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RESEARCH

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Network consensus analysis and optimization of distributed FANETs based on multi-agent consensus theory

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Abstract

Distributed flying ad hoc networks (FANETs) have been widely used in collaborative reconnaissance, situation construction, and other scenarios. In distributed FANETs with multi-hop and intermittent links, nodes only maintain neighbors' information and cannot obtain the whole network messages. There may be contradicting information collected across nodes, resulting in inconsistency problems. However, existing research on collaborative consensus focuses mainly on the control domain using multi-agent consensus theory. The study on distributed network consensus does not consider the effect of the multi-hop forwarding order, hence limiting the optimization of distributed FANETs. Based on this, we establish a network consensus model utilizing the multi-agent consensus theory and analyze the impact of the outage probability of links and untimely forwarding on the distributed consensus probability, considering the node density, link outage probability, and network maintenance times. Besides, using the election mechanism as an example, we establish distributed network performance analysis models considering consensus error to enhance the service delay and resource efficiency performance analysis of distributed FANETs. Finally, we construct a protocol-level simulation platform based on Visual Studio and extensive experiments to determine the optimal mechanism parameters under different network and channel parameters. The simulation results show that the optimal network maintenance times increase with the increasing outage probability of links. Moreover, distributed FANETs can achieve optimal resource efficiency without achieving complete consensus, that is, there is a tradeoff between network maintenance cost and network performance.

Keywords: Distributed FANET, Network consensus, Network maintenance, Service delay, Resource efficiency

1 Introduction

A flying ad hoc network (FANET) is a collection of vehicles equipped with communication and sensing capabilities [1–3], which can achieve cooperative division of labor and has been widely utilized in collaborative reconnaissance [1], situation construction [4], and other scenarios. In the circumstances above, vehicles use the advantage of high mobility and flexibility [5] to respond to changing collaboration tasks and boost network coverage by expanding network hops. The mobility of vehicles and the complexity of the

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electromagnetic environment cause the FANET to present the characteristics of multi-hop and intermittent links [6], in which the outage probability of links can reach 20–30% [7].

The network architectures and multiple access mechanisms based on them have a crucial role in determining the communication performance of FANETs and will also impact the cooperative method. There are mainly two types of existing networking architectures: centralized and distributed network architecture [8]. The central node maintains the whole network's information under the centralized network architecture and builds a maintenance tree. Based on the tree structure, all resource application information must be collected at the central node, and the central node completes resource allocation. Increased network hops and intermittent links will significantly raise the overhead of all information converging on the central node, reducing resource efficiency. Moreover, when the central node is damaged, the centralized network must reselect a central node, which incurs extra network reconfiguration costs. In comparison, each node in the distributed network stores a subset of its neighbors' information and makes decisions separately, whose resource efficiency and delay performance have apparent advantages over centralized networks with intermittent links [9, 10]. So, the distributed FANET becomes an inevitable choice in the complex battlefield environment.

However, in a distributed network, each node only maintains part of its neighbor messages and cannot obtain information about the whole network. There may be contradicting information collected across nodes, resulting in inconsistency problems. Suppose neighboring nodes store different network information (such as the number of neighbors, number of services and service requirements, etc.). In that case, their resource allocation results may conflict, leading to transmission collisions and resource waste. When the link outage probability increases, the failure possibility of data transmission and the probability of nodes receiving conflicting information increase. For example, suppose a distributed network consists of seven nodes from Node1 to Node7, and the nodes transmit network maintenance information in the order from Node1 to Node7, as shown in Fig. 1. During the first network maintenance, Node6 could not transmit data successfully owing to intermittent links. During the second period of maintenance, Node6 information was successfully sent. As shown in Table 1, after two times of network maintenance, the information maintained by Node1 and Node2 is inconsistent.

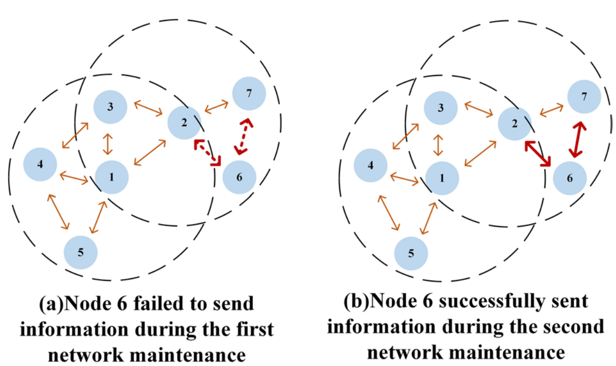

Fig. 1 A network maintenance example. Link outage probability affects maintenance information transmission in different maintenance periods

Table 1 Network information maintained by Node1 and Node2

Information maintained after first network maintenance	
Information maintained by Node1	[1, 2, 3, 4, 5]
Information maintained by Node2	[1, 2, 3, 7]
Information maintained after second network maintenance	
Information maintained by Node1	[1, 2, 3, 4, 5, 7]
Information maintained by Node2	[1, 2, 3, 4, 5, 6, 7]

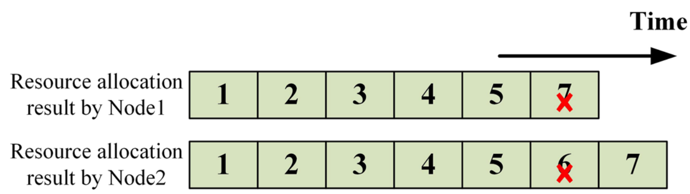

Fig. 2 Resource allocation results by Node1 and Node2 are in conflict

If resource allocation is based on the above information, the timeslot allocated by Node1 to Node7 will be slot 6, the same timeslot given by Node2 to Node6, as shown in Fig. 2. The resource allocation result is in conflict.

It can be seen from the above example that, due to the intermittent link during the first network maintenance, Node1 is unable to acquire information about Node6. Even if there is no link interruption, Node1 and Node2 still have different maintenance information. This is because information on some multi-hop neighbors is not forwarded in time during the second maintenance process due to the sending order of nodes. Evidently, the link outage probability and forwarding order affect the consensus of a distributed FANET.

Most research on distributed consensus analysis focuses on the cooperative control domain using multi-agent consensus theory. In the multi-agent consensus control analysis theory, nodes engage with their neighbors and adjust the output to make the vehicles converge to the desired state (same as the pilot node or average of global) globally. Olfati-Saber et al. [11] introduced the multi-agent consensus theory and provided the state update equation to analyze the system consensus using algebraic graph theory based on the noise-free Vicsek model. Abdessameud and Tayebi [12, 13] studied the consensus of multi-agent systems under directed topology and analyzed the relationship between network topology and control consensus probability. Savino et al. [14, 15] studied the influence of delay on the consensus error of the control system and obtained the delay range to ensure consensus. The impact of changing topology and the delay required to receive data packets successfully on the multi-agent consensus error was analyzed in [16, 17], and the conditions for the system to reach an agreement were given through linear matrix inequalities. It can be seen that the factors affecting the consensus of the multi-agent control system include the number of hops between nodes, packet loss and delay caused by intermittent links, etc.

