ABM-V: An Adaptive Backoff Mechanism for Mitigating Broadcast Storm in VANETs

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***Abstract*—In vehicular ad hoc networks (VANETs), the broadcast storm problem may disable road safety applications and cause congestion or traffic accidents. Existing schemes propose broadcast storm mitigation by reducing the number of relay vehicles. Concurrently, in improving reachability, these schemes stipulate that vehicles expected to transmit packets to more next-hop neighbors have higher relay priority. However, the potential redundancy caused by duplicate reception by neighbors is ignored, which exacerbates the contention and collisions in transmission. This paper proposes an adaptive backoff mechanism for mitigating broadcast storm in VANETs (ABM-V). Specifically, the receiver estimates the expected benefit and redundancy by combining the distribution of neighbors. Then, the receiver adaptively adjusts the backoff time by utilizing Dempster-Shafer evidence theory. Finally, the receiver with the shortest backoff time becomes the relay and rebroadcasts the packet to its neighbors. Simulation results illustrate that ABM-V significantly reduces the rebroadcast ratio and redundancy ratio compared with the existing typical schemes while maintaining stable reachability.**

***Index Terms*—VANETs, broadcast storm mitigation, multi-hop broadcast, adaptive backoff mechanism, Dempster-Shafer evidence theory.**

I. Introduction

IN vehicular ad hoc networks (VANETs), multi-hop Vehicle-to-Vehicle (V2V) broadcast is the primary way of transmitting information for various vehicular applications [1, 2]. However, the blind dissemination of packets by vehicles may lead to frequent contention and collisions in VANETs due to the shared wireless medium. That is the broadcast storm problem, which affects the transmission of information in the channel, thus reducing the quality of service provided by vehicular applications [3].

There are a substantial number of delay-sensitive road safety applications in VANETs, such as cooperative awareness, pre-crash sensing, intersection collision warning, and control loss warning, where packets have an expiration time of 500ms [4–6]. These applications realize the transmission between vehicles through Dedicated Short Range Communication (DSRC), which is supported by IEEE 802.11p and Wireless Access in Vehicular Environments (WAVE) protocol stack. Broadcast storm problem has an even more detrimental effect on such applications, possibly disabling them and causing congestion or even traffic accidents [7].

The most effective way to mitigate broadcast storms between vehicles is to reduce the number of relay nodes [8]. In existing schemes, the relay node that can transmit the packet to more next-hop vehicles (referred to as *benefit*) prioritizes rebroadcasting. However, these schemes do not consider whether the next-hop vehicles have already received the same packet, resulting in unnecessary redundancy. This intensifies contention and collisions and increases the risk of broadcast storms, especially in high-density scenarios (such as intersections in urban areas) [9]. Therefore, the relay vehicle in VANETs should consider the expected *benefit* and *redundancy* simultaneously when determining the rebroadcast decision.

In addition, vehicles move rapidly in VANETs, which causes dynamic changes in the topology and reduces the decisions accuracy of relay vehicles [10]. Beacon messages utilized in most V2V applications can effectively solve this problem, such as cooperative awareness messages (CAM) in ETSI [11] and basic safety messages (BSM) in SAE standards [12]. In these applications, a vehicle broadcasts beacons at a fixed frequency in the order of milliseconds to inform one-hop neighbors of its location, velocity, driving direction, and other essential information [13]. The change in the topology of the vehicles during the broadcast interval of the beacon is negligible [14]. Therefore, a relay can determine the rebroadcast decision based on the essential information provided by beacons to minimize the adverse impact of mobility.

Furthermore, vehicles in VANETs are limited by road structure and traffic conditions when changing the driving direction [15]. Therefore, to determine the appropriate region of interest (ROI) for a vehicular application, the broadcast source considers whether the vehicles in a particular geographical location that travel in a particular direction would be interested in the broadcast message [4]. In highway scenarios, vehicles generally have only two driving directions, and the broadcast source can set ROI to the same or opposite direction of its driving direction. In urban areas, vehicles have more choices of driving directions, and they change driving directions frequently, so the ROI is usually set to 360° [16]. Generally, vehicles that are not in the ROI will discard the packet after receiving it. In V2V broadcasting, the relay vehicle should consider the ROI of the message when determining the rebroadcast decision.

