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A multi-metric GPSR protocol based on fuzzy control

Linhui Wang[1], Zhijun Tang*[1,2], Wanqing Qiu[1]
(School of Information and Electrical Engineering, Hunan University of Science and Technology, Xiangtan 411201; 2. Hunan Software Vocational and Technical University, Xiangtan, China)
*corresponding author: zjtang@hnust.edu.cn

Abstract The Greedy Perimeter Stateless Routing (GPSR) protocol uses the location information of the node to select the next hop node without maintaining a complete routing table, so it is better suitable for the flying Ad-hoc network (FANET). However, the greedy forwarding mode only considers the node distance to select the next hop node. It is easy to have routing holes, resulting in link breakage, and the energy balance of nodes is not considered. On this basis, this paper proposes a fuzzy control based multi-metric GPSR protocol (FMM-GPSR). This protocol introduces the number of neighbors and residual energy ratio when selecting the next hop node in greedy forwarding mode, and applies fuzzy control theory to consider the effects of distance, energy and number of neighbors comprehensively in order to reduce the probability of occurrence of routing nulls, and to avoid the reuse of low-energy nodes to make them die of excessive energy depletion. Simulation results show that the protocol effectively improves the network survival time and has better performance in terms of packet delivery rate and throughput.

Keywords Flying Ad-hoc network; GSPR; Fuzzy control; Energy balance

1. Introduction

Flying ad-hoc network (FANET) is a kind of complex autonomous system for multi-UAV collaborative application to achieve rapid network deployment and information sharing. It is characterized by non-dependence on external infrastructure, fast and flexible deployment of nodes, etc., and has a broad application prospect in both civil and military fields [1-2]. Routing protocol is the core support technology of FANET network, which mainly solves the problem of real-time reliable transmission of data packets. The current routing protocols for FANET networks are mainly categorized into two main types of routing algorithms based on topology and geolocation information. Most of the existing topology-based routing algorithms do not consider the impact of the mobile characteristics of the UAV (Unmanned

Aerial Vehicle), which requires frequent transmission of control packets and a large amount of space for storing topology information. The geolocation-based routing algorithms utilize GPS (Global Positioning System) to determine the geographic location of the UAVs and utilize the location of the destination UAV and neighboring UAVs to select routing paths, which can reduce the overhead of frequent routing table updates. The most widely used geolocation-based routing algorithm is the Greedy Perimeter Stateless Routing (GPSR). Through the in-depth analysis and research of GPSR protocol, it can be concluded that the traditional GPSR protocol mainly has the following defects: the greedy forwarding mode of GPSR protocol selects the next-hop node only through the positional information and ignores other state information of the node, which is a single consideration, poorly adaptive, and prone to routing nulling problems, leading to link breakage [3-5]. The GPSR protocol relies on neighbor location information for route forwarding, however, the high mobility of nodes can lead to location information failure, and nodes utilizing the failed location information can lead to route failure [6-10]. In the perimeter forwarding state, the protocol constructs the floor plan and bypasses routing holes through the right-hand rule. However, in this state, each node needs to maintain a floor plan to describe the topology, which leads to an increased load on the nodes and the process of constructing the floor plan may remove valid paths. In addition the right hand rule is random in nature and the path selected through this rule is not always the shortest which will lead to less efficient routing [11-13] To summarize, greedy forwarding mode is the core part of GPSR protocol, this paper proposes a multi-metric GPSR protocol based on fuzzy theory to address the above issues. This protocol introduces the number of neighbors and residual energy ratio of a node as metrics in greedy forwarding mode and combines the fuzzy theory to consider the effects of distance, energy, and number of neighbors comprehensively in order to improve the performance of the network in terms of packet delivery rate, network survival time and network throughput.

