Cross-Layer Aware Routing Protocol for Hybrid Wireless Mesh Networks

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Abstract —Route selection in hybrid wireless mesh networks (WMNs) that contain mobile mesh clients with constrained energy is a critical research challenge. Existing routing protocols take the advantages of backbone mesh routing protocols but lack of consideration of the characteristics of clients. Most of these protocols capture interference and traffic load, but lack of considering the effect of mobility and energy constraints of clients. In this paper, we propose a Cross-Layer Aware (CLA) routing protocol, which is based on comprehensively considering characteristics of mesh routers and mesh clients for gateway traffic in hybrid WMNs. In CLA, we propose a new routing metric jointly considering four parameters in a cross-layer design: the MAC layer channel condition, the routing layer path length, the application layer mobility and constrained energy of clients. These parameters can capture the interference, traffic load, stability and energy efficiency, so as to select an optimum route. In addition, we develop a constrained forwarding mechanism to reduce flooding overhead by limiting the forwarding number of clients in CLA, which can reduce the energy consumption wasted in overhead. Simulation results show that the proposed CLA protocol can effectively improve the whole network performance.

Index Terms—Hybrid WMNs, routing protocol, cross-layer aware, constrained forwarding

I. INTRODUCTION

As the new type network to solve the Internet bottleneck problem of "last mile", Wireless Mesh Networks (WMNs) have attracted considerable attentions due to the advantages of self-organizing, self-healing, high-speed, high-capacity, low-cost and stable performance [1].

WMNs can be divided into three main types based on the functionality of the nodes: backbone WMNs, client WMNs and hybrid WMNs. Hybrid WMNs are the most generic type of WMNs, integrating the advantages of backbone WMNs and client WMNs. Hybrid WMNs consist of relatively static mesh routers which form the backbone of the network and mobile clients. Mobile clients can act as a dynamic extension of the backbone network by implementing routing functionality, and improve the connectivity and coverage inside the WMNs [2], [3]. In this paper, we mainly focus our research on hybrid WMNs. Hybrid mesh architecture determines its unique characteristics: 1) Mesh routers are equipped with multiple radios and have minimal mobility and no energy constraints. Mesh clients are equipped with one radio and typically have more energy constraints than mesh routers, so energy efficiency needs to be considered. 2) Due to the mobility of clients, the route which contains more mesh clients is less stable, while the route which contains mesh routers are more stable and higher-capacity. 3) The packet forwarding function of clients will increase the flooding overhead, path length and energy consumption.

Routing is a key challenge in WMNs, and routing metric is the core of routing protocol, which can significantly affect the performance of WMNs [4]. In addition, optimal routing mechanisms are imperative to gain the potential advantages of WMNs. Thus the design of routing protocol plays a crucial role for finding efficient routes in the network. As mentioned above, the characteristics of hybrid WMNs make it both intricate and exigent to select a high-throughput and stable path. Mesh routers and mesh clients can differ greatly in terms of their communication capabilities and capacity, which needs to be considered in the routing process. The forwarding capability of mesh clients can help mesh routers to route data packets and make the communication more conveniently between the different clients. However, it will bring serious flooding of route request (RREQ) packets, and some unnecessary forwarding of mesh clients will consume much more energy; Route failure, owing to the mobility of clients, brings more re-generated RREQ packets and increases the overhead. Higher overhead consumes higher energy, so reducing network overhead can help to save energy [5].

Contemporary routing protocols for WMNs capture interference and traffic load, but they don’t integrate the mobility and energy constraints of clients into routing protocol to select an optimal route. In order to select an optimal route in hybrid WMNs, the routing protocol needs to capture interference and traffic load and take mobility and energy constraints of clients into account. Therefore, a suitable routing protocol for hybrid WMNs is important to improve the whole performance.

