

BUFE-MAC: A Protocol With Bandwidth Utilization and Fairness Enhancements for Mesh-Backbone-Based VANETs

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Abstract—Vehicular ad hoc network technologies can improve traffic safety for drivers and provide comfort services for passengers. Because the hardware of a roadside unit (RSU) is costly, in most previous research, vehicles might exchange data with an RSU through multihop transmissions. However, the vehicle with a larger number of hops to the RSU has fewer opportunities and longer time to exchange its data with the RSU because the contentions and collisions increase with the number of hops. This paper proposes the bandwidth utilization and fairness enhancements medium access control (BUFE MAC) protocol, which considers a vehicular ad hoc network that accesses the Internet through fixed Internet Gateways along the road. BUFE-MAC aims at increasing bandwidth utilization, maintaining fairness, and avoiding collision. The performance study reveals that the proposed MAC protocol not only avoids the collision problem but improves the performance in terms of end-to-end throughput and fairness as well.

Index Terms—Bandwidth utilization, fairness, medium access control (MAC) protocol, vehicular ad hoc networks (VANETs).

I. INTRODUCTION

WITH THE rapid development technologies, vehicular ad hoc networks (VANETs) have recently received much attention [1]–[6], [21]–[25]. VANET technologies aim at enhancing traffic safety for drivers, providing comfort for passengers, or reducing transportation time and fuel consumption with many potential applications.

One of the greatest challenges of VANETs is to establish cost-effective connections between vehicles and vehicles or between vehicles and roadside units (RSUs). The fastest communication for a vehicle is communication with a RSU, which is called a mesh-backbone VANET [31], [32]. However, the vehicular networks that are fully covered by a large number

of RSUs are costly. To support vehicles with Internet access with low cost, an integrated network that combines a multihop VANET and several RSUs that are supported as the gateways between wired and wireless networks has been considered as a better candidate. In such an integrated-network mesh-backbone-based VANET, vehicles might exchange data with the RSU through multihop transmissions.

Because the dedicated short-range communications (DSRC) [7] standard is developed based on the IEEE 802.11 medium access control (MAC) protocol, vehicles that applied DSRC in a VANET exchange their data by contending the medium access, which raises significant contention and collision problems. As a result, vehicles that are far away from RSUs have fewer opportunities to exchange data with RSUs or even are facing starvation. Therefore, in a multihop VANET with non-fully covered deployment of RSUs, increasing bandwidth utilization while maintaining transmission fairness among vehicles is an important issue.

To increase bandwidth utilization and maintain transmission fairness, a good MAC protocol is significant for the network environment [27]–[30]. A number of VANET MAC protocols have been proposed to reduce the packet collisions and increase the bandwidth utilization. These works can roughly be classified into the following three categories: 1) contention-based approaches; 2) contention-free approaches; and 3) integrating approaches. Contention-based protocols [8], [9], [19], [20] determine the time point of transmission according to the distance between the vehicle and the destination vehicle. These protocols reduce the contention probability but increase the variation of forwarder selection. As a result, vehicles may transmit packets to inappropriate forwarders, which leads to redundant packet transmissions. On the contrary, contention-free protocols schedule the transmissions in advance to avoid contention. For example, the time-division multiple-access approach divides the time interval into several time slots and allocates the packet transmissions in these slots. Integrating protocols [10], [11], [26] combine the contention-based and contention-free concepts. These approaches collect the transmission requirement by applying a contention mechanism, and then, the transmissions can be scheduled in advance. Because the bandwidth utilization and transmission fairness can significantly be improved, these approaches are more flexible and efficient than contention-based approaches. The following paragraph reviews some integrating protocols that were developed for VANETs.

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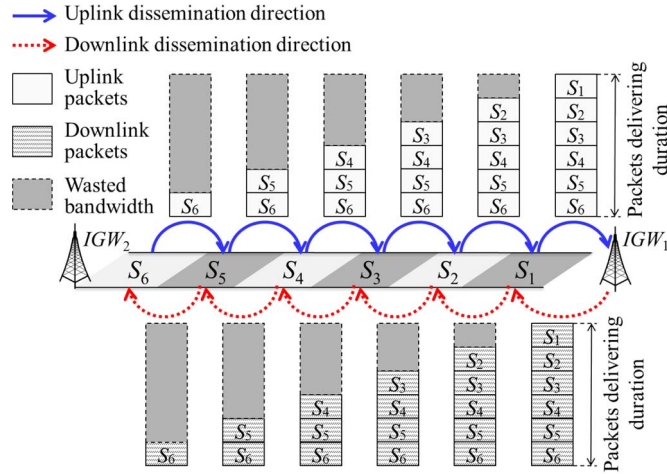


Fig. 1. Packet transmission in CVIA.

Korkmaz *et al.* [10] proposed a cross-layer protocol, called controlled vehicular Internet access (CVIA), for vehicular Internet access on highway applications. CVIA assumes that each vehicle is equipped with the Global Positioning System (GPS), which allows the vehicle to obtain its location and to synchronize its clock with all the other vehicles. The uplink and downlink Internet accesses are achieved by connecting to the same gateway in a multihop manner and using different channels. The CVIA protocol employs two vehicles as routers in each segment for relaying packets in each channel. Similar to the CVIA scheduling protocol, Yang *et al.* [11] proposed another cross-layer protocol, called coordinated external peer communication (CEPEC), for Internet access services and peer-to-peer communications in VANETs. The main differences between these approaches are that CEPEC is proposed for the IEEE 802.16 network environment and the policies for determining the segment length and selecting the segment router are different.

The existing CVIA and CEPEC approaches alleviate the packet collisions of the multihop transmission in VANETs. However, the channel utilizations for uplink and downlink transmissions are low. Fig. 1 gives an example to discuss the bandwidth utilization of the CVIA protocol. In Fig. 1, the CVIA protocol divides the service area of each gateway into a number of equal-sized segments, including $S_1, \dots, S_6$. The uplink and downlink Internet accesses are achieved by connecting to the same gateway IGW_1 in a multihop manner and using different channels. The basic scheduling policy is to assign a specific time slot to each segment so that the parallel transmission opportunities can be exploited, whereas the collisions and contentions can be avoided. For fairness, CVIA makes restrictions that vehicles in each segment can only transmit one sixth the amount of bandwidth accessing in its active time slot. This way, all segments have the same opportunity for transmitting their own data, and hence, CVIA likely achieves fairness. However, the bandwidth utilization is also restricted. For example, as shown in Fig. 1, where the shadow regions denote the bandwidth wastage, by applying the CVIA approach, the bandwidth utilizations of S_6 and S_5 are only one sixth and one third, respectively.

This paper proposes a MAC protocol with bandwidth utilization and fairness enhancements (BUFE-MAC) for mesh-backbone-based VANETs, aiming at improving the bandwidth utilization and maintaining the fairness opportunities of all vehicles. The novelty of the proposed protocol is integrating the uplink and downlink transmissions in a single channel and determining an appropriate segment length. The contribution is to increase the bandwidth utilization and network throughput while maintaining fairness. In the latter sections, because the RSU is used for Internet access, it is called an Internet Gateway (IGW).

The rest of this paper is organized as follows. Section II presents the basic concept of the proposed BUFE-MAC protocol and summarizes our contributions. Section III gives the network environment and problem statement of this paper, whereas Section IV presents the details of the proposed protocol. Section V analyzes and compares the improvement of the proposed BUFE-MAC to the existing CVIA protocols in terms of throughput and bandwidth utilization. Section VI investigates the performance evaluation of the proposed protocol. Section VII concludes this paper.

II. BASIC CONCEPT OF BANDWIDTH UTILIZATION AND FAIRNESS ENHANCEMENTS-MEDIUM ACCESS CONTROL

The basic concept of BUFE-MAC is dividing the cycle time into several time slots for vehicles in proper segment accessing bandwidth. In VANETs, the bandwidth is limited resource. However, increasing the bandwidth utilization may reduce the fairness of vehicles. For example, to maximize the bandwidth utilization, the vehicles in the segment far away from an IGW transmit their uplink data as much as possible, but segments that are close to IGWs may suffer from starvation. Therefore, for fairness, each segment has the same opportunity to access the bandwidth, but it causes low bandwidth utilization, as in CVIA [10].

The proposed BUFE-MAC integrates the uplink and downlink Internet access, aiming at taking into account both bandwidth utilization and fairness. We observe that the uplink bandwidth utilization of the segment that is closer to the uplink IGW is better than the farther segment, as shown in Fig. 1. Similarly, the segment that is closer to the downlink IGW has better downlink bandwidth utilization in its assigned slot. To cope with the bandwidth utilization problem, the proposed BUFE-MAC approach changes the transmission direction of downlink traffic, i.e., the uplink and downlink IGWs for a segment are different. Thus, the segment that is closer to its downlink IGW is farther from its uplink IGW. As a result, the downlink traffic can be allocated to the bandwidth hole of the uplink slot in each segment to maximize the bandwidth utilization. Thus, we need not divide the bandwidth into uplink and downlink channels, the same bandwidth can be available for transmitting more data, and the network throughput is improved.