The network consensus in the distributed FANET is that each node obtains accurate and timely neighbor information and minimizes resource collision or waste by adjusting resource allocation results. As described in Fig. 2, in distributed FANETs, there may be conflicts in resource allocation caused by network consensus error, leading to failure data transmission. Currently, most distributed network performance analysis and optimization studies have yet to consider the impact of network consensus, but reduce the effect of link outage rate and untimely forwarding through retransmission to meet the constraints for the success probability of data transmission [18, 19]. Resource allocation must be successful in this case, eliminating the impact of inconsistency in practice. Li and Li [20] pointed out that the link outage probability would cause packet loss and the emergence of nodes with unknown election interval information in the distributed network under the election mechanism, hence influencing the selection of election sets and the resource allocation outcomes. The above research investigated the effect of various election interval lengths on the success probability of resource allocation. However, it only considered the impact of packet loss in multi-hop information forwarding. It did not consider the forwarding order influence, resulting in the limited optimization of distributed FANET parameters. There are similarities between multi-agent control consensus and network consensus; thus, we can use the state update equation from multi-agent consensus analysis theory as a reference to study the consensus performance of distributed FANETs.

Considering the issues above, we concentrate on distributed FANETs with multi-hop and intermittent links and research network consensus analysis and optimization based on multi-agent consensus theory. In this paper, we establish a network consensus model using multi-agent consensus analysis theory, and analyze the impact of network and channel parameters on network consensus probability through theoretical models and two simulation methods: construction matrix and iteration (CMIT), construction matrix and intercept (CMIN). Besides, we establish network performance analysis and optimization models considering consensus error using the election mechanism as an example to enhance the service delay and resource efficiency performance analysis of distributed FANETs. Finally, a protocol-level simulation platform based on Visual Studio (VS) is built to validate the accuracy of models, and the optimal mechanism parameters under different network and channel parameters are given to improve the applicability of FANETs.

The article's contributions are as follows:

- We establish the network consensus model of distributed FANETs using the multi-agent consensus theory and analyze the consensus error affected by link outage probability and untimely forwarding under different node densities, link outage probabilities, and network maintenance times.
- We establish the service delay and resource efficiency model and optimization model of FANETs, taking the election mechanism as an example, considering the impact of network consistency, and analyze the effects of different network, channel, and mechanism parameters on FANETs performance.
- We build a protocol-level simulation platform based on VS and extensive experiments to study the network consensus performance through theoretical models, the CMIT, and the CMIN methods. The optimal mechanism parameters under different network and channel parameters are given through simulation to improve further the distributed FANETs' performance.

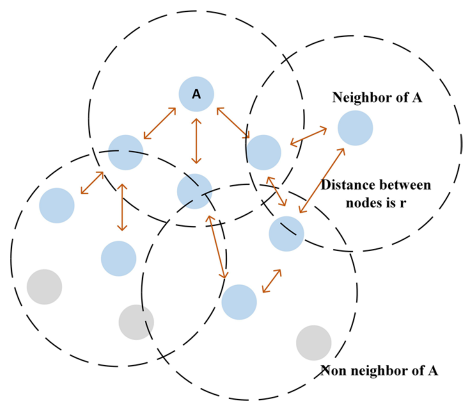

Fig. 3 Network architecture of a distributed FANET, where nodes only maintain the information of neighbors

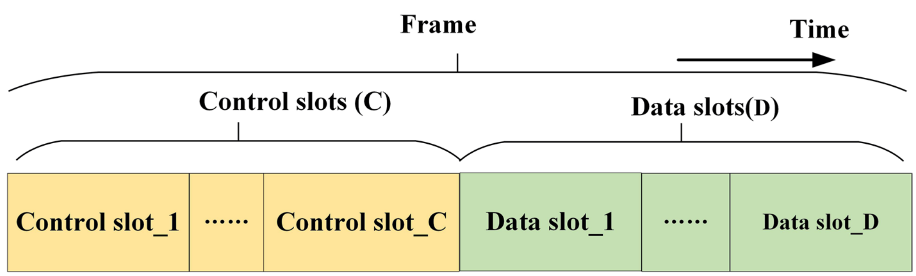

Fig. 4 Frame architecture of distributed FANETs which contains $C + D$ slots

The article is organized as follows: The first part is the introduction, in which we introduce the background, research objectives, and review of the relevant literature. Section 2 describes the system model, which includes the network model, frame structure, and critical processes of the election mechanism. The network consensus model is described in Sect. 3, taking advantage of the multi-agent consensus theory. Section 4 describes the network performance analysis and optimization models of distributed FANETs with an election mechanism. We build a simulation platform based on VS and conduct simulation analysis in Sect. 5. Section 6 summarizes the whole paper.

2 Methods

2.1 Network Model and Frame Structure

The network architecture of distributed FANET is shown in Fig. 3. In this network, the node density is λ, the number of network hops is H, and the coverage radius of a node is r. All nodes have services to transmit, and the number of data slots each node needs to occupy (that is, the traffic) is N_{data}. In distributed FANETs, nodes only maintain the information of neighbors. Taking the network maintenance hop is 2 as an example, the node with blue color represents the neighbor of node A, and the gray node is not.

The frame structure of distributed FANETs is shown in Fig. 4. The slot is the minimum resource allocation unit, and the node transmits various messages in different slots based on the slot type given in the frame structure. We divide each frame into $C + D$ slots, where C represents the number of control slots for transmitting network maintenance, resource request, and grant information, and D represents the number of data slots for data transfers. The duration of a slot is T_{slot}.

2.2 Process of election mechanism

As a typical multiple access mechanism in distributed networks, the election mechanism conducts periodic interaction between nodes to acquire service requirements of nodes, then determines the slot for nodes to send data messages based on the election algorithm. It is more appropriate than the competition and reservation method when all nodes have periodic services [21]. The process of the election mechanism is shown in Fig. 5.