Here are two traffic types consisting of internal traffic (traffic between clients) and external traffic (traffic between mesh clients and the Internet) in hybrid WMNs. External traffic is also called gateway traffic and most of the traffic in WMNs is gateway traffic. Therefore,
establishing high throughput paths for the gateway traffic will improve the performance of WMNs [6], [7]. Cross-layer design has been considered as a promising method to obtain information from different layers without requiring additional hardware, so that a better representation of network characteristics can be achieved. In this paper, we propose a Cross-Layer Aware (CLA) routing protocol which integrates a new routing metric and a constrained forwarding mechanism into Ad hoc On-Demand Distance Vector (AODV) [8] protocol for gateway traffic in hybrid WMNs. The key contributions of our work are:

- We propose a cross-layer aware routing metric, which is based on cross-layer information such as Channel Busy Time (CBT), path length, mobility and residual energy of mesh nodes. These parameters capture interference, traffic load and stability. The proposed metric helps select an optimum route which exploits the advantages of the backbone routers and the clients of hybrid WMNs. The route is more stable and higher-throughput, providing a lower energy consumption, control packet overhead and packet loss rate.

- We integrate a constrained forwarding mechanism to limit the forwarding number of mesh clients by being aware of the types of nodes. This reduces the flooding of RREQ and effectively uses high-throughput mesh routers to route packets, further reducing network overhead and saving the energy of clients.

The rest of this paper is organized as follows: Section II reviews the related work. In Section III, we give the presentation of our proposed CLA routing protocol. Section IV provides implementation details of CLA protocol. Section V presents evaluation of our proposed CLA routing protocol using network simulator version 2 (NS-2) [9]. The conclusions and our future works are presented in Section VI.

II. RELATED WORK

Cross-layer design is a popular information gathering method for capturing interference and traffic load from the MAC and physical layers. For this reason, the cross-layer design has been widely employed in routing metrics for backbone WMNs. The three main types routing metrics are interference aware routing metrics, load aware routing metrics and hybrid routing metrics. Interference aware routing metrics use measurements based on the physical and logical model to depict both intra-flow and inter-flow interference, such as MIC, INX and iAware. Load aware routing metrics help to provide load balancing between the paths, but fail to depict interference precisely, such as LAETT and WCETT-LB that only take consideration of the traffic load with the use of available bandwidth and average queue length respectively. Hybrid routing metrics take account of interference and traffic load, so as to be able to combine interference and traffic load measurements as the main measures. Thus, hybrid routing metrics have been considered as the most recent trend with regard to cross-layer routing metrics. The main hybrid measures that depict interference and traffic load together are sum of the delay of interfering links, sum of the queue length of interfering links and CBT. The ILA, C2WB, CATT and MIND are the representative hybrid routing metrics. CATT depicts the intra-flow and inter-flow interference as well as traffic load by making a sum of the delays of the interfering neighbors’ links that are 1and 2 hops away. ILA uses the average queue length of the interfering neighbors to depict inter-flow interference and traffic load, while C2WB and MIND use CBT to measure traffic load and logical interference [10]. However, there are few research of routing metrics for hybrid WMNs.

To choose a better path in hybrid WMNs, interference, traffic load, mobility and energy constraints of clients need to be considered into route selection. There are several routing protocols have been developed for hybrid WMNs. Multi-radio Ad hoc On-Demand Distance Vector (AODV-MR) [11] is an expansion of the traditional AODV protocol, which uses traditional hop-count routing metric and endeavors to minimize the path length. A hybrid mesh Ad-hoc On-Demand Distance Vector routing protocol (AODV-HM) [12] selects the route which contains the smaller number of mesh clients and makes use of a dynamic channel assignment technique. In addition, some existing routing mechanisms [13]-[15] applied in hybrid WMNs take advantages of mesh routers to reduce the delay and improve the network performance. But the research of routing metrics employed in hybrid WMNs is relatively small. There are several routing metrics that use cross-layer design as follows.

