Cross-layer and Reliable Opportunistic Routing Algorithm for Mobile Ad Hoc Networks

Ning Li, *student member, IEEE*, Jose-Fernan Martinez-Ortega, Vicente Hernandez Diaz

Abstract—For improving the efficiency and the reliability of the opportunistic routing algorithm, we propose a cross-layer and reliable opportunistic routing algorithm (CBRT) for Mobile Ad Hoc Networks, in which the fuzzy logic and topology control are introduced into the opportunistic routing algorithm. In CBRT, the inputs of the fuzzy logic system are the relative variances (rv) of the metrics rather than the metrics' values; by this, the number of fuzzy rules is reduced dramatically. Moreover, the number of fuzzy rules does not increase when the number of inputs increases. For improving routing reliability and reducing the control cost, in CBRT, the relay node degree is a range rather than a constant number. The nodes are divided into different categories based on their relay node degree. The nodes adjust their transmission power based on which categories that they belong to. Additionally, for investigating the effect of the node mobility on routing performance, we propose a link lifetime prediction algorithm which takes the moving speed and moving direction into account. In CBRT, the source node determines the relaying priorities of the candidate relay nodes based on their utilities. The relay node whose utility is large has high priority to forward the data packet to next hop. By these innovations, the performance of CBRT is much better than that of ExOR; however, the computation complexity does not increase in CBRT.

Index Terms—Cross-layer, fuzzy logic, topology control, opportunistic routing.

I. INTRODUCTION

The Mobile Ad Hoc Networks (MANETs) are widely used in the Internet of Things (IoT), such as in battlefield [1][2], vehicle networks [3][4][5], underwater cooperation robot networks [6][7][8], etc. In MANETs, one of the important issues is the routing protocol design, which guarantees reliable and efficient data transmission from source node to destination node. There are two routing strategies for the MANETs: deterministic routing and opportunistic routing [9]. In deterministic routing, the sender sends data packet to one neighbor which is chosen based on the optimal algorithms; in opportunistic routing, the sender sends the data packet to a set of relay nodes rather than only one relay node to improve the packet delivery ratio between sender and receiver [10][11][12][13]. In this paper, we mainly focus on the opportunistic routing.

A. Motivations

Ning Li, Jose-Fernan Martinez-Ortega, and Vicente Hernandez Diaz are with the Universidad Politecnica de Madrid, Madrid, Spain.

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In opportunistic routing, the source node chooses the candidate relay set (CRS) [13] and decides the priorities of the relay nodes based on specific metrics, such as the distance to the destination node, the expected transmission count (ETX), the propagation delay, the packet queue length, etc. [13]. These performance metrics are relevant and interplay; the more performance metrics are taken into account, the better routing performance is [14]. In traditional opportunistic routing algorithm, since the source node chooses the relay nodes based on a limited number of metrics, so it cannot reflect the comprehensive characteristics of the node. For instance, when the source node chooses and prioritizes the relaying nodes based on their ETX, the nodes whose ETX is small will be chosen and set with high priorities. However, considering the parameters in MAC layer, link layer, or physic layer, the node which the ETX is small does not mean that the other parameters are also optimal. For finding the tradeoff between different cross-layer parameters, the fuzzy logic has been introduced into the routing algorithm design, such as in [14], [15], [16], [17], and [18], etc. However, the main disadvantage of fuzzy logic is that when the number of inputs increases, the number of fuzzy rules increases exponentially, which will be proved in Section III. This will limit the future performance improvement in the fuzzy logic based opportunistic routing algorithms. In general, at the moment, the common number of inputs is no larger than 3 [14-18]. So one of the purposes in this paper is how to reduce the computation complexity of the fuzzy logic system that caused by the increase of the inputs' number.

In opportunistic routing, the more nodes in CRS, the higher packet delivery ratio between the sender and the CRS is; vice versa. However, due to the mobility of the nodes in MANETs, the number of neighbors changes frequently, so the packet delivery ratio between the sender and the CRS changes frequently, too. In case there are too few or too many relay nodes in CRS, we introduce the topology control, which is good at controlling the number of neighbors [19], into the opportunistic routing algorithm. However, due to the high mobility of nodes in MANETs, if each node maintains a constant number of nodes in CRS, the transmission power needs to be adjusted frequently, which will consume a plenty of network resource that could have been used in data packet transmission. So the topology control algorithm should be able to reduce the extra control cost as far as possible. Moreover, since the node mobility has great effect on the routing performance, so the node mobility, including the moving speed and moving direction, should also be taken into account during the routing algorithm design.

B. Main contributions

Motivated by these, we propose the cross-layer and reliable opportunistic routing algorithm (CBRT) for MANETs in this paper. In CBRT, the inputs of the fuzzy logic system are the relative variances (rv) of the metrics rather than the metrics' values, which can reduce the number of fuzzy rules dramatically. Moreover, the number of fuzzy rules does not increase when the number of inputs increases. For reducing the control cost, the number of nodes in CRS is a range rather than a constant number. The nodes are divided into different categories based on the numbers of nodes in their CRS. The nodes adjust their transmission power based on which categories that they belong to. The source node determines the priorities of the relay nodes in CRS based on the utilities of these nodes. The relay node which the utility is large has high relaying priority. The main contributions of this paper are summarized as follows:

- We propose a scatter based fuzzy logic algorithm (SBFL) which can handle multiple cross-layer parameters at the same time without increasing the computation complexity; to the best of our knowledge, this is the first algorithm which can take multiple cross-layer parameters into account without increasing the computation complexity seriously.
- We propose a link lifetime prediction algorithm which takes both the moving speed and the moving direction into account to improve the accuracy;
- We propose a packet delivery ratio based opportunistic topology control algorithm for maintaining stable node number in CRS; in this algorithm, the node number in CRS is stable and the transmission power adjustment ratio is low;
- Based on the topology control algorithm and SBFL algorithm, we propose the cross-layer balanced and reliable opportunistic routing algorithm, which utilizes both the fuzzy logic and topology control to improve the routing performance.

The remaining of this paper organized as follows: in Section 2, we introduce the related works; Section 3 introduces the principle of SBFL; the link lifetime prediction algorithm and the packet delivery ratio based topology control algorithm are presented in Section 4; moreover, the CBRT algorithm is also introduced in Section 4; Section 5 evaluates the performance of the SBFL algorithm and the CBRT algorithm, and compares the CBRT algorithm with the ExOR algorithm; Section 6 concludes the work in this paper.

