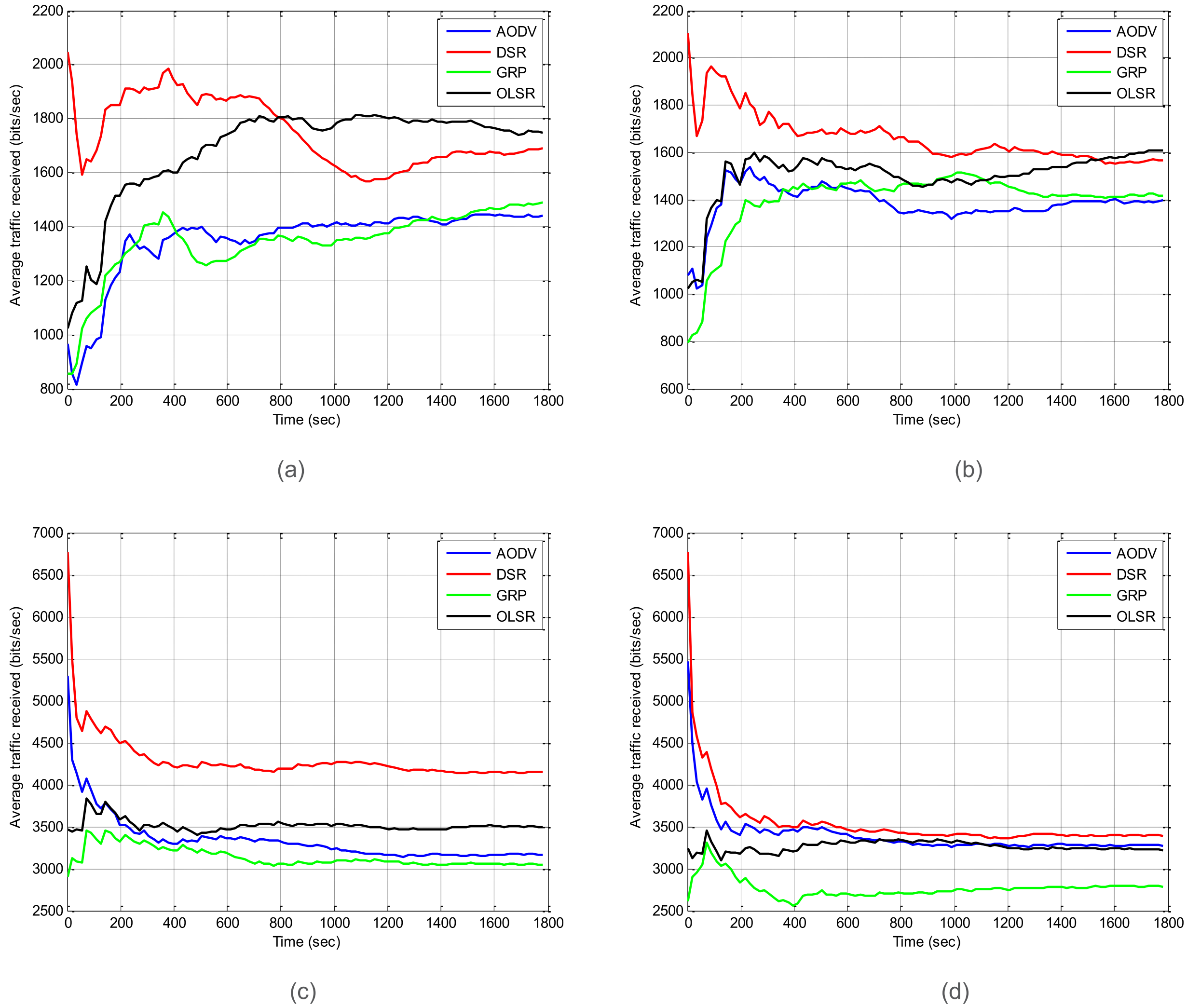

FIGURE 13. Average traffic received for different routing protocols. (a) The number of nodes is 20, the UAV speed is 10m/s. (b) The number of nodes is 20, the UAV speed is 20m/s. (c) The number of nodes is 40, the UAV speed is 10m/s. (d) The number of nodes is 40, the UAV speed is 20m/s.

