IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 5, 2020, accepted April 3, 2020, date of publication April 6, 2020, date of current version April 23, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2986078

A Multi-Path Routing Protocol Based on Link Lifetime and Energy Consumption Prediction for Mobile Edge Computing

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This work was supported in part by the National Natural Science Foundation of China under Grant 61571328, in part by the Tianjin Key Natural Science Foundation under Grant 18JCZDJC96800, in part by the Major Projects of Science and Technology in Tianjin under Grant 15ZXDSGX00050, in part by the Training Plan of Tianjin University Innovation Team under Grant TD12-5016, Grant TD13-5025, and Grant TD2015-23, and in part by the Major Projects of Science and Technology for their Services in Tianjin under Grant 16ZXFWGX00010 and Grant 17YFZC GX00360.

ABSTRACT During mobile edge computing, due to the movement of nodes and the exhaustion of node energy, link failure occurs thus reducing the network lifetime in the mobile ad-hoc network. When the route fails, because the single-path protocols need to restart the route discovery process, the delay of the network is greatly increased. Therefore, the multi-path routing protocol is proposed, saving the cost of route discovery. In this paper, we propose an ad hoc on-demand multi-path distance vector (AOMDV) routing protocol based on link lifetime and energy consumption prediction (named LLECP-AOMDV) for mobile edge computing. In the route discovery phase, the energy grading strategy is adopted. When the node energy is lower than the threshold, it no longer participates in the route discovery. In the routing selected phase, the path is selected based on the lifetime of the route link and the minimum energy consumption of the route. According to energy consumption, packet delivery rate, end-to-end delay performance indicators, we evaluate the comparison results. The result shows that under most network performance indicators and parameters, the proposed LLECP-AOMDV is superior to the other three protocols, which improves the network lifetime, reduces the node's energy consumption and the average end-to-end delay. The protocol is very useful for mobile edge computing.

INDEX TERMS Mobile edge computing, MANET, AOMDV, energy threshold, link lifetime, energy consumption.

I. INTRODUCTION

During mobile edge computing, the mobile ad hoc Network (MANET) is a collection of self-organizing, self- configuring and self-maintaining mobile hosts. It is a special wireless network that does not depend on any infrastructure or central management [1]–[3]. In recent years, due to its stupendous potential in military battlefields, emergency relief and civil applications, MANET has been a research hot-spot [4]–[7]. Dynamic topology, unstable links, limited energy, and lack of a fixed infrastructure are characteristics of MANET compared to wired networks. In MANET, the computing power, storage capacity, and battery power of the nodes (which are these mobile communication devices (such as mobile phone, iPAD, PDA, Laptop, and other mobile terminals)) are terminate. These features pose great challenges to routing protocol design [8]–[10]. The network model is shown in Figure 1. Routing has two operations. One is to discover the best route. The other is to transfer the packet. Therefore, routing plays a crucial role in wireless communication [11]–[15]. Without any infrastructure, it is not realistic to communication directly. Therefore, cooperation between nodes is required,

The associate editor coordinating the review of this manuscript and approving it for publication was Tawfik Al-Hadhrami.

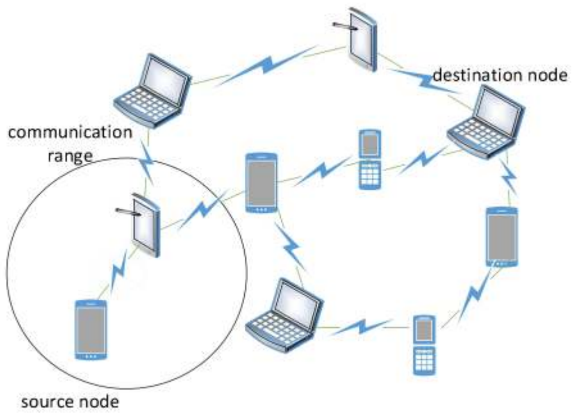

FIGURE 1. Example of network model for mobile edge computing.

and multi-hop routing is adopted, in which an intermediate node is used as a relay to transmit a data packet from a source node to a destination node [15]–[17].

In MANET, as the battery energy is exhausted, the link is broken. Therefore, the lifetime of the network is affected by the energy of the mobile node (which is the mobile communication device (such as mobile phone, iPAD, PDA, Laptop, and other mobile terminals)). So the routing protocol should take into account the energy of the mobile node to extend the lifetime of the network and ensure the connectivity of the network [18]–[20]. Through some techniques, the energy consumption is reduced by applying the energy-aware protocol. By employing this power- aware routing protocol, various path selection algorithms are studied to improve the energy efficiency in MANET [21]–[22].

When the node moves, the topology changes, and the established link has the possibility of disconnection. The traditional shortest path algorithm needs to replace the original link with other existing links or restart the route discovery. In order to solve the link failure caused by the mobile, when routing is selected, part of the routing protocol takes into account the stability of the link. These routing protocols predict the lifetime of the link by calculating the strength of the received signal of the node or the relative mobility of the nodes [23].

Compared with traditional single-path routing protocols, multi-path routing can reduce network congestion by transferring traffic to other paths, thereby improving network utilization and balancing network load. To a certain extent, the reliability of the network is effectively improved [24]. Ad Hoc On-demand Multi-path Distance Vector Routing (AOMDV) is an improved multi-path protocol based on the Ad Hoc On-demand Distance Vector Routing (AODV) routing protocol, in which multiple paths are found between a given source and destination node. There are two types of disjoint path, the node-disjoint path and link-disjoint path. In a node-disjoint path, except for the source and destination node, there is no common node in the multi-path routing. In a link-disjoint path, there is no common link [25]. In the process of selecting a path, only the hop count parameter is considered, and the stability of the path is neglected. It is possible to make the selected path have the smallest hop count, but the distance is distant or energy consumption is large, increasing the possibility of link disconnection. Based on AOMDV, we propose a multi-path routing protocol based on link lifetime and energy consumption prediction for mobile edge computing.

The rest of the paper is organized as follows: Section II discusses the background of AOMDV and existing research for mobile edge computing; Section III introduces multi-path routing protocol based on predicted link lifetime and minimum energy consumption for mobile edge computing; Section IV discusses the results of the experiment and comparison for mobile edge computing; Section V concludes this study and presents the future work.

II. RELATED WORKS

In order to support for mobile edge computing, AOMDV is an on-demand multi-path routing protocol. When a node (which is the mobile communication device (such as mobile phone, iPAD, PDA, Laptop, and other mobile terminals)) has a request to send, check whether there is a path to the destination node in the route list at first. If there is no path, a routing request is initiated. When one or more paths exist to the destination, path selection is performed based on the minimum hop count.