The congestion aware Ad hoc On-Demand Distance Vector (AODV-CA) routing protocol [16] uses Channel Diverse Congestion Aware (CDCA) metric to establish channel diverse routes through least congested areas. The metric which captures interference and traffic load is made up of two parts: the level of channel diversity (CD) in a route and the level of congestion (CG) in a route. This article computes the metric CDCA at any link i operating on channel Ci, as follows:

$$CDCA_i = CD_i \cdot CG_i$$  \hspace{1cm} (1)

where CD captures the intra-flow interference and can be computed from (2). The cumulative congestion CG operating on channel Ci can be computed as (3), and it reflects the interference and traffic load.

$$CD_i = \begin{cases} 1 & \text{if } C_i = C_{i-1} \text{ AND } C_i \neq C_{i-2} \\ 2 & \text{if } C_i = C_{i-1} \text{ AND } C_i \neq C_{i-2} \\ 3 & \text{if } C_i = C_{i-1} \text{ AND } C_i = C_{i-2} \end{cases}$$  \hspace{1cm} (2)

$$CG_i = \sum_{n=1}^{n} QDI_n$$  \hspace{1cm} (3)

where n is number of interfering flows, QDI represents the time a packet has to remain in the interface queue (IFQ).
The CDCA fully captures the interference and traffic load of hybrid WMNs, but has not considered the effect of mobility and energy constraints of clients. Due to the mobile clients, the interference in hybrid WMNs is varying and links are easily broken. Meanwhile, the route involving the clients without energy will fail.

The Adaptive Load-Aware Routing Metric (ALARM) [17] is computed using the IFQ length and the current data rate, which can be defined as

$$ALARM = \sum_{i=1}^{n} \frac{IFQ_i}{BW_i}$$

where $n$ is the total number of links on the route, $IFQ_i$ represents the IFQ length of link $i$ and $BW_i$ represents the current data rate of link $i$. The interference and traffic load have an impact on queue length, which is directly related to the incoming and outgoing rate of wireless frames and causes the queue length to grow and shrink accordingly. Thus the ALARM can capture the interference and traffic load without extra overhead. However, ALARM doesn’t consider the mobility and energy constraints of clients just like CDCA. When ALARM is integrated into AODV, it is called AODV-ALARM protocol.

The load aware routing metric Dynamic Weighted Cumulative Expected Transmission Time (D-WCETT) [18] extends the WCETT and takes transmission time and channel diversity into account while assigning weight to them on the basis of link congestion. D-WCETT of a path $p$ is defined as

$$D-WCETT_p = (1 - \beta) \sum_{i \in p} ETT_i + \beta \cdot \max_{1 \leq j \leq k} X_j$$

where $\max X_i$ is the sum of ETT(Expected Transmission Time) in the links $l$ on the same channel $j$. $k$ is the total number of channels. $\beta$ is a dynamic parameter subject to $0 \leq \beta \leq 1$, which is changing based on the level of congestion in the link and it is defined as

$$\beta = 1 - QDI$$

where QDI (Queue Discharge Interval) represents the time required by a packet in the IFQ before transmission. QDI is defined as the ratio between the IFQ length by the bandwidth of the channel. Thus, D-WCETT gives higher weight to sum of ETT when links are having higher network load.

D-WCETT dynamically builds routes based on the prevalent network load information, which can be able to cater for the changing network topology. But it uses active probing to measure ETT, which will introduce a lot of overhead. In addition, D-WCETT captures both interference and traffic load, but it fails to take energy and mobility of clients into account on the basis of application layer.

As analysis above, existing routing protocols fail to capture both the characteristics of mesh routers and the characteristics of clients. In this paper, we propose a cross-layer aware routing metric which uses CBT to capture the interference and traffic load, and it also takes path length, mobility and energy constraints of clients into account. CBT has been regarded as the accurate method to capture interference and load without introducing overhead. The speed and residual energy of clients is related to the stability of paths, and longer path length will increase the probability of link breakage. Thus, the proposed metric not only takes advantages of mesh routers but also considers the characteristics of clients. Due to AODV’s capability to deal with highly dynamic environments, we integrate the metric with AODV, called CLA protocol. However, reactive routing mechanisms can cause a large number of control packets because of multi-radio mesh routers of hybrid WMNs. The forwarding function of clients will increase the number of repetitive RREQ packets through the network and further increase the whole network overhead. Some unnecessary forwarding will consume clients’ energy. So a constrained forwarding mechanism which limits the forwarding number of clients is integrated with CLA to reduce the whole network overhead.