Fig. 2 depicts an example of the data transmission architecture of BUFE-MAC. The uplink packets are sent to IGW_1 , and the downlink packets are transmitted from IGW_2 by multihop transmissions. That is, vehicles in S_6 receive their downlink packets from IGW_2 , and then, the router in S_6 merges the

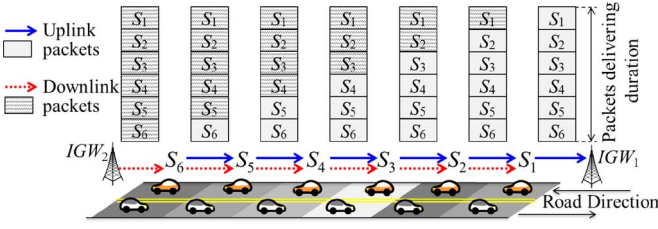


Fig. 2. Data transmission architecture in BUFE-MAC.

uplink packets of S_6 with the downlink packets of later segments S_1 – S_5 and transmits the merged packets to vehicles in S_5 . Afterward, vehicles in S_5 receive their downlink packets, and the router in S_5 merges uplink packets of S_5 with the downlink packets of S_1 – S_4 and transmits them to vehicles in S_4 . Finally, after vehicles in S_1 receive their downlink packets from S_2 , the router in S_1 transmits all uplink packets of segments S_1 – S_6 to IGW_1 . In each segment, a router integrates the uplink and downlink packets and transmits to the router of neighboring segment. As a result, the total number of transmitted packets, including uplink and downlink packets, is maximal.

Compared with previous researches, the proposed BUFE-MAC not only eliminates the channel division between the uplink and downlink but increases the bandwidth utilization and throughputs as well. The segment partitions of a multilane and a single lane are similar. All vehicles in the same segment can apply the BUFE-MAC and stay in the active or inactive state at the same time slot, regardless of their moving direction. For ease of presentation, we describe the detail only for a unidirectional single lane.

III. SYSTEM MODEL AND PROBLEM FORMULATION

This paper considers a vehicular network that accesses the Internet through fixed IGWs along the road. A set of k IGWs $\{IGW_1, IGW_2, \dots, IGW_k\}$ equally partition the road into $k - 1$ divisions $\{d_{IGW1,2}, d_{IGW2,3}, \dots, d_{IGWk-1,k}\}$, where $d_{IGWi,i+1}$ is located between IGW_i and IGW_{i+1} . The vehicles in division $d_{IGWi,i+1}$ receive downlink packets from IGW_{i+1} and transmit uplink packets to IGW_i . Moreover, $d_{IGWi,i+1}$ is divided into n equal-sized segments S_1 – S_n , and the length of each segment is $r_{com}/2$, where r_{com} is the communication range of each vehicle. An IGW can communicate with a vehicle that is far away from several times of transmission distance through multihop communication. In addition, the vehicles are assumed to be equipped with Global Positioning System (GPS) devices for time synchronization and location identification. BUFE-MAC can be applied to a complicated environment, such as a multilane with different directions. To simplify the presentation, BUFE-MAC is proposed based on a single-lane road environment. However, BUFE-MAC can easily be extended to the multilane road environment, although the directions of lanes are different. In some road situations such as a curved road, additional gateways can be deployed to support the single-hop communications for these roads.

This paper aims at developing a segment-based MAC scheduling protocol that arranges the packet transmissions for vehicles in each segment. The purpose of this paper is to

maximize the bandwidth utilization with fairness of bandwidth access. The *fairness index* I_f given by (1), as proposed by Jain *et al.* [12], is used to estimate the degree of fairness. In (1), notation n_{v_total} denotes the average number of vehicles in a division d_{IGW} , and $p_{k,vehicle}$ denotes the number of packets that are transmitted or received by vehicle v_k , where $1 \leq k \leq n_{v_total}$

$$I_f = \left(\sum_{k=1}^{n_{v_total}} p_{k,vehicle} \right)^2 / \left(n_{v_total} \sum_{k=1}^{n_{v_total}} p_{k,vehicle}^2 \right). \quad (1)$$

In addition, let $sc = \{t_1, t_2, \dots, t_m\}$ denote a *scheduling cycle* that schedules all segments for bandwidth access, where t_i denotes the i th time slot in the cycle, and the lengths of these time slots are the same, i.e., equal to t_{slot} . We assume that the maximum number of packets that are transmitted from a segment to the next segment in a time slot is p_{max} . Thus, the number of maximum transmitted packets without collision in a scheduling cycle is $p_{max} \times n$, where n is the number of segments between two neighboring IGWs. With the minimal fairness index constraint f_{thr} , the *bandwidth utilization index* I_u can be defined as in (2), where $p_{i,segment}$ denotes the number of packets that were transmitted in segment S_i at the allocated time slot

$$I_u = \left(\sum_{i=1}^n p_{i,segment} \right) / (p_{max} \times n), \quad \text{with } I_f \geq f_{thr}. \quad (2)$$

In this paper, we attempt to maximize the bandwidth utilization I_u , where the degree of fairness I_f is equal to or greater than the threshold f_{thr} . The details of the proposed algorithm will be described in the next section.

IV. PROPOSED BANDWIDTH UTILIZATION AND FAIRNESS ENHANCEMENTS-MEDIUM ACCESS CONTROL ALGORITHM

This section describes the details of the proposed BUFE-MAC algorithm. BUFE-MAC supports the following two modes: 1) the mesh-backbone-based mode and 2) the infrastructure mode. The mesh-backbone-based mode allows vehicles to transmit packets in a multihop manner, whereas the infrastructure mode supports vehicles to directly exchange data with a gateway. In the infrastructure mode, the interference problem can be avoided by well scheduling the transmissions of vehicles in segments that belong to the cured road. The IGWs for the infrastructure mode will periodically announce the communication time. Vehicles in the infrastructure mode need not know more information, except for the announcement of IGWs. The infrastructure mode has been proposed by other researches, and the mesh-backbone-based mode is the main contribution of this paper. Therefore, unless otherwise stated, BUFE-MAC in the latter sections represents the mesh-backbone-based mode only.

The mesh-backbone-based mode of BUFE-MAC consists of the following five phases:

- 1) inactive;
- 2) manager selection;
- 3) intersegment packet relaying;

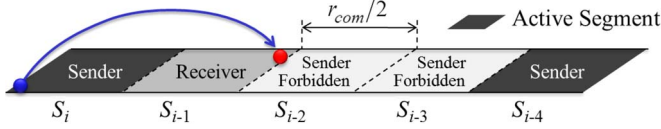


Fig. 3. Parallel transmission constraint of the BUFE-MAC algorithm.

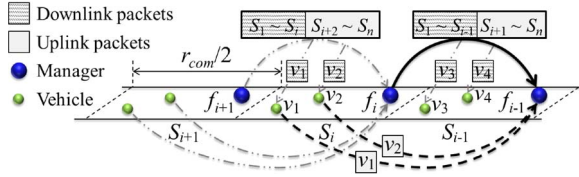


Fig. 4. Scenario of packet transmission in the BUFE-MAC algorithm.

- 4) minislot scheduling;
- 5) local packet sending.

Except for the *inactive phase*, vehicles in the other four phases are in the active state. In the inactive state, vehicles cannot transmit packets but receive packets that are transmitted from the active vehicles in the neighboring segment. Before introducing these five phases, the following paragraph presents the segment length designed in this paper.

The segment length is one of the most important factors that determine the performance of VANETs. In the BUFE-MAC algorithm, the proposed segment length is $r_{com}/2$, because $r_{com}/2$ is the maximal length that vehicles in neighboring segments can directly communicate with each other. Moreover, to avoid packet collision at a receiver, vehicles that are located within the distance of r_{com} from the receiver cannot transmit packets. For example, when vehicles in segment S_i are active in time slot t_j , the receivers are vehicles in segment S_{i-1} . Thus, only segments S_k can be in the active state for parallel transmitting packets with S_i , where $k \leq i - 4$, as shown in Fig. 3. As a result, the block region for collision avoidance is three segments. That is, vehicles in $S_i, S_{i+4}, \dots, S_{i+4m}$ can be in the active state at the same time slot.

After presenting the design of segment length, the following paragraph gives an overview of the five phases in the BUFE-MAC algorithm.