In the existing related research for mobile edge computing, multi-path routing protocols are mostly improved for routing selecting. In reference [26], Smail *et al.* proposed an Ad hoc On-demand Multi-path Routing with lifetime maximization (AOMR-LM). It utilized the residual energy of the node to calculate the energy level of the node and protect the node that has low energy. By analyzing the two parameters of energy threshold and coefficient, the nodes are classified and the protection of the node energy is ensured. The AOMR-LM protocol improves the performance of MANET by extending the lifetime of the network. In reference [21], Aqeel Taha *et al.* proposed a multi-path routing protocol with fitness function (FF-AOMDV). The fitness function is used to find the optimal path from the source node to the destination node to reduce energy consumption in multi-path routing. In reference [27], Mahmoud M. Shawara *et al.* proposed an energy-aware multi-path distance vector based on Ad-hoc on-demand multi-path distance vector (EA-AOMDV). In this protocol, paths are selected based on their energy metrics rather than hop count metrics to minimize average energy consumption and maximize network runtime. In reference [28], Akash Yadav *et al.* obtained the lifetime of the link between two nodes by estimating the instantaneous velocity and relative distance between the two nodes, and then polymerized them to find the duration of the path, which conduces to choose a stable path in the multi-path protocol. In reference [29], an energy efficient node disjoint multi-path routing protocol (E2NDjMRP) is proposed, and the shortest hop count and dynamic transmission range adjustment are used to determine the main path and secondary path. E2NDjMRP improves the overall performance of the network in terms of power consumption, control overhead, and energy efficiency. In references [30]–[38], Mahadev A. Gawas *et al.* proposed a QoS aware weight based on demand multi-path routing protocol (QMR) to improve QoS. QMR is based on cross-layer design, which collaboratively shares network state information in different protocol layers while maintaining separation of layers to improve overall network performance.

In the existing research for mobile edge computing [39]–[46], during the route discovery phase, on the one hand, the residual energy of the node is ignored by most methods, which increases the energy consumption of the low energy node, so that the discovered route may be disconnected early. On the other hand, due to the movement of nodes, the link is likely broken. Therefore, this paper will optimize and improve the route discovery and route selecting stages to balance the network load and prolong the network lifetime.

III. DESCRIPTION OF THE ALGORITHM

We proposed a new multi-path routing protocol called the LLECP-AOMDV routing protocol based on AOMDV for mobile edge computing. In the route discovery phase of mobile edge computing, a hierarchical strategy based on energy threshold is proposed. In the path selection phase, the energy consumption required for data transfer and the lifetime of the link are taken into account in our protocol. AOMDV has three control packets: Routing Request (RREQ), Routing Reply (RREP) and Routing Error (RERR).

A. PRIORITY PATH SELECTION STRATEGY

In the traditional multi-path protocol for mobile edge computing, the path is usually selected based on the minimum hop count. However, the residual energy of the node and the consumption of the path transmission data are neglected. Ignoring the stability of the path, it is possible to make the selected path with the minimum hop count, however the distance is far or energy consumption is high, increasing the possibility of link disconnection. Therefore, we propose a priority path selection strategy in this part. When path s is selected, the lifetime of the route and the energy consumption of the route transmission data are comprehensively considered to extend the lifetime of the network and improve the stability of the path.

1) ENERGY MODEL

In mobile edge computing based on MANET, when the node energy is exhausted, the link will break. Therefore, the lifetime of the link has a direct relationship with the energy of the node. The routing path should be selected to take into account the energy consumption of the node. Let $Total\_ENE(i)$ denote the energy consumption on the i^{th} path, $Total\_ENE(i)$ will be given as

$$Total\_ENE(i) = \sum_{j=0}^{j=N_i-1} Cost_{j,j+1} \tag{1}$$

where N_i represents the total number of nodes on the i^{th} path, $Cost_{j,j+1}$ represents the energy consumed to transmit and receive data from the node j to the next hop, $Cost_{j,j+1}$ can be expressed by the wireless sensor network node energy consumption $E_{Tx}(k, d_{j,j+1})$ and $E_{Rx}(k, d_{j,j+1})$, which can be calculated as

$$Cost_{j,j+1} = E_{Tx}(k, d_{j,j+1}) + E_{Rx}(k, d_{j,j+1}) \tag{2}$$

According to the radio energy consumption model, when a node transmits data to a neighbor node for each k bit data, the energy consumption of the node is computed as follows:

$$\begin{aligned} E_{Tx} &= E_{Tx-elec}(k, d) + E_{Tx-amp}(k, d) \\ &= \begin{cases} kE_{elec} + kE_{fs} \times d^2, k \le d_0 \\ kE_{elec} + kE_{mp} \times d^4, k > d_0 \end{cases} \end{aligned} \tag{3}$$

where d_0 can be calculated as

$$d_0 = \sqrt{\frac{Efs}{Emp}} \tag{4}$$

In (3), k is the number of bytes of the transmitted packet, d is the distance between the nodes. When d is less than or equal to the threshold d_0, the node adopts a free space mode; E_{fs} and E_{mp} are the energy dissipation coefficients of the circuit amplifier in the free space mode and the multi-path decline mode, respectively. When d is more than the threshold d_0, the node adopts a multi-path decline mode. RF energy consumption coefficient is $Eelec(nj/bit)$. The energy consumption calculation formula for receiving k bit message is as follows:

$$ERx(k) = ERx - elec(k) = kEelec \tag{5}$$

2) LINK LIFETIME

In a certain sense, the duration of the link determines the lifetime of the route. In this part, we analyze the lifetime of the link between two adjacent nodes. The nodes in the network are randomly distributed. Here we take Random Way Point model. For a given link, by estimating the relative speed of the two nodes and the location of the nodes, the duration of the link is estimated.

The network model is shown in Figure 2. In this, we consider two nodes p and q as neighbor nodes of a route. The link between them is denoted as $\{p, q\}$. The transmission range of the nodes is r. Let v_1 and v_2 be the velocity vector of nodes p and q respectively and $\theta(0 \le \theta \le 2\pi)$ be the angle between the velocity vector of these two nodes.

We assume node q is at position s at t_0. Let d_2 be the instantaneous distance between two nodes at t_0, and d_1 be the instantaneous distance between two nodes at $t_1(0 \le d_2, d_1 \le r)$. Where $ps = d_2, pm = d_1$. Node q moves to point m at t_1, and point e is where node q leaves the

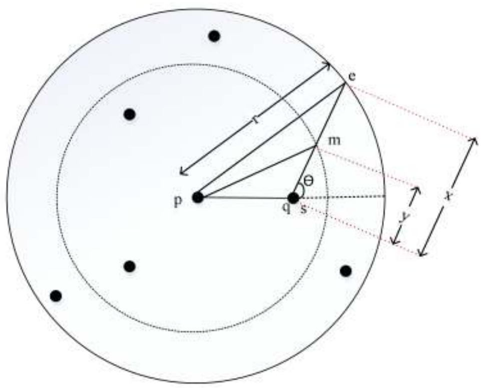

FIGURE 2. **Example graph of adjacent node network model.**

transmission range of node p at t. Node q moves at random. Although the nodes travel with different velocity, we can assume the node p to be stationary and compute their relative velocity v_r. v_r can be expressed as