II. RELATED WORKS

Since the opportunistic routing has been proposed by Sanjit Biswas and Robert Morris [20], many opportunistic routing algorithms have been developed in recent years. In [21], the authors propose a relaying node selection algorithm for a 1-D wireless sensor network, named energy saving via opportunistic routing (ENS_OR). The ENS_OR selects the candidate relays set and prioritizes the nodes in it based on their virtual optimal transmission distance and residual energy level. The nodes which are closer to the energy equivalent

nodes and have more residual energy than the source node will be selected as the relaying nodes. In [22], the authors propose two accurate energy consumption based objective functions, which exploit the knowledge of both the frame error ratio within the physical layer, the maximum number of retransmissions in the medium access control (MAC), and the number of relays in the network layer. Based on the objective functions, the routing algorithm is designed for opportunistic routing, which employs the objective functions to prioritize the nodes in the candidate relays set. The authors in [23] exploit the geographic opportunistic routing (GOR) for Quality of Services (QoS) provisioning with both the end to end reliability and delay constraints in wireless sensor networks (WSNs); moreover, the authors also define the problem of efficient GOR for multiconstrained QoS provisioning in WSNs. Based on these conclusions, the authors propose the Efficient QoS-aware GOR protocol for the WSNs, in which the energy efficiency, latency, and the time complexity are taken into account to select the relaying nodes. The authors in [24] propose a distributed optimal community-aware opportunistic routing algorithm, in which the home-aware community model is proposed. In this algorithm, first, the routing between lots of nodes are turned to the routing between a few community homes; then the algorithm maintains an optimal candidate relays set for each home. Each home only forwards its message to the node in its optimal candidate relays set. More opportunistic routings can be found in [25], [26] and [13]; especially in [13], the author reviews the opportunistic routing algorithms in recent years and identifies and discusses the future research directions related to the opportunistic routing design, optimization, and deployment.

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Recently, more and more researchers consider that integrate the topology control into the routing algorithm in wireless sensor network or ad hoc network is an effective way to improve the network performance. In [36], the authors proposed three alternative mathematical models for integrating topology control and routing decisions so as to prolong the lifetime of sensors. For reducing the effect of primary user (PU) activities and node mobility to the stability of links in mobile cognitive networks, in [37], the authors proposed a primary user activity prediction based joint topology control and stable routing protocol (PP-JTCSR), which can quantitatively capture channel utilization patterns of PUs. By topology control in PP-JTCSR, the most stable and shortest path can be found. In [38], the authors investigate the impact of two topology control methods for resolving the problem of void/isolated nodes appeared in geographic routing protocols, which can reduce the number of void/isolated nodes significantly. In [39], the authors have shown that joint topology control and routing assignment as an optimization problem is a NP-hard problem. For solving this problem, in this paper, the author proposed TORA (joint topology control and routing assignment) which seeks to jointly optimize topology and routing for DMesh (directional antennas in wireless mesh networks). There are also many researchers that combine the routing design with the topology control, which can be found in [40], [41], [42], and [43].

III. PRINCIPLE OF THE SCATTER BASED FUZZY LOGIC ALGORITHM

In this section, the principle of scatter based fuzzy logic algorithm (SBFL) will be introduced in detail.

A. Problem statement

As shown in Figure 1, the fuzzy logic system is divided into three modules: fuzzification, fuzzy logic inference, and defuzzification.

Fig. 1. The process of fuzzy logic system

In fuzzification module, the input variables are mapped to fuzzy set based on linguistic variables and membership functions. Assuming that the input universe is U and the fuzzy set of universe U is A ; μ_A is the membership function which maps universe U to fuzzy set A . The membership function represents the membership between universe U and fuzzy set A , i.e., $\mu_A: U \rightarrow A \in [0,1]$. The fuzzy set A can be expressed as: $A = \{(u_i, \mu_A(u_i)) | u_i \in U\}$, where u_i is the element of universe U . The general definition of the membership function is:

$$\begin{cases} \mu_A(u_i) = 1: & u_i \text{ belongs to } A \text{ complete;} \\ \mu_A(u_i) = 0: & u_i \text{ does not belong to } A \text{ complete;} \\ 0 < \mu_A(u_i) < 1: & u_i \text{ belongs to } A \text{ partly;} \end{cases} \quad (1)$$

The fuzzy set A is the input of the fuzzy inference module which will be used to calculate the output fuzzy set B . The core part of the fuzzy inference system is the *if-then* rules (fuzzy rules). The *if-then* rules determine the relationship between the inputs (fuzzy set A) and outputs (fuzzy set B). The form of the fuzzy rule is generally expressed as:

$$\text{If } A \text{ (input) then } B \text{ (output)} \quad (2)$$

where A and B are the fuzzy sets of universe X (input) and Y (output), respectively. The membership functions are $\mu_A(x_i)$ and $\mu_B(y_i)$, where $x_i \in X$, $y_i \in Y$. Thus according to the fuzzy mathematics theory (Mamdani fuzzy inference algorithm), the membership function between fuzzy set A and fuzzy set B can be decided by:

$$\mu_{A \rightarrow B}(x, y) = \mu_R(x, y) = \mu_A(x) \wedge \mu_B(y) \quad (3)$$

where R represents the fuzzy relationship between universe X and universe Y , i.e., $R = A \rightarrow B$; “ $\wedge$ ” is the conjunction operator in discrete mathematics. By (3), the fuzzy result can be got.

However, for taking more cross-layer performance metrics into account, the fuzzy rules will be much more complex than that shown in (2), which is a multi-inputs-single-output fuzzy system. In this scenario, the fuzzy rules will be:

$$\text{If } A_1, A_2, A_3, \dots, A_n \text{ then } B \quad (4)$$

where $A_1, A_2, A_3, \dots, A_n$ (inputs) and B (output) are the fuzzy sets of universes $U_1, U_2, U_3, \dots, U_n$ (inputs) and U (output), respectively. The membership functions are $\mu_{A_1}(u_1), \mu_{A_2}(u_2), \mu_{A_3}(u_3), \dots, \mu_{A_n}(u_n), \mu_B(u)$, where $u_1 \in U_1, u_2 \in U_2, u_3 \in U_3, \dots, u_n \in U_n, u \in U$. So the membership function can be expressed as:

$$\begin{aligned} \mu_{\{A_1, A_2, A_3, \dots, A_n\} \rightarrow B}(u_1, u_2, u_3, \dots, u_n, u) &= \mu_R(u_1, u_2, u_3, \dots, u_n, u) \\ &\stackrel{\Delta}{=} \mu_{A_1}(u_1) \wedge \mu_{A_2}(u_2) \wedge \mu_{A_3}(u_3) \cdots \wedge \mu_{A_n}(u_n) \wedge \mu_B(u) \end{aligned} \quad (5)$$

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As shown in (5), in the multi-inputs-single-output fuzzy system, the number of the permutation and combination between the fuzzy sets are huge. The (5) illustrates that with

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$$\begin{aligned} \mu_{\{A_1, A_2, A_3, \dots, A_n\} \rightarrow B}(u_1, u_2, u_3, \dots, u_n, u) &= \mu_R(u_1, u_2, u_3, \dots, u_n, u) \\ &\stackrel{\Delta}{=} \mu_{A_1}(u_1) \wedge \mu_{A_2}(u_2) \wedge \mu_{A_3}(u_3) \cdots \wedge \mu_{A_n}(u_n) \wedge \mu_B(u) \end{aligned} \quad (5)$$

where $R = \{A_1, A_2, A_3, \dots, A_n\} \rightarrow B$ is the fuzzy relationship between universe $U_1, U_2, U_3, \dots, U_n$ and U .