2. Related work

In recent years, many researchers have worked on the study and improvement of the GPSR protocol. To address the problem of the communication failure caused by nodes moving too fast, reference [12] proposes a Maximum Duration-Minimum Angle GPSR protocol (MM-GPSR). The protocol establishes an authorized communication region in greedy forwarding mode and selects the neighbor with the maximum cumulative communication time in it as the next hop node. If the node enters the peripheral forwarding mode, the angle between the source node and the neighboring nodes is calculated and compared and the node with the smallest angle is selected as the next hop node. However, the protocol does not consider the instability brought about by the communicating edge nodes and the effect of the node movement direction on the overall delay. Reference [14] proposes an adaptive multipath greedy perimeter stateless routing protocol (AM-GPSR), which redefines the hello broadcast period based on the speed of the UAVs and the error between the estimated position and the actual position, and adopts a greedy multipath forwarding strategy. AM-GPSR improves the performance of the network in terms of throughput and latency, but it has a high control overhead. Emergency information dissemination routing protocol for supporting medical surveillance in flying Ad-hoc networks (SF-GoeR) [15] selects intermediate nodes based on the stability coefficient determined by the distance ratio and residual energy ratio, which improves the link stability and network survival time, but the reliability of this routing protocol is weak during data transmission. By adding link risk degree and weight gradient, literature [16] proposes an improved greedy perimeter stateless routing protocol GPSR-WG. The GPSR-WG protocol enhances the greedy forwarding model by using metrics such as distance, direction, normalized speed factor, and link risk degree. In addition, when selecting the next hop node from neighboring UAVs, it performs a weight gradient strategy for these metrics, which improvement improves the performance of the routing process. However, energy efficiency is not considered in the routing process and the network lifetime is short. Reference [17] proposed TD-GPSR routing protocol by considering the time slot distance of UAVs. This protocol selects the next hop UAV based on the temporal distance of neighboring UAVs. This approach minimizes the number of hops and per-hop delay. It reduces the packet loss rate and delay compared to traditional GPSR protocol. However, existing routing algorithms sometimes fail to handle data predictability and uncertainty. The AGGR protocol proposed in reference [18] contains an adaptive hello mechanism and a greedy forwarding mechanism based on the relative motion of UAVs. In the adaptive hello mechanism, the UAV calculates the hello period based on the real-time relative special values between it and the upstream UAV. The greedy forwarding mode takes into account the relative motion characteristics of UAVs, which makes AGGR well adapted to the rapid changes in network topology. Compared with the GPSR algorithm, the AGGR algorithm significantly reduces the temporary communication blind spot problem and works well in FANET, but it does not take into account the energy consumption of the UAV. Reference [19] developed a multi-attribute bidding model based on game theory in perimeter forwarding mode to select the best next hop node by considering the distance and forwarding angle of the nodes. The optimization algorithm used in the boundary forwarding phase is able to increase the packet delivery rate while reducing the delivery delay and network overhead as compared to the traditional GPSR protocol.

Based on the above analysis, the traditional GPSR protocol has the problems of single metric and insufficient consideration of energy consumption, etc. Improvements for the GPSR protocol are mainly focused on the greedy forwarding mode, and the routing nulling problem occurring in the greedy forwarding mode is also prone to lead to link breakage and reduce the network performance. To try to solve the above problems, this paper proposes a multi-metric GPSR protocol based on fuzzy control.

3. FMM-GPSR protocol

In greedy forwarding mode, the GPSR protocol selects next hop nodes by considering only the distance factor, which not only tends to lead to the routing hole problem to reduce the packet delivery rate, but also fails to consider the energy equalization problem, which tends to reduce the average network survival time. For this reason, two metrics, the number of neighbors and the residual energy ratio, are added to select the next hop node in the greedy forwarding mode, and the fuzzy control theory is applied to consider the effects of distance, energy, and the number of neighbors in a comprehensive manner. The fuzzy control system generally contains the following main parts: inputs to the fuzzy control system, fuzzification module, fuzzy control rules and defuzzification module. The composition of the fuzzy control system is shown in Fig.1. FMM-GPSR is improved for the greedy forwarding mode of the GPSR protocol, and here we mainly elaborate the data processing when the next hop selects the next hop node.