$$v_{\mathrm{r}} = v_1 - v_2 \tag{6}$$

We assume that the node does not have any localization facility like GPS, so we cannot directly calculate the instantaneous distance between the two nodes. There are several ways to calculate the distance between nodes. One approach is to take advantage of the time difference of signal between the two nodes. The time difference will be in microseconds in this method, thus strict time synchronization between nodes is required. The second method is to use the transmission round trip time of signal transmission between the nodes. Thus this method consumes extra energy. In this work, the received signal strength indication (RSSI) is used to estimate the distance between two nodes, and RSSI can be calculated by the Two Ray Ground reflection model. The answer of the question on ''how Two ray ground reflection model is applicable in calculating real time power of mobile nodes where it is applicable in line of site static power level measurements'' can be found in the reference [31]. Thus d_2 can be calculated as

$$d_2 = \frac{\sqrt[4]{P_t G_t G_r A_t^2 A_r^2}}{P_r} \tag{7}$$

Here variables has following meaning as P_t: transmitted signal power, P_r: received signal power (RSSI), G_t: transmitter antenna gain, G_r: receiving antenna gain, A_t: altitude of transmitter antenna, and A_r: altitude of the receiver antenna. In our network, nodes equipped with omnidirectional antenna and terrain is flat. We assumed that P_t, G_t, G_r, A_t, and A_r are constant. According to formula (7), d_1 can also be estimated.

In triangle *psm*, by applying cosine rule we have:

$$d_1^2 = d_2^2 + y^2 - 2d_2 y \cos\theta \tag{8}$$

where $y = v(t_1 - t_0)$, v is the size of v_r.

In triangle *pse*, by applying cosine rule we have:

$$r^2 = d_2^2 + x^2 - 2d_2 x \cos\theta \tag{9}$$

where $x = v(t - t_0)$. In Figure 2, $S\Delta\mathrm{pse} = S\Delta psm + S\Delta pme$. Taking advantage of the Helen formula ($s = \sqrt{\ell(\ell-a)(\ell-b)(\ell-c)}$, s represents the area of the triangle. a, b and c represent the three sides of the triangle, and $\ell = \frac{a+b+c}{2}$) we get

$$\sqrt{\ell(\ell-d_2)(\ell\text{-r})(\ell-x)} = \sqrt{\ell_0(\ell_0-d_2)(\ell_0-d_1)(\ell_0-y)} + \sqrt{\ell_1(\ell_1-d_1)(\ell_1-r)(\ell_1--(x-y))} \tag{10}$$

where $\ell = \frac{d_2+r+x}{2}$, $\ell_0 = \frac{d_2+d_1+y}{2}$, $\ell_1 = \frac{d_1+r+x-y}{2}$. In equation (8)-(10), there are three unknown numbers (t, v, θ). Thus, the remaining lifetime $T_{C_{\mathrm{i,j}}}$ of the link between node j and the next hop node on the i^{th} path is calculated as follows:

$$T_{C_{i,\mathrm{j}}} = t - t_1 \tag{11}$$

Therefore, the link lifetime of the i^{th} path can be given as:

$$T_{C_{\mathrm{i}}} = \min\{T_{C_{\mathrm{i},0}}, T_{C_{i,1}}, \ldots, T_{C_{i,N_{\mathrm{i}}-1}}\} \tag{12}$$

where N_i represents the number of nodes on the i^{th} path.

3) PRIORITY CALCULATION

In multi-path selection phase for mobile edge computing, the source node selects the path with the highest priority among the multiple paths for data transmission. As a critical parameter, both the energy consumption of the path and the lifetime of the link priority should be taken into account to calculate priority. Let PRI_i denote the priority of the i^{th} path and can be given as:

$$PRI_i = \alpha \cdot Total\_ENE(i) + \beta \cdot \frac{1}{T_{C_{\mathrm{i}}}} \tag{13}$$

where $\alpha + \beta = 1$. It can be seen from the formula (7) that when the total energy consumption of the path is the least and the link lifetime is longer. The path with a higher priority should be selected. Considering that these two parameters are critical to the performance of the network, thus $\alpha = \beta = 0.5$ here. When a node sends a Hello packet to monitor the link state with other nodes, the distance of the neighboring node is obtained by formula (7), and the energy consumption and the lifetime of the link are updated, thereby passing the formula (13). Calculate the priority of the node and update dynamically.

B. LLECP-AOMDV ALGORITHM

For mobile edge computing, the routing table structure of the LLECP-AOMDV algorithm is shown in Figure 3. This protocol adds the priority field to the routing list field. The value of the priority is calculated as described in 3.1.3.

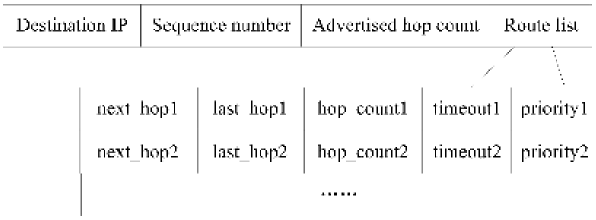

FIGURE 3. Routing table description.

TABLE 1. Energy level settings.

Energy level	Description	Percentage of the residual energy R
Normal	High residual energy of the node	Level<R<1.0
Danger	Low residual energy of the node	0.0<R<Level

1) ROUTING SELECTION BASED ON ENERGY LEVEL

In traditional routing for mobile edge computing, some nodes are frequently selected as intermediate nodes or are heavily loaded chronically, thus the energy of the battery is quickly exhausted. If the energy of the backbone node is exhausted, it is liable to cause the entire network to collapse. Therefore, the node with high energy status should be selected as much as possible during routing selection. The percentage of the residual energy of the node defined by this routing protocol can be expressed by R, which can be computed as:

$$R = \frac{E_{initialenergy}}{E_{residualenergy}} \tag{14}$$

where $E_{initialenergy}$ represents the initial energy of the node, $E_{residualenergy}$ represents the residual energy of the node.

According to R, nodes adopt different forwarding strategies at different energy levels. Due to frequent router switching, the network delay will increase. Based on the existing research on energy-aware routing, we employ two energy levels.

This protocol divides the energy level percentage into two types, Normal and Danger. The Level is the threshold for the percentage of two energy levels. The energy level settings are shown in Table 1.

When the node is in the normal level, the delay mechanism will increase the network delay. At the same time, it is possible that the routing request packet RREQ times out or the Time To Live (TTL) value is 0, thus re-transmission is required, which increases the load of the route and the congestion of the network are large. Therefore, when the node energy of this protocol is at the Normal level, the route discovery process is the same as the traditional AOMDV algorithm at this time.

In the late stage of the network for mobile edge computing, due to exhaustion of node energy, some nodes enter a state of death. In such a case, some RREQ data packets cannot reach the destination. Therefore, in order to establish a route, the source node needs to continuously re-transmit the RREQ thereby increasing a large amount of overhead and causing network congestion. When the residual energy of the node is lower than Level, the node is at the Danger level and should be protected. In the route forwarding phase, the strategy of directly discarding the route discovery control packet is adopted. Therefore, the node serves only as the sender and the receiver of the data and serves as the established route through the node. To the greatest extent, this method can reduce the energy consumption of nodes with low energy, making the energy consumption of nodes more balanced, and prolonging the lifetime of the network.