From the comparison between Fig. 13(b) and Fig. 13(d), it can be seen that when the UAV speed is high, the traffic received also increases significantly with the increase of the node density. Comparing four different routing protocols, it can be seen that the UAV communication network based on the routing protocol of DSR has the best traffic received performance.

C. DATA DROPPED PERFORMANCE ANALYSIS

Fig. 14 shows the comparison of the average data dropped of AODV, DSR, OLSR, and GRP under different number of nodes and UAV speed. Fig. 14(a) shows the average data dropped performance when the number of nodes is 20 and the UAV speed is 10 m/s. Fig. 14(b) shows the average data dropped performance when the number of nodes is 20 and the UAV speed is 20 m/s. Fig. 14(c) shows the average data dropped performance when the number of nodes is 40 and the UAV speed is 10 m/s. Fig. 14(d) shows the average data dropped performance when the number of nodes is 40 and the UAV speed is 20 m/s. From the comparison between Fig. 14(a) and Fig. 14(b), it can be seen that when the node density is low, the data dropped increases significantly with the acceleration of the UAV speed. From the comparison between Fig. 14(c) and Fig. 14(d), it can be seen that when the node density is high, the data dropped also increases significantly with the acceleration of the UAV speed. From the comparison between Fig. 14(a) and Fig. 14(c), it can be seen that when the UAV speed is low, the data dropped increases significantly with the increase of the node density. From the comparison between Fig. 14(b) and Fig. 14(d), it can be seen that when the UAV speed is high, the data dropped also increases significantly with the increase of the node density. Comparing four different routing protocols, it can be seen that the UAV communication network based on the routing protocol of AODV has the best data dropped performance.