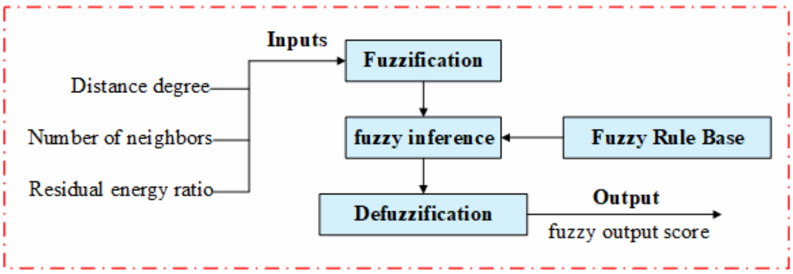

Fig.1. Fuzzy control system

3.1. Fuzzy control system inputs

1 Number of neighbors

The traditional GPSR protocol includes two forwarding modes: greedy forwarding and perimeter forwarding. In greedy forwarding mode, the source node selects the next hop forwarding node with reference to the distance factor only, which easily leads to the routing hole problem and reduces the packet delivery rate. In peripheral forwarding mode the planarization operation to solve the routing hole problem consumes more resources, so the metric of number of neighbors is introduced and the node with more neighbors is preferred when selecting the next node in order to avoid the routing hole problem as much as possible.

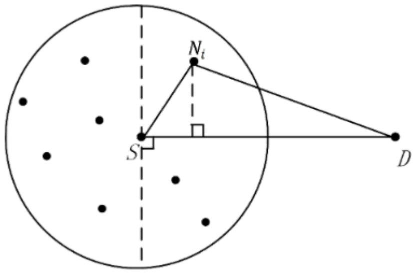

Fig.2. Node neighbors

As shown in Fig. 2, there exist a source node S, a neighbor node N, and a destination node D in the simulation scenario, and their coordinates are assumed to be (x_s, y_s, z_s), (x_n, y_n, z_n), (x_d, y_d, z_d) respectively. According to the Euclidean distance formula Eq.(1), the distances ρ_{SN}, ρ_{SD} and ρ_{ND} between three nodes can be calculated.

$$\rho = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

The cosine of the angle α between vectors $\overrightarrow{SN}$ and $\overrightarrow{SD}$ can be calculated from the cosine theorem Eq.(2).

$$\cos\theta = \frac{b^2 + c^2 - a^2}{2bc}$$

Determine whether the number of neighbors is increased or not according to the positive or negative of $\cos\theta$. The rule for counting the number of neighbors is in Eq (3): when $\cos\theta \geq 0$, the number of neighbors is added by one, and when $\cos\theta < 0$, the number of neighbors remains unchanged.

$$neighbornum = \begin{cases} neighbornum+1, & \cos\alpha \geq 0 \\ neighbornum, & other \end{cases}$$

(2) Distance

Greedy forwarding mode selects the node closest to the target node for data forwarding. The next-hop node selected using this method is likely to be located at or near the boundary of the communication range, so the reliability of this communication link is poor. Due to the high mobility of the UAVs, the selected next-hop node is likely to be out of communication range before the packet arrives, which will result in interruption of the communication link. According to the reference [20], it is known that the data transfer rate is close to 100% when the actual distance is less than or equal to 90% of the communication distance. Therefore, nodes with $\rho \leq 0.9R$ are preferred for data forwarding when selecting the next hop.