2) ROUTE UPDATE REGULATION

When node j receives a new control packet, the node determines its own energy level and performs different processing according to different levels. If node is at Normal level, create a reverse path to the source node or create a forward path to the destination node.

Let $seqnum_{\mathrm{P}}^{d}$ denote the node sequence number of the packet P with respect to the destination d, and $seqnum_j^d$ denote the node sequence number of the destination d in the routing table of the node j. Let $nexthop_j^d$ denote the next hop to the destination d in node j, $previous\_hop_P$ denote the last hop node through which packet P passes, and $first\_hop_P$ denote the first hop node through which packet P passes. $disjoint\_path\_lookup(pathlist_j^d, nexthop, lasthop)$ indicates that in the path list that reaches d, it is found whether there is a path with *nexthop* as the next hop and *lasthop* as the last hop. Update the route by following the steps described in Algorithm 1.

Algorithm 1 Route update algorithm

```
if (seqnum_j^d < seqnum_P^d) then
    seqnum_j^d = seqnum_P^d;
    advertised_hopcount_j^d = ∞;
    pathlist_j^d = NULL;
     insert(previous_hop_P, firsthop_P, hopcount + 1)
     into pathlist_j^d;
//let new router insert in rountlist
else if (seqnum_j^d == seqnum_P^d and hopcount_j^d
     > hopcount_P and
    disjoint_path_lookup(pathlist_j^d, nexthop, lasthop)
     == NULL) then
    insert(previous_hop_P, firsthop_P, hopcount + 1)
      into pathlist_j^d;
end if
```

Theorem 1: The route obtained by the LLECP- AOMDV protocol for mobile edge computing is loop free.

Proof: Since the LLECP-AOMDV protocol routing update rule is consistent with AOMDV, it proves that

LLECP-AOMDV is loop free and only need to prove that AOMDV is loop free. Suppose that there is an m-sized loop in a route to a destination d, and node links ($i_1 \rightarrow i_2 \rightarrow \cdots \rightarrow i_m \rightarrow i_1$) form in a loop route. Assume that nodes i and j are any two consecutive nodes in the route path, and $seqnum_i^d \leq seqnum_j^d$. The following inequality is established in the loop path:

$$seqnum_{i_1}^d \leq seqnum_{i_2}^d \leq \cdots \leq seqnum_{i_m}^d \leq seqnum_{i_1}^d \quad (15)$$

where $seqnum_i^d$ represents the sequence number of the destination d at node i, and $seqnum_{i_1}^d = seqnum_{i_2}^d = \cdots = seqnum_{i_m}^d = seqnum_{i_1}^d$ can be obtained according to the above inequality, that is to say, the destination sequence numbers are the same in this routing loop.

According to the AOMDV routing update rules,

$$advertised\_hopcount_{i_1}^d > advertised\_hopcount_{i_2}^d > \cdots > advertised\_hopcount_{i_m}^d > advertised\_hopcount_{i_1}^d$$

Obviously, the above inequality is impossible, thus routes formed by AOMDV route are loop free.

Theorem 2: The packet P broadcasted by the source S for mobile edge computing is received by the intermediate M. If P is from different neighbor nodes of S to M, then the path formed by packet P at the time of broadcast is node-disjoint.

Proof: It is assumed that two copies of the packet P arrive at the node M through two different paths, respectively, and the two paths respectively pass through two different neighbor nodes of S, and there is one common node J, so the packet P is broadcasted at least twice by the node J. However, according to the rules in the algorithm 1, the same packet P is broadcast at most once, so the two sides are contradictory, and the assumption is not established. Therefore, the path formed by the different neighbor nodes of the source node S reaching M is node-disjoint.

Theorem 3: If the nodes on each route from S to D for mobile edge computing have the identical destination sequence number, the route obtained by the LLECP-AOMDV algorithm is link- disjoint.

Proof: Assume that *Path1* and *Path2* are two distrinct paths from the source to the destination for mobile edge computing. In the routing table of S, *Path1* and *Path2* are identified by <D, nexthop, lasthop>. According to the route update rule, the identifiers of the two paths are different, that is, *nexthop* and *lasthop* are diverse.

It is assumed that *Path1* and *Path2* are link-disjoint and share an *I-J* link. Because *nexthop* is unique, there is only one path through J to D in the routing table of node I. Therefore, node I will only provide a J to D path to its upstream node (the source node or a node that is relatively close to the source node). Even though from J to D may have multiple paths. This has two path contradictions with S as the upstream node of I, thus the assumption is false. Therefore, *Path1* and *Path2* are link-disjoint.

3) ROUTE MAINTENANCE

During the route maintenance phase for mobile edge computing, each node monitors the link status with other nodes by sending a Hello packet. If a node is found not to answer the Hello packet, the link between the two nodes is considered to be broken, and the relevant routing information is deleted. If the link is disconnected, the node generates a RERR message listing the missing destinations. RERR is sent to the source node through the intermediate node. If the previous multi-hop of this link is used, the node broadcasts RERR. Upon receipt of RERR, the receiving node checks if the node transmitting RERR is its own next hop at first, towards any of the targets listed in RERR. If the sending node is the next hop of the receiving node, the receiving node will invalidate this routing table, and propagate RERR back to the source. In this way, RERR continues to be forwarded until the source receives RERR. Once this happens, if the failed route is still needed, route discovery can be initiated again. At this stage, the node updates the energy consumption of the link and the lifetime of the link by sending the Hello packet, and the distance between the nodes is obtained by formula (7), thereby calculating the priority of the node by formula (13) and updating.

C. DESCRIPTION OF THE ALGORITHM

The LLECP-AOMDV protocol is based on energy grading forwarding and the lifetime of link and energy consumption prediction for mobile edge computing.

Algorithm 2 The steps of LLECPP-AOMDV for mobile edge computing are described as follows:

Step 1: When a source needs to send data, it checks whether there is routing information to the destination node in the routing information table of the node. If there is no routing information, it initiates a routing request and sends a RREQ.

Step 2: If the RREQ is received by an intermediate node, it judges its own energy level at first, calculates the R according to formula (14), and judges the level of its own energy. When the node is at the Danger level, it adopts the principle of directly discarding RREQ; when the node is at the Normal level, the node checks whether there is a potential alternate reverse path, and updates the route according to Algorithm 1. Check if there is a forward path to the destination node, and the forward path is not used in any of the previous RREPs. If there is, the RREP is generated by this node, and the RREQ is not further propagated by the intermediate node. If there is no forward path to the destination node, the node broadcasts the first received RREQ copy. Here call Algorithm 3.

Step 3: When the RREQ copy is received by a destination, a reverse path is formed by the destination node. Unlike the intermediate node, if the RREQ copy comes from a different neighbor, the destination will generate a RREP.

Step 4: When a node generates a RREP, it checks whether there is a reverse path that is not used to send the RREP in this route discovery. If there is, it selects one of the not used ones to send the current RREP, otherwise, discards the RREP. Algorithm 4 is called here.