III. CROSS-LAYER AWARE ROUTING PROTOCOL

In this section, we provide details of the proposed CLA for hybrid WMNs in terms of energy consumption model, proposed routing metric and constrained forwarding mechanism. The CLA takes the different cross-layer parameters into consideration to select an optimum route. The aim of CLA is to capture inter-flow interference, traffic load, stability and energy efficiency, which contributes to selecting a high-throughput and stable path in hybrid WMNs. In addition, we want to reduce the overhead by a constrained mechanism.

A. Energy Consumption Model

Energy constraints have become an important issue in network with mobile clients that have limited energy [19]. In order to improve energy efficiency, energy consumption is taken into consideration as an important parameter to choose the best path.

Let $e_{tx}$, $e_{rx}$, $e_{ov}$ and $e_{co}$ represent the power required for transmitting, receiving, overhearing and being idle, respectively. The total energy consumed by a mesh client to transmit a packet successfully, is defined as

$$E_{\text{consumed}} = E^w + E^o + E^{ov} + E^{co}$$

where $E^w$ is the energy consumption for a successful packet transmission from the mesh client, $E^o$ is the energy consumed in collisions before the successful transmission, $E^{ov}$ is energy consumed in back-off time, and $E^{co}$ is the energy consumed in the state that the client has no pending packet between any two consecutive transmissions [20].

B. Proposed Routing Metric

In this paper, we explain the proposed routing metric of CLA, called $M_{CLA}$. The proposed metric includes four components: CBT, mobile speed, residual energy and hop-count. These factors concern inter-flow interference, traffic load, stability and energy efficiency. The CLA
protocol uses information from both the Medium Access Control (MAC) layer and application layer with a cross layer design. When selecting a route, CLA obtains the residual energy and mobile speed of nodes from application layer and gets the channel idle time from the MAC layer. It helps select a path involving more mesh routers. The path with the minimum value of metric is selected for transmitting data packets. $M_{CLA}$ is defined as

$$M_{CLA}(p) = \sum_{i=1}^{n} CBT_i + \max_{p \leq j \leq m} \frac{V_j}{V_{\text{max}}} + \max_{\text{node}} \frac{E_j}{\text{Hop count}_{\text{max}}},$$

(8)

where $n$ is the number of links and $m$ is the number of nodes on the path $p$, $V_{\text{max}}$ is the max speed of nodes on the entire path and $V_{\text{max}}$ is the max speed of nodes in the entire network. $V_{\text{max}}$ is a constant parameter which is defined in simulation environment. The ratio of $V_j$ to $V_{\text{max}}$ depicts information about the effect of clients’ mobility. The outage probability of link increases with the increase of the ratio in the path selection. $E_j$ represents the weight of residual energy of node $j$. The path length is related to stability of route. $\text{Hop count}$ is the path length and $\text{Hop count}_{\text{max}}$ is the maximum number of hops of RREQ forwarded within entire network. In AODV, $\text{Hop count}_{\text{max}}$ is generally defined as 30. Due to the energy constraints of mesh clients, energy is an important metric for selecting an appropriate route. We assign weight $E_j$ to interpret the energy as shown in Table I [21]. We set the maximum weight of energy of nodes on the entire path as a metric, avoiding route failure caused by an intermediate node that has exhausted energy.