(3) Residual energy ratio

It is more difficult to replenish the energy of UAVs due to the special characteristics of their working environment. So the residual energy of the nodes is also used as a metric to ensure that the same node is not frequently used for relay forwarding, thus prolonging the network survival time. The initial value of energy for the node energy model is set as $E_{initial}$ The energy consumption of a node consists of sending data energy consumption and receiving data energy consumption. Therefore the residual energy of the node is shown in Eq.(4). Where E_{sent} and $E_{receive}$ denote the energy consumption of the node for sending data and receiving data respectively. E_{remain} is the residual energy of the node.

$$E_{remain} = E_{initial} - E_{sent} - E_{receive}$$

The residual energy is normalized by dividing the residual energy with the initial energy to obtain the residual energy of the node as shown in Eq.(5), where E_{rr} is the residual energy ratio of the node.

$$E_{rr} = \frac{E_{remain}}{E_{initial}}$$

3.2 Fuzzification

In this paper, fuzzy input variables are fuzzified using triangular affiliation function Eq.(6) and trapezoidal affiliation function Eq.(7).

$$f\left(x;a,b,c\right) = \begin{Bmatrix} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{Bmatrix}$$

$$f\left(x;a,b,c\right) = \begin{Bmatrix} 0\ , & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ 0, & c \le x \end{Bmatrix}$$

The more the number of neighbors of an intermediate node, the lower the probability of a routing hole occurring when the source node uses it as the next hop node for data forwarding. At this time the probability of successful packet delivery is higher, so the node prefers the neighbor node with more number of neighbors as the next hop forwarding node. The affiliation function of the number of neighbors is shown in Fig.3.

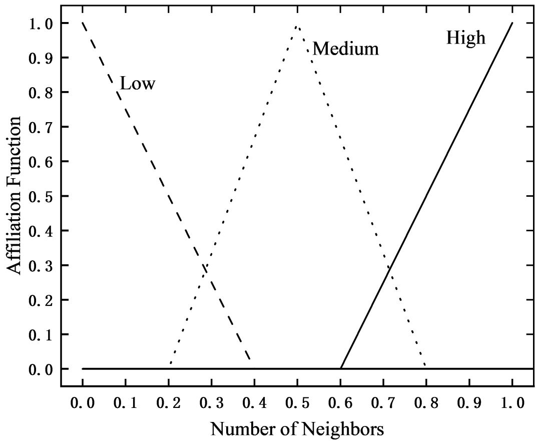

Fig.3. Affiliation function of the number of neighbors

For the distance, the closer the neighbor node to the target node in the range of $\rho \leq 0.9R$ the more likely it is to be selected as a relay node, the affiliation function of the distance is shown in Fig.4.

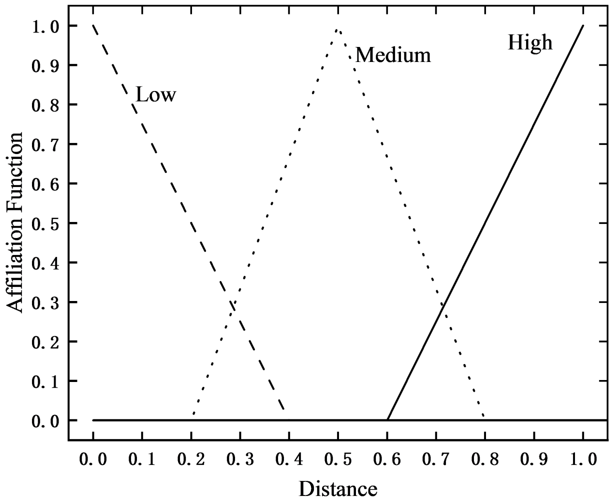

Fig.4. Affiliation function of the distance

For residual energy, the higher the residual energy of a node the easier it is to be selected as a relay node. At the same time, the residual energy of the node only needs to be maintained above a certain value to be selected as a selection object. So the residual energy is fuzzified using trapezoidal affiliation function and the affiliation function of residual energy ratio is shown in Fig.5.