Step 5: When the RREP is receive by a source, it will establish a routing table. At the same time, the R calculated by the formula (13) is inserted into the routing table. According to the theorem 1, 2 and 3, the obtained multiple routes are link-disjoint and each path is loop free; when data is transmitted, the higher priority of path is selected.

Algorithm 3 Handles the pseudo code of the RREQ packet algorithm

```
if (j received same seqnum) then   discardRREQ;   return;
 if (pathlist_j^s == NULL) then
    insert(nexthop, lasthop, hopcount+1);
//Let insert new router into routerlist
 else if (seqnum_j^d < seqnum_P^d) then
    seqnum_j^d = seqnum_P^d;   advertised_hopcount_j^d = ∞;
    pathlist_j^d = NULL;   insert(nexthop, lasthop,
    hopcount+1);
 else if (seqnum_j^d == seqnum_P^d
      &&hopcount_j^d > hopcpunt_P&&
pathlist_j^d == NULL) then
    if (firsthop_j^d == firsthop_P&&lasthop_j^d == lasthop_P)
   then
      update  pathlist_j^d;
   else if (firsthop_j^d != firsthop_P&&lasthop_j^d != lasthop_P)
   then
      insert(nexthop, lasthop, hopcount+1);
   end if
 end if
 if (j == d) then
   send  RREP;   return;
 else if (pathlist_j^d != NULL) then   send  RREP;   return;
 else
   Broadcast RREQ;   return;
 end if
```

Step 6: The intermediate node receives the HELLO of the neighboring node periodically. If it finds that a node does not answer the Hello packet, it considers that the link between the two nodes is disconnected and deletes the relevant routing information. Start the route maintenance process. The specific process is given in Section 3.2.3 for the route maintenance.

Step 7: Check weather the processing is successful or not? If Yes then EXIT else GOTO step 1. Or while (LLECP-AOMDV is NOT successful) step 7.

Algorithm 4 Handles the pseudo code of the RREP packet algorithm

```
if (pathlist_j^d == NULL)then
   insert(nexthop, lasthop, hopcount+1);
else if (seqnum_j^d < seqnum_P)then
   seqnum_j^d = seqnum_P;  advertised_hopcount_j^d = ∞;
  pathlist_j^d =NULL; insert(nexthop, lasthop, hopcount+1);
//Clear up rounterlist and insert new router
else if (seqnum_j^d == seqnum_P^d&&hopcount_j^d > hopcpunt_P
&&pathlist_j^d == NULL) then
    if (firsthop_j^d == firsthop_P&&lasthop_j^d == lasthop_P)
     then
     update  pathlist_j^d;
   else if (firsthop_j^d != firsthop_P&&lasthop_j^d != lasthop_P)
     then
     insert(nexthop, lasthop, hopcount+1);
   end if
end if
if (j == s)then
   search the smallest PRT_i router;  send DATA;
else if
   forward RREP;
end if
```

D. THEORETICAL ANALYSIS OF THE COMPLEXITY OF THE ALGORITHM

In this section, we analyze the complexity of the LLECP-AOMDV for mobile edge computing, and explain it from two aspects: time complexity and space complexity.

Theorem 4: The time complexity of the LLECP- AOMDV algorithm for mobile edge computing is $O(n)$.

Proof: The time complexity of the LLECP-AOMDV algorithm for mobile edge computing is determined by forwarding RREQ and RREP packets and handling link failure. Routing discovery is not required for every data transfer. This route discovery process can be considered as the basic operation of the N nodes of the mobile ad hoc network. In this algorithm, the worst case is that there are N-2 nodes between the source and destination, and communication between two nodes must rely on all intermediate nodes, thus the worst time complexity of this algorithm is $O(n)$. In the route discovery process, a source broadcasts the RREQ. When the intermediate node has a path to the destination or the destination receives the RREQ packet, the worst time complexity of this process is $O(n_1)$, and the generated RREP packet is forwarded to the source to form a forward path. The worst time complexity of this process is $O(n_2)$. When the link fails, the worst time complexity of processing link failure is $O(n_3)$. Let $n = n_1 + n_2 + n_3$, thus the time complexity of the LLECP- AOMDV algorithm is $O(n)$.

The AOMDV, AOMR-LM, and FF-AOMDV protocols all require route discovery and route failure processing, so the time complexity is $O(n)$.

Theorem 5: The space complexity of the LLECP- AOMDV algorithm for mobile edge computing is $O(n^2)$.

Proof: In the large sparse mobile ad hoc network for mobile edge computing, the frequent movement of nodes will generate link and link disconnection constantly. Therefore, it is more suitable to utilize the adjacency matrix of the graph to represent the nodes. Each node in this protocol stores the information and routing of neighbor nodes, thus the space complexity is $O(n^2)$.

IV. PERFORMANCE EVALUATION

A. TEST ENVIRONMENT AND PARAMETER SETTINGS

In this part, we take advantage of the NS-2 platform for simulation experiments to test this protocol for mobile edge computing. The agreement between this paper and the classical AOMDV algorithm and the proposed AOMR-LV and FF-AOMDV protocols are compared and analyzed. The data packet delivery rate, average end-to-end delay, and energy consumption are simulated and analyzed in different packet sizes, node speeds, and simulation times for mobile edge computing. For the accuracy of the experiment of mobile edge computing, the average performance results is collected from 50 simulation runs. The main measurement indicators of the simulation experiment are as follows:

1) PACKET DELIVERY RATE

The packet delivery rate refers to the ratio of the number of packets sent by the application layer to the number of packets received by the destination. This standard represents the quality of the routing protocol from a source to a destination. The greater the data packet delivery rate, the better the performance of the routing protocol. Let *PDR* indicate the data packet delivery rate, which is calculated as follows:

$$PDR = \frac{N_{packetreceived}}{N_{packetsent}} \times 100\% \tag{16}$$

where $N_{packetreceived}$ represents the number of received packets and $N_{packetsent}$ represents the number of packets sent.

2) AVERAGE END-TO-END DELAY

The average end-to-end delay refers to the delay generated by the data packet successfully from a source to a destination. We utilize *ETEdelay* to represent the average end-to-end delay. The calculation method is given as:

$$ETEdelay = \frac{1}{n}\sum_{i=1}^{n}[t_d(i) - t_s(i)] \tag{17}$$

where n represents the number of successfully transmitted data packets, $t_d(i)$ represents the transmitted time of the i^{th} packet, and $t_r(i)$ represents the time at which the packet was received.

3) ENERGY CONSUMPTION

Energy consumption refers to the sum of energy consumed by network nodes throughout the simulation. This is obtained by calculating the energy level of each node at the end of the simulation and considering the initial energy of each node. Let *ECenergyconsumption* represent energy consumption, which can be calculated as:

$$ECenergyconsumption = \sum_{i=1}^{N}[E_{initialenergy}(i) - E_{residualenergy}(i)] \tag{18}$$

TABLE 2. Simulation parameters.