Let an active time slot of vehicle v_k or segment S_i denote the time that the vehicle or segment is in the active state, respectively. Initially, each vehicle in the *inactive phase* cannot transmit packets, because it stays in the inactive state. The active time slots of a segment are determined at the beginning of the network initialization. When segment S_i changes state from inactive to active, all vehicles in S_i change from the *inactive phase* to the *manager selection phase*. In the *manager selection phase*, all vehicles in active segments first exchange their information, including the location and bandwidth requirement. Then, a manager for each active segment is selected. In the next phase, the *intersegment-packet-relaying phase*, the manager of each active segment relays the packets that are received in its inactive state to the vehicles in the neighboring segment. As shown in Fig. 4, the solid line depicts the transmission of manager f_i in the *intersegment packet relaying phase*. f_i relays the packets that are received from the vehicles in S_{i+1} to the vehicles in S_{i-1} . In the *minislot scheduling phase*, the

manager determines the transmission schedule of all vehicles in its segment according to the bandwidth requirements that are received in the *manager selection phase*. Then, the manager announces the schedule to all vehicles in the segment. Afterward, all vehicles in S_i switch to the *local packet sending phase* and transmit their own packets to the manager in neighboring segments. As shown in Fig. 4, the black dotted line depicts the transmission of vehicles in segment S_i in the *local packet sending phase*. Vehicles v_1 and v_2 transmit their own uplink packets to the manager f_{i-1} in segment S_{i-1} . The following sections introduce the details of the five phases designed in the proposed BUFE-MAC algorithm.

A. Inactive Phase

All vehicles in the phase are not allowed to transmit packets on account of avoiding collision. Herein, a general formula for vehicles is given to determine when they should be in the inactive state. Let Δd denote the distance between a vehicle and the uplink IGW and Δt denote the time interval between the current time and a defined reference time. Consider a vehicle in S_i at slot t_j , where $i = \lceil \Delta d / (r_{com}/2) \rceil$, and $j = \lceil \Delta t / t_{slot} \rceil$. If parameters i and j satisfy (3), where “%” gets the remainder of the division, then the vehicle is in the active state at this time slot; otherwise, the vehicle is in the inactive state and is forbidden to transmit packets:

$$(n - i + 1) \% 4 = j \% 4. \quad (3)$$

Using this rule, we have that, when S_i is in the active state, segments S_{i+1} , S_{i+2} , and S_{i+3} should stay in the *inactive state* to prevent the transmitted packets from a collision problem.

B. Manager Selection Phase

This phase aims at selecting a manager in a segment that is responsible for receiving the forwarding packets that were sent from the neighboring segment in the next inactive slot. To achieve this, all vehicles of an active segment exchange their location information by the carrier sense multiple access with collision avoidance mechanism. Then, the manager for each segment is selected according to the location information. The following paragraph presents the operations of this phase.

When a vehicle, e.g., v_k , switches to this phase, it selects a random waiting time tw from $[0, tu - tp)$, where tu is a predefined time period for information exchange, and tp is the time for a vehicle to transmit an uplink packet. After waiting for the time period tw , vehicle v_k senses the carrier and broadcasts its local information if the carrier is idle. The local information contains the identifier (ID_k), location (l_k), and time of location estimation (t_{LGT}), as well as the moving direction (d_k) of v_k and bandwidth request (BR_k). If the carrier is busy, then vehicle v_k selects a random waiting time from $[0, tr - tp)$, where tr represents the remaining time for information exchange. Let f_i be the current manager of S_i . In this phase, f_i should collect the local information of all vehicles in S_i .

After collecting the local information of vehicles in S_i , the current manager f_i selects a vehicle in segment S_i to be the

future manager $f_{i,next}$. Let the current slot be t_j . The selected $f_{i,next}$ should satisfy the condition that it still stays in segment S_i at the next active slot t_{j+4} . That is, $f_{i,next}$ must be in segment S_i in $[t_j, t_{j+4}]$. Let v_{max} denote the upper bound of velocity in segment S_i . Let l_k^{expect} denote the expected location of vehicle v_k at the end of t_{j+4} . Equation (4) gives the expected new location l_k^{expect} of vehicle v_k at the next active slot, where λ is equal to 1 when the moving directions of the vehicle and packets are the same; otherwise, λ is equal to -1

$$l_k^{expect} = l_k + \lambda \times [(t_{current} - t_{LGT}) + 5 \times t_{slot}] \times v_{max}. \quad (4)$$

Having expected new locations of vehicles, f_i selects the vehicle with the smallest $(l_i^{boundary} - l_k^{expect})$ to be the future manager $f_{i,next}$, where $l_i^{boundary}$ is the boundary between S_i and S_{i-1} . Note that $f_{i,next}$ not only relay the intersegment packets in slot t_{j+4} but also receive the intersegment packets at slot t_{j+3} when the segment S_{i+1} is active.

The selected manager must be a vehicle that is in the segment and will be in the same segment in the next active slot. We predict the expected new location by the upper bound of velocity. If the speed of the selected vehicle is slower, then the vehicle is still in the same segment in the next active slot, which does not violate our prediction.

When the network is in the initial stage, there is no current manager for each segment. Therefore, all vehicles in S_i should keep the packets transmitted from the vehicles in S_{i+1} at slot t_{j-1} , as well as the local information that was transmitted from vehicles in S_i . Each vehicle, e.g., v_k , in S_i calculates its own expected new location by (4). If the expected location is in S_i , v_k waits for a period of time. If no vehicle declares who the manager is during the period, v_k declares that it is the current and future manager. The waiting time is $t_{select} \times (|l_i^{boundary} - l_k^{expect}| / (r_{com}/2))$, where t_{select} is the predefined time for the manager selection phase, and $l_i^{boundary}$ is the boundary location between S_i and S_{i-1} . As a result, the vehicle whose expected location is the closest to S_{i-1} will be the first vehicle to declare that it is the current and future manager of S_i . Upon receiving the declaration of the manager, all the other vehicles in S_i will stop the process of new manager selection.

C. Intersegment Packet Relaying Phase

In this phase, the manager f_i transmits the forwarded packets to S_{i-1} . These packets include the uplink packets of segments $S_{i+1}-S_n$ and the downlink packets of segments S_1-S_{i-1} . Although the vehicles in S_{i-1} are in the inactive state, they can receive their own downlink packets. In addition, the manager f_{i-1} can also receive the downlink packets of segments S_1-S_{i-2} , as well as the uplink packets of segments $S_{i+1}-S_n$. Before forwarding, f_i counts the number of uplink packets in the forwarded packets, which are denoted as $p_{i,previous}$.

D. Minislot Scheduling Phase

In this phase, manager f_i divides the remaining time of the active slot into a number of minislots (MTSs), which will be

allocated to vehicles in S_i for transmitting their uplink packets to f_{i-1} . The allocation of MTSs will be given later. A MTS is a time unit that is required for transmitting a packet. To achieve fairness, for each segment, the maximal number of uplink packets is p_{max}/n , where p_{max} is the maximal number of packets that are transmitted between two neighboring IGWs, and n is the number of segments between the two neighboring IGWs. Hence, the maximal accumulative number of uplink packets for segments S_n-S_i is defined in (5). Thus, the number of MTSs for S_i , MTS_i is calculated in (6), where $p_{i,previous}$ is the number of uplink packets that were transmitted from previous segments $S_n, S_{n-1}, \dots, S_{i+1}$. The manager f_i calculates MTS_i and then allocates these slots to vehicles in segment S_i . The advantage is that this approach increases the bandwidth utilization. For example, when the first $i-1$ segments have less uplink data, then the i th segment can transmit more uplink data if needed. Thus, the utilization of bandwidth is increased, i.e.,

$$(p_{max}/n) \times (n - i + 1) \quad (5)$$

$$MTS_i = (p_{max}/n) \times (n - i + 1) - p_{i,previous}. \quad (6)$$

The allocation algorithm, i.e., Algorithm 1, allocates the MTSs for vehicles in segment S_i . After calculating MTS_i by (6), we employ a fair approach to allocate the MTSs for vehicles in S_i . When the number of MTS_i is greater than the number of uplink vehicles in segment S_i , MTS_i can fairly be allocated to each vehicle. On the other hand, when the number of MTS_i is less than the number of uplink vehicles, vehicles that can transmit are randomly chosen. Note that the uplink demand of each vehicle may be different. When the MTSs are allocated, the manager f_i broadcasts the transmission schedule to all vehicles in S_i , and then, this phase is finished.

Algorithm 1: Minislot allocation algorithm.

Input: List of vehicle's ID and bandwidth request in segment S_i , ListVID, and ListVBR, respectively. The total number of minislots is called Total_MTS.

Output: ListMTS: The result of scheduled minislots.