<table>
<thead>
<tr>
<th>Table I: Node Energy Weight</th>
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<tr>
<td>Residual Energy</td>
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<tr>
<td>$E_j$</td>
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</table>

CBT which is the time fraction when data keeps the channel busy, including the time that the node is transmitting data on this channel and the time that the channel is occupied by adjacent transmissions. IEEE 802.11 MAC layer uses a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism. A node first needs to monitor the channel before sending out a packet. If the channel is idle for a Short Inter-Frame Space (SIFS) period, the node will begin to transmit data, or it will enter the back-off state. CBT uses a complementary calculation through the idle period, defined as

$$CBT = \frac{T_{\text{total}} - T_{idle}}{T_{\text{total}}}$$

(9)

where $T_{\text{total}}$ is the entire monitoring time and $T_{idle}$ is the time that no data keeps the channel busy. CBT has been proven to be the most accurate method of measuring utilization of channel for wireless network and it can accurately measure the logical inter-flow interference and traffic load [10]. The fraction of channel idle time during the past history can be a simple approximation of local available bandwidth under inter-flow interference. Therefore, we use CBT as metrics for capturing the network interference and traffic load simply and effectively.

As analysis above, the proposed routing metric has following advantages:

- It considers stability and energy efficiency by obtaining mobile speed and residual energy of clients, which avoids frequent changes on the path and prolong the network lifetime in hybrid WMNs. In addition, it obtains the speed and residual energy of nodes from application directly, which will not introduce overhead.
- It estimates CBT to capture both logical inter-flow interference and traffic load, because CBT can be able to pick up the precise time of the channel contention.
- It uses cross-layer design integrate parameters from physical, MAC, routing and application layers, which is helpful to improve the whole network performance. In physical layer, it obtains the residual energy of mesh nodes. In MAC layer, it monitors channel state to capture the logical interference and load. In application layer, it obtains the mobile speed of mesh nodes in real time to avoid frequent changes. In routing layer, it calculates path length to avoid longer paths and to achieve a lower transmission rate.
- It uses passive mechanism to pick up parameters from different layers, which can reduce network overhead to a certain extent compared with active probing.

C. Constrained Forwarding Mechanism of CLA

The main difference between hybrid WMNs and backbone WMNs is that clients have the ability to forward packets. However, the mobility and energy constraints of mesh clients will make path unstable. In order to utilize the advantages of high throughput and stable mesh routers and reduce the whole network overhead, we propose a constrained forwarding mechanism by limiting the forwarding number of clients. As we research the route selection for gateway traffic, the RREQ packets which are forwarded by mesh routers will not be processed by clients in the proposed mechanism. To implement proposed scheme, the process of RREQ packets at mesh routers and mesh clients is different. For this purpose, we add a field in the RREQ header to indicate whether the RREQ packet is received by a mesh client or a mesh router, called rq_mark. The initial value of rq_mark is 0. When the RREQ is received by a mesh router, the rq_mark is set to 1.

Due to the mobility of clients, path becomes less stable with the increase of path length. Most of the throughput gain can be obtained with the use of a two-hop and three-hop relaying scheme for mobile networks [22]. In this paper, we limit the maximum path length among mesh clients to three-hop. When a source client wants to send data to a destination node outside the hybrid WMN, if it doesn’t have a route to the gateway, it will broadcast the RREQ with a rq_mark. When receiving RREQ packets, a
client first determines whether rq_mark value in the RREQ is 0, if not, then the node discards RREQ packets; If the rq_mark value in the RREQ is 0 and the hop-count is equal to or less than 2, the intermediate node forwards the RREQ packets. If the rq_mark value in the RREQ is 0, but the hop-count is more than 2, the intermediate node just discards the RREQ packets, as shown in Fig. 1.

![Fig. 1. Process RREQ at the mesh client](image1)

Mesh routers have less resource constraints than mesh clients, and they are characterized by high throughput and stability. So we maximize the involvement of mesh routers into routing process. When a mesh router receives the RREQ, it determines whether the rq_mark value is 0, if not, the router directly forwards the RREQ packet. If the rq_mark value is 0 and the hop-count is less than 4, the rq_mark is set to 1 and the RREQ packet is forwarded, or the RREQ is discarded, as shown in Fig. 2. It can be acknowledged that the RREQ packet will not be transmitted beyond three hops among mesh clients and the RREQ forwarded by mesh routers will not be forwarded by clients. The proposed scheme preferentially routes packets via paths consisting of high throughput mesh routers. Thus it can significantly reduce routing overhead. Since higher routing overhead causes higher energy consumption, it achieves the goal of enhancing the stability of paths, consuming much less energy of clients and extending the network lifetime.

