A Cross-Layer Protocol for Mobile Ad Hoc Network Based on Hexagonal Clustering and Hybrid MAC Access Approach

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Abstract. Due to its flexible and convenient networking, Ad hoc networks have been used in more and more scenarios. But, the features of mobility, constantly changing topologies and centerless architecture limit its applications. In order to improve the performance of Ad hoc, this paper proposes a cross-layer protocol for mobile Ad hoc network based on Hexagonal Clustering and Hybrid MAC Access (HCHMA) approach. Through the clustering algorithm, cluster heads are selected to form a backbone network for route discovery and establishment. And the MAC layer uses two different access mechanisms to ensure efficient transmission of routing packets and data packets. Benefiting from the above approaches, network overhead is greatly reduced and the throughput is improved. By doing simulations in the network simulator 2 (NS2) software, the HCHMA protocol shows better packet delivery rate, higher throughput and lower end-to-end delay compared with the Ad hoc On-demand Distance Vector Routing (AODV) protocol and the Optimized Link State Routing (OLSR) protocol.

Keywords: Ad hoc network · Hybrid MAC access · Clustering · Cross-layer protocol · Location-based

1 Introduction

Mobile ad hoc networks (MANETs) have attracted increasing attention in recent years due to the capacity in support of multi-hop communications, infrastructure- independent network topology, self-management and easy-deployment. In terms of applications, MANETs have been widely used in the civil and military area to provide ad hoc based communication capacity in support

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of emergency evacuation in the natural disaster or mission-based operations in battlefield [1]. As for its self-management, ad hoc networks need well-organized distributed algorithms to determine network organization, link scheduling, and routing [2]. As two core technologies of Ad hoc network, the channel intervention mechanism of medium access control (MAC) layer and the routing technology of network layer, still have many problems and need more efficient, stable and robust algorithm.

MAC protocol plays an important role in MANETs to provide efficient data transmission service. In order to improve the utilization of the Ad hoc network, a lot of work has been done. In [3], the authors propose a dynamic TDMA protocol based on node neighborhood information (TDMA-NNI) which at different packet send rates. The delay, throughput, and packet loss rate have been improved. How- ever, it has high requirements for the efficient transmission of messages from neighbor nodes. In [4], a hybrid channel access strategy with CSMA/CA and Self-Organized Time Division Multiple Access (SOTDMA) is implemented to improve the application performance of MANETs. To ensure stability and trans- mission efficiency of MANETs, CSMA/CA and SOTDMA are considered to switch according throughput rate of network automatically or manually. In order to further improve network throughput, the time synchronization is specially designed for SOTDMA, and a new power control scheme of multi-hop communication is proposed to increase the stability of hybrid channel access. However, switching requires more signaling frames to collect information, wastes a certain amount of bandwidth, and even requires manual switching.

Routing is a significant issue in Mobile Ad hoc Networks. There are two classifications of routing protocols in MANETs: 1. Table driven routing protocols; 2. Reactive or on-demand routing protocols. Many routing protocols are proposed in MANETs like AODV, DSR and OLSR [5]. Many scholars are also doing further research on routing protocols. In [6], the authors proposed an AODV based routing algorithm "Q-AODV" by controlling the broadcast storm and reducing the total number of RREQ relayed during the route discovery process. It improves QoS parameters, namely average jitter, throughput and average end to end delay. However, it does not perform particularly well on sparse networks. To mitigate the problem caused by route fractures, [7] presents a new routing algorithm. It stores all the available paths. Therefore, whenever the link between the nodes gets break, it can immediately replace with the new route. However, the backup route is not real-time and the protocol is insensitive to changes in network topology.

In traditional methods, most researchers conclude the problems faced by adhoc a routing problem and only solve it in the network by considering routing cost, such as delay, congestion metric and distance. And the others only consider the dynamic changes of the spectrum in the MAC layer [8]. Due to the dynamic changes of network nodes, limited bandwidth and unpredictable channel conditions, the traditional hierarchical optimization method is not enough to improve the performance of Ad hoc network. In order to further improve the network quality of Ad hoc, it is necessary to use available information across layers, that is, to exchange information directly between layers to perform subsequent operations [9]. [10] is based on the cross layer design of AODV protocol, and let the routing layer interact with MAC layer to obtain the link quality information. In addition to considering the path hop count, the link information is also used as the basis when selecting the route.