Initialization: Total_MTS $\leftarrow (p_{max}/n) \times (n - i + 1) -$

$p_{i,previous}$

ListMTS[1 to Total_MTS] $\leftarrow$ null

Remain_MTS $\leftarrow$ Total_MTS

1: **if** Total_MTS $\geq \sum_{k=1}^{|ListVBR|} ListVBR[k]$ **then**

2: **for** $k \leftarrow 1$ to $|ListVID|$ **do**

3: Current $\leftarrow$ Total_MTS - Remain_MTS + 1;

4: ListMTS[Current to Current + ListVBR[k]] $\leftarrow$ ListVID[k];

5: Remain_MTS $\leftarrow$ Remain_MTS - ListVBR[k];

6: **end for**

7: **else**

8: Remain_Vehicle $\leftarrow$ number of vehicles that request > 0;

9: **while** Remain_MTS > 0 and Remain_Vehicle > 0 **do**

10: **if** Remain_MTS $\geq$ Remain_Vehicle **then**

11: **for** $k \leftarrow 1$ to $|ListVID|$ **do**

12: **if** ListVBR[k] > 0 **then**

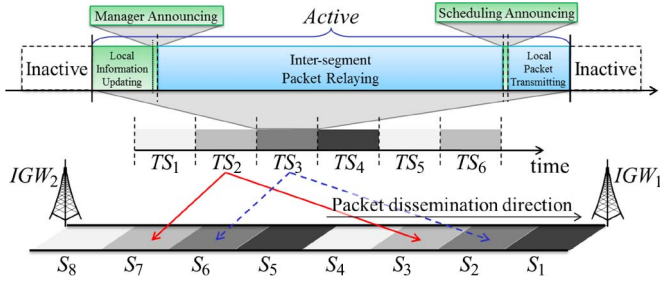


Fig. 5. Overall timing diagram in an active slot of the BUFE-MAC protocol.

