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Research Article

Delay-Constrained Routing Based on Stochastic Model for Flying Ad Hoc Networks

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This paper aims at solving the end-to-end delay-constrained routing problem in a local way for flying ad hoc networks (FANETs). Due to the high mobility, it is difficult for each node in FANETs to obtain the global information. To solve this issue, we propose an adaptive delay-constrained routing with the aid of a stochastic model, which allows the senders to deliver the packets with only local information. We represent the problem in a mathematical form, where the effective transmission rate is viewed as the optimization objective and the link quality and end-to-end delay as the constraints. And, some mathematical tools are used to obtain the approximate solutions for the optimization problem. Before designing the routing scheme, the senders calculate the transition probability for its relay node by jointly considering local delay estimation and expected one-hop delay. Then, the sender transmits the packets to their relay node with transition probability. Finally, we prove the convergence of the proposed routing algorithm and analyse its performances. The simulation results show that the proposed routing policy can improve the network performance effectively in terms of throughput, loss rate, and end-to-end delay.

1. Introduction

Unmanned aerial vehicles (UAVs) can serve as the role of sensors to collect environmental data (such as temperature, humidity, and wind speed) [1] and transmit these collected data to a ground base (GB). Because of the versatility, flexibility, and easy installation of UAVs, single-UAV systems have been in use for decades, but the simple function and limited coverage of these systems restrict their further applications. Hence, the multi-UAV system is built to improve the operational performance through cooperation. In the case of multi-UAV system [2], to solve the problem that the links between UAVs and GB become disconnected caused by the limited communication radius, an alternative solution is to establish ad hoc networks among UAVs, which are called flying ad hoc networks (FANETs). It does not demand a link between each UAV and GB in FANETs; only a subset of UAVs which have direct links with GB is required to help other UAVs transmitting the packets. FANETs can be used in many potential application domains including emergency and rescue operations, disaster relief, and military applications. In these environments, FANETs are particularly vulnerable to the motion of nodes and link failures, which can dramatically impact on the network performance.

As pointed out in [2], FANETs can be viewed as a special case of mobile ad hoc networks (MANETs) characterized by a higher mobility. Therefore, routing is one of the most challenging and crucial issues for FANETs, where real-time and reliable transmissions of critical information are vital for mission completion. The routing algorithms designed for existing MANETs [3] adapt not well to environment variations, because the topologies of FANETs change more frequently than that of typical MANETs. The routing methods proposed for delay tolerant network (DTN), such as EPIDEMIC [4], BUBBLE [5], GDTN [6], and PROPHET [7], are destined to handle the recurrent disconnections of the links due to the high degree of nodes' mobility. In most cases, this category of routing methods uses the technique of store-carry-and-forward when the senders lose connectivity with their neighbors to deliver the packets to destination. This well-known technique allows the nodes to store data packets for a certain distance until they meet the suitable nodes moving toward the destination. Although these routing methods can be well adapted to the dynamic network topology of FANETs, they create more delays in completing the transmission for each session due to the lack of delay control mechanism. In addition, the routing methods for DTN mainly focus on the best-effort delivery with less consideration of the various channel statuses, which are not well adapted to real-time applications because of increasing delay consumption for single-hop transmission. Most of routing algorithms designed for FANETs fail to follow the fast evolution of channel states, which may cause the path established by the source out of service soon. These algorithms will take up lots of time to maintain the end-to-end path between the source and GB, which is unacceptable to FANETs where the channel states between any pair of UAVs change more dramatically than traditional MANETs. A new routing method called stochastic routing [8] has been proposed to solve the insufficiency presented above. Stochastic routing initiates a session without preselected path and allows the relay nodes to decide the optimal route in a local way.

In this paper, each packet attaches to a time stamp; a successful mission completion means that the end-to-end delay is less than the given threshold; otherwise, the transmission would be deemed invalid. To meet the requirement of the end-to-end delay constraint, we consider the link quality as an optimization objective, which can reduce delays consumed by each transmission due to the less retransmission. In addition, each sender uses remaining delays as a parameter to obtain transition probability, which ensures that the end-to-end transmission meets the delay requirement with certain probability rather than mandatory. As we know, there are few works to study the routing problem with a delay constraint for FANETs. The main goal of this paper is to maximize the effective transmission rate and ensure the total delay within the threshold while there is no global information available for each intermediate node.

Our contributions in this paper are listed as below:

(i) We design an optimization framework to maximize the minimum effective transmission rate with end-to-end delay constraint in FANETs. Considering the relationship between the transmission rate and queuing delay, the original optimization problem is transformed into the distributed problem. Then, we jointly use one-order derivative and projection method to get the local optimal solution which shows that the balance between the transmission rate and delay is obtained at relay nodes.

(ii) We propose a delay-constrained stochastic routing algorithm which only requires relay nodes to collect their local channel information. And, the approximate local solution is used as the routing index to select the relay node. To satisfy the requirement of the end-to-end delay constraint, we combine the remaining delays and the distance from the relay node to GB to obtain transition probability which is used as a guide for transmissions. Finally, we prove the convergence of the algorithm.

The remainder of this paper is organized as follows: In Section 2, we introduce some previous work researched by others. In Section 3, we present some preparatory work and parameter estimation. In Section 4, we provide the detailed implement process of the stochastic routing algorithm and analyse the convergence of algorithm. In Section 5, we show the experiment results for the proposed routing algorithm. Finally, we conclude the paper and discuss the future work in Section 6.

2. Related Work

There are many researches proposed for the routing problem in FANETs to consider the different network performances [9, 10], but only few of them consider the end-to-end delay constraint problem. Vasiliev et al. [11] analysed Quality of Service (QoS) metrics for AODV, OLSR, and HWMP routing protocols in FANETs and compared these three routing protocols to search and maintain paths in FANETs based on the hop count, packet delivery ratio, and overheads metrics. In recent years, some methods are proposed to design the routing algorithms considering the high mobility of FANETs. In order to adapt the routing algorithms to dynamic topologies in FANETs, some researches focus on the prediction technique [12] and the idea of distance vector routing protocols [13] to design the routing algorithms for FANETs. Sugranes and Razi [14] proposed an optimal routing method based on Dijkstra's shortest path algorithm (OR-DSP) and prediction technique for UAV networks with queued communication systems by incorporating predicted network topology. Rosati et al. [15] proposed predictive OLSR (P-OLSR) which is an OLSR extension designed for FANETs, to solve the challenging issues that the existing routing protocols designed for MANETs partly fail in tracking network topology changes. P-OLSR computes the relative speed between two nodes and takes the relative speed as a parameter of path metric to help each node making a wise routing decision. In order to adapt the routing strategy to high-speed mobility and frequent topology changes of FANETs, Gankhuyag et al. [16] proposed adaptive hybrid communication protocols including a novel position-prediction-based directional MAC protocol (PPMAC) and a self-learning routing protocol based on reinforcement learning (RLSRP), which can meet the demands of autonomy in FANETs.