To apply ad hoc in fishery communication system, this paper proposes a cross-layer protocol based on Hexagonal Clustering and Hybrid MAC Access (HCHMA) approach, which combines the MAC layer and the network routing layer together. The HCHMA protocol divides the time slots according to the geographic location in the neighborhood discovery phase and adopts CSMA/CA mechanism in the data transmission phase. The cluster heads are selected after the ends of neighbor node discovery phase. It establish routing by transmitting route request (RREQ) messages and route reply (RREP) messages only between cluster heads. Therefore, routing overhead and delay can be optimized.

The paper is organized as follows. Section 2 presents the system model. Then, we design the cross-layer protocol in Sect. 3. Simulation results and analyses are provided in Sect. 4. Finally, conclusions are made in Sect. 5.

2 System Model

2.1 Geographic Location Based Clustering

In the HCHMA protocol, we assume that each node obtains its own geographic location information through geographic information system (GIS) and keeps the clocks synchronized. And there is no fixed central node in any cluster.

The proposed protocol adopts hexagonal clustering. As shown in Fig. 1, the entire network area is divided into multiple hexagons by corresponding algorithm based on location information. There are no empty nodes or overlapping areas between clusters. Through this clustering method, nodes can clearly know the clusters to which they belong according to their geographic location information. Based on these advantages, regular hexagon clustering method has been widely studied and applied.

In Fig. 1, a hexagon cluster is further divided into 6 equilateral triangles and marked from 1 to 6. Each index corresponds to a time slot. By this way, the nodes in the same cluster with different indexs can avoid communication collision, while the nodes in different clusters with the same index can implement space division multiplexing.

2.2 Communication Range

In this paper, the radius of a hexagon is R and the communication radius of member nodes is set to $3/2R$. By reduce the communication rate, the communication radius are increased and the neighbor cluster header can communicate with each other directly.

$$L_{bf} = 32.4 + 20 \log f + 20 \log d \tag{1}$$

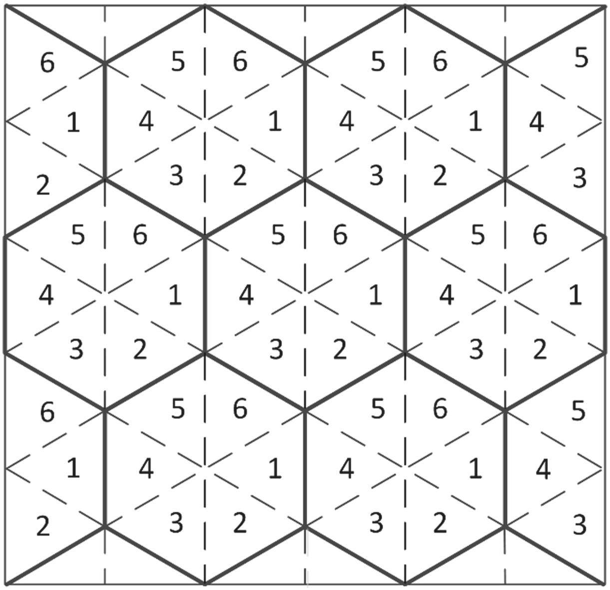


Fig. 1. Network scenario divided with hexagon

Equation (1) describes the relationship between free space loss (L_{bf}) and frequency (f) and transmission distance (d), where L_{bf} in dB, f in MHz and d in km [11].

$$S_i(dbm) = -174 + 10\log B + NF + (S/N)_o \tag{2}$$

Equation (2) describes the relationship between receiver sensitivity (S_i)and thermal noise (NF), bandwidth (B), and output signal-to-noise ratio of the receiver ($(S/N)_o$) when phase noise is not considered in a non-spread spectrum system. The unit of B is Hz [12].

$$P_t - L_{bf} = S_i(dbm) \tag{3}$$

In (3), P_t represents the transmit power. By combining (1), (2) and (3), it can be concluded that when d is need to be doubled, we can only reduce B by four times to make the equation tenable. In the common modulation modes such as MASK, MPSK, and MQAM, B is approximately proportional to the data transmission rate. Therefore, in HCHMA protocol, the transmission rate between cluster heads is 1/4 of the normal transmissions.

