

A Markov Analytical Model between MANET Single-path and Multi-path Load Balancing Routing Protocol

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Abstract—Mobile Ad Hoc Network (MANET) is a network consisting of a set of wireless nodes that communicate through a wireless medium. It is widely used due to its characteristics such as centerlessness and self-organization for easy deployment, but these applications are based on having efficient routing algorithms. In this paper, we propose a Markov process-based algorithm analysis model to analyze the superiority of multipath algorithms and single-path algorithms in MANETs in terms of energy consumption, stability, throughput and delay. Simulation results further confirm this analysis, showing that the multipath algorithm is 37% more stable than the single-path algorithm. Under the condition of sending the same number of packets, the multipath algorithm will be more energy-efficient and time-saving than the single-path. In addition, the multipath algorithm has a higher throughput than the single-path for the same energy value.

Keyword—Analytical model, Energy consumption, Stability, Throughput, Delay.

I. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are collection of wireless mobile nodes. It is dynamically constructed without using any existing network infrastructure or centralized management[1-4]. MANET has the characteristics of no center, self-organization, dynamic topology, multi-hop routing, and easy deploying[5-7]. Ad hoc networks are used in a variety of scenarios. For example, emergency mobile communications, smart home connectivity, warrior-only combat systems, field work, and medical monitoring systems[7-9]. The capacity of wireless links is much lower than that of wired links, thus making it easier to cause network congestion and reduce network performance [10-13], which is the biggest challenge in mobile self-organizing networks. To cope with these problems, a series of routing algorithm have

been developed for network communication to improve the performance, but different routing protocols have different advantages and disadvantages.

Although simple and easy to manage and configure, single-path routing protocols do not take into account fairness. The single-path routing protocol puts all the load on the shortest path from the source node to the destination node, and only one path is discovered during the route discovery phase, which does not effectively utilize the topological information of the entire network and leads to an increase in routing overhead. Although the current multipath routing protocol discovers multiple paths and improves network utilization to some extent, it does not take into account the limited resources of the network and simply uses one parameter as the routing criterion, which can lead to excessive load on the central node, excessive energy consumption without replenishment and thus loss of communication capability, causing network congestion, packet loss, link disconnection, etc.

In order to compare the advantages and disadvantages of single-path routing algorithms and multipath routing algorithms, and to show the research direction to later researchers, this paper conducts an in-depth study on multipath load balancing routing techniques and proposes a Markovian-based analytical model to compare the advantages and disadvantages between multipath load balancing protocols and single-path routing protocols. The advantages and disadvantages of single-path and multi-path algorithms in wireless communication are analyzed in four aspects: energy consumption, stability probability, throughput and delay. The results show that the single-path algorithm is more energy-efficient when the data volume is small. As the data volume increases, the multi-path algorithm has better performance.

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The rest of this article is organized as follows: the second part summarizes the routing protocol; the third part introduces the related work in this field; the fourth part presents the analytical model and analyzes the performance of routing protocol; the fifth section introduces the simulation results and the last part summarizes the paper.

II. RELATED WORK

In order to address the limited energy and processing power of nodes in MANETs, a series of routing algorithms have been investigated to improve the performance of network communication.

In 2013, ALGhafran et al. proposed a cluster-based load balancing algorithm for solving the load balancing problem in MANET [14]. Firstly, cluster heads of nodes within a certain range are selected through an election mechanism, and information is interacted between neighboring cluster heads periodically, and when the load difference between the cluster head with high load and the cluster head with low load exceeds a set threshold, the load balancing mechanism is invoked so that the cluster head with high load reduces the transmission range and the cluster head with low load expands the transmission range to achieve a balanced state between the cluster heads and increase the lifetime of the network.

In 2013, Malviya, L.K et al. modified Dynamic Source Routing Protocol (DSR) to Load Balanced Multipath Dynamic Source Routing Protocol (LMP-DSR) [15]. Two data structures were introduced in this new protocol: route cache and load table. The route cache maintains routes to the destination node, but only up to five routes, while the load table maintains the amount of data for a given route. Experimental results show that LMP-DSR outperforms DSR and AOMDV in terms of throughput and packet delivery rate, and outperforms DSR but outperforms AOMDV in terms of end-to-end delay.

In 2014, Monika, Malik, P.Y et al. improved on the AOMDV protocol and proposed an AOMDV-based load balancing algorithm (LBA-AOMDV) [16] protocol. This protocol analyzes the load of neighboring nodes of the current node by different parameters such as loss rate, communication rate and delay. By comparing with a predefined threshold, high, medium and low priorities are assigned to the neighboring nodes and the node with the highest priority is selected as the path to the destination. The LBA-AODV protocol shows significant improvements in packet loss rate, end-to-end delay and throughput compared to the AOMDV protocol.