Due to the high degree of nodes' mobility, the network would suffer from recurrent disconnections which result in distorting the end-to-end paths built gradually to the target destination. Therefore, the researches take more attention to the routing methods designed for DTN and attempt to apply them to FANETs. Peters et al. [17] and Jabbars and Sterbenz [18] proposed Aeronautical Routing Protocol (AeroRP), which is a geographical delay tolerant routing protocol designed for aeronautical networks. AeroRP requires each node to calculate a metric called Time to Intercept (TTI) based on positions and velocities of its neighboring nodes and selects the fastest relay node among its neighboring nodes moving toward destination. Hyeon et al. [19] proposed the Geographic Routing protocol for Aircraft Ad hoc Network (GRAA) based on Greedy Perimeter Stateless Routing (GPSR). The core idea of GRAA is that each node takes into account the position and the velocity of its neighbors and the destination to make a routing decision locally at each intermediate node. Next, we introduce some other types of routing algorithms designed for FANETs; Vasiliev and Abilov [20] investigated throughput efficiencies of relaying algorithms with the ideal selective-repeat ARQ in FANETs. Multiple token structure has been implemented for UAVs in [21] acting with a dynamic topology, and the results show that it enables each node to obtain more accurate position information of other nodes. Gankhuyag et al. [22] proposed a combined omnidirectional and directional transmission scheme with dynamic angle adjustment to overcome the obstacles that the routing protocols in MANETs are not suitable for FANETs due to high-speed mobility. The routing algorithms presented above only consider the reachability of transmission and ignore the delay constraint attached to the packets. Li et al. [23] conducted a statistical analysis for the packet delay in a wireless network of UAVs under nonsaturated traffic and channel fading conditions. The one-hop packet delay computed in [23] cannot be applied in FANETs which implements the routing in multihop manner rather than one-hop manner. Therefore, we propose a delay-constrained routing algorithm for FANETs to overcome the weaknesses in transmission quality and real time. In Table 1, we list the comparison results between the proposed algorithm and existing routing algorithms in terms of several important performance metrics.

3. System Model

3.1. Network Model. In this paper, we focus on the FANETs composed of multiple UAVs and one GB, where the location of GB is unchangeable. There are some UAVs that are located in the communication range of GB all the time, and all UAVs communicate with GB in single-hop or multihop mode, as shown in Figure 1. A standard undirected graph $G = (V, L)$ is used to represent the network topology, where V is a node set containing all UAVs, and L is an edge set consisting of all links (the dotted lines in Figure 1) between any pair of UAVs. The tuple (i, j) denotes a link with two endpoints i and j in subsequent sections, and the transmission rate r_{ij} over link (i, j) at time t is decided by current channel state information (CSI). When node i broadcasts a radio signal, and if node j decodes it correctly and returns acknowledgement information to i, node j is regarded as a neighbor of node i, namely, $j \in N_i^t$, where N_i^t is a neighbor set of node i at time t. Let $L(N_i^t)$ denote the set of all links between node i and its neighbors at time t. There is a pair of source s and GB; let p_s be an end-to-end path selected by s to transmit the packets to GB. Let $L(p_s)$ be a set containing all links on path p_s. For each link on the path p_s, the delay for one-hop transmission on the link $(i, j) \in L(p_s)$ is $\overline{D}_{ij}$, and the total delay $T(p_s)$ for all links on the path p_s should be within the delay threshold $\mathfrak{T}_s$, where $T(p_s) = \sum_{(i,j)\in L(p_s)} \overline{D}_{ij}$. In this paper, we assume that all packets have the same delay threshold. The definitions of all parameters used in this paper are shown in Notations.

3.2. SINR Prediction and Outage Probability Model. In our scenario, all nodes in the network are not stationary, and the distance between any pair of nodes changes with time elapse. The interference prediction method proposed in [24] can capture this dynamic nature and be used to estimate the interference value at node i after Δt time. Assume that the current time is t_0 and the future time is t after elapsing Δt time. The quantity $I(t \mid t_0)$ represents the interference prediction at time t based on the information available at time t_0; hence, it is a random variable due to the uncertainty in mobility over the time duration from t_0 to t. If $t_0 = t$, the quantity $I(t \mid t)$ is equal to the instantaneous interference value [25] at time t.

Assume that the mobility of nodes follows the same distribution model; let $f_y(y)$ represent the probability density function of distance y at current time between any pair of UAVs, and $g_{ij}(y)$ denote path fading gain of link (i, j). Let $y(t_0)$ denote a function of distance between two UAVs at time t_0; the detailed form can refer to the Rayleigh model. So the mean interference prediction at node j can be expressed as an integral form:

$$\mathbb{E}\left[I_j(t \mid t_0)\right] = \sum_{(i,k)\in L, k\neq j} \frac{1}{\Delta t}\int_{t_0}^{t} g_{ik}(y(t)) \cdot f_y(y(t))\, dt. \tag{1}$$

Using (1), we calculate the signal-interference-noise ratio (SINR) at node j:

$$\begin{aligned}\overline{\gamma}_j^i(t \mid t_0) &= \frac{\mathbb{E}\left[(1/\Delta t)\int_{t_0}^{t} g_{ij}(y(t)) \cdot f_y(y(t))\, dt\right]}{N_0 + \mathbb{E}\left[I_j(t \mid t_0)\right]}, \\ &= \frac{\chi_j^i(t \mid t_0)}{N_0 + \mathbb{E}\left[I_j(t \mid t_0)\right]},\end{aligned} \tag{2}$$

where $\chi_j^i(t \mid t_0) = \mathbb{E}[(1/\Delta t)\int_{t_0}^{t} g_{ij}(y(t)) \cdot f_y(y(t))\, dt]$. The variable $\overline{\gamma}_j^i(t \mid t_0)$ is abbreviated as $\overline{\gamma}_j^i$ in following sections.

To obtain the accurate value of link quality, we define the rate-outage probability as the probability that the transmission rate r_{ij} on the link exceeds the instantaneous Shannon capacity c_{ij} similar to [26, 27]. The rate-outage constraint can be expressed as follows:

$$\Pr\left(r_{ij} > c_{ij}\right) \leq \delta_{ij}^{\max}, \quad \forall (i, j) \in L, \tag{3}$$

where $\delta_{ij}^{\max} \in (0, 1)$ is a constant and denotes the maximum probability value with outage on each link. For the Rayleigh fading model, the δ-outage capacity can be obtained according to the result presented in [28]:

$$\widetilde{c}_{ij} = W \log\left[1 + \Phi \cdot \overline{\gamma}_j^i\right], \tag{4}$$

Table 1: Comparison of existing routing algorithms.