3 Cross-Layer Protocol Design

In the proposed protocol, the TDMA mechanism is used to divide the time into time frame cycles. As shown in Fig. 2, each time frame cycle is T which includes a neighbor node discovery period T_1 and a data transmission period T_2.

The hexagon is divided into 6 equilateral triangles, and the neighbor node discovery period is correspondingly divided into 6 time slots. During the neighbor node discovery period, the nodes with different indexes take different time slots to transmit hello messages and the nodes with same index share same time slots by CSMA/CA mechanism. The nodes with the same index but in different clusters can send hello messages at the same time. The time slots are divided by geographical locations, and the total number of nodes competing for channels at the same time is relatively reduced. Therefore, in this way, the probability of the message collision occurrence is reduced, channel utilization is improved, and hello messages can be transmitted more efficiently.

During the data transmission period, route messages and the data messages share the same time slots by CSMA/CA mechanism. However, in order to make the routing messages have higher priority, the fixed backoff of the routing messages is smaller than the data packets in the random backoff algorithm of the MAC layer. Meanwhile, Handshake mechanism is required before point-to-point data transmission. In order to achieve effective wireless shared channel, refer to the IEEE 802.11 protocol, the node first uses the RTS/CTS to perform control channel reservation, and the data transmission can be performed after the reservation is successful. The data is transmitted through the DATA/ACK process to ensure the reliability of the network. The detail process of the route establishment will be given later.

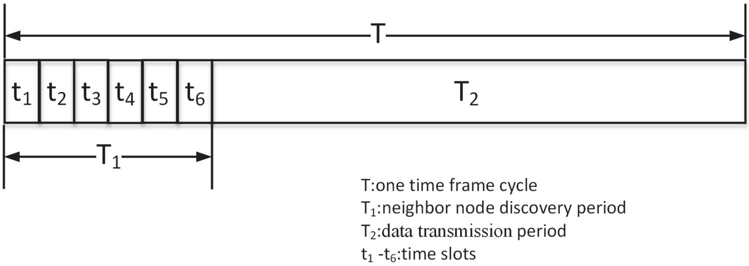


Fig. 2. TDMA frame allocation

3.1 Neighbor Node Discovery

Neighbor nodes of a node refer to nodes within the communication range of the node. During neighbor node discovery period, the nodes send hello messages according to the time frame corresponding to their geographic location. The hello messages are generated and sent only during the discovery period of the neighboring node. There is no re-transmission mechanism. If it is not sent within the specified neighbor discovery time, discard will happen. In order to reduce collisions occurred when more than one node send messages at the same time slot, a random backoff is added before the hello message is sent according to the

CSMA/CA mechanism. The hello message contains the sender IP address and geographic location information. The nodes that are not in the current sending slot are silent to receive the hello messages and updates their neighbor node tables.

The detail process of this neighbor node discovery can be found in our previous work [13].

3.2 Cluster Head Election Algorithm

After six time slots, each node locally compares its own location with that of its neighbors in the same cluster, and the nearest node to the cluster center declares to be the cluster head while the other nodes remain members in the cluster. As we set the communication range to be $3/2R$, the cluster head which locals within $1/2R$ radius of the cluster can communicate with any node in the same cluster. For a few cases where there are no nodes within $1/2R$ radius, some edge nodes are not within the communication range of the selected cluster head node. Another cluster head will be selected among these edge nodes, which will be explained later.