![Fig. 2. Process RREQ at the mesh router](image2)

IV. IMPLEMENTATION DETAILS

We extend AODV routing protocol to implement the proposed metric and constrained forwarding mechanism in hybrid WMNs. So CLA and AODV have the similar routing way. The CLA uses cross-layer design to exchange information between different layers. To implement CLA, we add four fields to the RREQ header aiming at capturing CBT, mobile speed, residual energy and node types. The RREQ header contains the following fields: source IP address, destination IP address, source sequence number, CLA value, CBT, rq_mark and so on. The route reply (RREP) has the response fields to RREQ.

The CLA protocol adopts the passive mechanism to obtain information from different layers, which will not introduce extra overhead. In addition, we propose a constrained forwarding mechanism which can effectively reduce the whole network overhead.

V. PERFORMANCE ANALYSIS

In this section, we analyze the performance of the CLA proposed for hybrid WMNs and compare it with AODV-CA and AODV-ALARM by using NS-2. We modify the NS to support multi-radio multi-channel technology and modify AODV protocol to implement CLA, AODV-CA and AODV-ALARM. IEEE 802.11b is used as the MAC layer and data transmission rate is 2Mbps. The details of simulation parameters are shown in Table II.

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>Simulation time</td>
<td>900 s</td>
</tr>
<tr>
<td>Traffic type</td>
<td>UDP</td>
</tr>
<tr>
<td>Packet size</td>
<td>512 bytes</td>
</tr>
<tr>
<td>Packet rate</td>
<td>80kbps</td>
</tr>
<tr>
<td>Number of static mesh routers</td>
<td>25</td>
</tr>
<tr>
<td>Number of mobile mesh clients</td>
<td>50</td>
</tr>
<tr>
<td>Number of radios in each router</td>
<td>3</td>
</tr>
<tr>
<td>Number of channels in each router</td>
<td>3 channels (1, 6 and 11)</td>
</tr>
<tr>
<td>Number of radios in each client</td>
<td>1</td>
</tr>
<tr>
<td>Number of channels in each client</td>
<td>1 channel (1)</td>
</tr>
<tr>
<td>Initial energy of each router</td>
<td>10000</td>
</tr>
<tr>
<td>Initial energy of each client</td>
<td>100</td>
</tr>
<tr>
<td>Transmission range</td>
<td>250 m</td>
</tr>
<tr>
<td>Interference range</td>
<td>550 m</td>
</tr>
<tr>
<td>Propagation model</td>
<td>Two Ray Ground</td>
</tr>
<tr>
<td>Mobility model</td>
<td>Random way point</td>
</tr>
<tr>
<td>Antenna</td>
<td>Omnidirectional</td>
</tr>
</tbody>
</table>
A. Performance Metrics

Average network throughput: it is defined as the data bits successfully received by all destination nodes per unit time.

Average packet loss rate: it is defined as the ratio between number of packets received unsuccessfully by all destinations and total number of packets sent out by all sources.

Average end-to-end delay: it is defined as the average amount of time taken by all data packets from sources to destinations over total number of successful received data packets.

Average routing overhead: it is defined as the ratio between the total number of routing control packets by all sources and the total number of successfully received data packets by the destinations.

Energy consumption of clients per packet: it is defined as the ratio between the total energy consumption of clients and the total number of successfully received data packets by the destinations. It can describe the energy efficiency better [5].

B. Simulation Results and Analysis on Hybrid WMNs with Grid Backbone Networks

B1. Performance comparison under different number of flows

In this part, we use the general hybrid mesh network environment. There are 25 mesh routers uniformly deployed into a grid and 50 mesh clients randomly distributed in a 1000m × 1000m network topology environment. The mesh router in the upper right corner is the gateway. We compare the performance of CLA with AODV-CA and AODV-ALARM in the scenes with different number of gateway flows. We fix the maximum speed of clients as 10m/s with the pause time 1s and change the number of flows to analyze the efficiency of CLA. The obtained average network throughput, average packet loss rate, average end-to-end delay, average routing overhead and the energy consumption of clients per packet are shown in Fig. 3 to Fig. 7.