Routing algorithm	Type	Dynamic adaptive	Link quality	Real time	Routing metric
OR-DSP [14]	Reactive	Yes	No	No	Shortest path and waiting time
P-OLSR [15]	Proactive	No	Yes	No	Optimized link
PPMAC [16]	Reactive	Yes	No	No	Shortest path
AeroRP [17, 18]	Position-based	Yes	No	No	Shortest path
GRAA [19]	Position-based	Yes	No	No	Shortest path
RARP [22]	Reactive	Yes	No	No	Connection time, hops, and maximum risk
Proposed method	Reactive	Yes	Yes	Yes	Effective transmission rate and delay

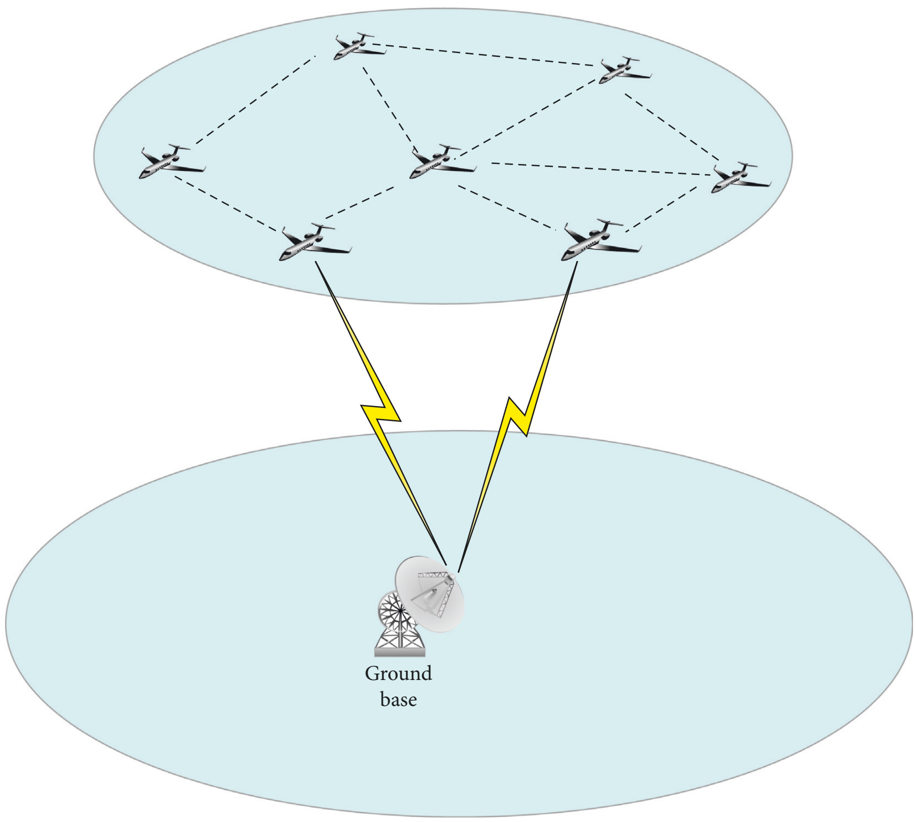

Figure 1: The FANETs model.

where Φ is SINR gap which reflects a particular modulation and coding scheme and $\Phi = -\log(1-\delta_{ij}^{\max})$. The rate-outage probability in the closed form for the Rayleigh fading model by considering both (3) and (4) can be expressed as follows [28]:

$$\Pr\left(r_{ij} > \tilde{c}_{ij}\right) = 1 - q_{ij}, \tag{5}$$

where q_{ij} is the quality of link (i, j), and the detailed definition can be found in [28].

3.3. Expected Queuing Delay. We assume that all packets have an exponentially distributed length with a mean K bits and each node maintains a unique queue [29]. According to [30], we can get an approximate value of expected queuing delay for link (i, j):

$$\overline{D}_{ij} = \frac{K}{\tilde{c}_{ij} - r_{ij}}, \tag{6}$$

where r_{ij} and $\tilde{c}_{ij}$ are the transmission rate and outage rate, respectively.

4. Problem Formulation and Distributed Solution

4.1. Problem Formulation. The transmission rate on each link only reflects the current CSI, but does not represent the link quality in the time interval Δt. To let each sender to know CSI more accurately and reliably from its receivers, the effective transmission rate [31] is defined as the total probability multiplied by the transmission rate on link (i, j):

$$\mathbb{R}_{ij} = r_{ij} \cdot q_{ij}. \tag{7}$$

Based on the rate-outage probability and delay constraint, we define the problem in a mathematical form with effective transmission rate as the objective function and the rate-outage probability and total delay on the selected path as the constraints. The detailed form is expressed as follows:

$$\begin{aligned} &\max \quad \min_{(i,j)\in L(p_s)} \mathbb{R}_{ij}, \\ &\text{s.t.} \begin{cases} \Pr\left(r_{ij} > c_{ij}\right) \le \delta_{ij}^{\max} & \forall (i,j) \in L(p_s), \\ T(p_s) \le \mathfrak{T}_s & \forall s \in S, \\ m_s \le r_{ij} \le M_s & \forall (i,j) \in L(p_s). \end{cases} \end{aligned} \tag{8}$$

4.2. Distributed Solution. To make the routing algorithm adapt to the changes of the link states, it is necessary to convert problem (8) into the problem that can be solved in a distributed mode. To solve this problem, we assume that there always exists at least one end-to-end path that meets the delay constraint. Because of the existence of the delay constraint, if no one path satisfies the constraint, all packets will be discarded at intermediate nodes. In this case, no packets arrive at GB within the delay threshold, which results in failures to provide services for any sources. Due to the absence of end-to-end link state information, each sender uses the current remaining delays to distinguish the available node set. To ensure that the distributed solution meets the requirement of the delay constraint, an alternative method is to optimize two objective functions including the effective transmission rate and one-hop delay at relay nodes, that is, to maximize the one-hop effective transmission rate and minimize the one-hop delay of all links. The first objective can be expressed mathematically by $\max_{(i,j)\in L(S_i^t)} \mathbb{R}_{ij}$, and the second one can be characterized by $\min_{(i,j)\in L(S_i^t)} \overline{D}_{ij}$.

Based on the fact that the function $\min f(\cdot)$ is equivalent to $\max -f(\cdot)$, the two objectives defined above can be combined into one function. Considering the rate-outage constraint and the one-hop delay constraint, the problem can be completely expressed as follows:

$$\begin{aligned} &\max_{(i,j)\in L(N_i^t)} \quad \mathbb{R}_{ij} - \overline{D}_{ij}, \\ &\text{s.t.} \begin{cases} \Pr\left(r_{ij} > c_{ij}\right) \le \delta_{ij}^{\max}, \\ m_s \le r_{ij} \le M_s. \end{cases} \end{aligned} \tag{9}$$

It is noted that the outage probability $\delta_{ij}^{\max}$ is intimately related to the tradeoff between the transmission rate r_{ij} and maximum transmission rate M_s.

The higher transmission rate indicates that more packets loss may occur, which can be interpreted with (5). If the transmission rate is smaller than the outage capacity to transmit the packets, GB will receive the packet correctly with the probability infinitely approaching to 1. Hence the maximum transmission rate for each node can be defined as outage capacity $\widetilde{c}_{ij}$; the optimization problem presented in (9) is rewritten as

$$\begin{aligned} &\max_{(i,j)\in L(N_i^t)} \quad \mathbb{R}_{ij} - \overline{D}_{ij}, \\ &\text{s.t.} \quad m_s \le r_{ij} \le \widetilde{c}_{ij}. \end{aligned} \tag{10}$$

The problem in (10) only considers the quality of one-hop transmission, and the scale of the problem is small enough to enable local transmission to obtain the optimal performance in polynomial time.