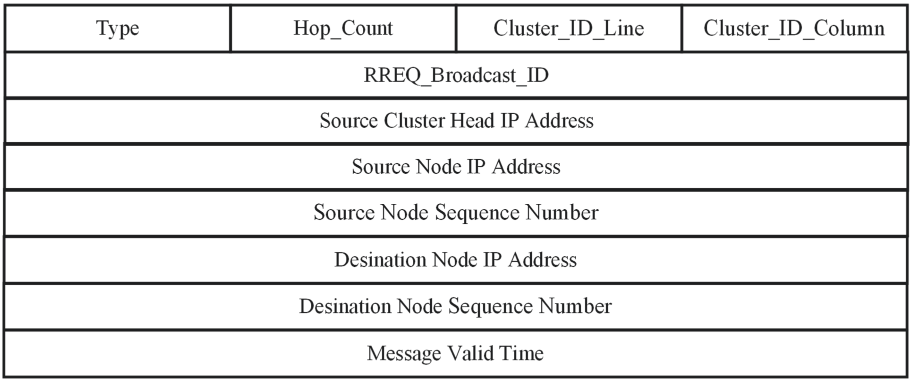
After the election of the cluster head, the nodes which are elected to a cluster head periodically generated the cluster hello message sending to the cluster heads of the neighboring cluster. Same as the hello message, there is no re-transmission mechanism and a random backoff is added before the hello message is sent. The hello message contains the IP address and geographic location of the neighbor nodes of the cluster head. In order to facilitate sending and receiving messages between cluster heads in its cluster, the cluster heads use low speed for transmission to expand the communication range. The propagation range of the routing messages generated by the cluster head is 3R, and all nodes in the hexagonal cluster can receive and parse them. The edge nodes mentioned in the previous paragraph are verifying that they are not in the cluster by parsing these packages. Among these edge nodes, the node closest to the center of the cluster becomes a new cluster head.

After this process, the cluster head node obtains the IP address and geographical location of the nodes in the neighbor cluster. The distance between the nodes in its own cluster and those in the neighbor clusters is calculated through the obtained geographical location. By comparing the result with the communication radius, we can calculate whether there is a connection between our own cluster and the neighboring cluster, which is used for route discovery and establishment.

3.3 Network Topology Discovery

When a node has a data packet to send, it first detects whether there is a route from itself to the destination node. If there is a route, it will forward the data to the next hop node. If there is no route, it needs to find the route. The node sends a RREQ message to the cluster head, and the message is unicast. After receiving the RREQ from the node in its own cluster, the cluster head broadcasts the RREQ to the neighbor cluster heads. Similarly, in order to facilitate sending and receiving messages between cluster heads, the cluster heads use low speed for transmission to expand the communication range.

The RREQ message format is given in Fig. 3. As is shown in Fig. 3, besides the intra-cluster node information, the RREQ packet mainly includes the following fields:



<table>
<tr><td>Type</td><td>Hop_Count</td><td>Cluster_ID_Line</td><td>Cluster_ID_Column</td></tr>
<tr><td colspan="4">RREQ_Broadcast_ID</td></tr>
<tr><td colspan="4">Source Cluster Head IP Address</td></tr>
<tr><td colspan="4">Source Node IP Address</td></tr>
<tr><td colspan="4">Source Node Sequence Number</td></tr>
<tr><td colspan="4">Desination Node IP Address</td></tr>
<tr><td colspan="4">Desination Node Sequence Number</td></tr>
<tr><td colspan="4">Message Valid Time</td></tr>
</table>

Fig. 3. RREQ message frame structure

Type: Used to indicate the message type, such as TC message, 8-bit storage.

Hop_count: Used to record the number of hops that the RREQ message propagates, 8-bit storage.

Cluster_ID_Line and Cluster_ID_Column: Used to indicate source cluster ID, 16-bit storage.

RREQ_Broadcast_ID: Used to record the ID of RREQ message and prevent retransmission, 32-bit storage.

Sequence Number: Used to indicate the latest serial number of the node and to update route, 32-bit storage.

When the member node receives the RREQ message, it simply discards the message without any processing. When the cluster head receives the RREQ message, the following steps are performed:

Step 1: If such a RREQ has been received before, the node silently discards the newly received RREQ and the process ends. Otherwise, the next step is performed.

Step 2: If the nodes in own cluster does not connect with nodes in the neighbor cluster whose cluster head sent this message, the node silently discards the newly received RREQ and the process ends. Otherwise, the next step is performed.

Step 3: The cluster head records the inter-cluster routing to the RREQ message source cluster head node and perform the next step.

Step 4: If the destination node found by RREQ is in this cluster, it produces the RREP message. Otherwise,the message is forwarded and the process ends.

Let's use the example in Fig. 4 to illustrate the proposed routing discovery process. The source node S sends an RREQ message to its cluster head node 2. After receiving the message, node 2 starts flooding the message among the neighbor cluster heads. After the cluster head node 4 receives it, because the node 3 in its own cluster and the node 1 in the cluster of node 2 are in communication range, node 4 records the route to cluster head 2 which generates the RREQ message, and then forwards the RREQ message. Conversely, since the nodes in the cluster can not connected to the nodes in the cluster of node 2, node 9 discards the RREQ message, as well as the node 10. After receiving the RREQ message, node 7 starts to send a route reply because the destination node D is in its cluster.