In 2015, M Naseem proposed a new protocol called congestion-aware Fibonacci queue-based multipath routing protocol [17]. This protocol is modified from AOMDV, in which the source node sorts multiple paths based on the round-trip time of packet requests and replies during route discovery, and assigns packets according to the Fibonacci queue sequence number, assigning different Fibonacci values according to the size of the round-trip time from smallest to largest, incrementing gradually until the packet is sent.

In 2016, Alghamdi proposed a load-balanced multipath routing protocol (LBMMRE-AOMDV) based on the maximum minimum node residual energy in the AOMDV

protocol [18]. This protocol discovers N paths in the route discovery phase and monitors the minimum node residual energy of each route as the path energy value, and then ranks multiple routes according to the residual energy of the nodes, sets the path with the minimum node residual energy as the alternate path, and continues to use the remaining $N-1$ link disjoint paths for data transmission. This protocol reduces the lost traffic and maintains the node energy while This protocol can be used to balance the data load between the disjoint paths of the generated links, this protocol has all improvements in packet delivery rate, throughput, and end-to-end delay compared to the AOMDV protocol.

In 2017, MV Patil et al. proposed a reliable, secure and load-efficient routing protocol LBSTAR [19]. To address the problem that the process of information exchange between nodes requires the delivery of intermediate nodes, which may cause the original link to break due to battery depletion and attacks on intermediate nodes, reducing the reliability of data transmission and packet delivery rate. In this paper, we propose a security mechanism that initially gives nodes high, medium, and low trust values and dynamically changes them during transmission to determine whether neighboring nodes are trustworthy by trust values and energy sensing and find the best available route for load balancing during data transmission.

In 2017, Mallapur S et al. proposed a multipath congestion control load balancing technique (MLBCC) [20] to effectively balance the load between multiple paths by reducing congestion. This protocol detects congestion during data transmission by using the arrival and efferent rates for a specific time interval T . Then link cost and path cost are used to select gateway nodes to efficiently distribute the load by selecting the most desirable path, whenever the load exceeds the maximum threshold it is considered as overload and will distribute the traffic through the gateway nodes by segmenting the packets and distributing them evenly to randomly select different paths for sending in a round robin manner.

In 2017, FA Pitchaimuthu et al. proposed ant colony based multipath backbone routing [21] for data transmission in MANETs. The operating mechanism of this protocol is to estimate the path preference probability based on next-hop availability, delay and bandwidth when the source wants to transmit data to the destination and select multiple routes with maximum path preference probability using population-based ant colony optimization (ACO) technique. During route discovery, nodes that fail are identified and the associated paths are skipped. Each backbone node is then indexed to balance the network load on the route in order to distribute data traffic equally over the links from the source to the destination.

In 2017, Bhattacharya et al. proposed a new multipath routing protocol called Least Common Multiple based routing (LCMR) [22]. This protocol finds multiple paths from the source node to the destination node, records the sorted round-trip time, and then uses the round-trip time to calculate the least common multiple. The number of packets transmitted in each path is denoted as n_k , n_k is the least common multiple divided by the round-trip time, and if the

remaining number of packets is not enough to send in one cycle, the remaining packets are sent proportionally. For example, there are k paths, n is the total number of packets sent in each cycle, and the previous an packets are sent cyclically along the k paths. If there are r packets left ($r < n$), the number of packets sent for each path is calculated by $\frac{r}{n} \times n_k$. In 2019, Aouiz et al. proposed the CBMLB protocol

[23] to perform load balancing. It is an enhanced version of the AOMDV protocol, in which a new parameter is proposed to measure the network centrality based on the channel busyness by selecting the node with the minimum busy time for the MAC channel in addition to the minimum packet transmission time. Equation (1) shows that the channel busy ratio is defined as the ratio of channel-aware busy time plus transmission time (idle + busy time + transmission time) to upper-layer channel-aware busy time plus transmission time plus idle time. Transmission time includes the time of conflict and busy time is the time when the channel is perceived as busy due to the transmission of other nodes. In the route discovery process, as shown in Equation (2), each node writes down its channel busy ratio in the packet and chooses the smallest sum of busy for transmission.

$$C(m) = \frac{\sum \text{Transmission} + \sum \text{busyness}}{\sum \text{idle} + \sum \text{Transmission} + \sum \text{busyness}} \quad (1)$$

$$C(p) = \frac{n}{n+1} c(n) + \frac{1}{n+1} c(n+1) \quad (2)$$

Table 1 shows the comparison of routing protocols in recent years.