Fig. 3 shows that average throughput of CLA is always higher than AODV-CA and AODV-ALARM. AODV-CA, AODV-ALARM and CLA all capture the traffic load and interference to select route. In addition, the proposed CLA also takes the mobility and energy constraints of clients into consideration, which contributes to selecting a route involving more low-mobility and high-throughput mesh routers and making the route more stable and higher-throughput. The average network throughput of CLA improves 37.6% and 34.2% higher than AODV-CA and AODV-ALARM respectively when number of flows is 13.

Fig. 4 shows that the average packet loss rate of CLA is always lower than AODV-CA and AODV-ALARM, which matches Fig. 3. We can see that packet loss rate is reaching a minimum value at lower traffic flows, incrementing with an increment in traffic flows. The AODV-CA and AODV-ALARM do not distinguish the type of nodes. Thus both the mesh routers and mesh clients can be selected in establishing a route. Routes consisting mostly of single-radio mesh clients have a higher packet loss due to the extended contention for the wireless medium, which can lead to saturated interface queues and packets being dropped. Since mesh clients are characterized by forwarding function, mobility and limited energy, the RREQ packets flooded in the network will increase, the link breakage will increase owing to the mobility and constrained energy. AODV-CA and AODV-ALARM ignore the mobility and energy constraints of
clients, which makes the selected routes unstable. In contrast, the CLA considers both the characteristics of backbone mesh and client mesh on the basis of channel loading, path length, mobility and energy constraints of clients, and it selects route containing more mesh routers by limiting forwarding number of clients. Therefore, CLA selects the more stable paths and decreases the possibility of loss. The average packet loss rate of CLA decreases by 23.9% and 26.0% compared with AODV-CA and AODV-ALARM respectively when number of flows is 13.

Fig. 5 shows that the average end-to-end delay of the CLA is always smaller than AODV-CA and AODV-ALARM. As we know, when the number of flow increases, the contention at link layer and back-off time at MAC layer will increase, which results in longer buffer queue and longer delay. The proposed CLA uses CBT to select the path away from interference concentrated area. It simultaneously considers mobility and energy of clients as part of metric and integrates a constrained forwarding mechanism limiting clients’ forwarding number, which makes the selected path more stable and higher-throughput. So the shorter buffer queue and transmission time contribute to shorter delay. The average end-to-end delay of CLA decreases by at least 16.4% and 5.3% compared with AODV-CA and AODV-ALARM respectively.

Fig. 6 shows that the average routing overhead of CLA is always smaller than AODV-CA and AODV-ALARM and the route overhead increases when increasing flows. More forwarding number of RREQ packets contributes to more routing overhead. When using speed and energy of nodes as metric to select paths, CLA can choose the more stable path and reduce the forwarding number of clients. In addition, the proposed mechanism limits the forwarding number of clients, contributing to lower flooding overhead. This in turn reduces the number of route discoveries in the network, thereby lowering the control packet overhead.

Fig. 7 shows that energy consumption of clients per packet of the CLA is always smaller than AODV-CA and AODV-ALARM. The CLA uses the residual energy as a metric to select path, which help to avoid the mesh clients that have much less energy and decrease the probability of link breakages. In addition, the proposed constrained forwarding mechanism in CLA can effectively reduce the network overhead. As higher overhead consumes higher energy and CLA has lower overhead compared with AODV-CA and AODV-ALARM, so CLA achieves energy efficiency. The energy consumption of clients per packet of CLA lowers by at most 32.2% and 28.0% compared with AODV-CA and AODV-ALARM respectively.