In FANETs, the link quality and the length of each queue are unstable, which introduces additional delays for one-hop transmissions. When time t approaches infinity, the system is considered to achieve a stable state, in which the average delay consumed by the one-hop transmission is equal to expected delay of the link. Assume that a node selects a link with minimum expected delay $\overline{D}_{ij}$ to transmit the packet. The objective function is modified as $\max_{(i,j)\in L(N_i^t)} f(r_{ij})$, where $f(r_{ij})$ is a function with the transmission rate r_{ij} as parameter, $f(r_{ij}) = r_{ij} \cdot q_{ij} - (K/(\widetilde{c} - r_{ij}))$. We use a generally approved inequality $1 + x \le e^x$ to simplify the double exponential form as $q_{ij} = \exp(-(r_{ij}/W \cdot \overline{\gamma}_j^i))$. The closed-form solution of problem (10) is difficult to obtain due to the unconcave attribution of the effective transmission rate in (7). To solve this obstacle, the logarithmic form is taken for each parameter including effective transmission rate and expected queuing delay. Using the mathematical tools, we can get the approximate expression of transmission rate:

$$r_{ij} = \left[f'\left(r_{ij}\right)\right]_{m_s}^{\widetilde{c}_{ij}}, \tag{11}$$

where $f'(r_{ij})$ denotes one-order derivative of function $f(r_{ij})$, $[x]_a^b$ is a projection operation and its value takes $\min\{\max\{a, x\}, b\}$. Equation (11) denotes the transmission rate on each link when the tradeoff between transmission rate and one-hop delay is achieved.

4.3. Algorithm Description and Implementation. It is obvious that some optimization loss will occur in (10) as opposed to the optimization problem (8) due to the volatility of the estimated delay compared to the expected delay at the current sender. We will introduce some other parameters to reduce the optimization loss as far as possible for each session in the execution process of the routing algorithm. Before starting the operation, we first estimate the one-hop delay for node i depending on the remaining delay denoted by T_s^i. If the neighbor j is selected as a relay by i, the single-hop packet progress [32] to GB is defined as

$$sp_{ij} = \overline{d}_i - \overline{d}_j, \tag{12}$$

where $\overline{d}_i$ is the distance from node i to GB and $\overline{d}_i > 0$. If node i has received a packet from its upstream node correctly and selects node j as relay node, the value of estimated one-hop delay can be obtained with the following equation:

$$\widehat{T}_{ij} = \frac{sp_{ij}}{\overline{d}_i} \cdot T_s^i. \tag{13}$$

We define the notation H_{ij} as the probability that the expected delay calculated in (6) is less than the estimated one-hop delay in (13), and the expression of H_{ij} is

$$\mathrm{H}_{ij} = e^{-\left(\overline{D}_{ij}/\widehat{T}_{ij}\right)}. \tag{14}$$

From (14), we can see that there is a positive correlation between H_{ij} and $\widehat{T}_{ij}$. It is noted that the larger value of $\widehat{T}_{ij}$

denotes the closer distance from node j to GB than any other neighbor of i as shown in (14). There is an opposite trend between the values of H_{ij} and $\overline{D}_{ij}$, and the senders may select the neighbor with a smaller $\overline{D}_{ij}$ as the relay node due to the delay constraint.

To make a wise decision at each relay node, we define an indicator notation $\mathbb{N}_j^i$ as the number of times that the link (i, j) has been selected by node i up to present time. We jointly consider parameters H_{ij} and $\mathbb{N}_j^i$ to obtain the transition probability $\mathbb{F}_{ij}^t$, and the detailed expression is listed as below:

$$\mathbb{F}_{ij}^t = \mathrm{H}_{ij}^{1/\left(\mathbb{N}_j^i+1\right)}. \tag{15}$$

It is noted that there is a positive correlation between the value of $\mathbb{F}_{ij}^t$ and the selection times of relay nodes. In addition, if $\mathbb{N}_j^i \to \infty$ holds, the value of $\mathbb{F}_{ij}^t$ approaches 1.

Before discussing the stochastic routing algorithm, we provide the following notations. Let $S_i^t \in N_i^t$ denote the potential relay set of neighbors of node i; these nodes not only receive the packets from i correctly but also satisfy the transmission condition as relay nodes. The notation $A(S_i^t)$ is defined as the available relay set that node i can take at time t, and a_i^t is actual relay selected by node i at time t. Before implementing the routing algorithm, we need to solve the problem that how to assign the transition probability to each available relay in $A(S_i^t)$. The detailed process of routing algorithm is as follows.

(1) //Initialization;
(2) **if** node i has received the packet **then**
(3) $\quad S_i^t \longleftarrow N_i^t$;
(4) $\quad$**for** each node $j \in S_i^t$ **do**
(5) $\quad\quad$**if** $\mathrm{sp}_{ij} > 0$ and $\overline{D}_{ij} \leq \widehat{T}_{ij}$ **then**
(6) $\quad\quad\quad A(S_i^t) \longleftarrow j$;
(7) $\quad\quad$**end if**
(8) $\quad$**end for**
(9) $\quad$**for** each node $j \in A(S_i^t)$ **do**
(10) $\quad\quad$Uses (5) and (11) to compute q_{ij} and r_{ij};
(11) $\quad$**end for**
(12) $\quad$Uses (7) to obtain $\mathbb{R}_{ij}$;
(13) $\quad$**if** more than one node satisfy $\max_{j\in A(S_i^t)}\{\mathbb{R}_{ij}\}$ **then**
(14) $\quad\quad$Selects the node with $\max_{j\in A(S_i^t)}\{\mathrm{H}_{ij}\}$ as relay node;
(15) $\quad$**else**
(16) $\quad\quad$Selects the node with $\max_{j\in A(S_i^t)}\{\mathbb{R}_{ij}\}$ as relay node;
(17) $\quad$**end if**
(18) $\quad$Computes $\mathbb{F}_{ij}^t$ based on (15);
(19) $\quad$Node i transmits the packet to j with $\mathbb{F}_{ij}^t$;
(20) $\quad$**if** $a_i^t = j$ **then**
(21) $\quad\quad \mathbb{N}_j^i = \mathbb{N}_j^i + 1$;
(22) $\quad$**end if**
(23) **end if**

Algorithm 1: Delay-constrained stochastic routing algorithm.

Algorithm 1 is executed in a local way, in which each node transmits the received packets based on the one-hop channel conditions of its neighbors in step 4–8. It does not require all nodes to have the global synchronization information, the steps 2–20 are independently processed at each intermediate node. In initialization phase, each node configures its own parameters (such as location and cache) independently and periodically exchanges the beacon message with its neighbors; this operation runs in the asynchronous mode. In transmission phase, the senders collect the CSI from their neighbors N_i^t and exploit the judgement condition of step 5-6 to decide the candidate set $A(S_i^t)$. Next, each sender selects its relay node by running steps 9–20 and transmits the packet to selected relay node; this operation is terminated until the packet arrives at GB. If there are more than one relay nodes that have same metric value as described in step 13, the senders select the relay nodes from their candidate set by exploiting different operations as described in steps 13–16. From (14), we can see that the value of H_{ij} increases with the increase of $\widehat{T}_{ij}$; hence, step 14 can ensure that more packets arrive at GB within delay threshold. In our channel model, CSI remains unchanged in a given interval which results in the optimality of selected link between the sender and its relay node until the interval ends. Therefore, step 21 ensures that the packets transmitted to GB along the optimal path in a given interval. After determining the relay node, the sender calculates transition probability $\mathbb{F}_{ij}^t$ and transmits the packet to its relay node with $\mathbb{F}_{ij}^t$ as shown in steps 18 and 19. The advantage of step 19 is to avoid the routing process falling into local optimum. The transmission rate, outage probability, and expected delay are updated at each transmission; these operations are performed in the local way rather than in the global way. Considering the local operation, the transmissions at relay nodes are only related to the current time and independent of other transmissions in our scenario, which makes Algorithm 1 more suitable for FANETs.