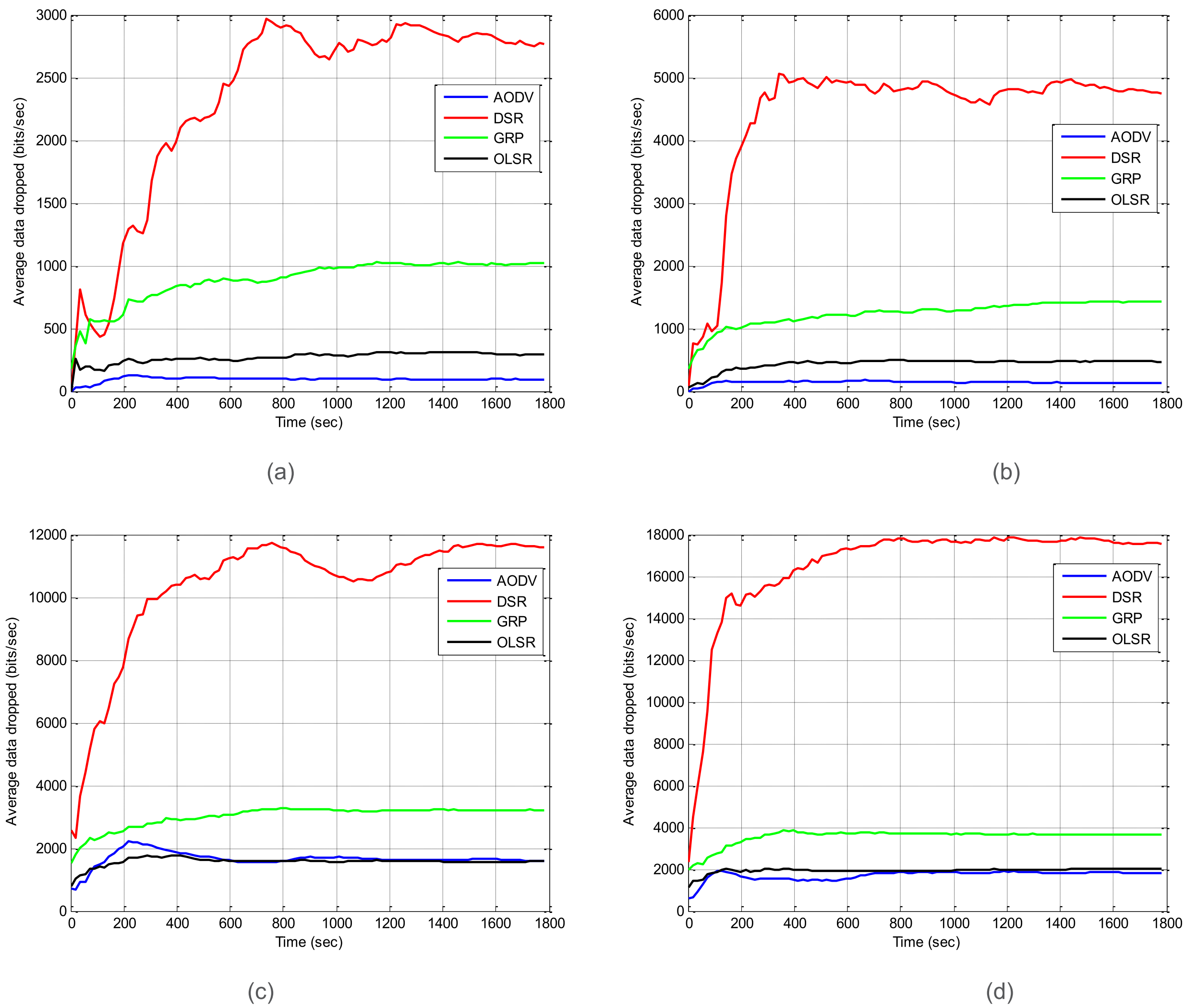

FIGURE 14. **Average data dropped for different routing protocols. (a) The number of nodes is 20, the UAV speed is 10m/s. (b) The number of nodes is 20, the UAV speed is 20m/s. (c) The number of nodes is 40, the UAV speed is 10m/s. (d) The number of nodes is 40, the UAV speed is 20m/s.**

D. THROUGHPUT PERFORMANCE ANALYSIS

Fig. 15 shows the comparison of the average throughput of AODV, DSR, OLSR, and GRP under different number of nodes and UAV speed. Fig. 15(a) shows the average throughput performance when the number of nodes is 20 and the UAV speed is 10 m/s. Fig. 15(b) shows the average throughput performance when the number of nodes is 20 and the UAV speed is 20 m/s. Fig. 15(c) shows the average throughput performance when the number of nodes is 40 and the UAV speed is 10 m/s. Fig. 15(d) shows the average throughput performance when the number of nodes is 40 and the UAV speed is 20 m/s. From the comparison between Fig. 15(a) and Fig. 15(b), it can be seen that when the node density is low, the throughput performance based on the routing protocols of AODV, DSR and GRP is little affected by the UAV speed. However, the throughput based on the routing protocol of OLSR increases with the acceleration of the UAV speed. From the comparison between Fig. 15(c) and Fig. 15(d), it can be seen that when the node density is high, the throughput performance based on the routing protocols of AODV, DSR and GRP is little affected by the UAV speed, while the throughput based on the routing protocol of OLSR increases with the acceleration of the UAV speed. From the comparison between Fig. 15(a) and Fig. 15(c), it can be seen that when the UAV speed is low, the throughput increases significantly with the increase of the node density. From the comparison between Fig. 15(b) and Fig. 15(d), it can be seen that when the UAV speed is high, the throughput also increases significantly with the increase of the node density. Comparing four different routing protocols, it can be seen that the UAV communication network based on the routing protocol of OLSR has the best throughput performance.