TABLE I
ROUTING ALGORITHM COMPARISON

Algorithm	Delay	Pdr	Throug hput	Comparable protocol
DIR-ANT[24]	Low	Mid	High	MULTI-OMNI-ETA, MULTI-OMNI- GAMMA
AODV-LB[25]	-	High	-	AODV, E^2 AOMDV
LMP-DSR	High	Mid	High	DSR, AODV, AOMDV
LBA-AOMDV	Low	High	Low	AOMDV
HLRMLB[26]	Low	Low	High	MCR
MLBCC	Low	High	-	FMLB, AOMDV
AMBRLB	Low	Mid	Low	QAMR, MC-AOMDV
M-EALBM[27]	Low	High	High	EALBM
TALB- AOMDV	Low	High	High	AOMDV
CBMLB	Mid	High	-	AODV, AOMDV, QMLB
LBMDSR[28]	Low	High	-	MRDSR, DSR
CAFMLB	Mid	High	-	AODV, FLMB
LBMRE- AOMDV	Mid	Mid	-	MMRE-AOMDV, AOMDV
QMLB[29]	Low	High	-	AODV, FMLB
LCMR	Mid	-	-	MAODVHC, MAODVRT, FLMBHC, FMLBRT

III. ANALYSIS MODEL

In MANET, single-path routing algorithm usually finds a path for data transmission during route discovery, and multipath routing algorithm is usually designed to share traffic from paths formed by different nodes, so that traffic is distributed from different paths to reduce the pressure on nodes, but there is no suitable comparison scheme for the

advantages and disadvantages of single-path routing algorithm and multipath routing algorithm. In order to compare the performance of multipath load balancing algorithms with that of single-path load balancing algorithms, this paper proposes a new analytical model for performance comparison. The summary of the parameters used in this chapter is given in the following table 2.

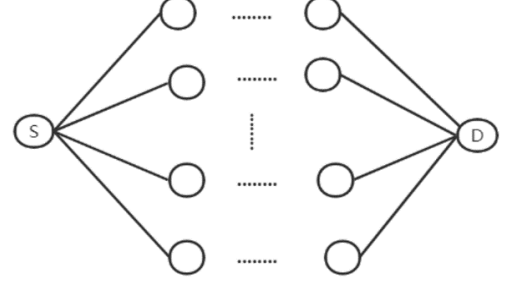


Fig. 1. Random network topology model

TABLE II
SUMMARY OF PARAMETER

Parameter	Meaning
n	Number of paths from S to D
n_i	Number of nodes of the i-th path
H_i	Energy consumed of the i-th path
E_{li}	Energy loss of the i-th path
λ	Probability of energy loss
f_l	Loss of potential energy to send a packet
f_c	Energy consumption for sending a packet
H_i	Number of hops in the i-th path
E_i	Residual energy of the i-th path
F_i	Selection factor
M	Smoothness parameters
d_i	Number of packets sent on the i-th path
d	Total number of packets in the transmission
E_l	the lost energy to send a packet
P_{ij}	Probability of path transfer
π_j	Steady-state probability of choosing path j
E_{sc}	Total energy consumed of a single-path
E_{mci}	The consumes energy of i-th path
P	Node damage probability
M_s	Single-path stability probability
M_m	Multi-path stability probability
TH_s	Single-path Throughput
TH_m	Multi-path Throughput
a	Number of packets in a set
T_s	Single-path transmission delay
T_m	Multi-path transmission delay
E_0	Initial energy of the node

Figure 1 shows a simple random network topology in MANET, where the source node is S and the destination node is D. The n paths from the source node S to the destination node D

are considered as disjoint paths. When S communicates with D, with the help of neighboring nodes, the nodes on the path relay packets for transmission, using dynamic wireless links to deliver data traffic from the source node to the destination node.