In our routing algorithm, we do not explicitly propose the mechanism for load balancing which is achieved by controlling the queue length at intermediate nodes. From (6), it is noted that the queuing length is related to the rate r_{ij}; hence, the load balancing can be achieved by adjusting the size of r_{ij}. In addition, the stochastic model requires the senders to transmit the packets to their relay nodes with the transition probability, which also avoids transmitting the packets through the same path.

4.4. Algorithm Analysis. From Algorithm 1 we can see the routing decision is made at each intermediate node in an adaptive manner rather than at the source. A better routing strategy needs to have the approximate optimal performance; hence, we would like to show that the proposed routing method can converge to the optimal routing method under some mild assumptions. For the convenience of analysis, it is reasonable to assume that the one-hop transmission can be completed in one slot, such that the maximum delay constraint is equal to the maximum hop count constraint. Before proving the convergence of Algorithm 1, we need to do some preliminary work.

For the sake of convenience, we use the notation π^* to denote the optimal routing policy and the notation ϕ to denote the routing policy proposed in this paper, and assume that ϕ is a uniformly good policy [33]. We define the termination time $\upsilon_{\mathrm{T}}^{k}$ to be the stopping time when packet k is terminated within delay constraint and $\upsilon_{\mathrm{s}}^{k}$ to be the stopping timeout of delay threshold. The notation $\mu_{k,n}$ denotes the transmission gain when the packet k is transmitted at slot n, and $\mu_{k,n} < \infty$. Assume that the maximum number of hops ($H_{\max}$) of all sessions is bounded as $O(\log|V|)$. We use the notation $\mathbb{V}^*$ to denote the transmission gain under the policy π^*. Before analysing the performance of Algorithm 1, there are some assumptions have to be provided.

Assumption 1. If node i receives the packet from its upstream correctly, the event that i selects a candidate set S_i^t from its neighbor set N_i^t occurs with probability $P(S_i^t \mid i)$ which is independent of time and all other routing decisions.

In FANETs, the link quality is unstable and the packets are received by relay nodes with a certain probability. When the relay node fails to receive the packets, its upstream node needs to transmit the same packet again; hence, node i is always a recipient of its own transmission, namely, $i \in S_i^t$. If $i \notin S_i^t$, the probability $P(S_i^t \mid i) = 0$.

Assumption 2. Node i is able to receive the acknowledgement information from all nodes in set S_i^t which receive the packet from node i correctly.

In practice, Assumption 2 is hard to be satisfied, because the channel states change dramatically and the set S_i^t is time-variant. To make two assumptions presented above hold, we also propose another assumption.

Assumption 3. There is a time interval $\Delta t > 0$; the link quality keeps relatively stable, and all components in set S_i^t remains invariant within interval Δt.

Lemma 1. *If the routing policy ϕ is followed, $\Delta t \to \infty$, and when state S_i^t is visited infinitely often (i.o) for $\forall i \in V$, then the active $a_i^t \in S_i^t$ is visited i.o, and each state-action (S_i^t, a_i^t) for $\forall i \in V$ is visited i.o.*

The proof of Lemma 1 is similar to ([34], Lemma 5, and Lemma 6), and the interested readers can refer to [34].

Definition 1. There exists a sequence of relay nodes which possess the knowledge about local network topology; if Lemma 1 holds, the expected transmission gain for packet k under policy ϕ is defined as $\mathbb{E}^{\phi}[\sum_{n=\upsilon_{\mathrm{s}}^{k}}^{\upsilon_{\mathrm{T}}^{k}} \mu_{k,n}]$.

Lemma 2. *If Assumptions 1–3 hold and $\Delta t \to \infty$, the proposed routing method ϕ can converge to the optimal policy π^* under the consideration of Lemma 1; in other words, the difference of transmission gain between two routing methods approaches zero.*

Proof. Given a constant $\alpha \geq 0$, for a packet with index k, when $n > \upsilon_{\mathrm{s}}^{k}$, and $\xi_n(i, S_i^t) = 1 - \mathbb{F}_{ij}^{n}$, $\max_{i,S_i^t} \xi_n(i, S_i^t) \leq \alpha$ with probability 1. To generalize our problem, assume that there exists a constant $k_0 < \infty$; for the packet index k, let $k > k_0$. Packet k is generated at source s at time $\upsilon_{\mathrm{s}}^{k}$. Now, we define an event Ψ_m^k, which denotes there exist m instances when Algorithm 1 transmits packet k differently from the possible set of optimal relays. Mathematically speaking, event Ψ_m^k occurs if there are m instances $\tau_{\mathrm{s}}^{k} \leq n_1^k \leq n_2^k, \ldots, \leq n_m^k \leq \tau_{\mathrm{T}}^{k}$ satisfying $\mu_{k,n_m^k} \neq \max_{\forall j \in A_n(S_i^t)} \mu_{k,n_m^k}(j)$, where $l = 1, 2, \ldots, k$ and $\mu_{k,n_m^k}(j)$ is transmission gain of node j for packet k. We call event Ψ_m^k a miss routing of order k. Such that, we can obtain an inequality as $P(\Psi_m^k) \leq \max_{i,S_i^t} \xi_n(i, S_i^t) \leq \alpha^m$.

Considering the definition of the expected transmission gain, for packets $k > k_0$, the differential regret under policies ϕ and π^* is computed as follows:

$$\begin{aligned}
\mathbb{R}_{\phi} &= \mathbb{E}^{\pi^*}\left[\sum_{n=\upsilon_{\mathrm{s}}^{k}}^{\upsilon_{\mathrm{T}}^{k}} \mu_{k,n}\right] - \mathbb{E}^{\phi}\left[\sum_{n=\upsilon_{\mathrm{s}}^{k}}^{\upsilon_{\mathrm{T}}^{k}} \mu_{k,n}\right], \\
&= \mathbb{V}^* - \mathbb{E}^{\phi}\left[\sum_{n=\upsilon_{\mathrm{s}}^{k}}^{\upsilon_{\mathrm{T}}^{k}} \mu_{k,n}\right], \\
&= \sum_{m=0}^{\infty} \mathbb{E}^{\phi}\left[\sum_{n=\upsilon_{\mathrm{s}}^{k}}^{\upsilon_{\mathrm{T}}^{k}} \mu_{k,n} \middle| \Psi_m^k\right] \cdot P\left(\Psi_m^k\right), \\
&\leq \sum_{m=0}^{\infty} m \cdot \left(H_{\max}\Delta_{\max}\right) \cdot P\left(\Psi_m^k\right), \\
&\leq H_{\max}\Delta_{\max} \cdot \sum_{m=0}^{\infty} m \cdot \alpha^m \leq \varsigma,
\end{aligned} \tag{16}$$

where $\Delta_{\max} = \max_{\substack{p,q \in S_i^n \\ p \neq q}} \left\{\left|\mu_{k,n}(p) - \mu_{k,n}(q)\right|\right\}$ for each $n \in [\upsilon_{\mathrm{s}}^{k}, \upsilon_{\mathrm{T}}^{k}]$, and $\varsigma = ((H_{\max}\Delta_{\max} \cdot \alpha)/(1-\alpha)^2)$; let $\alpha = \max_{i \in V}\{\xi_n(i, S)\}$, and the difference between $\upsilon_{\mathrm{s}}^{k}$ and $\upsilon_{\mathrm{T}}^{k}$ is equal to the maximum delay threshold, $(\upsilon_{\mathrm{T}}^{k} - \upsilon_{\mathrm{s}}^{k}) \leq \mathfrak{T}_{\mathrm{s}}$. We assume that there is a nonnegative constant $\delta_0 > 1$ that the equation $H_{\max} = \delta_0 \log|V|$ is followed, so the value ς is rewritten as $\varsigma = (\delta_0 \log|V|\Delta_{\max} \cdot \alpha)/(1-\alpha)^2$. Based on the practical routing implementation, it is reasonable that $\mathbb{R}_{\phi} \geq 0$.