By passing RREQ packets between cluster heads (backbone network) to reduced the number of RREP message forwardings, the routing overhead is reduced.

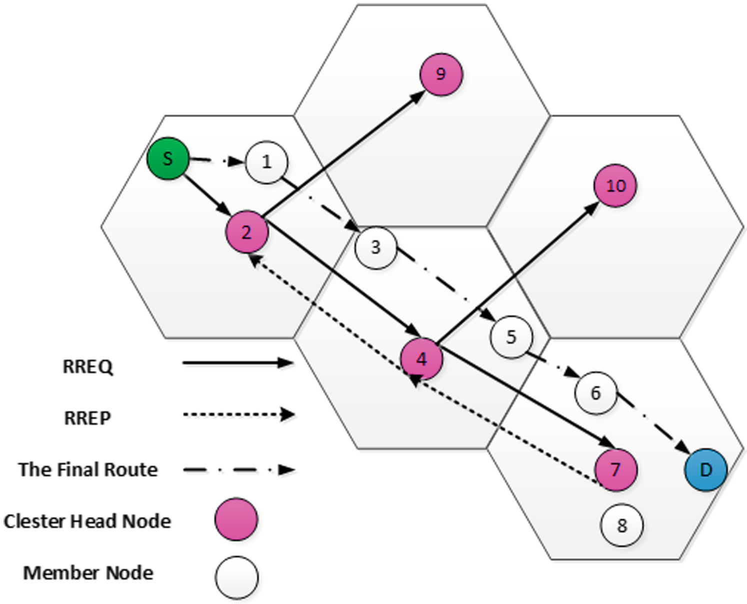


Fig. 4. Route discovery and route establishment

3.4 Route Establishment

The cluster head where the destination node is located responds to the received RREQ message by generating a RREP message. The RREP message is broadcast to the next hop, in the opposite direction of the RREP message propagation path. Similarly, the propagation range of RREP message generated by the cluster head is twice that of member nodes.

The format of the package is given in Fig. 5.

<table>
<tr><td>Type</td><td>Reserved</td><td>Hop_Count</td><td>Node_Num_In_Route</td></tr>
<tr><td colspan="4">Next Cluster Head IP Address</td></tr>
<tr><td colspan="4">The IP Address of the Last Node of Last Cluster in Route</td></tr>
<tr><td colspan="4">The IP Address of the Node of This Cluster in Route[1]</td></tr>
<tr><td colspan="4">The IP Address of the Node of This Cluster in Route[2]</td></tr>
<tr><td colspan="4">.........</td></tr>
<tr><td colspan="4">The IP Address of the Node of This Cluster in Route[Node_Num_In_Route]</td></tr>
<tr><td colspan="4">The Geographic Location Information of the last Node of This Cluster in Route</td></tr>
<tr><td colspan="4">Desination Node Sequence Number</td></tr>
<tr><td colspan="4">Desination Node IP Address</td></tr>
<tr><td colspan="4">Source Node IP Address</td></tr>
<tr><td colspan="4">Message Valid Time</td></tr>
</table>

Fig. 5. RREP message frame structure

Node_Num_In_Route: The number of nodes in the routing link calculated by the cluster head in this cluster, 8-bit storage.

To establish a route, the destination node is selected as the first node participating in the route. The cluster head is responsible for selecting and assigning which nodes within the cluster to participate in route establishment. We set the initial value of i to 1. The process of a cluster head to select cluster members in this routing link is given by follow steps:

Step 1: The cluster head select the node that can connect with the last node that has participated in the routing, as candidate nodes. The nodes participating in the routing that are selected by the cluster head one by one from the destination node to the source node. Then from these candidate nodes, select the node nearest to the geographic center of the next cluster which cluster head the RREP message will send to. The IP address of this node will be recorded in *The IP Address of the Node of This Cluster in Route*$[i]$ in the RREP packet. Then the value of i is incremented by one. And this selected node will become the latest node that has participated in the routing.

Step 2: This cluster head determines if this selected node is connected to any of the nodes in the next cluster. Yes, perform step 3. No, go back to step 1.