The mechanism process is explained as follows:

(1) After a successful election and data message transfer, the backoff procedure begins, and the node receives network maintenance information from its neighbors.
(2) During the backoff, the node gets network maintenance information sent by its 1-hop neighbors. The election interval of neighbors is obtained by examining the election unit included inside the message. In addition, the node parses the election unit of the neighbors within the H_{sch}-hop forwarded by the 1-hop neighbors, where

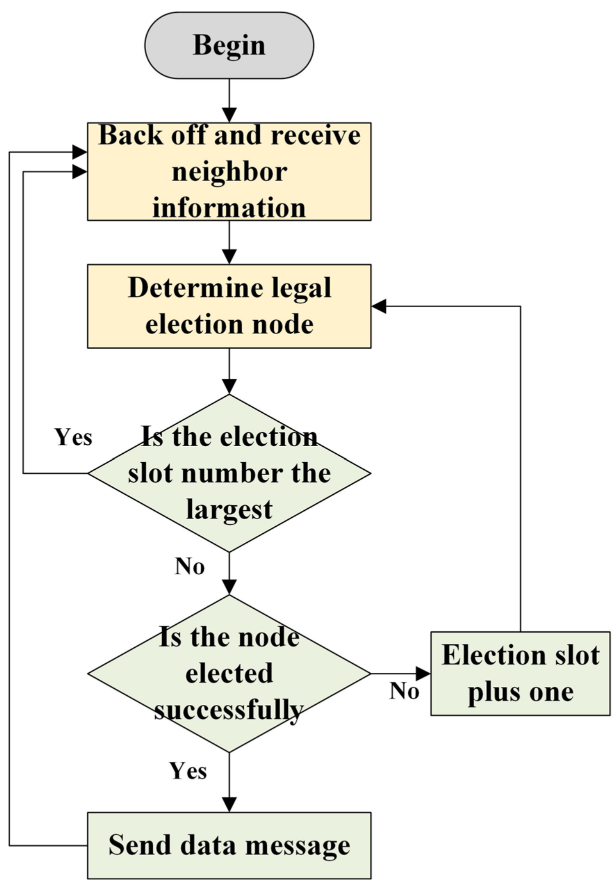

Fig. 5 The process of the election mechanism. The election mechanism conducts periodic interaction between nodes to acquire service requirements of nodes, then determines the slot for nodes to send data messages based on the election algorithm

H_{sch} is the network maintenance hop. According to the above information, the node determines the legal election node [22], which competes with this node.

(3) Then, the node starts the election process, determines the initial slot of this election interval, and starts the election. The node judges whether the current slot number reaches the maximum; if so, go to step (1). If not, the node inputs its ID, the ID of other legal election nodes, and the current slot number into the Hash Function [22] to calculate the election result. If the node is elected successfully, the slot number is recorded, and the resource scheduling is finished, the data message is sent when the slot arrives; then, go to step (1). Otherwise, the number of the election slot plus one and go to step (2).

The schematic diagram of the Hash Function is shown in Fig. 6, and its input parameters include the node ID, the ID of other legal election nodes in the election set, and the slot that can be used for the election. The Hash Function calculates the mixed value of the node ID and slot number, and the mixed value of other legal election node ID and slot numbers. If the mixed value of this node is the largest, this node is elected successfully.

It can be seen that the election mechanism includes an effective election interval and a backoff interval. The maximum number of slots in the effective election interval is 2^{exp} (i.e., the maximum number of election slots). The number of slots in the backoff interval is $h = 2^{\text{exp}+\text{basic}}$, where exp and basic is election index, and $\text{exp} = 1$, $\text{basic} = 4$ [22].

3 Network consensus model based on multi-agent consensus theory

In this section, we use the multi-agent consensus theory to establish a network consensus error model of distributed FANETs considering the node density, outage probability of links, and network maintenance times, which sets the basis for the performance analysis models. The parameters involved in models are shown in Table 2.

3.1 Overview of multi-agent consensus theory

The consensus control model of a multi-agent system includes a cooperative control model and a single control model. The neighboring states of a node and its current state are utilized as inputs for the cooperative control algorithm, which determines the predicted location and speed. Each node in the system continuously adjusts its own state according to the above process until it reaches the desired state. Generally, Eq. (1) is the state update equation to describe the state update process.

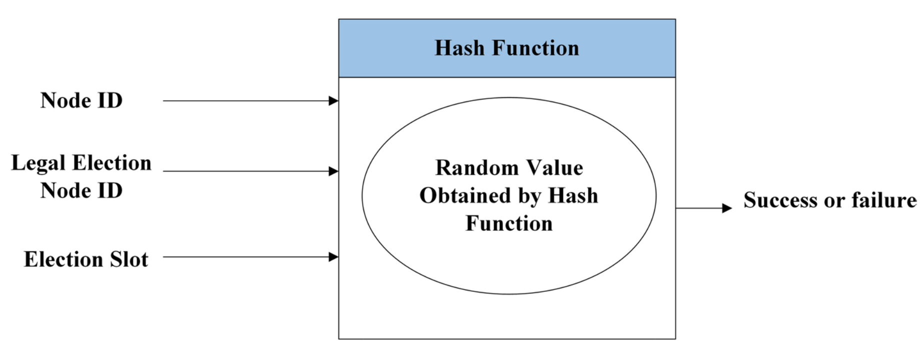

Fig. 6 The schematic diagram of the Hash Function, which is used to determine the election results

Table 2 The parameters involved in the models

Parameter	Definition
λ	Node density
r	The coverage radius of a node
p_{out}	The outage probability of links
p_{ofw}	Probability of delayed forwarding
p_{ele}	Success probability in election
H_{sch}	Network maintenance hops of distributed FANETs.
K_{sch}	Network maintenance times
K_{data}	Data transmission times
θ	Threshold of network consensus
N_{data}	Traffic of each node
T_{slot}	Duration of a slot
T_{sch}	Duration of a network maintenance process
T_{data}	Duration of one-time data transmission
$p_{\text{suc-data}}$	Constraints on data transmission success probability

$$\begin{aligned} p_i[k+1] &= p_i[k] + hv_i[k] + \frac{h^2}{2}u_i[k] \\ v_i[k+1] &= v_i[k] + hu_i[k] \end{aligned} \tag{1}$$

where h indicates the sampling interval, k indicates the sampling time, p_i is the position of node i, v_i is the speed of node i, and u_i represents the acceleration of the node. The value of u_i is determined by its own position and velocity, its neighbor's position and velocity, and the cooperative control algorithm.