As shown in (5), in the multi-inputs-single-output fuzzy system, the number of the permutation and combination between the fuzzy sets are huge. The (5) illustrates that with

the increase of the fuzzy set, the calculation complexity of the fuzzy logic system increases seriously. Moreover, if we take the number of linguistic variables into account, the calculation is too complex to be accepted. For instance, if the number of linguistic variables is n and the number of fuzzy sets is m , then according to (5), the total number of the fuzzy rules is n^m . This means that with the increase of either the fuzzy set or the linguistic variables, the number of the fuzzy rules increases exponentially. A large number of fuzzy rules need large memory space, which is always impractical in MANETs. For solving this issue, we propose an algorithm which can isolate the effect of the number of inputs on calculation from the fuzzy inference system, i.e., the number of fuzzy rules does not increase when the number of inputs increases. This algorithm is named the scatter based balanced fuzzy logic algorithm, shorted as SBFL.

B. Principle of the SBFL algorithm

Considering the fact that during the relay node selection and prioritization, the performance metric (such as the residual energy, the ETX, the distance to the destination node, etc.) whose variation rate is large has greater effect on the routing performance than that of the metric whose variation rate is small. For instance, as the performance metrics shown in Table 1, in which the variation rate of Metric_1 is smaller than that of Metric_2. During the relaying node selection and prioritization, from the point of view of Metric_1, which node is chosen as the next hop relay node has small effect on the routing performance, since the values of Metric_1 in these three nodes are similar; however, considering the values of Metric_2, which node is chosen has greater effect on the routing performance than that of Metric_1. For evaluating the variation rate of the metrics, one of the available parameters is the variance. However, as shown in Table 1, the variance is affected seriously by the metric's value. In Table 1, the variance of Metric_1 is larger than that of Metric_2; however, taking the metrics' values into account, the variation rate of Metric_1 is smaller than that of Metric_2 in fact. So a new parameter should be developed for reflecting the accurate variation rate of the performance metrics.

TABLE 1
METRICS AND PRIORITIES

	node1	node2	node3	V	rv	weight ¹
Metric_1	1001	1002	1003	0.667	6.64×10^{-6}	0.0523
Order of Metric_1	1	2	3			
Metric_2	0.5	0.8	0.1	0.0822	0.377	0.753
Order of Metric_2	2	3	1			
Metric_3	1000	2000	3000	666667	0.167	0.333
Order of Metric_3	1	2	3			
Node utility ²	1.891	2.697	1.909			

¹ this weight is calculated by the traditional fuzzy logic algorithm, in which the number of linguistic variables is 3 [29];

² this utility is calculated by (12).

universes, which is $U = [U_1, U_2, U_3, \dots, U_n]$; for each universe, there are m elements, i.e. $U_i = [U_i^1, U_i^2, U_i^3, \dots, U_i^m]^T$; therefore,

$$U \text{ is a } n \times m \text{ matrix: } \begin{bmatrix} U_1^1, U_2^1, U_3^1, \dots, U_n^1 \\ U_1^2, U_2^2, U_3^2, \dots, U_n^2 \\ U_1^3, U_2^3, U_3^3, \dots, U_n^3 \\ \vdots \\ U_1^m, U_2^m, U_3^m, \dots, U_n^m \end{bmatrix}.$$

For reflecting the variation rate of the metric more accurately, we propose the relative variance (rv) which takes the average value of the metrics into account to evaluate the variation rate of the metric, defined as:

$$D_i = \frac{1}{m} \sum_{j=1}^m \left(\frac{U_i^j - \bar{U}_i}{\bar{U}_i} \right)^2, i \in [1, n] \quad (6)$$

where U_i^j means the j th element of U_i ; $\bar{U}_i$ is the mean value of the parameters in U_i and can be calculated as:

$$\bar{U}_i = \frac{1}{m} \sum_{j=1}^m U_i^j, i \in [1, n] \quad (7)$$

In (6), the variation rate is not affected by the metric's value, which can be found in Table 1. In Table 1, even the variance of Metric_1 is larger than that of Metric_2, the rv of Metric_1 is much smaller than that of Metric_2; so the relative variance can reflect the variation rate of the metric more accurately than variance.

In SBFL, the input universes $U_1, U_2, \dots, U_n$ are replaced by the relative variance D as the input of the fuzzy inference system. The fuzzy set A_D can be expressed as:

$$A_D = \{(d, d_A(d_i)) | d_i \in D\} \\ = [d_A(d_1), d_A(d_2), d_A(d_3), \dots, d_A(d_n)] \quad (8)$$

where $d_A(d_i)$ is the membership function between scatter D and fuzzy set A_D . Since the scatter D is a $1 \times n$ matrix, so the fuzzy rules shown in (5) can be rewritten as: *If A_D then B* . Therefore, the membership function between A_D and B will be:

$$\mu_{D \rightarrow B}(z, y) = \mu_R(z, y) = \mu_D(z) \wedge \mu_B(y) \quad (9)$$

As shown above, the membership function in (9) is much simpler than that in (5). By using the concept of relative variance, the number of the fuzzy sets has been reduced from n to 1, so the calculation complexity is reduced. Moreover, the number of fuzzy rules in SBFL does not increase when the number of fuzzy set and the linguistic variables increase. Additionally, as shown in Figure 2, the complexity caused by the increase of the number of inputs has been isolated from the fuzzy inference system successfully. This means no matter how many different universes are used, the number of fuzzy logic input is only one by using SBFL, which means that the computation complexity is low.

In SBFL algorithm, assuming that there are n input

Fig. 2. (a) The principle of the traditional fuzzy logic system; (b) The principle of SBFL algorithm.

The outputs of SBFL are the weights of the cross-layer metrics:

$$\omega = [\omega_1, \omega_2, \omega_3, \omega_4, \dots, \omega_m] \quad (10)$$

In SBFL, the cross-layer metrics whose rv are high have great effect on the relay node selection, vice versa; therefore, the weights of the metrics are large when their rv are large; otherwise, the weights are small. Moreover, as the number of the linguistic variables in SBFL can be set as large as possible, so according to [14], the number of the linguistic variables is set to 7 in this paper (the number of linguistic variables can be any positive integer; the more linguistic variables, the more accuracy of the result is; however, the computation complexity increases slightly). The fuzzy linguistic variables and the fuzzy rules are shown in Table 2.

TABLE 2
FUZZY LOGIC RULES

IF Input (D)	THEN Output (ω)
very small	very small
medium small	medium small
small	small
medium	medium
large	large
medium large	medium large
very large	very large

When the weight of each cross-layer metric has been got, the ω and U will be used to calculate the utilities of nodes in CRS:

$$\begin{aligned} \psi &= \omega \times U = [\psi_1, \psi_2, \psi_3, \psi_4, \dots, \psi_n] \\ &= [\sum_{j=1}^m \omega_j \cdot U_1^j, \sum_{j=1}^m \omega_j \cdot U_2^j, \dots, \sum_{j=1}^m \omega_j \cdot U_n^j] \end{aligned} \quad (11)$$

However, the important issue should be paid attention in SBFL is that the order-of-magnitude of the metrics are different, which have great effect on the algorithm. If we use the values of these metrics directly in SBFL algorithm, there will have mistakes. For instance, considering the metrics shown in Table 1, the values in Metric_3 is much larger than that in Metric_2 and Metric_1. If the SBFL algorithm is applied directly, the utilities of node1, node2, and node3 are 385.73, 719, and 1051.54, respectively. As a result, the priorities of these nodes are: $node3 \rightarrow node2 \rightarrow node1$; however, these node utilities are decided mainly by the value of Metric_3. The Metric_3 will cover up the effect of Metric_1 and Metric_2 on the relay node selection. The reason is that the metrics in Table 2 are not in the same order-of-magnitude; therefore, the parameters whose order-of-magnitudes are larger than others have great effect on the SBFL algorithm.