Parameters	values
Size of topology(m)	1000*1000
MAC Channel	MAC/802.11
Mobility model	Nakagami
Number of nodes	50
Traffic type	CBR
Transmission range (m)	250
Initial energy (J)	100
Routing protocols	AOMDV, LLECP-AOMDV, AOMR-LM, FF-AOMDV
Simulation time (sec)	10,20,30,40,50
Energy level	Level=0.2
Speed of nodes (m/s)	0,2.5,5,7.5,10
E_{elec}	5.0×10-8J/bit
Channel propagation model energy consumption coefficient	E_{fs} :1.0×10-11J/(bit*m-2), E_{mp} :1.3×10-15J/(bit*m-4)

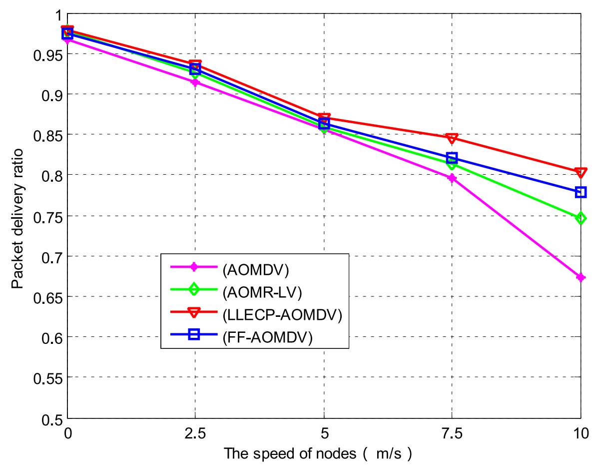

FIGURE 4. The relationship between different node speeds and data packet delivery rates.

where N represents the total number of nodes in the network, $E_{initialenergy}$ represents the initial energy of the node, and $E_{residualenergy}$ represents the remaining energy of the node.

B. EXPERIMENT TESTS BASED ON SIMULATION AND ANALYSIS

As shown in Figure 4, Figure 5 and Figure 6, under the condition of mobile edge computing that the data packet size and the simulation time are constant, and the moving speed of nodes is changed, the performance of the four routing networks is compared. Each node moves at a uniform speed of (0, 2.5, 5, 7.5, 10) m/s, and the direction of movement is random. The size of the packet is 256 bytes and the simulation time is 50 s.

The effect of different node speeds on the data packet delivery rate can be clearly seen from Figure 4. When the speed of the node increases, the packet delivery rate of LLECP-AOMDV, FF-AOMDV, AOMR-LV and AOMDV will decrease. The data packet delivery rate of

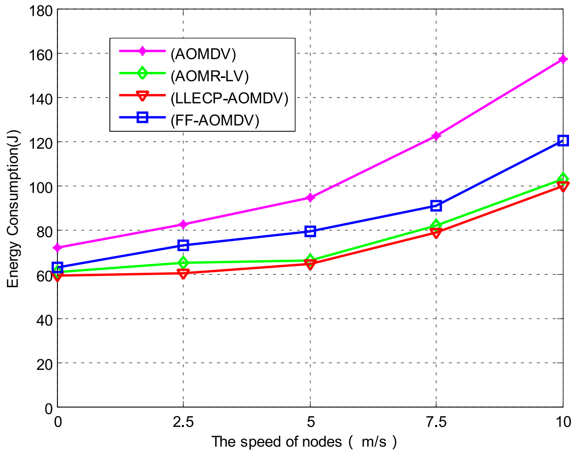

FIGURE 5. **The relationship between moving speed and energy consumption of different nodes.**

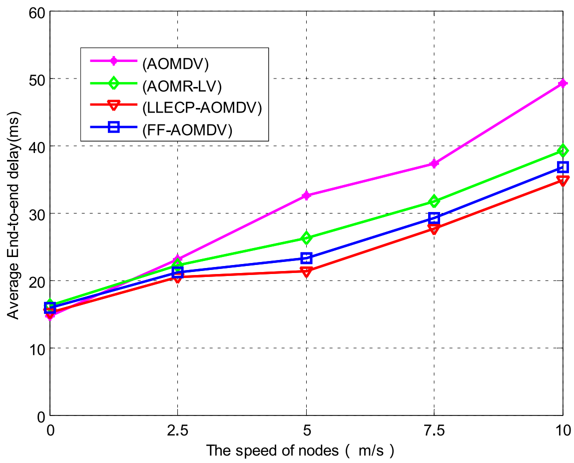

FIGURE 6. **The relationship between different node moving speeds and average end-to-end delay.**

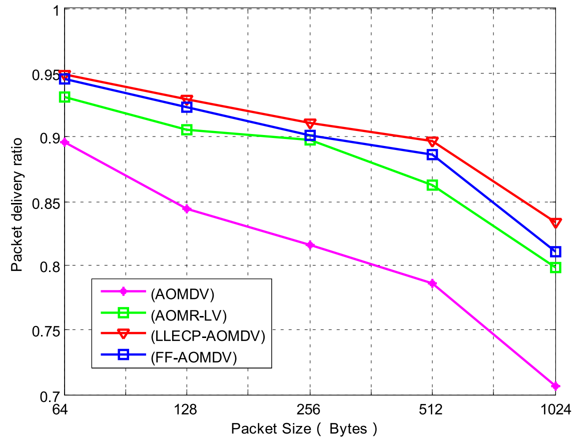

FIGURE 7. **The relationship between different packet sizes and data packet delivery rates.**

LLECP-AOMDV proposed in this paper reduced from 0.979 to 0.804, the FF-AOMDV algorithm reduced from 0.975 to 0.778, the AOMR-LV algorithm reduced from 0.977 to 0.747, and the AOMDV algorithm reduced from 0.967 to 0.673. To a certain extent, the LLECP-AOMDV protocol proposed in this paper is superior to other protocols. The LLECP-AOMDV protocol selects a relatively stable priority with high priority, that is, a path with a long link lifetime and low energy consumption reduces the possibility of link failure and reduces the packet loss rate.

Figure 5 shows the energy consumption of LLECP-AOMDV, FF-AOMDV, AOMR-LV and AOMDV at different node moving speeds. When the speed of the node increases at (0, 2.5, 5, 7.5, 10) m/s, the energy consumption of network also increases. The energy consumption of the LLECP-AOMDV algorithm increased from 59J to 100J, the energy consumption of FF-AOMDV increased from 63J to 120J, the energy consumption of AOMR-LV increased from 61J to 103J, and the energy consumption of AOMDV increased from 72J to 157J. The LLECP-AOMDV routing protocol selects the link with the least energy consumption and the most stable link for data transmission. According to the energy level of nodes, the AOMR-LV protocol is graded. When the data packet is transmitted, the source node distributes the data packet through high energy routing and average load to balance the load on multiple routes. Therefore, energy consumption is saved. It can be seen from Figure 5 that the method proposed in this paper is basically consistent with the AOMR-LV method in terms of energy consumption. Compared with the traditional AOMDV and FF-AOMDV protocols, it has better performance.