Through the comprehensive analysis of the above four routing protocols, it can be seen that AODV is more suitable for scenarios with higher requirements for data dropped of UAV communication network. DSR is more suitable for

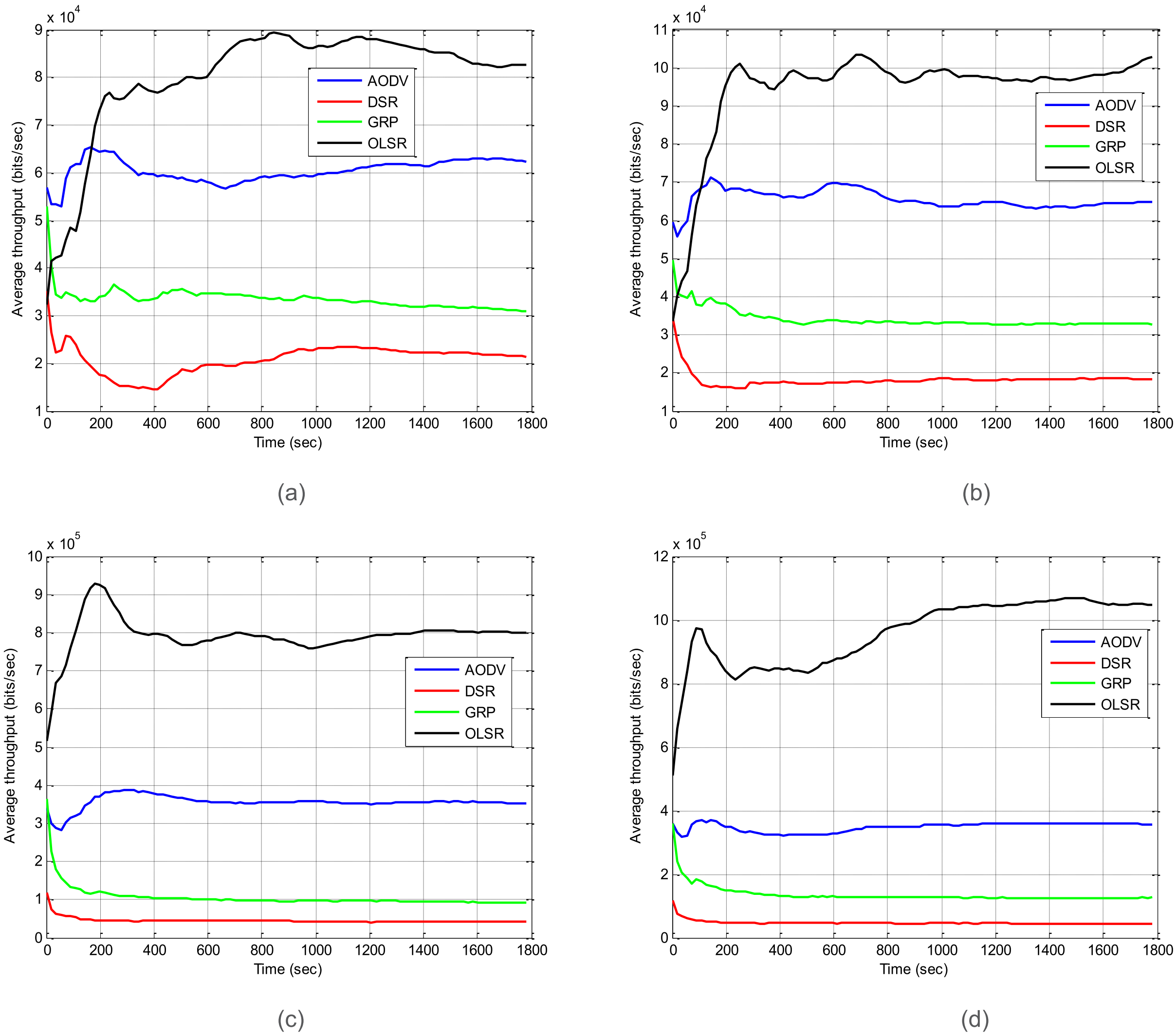

FIGURE 15. Average throughput for different routing protocols. (a) The number of nodes is 20, the UAV speed is 10m/s. (b) The number of nodes is 20, the UAV speed is 20m/s. (c) The number of nodes is 40, the UAV speed is 10m/s. (d) The number of nodes is 40, the UAV speed is 20m/s.

scenarios with higher requirements for traffic received of UAV communication network. OLSR is more suitable for scenarios with higher requirements for network delay and throughput of UAV communication network.