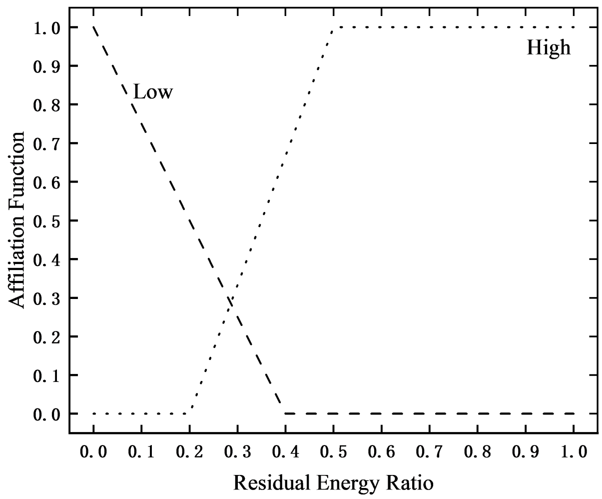

Fig.5. Affiliation function of residual energy ratio

3.3 Fuzzy control rules

This protocol uses fuzzy control rules in the form of IF/THEN, i.e., if A, B, and C, then D, where A, B, C, and D represent the number of neighbors, distance, residual energy ratio, and fuzzy score, respectively. All the fuzzy rules are shown in Table 1.

Table 1 IF/ZHEN rules mapping table

Input			Output
Number of Neighbors	Distance	Residual Energy Ratio	Fuzzy Score
High	Low	High	Extremely-High
	Low	Low	Very-High
	Medium	High	High
	Medium	Low	Medium
	High	High	Medium
	High	Low	Low
Medium	Low	High	Very-High
	Low	Low	High
	Medium	High	Medium
	Medium	Low	Low
	High	High	Low
	High	Low	Very-Low
Low	Low	High	High
	Low	Low	Medium
	Medium	High	Low
	Medium	Low	Very-Low
	High	High	Very-Low
	High	Low	Extremely-Low

3.4 Defuzzification

By defuzzification, the fuzzy sets mapped by the above rules are transformed into specific values, which are used as scores of the fuzzy outputs for comparison to select the next hop node. The fuzzy output affiliation function is shown in Fig.6.

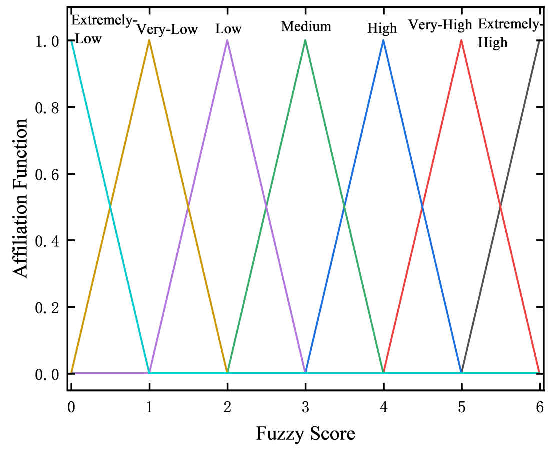

Fig.6. Affiliation function of fuzzy output

The method taken for defuzzification is the center of gravity method, by calculating the horizontal coordinates of the center of gravity of the area enclosed by the curve of the affiliation function and the horizontal coordinate axis as the fuzzy output. Assuming that the affiliation function of the set A of F on the domain U is $A(u)$,where $u \in U$, the result u_{cen} from the center of gravity method can be expressed by Eq.(8) according to the definition.

$$u_{cen} = \frac{\int_U A(u)udu}{\int_U A(u)du}$$

5. Simulation and Analysis

To analyze and validate the performance of the improved FMM-GPSR routing protocol, this paper verifies the impact on four performance metrics, namely, packet delivery rate, network throughput, network survival time, and average end-to-end delay, under different node density scenarios by varying the number of nodes. And comparative analysis with AODV, GPSR, OLSR routing protocols is done.