Equation (1) can be further expressed as

$$\underbrace{\begin{bmatrix} p[k+1] - p_L[k+1] \\ v[k+1] - v_L[k+1] \end{bmatrix}}_{\delta[k+1]} = \underbrace{\begin{bmatrix} I_N - \frac{h^2}{2}\varphi_1\Gamma & hI_N - \frac{h^2}{2}\varphi_1\varphi_2\Gamma \\ -h\varphi_1\Gamma & -h\varphi_1\varphi_2\Gamma \end{bmatrix}}_{F} * \underbrace{\begin{bmatrix} p[k+1] - p_L[k+1] \\ v[k+1] - v_L[k+1] \end{bmatrix}}_{\delta[k]} \tag{2}$$

where $\Gamma = \Omega + \Xi$. Ξ is the Laplace matrix transformed from the node adjacency matrix. When pilot nodes exist, Ω describes the network topology between nodes and the pilot node. $p[k] = [p_1[k], p_2[k], \ldots, p_N[k]]^T$ and $p_L[k] = [p_L[k], p_L[k], \ldots, p_L[k]]^T$ represent the position column vector of the node and the pilot node. $v[k] = [v_1[k], v_2[k], \ldots, v_N[k]]^T$ and $v_L[k] = [v_L[k], v_L[k], \ldots, v_L[k]]^T$ represent the speed column vector of the node and the pilot node. I_N is N identity matrix. $\delta[k]$ represents the deviation column vector.

The condition for control system consensus is

$$\lim_{k\to\infty} E||\delta[k]||^2 = 0 \tag{3}$$

3.2 Network consensus model

When the network maintenance hops count is H_{sch}, the number of neighbors that a node needs to maintain is $N = \pi(H_{\text{sch}}r)^2\lambda$. According to Eq. (1), the network information of distributed FANETs held by the node i after the k-times maintenance is expressed as

$$\mathbf{x_i}[k+1]_{N\times N} = \mathbf{x_i}[k]_{N\times N} + \mathbf{A_{ij}}[k]_{N\times N} \quad (4)$$

where $\mathbf{A_{ij}}[k]_{N\times N}$ represents the messages reception of node i and node j during the kth maintenance, where 0 in the matrix indicates that the network maintenance message is lost. In contrast, 1 in the matrix indicates that the network maintenance message has been successfully received.

The values of $\mathbf{A_{ij}}[k]_{N\times N}$ are related to the outage probability of links and forwarding timeliness probability.

$$\mathbf{A_{ij}}[k]_{N\times N} = \{a_{ij}[k] | i,j = 1,2,\ldots,N\} \quad (5)$$

The probability of $\mathbf{A_{ij}}[k]_{N\times N}$' value taking 1 is $P(a_{ij}[k]=1) = (1-p_{out})^{H_{ij}}(1-p_{ofw})^{H_{ij}-1}$, where H_{ij} in the number of hops between node i and node j, the value range of H_{ij} is $[1, H_{sch}]$.

p_{ofw} is described in detail below. Take the distributed FANET with network maintenance hops $H_{sch}=2$ as an example to illustrate. The information of the node's 2-hop neighbors needs to be forwarded by the 1-hop neighbors before it can be obtained. During each election period, the node and its 2-hop neighbors all have an opportunity to transmit, but the sending order is determined randomly. Consequently, it is possible that once a 2-hop neighbor sends a maintenance message, no 1-hop neighbor can transfer the message, and the node cannot acquire the information of the 2-hop neighbor, that is, the forwarding is not timely. As shown in Fig. 7, node B and node C are 2-hop neighbors to each other. If Node B successfully elects to send messages after node A, node C cannot know the relevant information of Node B during this maintenance process, so $a_{i=B,j=C}[k]=0$.

The intersection area formed by 2-hop nodes is

$$A(x) = 2r^2 \text{arc}\cos\left(\frac{x}{2r}\right) - \frac{1}{2r}\sqrt{4r^2 - x^2} \quad (6)$$

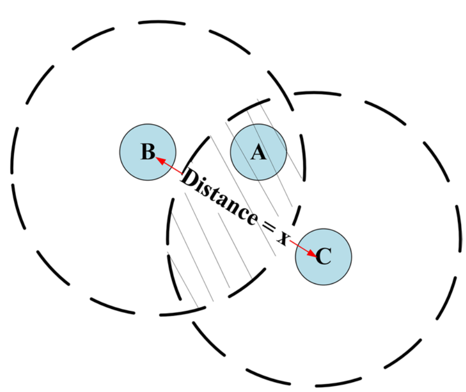

Fig. 7 Node maintenance diagram. If Node B successfully elects to send messages after Node A, Node C cannot know the information of Node B during this maintenance process

The number of common 1-hop neighbors of 2-hop nodes is $N_{\text{com}} = A(x)\lambda$. The 2-hop neighbor can't be maintained when there is no joint 1-hop neighbor election successfully after it sends the message. Therefore, the probability of delayed forwarding is

$$P_{ofw} = 1 - \int_r^{2r} \left[\sum_{s=1}^{N_{\text{com}}} \sum_{t_0=1}^{h} \sum_{q=\max(s+1-t_0,0)}^{\min(h-t_0,s)} C_s^q \left(\frac{h-t_0}{h-1} \right)^q \left(\frac{t_0-1}{h-1} \right)^{s-q} \right] dx \tag{7}$$

It can be seen that, for the 1-hop neighbor of node i, the mean value of $\mathbf{A_{ij}}[k]_{N\times N}$ is $\mu_1 = 1 - p_{\text{out}}$, the variance is $\sigma_1^2 = p_{\text{out}}(1-p_{\text{out}})$. For the 2-hop neighbor of node i, the mean value of $\mathbf{A_{ij}}[k]_{N\times N}$ is $\mu_2 = (1-p_{\text{out}})^2(1-p_{\text{ofw}})$, and the variance is $\sigma_2^2 = \mu_2(1-\mu_2)$.

Referring to Eq. (2), convert Eq. (4) into

$$\underbrace{[\mathbf{x}[k+1] - \mathbf{x_L}[k+1]]}_{\delta[k+1]} = \underbrace{[\mathbf{A}][\mathbf{x_j}[k]]}_{\mathbf{F}} + \underbrace{[\mathbf{x}[k] - \mathbf{x_L}[k]]}_{\delta[k]} \tag{8}$$

where $\mathbf{x_L}[k]$ is consensus threshold, $\mathbf{x_L}[k] = \{r_{1,n} | n = 1, \ldots, N\}, r_{1,n} = \theta$.

The condition for network consensus is the same as those stated in Eq. (3). When $[\mathbf{x}[k+1] - \mathbf{x_L}[k+1]] = \delta[k+1] = 0$, i.e., the sum of matrix values of $\mathbf{A}$ after $k+1$ -times maintenance is larger than or equal to θ, the network maintenance is consensus. That is, the number of the neighbor's information correctly received in the K maintenance process is larger than or equal to θ, and the network maintenance is consensus.