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13:   ListMTS[Total_MTS - Remain_MTS +
1] ← ListVID[k];
14:   Remain_MTS ← Remain_MTS - 1;
15:   ListVBR[k] ← ListVBR[k] - 1;
16:   if ListVBR[k] = 0 then
17:     Remain_Vehicle ← Remain_Vehicle - 1;
18:   end if
19: end if
20: end for
21: else
22: while Remain_MTS > 0 do
23:   rand ← random number between 1 and |ListVID|;
24:   if ListVBR[rand] > 0 then
25:     ListMTS[Total_MTS - Remain_MTS +
1] ← ListVID[rand];
26:     Remain_MTS ← Remain_MTS - 1;
27:     ListVBR[rand] ← 0;
28:   end if
29: end while
30: end if
31: end while
32: end if
33: return(ListMTS)

```

E. Local Packet Sending Phase

According to the transmission schedule of f_i , each vehicle in S_i transmits its uplink packets on schedule. Because the segment length is $r_{com}/2$, each vehicle can directly transmit its packet to f_{i-1} in S_{i-1} . The whole active slot is finished when all the MTSs are finished. Then, each vehicle v_k in S_i switches its state to inactive, waiting for the next active slot.

Note that vehicles in S_{i-1} cannot transmit packets when they are inactive, but they can receive their downlink packets when vehicles in segment S_i are in the intersegment packet relaying phase. Moreover, the manager f_{i-1} of segment S_{i-1} can receive packets from vehicles in segment S_i when S_i is in the intersegment packet relaying phase or the local packet sending phase, i.e., there are two transmission phases in an active slot of the BUFE-MAC algorithm. The overall timing diagram in an active slot of BUFE-MAC is shown in Fig. 5. The local information updating and manager announcing belong to the manager selection phase, the intersegment packet relaying acts in the intersegment packet relaying phase, the scheduling announcing acts in the minislot scheduling phase, and the local packet transmitting acts in the local packet sending phase.

In our protocol, the equipped GPS of each vehicle can deal with synchronization and segment determination. The overhead of the algorithm is that each vehicle should broadcast its location every fourth slot and the selected managers should arrange the transmission time of vehicles in their segment and transmit the uplink packets and downlink packets for vehicles in other segments. Compared with broadcasting information, the overhead of broadcasting location is much less. Moreover, compared with collision and retransmission, the overhead of transmitting by selected managers is significantly small.

Because vehicles have their located segments from a road information system, the system should modify the information of road map and segments when the physical roads are changed. In general, the roads will not frequently be changed. The update will not be frequent, and the update overhead of the system is not significant. Furthermore, if the roads are not straight, such as a curved road, we can avoid the interference between segments by setting the communication in the infrastructure mode. When parallel segments are in the communication range of each other but in opposite directions, the protocol can treat these segments as a multilane and bidirectional road segment. Therefore, our protocol can be applied to a complicated environment.

V. ANALYSIS

This section analyzes the performance of the proposed BUFE-MAC and existing CVIA, which is currently the best algorithm in multihop mesh-backbone-based VANETs. One major difference between BUFE-MAC and CVIA is the design in segment length, which results in different block ranges, time slot lengths, and the number of vehicles in a segment. Another major difference between BUFE-MAC and CVIA is the data transmission architecture. For vehicles in a segment, CVIA uses the same IGW to handle the uplink and downlink traffics for a vehicle, whereas BUFE-MAC uses different IGWs to handle the uplink and downlink traffics for a vehicle. The performance is evaluated based on the matrix of some important parameters as follows.

Let t_{min}^A denote the minimum time for algorithm A to perform operations in an active segment. Let $r_{interference}^A$, P^A , and B^A represent the interference segment, throughput, and bandwidth utilization by applying algorithm A (the proposed BUFE-MAC or the existing CVIA algorithm), respectively. Let the number of segments between two neighboring IGWs be denoted by $n_{segment}^A$. These parameters highly impact the performance of an algorithm.

Assume that the vehicles are uniformly distributed in the environment. Let V_{avg}^A denote the average number of vehicles in a segment by applying the algorithm A . The V_{avg}^A is equal to $n_{v_total}/n_{segment}^A$, where n_{v_total} is the average number of vehicles between two neighboring IGWs.

The minimum length of time slot for the existing CVIA protocol is analyzed as follows. The total number of transmissions required in each active segment is discussed, because it determines the t_{min}^{CVIA} . In the design of CVIA protocol, the segment length is r_{com} . To successfully transmit the uplink

or downlink packets, two forwarders are needed in CVIA, for example, $f_{i,in}$ and $f_{i,out}$ for segment S_i . In each active slot of S_i , CVIA needs three transmission phases. Take the uplink transmission as an example. First, $f_{i,in}$ needs to relay the uplink packets of segments $S_j, S_{j-1}, \dots, S_{i+1}$ to $f_{i,out}$, where j is $n_{segment}^{CVIA}$. On the average, the number of packets that are relayed by $f_{i,in}$ is $(n_{segment}^{CVIA} - i) \times V_{avg}^{CVIA}$. Second, each vehicle in S_i transmits its own uplink packet to $f_{i,out}$. As a result, the number of packets is $V_{avg}^{CVIA} - 1$. Third, forwarder $f_{i,out}$ relays the uplink packets of segments S_j , where $i \leq j \leq n_{segment}^{CVIA}$, to S_{i-1} . The average number of forwarded packets is $(n_{segment}^{CVIA} - i + 1) \times V_{avg}^{CVIA}$. In these transmissions, the total number of packets transmitted for segment S_i is

$$2 \times (n_{segment}^{CVIA} - i + 1) \times V_{avg}^{CVIA} - 1. \quad (7)$$

Therefore, the total number of transmitted packets is maximal when $i = 1$. That is, the maximal number of transmitted packets is in S_1 . Assuming that it takes a time unit for transmitting a packet, we evaluate that the minimum required length of time slot t_{min}^{CVIA} should be the total transmitted packets in S_1 , because all the packets in S_1 should be transmitted in the active time slot. Thus, we have t_{min}^{CVIA} as follows:

$$\begin{aligned} t_{min}^{CVIA} &= 2n_{segment}^{CVIA} \times V_{avg}^{CVIA} - 1 \\ &= 2n_{v_total} - 1. \end{aligned} \quad (8)$$

The minimum length of time slot of BUFE-MAC is analyzed as follows. As aforementioned, each segment S_i needs only one forwarder f_i and two transmission phases in BUFE-MAC. Consider the transmissions that occurred in segment S_i . In the first transmission phase, the manager f_i forwards the uplink packets for segments $S_j, S_{j-1}, \dots, S_{i+1}$, where j is $n_{segment}^{BUFE}$ and the number of downlink packets for segments $S_{i-1}, S_{i-2}, \dots, S_1$. The total number of these packets is $(n_{segment}^{BUFE} - i) \times V_{avg}^{BUFE} + (i - 1) \times V_{avg}^{BUFE}$. Second, the vehicles in S_i transmit the average V_{avg}^{BUFE} uplink packets to f_{i-1} by themselves. Therefore, the total number of transmitted packets in segment S_i is given as follows:

$$\begin{aligned} (n_{segment}^{BUFE} - i) \times V_{avg}^{BUFE} + (i - 1) \\ \times V_{avg}^{BUFE} + V_{avg}^{BUFE} = n_{v_total}. \end{aligned}$$

Assuming that it takes a time unit to transmit a packet, the minimum length of time slot t_{min}^{BUFE} for BUFE-MAC is given as follows:

$$t_{min}^{BUFE} = n_{v_total}. \quad (9)$$

The throughputs of the BUFE-MAC and CVIA algorithms are investigated as follows. We define P^A as the total number of data packets that are successfully transmitted from segments to their neighbors between two IGWs in a specific time period t_{total} . In addition, let n_{sc}^A denote the number of scheduling cycles in t_{total} and $r_{interference}^A$ denote the number of interference sections in algorithm A . As described in the previous sections, the segment length of BUFE-MAC and CVIA are r_{com} and $r_{com}/2$, respectively. Thus, $r_{interference}^{BUFE}$ and $r_{interference}^{CVIA}$ are 4 and 2, respectively. Because the number of time slots for

vehicles between two IGWs is decided by $\lfloor t_{total}/t_{min}^A \rfloor$ and the time slots are allocated to the groups of parallel transmitting, n_{sc}^A can be evaluated by

$$n_{sc}^A = \lfloor \lfloor t_{total}/t_{min}^A \rfloor / r_{interference}^A \rfloor. \quad (10)$$

Let n_{slot_remain} denote the number of remaining time slots, which is insufficient for a segment scheduling cycle sc . Equation (11) evaluates the value of n_{slot_remain} for algorithm A

$$n_{slot_remain}^A = \lfloor t_{total}/t_{min}^A \rfloor \% (r_{interference}^A). \quad (11)$$

The throughput P^A can be evaluated by the product of the number of active segments and the average of packets V_{avg}^A in each segment. If $n_{slot_remain}^A$ is equal to 0, then the total number of active segments is the product of the number of scheduling cycles in t_{total} and the number of segments between two neighboring IGWs. Thus, the throughput of algorithm A is shown as follows:

$$P^A = (n_{sc}^A \times n_{segment}^A) \times V_{avg}^A.$$

On the other hand, when some remaining slots exist, some segments will have one more chance to be in the active state during the remaining slots. According to (3), the segment S_j can stay at the active state in the i th time slot of a scheduling cycle, where $j = n_{segment}^A - i + 1$, and $1 \leq i \leq r_{interference}^A$. Meanwhile, the segments S_k can stay at the active state for parallel transmitting packets when $k = j - m \times r_{interference}^A$, where $m \geq 1$. Thus, the number of segments that have been at the active state for parallel transmitting packets in the i th time slot of a scheduling cycle is $\lceil (n_{segment}^A - i + 1)/r_{interference}^A \rceil$. Let $n_{seg_remain}^A$ denote the number of segments that have been at the active state in the remaining slots. The value of $n_{seg_remain}^A$ can be calculated by

$$n_{seg_remain}^A = \sum_{i=1}^{n_{slot_remain}^A} \lceil (n_{segment}^A - i + 1)/r_{interference}^A \rceil. \quad (12)$$

Consequently, the throughput P^A in t_{total} is evaluated by

$$P^A = (n_{sc}^A \times n_{segment}^A + n_{seg_remain}^A) \times V_{avg}^A. \quad (13)$$

Because the proposed BUFE-MAC protocol integrates the uplink and downlink packets together, each vehicle can transmit an uplink packet and receive a downlink packet in a single channel of each active slot. However, each vehicle that applies CVIA transmits either an uplink packet or receives a downlink packet in a single channel of each active slot. Therefore, the throughputs of P^{CVIA} and P^{BUFE} can be derived by (14), shown at the bottom of the next page.

Let $\xi_{throughput}$ denote the improvement ratio of the proposed BUFE-MAC to the existing CVIA algorithm in terms of throughput. The throughput improvement ratio can be obtained by applying

$$\xi_{throughput} = (P^{BUFE} - P^{CVIA}) / P^{CVIA}. \quad (15)$$

Obviously, when $\xi_{throughput}$ is number x , BUFE-MAC is $x + 1$ times the throughput of CVIA. For ease of comparison,

we assume that $n_{seg_remain}^A$ is zero. Based on (8)–(11), (14), and (15), we have

$$\xi_{throughput} = (n_{v_total} - 1) / n_{v_total}. \quad (16)$$

Therefore, when n_{v_total} is larger than 1, $\xi_{throughput}$ is larger than 0. That is, the throughput of the proposed BUFE-MAC outperforms the CVIA protocol, because the value of n_{v_total} is usually larger than 1. Moreover, the throughput improvement ratio of BUFE-MAC to CVIA is increased with the vehicle density. Therefore, when the number of vehicles between two IGWs is large enough, BUFE-MAC is double the throughput of CVIA.

From another point of view, in the existing CVIA protocol, each channel supports either uplink or downlink packet transmissions. On the contrary, the proposed BUFE-MAC integrates the uplink and downlink transmissions together so that each channel can simultaneously support uplink and downlink packet transmissions. As a result, the throughput for CVIA using two channels is the same as the throughput for BUFE-MAC using one channel. Therefore, with the same bandwidth, the throughput of BUFE-MAC is double the throughput of CVIA.

Finally, we further analyze the bandwidth utilizations of the CVIA and BUFE-MAC protocols as follows. To simplify the analysis, we assume that the number of data packets is not smaller than what segments can transmit in the limited bandwidth. Let b_i^A denote the bandwidth utilization of segment S_i . First, the bandwidth utilization B^{CVIA} of CVIA is analyzed as follows. b_i^{CVIA} can be defined as the number of data packets that were transmitted in segment S_i divided by the number of data packets that were transmitted in a minimum time slot t_{min}^{CVIA} . Because the minimum length of time slot t_{min}^{CVIA} is defined in (8) and the number of data packets that were transmitted in segment S_i is defined in (7), the bandwidth utilization of CVIA in segment S_i can be derived by (7) and (8), as shown in

$$b_i^{CVIA} = (2(n_{segment}^{CVIA} - i + 1) \times V_{avg}^{CVIA} - 1) / (2n_{v_total} - 1). \quad (17)$$

Thus, the average bandwidth utilization of CVIA B^{CVIA} is shown as

$$B^{CVIA} = \left(\sum_{i=1}^{n_{segment}^{CVIA}} b_i^{CVIA} \right) / n_{segment}^{CVIA}. \quad (18)$$

With regard to the BUFE-MAC protocol, according to (9), the number of data packets allowed to be transmitted in a minimum time slot is n_{v_total} , and the total number of data packets that were transmitted in segment S_i is also n_{v_total} . Therefore, the bandwidth utilization of BUFE-MAC B^{BUFE} is 1. As a result, the improvement ratio, denoted by notation ξ_{bw_utiz} , of BUFE-MAC to CVIA in terms of bandwidth utilization can be derived by

$$\xi_{bw_utiz} = (B^{BUFE} - B^{CVIA}) / B^{CVIA}. \quad (19)$$

Because B^{BUFE} is 1 and B^{CVIA} is always less than 1, ξ_{bw_utiz} must be larger than 0, i.e., the bandwidth utilization of the proposed BUFE-MAC is better than CVIA. Moreover, based on (17)–(19), we have (20), which indicates that the bandwidth utilization improvement ratio of BUFE-MAC to CVIA is increased with the vehicle density and the number of segments in a d_{IGW} . Furthermore, the larger the values of $n_{segment}^{CVIA}$ and V_{avg}^{CVIA} are, the larger the ξ_{bw_utiz} is, and the best ξ_{bw_utiz} is 1. That is, the average bandwidth utilization of BUFE-MAC B^{BUFE} is almost double the average bandwidth utilization of CVIA B^{CVIA} when $n_{segment}^{CVIA}$ and V_{avg}^{CVIA} are very large

$$\xi_{bw_utiz} = 1 - (V_{avg}^{CVIA} - 1) / (V_{avg}^{CVIA} \times (n_{segment}^{CVIA} + 1) - 1). \quad (20)$$

From another viewpoint, by applying the CVIA protocol, the bandwidth utilization of segments that are farther away from the IGW is poor. Compared with CVIA, the proposed BUFE-MAC integrates the uplink and downlink packets in the same channel, and the uplink and downlink packets are received and transmitted by different IGWs to balance the bandwidth utilization of each segment. As a result, the bandwidth utilization of the BUFE-MAC protocol is much better, at most twice, than the CVIA protocol.

VI. PERFORMANCE EVALUATION

This section studies the performance of the proposed BUFE-MAC algorithm against the existing CVIA [10] MAC protocol in terms of throughput, average packet transmission delay time, packet collision ratio, and fairness of bandwidth access. Other factors such as network partition, packet relay times, bandwidth utilization, and interrelay interference are also investigated.

$$P^A = \alpha (n_{tsc}^A \times n_{segment}^A + n_{seg_remain}^A) \times V_{avg}^A$$

Where

$$\begin{cases} \alpha = 1 & \text{if } A \text{ is CVIA} \\ \alpha = 2 & \text{if } A \text{ is BUFE} \end{cases}$$

and

$$\begin{cases} n_{seg_remain}^A = 0, & \text{if } n_{slot_remain}^A = 0 \\ n_{seg_remain}^A = \sum_{i=1}^{n_{slot_remain}^A} \left[(n_{segment}^A - i + 1) / r_{interference}^A \right], & \text{if } 0 < n_{slot_remain}^A < r_{interference}^A \end{cases} \quad (14)$$

TABLE I
NOTATIONS OF CAR FOLLOWING

Notation	Meaning
$v_i(t)$	The speed of the rear vehicle at time t .
$v_{i-1}(t)$	The speed of the front vehicle at time t .
$x_i(t)$	The location of the rear vehicle at time t .
$x_{i-1}(t)$	The location of the front vehicle at time t .
T	Driver reaction time.
α	Acceleration rate of vehicles.
m, l	Positive coefficient

To simulate the realistic situation, we employ Network Simulator (NS-2) Ver.2.35 [14], which simulates realistic and expandable networks, to simulate the network environment. The IGWs communicate with each other by a wired network while using the built-in Iango Purushothaman IEEE 802.11 infrastructure mode. In addition, we simulate a 12-km four-lane bidirection and 140-km/h-speed-limitation highway vehicles network environment by using Simulation of Urban Mobility (SUMO) Ver. 0.12.3 [15] and Mobility model generator for Vehicular networks (MOVE) [16] Ver. 2.8.1. To improve the reality, the mobility of vehicles is simulated by the car-following model [17]. Furthermore, four different acceleration styles of vehicles are randomly deployed in different lanes, and we use minimizing overall braking deceleration induced by lane change (MOBIL) [17] as our lane-changing model. In the MOBIL model, the vehicles are randomly distributed on the road, and the vehicles change their lanes when the new lane is more attractive than the original lane without concerns about safety. The attractiveness is decided by the accelerations and decelerations of vehicles in the network. Because the performance and stability of a VANET protocol are usually affected by the density of vehicles and the volume of transmissions, we vary the factors of these properties in our simulation to verify our protocol.

A. Mobility Model and Simulation Environment

The car-following model is a popular model that simulates the vehicles' moving action. Although far away from its front vehicle, the vehicle will drive at the limit speed; on the contrary, the vehicle will keep away from the front vehicle in a safe distance. The action is depicted in (21), and the symbols in (21) are described in Table I