5.1 Evaluation of metrics

(1) Packet delivery ratio (PDR)

Packet delivery rate is the ratio of the sum of packets successfully received by the destination node to the sum of packets sent from the source node to the destination node. It reflects the reliability of packet delivery in the network, the higher the packet delivery rate, the better the routing effect and the higher reliability of data delivery. The calculation formula of packet delivery rate is shown in Eq.(9).

$$PDR = \frac{P_R}{P_S} \times 100\%$$

Where P_R represents the sum of packets successfully received by the destination node, P_S represents the sum of packets sent from the source node to the destination node

(2) Network lifecycle

Network lifecycle is the time elapsed from the time when all the nodes in the network start working to the death of the first node. It reflects the energy consumption of the whole network, the longer the network survival time, the more efficiently the network utilizes the energy. The network survival time is calculated as shown in Eq.(10).

$$TTL = T_{end} - T_{start}$$

Where T_{start} represents the time when the network starts working and T_{end} represents the time when the first node dies.

(3) Throughput (Th)

Throughput indicates the amount of data transmitted by the network per unit of time. Throughput reflects the network's data processing capacity, bandwidth utilization, and load capacity. The greater the network throughput, the greater the network's ability to process data and the more efficient the data transmission. Network throughput can be expressed by Eq.(11).

$$Th = \frac{1}{T_{end} - T_{start}} \sum_{i=0}^{N} R_{byte}(i) \times 8$$

where T_{start} and T_{end} represent the simulation start time and the first node death time respectively. $R_{byte}(i)$ denotes the total number of bytes of the packet successfully received by node i, and N represents the number of nodes in the entire network.

(4) Average end-to-end delay (Avdelay)

The average end-to-end delay represents the average time taken from the source node to send the data to the target node to receive the data. The average end to end delay is calculated as shown in Eq.(12).

$$Avdelay = \frac{1}{N} \sum_{i=0}^{N} \left(T_{receive(i)} - T_{send(i)} \right)$$

Where N is the total number of packets received by the destination node. $T_{receive}$ indicates the time when the destination node received the last sent message. T_{send} indicates the time when the source node started sending the first message.

5.2 Simulation parameter settings

In this paper, the protocol is simulated based on NS-2 simulation platform. The simulation scene is a three-dimensional space area of 2000m×2000m×1000m. The link layer protocol is 802.11 MAC layer protocol. The node transmission radius is 300 m. The simulation results are the average of 10 simulations. The specific parameter settings for these simulations are shown in Table 2.

Table 2 Simulation parameters

Parameter Value	Parameter Value
MAC	802.11
Dissemination Model	Freespace
Signal Channel	WirelessChannel
Physical Layer	WirelessPhy
Queueing Model	PriQueue
Queue Length	50
Logical Link Layer Model	LL
Number of Nodes	50
Simulation Time	200s
Simulation Scenario	2000m×2000m×1000m
Data Flow	CBR
Movement Model	RWP
Receive Power	200J
Receive Power	1.6W
Receive Power	1.2W

5.3 Results and analysis

The impact of the number of nodes on network survival time is illustrated in Fig. 7. As the number of nodes increases, the density within the network also rises. To facilitate data forwarding, nodes must expend more energy to transmit control messages, leading to accelerated energy consumption and a subsequent decrease in network survival time. The OLSR protocol is a table-driven approach that necessitates frequent transmission of control messages to maintain its routing table; consequently, this results in faster energy depletion within the network. Therefore, the OLSR protocol exhibits the shortest network lifecycle. In contrast, the GPSR protocol relies solely on node location information for selecting next-hop nodes and does not require maintenance of a routing table, resulting in lower energy consumption. The FMI-GPSR protocol further enhances efficiency by considering residual energy levels when selecting next-hop nodes; this strategy helps avoid over-reliance on low-energy nodes that could deplete their resources too quickly and fail prematurely. By promoting an equitable distribution of energy usage across nodes, FMI-GPSR effectively improves overall network survival time. The network lifecycle performance of FMM-GPSR routing protocol outperforms GPSR by 23%, AODV by 31%, OLSR by 45% at node count of 100.