Then, after maintaining K_{sch} times, the network consensus error is

$$\varepsilon_{\text{sch}} = \frac{\sum_{i,j\in N} P(\theta - \sum_{k=1}^{K_{\text{sch}}} A_{ij} < 0)}{N} = \frac{\sum_{i,j\in N} P(\theta - \sum_{k=1}^{K_{\text{sch}}} A_{ij} < 0)}{\pi (H_{\text{sch}} r)^2 \lambda}, H_{ij} = [1, H_{sch}] \tag{9}$$

Furthermore, according to Lindbergh Levy central limit theorem [23], the value of $\mathbf{A_{ij}}[k]_{N\times N}$ follows normal distribution after K_{sch} times maintenance. So,

$$\varepsilon_{\text{sch}} = P\left(\frac{\sum X - K_{\text{sch}}\mu_i}{\sqrt{K_{\text{sch}}\sigma^2{}_i}} \le \frac{\theta - K_{\text{sch}}\mu_i}{\sqrt{K_{\text{sch}}\sigma^2{}_i}} \right) = \Phi\left(\frac{\theta - K_{\text{sch}}\mu_i}{\sqrt{K_{\text{sch}}\sigma^2{}_i}} \right), i = [1, H_{sch}] \tag{10}$$

We have completed establishing the network consensus error model based on the multi-agent consensus theory. It can be seen from Eq. (10) that the network consensus error is related to the node density, outage probability of links, and network maintenance times and will further impact the resource allocation performance.

4 Performance models of distributed FANETs with election mechanism

In this section, we consider the impact of network consensus error and establish the service delay, resource efficiency, and resource efficiency optimization models to analyze the impact of different network, channel, and mechanism parameters on FANET performance.

4.1 One hop service delay model

The one-hop service delay is the sum of neighbor maintenance delay and data transmission delay in distributed FANETs with the election mechanism, which can be expressed as

$$T = K_{\text{sch}} T_{\text{sch}} + K_{\text{data}} T_{\text{data}} \tag{11}$$

Specifically, the delay of one network maintenance is the time that a node and its H_{sch} -hop neighbors send control messages once.

$$T_{\text{sch}} = \left(2^{\exp+\text{basic}} + \frac{1}{p_{\text{ele}}}\right) T_{\text{slot}} \tag{12}$$

where $\frac{1}{p_{\text{ele}}} = (\pi {H_{sch}}^2 r^2 \lambda - 1)\frac{2^{\exp}+1/p_{ele}}{h+1/p_{ele}} + 1$ [6].

The one-time data transmission delay is

$$T_{\text{data}} = N_{\text{data}} \left(2^{\exp+\text{basic}} + \frac{1}{p_{\text{ele2}}}\right) T_{\text{slot}} \tag{13}$$

where p_{ele2} indicates the successful probability of node maintained in the election process, $\frac{1}{p_{\text{ele2}}} = [\pi {H_{\text{sch}}}^2 r^2 \lambda(1-\varepsilon_{\text{sch}}) - 1]\frac{2^{\exp}+1/p_{\text{ele2}}}{h+1/p_{\text{ele2}}} + 1$.

Then, we analyze the success probability of data transmission. After K_{data}-times of network maintenance, the node that has not been maintained will collide with the node that maintains consensus during the data transmission process. Therefore, the collision-free probability of a node is

$$p_{\text{suc}-\text{ele}} = (1 - p_{\text{ele1}})^{\pi (H_{\text{sch}} l)^2 \lambda \varepsilon_{\text{sch}}} \tag{14}$$

where p_{ele1} indicates the successful probability of node didn't be maintained in the election process, $\frac{1}{p_{\text{ele1}}} = [\pi {H_{\text{sch}}}^2 r^2 \lambda(1-\varepsilon_{\text{sch}})]\frac{2^{\exp}+1/p_{\text{ele1}}}{h+1/p_{\text{ele1}}} + 1$.

After K_{data} transmissions, the total success probability of data transmission p_{suc} is

$$p_{\text{suc}} = 1 - [1 - p_{\text{suc}-\text{ele}}(1 - p_{\text{out}})]^{K_{\text{data}}} \tag{15}$$

4.2 Resource efficiency model

We express the resource efficiency η as the ratio of the effective duration of data transmission to the total delay:

$$\eta = \frac{p_{\text{suc}} N_{\text{data}} (2^{\exp+\text{basic}} + 1) T_{\text{slot}}}{T} \tag{16}$$

4.3 Resource efficiency optimization model

It can be seen that not only network characteristics such as node density and coverage radius of a node, channel parameters such as the outage probability of links, but also mechanism parameters impact the performance of distributed FANETs. Considering the quality of service (QoS) constraints, we establish the resource efficiency optimization model and define the optimal values of network maintenance times and data retransmission times to improve the mechanism's performance.

The resource efficiency optimization model is

$$\begin{aligned} &\max : \eta = f(\lambda, p_{\text{out}}, K_{\text{sch}}, K_{\text{data}}) \\ &s.t: \quad p_{\text{suc}} \geq p_{\text{suc-data}} \end{aligned} \tag{17}$$

An artificial intelligence method and successive convex approximation SCA method are used in [10, 24, 25] to solve optimization problems, and provide us with a good reference for solving our resource efficiency optimization problem.

Through the above research, we have completed the performance model establishment considering network consensus error, which is related to the node density, the outage probability of links, and network maintenance times.

5 The experiment

In this section, we perform simulation experiments to simulate the consensus of distributed FANETs and compare the simulation with the theoretical model calculation results.

5.1 Simulation experiments setup

To validate the correctness of models, we develop a protocol-level simulation platform based on VS. As seen in Fig. 8, the architecture of the platform consists of a network layer transceiver module, a MAC layer transceiver module, a physical transceiver module, a simulation operation module, and a time-controlling module, where the MAC layer transceiver module includes a network maintenance module and an election algorithm module. The network maintenance module performs network maintenance and submits the network maintenance results to the election algorithm module. The election algorithm module executes the election algorithm according to the network maintenance results and outputs the election results.