Assume that the network can achieve the stable state presented in Lemma 1 during the interval Δt; the nodes that satisfy the transmission requirements will be selected with higher probability. If $\Delta t \to \infty$, we can know that the parameter $\mathbb{N}_j^i$ also approaches ∞. In this case, it is easy to obtain the conclusion that $\mathbb{F}_{ij}^{t} \to 1$ by considering (15) for each link. According to the definition of $\xi_n(i, S_i^t)$, we can see, if $\mathbb{F}_{ij}^{t} \to 1$ holds, the value of $\xi_n(i, S_i^t)$ approaches zero; hence, we have the relation $\max_{i,S_i^t} \xi_n(i, S_i^t) \to 0$. If the value of α is zero, it is easy to obtain that $\varsigma = 0$ according to the relationship between ς and α. Considering inequality (16), the following inequality holds $\mathbb{R}_{\phi} \leq 0$. Concluding the analysis above, it is obvious that the proposed routing method can converge to optimal solution under some assumptions.

5. Analysis of the Simulation Result

In this paper, we use OMNeT++ 5.0 to simulate the network scenario and collect relevant results. In the initialization phase, the nodes spread uniformly in an area of

5 km ∗ 5 km ∗ 2 km and randomly move with the Random Way-Point model [17]. All end-to-end transmissions have the same delay constraint which is set to 0.1 s. Each node is able to send the packets using same transmission power 1000 mw and different transmission rates which vary from 1 Mbps to 3 Mbps. The sources randomly generate packets with a generation rate of 25 packets per second and the size of each packet is 20 kb. The coordinate of GB is unchangeable, and other nodes can move randomly with a certain speed in the specified region. All nodes transmit the packets with same power, and the communication radius of nodes is set to 1 km. When the nodes transmit packets to the relay nodes, the receivers obtain a random interference value from other transmissions. To get more accurate results, we perform five times for each parameter under the same network configuration, and the final results are collected by calculating the mean value based on the five groups of results.

Considering several kinds of physical parameters including number of nodes, speeds, and hello intervals, we collected the results and generated the Figures 2–10. For simplifying the transmission process, each relay node only has one chance to retransmit the packet on each link. We divide the experimental results into two parts: Figures 2–4 show the changing trends of network parameters when the different moving speeds and hello intervals are considered that only our proposed routing policy is followed, and the Figures 5–10 indicate the different network performances under two different routing policies which include the proposed method, OR-DSP [14], P-OLSR [15], and GRAA [19]. The reason for comparison with these three routing algorithms is the different path selection criteria for designing the routing algorithms. From the introduction in Section 2, we can see that OR-DSP mainly exploits Dijkstra's shortest path and anticipated locations of intermediate nodes to design the routing algorithm. P-OLSR incorporates relative speed between two nodes and links states into routing selection, and the routing process employed by GRAA exploits a time-based movement prediction of the nodes and the routing idea designed for DTN to improve the performance of the position-based routing. The evaluation results of different network parameters, which include timeout rate, packet loss rate, and throughput, are displayed in Figures 5–10 under different speeds and the number of nodes. From Figure 2, we can see that the total packet loss rate increases with the increase of speeds. There are two major factors to decide the total packet loss rate: link quality and delay constraint. The previous factor will bring more retransmissions which could increase the end-to-end delay. It also hints that the total delay consumed by the packet would exceed the delay threshold with greater possibility. The latter factor increases the loss rate because the packets will be discarded by relay nodes when the delays consumed for transmissions are larger than the given threshold.

The proposed routing policy in this paper only collects the local information from the one-hop neighbors and uses them to make a routing decision. The interval to exchange the beacons between a pair of nodes seriously affects the reliability of one-hop transmission, where the senders select

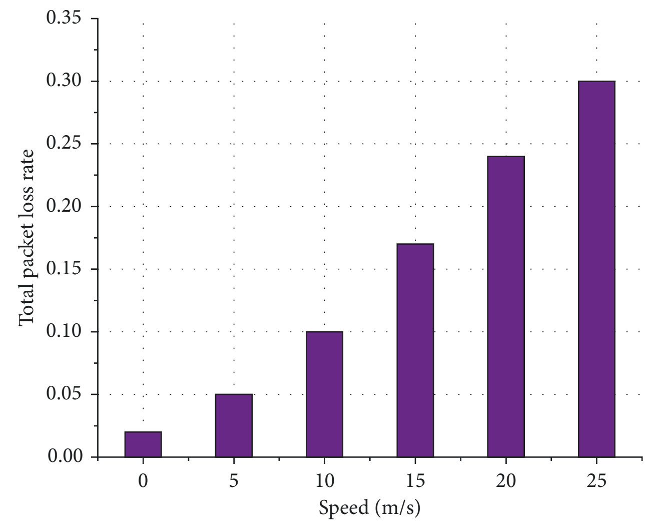

Figure 2: The total packet loss ratio for each transmission under different speeds.

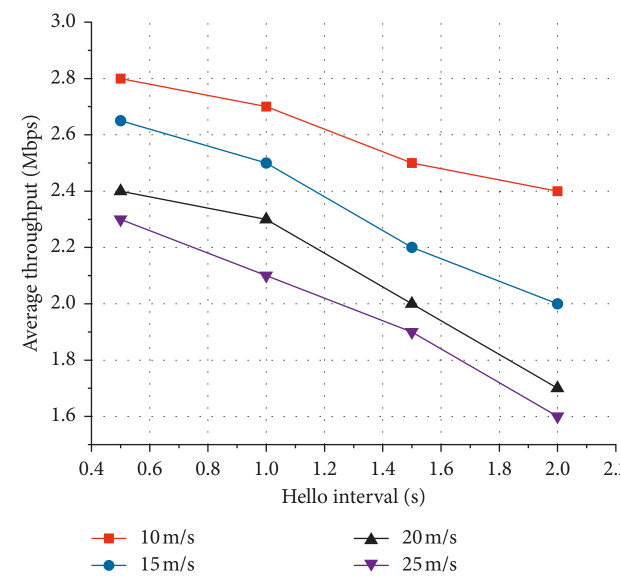

Figure 3: The average throughput with different speeds under different hello intervals.