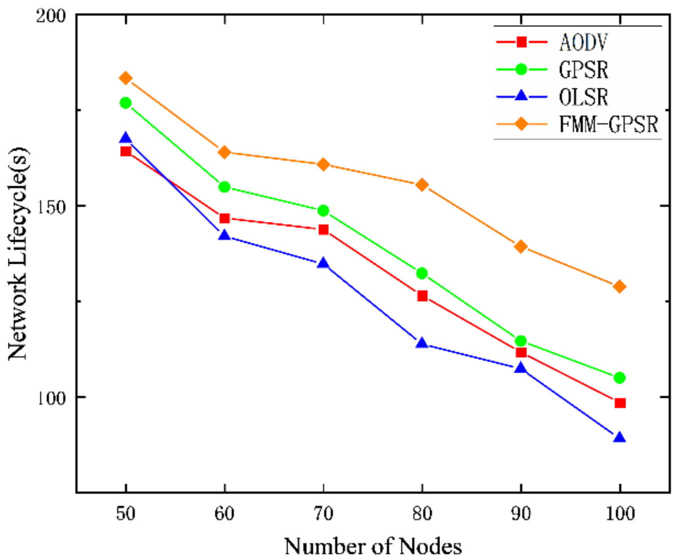

Fig.7. Effect of number of nodes on network lifecycle

Fig.8 reflects the effect of the number of nodes on the packet delivery rate. As the number of nodes increases, the density of nodes also rises. Consequently, the number of data transmission links that can be established within the network increases, leading to a gradual enhancement in the packet delivery rate of the network. Among the evaluated protocols, the FMI-GPSR protocol demonstrates superior performance. Among the remaining three protocols, the GPSR protocol also exhibits optimal results. This can be attributed to GPSR's reliance on node location for forwarding decisions, which is more effectively suited to the highly dynamic topology of FANETs and yields a higher packet delivery success rate compared to AODV and OLSR. Conversely, OLSR operates as a table-driven routing protocol; its locally stored routing tables are not updated in a timely manner and necessitate significant control overhead, resulting in suboptimal network performance. The PDR performance of FMM-GPSR routing protocol outperforms GPSR by 11%, AODV by 21%, OLSR by 69% at node count of 100.

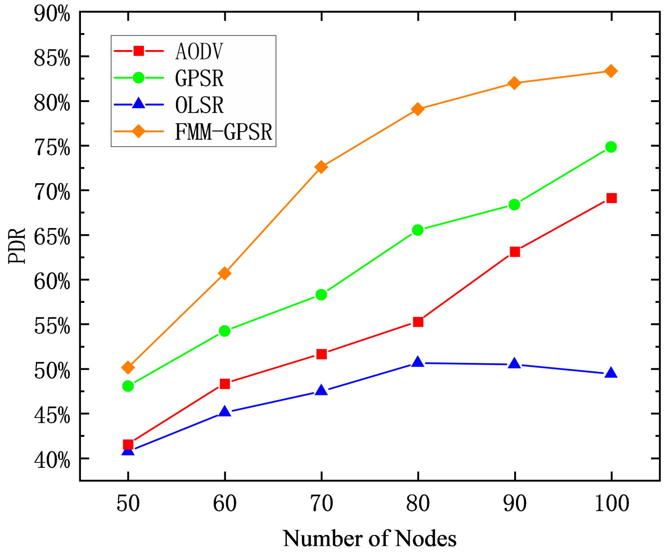

Fig.8. Effect of the number of nodes on PDR

The effects of the number of nodes on network throughput are illustrated in Fig. 9. Network throughput tends to increase with an increasing number of nodes; however, once the node count reaches a certain threshold, throughput begins to decline. This phenomenon can be attributed to the rise in data transmission as more nodes are added, which initially enhances network throughput. Nevertheless, when there is an excessive number of nodes, contention for channel access intensifies and consequently increases the channel load, resulting in network congestion and a reduction in overall throughput. Furthermore, FMI-GPSR mitigates the likelihood of routing voids during the greedy forwarding phase and consequently enhances network communication capacity. When comparing systems with 100 nodes, FMI-GPSR demonstrates a 17% improvement in throughput relative to GPSR.