In this paper, we propose an adaptive backoff mechanism for

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TABLE I
SUMMARY OF ACRONYMS

Acronym	Full name
VANETs	Vehicular Ad Hoc Networks
V2V	Vehicle-to-Vehicle
DSRC	Dedicated Short Range Communication
WAVE	Wireless Access in Vehicular Environments
CAM	Cooperative Awareness Messages
BSM	Basic Safety Messages
ROI	Region of Interest
NLOS	Non-line-of-sight
TTL	Time to Live
WSM	WAVE Short Message
BPAs	Basic Probability Assignments
PDR	Packet Delivery Ratio

mitigating broadcast storm in VANETs (ABM-V). In ABM-V, the broadcast source determines the ROI according to the application and scenario requirements. The receiver utilizes ROI and essential information such as direction and location from beacon messages to estimate the expected *benefit* and *redundancy* and adaptively adjust the back-off time accordingly. Additionally, to avoid link disconnection and improve broadcast reachability, the relay vehicle determines whether to rebroadcast the packet again via neighbors' behavior. The main contributions of this paper are as follows:

1) We incorporate to measure neighbors' distribution by dividing the neighbors into benefit set and redundancy set, which are used for subsequent quantification.

2) We propose a quantification method based on neighbors' distribution and link quality to quantify the expected *benefit* and *redundancy* of the receiver under different road and communication conditions in VANETs.

3) We propose a fusion method based on Dempster Shafer evidence theory, which fuses expected *benefit* and *redundancy* to adjust the backoff time adaptively and effectively reduce the number of relays to mitigate the broadcast storm.

The rest of the paper is organized as follows: Section II reviews related works. Section III presents an overview of ABM-V. Section IV introduces the implementation of the adaptive backoff mechanism. We evaluate the performance of ABM-V in Section V and summarize our work in Section VI.

II. Related Work

There are two main categories of existing broadcast storm mitigation schemes in VANETs: sender-based and receiver-based schemes.

A. Sender-based Scheme

In sender-based schemes, the sender selects all relay vehicles through a predetermined strategy and inserts the result into the packet. The receiver makes the rebroadcast decision based on the relay list in the received packet.

Yoo and Kim [17] proposed a robust and fast-forwarding (ROFF) protocol, in which a candidate uses the empty space distribution bitmap to obtain its forwarding priority and uses the waiting time inversely proportional to its forwarding priority to reduce unnecessary delays. Zhang *et al.* [18] proposed an adaptive fast broadcast (AFB) protocol, in which a sender defines the control information through an index-based control structure and uses a segmentation-based partition algorithm to minimize the size of the control information. Kamakshi *et al.* [16] proposed a modularity-based mobility-aware community detection scheme, in which the following forwarders are selected from vehicle communities. Hao *et al.* [19] proposed BlockP2P-EP, in which a sender first leverages the K-Means algorithm for gathering proximity vehicles into clusters and then conducts the parallel spanning-tree broadcast algorithm to enable fast data broadcast among vehicles.

However, there are non-line-of-sight (NLOS) conditions in VANETs, which leads to frequent packet loss between vehicles [14]. It means that the relay vehicles selected by the sender may not receive the packet and relay strategy, which will affect the broadcast performance of the above sender-based schemes.

B. Receiver-based Scheme

In receiver-based schemes, the receiver adjusts the rebroadcast probability by itself and is not directly restricted by other vehicles. In the following, we introduce several receiver-based broadcast schemes in VANETs, which are based on different methods for calculating rebroadcast probability.

Fixed probability routing is a typical receiver-based scheme to mitigate the broadcast storm. Haas *et al.* [20] proposed a distributed gossip-based scheme, in which each node rebroadcasts the packet with a fixed probability $k \leq 1$. This kind of scheme is suitable for static networks with evenly distributed nodes and is not practical enough in dynamic VANETs. Therefore, many dynamic probability schemes have emerged.