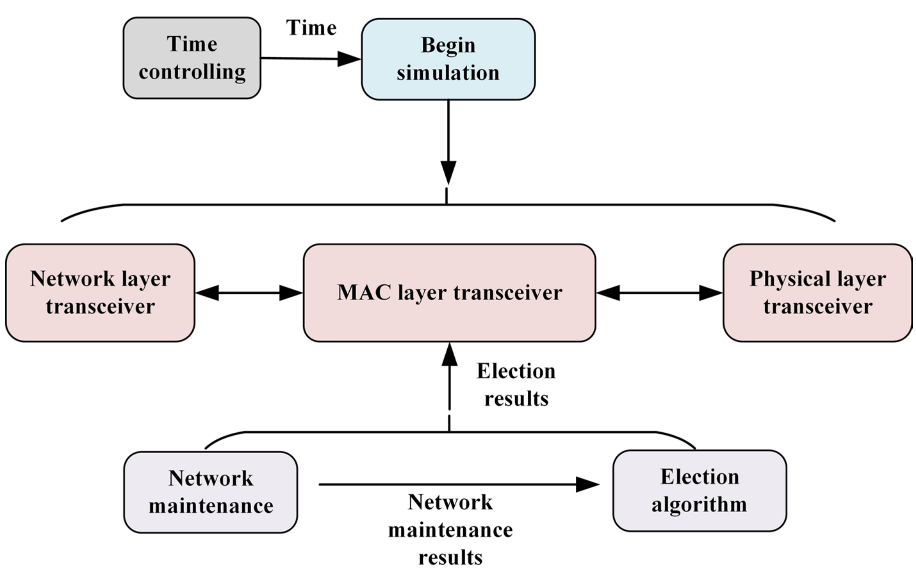

Fig. 8 System architecture of simulation verification platform based on VS

Table 3 Distributed network consensus performance simulation method

Method	Specific description
Theoretical model calculation	Calculate the network consensus error according to Eq. (10)
Construction matrix and iteration (CMIT)	The single topology maintenance matrix is constructed according to the value-taking probability of the matrix $\mathbf{A_{ij}}[k]_{N\times N}$, and K_{sch} iterations are conducted to determine the final maintenance information matrix to obtain the consensus error further
Construction matrix and intercept (CMIN)	The K-dimensional topology maintenance matrix ($K \geq K_{sch}$) is constructed according to the value-taking probability of the matrix $\mathbf{A_{ij}}[k]_{N\times N}$, and the sum of the K_{sch}-dimensional matrix information is intercepted from it as the maintenance result to obtain the consistency error further

Table 4 The parameter value of VS-based simulation verification platform

Parameter	Value
λ	$0.25 \leq \lambda \leq 0.55$nodes/km^2
r	$r = 4$ km
p_{out}	$0 \leq p_{out} \leq 0.3$
H_{sch}	$H_{sch} = 2$
θ	$\theta = 2$
N_{data}	$N_{data} = 20$
T_{slot}	$T_{slot} = 300$ us
$p_{suc-data}$	$p_{suc-data} = 0.9$

We set different node densities, link outage probabilities, and network maintenance times, and use CMIT and CMIN methods to simulate the consensus of distributed FANETs. The simulation method is described in Table 3. We analyze the impact of service delay and resource efficiency performance with the election mechanism. The optimal maintenance times under different network and channel parameters are given in this section.

The simulation parameters are shown in Table 4.

5.2 Simulation results and discussion

5.2.1 Network consensus error under different simulation methods

Taking 20 nodes organized in a network with a length of 5 km and a width of 8 km as an example, Fig. 9 depicts the distributed network consensus error under different simulation methods.

The network consensus error ε_{sch} of distributed FANETs under different link outage probabilities p_{out} and network maintenance times K_{sch} is shown in Fig. 10.

Under the same p_{out}, it can be seen that the ε_{sch} reduces as K_{sch} grows. This is because the distributed FANET has a greater chance of achieving the consensus threshold as K_{sch} increases. With the increased p_{out}, the network consensus probability decreases under the same K_{sch}. This is because when p_{out} increases, the probability of the network maintenance matrix value being one drops, as does the consensus probability. That is,

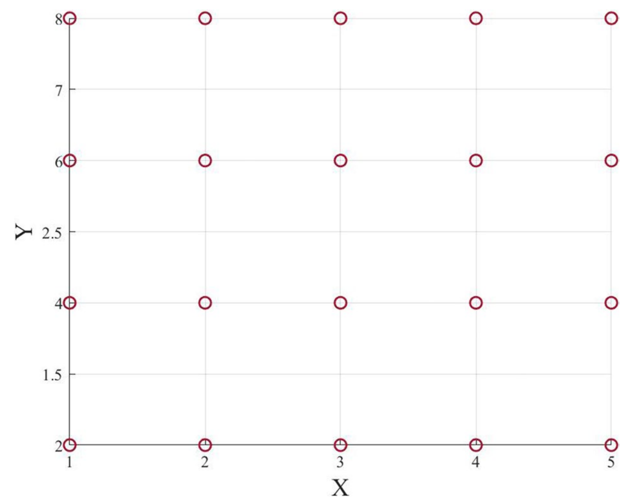

Fig. 9 Distributed network consensus error simulation scenario with 20 nodes

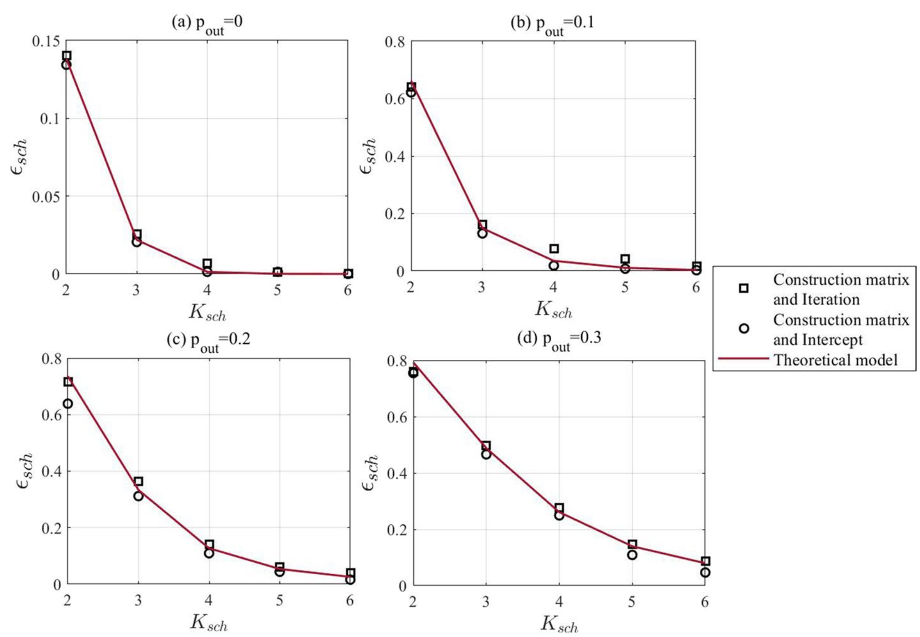

Fig. 10 Network consensus error with varying simulation methods. Lines represent the calculation results by theoretical models, while points represent CMIT and CMIN simulation results. Through the simulation, the accuracy of the network consensus model can be proved

increasing network maintenance times can improve the consensus performance of distributed FANETs.