In this paper, for solving this issue, we introduce the metric

priority into the node utility calculation. The metric priority can reflect the relationship of these metrics. For instance, as the metrics in Table 1, the priorities of each metrics are given. The priority of Metric_i is denoted as R_{Metric_i} . So the (11) can be rewritten as:

$$\begin{aligned} \psi &= \omega \times R = [\psi_1, \psi_2, \psi_3, \psi_4, \dots, \psi_n] \\ &= [\sum_{j=1}^m \omega_j \cdot R_{Metric_1}^j, \sum_{j=1}^m \omega_j \cdot R_{Metric_2}^j, \dots, \sum_{j=1}^m \omega_j \cdot R_{Metric_n}^j] \end{aligned} \quad (12)$$

According to (12), the utilities of these three nodes are shown in Table 1. By using (12), the node priorities will be: $node2 \rightarrow node3 \rightarrow node1$, which is more reasonable than that of the node utilities that calculated by (11). As shown in Table 1, the orders of the node utilities are decided by these three performance metrics jointly; the order of the node utilities is different with the order of any performance metrics.

A simple example can be found as follows. In this example, we will evaluate the effectiveness of SBFL algorithm. The parameters are shown in Table 3. There are five nodes and three metrics for each node.

TABLE 3
AN EXAMPLE

	node1	node2	node3	node4	node5	rv	weight ³
metric1	45.1	84	22.9	91.3	15.2	0.361	0.849
R_{metric_1}	3	4	2	5	1		
metric2	0.602	0.263	0.654	0.689	0.784	0.091	0.233
R_{metric_2}	2	1	3	4	5		
metric3	826	538	996	78	443	0.305	0.76
R_{metric_3}	4	3	5	1	2		
Utility1 ¹	6.053	5.909	6.197	5.931	3.534		
Utility2 ²	0.501	0.467	0.527	0.5	0.44		

¹ the node utility calculated by (12);

² the node utility calculated by the traditional fully logic algorithm, which the number of linguistic variables is 3 [29];

³ the weight is calculated based the fuzzy logic algorithm proposed in this algorithm.

Table 3 shows the performance of the traditional fuzzy logic algorithm and SBFL algorithm on determining the nodes' priorities, respectively. Table 3 demonstrates that based on SBFL algorithm, the utilities of node1, node2, and node4 are similar, which are larger than node5; the utility of node3 is the largest in these five nodes. Therefore, the priorities of these nodes are: $node3 \rightarrow node1 \rightarrow node4 \rightarrow node2 \rightarrow node5$. The priorities of the nodes that decided by the traditional fuzzy logic algorithm are also presented in Table 3, which are: $node3 \rightarrow node1 \rightarrow node4 \rightarrow node2 \rightarrow node5$; this is the same as the node utilities that calculated by (12). This demonstrates that the approach shown in (12) is effective on determining the relay priorities of the relay nodes.

Another disadvantage of the traditional fuzzy logic algorithm is the calculation complexity. In this simulation, to the traditional fuzzy logic algorithm, the number of the performance metric is 3 in each node and the number of the linguistic variable is 3, so the number of fuzzy rules is 27; however, in the SBFL algorithm, this number is only 7, which is equal to the number of the linguistic variables. This can be found in Figure 3. In Figure 3(a), with the increase of the fuzzy sets, the number of the fuzzy rules in traditional fuzzy

logic algorithm increases exponentially; however, this number will keep constant in SBFL algorithm. The similar result can be found in Figure 3(b). In Figure 3(b), with the increase of the linguistic variables, the fuzzy rules in the traditional fuzzy logic system increase exponentially like that in Figure 3(a); however, in SBFL algorithm, the increase is slight and equals to the number of the linguistic variables. Figure 3 demonstrates that the SBFL algorithm has great advantages on dealing with the multi-inputs issues.

Fig. 3. The number of rules: (a) the number of linguistic variables is fixed; (b) the number of the fuzzy set is fixed.

IV. CROSS-LAYER BALANCED AND RELIABLE OPPORTUNISTIC ROUTING ALGORITHM

Based on the SBFL algorithm that proposed in Section 3, we propose the cross-layer and reliable opportunistic routing algorithm (CBRT) for MANETs in this section. Considering the node mobility in MANETs, the topology control algorithm and the link lifetime prediction algorithm which takes both the moving speed and the moving direction into account are developed in this section.

A. Link lifetime prediction algorithm

In MANETs, due to the node mobility, the network topology changes frequently, so the route easy to be broken and cannot last a long time [44]. The link lifetime is affected by the node mobility seriously. The node mobility includes the moving speed and moving direction. Both these two parameters can affect the link lifetime. However, in the

previous works, the effect of the moving direction on the link lifetime has not been fully investigated. In this section, this issue will be investigated in detail.

The link lifetime prediction is difficult in MANETs because the nodes can move freely [44]. During the calculation, we assume that the link connections are unstable and can only last a short period of time [44]; so we can assume reasonably and simply that the nodes move at a constant speed and do not change their moving direction in such a short period [44][56-59]. Moreover, in CBRT, each node equips a GPS device [44], which can be used to obtain the node's coordinate and the moving speed and direction [44][56-59].

The node acquires other nodes' location by periodical probe packet exchanging. In this algorithm, only the neighbors whose distances to the destination node are smaller than that of the source node can be considered as the candidate relay nodes. As shown in Figure 4, when the nodes located in the red area (which is defined as the survival area; the survival area means that in this area, the link connection can be guaranteed), the link lifetimes are larger than 0. The value of the link lifetime relates to the source node s , the relaying node r , and the destination node d . Due to the mobility of the source node s and the destination node d , the survival area changes continuously. In addition, considering the mobility of the relaying node r , the communication link will be broken when the node r moves out of the survival area. Therefore, the relative velocity of node r relative to node s and node d need to be calculated. The calculation of the relative velocity is shown in Figure 5.

The proposed link lifetime prediction algorithm is different with the previous works on the following aspects: 1) in the previous works, the link lifetime prediction need extra sample packets, such as, in [56], three sample packets are needed during the prediction, in [44], two sample packets are needed; however, in CBRT, no extra sample packet is needed; 2) in the previous works, the prediction area is the whole coverage area of the node and the coverage area only relates to node s and does not change relative to node s , i.e., the cycle shown in Fig. 4; however, in this paper, the prediction area is the survival area, which relates to both the node s and node d , and changes continuously relative these two nodes; so it puts more challenges than the previous works; 3) in the previous works, the moving direction of the node is not taken into account during the link lifetime prediction.