relay nodes with outdated CSI to make a worse decision. The CIS computed in (2) is closely related to the distance between two nodes; when the moving speed of nodes changes dramatically, the increasing hello interval will decrease the network performances. Therefore, from Figure 3, we can see that when the relay nodes use the previously stored CSI to select the next node, the stored CSI does not characterize the current link quality and may mislead nodes to make a worse routing decision, which will dramatically decrease the number of packets received correctly by GB. In the practical implement process, we are interested to know how to set the hello interval to meet the success rate requirement for each transmission when the moving speed of nodes is fixed. Figure 4 indicates the relationship between hello interval and moving speed of nodes when the network requires the

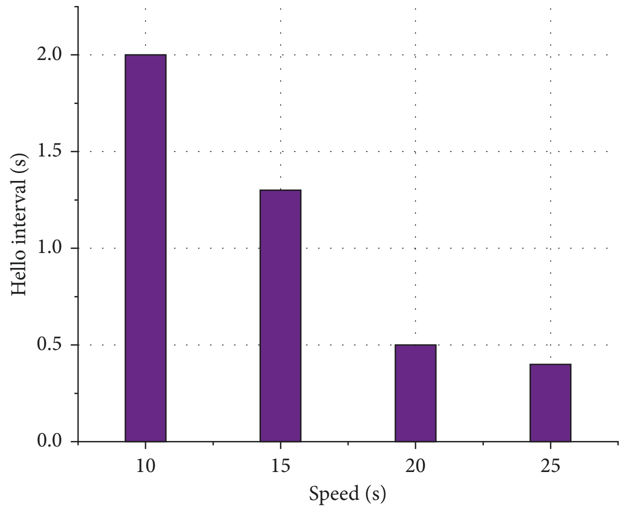

Figure 4: When the transmission success rate reaches 80%, the hello intervals under different speeds.

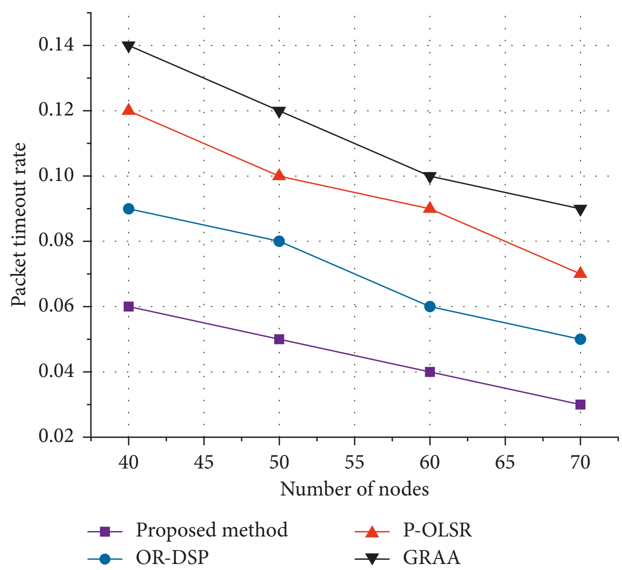

Figure 5: The packet timeout rate with different number of nodes under four routing policies.

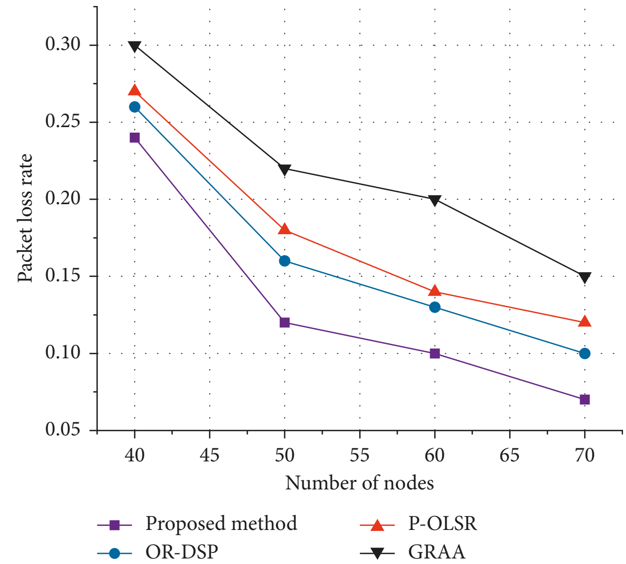

Figure 6: The packet loss rate with different number of nodes under four routing policies.

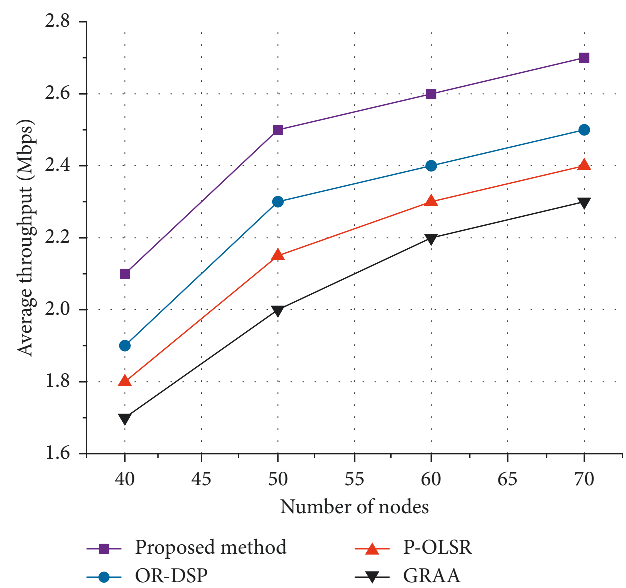

Figure 7: The average throughput with different number of nodes under four routing policies.

transmission rate to reach 80%. The coordinate of each node changes gently in slower moving mode, and the current link quality is closer to the previous CSI. The transmitters only use stored CSI to select relay node rather than exchanging the beacons to obtain current CSI, which can reach similar network performance with current CSI.

Next, we analyse the different network performances under the proposed methods: OR-DSP, P-OLSR, and GRAA. The delay constraint condition is an important factor to be considered in the design process of the routing algorithm for the proposed method. Therefore, the optimization iteration at each relay node not only considers the different network metrics (such as link quality) but also takes attention to the delay requirement. Although OR-DSP incorporates the waiting time at intermediate nodes into path selection to reduce end-to-end delay, as with other routing algorithms (P-OLSR and GRAA), OR-DSP does not explicitly consider end-to-end delay constraint problem, and reducing one-hop delay does not mean that the total delay can meet the given delay threshold. Therefore, when OR-DSP, P-OLSR, and GRAA are performing, the packet timeout rate is larger than that of the proposed method, which can be validated in Figures 5 and 8. From Figure 8, it is noted that the timeout rate increases with the increase of moving speeds in four methods; the reason can be explained as the high mobility of nodes introduce worse link quality at each transmission. A main optimization goal of the proposed method is to maximize the effective transmission rate which considers the practical

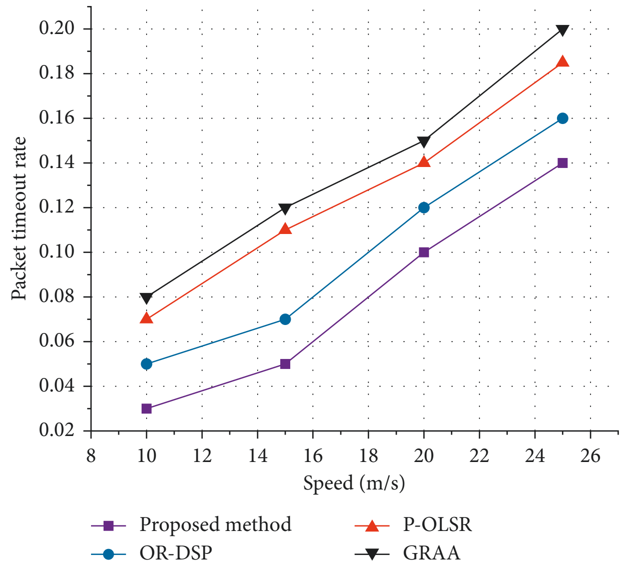

Figure 8: The packet timeout rate with different speeds under four routing policies.