The distance-based schemes adjust the rebroadcast probability based on the Euclidean distance between vehicles. Tonguz *et al.* [3, 21, 22] proposed the weighted p-persistence scheme, which reduces the rebroadcast probability of receivers closer to the sender to mitigate the broadcast storm. Zhang *et al.* [8] proposed a broadcast scheme based on the prediction of dynamics (BPD) that combined the distance and link quality, in which a receiver utilizes the dynamic information to achieve the model-based prediction. Chuang and Chen [23] proposed a density-aware emergency message extension protocol (DEEP), in which the source vehicle divides the coverage of the message into many blocks by vehicle density and assigns a deferral time to each block by the relative distance. Receivers in these schemes determine the rebroadcast probability by estimating the extra area that can benefit from the rebroadcast, and they assume that the size of the extra area is directly proportional to the number of vehicles in it [24]. Unfortunately, this assumption only holds when the vehicles are uniformly distributed, which is often not met in VANETs due to, for instance, irregular road topologies [25].

Some studies proposed dynamic probability schemes from different perspectives. Tian *et al.* [15] proposed that the receiver can judge its expected benefit from the correlation between its location and the region of interest carried in the packet. Feukeu *et al.* [7] proposed a dynamic broadcast storm mitigation approach (DBSMA), which uses the density and velocities of vehicles to adjust the broadcast delay. These two schemes are suitable for emergency broadcast applications on one-dimensional roads (such as highways). Cheng *et al.* [26] proposed a dynamic clustering model, in which the vehicle makes the routing decision on the received packet based on its identity in the cluster. Xu *et al.* [27] proposed that the receiver adjust the rebroadcast probability according to neighbors reputations because vehicles with high reputations actively participate in rebroadcast. However, when the proportion of malicious vehicles is low, this scheme degenerates into a gossip-based scheme with a fixed probability since the reputation values of all vehicles are similar.

In the above receiver-based schemes, receivers only pay attention to how many neighbors can receive the packet, regardless of whether they have already received the packet from other vehicles, which may cause frequent contention and collisions. To address this problem, we design a new receiver-based broadcast storm mitigation scheme with stable performance in various scenarios and full consideration of broadcast redundancy.

III. Scheme Overview

This section introduces the architecture of ABM-V. As shown in Fig.1, ABM-V consists of three components: *rebroadcast decision model*, *adaptive backoff mechanism*, and *monitoring mechanism*.

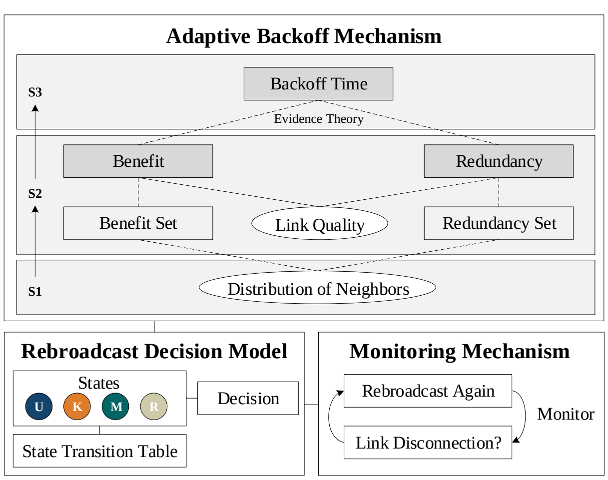


Fig. 1. **Architecture of ABM-V.**

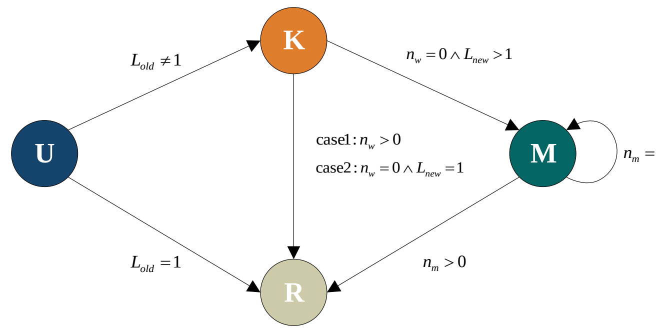


Fig. 2. **State transition diagram.**

In ABM-V, receivers determine how to deal with a particular packet through the rebroadcast decision model. Then, they initiate the adaptive backoff mechanism to determine their relay priority. Only the receiver with the shortest backoff time within its transmission range can become a relay and rebroadcast the packet, which reduces the rebroadcast probability and mitigates the broadcast storm. After rebroadcasting, the relay executes the monitoring mechanism to avoid link disconnection.