Fig. 4. Geographic based relay node selection

Fig. 5. The principle of the velocity vector operation

In Figure 5, the moving velocities of node s , node r , and node d are $\vec{v}_s$ (the moving speed is v_s and the moving direction is θ_s), $\vec{v}_r$ (the moving speed is v_r and the moving direction is θ_r), and $\vec{v}_d$ (the moving speed is v_d and the moving direction is θ_d), respectively. If the destination node d is chosen as the reference frame, then the relative velocity of source node s relative to node d is given by: $\vec{v}_{sd} = \vec{v}_s - \vec{v}_d$. According to the vector synthesis theory, the relative moving speed and moving direction of $\vec{v}_{sd}$ can be given by: $v_{sd} = \sqrt{v_{xsd}^2 + v_{ysd}^2}$, $\theta_{sd} = \arctan(v_{xsd} / v_{ysd})$, $v_{xsd} = v_s \cos \theta_s + v_d \cos \theta_d$, and $v_{ysd} = v_s \sin \theta_s + v_d \sin \theta_d$; where v_{xsd} is the moving speed of $\vec{v}_{sd}$ in x -axis and v_{ysd} is the moving speed of $\vec{v}_{sd}$ in y -axis. Therefore, the relative velocity of relay node r relative to $\vec{v}_{sd}$ can be calculated as: $\vec{v}_{sdr} = \vec{v}_r - \vec{v}_{sd}$. Similar to that shown above, the relative moving speed and moving direction of $\vec{v}_{sdr}$ can be got from: $v_{sdr} = \sqrt{v_{xsdr}^2 + v_{ysdr}^2}$, $\theta_{sdr} = \arctan(v_{xsdr} / v_{ysdr})$, $v_{xsdr} = v_r \cos \theta_r + v_{sd} \cos \theta_{sd}$, and $v_{ysdr} = v_r \sin \theta_r + v_{sd} \sin \theta_{sd}$, where v_{xsdr} is the speed of $\vec{v}_{sdr}$ in x -axis and v_{ysdr} is the speed of $\vec{v}_{sdr}$ in y -axis.

As shown in Figure 6, node r moves with velocity $\vec{v}_{sdr}$. Assuming that the node r will move out of the survival area at time t , according to Figure 6, there are two different scenarios about this issue: (1) the relaying node moves toward to the destination node; (2) the relaying node moves far away from the destination node. For solving this problem, we need to calculate the relative velocity angle for node r .

Fig. 6. The principle of the residual link lifetime calculation

As shown in Figure 6, assuming the coordinate of node s is (x_s, y_s) and the coordinate of node d is (x_d, y_d) , then the angle of $\vec{sd}$ relative to the x -axis can be got from:

$\theta_{sd} = \arctan(\frac{y_d - y_s}{x_d - x_s})$. According to $\theta_{sdr} = \arctan(v_{xsdr} / v_{ysdr})$ and the triangle geometry theory, the velocity angle of node r relative to $\vec{sd}$ is: $\theta_{rel} = \theta_{sdr} - \theta_{sd}$.

Therefore, if $\theta_{rel} \in [0, \pi/2] \cup [3\pi/2, 2\pi]$, the node r moves close to the destination node in x -axis or y -axis; otherwise, when $\theta_{rel} \in [\pi/2, 3\pi/2]$, the node r moves far away from the destination node in both x -axis and y -axis. So the link lifetime prediction should be divided into two different scenarios.

1. When $\theta_{rel} \in [0, \pi/2] \cup [3\pi/2, 2\pi]$

In this scenario, the relay node r moves toward to the destination node d in x -axis or y -axis. According to Figure 5 and the law of cosines, in triangle srd we can get the function as follows:

$$d_{dr}^2 = d_0^2 + d_{ds}^2 - 2d_0d_{ds}\cos\phi_3 \quad (13)$$

where d_{dr} is the distance between relay node r and destination node d ; d_0 is the distance between source node s and relay node r at the time t_0 ; d_{ds} is the distance between source node s and destination node d . Since the values of d_{dr} , d_0 , and d_{ds} can be calculated based on the coordinates of these nodes, so the value of ϕ_3 can be got from (13). Therefore, ϕ_2 can be calculated as: $\phi_2 = \pi - \phi_3$.

Additionally, in triangle srC , θ_{rel} and ϕ_3 are all known, so the angle α can be calculated: $\alpha = \pi - \phi_3 - \theta_{rel}$. In triangle srA , according to the law of cosines, we can get:

$$R^2 = d_0^2 + [v_{sdr}(t - t_0)]^2 - 2d_0v_{sdr}(t - t_0)\cos\alpha \quad (14)$$

where R is the transmission range of source node s . Therefore, the t can be calculated by (14).

Thus in this scenario, the residual link lifetime is:

$$T_r = t - t_0 \quad (15)$$

2. When $\theta_{rel} \in [\pi/2, 3\pi/2]$

When $\theta_{rel} \in [\pi/2, 3\pi/2]$, the link lifetime prediction is similar to that when $\theta_{rel} \in [0, \pi/2] \cup [3\pi/2, 2\pi]$. The distance between the destination node d and relay node r at time t_0 is d_{dr} and the length of line dD is equal to d_{ds} . Moreover, in triangle drD , the $\angle drD$ can be calculated as:

$$\angle drD = \phi_5 = \pi - (\phi_2 - \phi_1) \quad (16)$$

Additionally, in triangle srd , according to the law of cosines we can get:

$$d_{ds}^2 = d_0^2 + d_{dr}^2 - 2d_0d_{dr}\cos\phi_4 \quad (17)$$

$$\phi_1 = \pi - \phi_4 \quad (18)$$

In (16), the ϕ_2 can be calculated by $\phi_2 = \pi - \phi_3$ and ϕ_1 can be calculated by (17) and (18), so in triangle drD , we have:

$$d_{ds}^2 = d_{dr}^2 + [v_{sdr}(t - t_0)]^2 - 2d_{dr}v_{sdr}(t - t_0)\cos\phi_5 \quad (19)$$

In (19), the t can be calculated. So the residual link lifetime in this scenario can be calculated by (15).

B. Packet delivery ratio based opportunistic topology control algorithm

In this section, we propose the packet delivery ratio based opportunistic topology control algorithm (OTC). The OTC is inspired by the humoral regulation, in which the feasible solution is a range rather than a single value. In OTC, the transmission power is adjusted dynamically to maintain the stability of the packet delivery ratio; moreover, it can reduce the topology control cost by dividing the nodes into different categories.

Before proposing the topology control algorithm, we first define the necessary definitions which will be used in this section.

Definition 1: The relay node degree (RND) is defined as the number of neighbors whose distances to the destination node are smaller than that of the source node, i.e., the number of nodes in the survival area (shown in Figure 4).

Definition 2: The transmission power adjustment ratio is defined as the ratio of the number of nodes which adjust their transmission power to the number of nodes in the whole network, which can be expressed as:

$$C_{orc} = \frac{\text{nodes adjust the transmission power}}{\text{total nodes in the network}}.$$

The transmission power adjustment ratio is the smaller the better; since the small transmission power adjustment ratio means that there is small part of nodes in the network need to change their transmission power, which also means less control cost of the network.