Since most of the existing routing algorithms only consider some factors that affect packet transmission, such as only single factors like hop count, and do not consider energy consumption and routing during data transmission. In MANET, the residual energy of the node and the number of hops of the path affect the processing capacity and transmission delay of the node, so the model integrates the two factors of residual energy and hop count to set the path selection parameters and establish the analytical model. We define the energy consumed by sending a data packet as f_c . The potential energy lost by sending a data packet is expressed as f_l , the lost energy fits a Bernoulli distribution with probability λ and the lost energy is E_l . Using formula (3) to calculate the number of hops of path i .

$$H_i = n_i + 1 \quad (3)$$

Assuming that there are d packets waiting to be sent during a transmission from S to D. The packets sent each path are d_i .

$$d = \sum_{i=1}^n d_i \quad (4)$$

Energy consumed to send data on path i is defined as

$$E_{ci} = d_i f_c \quad (5)$$

The residual energy of the i -th path is defined as follows

$$E_i = \min(E_i - E_{ci} - E_l) \quad (6)$$

The path selection factor is defined as

$$F_i = \alpha E_i + (1 - \alpha) \frac{1}{H_i} \quad (7)$$

Next, the analytical model is defined based on the above constants, as shown in Equation (8), and the path selection model shown in Equation (9), P_{ij} is the probability of selecting path i for the n th time and path j for the $n+1$ th time for data transmission, and since each data transmission will cause a change in energy, resulting in a change of the selection factor, the same path will not be selected twice in a row for transmission, which can maintain the load balance between different paths. When the next path selection is made, the probability of selection is the proportional size of the current selection factor.

$$P_{ij} = P(X_{n+1} = j | X_n = i) \quad (8)$$

$$P_{ij} = \begin{cases} \frac{F_j}{\sum_{i=1}^n F_i - F_i} & i \neq j \\ 0 & i = j \end{cases} \quad (9)$$

This path selection model conforms to a Markov process, and a theoretical proof that the model conforms to a Markov process will be given below, and the steady-state probability that the model selects path j during the path sending process is equation (10).

$$\pi_j = \frac{F_j}{\sum_{i=1}^n F_i} \quad (10)$$

Proof :

Based on the variables defined above, the path selection is performed using our path selection factor, and the path selection model is written as shown in Equation (8), Equation (9), where the probability of selecting path i in the previous step and path j in the next step is P_{ij} , P_{ij} represented by the one-step transfer probability from the n th step to the $n+1$ th step.

The path selection probability $\{X(n), n = 0, 1, 2, 3L\}$ is a random sequence defined on the probability space (Ω, F, P) . The path selection for the next transmission is only related to the previous path transmission. For each data transmission, there is

$$P\{X_{n+1} = j | X_0 = 0, X_1 = 1L, X_n = i\} = P\{X_{n+1} = j | X_n = i\} \quad (11)$$

So the path selection probability $\{X(n), n = 0, 1, 2, 3L\}$ is a Markov process that conforms to a finite. Based on the path selection model, we can calculate the steady-state probability of selecting path j . First, the transfer probability matrix of the model is calculated as shown in Equation (12).

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix} \quad (12)$$

Since the path selection model conforms to a finite Markov process, this model has a unique smooth distribution. The steady-state convergence theorem can be used to solve for the steady-state probability, i.e., the magnitude of the probability of choosing path j . Equations (13), (14), and (15) can be obtained based on the steady-state convergence theorem.

$$\lim_{n \rightarrow \infty} r_{ij}(n) = \pi_j \quad (13)$$

$$\pi_j = \sum_{k=1}^m \pi_k P_{kj} \quad (14)$$

$$\sum_{k=1}^m \pi_k = 1 \quad (15)$$

The steady-state probability equation can be obtained from equation (13) (14)

$$\begin{cases} \pi_1 = \pi_2 P_{21} + \pi_3 P_{31} + \cdots + \pi_n P_{n1} \\ \pi_2 = \pi_1 P_{12} + \pi_3 P_{32} + \cdots + \pi_n P_{n2} \\ \vdots \\ \pi_n = \pi_1 P_{1n} + \pi_2 P_{2n} + \cdots + \pi_{n-1} P_{n-1n} \end{cases} \quad (16)$$

Solving the equations obtains the coefficient matrix as

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix} \quad (17)$$

$$\begin{bmatrix} -\left(\sum_{i=1}^n F_i - F_1\right) & F_1 & \cdots & F_1 \\ F_2 & -\left(\sum_{i=1}^n F_i - F_2\right) & \cdots & F_2 \\ \vdots & \vdots & \ddots & \vdots \\ F_n & F_n & \cdots & -\left(\sum_{i=1}^n F_i - F_n\right) \end{bmatrix} \quad (18)$$

Solving the system of equations yields the probability of choosing the j -th path as

$$\pi_j = \frac{F_j}{\sum_{i=1}^n F_i} \quad (19)$$

According to the above definition, we compare performance in four aspects: energy consumption, stability probability, throughput and delay, and give the corresponding proof as follows:

A. Energy Consumption

Define the energy consumed by the i th path to be E_{mci} when data is sent using the multipath load balancing routing algorithm, and the energy consumed by the i th path to be E_{sci} when data is completed by the single-path routing algorithm. then we have

$$E_{mci} \leq E_{sci} \quad (20)$$

Without considering the occurrence of congestion, the same number of packets are sent using both algorithms, where each path using the multipath routing algorithm consumes less transmission energy than the path in the single-path routing algorithm, which can effectively reduce the local load and avoid congestion caused by the concentration of load on a particular path.