V. CONCLUSION

In this paper, the performance of UAV communication networks under different routing protocols and network environment is analyzed by simulation. Through the simulation of four kinds of UAV communication network routing protocols (AODV, DSR, OLSR, GRP), the performance merits such as network delay, traffic received, data dropped and throughput are compared. The simulation results show that the routing protocol of OLSR has lower network delay and higher throughput, the routing protocol of DSR has higher traffic received and the routing protocol of AODV has lower data dropped. Therefore, none of the four routing protocols can achieve the optimal performance among all the performance merits. Under different node density and node moving speed, various routing protocols have different performance in UAV communication networks. In order to optimize the performance of UAV communication networks, it is necessary to choose the most suitable routing protocol according to the node density and moving speed of UAV, so as to provide better communication guarantee for UAV cluster.

REFERENCES

[1] B. P. Banerjee, S. Raval, and P. J. Cullen, "UAV-hyperspectral imaging of spectrally complex environments," *Int. J. Remote Sens.*, vol. 41, no. 11, pp. 4136–4159, Jun. 2020.
[2] X. Zhang and L. Duan, "Fast deployment of UAV networks for optimal wireless coverage," *IEEE Trans. Mobile Comput.*, vol. 18, no. 3, pp. 588–601, Mar. 2019.
[3] B. Li, Z. Fei, Y. Zhang, and M. Guizani, "Secure UAV communication networks over 5G," *IEEE Wireless Commun.*, vol. 26, no. 5, pp. 114–120, Oct. 2019.
[4] K. Lei, Q. Zhang, J. Lou, B. Bai, and K. Xu, "Securing ICN-based UAV ad hoc networks with blockchain," *IEEE Commun. Mag.*, vol. 57, no. 6, pp. 26–32, Jun. 2019.
[5] F. Koohifar, I. Guvenc, and M. L. Sichitiu, "Autonomous tracking of intermittent RF source using a UAV swarm," *IEEE Access*, vol. 6, pp. 15884–15897, 2018.

[6] F. Xiong, A. Li, H. Wang, and L. Tang, "An SDN-MQTT based communication system for battlefield UAV swarms," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 41–47, Aug. 2019.

[7] J. Gu, T. Su, Q. Wang, X. Du, and M. Guizani, "Multiple moving targets surveillance based on a cooperative network for multi-UAV," *IEEE Commun. Mag.*, vol. 56, no. 4, pp. 82–89, Apr. 2018.

[8] E. Turgut and M. C. Gursoy, "Downlink analysis in unmanned aerial vehicle (UAV) assisted cellular networks with clustered users," *IEEE Access*, vol. 6, pp. 36313–36324, 2018.

[9] K. Singh and A. K. Verma, "A fuzzy-based trust model for flying ad hoc networks (FANETs)," *Int. J. Commun. Syst.*, vol. 31, no. 6, pp. 1–19, Jan. 2018.

[10] X. Li and J. Huang, "ABPP: An adaptive beacon scheme for geographic routing in FANET," in *Proc. 18th Int. Conf. Parallel Distrib. Comput., Appl. Technol. (PDCAT)*, Taipei, China, Dec. 2017, pp. 293–299.

[11] T. Zhang, S. Zhao, Y. Shi, B. Ren, B. Cheng, and J. Chen, "The implementation of improved MPTCP in MANETs," in *Proc. IEEE 25th Int. Conf. Netw. Protocols (ICNP)*, Toronto, ON, Canada, Oct. 2017, pp. 1–2.

[12] E. Larsen, L. Landmark, and O. Kure, "Optimal UAV relay positions in multi-rate networks," in *Proc. Wireless Days*, Porto, Portugal, Mar. 2017, pp. 8–14.

[13] H. Wang, J. Wang, J. Chen, Y. Gong, and G. Ding, "Network-connected UAV communications: Potentials and challenges," *China Commun.*, vol. 15, no. 12, pp. 111–121, Dec. 2018.

[14] O. S. Oubbati, M. Mozaffari, N. Chaib, P. Lorenz, and A. Jamalipour, "ECaD: Energy-efficient routing in flying ad hoc networks," *Int. J. Commun. Syst.*, vol. 32, no. 18, pp. 1–13, Aug. 2019.