In opportunistic routing algorithm, the packet delivery ratio between source node and CRS can be calculated as [20]:

$$PTP = 1 - (1 - p_i)^n \quad (20)$$

where p_i is the packet delivery ratio between sender and one neighbor node, and can be determined by periodically beacon message exchanging between sender and its neighbors [45][46][53]; n is the RND of the CRS. According to (20), to different RND of the CRS, the packet delivery ratio varies greatly, especially in MANETs. For getting stable packet delivery ratio, the RND should keep constant in CRS. However, due to the high mobility of MANETs, the network topology changes frequently; so if each node maintains constant RND in CRS, the transmission power needs to be adjusted frequently and the transmission power adjustment ratio is high. The high adjustment ratio makes the communication channel more and more congested. Therefore, for reducing the adjustment ratio, the nodes are divided into different categories in OTC according to their packet delivery ratio. Whether the transmission ranges need to be adjusted or not will be decided by which categories that the nodes belong to. The definitions of different categories are shown in Definition 3.

Definition 3. When the packet delivery ratio of the node (PTP) is in the region (P_1, P_2) ; then the node is healthy; otherwise, the node is unhealthy.

The definition is shown in Figure 7 and expressed in (34).

Fig. 7. The definition of the different categories

$$\begin{cases} R_H \in (PTP | PTP \in [P_1, P_2]) \\ R_{UH} \in (PTP | PTP \in [0, P_1] \cup (P_2, 1]) \end{cases} \quad (21)$$

where P_1 and P_2 are the boundary values of different categories; R_H means the healthy region; R_{UH} means the unhealthy region. To the specific packet delivery ratio, the needed RND of the CRS can be calculated by (20). So the (21) can also be expressed by RND, which is:

$$\begin{cases} R_H \in (n | n \in [n_1, n_2]) \\ R_{UH} \in (n | n \in [0, n_1] \cup (n_2, N]) \end{cases} \quad (22)$$

where n is RND, N is the node number in the network.

The source node calculates the RND in the candidate relays set and adjusts the transmission power according to the value of RND. For reducing the transmission power adjustment ratio, in OTC, the transmission power adjustment probabilities are different in different regions. In health region, this probability is 0; however, in the unhealthy region, this probability varies from 0 to 1 based on the value of RND, which can be expressed as:

$$\begin{cases} p_h = 0, n \in [n_1, n_2] \\ p_u = (0, 1], n \in [0, n_1] \cup (n_2, N] \end{cases} \quad (23)$$

where p_h is the transmission power adjustment probability of healthy region; p_u is the probability of unhealthy region.

In the unhealthy region, the adjustment probability varies and is decided by the deviation of the RND in the unhealthy region to the boundary values. When the RND is far from the healthy region, the adjustment probability should be high to guarantee the reliability and packet delivery ratio, vice versa. So the adjustment probability can be calculated as:

$$p_{si} = \begin{cases} (n_1 - n_i) / n_1, n_i \in [0, n_1] \\ (n_i - n_2) / (N - n_2), n_i \in (n_2, N] \end{cases} \quad (24)$$

where n_i is the RND of node i ; p_{si} is the transmission power adjustment probability of node i and $0 \leq p_{si} \leq 1$.

As shown in [47], the probability that the node number is n in the coverage area of the node is Poisson distribution; therefore, the probability that there are n nodes in the survival area is:

$$P(n) = \frac{(\rho\Delta)^n}{n!} e^{-\rho\Delta} \quad (25)$$

where Δ is the survival area that shown in Figure 4; ρ is

the node density of the network; n is the RND in the CRS.

According to (25), the probability that the RND is in the region $[n_1, n_2]$ can be calculated as:

$$P(n_1 \leq n \leq n_2) = \sum_{n=n_1}^{n_2} \frac{(\rho\Delta)^n}{n!} e^{-\rho\Delta} \quad (26)$$

When $P'(n_1 \leq n \leq n_2)|_{\Delta} = 0$, the (26) will get the maximum value. This means the probability that there are n nodes in the survival area Δ is the highest. Moreover:

$$P'(n_1 \leq n \leq n_2)|_{\Delta} = \sum_{n=n_1}^{n_2} \frac{1}{n!} (\rho\Delta)^{n-1} (n\rho e^{-\rho\Delta} - (\rho\Delta)\rho e^{-\rho\Delta}) \quad (27)$$

when $P'(n_1 \leq n \leq n_2)|_{\Delta} = 0$, we can get the optimal survival area Δ^* .

In Figure 6, the transmission range of node s is r and the distance between node s and node d is d . So the line Bd is also equal to d . Then the triangle sBd is an isosceles triangle. Therefore, the angle of θ_{Bsd} can be calculated as:

$$\theta_{Bsd} = \arccos(r / (2d)) \quad (28)$$

Then the optimal value of the transmission range can be calculated as:

$$\Delta^* = r^2 \cdot \arccos(r / (2d)) \quad (29)$$

where $r^2 \cdot \arccos(r / (2d))$ is the area of the survival area.

Based on (28) and (29), we can get the optimal transmission range r^* for the source node. This transmission range has the highest probability to guarantee that the RND in CRS is in the region $[n_1, n_2]$. Therefore, when the node is in the unhealthy region, the node transmission ranges will be adjusted to r^* .

Therefore, according to (24) and Definition 2, we can calculate the transmission power adjustment ratio of OTC as follows:

$$C_{OTC} = P_u + \frac{1}{N} \sum_{i=1}^{NP} p_{si} \quad (30)$$

where P_u means the probability that the node is in the unhealthy region; p_{si} is the transmission power adjustment probability of node i ; N is the node number in the network. According to (25) and (26), the P_u can be calculated as:

$$P_u = P[(0 \leq n < n_1) \cup (n_2 < n \leq N)] \\ = \sum_{n=0}^{n_1-1} \frac{(\rho\Delta^*)^n}{n!} e^{-\rho\Delta^*} + \sum_{n=n_2+1}^N \frac{(\rho\Delta^*)^n}{n!} e^{-\rho\Delta^*} \quad (31)$$

There are two application-specific parameters in OTC, which are the boundary values of the healthy region: P_1 and P_2 . Since different applications have different network parameters and QoS requirements, so these two parameters are not fixed; they are different with different applications. For instance, if the application requires that the packet delivery ratio should larger than 0.9, then the healthy region can be decided as $[0.9, 0.99]$, since the probability can not equal to 1; then the RND can be calculated based on these two probabilities and (20).

C. Cross-layer and reliable opportunistic routing algorithm

Based on the link lifetime prediction algorithm and the OTC algorithm, we propose the cross-layer balanced and reliable opportunistic routing algorithm for MANETs in this section. The data packet transmission in opportunistic routing is store-and-forward.

In CBRT, each node acquires the locations of other nodes in the network through periodic probe packet exchanging. Only the locations of other nodes are maintained periodically by each node. Once the source node wants to send data packet to the destination node, first, it will broadcast the RREQ (Route Request) to its neighbors. The neighbors are the nodes who have one-hop bi-directional communication links with the source node. The RREQ includes the node IDs of the source node and the destination node. The neighbors who receive this message will calculate the distances to the destination node. The neighbor nodes whose distances to the destination node are larger than the distance between the source node and destination node will drop the RREQ packet directly. Only the neighbor nodes whose distances to the destination node are smaller than the source node will reply RREP (Route Request Response) message to the source node.