Proof :

$$E_{sci} = df_c + E_{lt} \quad (21)$$

$$E_{mci} = \frac{F_i}{\sum_{i=1}^n F_i} df_c + E_{li} \quad (22)$$

$$\text{When } n=1 \quad d = \frac{F_i}{\sum_{i=1}^n F_i} d \quad (23)$$

$$\text{When } n>1 \quad d > \frac{F_i}{\sum_{i=1}^n F_i} d \quad (24)$$

Since the natural loss on each path is determined by how many packets a node sends, a single-path has a relatively higher loss than a multipath, so

$$E_{mci} = \frac{F_i}{\sum_{i=1}^n F_i} df_c + E_{li} \leq E_{sci} = df_c + E_{lt} \quad (25)$$

This means that using a multipath routing algorithm has less energy consumption per path than a single-path routing algorithm.

B. Throughput

It is assumed that during transmission, packets will continue to be sent as long as the path is not interrupted, until the path energy is exhausted. We assume that each packet is of the same size, then the throughput can be expressed as the number of packets sent. TH_m is the multipath routing algorithm throughput and TH_s is the single-path routing algorithm throughput, then

$$TH_m \geq TH_s \quad (26)$$

It can be seen that a multipath routing algorithm will send more data than a single-path routing algorithm in the same situation, with higher throughput and higher fault tolerance and data transfer capability during transmission.

Proof :

Single-path routing algorithm:

$$TH_s = \frac{E_0 - E_{lt}}{f_c} \quad (27)$$

multi-path routing algorithm:

$$TH_m = \sum_{i=1}^n \frac{E_0 - E_{li}}{f_c} \quad (28)$$

Since the t th entry is only one path in a multipath, we have

$$TH_m = \sum_{i=1}^n \frac{E_0 - E_{li}}{f_c} = \frac{E_0 - E_{lt}}{f_c} + \sum_{i=1}^{n-1} \frac{E_0 - E_{li}}{f_c} \quad (29)$$

When $n=1$

$$\sum_{i=1}^{n-1} \frac{E_0 - E_{li}}{f_c} = 0 \quad (30)$$

When $n>1$

$$\sum_{i=1}^{n-1} \frac{E_0 - E_{li}}{f_c} > 0 \quad (31)$$

So

$$TH_m = \sum_{i=1}^n \frac{E_0 - E_{li}}{f_c} > TH_s = \frac{E_0 - E_{lt}}{f_c} \quad (32)$$

So a multipath routing algorithm can send more data and have better throughput than a single-path routing algorithm in the same situation.

C. Stable probability

Path stability represents the probability that the current path will complete the data transfer process without interruption. The path is not interrupted, there is no need to re-execute the route discovery process and more energy can be saved. So path stability plays an important role in the performance of routing algorithms.

Assume that the damage probability of each node is p , ($0 < p < 1$). The single-path routing algorithm selects the t th path for data transmission, and the stability probability of the single-path routing algorithm is M_s :

$$M_s = (1 - p)^{n_t} \quad (33)$$

Data transmission using a multipath routing algorithm with a stability probability of M_m :

$$M_m = 1 - \prod_{i=1}^n (1 - (1 - p)^{n_i}) \quad (34)$$

It can be obtained

$$M_m \geq M_s \quad (35)$$

Therefore, multipath routing algorithms have higher stability than single-path routing algorithms, and it is easier to perform the route discovery process only once to complete data delivery without performing multiple route discovery processes.