Step 3: Information of nodes in the cluster selected to participate in route establishment is packed by the cluster head and broadcast to the next cluster head.

When a member node receives a RREP message, it first detects whether the message is sent by its cluster head. If not, discard the package directly. If so, it further detects whether it is in the routing link calculated by the cluster head. In other words, it is determined whether its IP address is the same as $The\ IP\ Address\ of\ the\ Node\ of\ This\ Cluster\ in\ Route[i]$ in the RREP message. If not, discard the package. If so, this node records the next hop to destination node is $The\ IP\ Address\ of\ the\ Node\ of\ This\ Cluster\ in\ Route[i-1]$. If $i = 1$, the next hop is $The\ IP\ Address\ of\ the\ Last\ Node\ of\ Last\ Cluster\ in\ Route$. The member nodes analyze the RREP message sent by the cluster heads, and the route is established hop by hop.

After the cluster header node receives the RREP message, it detects whether it is the next hop of the message. If not, discard the package directly. If so, select the nodes participating in the routing as described above, pack the information of the selected nodes in its cluster, and forward the packet.

Similarly, Let's use the example in Fig. 4 to illustrate this process. After receiving the RREQ message, node 7 begins to generate a RREP message. First, the nodes 6 and 8 will be found in the cluster that have connections with the destination node D. Then, by comparing the distances between the two nodes and the central geographic location of the cluster where the node 4 is located, the node 6 is selected as the previous hop node of the destination node. Since node 5 can be connected to node 6 of the cluster in which node 4 is located, there is no need to select other nodes in this cluster to participate in routing. Then, node 7 broadcasts a RREP message to the cluster head node 4. After receiving the broadcasted RREP message, nodes 7 makes a route to the destination node by parsing the packet. After receiving the RREP packet, the cluster head node 4 first selects a node 5 that is connected to the node 6. However node 5 can not connect with the nodes of the cluster where the node 2 is located. Therefore, another node need to be selected. Then, the node 3 is selected because it is connected to the node 5 and has a connection with the node of the cluster where the node 2 is located. The cluster head node 4 records the selected nodes into the RREP message and broadcasts it out. Similarly, nodes 3 and 5 use the information in the broadcast packet to make a route to the destination node. In this way, the route labeled in Fig. 4 is finally made.

Because of the existence of cluster heads, a backbone network is formed in the whole network. The direct communication between cluster heads is used to establish routes, which effectively reduces the flooding of routing messages. In addition, GPS is used to calculate routing, which effectively reduces the amount of data required to establish routing interactions and reduces routing overhead.

4 Simulation Results and Analysis

NS-2 is used to visualize the ns simulations and trace packet data. The trace file contains topology information like nodes, links, queues, node connectivity and packet trace information. In the simulation, 60 nodes are randomly distributed within a square of $1000\,\mathrm{m} \times 1000\,\mathrm{m}$. The wireless transmission distance D_t is

250 m, the carrier sensing range D_r is 550 m, the radius of hexagonal cellular is set to 166.7 m, the channel bandwidth is 1 Mbps, the neighbor node discovery period T1 of HCHMA is 60 ms, and the time frame cycle T of HCHMA is 2 s. The simulations run for 100 s and apply Constant Bit Rate (CBR) sources where the packet generated rate is from 50 to 300 kbps. The max moving speed of nodes is 1 m/s. The unlisted parameters are set to the default value in NS2. We selected traditional proactive routing OLSR and traditional passive routing AODV for comparison, in which MAC layer are applied by IEEE 802.11. We will compare the performance of these three protocols from the average end-to-end delay (AEED), packet loss rate and throughput. The results are given by the averages of 20 times simulations.

Figure 6 presents the relationship between the AEED and the data generation rate. The AEED is caused by two reasons: one is the waiting time before the route established at the routing layer, the other is the waiting time for the access channel and collision retransmission at the MAC layer. The HCHMA protocol uses the backbone network formed by the cluster head to establish routes, which reduces the number of flooding of routing messages, reduces the time required to establish routes, and reduces AEED.