In CBRT, we take several performance metrics into account during the routing decision. For these performance metrics, only the nodes' location needed to be maintained by each node periodically. For the rest of performance metrics, the source node acquires them only when there is a routing request. That means when the source node begins a routing discovery process and sends RREQ to the neighbor nodes, the neighbor nodes whose distances to the destination node are smaller than the source node will reply the RREP to the source node; in this RREP packet, the concerned cross-layer performance metrics (including the residual energy, moving speed and direction, etc.) are included, i.e., piggyback information of RREQ and RREP packets during the routing discovery [44]. If there has no routing request, the source node does not need to maintain these performance metrics, except the other nodes' location.

When the source node receives the RREP packet, it will calculate the RND in CRS and decide which region that it belongs to according to the value of RND. The source node adjusts its transmission power based on OTC algorithm. After the transmission power adjustment, the source node will update the CRS. If the optimal transmission power is smaller than the previous one, then the source node deletes the nodes whose distances to the source node are larger than the transmission range from the CRS. If the transmission power is larger than the previous one, the source node needs to broadcast RREQ packet again. Only the nodes which are not in the CRS and the distances to the destination node are smaller than the source node reply RREP message to the source node. After the CRS updating, the source node extracts the cross-layer parameters from the RREP packets. According to (6), the source node calculates the scatter D_i of each cross-layer parameters. These scatters D_i are the inputs of the fuzzy logic inference system. The source node relays the data packet to the nodes in CRS. The transmission priorities of the relaying nodes in CRS are decided by the utilities that

calculated by (12). When the relaying nodes receive the data packet, they will repeat the transmission process that introduced above till the data packet is received by the destination node.

The process of the cross-layer balanced and reliable opportunistic routing algorithm is shown as follows:

Algorithm 1. Cross-layer and reliable opportunistic routing algorithm

1. source node broads RREQ to its neighbor nodes;
 2. if $\text{distance}(\text{node}_i, \text{destination_node}) < \text{distance}(\text{source_node}, \text{destination_node});$
 3. node i send RREP to source node;
 4. source node calculates the RND by using OTC algorithm;
 5. end if
 6. if $(U_i^f \geq U_i^{th})$
 7. node_status $\leftarrow$ true;
 8. else if $(U_i^f < U_i^{th})$
 9. node_status $\leftarrow$ false;
 10. end if
 11. while node_status==true do
 12. if $0 < RND < n_1$ or $n_2 < RND < N$
 13. $p_{si} = P_{si}(RND);$
 14. $r_i \leftarrow \frac{p_{si}}{r_i^*};$
 15. else if $n_1 < RND < n_2$
 16. $p_{si} = 0;$
 17. $r_i = r_i^*;$
 18. end if
 19. source node update the candidate relays set;
 20. source node extract cross-layer parameters from RREP;
 21. parameters normalization;
 22. $D_i \leftarrow \text{Dispersion}(U_i^f);$
 23. $\omega_i \leftarrow \text{Fuzzylogic}(D_i);$
 24. $\psi \leftarrow \text{Utility}(U_i^f, \omega_i);$
 25. ranking(ψ);
 26. end while
 27. source node sends data packet to the relaying nodes with the priority list;
 28. relaying nodes relay the data packet according to the priority in the priority list;
 29. The relaying nodes repeat 1-28 till the data packet received by the destination node.
-

V. SIMULATION AND DISCUSSION

In this section, the performance of CBRT algorithm will be evaluated and compared with the ExOR algorithm. The effectiveness of SBFL algorithm has been demonstrated in Section 3; so in the first part of this section, the performance of the packet delivery ratio based topology control algorithm is presented; in the second part of this section, the performance of CBRT and ExOR will be compared in detail. The simulator is NS-2 in this simulation.

A. Performance of packet delivery ratio based opportunistic topology control algorithm (OTC)

In this section, the performance of the packet delivery ratio

based opportunistic topology control algorithm will be evaluated.

Fig. 8. The transmission power adjustment ratio of OTC and k -connection algorithm.

Fig. 9. The node degree of OTC and k -connection algorithm.

In this simulation, we compare the OTC with the traditional k -connection algorithm which is the most popular topology control algorithm in wireless sensor and ad hoc networks [48][49][50]. In this simulation, the boundary values of the different regions are the same as that shown in Section 4; the value of k in the k -connection algorithm is equal to 5. The simulation results can be found in Figure 8 and Figure 9. The parameters of the simulation are: deployment area: 1000m×1000m; initial node transmission range: 100m; traffic type: CBR (constant bit rate); CBR rate: 512 Bytes × 6 per second [44][53]; initial energy: 5J; high transmission power: 0.8W; low transmission power: 0.1W; node number 50-200; average moving speed: 0.2m/s; receiving power: 0.05W.

From Figure 8, we can conclude that the transmission power adjustment ratio of OTC is smaller than that of the k -connection algorithm. With the increase of the node number, both the adjustment ratios of OTC and k -connection increase. Additionally, when the number of node increases, the difference of the adjustment ratios between OTC algorithm and k -connection algorithm decreases. In Figure 9, the node degrees of k -connection algorithm vary around 5, which is consistent with the value that we set in this simulation. In OTC algorithm, the node degree varies from 7 to 9 which are the boundary values that calculated in Section 4. The results in Figure 9 illustrates that the OTC algorithm is effective on controlling the network topology.

B. Performance of the cross-layer and reliable opportunistic routing algorithm (CBRT)

As demonstrated in Section 3, since the SBFL algorithm can handle more cross-layer parameters than the traditional algorithms without increasing the computation complexity, so in this simulation, the residual energy of the relaying node, the ETX of the communication link, the packet queue length of the relaying node, the transmission delay of the relaying node, the distance to the destination node, the moving speed, and the moving direction will be taken into account to choose and prioritize the relay nodes for the opportunistic routing. All these metrics are local metrics and can be calculated or obtained as follows.

1. *The residual energy.* The residual energy is a local metric of the node; the nodes can acquire their energy status by the detection circuit in node [27][29][51][52];

2. *The ETX of the link.* The link's ETX is defined as the expected number of transmissions needed to send a packet to the relay node [53]. It can be calculated as: $\frac{1}{(1-p_f)(1-p_r)}$,

where p_f and p_r are the loss probabilities of the link in the forward and reverse directions, respectively. Each node can measure the loss rate of its links to and from its neighbors by broadcasting probe packet periodically [44][53].

3. *The packet queue length.* This metric is used to demonstrate the residual buffer space of the node. Each node can get the packet queue length by checking the status of the buffer.

4. *The transmission delay of the relay node.* In this paper, the delay of the relay node can be got by broadcasting probe packet periodically, which is the same process with the measurement of the link's ETX [44][53], i.e., this metric can be measured in the same process of link's ETX measurement.

5. *The distance to the destination node.* In this algorithm, since each node equips a GPS device, which can be used to obtain the coordinate of the node, so the distance from the relay node to the destination node can be calculated.