Proof :

Use mathematical induction for proof

When $n=1$

$$M_m = 1 - \prod_{i=1}^n (1 - (1-p)^{n_i}) = (1-p)^{n_i} \quad (36)$$

$$M_m = (1-p)^{n_i} \geq (1-p)^{n_i} = M_s \quad (37)$$

Assuming that for $n = m$

$$M_m = 1 - \prod_{i=1}^m (1 - (1-p)^{n_i}) \geq (1-p)^{n_i} = M_s \quad (38)$$

When $n = m + 1$

$$\begin{aligned} M_m &= 1 - \prod_{i=1}^{m+1} (1 - (1-p)^{n_i}) \\ &= 1 - \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1 - (1-p)^{n_{m+1}}) \\ &= 1 - \prod_{i=1}^m (1 - (1-p)^{n_i}) + \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1-p)^{n_{m+1}} \quad (39) \\ &\geq 1 - (1-p)^{n_i} + \left\{ \prod_{i=1}^m (1 - (1-p)^{n_i}) \right\} (1-p)^{n_{m+1}} \\ &\geq (1-p)^{n_i} = M_s \end{aligned}$$

This is proved by equations (37), (38) and (39)

$$M_m = 1 - \prod_{i=1}^n (1 - (1-p)^{n_i}) \geq (1-p)^{n_i} \quad (40)$$

It can be seen that the multipath routing algorithm has higher stability than the single path routing algorithm, the link is not easily interrupted, and the sending of routing control packets can be reduced to complete the data transmission with minimum cost.

D. Delay

The data transmission delay is related to the processing power of the node and the number of node hops. There are d data packets waiting to be transmitted during one transmission. Defines the time to transmit a packet on path i as $1/F_i$. A set of data is composed of a packets, and each packet has the same size.

The single-path routing algorithm delay is T_s , and the multipath routing algorithm delay is T_m , we can get

$$T_m \leq T_s \quad (41)$$

If the same packet is sent without considering blocking, the transmission delay of multipath routing algorithm is smaller than that of single-path routing algorithm, which can finish sending data faster.

Proof :

Single-path routing algorithm:

$$T_s = \frac{d \times \frac{1}{F_t}}{d} \times a = \frac{a}{F_t} \quad (42)$$

multi-path routing algorithm:

$$\begin{aligned} T_m &= \frac{\sum_{i=1}^n d_i \times \frac{1}{F_i}}{d} \times a \\ &= \frac{\sum_{i=1}^n \frac{F_i}{\sum_{i=1}^n F_i} \times d \times \frac{1}{F_i}}{d} \times a \quad (43) \\ &= \frac{a}{\sum_{i=1}^n F_i} \end{aligned}$$

When $n=1$

$$\frac{1}{F_t} = \frac{1}{\sum_{i=1}^n F_i} \quad (44)$$

$$T_m = T_s \quad (45)$$

When $n>1$

$$F_t < \sum_{i=1}^n F_i \quad (46)$$

$$\frac{1}{F_t} > \frac{1}{\sum_{i=1}^n F_i} \quad (47)$$

$$T_m < T_s \quad (48)$$

So, when blocking is not considered, there is

$$T_m \leq T_s \quad (49)$$

Then the transmission delay of multipath routing algorithm is smaller than that of single-path routing algorithm for sending the same packets.

IV. SIMULATION RESULTS

This subsection further verifies the validity of the model through simulation experiments. The simulation experiments are carried out with the help of MATLAB R2016b. The corresponding MATLAB language program is written to simulate the analytical model of the routing algorithm based on Markov process and to demonstrate the validity of the model in terms of energy consumption, time delay, path stability and throughput. Since in multipath transmission the more paths there are, the more energy is consumed in the route discovery process, the more complex the data will be, and if there are fewer paths the effectiveness of the comparison will be lacking, so this paper uses 5 paths for simulation. The values of the simulation parameters are defined in Table 3.

The four performance indicators compared in this experiment are shown below.

Energy consumption: the amount of energy consumed to execute a complete transmission process.

Stable probability: the probability of successfully completing a data transfer process without interruption.

Throughput: the number of packets that can be sent if energy is depleted.

Delay: the time required to send a set of data packets.

TABLE III
SIMULATION PARAMETER

Parameter	Value
n	5
n_1	5
n_2	6
n_3	7
n_4	8
n_5	9
p	0.2
f_c	5
f_l	2
λ	0.2
α	0.75
d	500
E_0	3000

A. Energy Consumption

In order to compare the energy consumption of the two different routing algorithms during data transmission, this experiment gradually increases the total number of packets sent, with both single-path and multipath routing algorithms using all available paths for data transmission, and records the energy consumption during data transmission. It is assumed that the number of packets waiting to be transmitted during transmission from source node S to destination node D gradually increases from 0 to 500. The experimental simulation results are shown in Figure 2, using the single-path routing algorithm and the multipath routing algorithm for data transmission respectively.