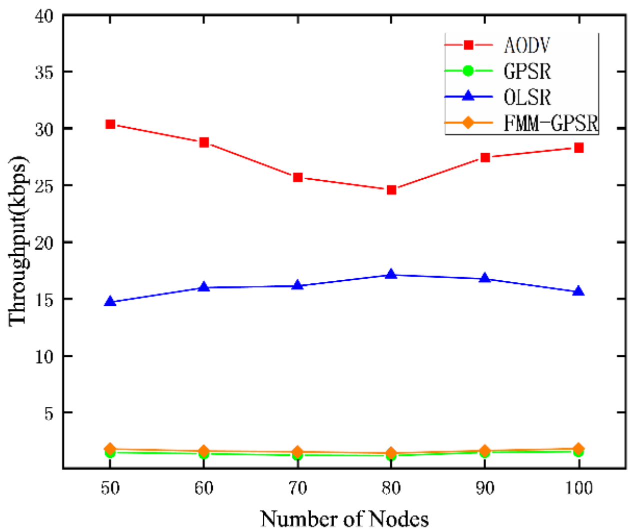

Fig.9. Effect of number of nodes on network throughput

As illustrated in Fig.10, the average end-to-end delay of data transmission tends to increase with a higher number of nodes. This phenomenon is primarily attributed to the growing contention among nodes for channel access, which consequently elevates the queuing time necessary for data transmission. Additionally, an increase in network overhead contributes further to delays in data transmission. Among the four protocols examined, GPSR leverages geographical location information to select the next hop without requiring a complete routing table, resulting in minimal delay. In contrast, AODV operates as an on-demand routing protocol that necessitates route discovery when initiating communication from the source node; this leads to its relatively poor performance concerning end-to-end delay. FMI-GPSR incorporates additional metrics in selecting the next hop node and employs fuzzy logic for data processing; therefore, it experiences an increased end-to-end delay compared to GPSR.

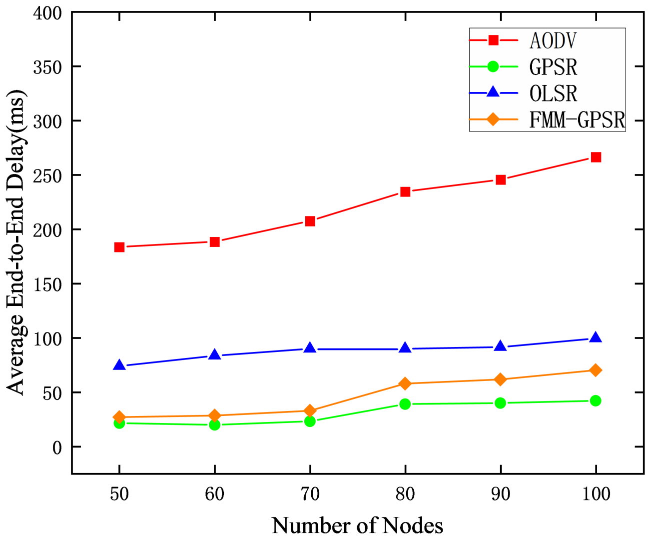

Fig.10. Effect of number of nodes on average end-to-end delay

6. Conclusion

The GPSR greedy forwarding model, which exclusively utilizes distance as the sole metric for routing path selection, is prone to encountering routing voids and communication link failures. Moreover, it fails to address the critical issue of energy balancing. To mitigate these limitations, this paper proposes a multi-metric FMM-GPSR routing algorithm based on fuzzy logic theory. The FMM-GPSR algorithm incorporates three key metrics—number of neighbors, residual energy ratio, and distance—for selecting the next-hop node, while introducing a refined definition for the number of neighbors. Additionally, it establishes an energy consumption model for nodes and integrates fuzzy logic to comprehensively evaluate the combined impact of these three metrics. This approach effectively reduces the occurrence of routing voids, achieves energy balance, and significantly enhances overall network performance. Simulation results indicate that the FMM-GPSR routing protocol surpasses existing methods in terms of network longevity, packet delivery rate, and throughput.

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