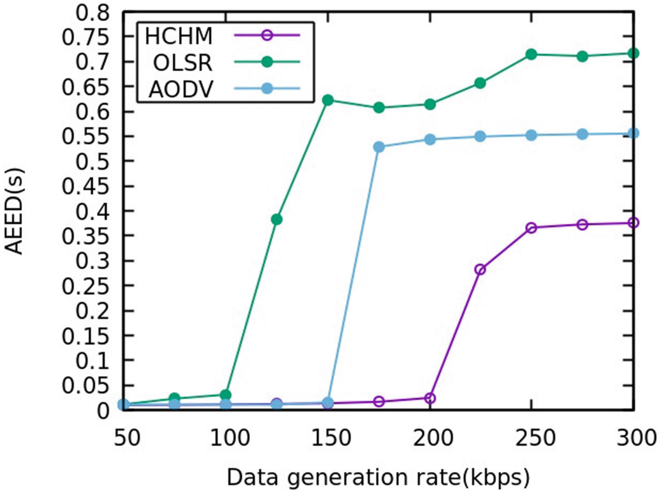


Fig. 6. AEED vs. data generation rate

Figure 7 presents the relationship between the packet loss rate and the data generation rate. As can be seen from the figure, our protocol outperforms the other two protocols in terms of packet loss rate performance. This is because we use different channel access algorithms to ensure the effective transmission of neighboring node detection messages and routing messages, and improve the success rate of route establishment.

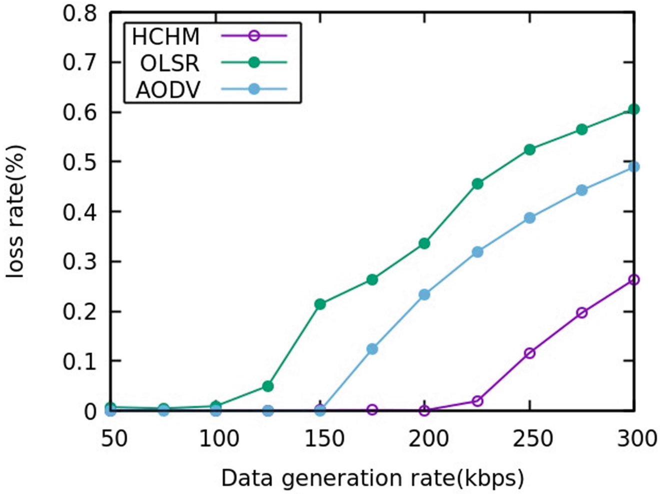


Fig. 7. Packet Loss rate vs. data generation rate

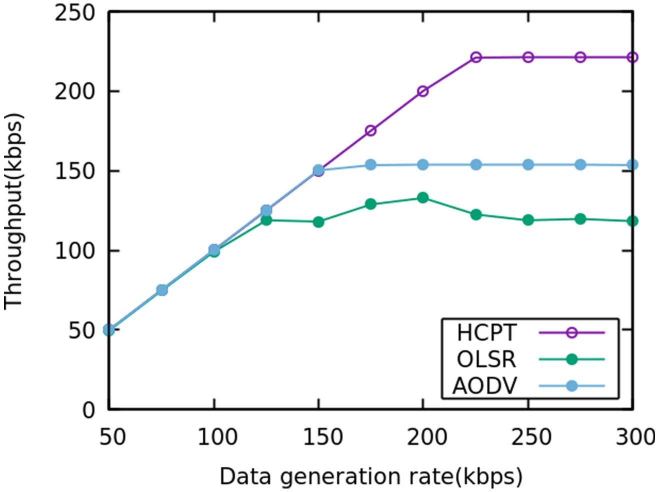


Fig. 8. Throughput vs. data generation rate

Figure 8 shows the throughput vs. the data generation rate. As the rate of data generation increases, each protocol reaches its own throughput maximum and remains the same. As we can see from the figure, The throughput of our protocol is higher than the other two protocols. We have better AAED and packet loss rates because of the advantages described above, so we have higher throughput accordingly.

5 Conclusion

In this paper, we propose a cross-layer protocol named HCHMA. The protocol guarantees the effective transmission of different types of messages through different MAC layer algorithms and forms the backbone network by using the cluster head generated by the clustering algorithm, which effectively improves the probability of successful route establishment and reduces the average end-to-end delay. Compared with the traditional AODV and OLSR protocols, the HCHMA protocol has lower latency and packet loss rate and higher throughput.

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