$$v_i(t) = \alpha \frac{[v_i(t)]^m}{[x_{i-1}(t-T) - x_i(t-T)]^l} [v_{i-1}(t-T) - v_i(t-T)]. \quad (21)$$

Our simulation parameters are depicted in Table II. In the DSRC standard, the maximum transmission power is 28.5 dBm, and the receiver sensitivity is set by -77 dBm such that the transmission range is approximately 1000 m. However, the large transmission range reduces the transmission parallelism, because it blocks a large number of transmitting packets. Therefore, we assume that vehicles are equipped with omnidirectional antennas that can radiate fixed and equal transmission power of 17 dBm such that the transmission range

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation Tool	NS-2 version 2.35
Channel Model	Two-ray-ground
Simulation Area	12km (4-lane 2-directional highway)
Vehicle Density:	50~100 vehicles/km
Speed:	80~140 km/h
Transmission Range:	300 m
Interference range:	300 m
Data rate:	27 Mbps
Packet Size:	2312 bytes
Total Input Load:	0~3000 packets/s
Simulation duration:	600 s
Simulation repetitions:	50

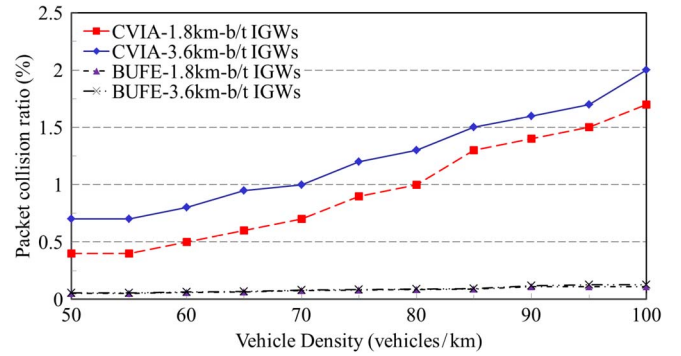


Fig. 6. Packet collision ratio of BUFE-MAC and CVIA.

is approximate 300 m, which is recommended by the Vehicle Safety Communications Consortium (VSCC) [18]. The channel model is two-ray ground, which considers a ground-reflected propagation path between transmitter and a receiver in addition to the line of sight. We model the simulation area as a 12-km bidirectional highway with two lanes in each direction. The simulation result is obtained from the average of 50 independent runs for high confidence.

This paper considers two network scenarios. First, the distance between two IGWs is 1.8 km, and the numbers of segments in CVIA and BUFE-MAC are 6 and 12, respectively. In the other scenario, the distance between two IGWs is 3.6 km, and the numbers of segments in CVIA and BUFE-MAC are 12 and 24, respectively. The simulation considers the two scenarios to verify the effect on the performance of different transmitting hops between vehicles and IGWs.

B. Simulation Results

Fig. 6 studies the packet collision ratio of the BUFE-MAC and CVIA protocols in two different scenarios. The offered load is 1500 packets/s. The density of vehicles varies, ranging in 50–100 vehicles/km. In general, collisions might occur in the following two types of transmission: 1) uplink packets and 2) information update packets. Because the CVIA adapts the contention-based approach for transmitting the uplink packets, a considerable number of collisions occurred [13]. In addition, the collision ratio increases when the vehicle density increases. Therefore, the collision ratio is higher when the density of IGWs is lower, because the less IGW raises more contentions.

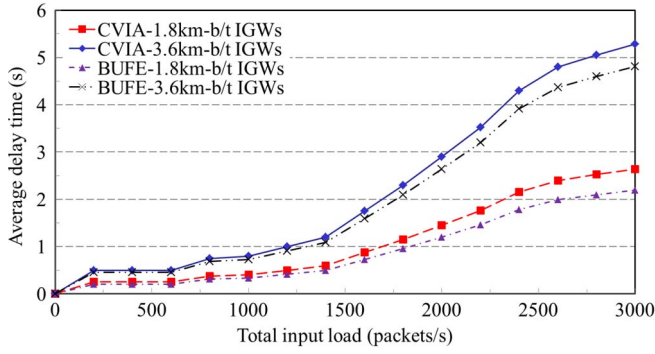


Fig. 7. Average delay time of BUFE-MAC and CVIA.

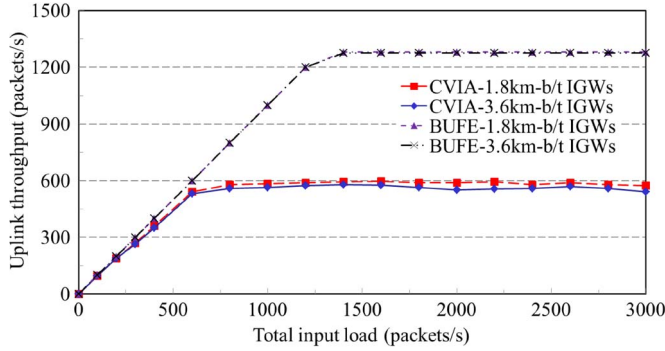


Fig. 8. Uplink throughput of BUFE-MAC and CVIA.

Instead of applying a contention-based mechanism, BUFE-MAC schedules uplink transmissions. Therefore, no collision occurs in the transmission of uplink packets in BUFE-MAC.

We investigate the uplink average delays of BUFE-MAC and CVIA in two different scenarios. Suppose that the vehicle density is 75 vehicles/km. The offered load is controlled, ranging from 0 packet/s to 3000 packets/s. In the CVIA protocol, the forwarder in each segment needs to collect the uplink packets from each vehicle and then relays the received packets to another forwarder in the next segment. As a result, CVIA increases the packet delay time with the offered load. On the other hand, the proposed BUFE-MAC efficiently alleviates the occurrence of collision. In addition, BUFE-MAC sets the segment length by $r_{com}/2$ such that all vehicles can directly send packets to the forwarder of the next segment. With the BUFE-MAC design, much packet forwarding can be eliminated, and t_{slot} can significantly be reduced to improve the transmission delay of uplink packets. Consequently, BUFE-MAC reduces the average delay with the offered load, as shown in Fig. 7. Fig. 7 depicts that the delay time of BUFE-MAC is less than the delay time of CVIA. Moreover, because the transmission delay will increase when the number of transmitting hops increases, the scenarios with longer distance between IGWs have more delay time than the scenarios with shorter distance.

Fig. 8 compares the CVIA and BUFE-MAC protocols in terms of uplink throughput in the two scenarios. The vehicle density is set as 75 vehicles/km. The offered load varies, ranging from 0 packet/s to 3000 packets/s. The proposed BUFE-MAC significantly improves the uplink throughput compared with CVIA. CVIA considers the fairness issue, and thus, it restricts the maximal number of packets that are transmitted in

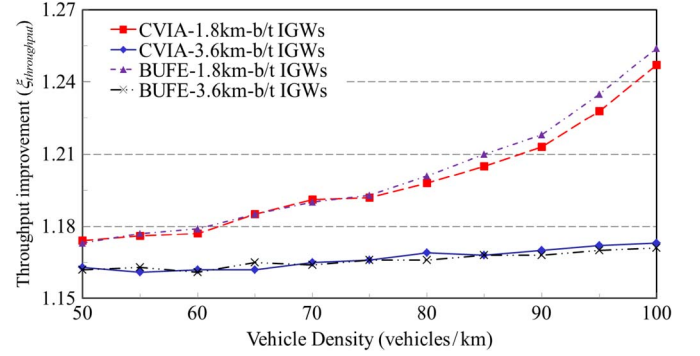


Fig. 9. Throughput improvement comparison.

each segment, resulting in the inefficient bandwidth utilization. However, the proposed BUFE-MAC protocol integrates the uplink and downlink packets together and uses different IGWs to significantly increase the bandwidth utilization. Moreover, because of existing collisions between packets in CVIA, the throughput decreases, whereas the number of transmitting hops increases. On the contrary, because there is no collision problem, the throughput is not affected by the number of transmitting hops in BUFE-MAC.

Fig. 9 depicts the throughput improvement of BUFE-MAC compared with CVIA, as defined in (15). The offered load is 1500 packets/s, whereas the vehicle density varies, ranging from 50 vehicles/km to 100 vehicles/km. In the existing CVIA protocol, each channel either supports uplink or downlink packets transmission at the same time. In addition, because the CVIA adapts the contention-based approach for transmitting the uplink packets, a considerable number of collisions will occur. Different from CVIA, the proposed BUFE-MAC integrates the uplink and downlink transmissions, and each channel can simultaneously support uplink and downlink packet transmissions. Furthermore, BUFE-MAC schedules the uplink transmissions instead of applying a contention-based policy. Consequently, no collision will occur in transmitting the uplink packets. As a result, the throughput improvement of BUFE-MAC to CVIA is significant. The throughput improvement of BUFE-MAC, compared with CVIA, varies, ranging from 117.3% to 125.4% of uplink transmission and ranging from 116.2% to 117.7% of downlink transmission, as shown in Fig. 9. Note that the throughput of BUFE-MAC is double the throughput of CVIA when $\xi_{throughput}$ is equal to 1, as defined in (15). Fig. 9 shows that the throughput improvements of uplink and downlink are more than 1 and the uplink throughput improvement is better than the downlink throughput improvement in both scenarios. The throughput improvements are, by reason, of improved bandwidth utilization, because BUFE-MAC integrates the uplink and downlink packets together and uses different IGWs.

Fig. 10 further compares the fairness of bandwidth access of BUFE-MAC and CVIA. The offered load is 1500 packets/s. The proposed BUFE-MAC protocol allocates the bandwidth according to the number of vehicles in each segment. Thus, vehicles in the same segment can be allocated with the same bandwidth, and each segment can also be allocated the same bandwidth. Although CVIA allocates all segments with the

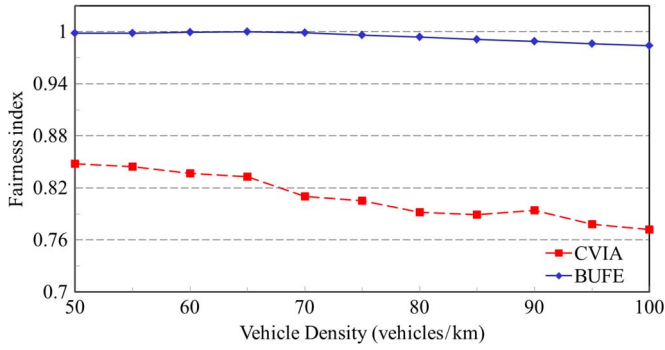


Fig. 10. Fairness index at the variation of vehicle density.

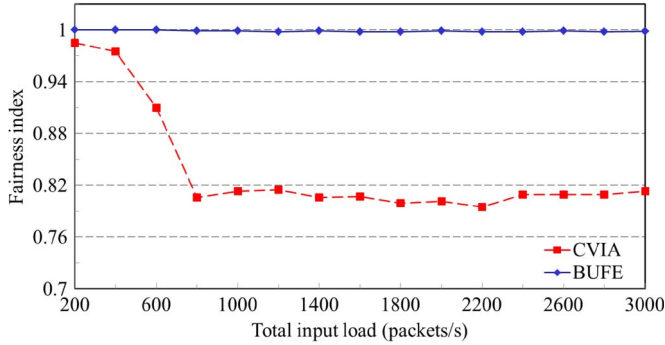


Fig. 11. Fairness index at the variation of input load.

same bandwidth, the CVIA protocol adapts the contention-based approach for uplink transmissions. Therefore, vehicles in the same segment cannot fairly access the bandwidth. Herein, the fairness index in [12] is used to measure the transmission fairness of the two protocols compared.

The value of fairness index of the bandwidth access among vehicles is between 77.2% and 84.7% in CVIA. The contention probability is increased with the density of vehicles. On the other hand, the value of fairness index of the proposed BUFE-MAC protocol is between 98.4% and 100%. The fairness index of BUFE-MAC is likely decreased with the vehicle density. In general, the fairness index of BUFE-MAC is higher than the fairness index of CVIA. In particular, the fairness index of the proposed BUFE-MAC is above 99.6% when the vehicle density is smaller than 75 vehicles/km.

Fig. 11 compares the fairness index in various network throughputs of the CVIA and BUFE-MAC MAC protocols. The vehicle density is set by 75 vehicles/km, and the offered load varies, ranging from 200 packets/s to 3000 packets/s. In the CVIA protocol, the fairness index is above 90% when the network throughput is lower than 600 packets/s. However, the more the input load demands, the lower the fairness index becomes. The proposed BUFE-MAC results in a stable fairness index of bandwidth access. As shown in Fig. 11, BUFE-MAC maintains a near-constant value (between 99.8% and 100%) of the fairness index, regardless of how much the input load is.