As can be seen from the graph, the energy consumption of the single-path routing algorithm and the multipath routing algorithm gradually increases as the number of packets gradually increases. When the multipath completes the entire transmission process, the energy consumption tends to a constant value. In contrast, the energy consumption of the single-path routing algorithm increases before it has completed the entire transmission process. When the number of packets is small, the total energy used by the single-path and multipath routing algorithms is essentially the same, but as the number of packets increases, the energy consumption per path in the multipath routing algorithm is much less than the energy consumption of the single-path. Moreover, as the energy of the nodes gradually decreases, the nodes' sending efficiency will decrease, causing congestion, which will further increase the energy consumption of the single-path routing algorithm, and when the number of packets is large enough, the single-path routing algorithm may not be able to complete the transmission process. Experimental results show that the multipath routing algorithm consumes less per path than the single-path routing algorithm, which can balance the load between different paths and avoid the situation where the transmission cannot be completed due to too many packets and too much energy consumption leads to link disruption.

B. Throughput

The actual throughput of a computer network refers to the maximum rate that a device can receive without losing frames and is an important tool for performing network tests. As the energy source of the wireless nodes is the battery, the energy is limited. In this model, a certain size is set for each packet in this experiment and the throughput can be expressed as the number of packets sent in a given time. It is assumed that the data volume is large enough that data transmission can continue to be sent from source node S to destination node D without considering node damage interruptions until the node runs out of energy. The initial energy value for each node is defined as 200 and is incremented by 10. The throughput of the single-path routing algorithm and the multipath routing algorithm are shown in Figure 3.

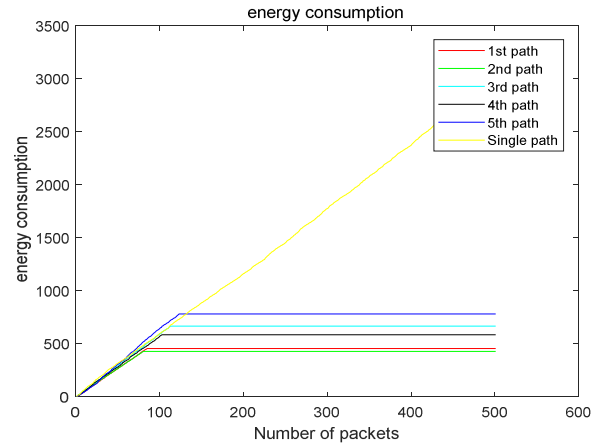


Fig. 2. Energy Consumption Simulation Result

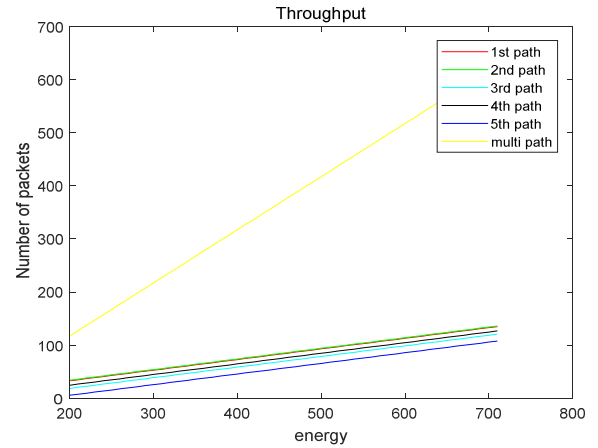


Fig. 3. Throughput Simulation Result

The graph shows that as the node energy value grows from 200 to 700, the throughput of both the single-path routing algorithm and the multi-path routing algorithm grow gradually, but the throughput of the multi-path routing algorithm grows faster than the single-path routing algorithm. As the energy value gets larger, the difference between the throughput of the multi-path routing algorithm and the single-path routing algorithm also gets larger. The experimental results show that for the same situation, the throughput of the multi-path routing algorithm is much greater than that of the single-path routing algorithm, and this difference becomes even greater as the transmission time increases. Due to the poor stability of the single-path routing

algorithm, this gap becomes even more pronounced in the event of node corruption.

C. Stable probability

During data transmission, as soon as one node on the path is corrupted, the entire link is broken and when all available paths are corrupted, the route discovery process is restarted and the path is found again. A single-path routing algorithm with only one path will restart the route discovery process as soon as one node is damaged. However, in a multi-path routing algorithm, even if a path is corrupted, tasks on that path are assigned to other paths until the data transfer is complete. To compare the stability of the single-path routing algorithm and the multi-path routing algorithm, this experiment assumes that the probability of damage to a single node is 0.2 for simulation experiments, and the stability probabilities of the single-path routing algorithm and the multi-path routing algorithm are shown in Figure 4.