6. *The moving speed and direction.* The same as the distance to the destination node, the moving speed and moving direction of the node can be got through the GPS device. The moving speed and direction of the candidate nodes are carried by the RREP packets, so when the candidate nodes reply the RREP packets to the source node, the source node can receive the moving speed and direction of the candidate nodes. Since the time needed to send RREP packet from candidate nodes to source node is quite short, so we regard the moving speed and direction that the sender received is up-to-date.

Based on the induction above, the residual energy, the packet queue length, and the moving speed and moving direction of the neighbors are needed to be sent to the sender; the link's ETX, the transmission delay of the neighbors, and the neighbors' distance to the destination node can be calculated or measured by the sender.

It should be noted that the number and kind of the parameters used in this algorithm are not fixed; they can be changed according to the different applications easily and conveniently. This is also the advantage of CBRT, which is flexible without increase the algorithm complexity.

In this section, we compare the performance of CBRT with the traditional opportunistic routing ExOR [20]. The results can be found in Figure 10 to Figure 17. The parameters of the simulation are: deployment area: 1000m×1000m; radio propagation model: two ray ground [44]; initial node transmission range: 500m; initial energy: 5J; high transmission power: 0.8W; low transmission power: 0.1W; node number 25-150; average moving speed: 0.2m/s; receiving power: 0.05W; maximum allowed packet queue length: 20 packets; traffic type: CBR (constant bit rate); CBR rate: 512 Bytes × 6 per second [44][53]. Moreover, this simulation mainly concentrates on the network layer and the MAC layer protocol is IEEE 802.11[44][53-55]. In this simulation, the variable is the number of node in the network, i.e., the density of the network¹.

Fig. 10. The ETX of ExOR and CBRT.

Fig. 11. The transmission delay of ExOR and CBRT.

¹In this simulation, we only takes the node number as the variable; however, other simulation parameters, such as the traffic load, the transmission power, the moving speed, the congestion, etc., also can affect the results of the simulation; the effect of these parameters will be investigated in the future work.

Fig. 12. The packet queue length of ExOR and CBRT.

In Figure 10, the ETX of CBRT and ExOR are compared. From Figure 10, we can find that with the increase of the node number, the ETX in ExOR varies between 6 and 7; however, this value is only 1 in CBRT. This conclusion demonstrates that in ExOR, the ETX is about 6 times larger than that in CBRT. In MANETs, small ETX means small transmission delay, which can be found in Figure 11. In Figure 11, with the increase of the node number, both the transmission delays in CBRT and ExOR increase. However, the increase in ExOR is more serious than that in CBRT. This is due to the high ETX in ExOR. Not only the high ETX but also the packet queue length of the node can increase the transmission delay. As shown in Figure 12, the packet queue length in ExOR is also larger than that in CBRT. With the increase of the node number, the packet queue length increases both in ExOR and CBRT algorithm. However, the packet queue length increases faster in ExOR than CBRT. The Figure 11 and Figure 12 can be explained by each other: the large packet queue length means large transmission delay; conversely, the large transmission delay causes the increase of the packet queue length. Moreover, as shown in Figure 10 and Figure 12, large ETX and packet queue length deteriorate the performance of transmission delay in ExOR.

The Figure 10, Figure 11 and Figure 12 demonstrate that the network performance has been improved greatly by CBRT. As shown in Figure 10, Figure 11, and Figure 12, the parameters in the network are not alone; they relate to each other and can affect each other. Therefore, the more cross-layer parameters are taken into account, the better network performance is. Since the CBRT have the ability to handle multi-parameters without increasing the complexity of the algorithm, so the CBRT is more effective than the traditional opportunistic routing algorithm.

Fig. 13. The node degree of ExOR and CBRT.

Fig. 14. The transmission range of ExOR and CBRT.

As shown in Figure 13, due to the topology control in CBRT, the RND in CBRT varies between 6 and 10, which is in the healthy region that we define. In Figure 13, when the node number increases, due to the lack of topology control in ExOR, the node degree in ExOR varies greatly. For instance, when the node number is 150, the node degree in ExOR is about 5 times larger than that when the node number is 25. The reason is that the transmission power is constant in ExOR, so when the node number increases, the node degree will increase greatly. This also means that the packet delivery ratio varies greatly in ExOR. However, due to the topology control in CBRT, when the node number increases, for maintaining stable RND in the candidate relays set, the transmission power will be adjusted according to the value of RND, which can be found in Figure 14. In Figure 14, when the node number increases, due to the OTC algorithm, the transmission power of CBRT decreases to maintain stable RND in the candidate relays set, i.e. the more nodes in the network, the smaller transmission range is. So in Figure 13, the RND in CBRT algorithm varies slightly, which is in the region that we set in Section 4.

Fig. 15. The residual energy of ExOR and CBRT.

Fig. 16. The through of ExOR and CBRT.

Fig.17. The enlarged view of Fig. 16.

Another advantage of CBRT is the energy consumption. As shown in Figure 15, the residual energy in CBRT is larger than that in ExOR. With the increase of the node number, the residual energy decreases both in ExOR and CBRT. However, the energy is consumed faster in ExOR than that in CBRT. The excellent performance of energy consumption in CBRT owes to the balanced performance of the cross-layer parameters, which can be found in Figure 10, Figure 11, Figure 12, and Figure 14. The excellent performance of link's ETX, transmission delay, packet queue length, and transmission power in CBRT deduces the energy consumption greatly. Similar to the residual energy, in Figure 16 and Figure 17, with the increasing of the node number, the throughput both in ExOR and CBRT will decrease; moreover, the decreasing in

ExOR is faster than that in CBRT. This is also because of the balanced performance of cross-layer parameters in CBRT. In Figure 16, the throughputs of CBRT under different node number are seems the same; however, they are different in fact. This is because the differences between these throughputs are slight, so they are similar. For explain this clearly, we drew the enlarged view of Figure 16 in Figure 17. In Figure 17, we can find that the throughputs under different node number are different; and with the increase of the node number, the throughputs reduce.

As shown in Figure 18, the only disadvantage of CBRT is that with the increase of the node number, the link lifetime in CBRT decreases; however, the link lifetime varies slightly in ExOR. This can be explained by Figure 14. As shown in Section 4, when the moving speed is stable, the larger transmission power, the smaller link lifetime is. Moreover, in CBRT, when the node number increases, the transmission power decreases, which also means small link lifetime. However, since the transmission power is not adjusted in ExOR, so the link lifetime keeps constant.

Fig. 18. The residual link lifetime of ExOR and CBRT.

VI. CONCLUSION

In this paper, we propose the cross-layer and reliable opportunistic routing algorithm (CBRT) for MANETs. In CBRT, the RND in the CRS is a range rather than a constant number. The node is divided into different categories based on the value of RND. The nodes adjust their transmission power according to the RND in CRS. The cross-layer metrics are not inputted into the fuzzy logic system directly; the inputs are the relative variances of these metrics. The calculation of the node utility is weight based. The weight and the priority of the metric are used to calculate the node utility. The relaying node whose node utility is high will have high priority to relay the data packet. By these innovations, the network performance in CBRT is much better than that in ExOR; however, the computation complexity is not increased.

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