The ε_{sch} calculated based on models is between the CMIT method and the CMIN method. When $K_{\text{sch}} = \theta$, ε_{sch} calculated based on models is the largest. This is because, in CMIT and CMIN methods, the value of the network maintenance matrix is determined based on probability; however, when K_{sch} is small, the actual value may not be entirely consistent with the probability distribution, and the probability of the matrix value is one may be more significant, so ε_{sch} is more diminutive.

Besides, since the CMIN method generates K-dimension matrix randomly according to probability, and then extracted. The extracted possibility of the matrix value is one is greater than the actual, so $\varepsilon_{\mathrm{sch}}$ obtained by CMIN is the minimum. While in the CMIT method, to ensure the symmetry of the network topology matrix, the condition that the network maintenance matrix value is one is when the matrix value between two nodes is one simultaneously. This artificially reduces the probability that the network maintenance matrix is 1, which leads to a larger $\varepsilon_{\mathrm{sch}}$. The theoretical models can avoid deviation between the random simulation and the actual. Through the above simulation, the accuracy of the network consensus model can be proved.

5.2.2 Network consensus error under different parameters

The network consensus error of distributed FANETs under different node densities, outage rates of links, and network maintenance times is shown in Fig. 11.

Similar to the conclusion in Fig. 10, as shown in Fig. 11, under the same node density λ and outage probability of links p_{out}, the network consensus errors $\varepsilon_{\mathrm{sch}}$ decrease with the increased network maintenance times K_{sch}. Under the same K_{sch}, $\varepsilon_{\mathrm{sch}}$ increases with the increasing p_{out}. Besides, with the increase in λ, $\varepsilon_{\mathrm{sch}}$ drops modestly over the same K_{sch}. This is because as λ grows, the number of common neighbors between 2-hop nodes increases, which raises the probability of timely forwarding and the probability that the network maintenance matrix value is 1, decreasing $\varepsilon_{\mathrm{sch}}$. It can be seen that given the node density, the outage probability of links, network maintenance times, and other parameters, the minimum network maintenance times that satisfy the network consensus error restrictions can be found.

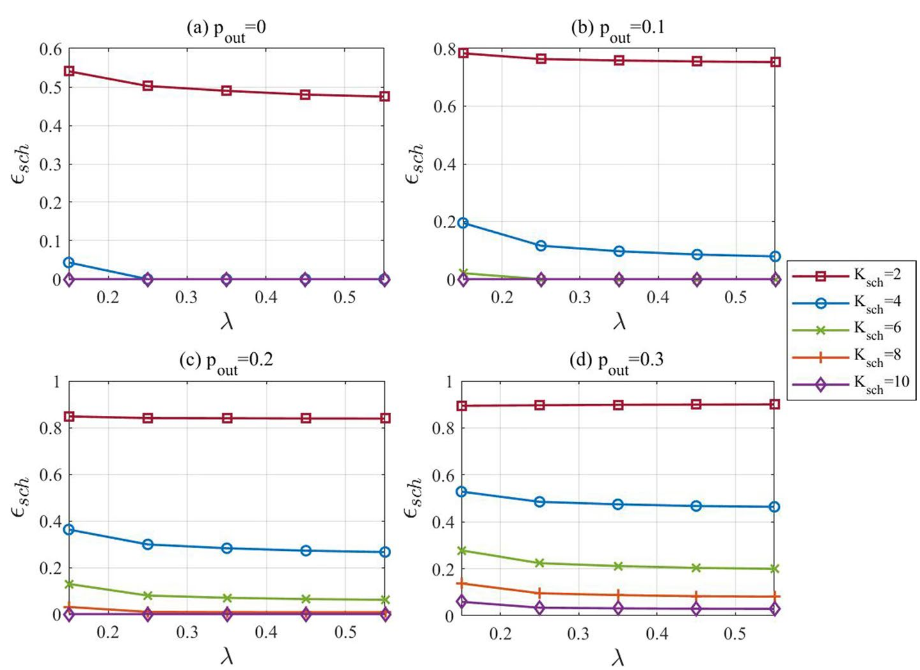

Fig. 11 Network consensus error under different node densities, outage rates of links, and network maintenance times. Under the same node density and outage probability of links, the network consensus error decreases with the increased network maintenance times

5.2.3 Service delay and resource efficiency of distributed FANETs with election mechanism

The service delay and resource efficiency of distributed FANETs under different node densities, outage probabilities of links, and network maintenance times are shown in Figs. 12 and 13. Using $\lambda = 0.35\text{nodes/km}^2$ as an example, the optimal network maintenance times are shown by the arrows in the figure. The dotted red line indicates the service delay and resource efficiency performance when the Qos is guaranteed entirely by data retransmission, ignoring the impact of consensus when $\lambda = 0.35\text{nodes/km}^2$. When $p_{\text{out}} > 0.1$, the service delay is omitted in the figure for the extra large value.

It can be seen that when the outage probability of links $p_{\text{out}} = 0$, the one-hop service delay T and resource efficiency η performance decrease as the number of network maintenance times K_{sch} increases, and the optimal K_{sch} is 4. When $p_{\text{out}} > 0$, as K_{sch} increases, the service delay of distributed FANETs with election mechanism decreases first and then increases, and the resource efficiency rises first and then decreases. There is a trade-off between network maintenance cost and performance. This is because, with the increase in K_{sch}, the network maintenance consensus probability improves, and the number of data retransmissions decreases, resulting in enhanced service delay and resource efficiency performance. However, with further increase of K_{sch}, the network maintenance overhead increases, but the network consensus probability no longer increases, resulting in decreased service delay and resource efficiency performance.