As shown in Figure 6, the average end-to-end delay of the four algorithms increases as the node moves faster. Because the faster the node, the faster the network topology transforms, increasing the possibility of network link disconnection. When a route fails, other routes may also be disconnected. Due to on-demand routing, when the network topology changes, it is very likely that the route discovery needs to be restarted, thus the average end-to-end delay increases. The average end-to-end delay of LLECP-AOMDV increased from 15.61ms to 36.9ms, the FF-AOMDV protocol increased from 15.87ms to 36.7ms, the AOMR-LV protocol increased from 16.31ms to 39.21ms, and the AOMDV protocol increased from 14.63ms to 49.21ms. Overall, the proposed protocol is superior to the other protocols.

As shown in Figure 7, Figure 8, and Figure 9, the performance of the four algorithms is compared when the simulation time is identical, the speed of mobile node is identical, and the size of packets is different. The speed of nodes in the network is 2.5m/s, the direction of movement is random, and the simulation time is 50ms. The size of packets is (64, 128, 256, 512, 1024) Bytes.

As shown in Figure 7, when the simulation time is the same, the node moves at the same speed, and the size of packets is varied, as the size of packets enlarges, the data packet delivery rate decreases. The data packet delivery rate of the LLECP-AOMDV algorithm decreased from 0.942 to 0.834, the FF-AOMDV protocol reduced

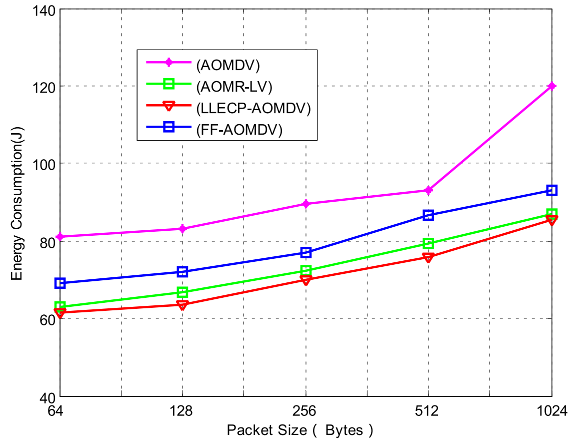

FIGURE 8. **The relationship between different packet sizes and energy consumption.**

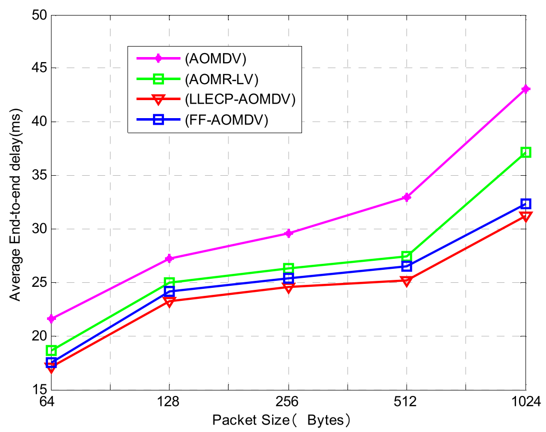

FIGURE 9. **The relationship between different packet sizes and average end-to-end delay.**

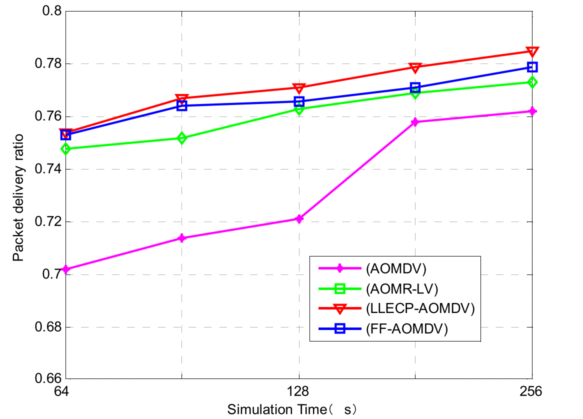

FIGURE 10. **The relationship between simulation time and data packet delivery rate.**

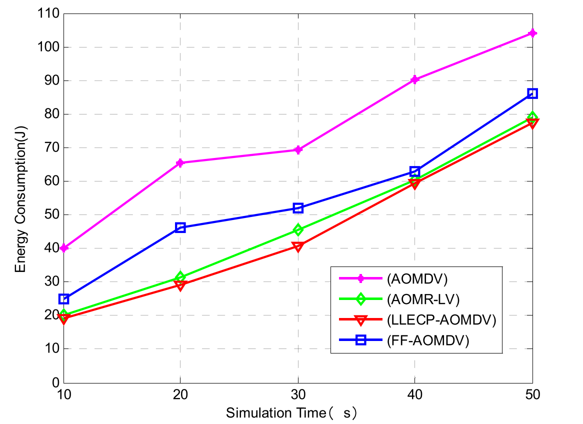

FIGURE 11. **The relationship between simulation time and energy consumption.**

from 0.945 to 0.811, the AOMR-LV protocol reduced from 0.931 to 0.799, and the AOMDV protocol reduced from 0.896 to 0.707. Due to the LLECP-AOMDV considers the stability of the link and low-energy nodes, the protocol proposed is superior to other protocols.

As shown in Figure 8, when the simulation time is the same, the speed of nodes is constant, and the size of packets is different, as the size of packets increases, the energy consumption of the network also increases. The network energy consumption of the LLECP-AOMDV algorithm increased from 61J to 85J, the FF-AOMDV protocol increased from 69J to 93J, the AOMR-LV protocol increased from 63J to 87J, and the AOMDV increased from 81J to 120J. The energy consumption of the LLECP-AOMDV and AOMR-LV protocols is basically identical, which is obviously superior to the traditional AOMDV and FF-AOMDV protocols.

It can be seen from Figure 9 that when the simulation time and the speed of nodes are constant, and the size of packets is metabolic, as the size of packets increases, the average end-to-end delay increases. The average end-to-end delay of the LLECP-AOMDV algorithm increased from 17.6ms to 32.92ms, the FF-AOMDV protocol increased from 17.53ms to 32.23ms, the AOMR-LV protocol increased from 18.64ms to 37.12ms, and the AOMDV increased from 21.63ms to 43.06ms. The performance of the LLECP-AOMDV protocol is superior to other protocols because the route selected by this protocol is stable, which reduces the possibility of link disconnection, thus reducing the delay.

As shown in Figure 10, Figure 11, and Figure 12, when the speed of nodes and the size of packets are constant, and the simulation time increases by (10, 20, 30, 40, 50) s, the four algorithms are compared. The speed of each node is 2.5m/s, the direction is random, and the size of packets is 256 Bytes.

It can be clearly seen from Figure 10 that as the simulation time increases, the data packet delivery rate also increases. When the simulation time increased from 10s to 50s, the data packet delivery rate of the LLECP-AOMDV algorithm increased from 0.752 to 0.781, the FF-AOMDV protocol increased from 0.753 to 0.779, the AOMR-LV protocol increased from 0.748 to 0.773, and the AOMDV increased from 0.702 to 0.762. The simulation results clearly prove that the protocol proposed in this paper is superior to other protocols.