[15] C. Pu, "Link-quality and traffic-load aware routing for UAV ad hoc networks," in *Proc. IEEE 4th Int. Conf. Collaboration Internet Comput. (CIC)*, Philadelphia, PA, USA, Oct. 2018, pp. 71–79.

[16] C. Li, L. Zheng, W. Xie, and P. Yang, "Ad hoc network routing protocol based on location and neighbor sensing," in *Proc. IEEE Int. Conf. Comput. Commun. Eng. Technol. (CCET)*, Beijing, China, Aug. 2018, pp. 1–5.

[17] V. Sharma and K. Srinivasan, "Qos-aware routing in wireless networks using aerial vehicles," *J. Internet Technol.*, vol. 19, no. 1, pp. 73–89, Apr. 2018.

[18] L. Chen, S. Qian, M. Lim, and S. Wang, "An enhanced direct anonymous attestation scheme with mutual authentication for network-connected UAV communication systems," *China Commun.*, vol. 15, no. 5, pp. 61–76, May 2018.

[19] S. Ur Rahman, G.-H. Kim, Y.-Z. Cho, and A. Khan, "Positioning of UAVs for throughput maximization in software-defined disaster area UAV communication networks," *J. Commun. Netw.*, vol. 20, no. 5, pp. 452–463, Oct. 2018.

[20] M. Mustaqim, B. A. Khawaja, A. A. Razzaqi, S. S. H. Zaidi, S. A. Jawed, and S. H. Qazi, "Wideband and high gain antenna arrays for UAV-to-UAV and UAV-to-ground communication in flying ad-hoc networks (FANETs)," *Microw. Opt. Technol. Lett.*, vol. 60, no. 5, pp. 1164–1170, May 2018.

[21] F. Liang, J. Nguyen, W. Gao, W. G. Hatcher, and W. Yu, "Towards UAV assisted multi-path data streaming in mobile ad-hoc networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Maui, HI, USA, Mar. 2018, pp. 599–603.

[22] A. M. Hayajneh, S. A. R. Zaidi, D. C. McLernon, M. Di Renzo, and M. Ghogho, "Performance analysis of UAV enabled disaster recovery networks: A stochastic geometric framework based on cluster processes," *IEEE Access*, vol. 6, pp. 26215–26230, 2018.

[23] H. H. Choi, S. H. Nam, and T. Shon, "Two tier search scheme using micro UAV swarm," *Wireless Pers. Commun.*, vol. 93, no. 2, pp. 1–15, Feb. 2016.

[24] M. F. Sohail, C. Y. Leow, and S. Won, "Non-orthogonal multiple access for unmanned aerial vehicle assisted communication," *IEEE Access*, vol. 6, pp. 22716–22727, 2018.

[25] P. Sarao, P. Sindhu, and V. Navakishor, "Analysis of routing protocols based on network parameters in WANET," *Int. J. Comput. Sci. Eng.*, vol. 6, no. 4, pp. 8–13, Apr. 2018.

[26] J. Jiang and G. Han, "Routing protocols for unmanned aerial vehicles," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 58–63, Jan. 2018.

[27] I. A. Abbasi and A. S. Khan, "A review of vehicle to vehicle communication protocols for VANETs in the urban environment," *Fut. Internet.*, vol. 10, no. 2, pp. 14–28, Jan. 2018.

[28] S. Sarkar, "Reliable and energy-aware routing in mobile ad-hoc networks," *Int. J. Wireless Mob. Comput.*, vol. 16, no. 2, pp. 117–127, Jan. 2019.

[29] O. S. Gnana Prakasi and P. Varalakshmi, "Decision tree based routing protocol (DTRP) for reliable path in MANET," *Wireless Pers. Commun.*, vol. 109, no. 1, pp. 257–270, May 2019.

[30] S. Badiwal, A. Kulshrestha, and N. Garg, "Analysis of black hole attack in MANET using AODV routing protocol," *Int. J. Comput. Appl.*, vol. 168, no. 8, pp. 27–33, Jun. 2017.

[31] P. Sethuraman and N. Kannan, "Refined trust energy-ad hoc on demand distance vector (ReTE-AODV) routing algorithm for secured routing in MANET," *Wireless Netw.*, vol. 23, no. 7, pp. 1–11, May 2016.