B2. Performance Under Different Maximum Speed of Mesh Clients

To further prove that CLA performs better than AODV-CA and AODV-ALARM, we fix the number of flows as 11 and change the maximum speed of clients to analyze the efficiency of CLA. The obtained average network throughput, average packet loss rate, average end-to-end delay, average routing overhead and energy consumption of clients per packet are shown in Fig. 8 to Fig. 12.
CLA performs better than AODV-CA and AODV-ALARM in terms of average network throughput, average packet loss rate, average end-to-end delay, average routing overhead and the energy consumption of clients per packet. When the mesh clients move at a higher speed, the routes are frequently broken and recreated, which contributes to more packet drops and routing overhead. However, CLA can select routes based on speed of clients and decrease the number of clients in the route by the constrained forwarding mechanism.

![Fig. 9. Average packet loss rate versus maximum speed of clients on hybrid WMNs with grid backbone networks](image)

![Fig. 10. Average end-to-end delay versus maximum speed of clients on hybrid WMNs with grid backbone networks](image)

![Fig. 11. Average routing overhead versus maximum speed of clients on hybrid WMNs with grid backbone networks](image)

![Fig. 12. Energy consumption of clients per packet versus maximum speed of clients on hybrid WMNs with grid backbone networks](image)

C. Simulation Results and Analysis on Hybrid WMNs with General Backbone Networks

In this part, we evaluate the performance in a random topology. 25 mesh routers and 50 mesh clients are randomly distributed in an area of 1000m by 1000m. Other main simulation parameters are the same as Table II. We fix the maximum speed of clients as 10m/s with the pause time 1s and change the number of flows to analyze the efficiency of CLA. As average packet loss rate is complementary to the network throughput. The obtained average packet loss rate, average end-to-end delay, average routing overhead and the energy consumption of clients per packet are shown in Fig. 13 to Fig. 16.

![Fig. 13. Average packet loss rate versus the number of flows on hybrid WMNs with general backbone networks](image)

![Fig. 14. Average end-to-end delay versus the number of flows on hybrid WMNs with general backbone networks](image)

![Fig. 15. Average routing overhead versus the number of flows on hybrid WMNs with general backbone networks](image)

From Fig. 13 to Fig. 16, we can see that average packet loss rate, average end-to-end delay, average routing overhead and the energy consumption of clients per packet of CLA are better than AODV-CA and AODV-ALARM, which is similar to the performance in hybrid WMNs with grid backbone topology. When number of flows is 13, The average packet loss rate of CLA decreases by 26.8% and 22.4% compared with AODV-CA and AODV-ALARM respectively.
As analysis above, we can draw the conclusion that CLA outperforms AODV-CA and AODV-ALARM. CLA captures interference, load, and stability with a cross-layer design and reduces the overall network overhead with a constrained forwarding mechanism. CLA can be aware of heavy load and interference areas and selects a high throughput and stable route, thus network performance is improved.

VI. CONCLUSIONS

In this paper, we research on the problem of route selection for gateway traffic in hybrid WMNs. On the analysis of the features of hybrid mesh architecture and the limitations of the current routing protocols, we present a CLA routing protocol based on considering the characteristics of backbone nodes and client nodes of the hybrid WMNs with a cross-layer design comprehensively. The components of CLA includes: 1) a new routing metric $M_{CLA}$, which takes interference, traffic load and stability on the basis of CBT, path length, mobility and energy constraints of clients into consideration; 2) a constrained forwarding mechanism that limits the number of RREQ forwarded by clients to minimize the entire network overhead and energy consumption of clients. We have performed simulations to evaluate the performance of CLA for gateway traffic and compared it with AODV-CA and AODV-ALARM. The results show that network performance of CLA including network throughput, packet loss rate, end-to-end delay, routing overhead and energy consumption is dramatically improved.

As the speed of mesh nodes changes frequently, we use cross-layer design to obtain the speed of mesh nodes from application layer directly. In the future, we will research on the more efficient method for obtaining the speed of mesh clients, so as to adapt to the dynamic network topology.

As the mesh clients can be equipped with multiple radios. In the future, we will extend our proposed CLA to hybrid WMNs with multi-radio multi-channel clients and evaluate its performance.

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