As shown in Figure 11, as the simulation time increases, the energy consumption increases. When the simulation

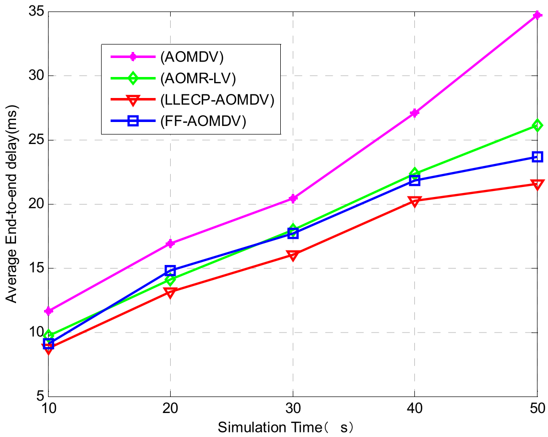

FIGURE 12. The relationship between simulation time and average end-to-end delay.

time increased from 10s to 50s, the energy consumption of the LLECP-AOMDV algorithm increased from 19J to77.5J, the energy consumption of FF-AOMDV increased from 25J to 86J, the energy consumption of AOMR-LV increased from 20J to79J, and the AOMDV protocol increased from 40J to104J. As can be seen from the figure, the protocol proposed in this paper is equivalent to the energy consumption of the AOMR-LV protocol, and there is no obvious improvement. However, compared to the traditional AOMDV and FF-AOMDV protocols, the performance of LLECP-AOMDV is still appreciated.

As shown in Figure 12, as the simulation time increases, the average end-to-end delay also increases. When the simulation time is 10s, the average end-to-end delay of the LLECP-AOMDV algorithm is 19.2ms, the FF-AOMDV protocol is 9.1ms, the AOMR-LV protocol is 9.67ms, and the AOMDV protocol is 11.6ms. When the simulation time is 50s, the end-to-end delay of the LLECP-AOMDV algorithm is 23.2ms, the FF-AOMDV protocol is 23.6ms, the AOMR-LV protocol is 26.07ms, and the AOMDV protocol is 34.68ms. As can be seen from the figure, the LLECP-AOMDV protocol proposed in this paper is superior to other protocols.

As shown in Figure 13, we show the average hop count of the proposed protocol comparing with other approaches for mobile edge computing.

C. TESTS WITH REAL SCENARIOS

With the rise of fifth-generation (5G) communication technologies, society of mobile edge computing is rapidly transforming into a fully interconnected world. The future of the Internet can be foreseen by an infinite number of software components and things that coordinate with each other to achieve different applications of mobile edge computing. As one of the most important systems in the future mobile edge computing, the smart mobile edge computing system will be connected, as well as the rapid development of cooperative and automated interaction to achieve smart learning [32].

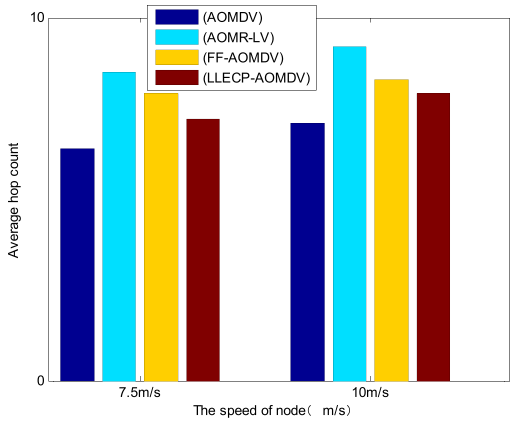

FIGURE 13. The relationship between the speed of node and average hop count.

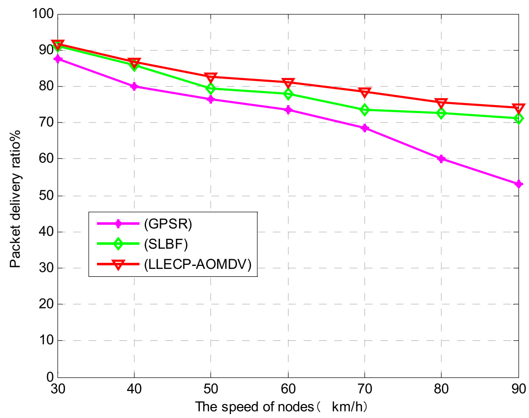

FIGURE 14. The relationship between the speed of node and test packet delivery rate.

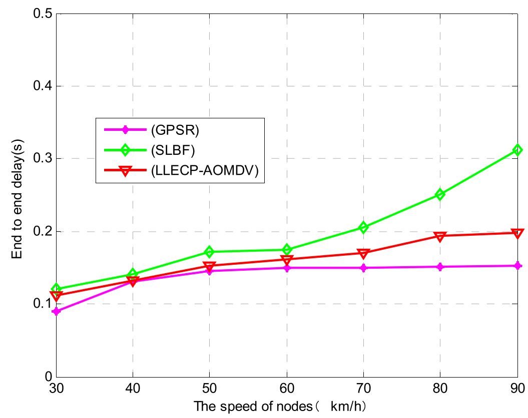

FIGURE 15. The relationship between the speed of node and test end to end delay.

The routing protocol proposed in this paper can be applied to smart mobile edge computing. Similarly, the person equipped with mobile communication learning devices (such as mobile phone, iPAD, PDA, Laptop, and other mobile terminals) [47]–[55] are regarded as mobile nodes, and the routing protocols proposed in this paper can also be applied which improves the quality of communication of mobile edge computing.

In order to verify the validation of this method in mobile edge computing network, in this paper, a 1500m × 1500m mobile edge computing scene is generated by using the mobile edge computing Generator (MobiSim) [56]–[61]. The agreement between this paper and the classical AOMDV algorithm and the proposed GPSR [33] and SLBF [34] protocols are compared. A mobile edge computing device represents a node. The comparison result is shown in Figure 14 and Figure 15. Through test comparison, the LLECP- AOMDV proposed in this paper is superior to the other protocols.

V. CONCLUSION

A multi-path routing protocol based on predicting link lifetime and minimum energy consumption (LLECP- AOMDV) for mobile edge computing is proposed in this paper. In the path discovery and path selecting phase, the energy level of the node determines whether the node participates in route discovery. Simultaneously, the distance between the nodes is estimated by RSSI to calculate the energy consumption which is required for data transmission and link lifetime. After calculating the priority of multiple paths, it selects the path with higher priority for data transmission. In the route maintenance phase, the priority is dynamically updated through the transmission of the HELLO packet. Compared with the traditional AOMDV, AOMR-LV and FF-AOMDV protocols, simulation and test experiments show that the proposed strategy reduces the end-to-end delay and the network energy consumption, and improves the delivery rate of data packets. It extends the lifetime of the network and improves the overall efficiency of the network for mobile edge computing.

COMPLIANCE WITH ETHICAL STANDARDS NO CONFLICT EXISTS

Author De-gan Zhang, Lu Chen, Jie Zhang, Jie Chen, Ting Zhang, Ya-meng Tang, and Jian-ning Qiu declare that they have no conflict of interest.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animals performed by any of the authors.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

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