CVIA divides the road into segments with r_{com} -length, where r_{com} is the communication range of each vehicle. Then, CVIA employs two vehicles as temporary routers in each segment. One router is responsible for receiving and relaying all packets from previous segments, and the other router is

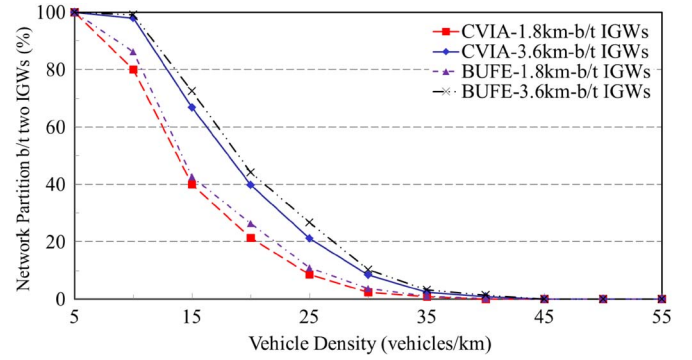


Fig. 12. Network partition at the variation of vehicle density.

responsible for gathering and sending all packets of the current segment to the next segment. In contrast, the segment length of the proposed BUFE-MAC algorithm is $r_{com}/2$, which is the maximal length that vehicles can directly communicate with any vehicle in the neighboring segments. Thus, BUFE-MAC employs only one vehicle as the manager in each segment for receiving and relaying all packets to the next segment. In the scenario of low vehicle density, some segments may not have vehicles to relay packets. Thus, low vehicle density may lead to network partition. Fig. 12 compares the network partition ratio of the CVIA and BUFE-MAC protocols in various vehicle densities. Because the proposed BUFE-MAC protocol has a smaller segment length, the network partition ratio is slightly higher than CVIA, as shown in Fig. 12. When the vehicle density is larger than 30 vehicles/km, the difference of network partition ratio between the CVIA and BUFE-MAC protocols is less than 1%. Note that, if a partition occurs in the area between IGW_i and IGW_{i+1} , it does not affect the transmissions in other areas of the network. When the vehicle density is lower, the average delay time of BUFE-MAC is more than the time of CVIA. However, because the BUFE-MAC protocol has better bandwidth utilization, the throughput of BUFE-MAC is much better than CVIA, even if the vehicle density is low.

We now probe into the bandwidth utilization of BUFE-MAC and CVIA. As we have mentioned in the previous section, BUFE-MAC has better bandwidth utilization. In the best situation, the bandwidth utilization of BUFE-MAC is almost double to the bandwidth utilization of CVIA. Now, we can consider it from another point of view. Bandwidth utilization is the ratio of the actual transmission time to the whole active slot. Because the segment manager and the vehicles that apply CVIA or BUFE-MAC have to arrange a partial time to announce information at an active time slot, the bandwidth utilization cannot achieve 100%. To achieve the purpose of fairly using bandwidth, CVIA restricts the number of packets in each segment to be transmitted in its active time slot. With this restriction, all segments have the same transmission opportunity for transmitting their own data, and hence, CVIA likely achieves fairness. However, for fair restriction, segments that are farther away from an IGW suffer from the low bandwidth utilization. For those vehicles in the same segment, the uplink IGW is also the downlink IGW. Hence, the traffic directions of downlink and uplink are different. In contrast, BUFE-MAC reverses the transmission direction of downlink traffic. In other words, for

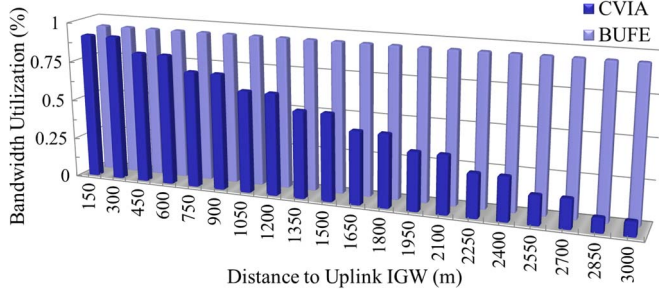


Fig. 13. Bandwidth utilization for each segment.

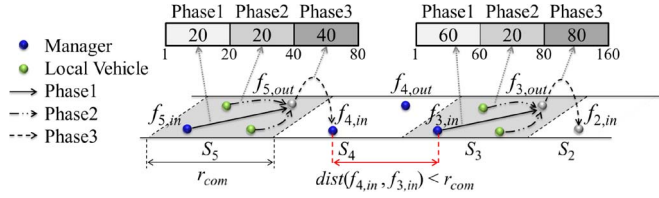


Fig. 14. Interrelay interference.

vehicles that are located between IGW_i and IGW_{i-1} , the uplink IGW is IGW_{i-1} , and the downlink IGW is IGW_i . Hence, the traffic directions of uplink and downlink are the same. Moreover, BUFE-MAC integrates the uplink and downlink packets. Therefore, the segment that is closer to the downlink IGW has more downlink packets but fewer uplink packets in traffic, and the segment that is closer to the uplink IGW has more uplink packets but fewer downlink packets in traffic. As a result, the downlink and uplink traffic in each segment can be merged to maximize the slot utilization.

Fig. 13 compares the bandwidth utilization of CVIA and BUFE-MAC at different distances to the uplink IGW. The vehicle density is set as 75 vehicles/km, and the offered load of uplink and downlink are set as 1500 packets/s. In the CVIA protocol, the bandwidth utilization of the first segment is above 90%. However, the farther the segment is away from the IGW, the lower bandwidth utilization becomes. As shown in Fig. 13, the proposed BUFE-MAC maintains the bandwidth utilization above 95%, and the bandwidth utilization will not be decreased with the distance between the segment and the IGW. From this viewpoint, the average bandwidth utilization of BUFE-MAC is almost double that of CVIA.

Finally, we describe another contribution of BUFE-MAC, which prevents the transmissions between neighboring segments from interference. In an active time slot, the transmission of CVIA is divided into the following three phases: 1) intrasegment packets relaying; 2) local packets gathering; and 3) intersegment packets transmitting. For fairness bandwidth access, CVIA restricts the size of data that were generated by the vehicles in a segment. However, the relaying packets will be accumulated to the later segment. As a result, the later segments should have a bigger size of data that are expected to forward to the next segment. For example, assume that there are six segments between two IGWs. The transmission rate is 120 b/time slot. For fairness, each segment can only have a capacity of 20 b in its active time slot. With this restriction, the router $f_{6,out}$ in segment S_6 transmits 20 b to

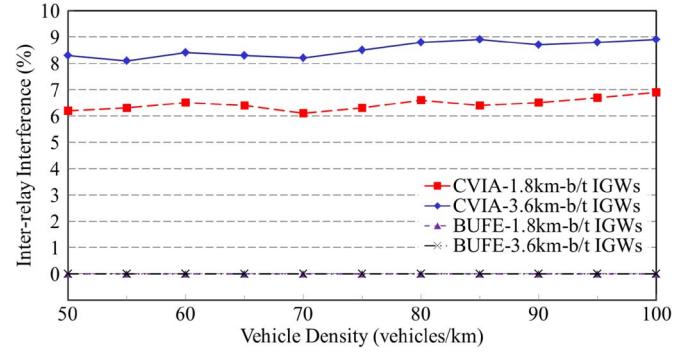


Fig. 15. Interrelay interference at the variation of vehicle density.

the router $f_{5,in}$ in segment S_5 . However, an additional 20 b is generated by vehicles in S_5 . Therefore, the router $f_{5,out}$ in segment S_5 transmits 40 b to the router $f_{4,in}$ in segment S_4 . As shown in Fig. 14, the quantities of transmission packets in the three phases of segments S_5 are 20, 20, and 40, respectively. Similarly, the sizes of data transmitted in the three phases of segment S_3 are 60, 20, and 80, respectively. In this case, the data transmission of phase 3 in segment S_5 might be simultaneous with the data transmission of phase 1 in segment S_3 , resulting in the interference that occurred in $f_{4,in}$. The interference problem that occurred in CVIA was mainly caused by the nonsynchronization of the phases in different active segments. However, BUFE-MAC merges the uplink and downlink data into the same packets, and thus, the data sizes that are expected to be transmitted in phase 1 of any two active segments will be identical, which avoids the interference problem. Consequently, BUFE-MAC has better performance than CVIA in terms of the interrelay interference.

Fig. 15 compares the interrelay interference of BUFE-MAC and CVIA in various vehicle densities. Interrelay interference is the ratio of the number of interfered packet transmissions to the number of all transmissions. The performance result reflects the aforementioned arguments, and hence, BUFE-MAC significantly improves the interference situation compared with the existing CVIA and likely maintains 0% of the interrelay interference ratio in all cases.

Summarizing these simulation results, we know that the packet collision ratio and the average delay time of BUFE-MAC are less than those of CVIA. Moreover, the throughput and fairness of BUFE-MAC are much improved than those of CVIA. Furthermore, BUFE-MAC prevents the transmission from interrelay interference. Therefore, we have verified that our protocol is much better than CVIA.

VII. CONCLUSION

This paper has proposed a multihop MAC protocol, called BUFE-MAC, for the uplink and downlink communication services between RSUs and vehicles. In addition to maintaining fairness, the proposed BUFE-MAC increases the bandwidth utilization by integrating the uplink and downlink traffic. Moreover, BUFE-MAC significantly reduces the number of transmissions and transmission delay by setting the proper segment length. Therefore, without reducing the degree of parallelism,

the network throughput can be increased at most twice by employing the BUFE-MAC protocol compared with CVIA. Performance study shows that the proposed BUFE-MAC outperforms the existing CVIA in terms of bandwidth utilization, transmission delay, packets collision, fairness, and network throughput.

In the DSRC standard, the single-hop communication between vehicles can be extended to multihop communications, because each vehicle can play the role of a forwarder and transmit the received data to the next hop forwarder or destination. Therefore, BUFE-MAC, which is developed based on the multihop communication between two IGWs, can be implemented based on the standard. Because our protocol is dependent on the accurate knowledge of locations, the location error may increase the probability of packet collisions. Hence, the performance of BUFE-MAC will be impacted by the GPS inaccuracy. Currently, new localization mechanisms such as integrating GPS and AGPS have been proposed to improve the location accuracy. With the rapid development of localization schemes, the BUFE-MAC can be an extensively accomplished protocol.

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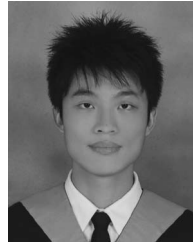


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