Moreover, with the increase of p_{out}, ε_{sch} increases under the same K_{sch}, which requires larger K_{sch} to improve the network maintenance consensus performance. Therefore, the optimal K_{sch} increase, and the optimal service delay and resource efficiency decline. That's why the simulation data in Fig. 12d has obvious multi-stage changes compared

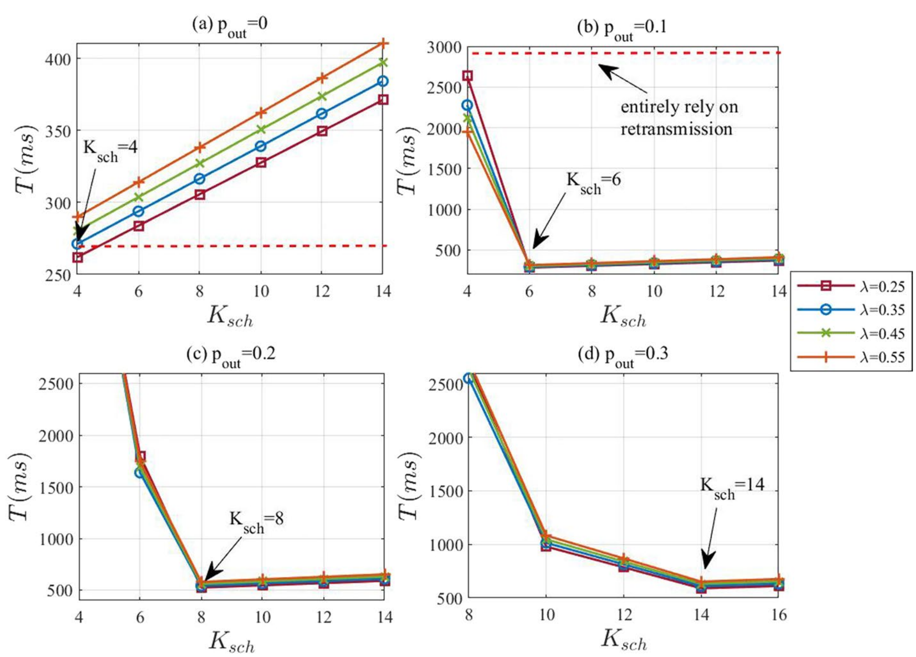

Fig. 12 1-hop service delay of distributed FANETs with election mechanism. The point in the picture indicates the average value after ten simulations based on the simulation platform, while the line in the figure reflects the average value based on theoretical models. It can be observed that the mathematical results and simulation results are congruent

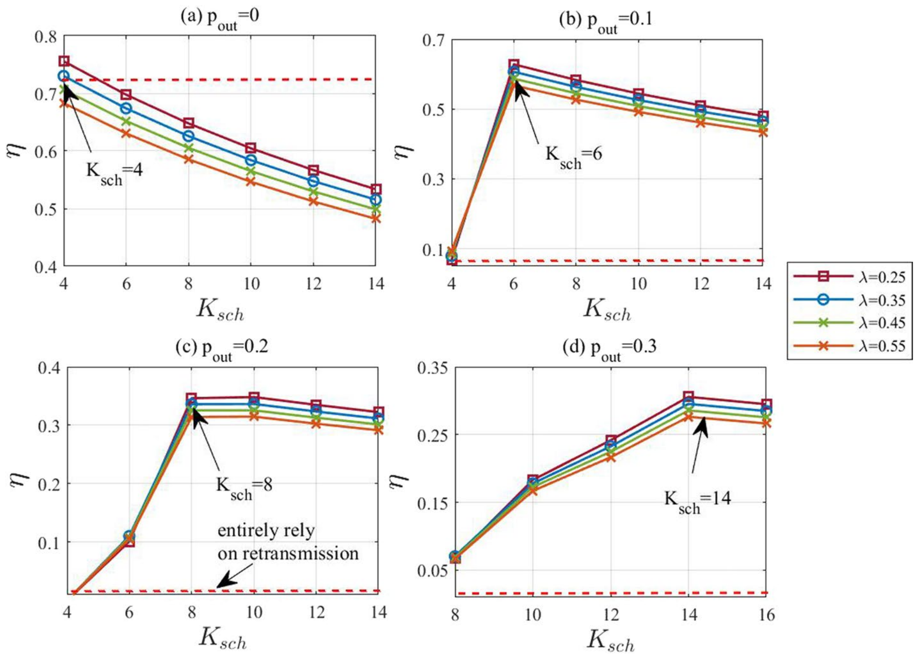

Fig. 13 Resource efficiency of distributed FANETs with election mechanism. The point in the picture indicates the average value after ten simulations based on the simulation platform, while the line in the figure reflects the average value based on theoretical models. It can be observed that the mathematical results and simulation results are congruent

with it in Fig. 12a–c when K_{sch} is small. When $p_{\mathrm{out}} = 0.2$, the optimal $K_{\mathrm{sch}} = 8$, while when $p_{\mathrm{out}} = 0.3$, the optimal $K_{\mathrm{sch}} = 14$. When ignoring the impact of network maintenance consensus and relying entirely on data retransmission to meet the QoS constraints, the performance drops sharply when the p_{out} is high.

Comparing with Fig. 11, it can be seen that the optimal K_{sch} is different from the K_{sch} when $\varepsilon_{\mathrm{sch}} = 0$. For example, when $p_{\mathrm{out}} = 0.1$, the optimal $K_{\mathrm{sch}} = 6$ and $\varepsilon_{\mathrm{sch}} = 0$. However, when $p_{\mathrm{out}} = 0.2$, the optimal $K_{\mathrm{sch}} = 8$, while, $K_{\mathrm{sch}} = 10$ when $\varepsilon_{\mathrm{sch}}$ reaches 0 at this time. In other words, the network may have yet to have complete consensus under the optimal network maintenance times.

It can be seen that network maintenance is essential in distributed FANETs using the election mechanism. We can reduce the number of data retransmissions by increasing the network maintenance times. Especially when the control messages are small and data messages are large, the cost of increasing the number of network maintenance times is less than the cost of data retransmission. Currently, network maintenance dramatically increases network performance. In addition, vis a compromise between network maintenance, network consensus, and data retransmission, distributed FANETs can achieve better performance without complete consensus.

6 Conclusion

Facing the need to improve the performance of distributed FANETs with multi-hop and intermittent links, in this paper, we investigate the network consensus and optimization of distributed FANETs, addressing the issue that previous research did not consider the influence of the multi-hop forwarding order. We establish network consensus and performance analysis models based on multi-agent consensus theory considering network, channel, and mechanism factors. Finally, the VS-based protocol-level simulation platform is constructed, and the optimal mechanism parameters are given under different network and channel parameters. The simulation results indicate that the optimal network maintenance times grow as the link outage probability increases. If we disregard the influence of consensus and rely simply on retransmission to maintain service quality, the resource efficiency would fall significantly with intermittent links. Moreover, distributed FANETs can achieve optimal resource efficiency without achieving complete consensus, that is, there is a trade-off between network maintenance cost and network performance.

Abbreviations

FANET	Distributed flying ad hoc network
CMIT	Construction matrix and iteration
CMIN	Construction matrix and intercept
VS	Visual studio
MAC	Medium access control

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Availability of data and materials
The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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