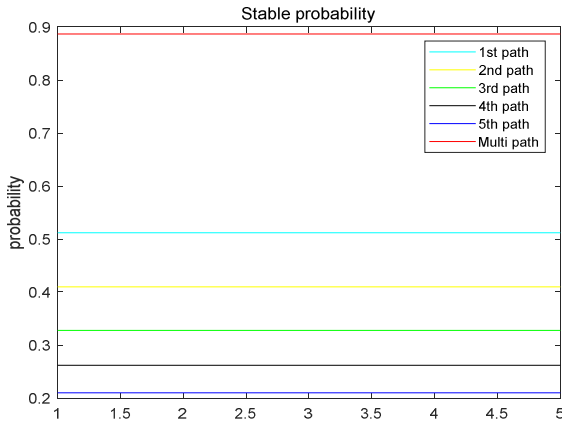


Fig. 4. Stable Probability Simulation Result

The graph shows that using a single-path for data transmission has the highest probability of node stability at 51.2%, followed by 40.96%, 32.77%, 26.21% and 20.97%. The stability probability of a single-path decreases as the number of nodes in the path increases; the more nodes there are, the more likely the data transmission is to be interrupted. The stability probability of multi-path routing algorithm is much higher than that of single-path routing algorithm, reaching 88.70%, the more paths there are, the higher the stability of the link. The experimental results show that the multi-path routing algorithm is more stable than the single-path routing algorithm, and it has a higher probability of successfully completing the data transmission without interruption.

D. Delay

The end-to-end delay is defined as the propagation delay, and the time it takes for data to propagate from the source node S of that link to the destination node D is the propagation delay. To compare the effect of the number of packets on the delay, this experiment gradually increased the number of packets and used the single-path routing algorithm and the multi-path routing algorithm for packet transmission respectively. In the experiment, the packets were gradually increased from 0 to 500, and then the propagation delay was tested. The results of the end-to-end delay experiment are

shown in Figure 5.

The experimental results show that the latency of the single-path routing algorithm and the multi-path routing algorithm grows with the number of packets, but the single-path routing algorithm grows faster than the multi-path routing algorithm. It can also be seen that for the same amount of data sent, the multi-path routing algorithm has a lower latency than the single-path routing algorithm. This latency becomes more pronounced as more and more packets are sent, as the more packets sent, the less energy the node has, resulting in reduced processing power and a corresponding increase in latency. As buffers have a certain size and the packet delivery rate of a single-path is low, if more packets come in at the same time, it will cause congestion on the link, resulting in increased queuing delays, whereas a multi-path routing algorithm has multiple paths to share the task, which will not cause congestion or less congestion and will have less delay than a single-path routing algorithm.

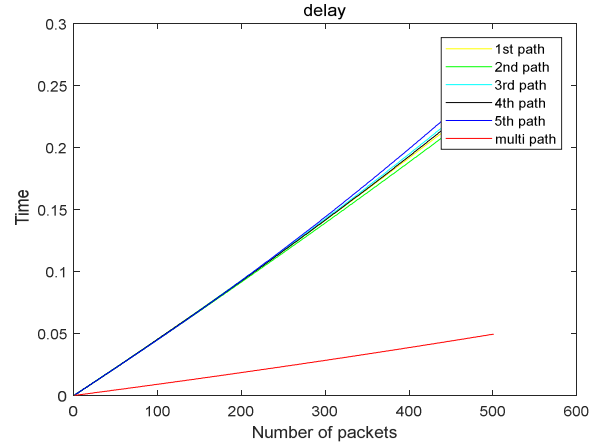


Fig. 5. Delay Simulation Result

V. CONCLUSION

This paper addresses the performance of multi-path routing protocols and single-path routing protocols. The randomness and the possible energy loss during transmission are considered, and the path selection is established in the form of a finite Markov model with the residual energy and the number of path hops as the selection conditions. The four metrics of energy consumption, stability probability, throughput, and delay in single-path and multi-path data transmission are analyzed theoretically and simulated experimentally, and the experimental results prove that the multi-path routing protocol performance is better than the single-path routing protocol performance. Further research in the future will focus on the path congestion and the impact of link coupling on performance.

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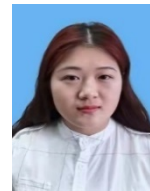
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