[32] H. K. Ashwini, V. Rao K. P., and I. Ginimav, "CM-AODV: An efficient usage of network bandwidth in AODV protocol," in *Proc. Int. Conf. Design Innov. 3Cs Comput. Commun. Control (ICDI C)*, Bangalore, India, Apr. 2018, pp. 111–114.

[33] J. Kaur and G. Singh, "Hybrid AODV algorithm for path establishment in MANET using bio inspired techniques," in *Proc. IEEE Int. Conf. Power, Control, Signals Instrum. Eng. (ICPCSI)*, Chennai, India, Sep. 2017, pp. 823–829.

[34] S. Ghaleb, S. Ba, S. Akram, and V. Vasanthi, "Energy aware issues of DSR routing protocols in mobile ad hoc network," *Int. J. Comput. Appl.*, vol. 178, no. 3, pp. 8–11, Nov. 2017.

[35] B. Singh and K. Kaur, "Performance analysis of propagation structures on DSR routing protocol in mobile ad-hoc networks," in *Proc. NGCT*, Dehradun, India, 2017, pp. 105–114.

[36] A. Barve, A. Kini, O. Ekbote, and J. Abraham, "Optimization of DSR routing protocol in MANET using passive clustering," in *Proc. 2nd Int. Conf. Commun. Control Intell. Syst. (CCIS)*, Mathura, India, Nov. 2016, pp. 23–27.

[37] A. Chauhan, D. K. Gupta, and M. Kumar, "Detection of packet dropping nodes in MANET using DSR routing protocol," *Int. J. Comput. Appl.*, vol. 123, no. 7, pp. 10–16, Aug. 2015.

[38] S. Y. Dong, "Optimization of OLSR routing protocol in UAV ad HOC network," in *Proc. 13th Int. Comput. Conf. Wavelet Act. Media Technol. Inf. Process. (ICCWAMTIP)*, Chengdu, China, Dec. 2016, pp. 90–94.

[39] C. Bouras, V. Kapoulas, K. Stamos, and N. Stathopoulos, "Evaluation of power control mechanism on OLSR routing protocol," in *Proc. 30th Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, Crans-Montana, Switzerland, Mar. 2016, pp. 766–771.

[40] K. A. Adoni and A. S. Tavildar, "Trust aware routing framework for OLSR protocol to enhance performance of mobile ad-hoc networks," in *Proc. Int. Conf. Pervas. Comput. (ICPC)*, Pune, India, Jan. 2015, pp. 1–7.

[41] K. Yamaguchi, T. Nagahashi, T. Akiyama, T. Yamaguchi, and H. Matsue, "A routing based on OLSR with traffic load balancing and QoS for Wi-Fi mesh network," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Kota Kinabalu, Malaysia, Jan. 2016, pp. 102–107.

[42] P. Saravanan and T. Arunkumar, "Fuzzy enabled geographic routing protocol for vehicular ad hoc networks," *Int. Rev. Comput. Soft.*, vol. 9, no. 6, pp. 1101–1107, Jun. 2014.

[43] C. Li, C. Zhao, L. Zhu, H. Lin, and J. Li, "Geographic routing protocol for vehicular ad hoc networks in city scenarios: A proposal and analysis," *Int. J. Commun. Syst.*, vol. 27, no. 12, pp. 4126–4143, Dec. 2014.

[44] V. N. G. J. Soares, J. J. P. C. Rodrigues, and F. Farahmand, "GeoSpray: A geographic routing protocol for vehicular delay-tolerant networks," *Inf. Fusion*, vol. 15, pp. 102–113, Jan. 2014.

[45] J. Uddin, "Geographic routing protocol in mobile ad-hoc networks for reliable ftp traffic communication," *Inf. Jpn.*, vol. 17, no. 10, pp. 4885–4892, Aug. 2014.

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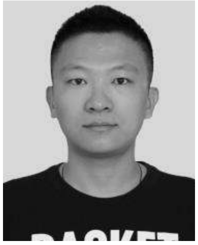

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