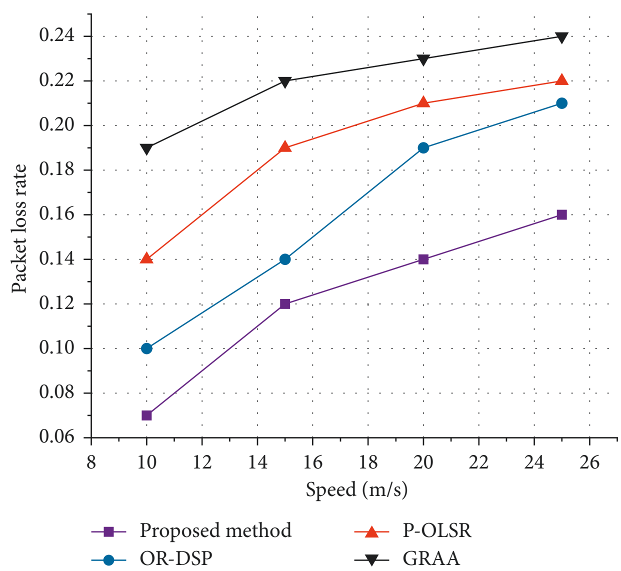

Figure 9: The packet loss rate with different speeds under four routing policies.

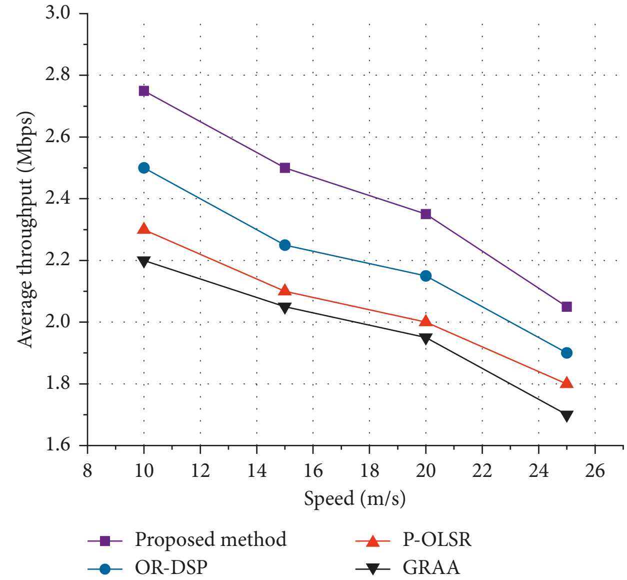

Figure 10: The average throughput with different speeds under four routing policies.

transmission rate and link quality simultaneously. The adjustable transmission rate can adapt to the changes in network topology and provide better link quality; hence, we can get the conclusion that the timeout rate calculated in the proposed method has a weak relationship with the moving speed. More number of nodes can provide more chances for each transmission to make a wise routing decision and ensure the link quality. Hence, the timeout rate decreases with the increase of the number of nodes, as shown in Figure 5.

In addition, this paper considers the interference from other transmissions and calculates the link quality for each transmission depending on (5). In our simulation, assume that each relay node has one chance to retransmit the packet, which means that more packets will be discarded at relay nodes with poorer link quality. The proposed method regards the transmission rate and link quality as optimization goals; the packets will consume less delays to arrive at GB. The consideration of link quality ensures that the packet can arrive at GB with higher probability. P-OLSR regards the link quality as part of routing metric to adapt to dynamic network topology of FANETs rather than the variations of channel status. OR-DSP and GRAA only focuses on the location prediction and the shortest distance between two nodes as routing metric. These three methods do not consider the impact of the interference on link quality; hence, the relay nodes may select the links with lower reliability as parts of the end-to-end path. The worse link quality leads to more retransmissions at relay nodes for each session, which increases the total delays and the number of the packets discarded at relay nodes. Summarizing the above analysis, we get two conclusions: one is that the proposed method can provide better reliability for end-to-end transmission than OR-DSP, P-OLSR, and GRAA. Hence the packet loss rate which does not include packet timeout rate in the proposed method is smaller than that in OR-DSP, P-OLSR, and GRAA as shown in Figures 6 and 9. The other is that the throughput in our method is higher than that in OR-DSP, P-OLSR, and GRAA under different number of nodes and speeds, as shown in Figures 7 and 10.

6. Conclusion

To solve the delay-constrained routing problem in FANETs, we formalize it into a global optimization problem. By considering the link quality and one-hop delay estimation, the global optimization is converted into a distributed optimization, and we use the one-order derivative and projection method to obtain the local optimal solution in polynomial time. In order to avoid the routing process falling into local optimum, the transition probability is calculated by jointly considering remaining delay and the distance to GB for relay nodes. From the simulation results we can see, the proposed routing algorithm can improve the network performance in terms of network throughput, packet loss rate, and packet timeout rate.

There are some open issues that need to be solved in FANETs including the link connectivity and the void region problems. The selection of the relay node only refers to effective transmission rate, and it is insufficient to ensure network performance. For example, there is a link connecting nodes i and j at time t_0, but the link will disappear during transmission due to the mobility of nodes. In a worst case, the sender cannot find any available neighbors to relay packets, and if nothing else is done, the packet would be discarded in our scenario. The consideration of connection time as in [22] can reduce link maintenance costs and avoid the void region problem. Therefore, our future work will consider these problems in our optimization framework.

Notations

V: Set of all nodes
L: Set of all links
(i, j): A link connecting node i and j
r_{ij}: Transmission rate over link (i, j)
$\mathbb{R}_{ij}$: Effective transmission rate over link (i, j)
N_i^t: Neighbor set of node i at time t
$L(N_i^t)$: Link set between node i and its neighbors at time t
$\mathfrak{T}_s$: Delay threshold for source s
c_{ij}: Instantaneous capacity of link (i, j)
$\widetilde{c}_{ij}$: Outage capacity of link (i, j)
q_{ij}: Quality of link (i, j) for session s
$\overline{D}_{ij}$: Expected queuing delay on link (i, j)
p_s: The end-to-end path selected by s
$L(p_s)$: Link set on path p_s
$T(p_s)$: Total delays on path p_s
K: Length of data packet
$\overline{d}_i$: Distance from node i to GB
T_s^i: Remaining delays the packet from s arrive at i
$\widehat{T}_{ij}$: Estimated one-hop delay of link (i, j)
$\mathbb{F}_{ij}^t$: Transition probability over link (i, j) at time t
S_i^t: Potential relay set of node i at time t
$A(S_i^t)$: Available relay set of node i
$H_{\max}$: Maximum hops for all end-to-end path.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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