A. Rebroadcast Decision Model

As shown in Fig.2, we define four states and the transition relationship between them in rebroadcast decision model. For a particular multi-hop broadcast packet p, there are four states for the vehicles: (1) Unknown (U) - the vehicle has not yet received p. (2) Known (K) - the vehicle has received p and determines whether to rebroadcast it by the rebroadcast decision model. (3) Monitory (M) - the vehicle monitors its neighbors after rebroadcast p. (4) Removed (R) - the vehicle no longer rebroadcast p again and will discard the repeatedly received p.

When the vehicle in state U receives p for the first time, it checks field L (a positive integer) in the packet and sets $L_{old} = L$, where L is the time to live (TTL) in IPv6 packet or expiry time in WAVE short message (WSM) [28]. If $L_{old} = 1$, the vehicle determines that it is the last hop receiver and does not need to rebroadcast p, so it changes to state R; if $L_{old} > 1$, the vehicle changes to state K.

The vehicle in state K executes the adaptive backoff mechanism. Specifically, it adaptively adjusts the backoff time and waits for the corresponding length of time. During this period, the vehicle records the number of p received from neighbors and denotes it as n_w. If $n_w > 0$, the vehicle changes to state R; if $n_w = 0$, it sets $L_{new} = L_{old} - 1$ and rebroadcasts p. Then, if $L_{new} = 1$, the vehicle changes to state R; if $L_{new} > 1$, it changes to state M.

The vehicle in state M executes the monitoring mechanism. Specifically, the vehicle waits for a fixed time and records the number of p received from neighbors as n_m. If $n_m > 0$, the vehicle changes to state R; otherwise, it rebroadcasts p again and repeats the monitoring mechanism.

B. Adaptive Backoff Mechanism

The vehicle in state K executes the adaptive backoff mechanism to mitigate the broadcast storm. Firstly, it calculates the backoff time through three steps:

S1. The vehicle filters the neighbors in ROI according to basic information such as location and driving direction [29, 30]. Then, the vehicle divides neighbors that meet the ROI condition into a benefit set and redundancy set according to the relative distance between the neighbors and the sender.

S2. The vehicle quantifies the expected *benefit* and *redundancy* in combination with the link quality and the two sets obtained by S1.

S3. The vehicle obtains the backoff time by fusing the expected *benefit* and *redundancy* through Dempster-Shafer evidence theory.

Then, the vehicle waits according to the calculated backoff time. If the vehicle does not receive the packet repeatedly, it determines that it has the highest relay priority and rebroadcasts the packet. The implementation details of S1-S3 are given in Section IV.

C. Monitoring Mechanism

After rebroadcasting the packet p, the relay vehicle executes the monitoring mechanism to avoid link disconnection and maintain the stability of broadcast reachability. Specifically, the vehicle waits for a preset fixed duration $Time_{mon}$ and records the number of p received from neighbors during this period. We need to set $Time_{mon} \geq (Time_{dsrc} + Time_{com} + Time_{wait})$ to ensure that a vehicle can collect the rebroadcast decision of all neighbors during the monitoring process, where $Time_{dsrc}$ is the propagation delay caused by DSRC, $Time_{com}$ is the computational delay of ABM-V, and $Time_{wait}$ is the maximum backoff time. If at least one neighbor rebroadcasts the same packet p, the vehicle interrupts monitoring and completes the rebroadcast. Otherwise, it rebroadcasts p and executes the monitoring mechanism again.

IV. Implementation of Adaptive Backoff Mechanism

This section introduces the implementation details of S1-S3 in the adaptive backoff mechanism in Fig.1. The main notations in this section are given in Table II. Algorithm 1 gives the whole process of implementing the adaptive backoff mechanism.

A. Distribution of Neighbors

In ABM-V, a receiver v_r records the number of packets it successfully received as n_r within a fixed time. Then, v_r records all those packets as a set $P = \{p_1, p_2, ..., p_{n_r}\}$, and all one-hop neighbors as a set N. For a particular broadcast packet p_i, where $i \in \{1, 2, ..., n_r\}$, v_r obtains the distribution of neighbors through three steps.

Firstly, v_r filters all one-hop neighbors in the ROI of p_i according to basic information such as location and driving direction and forms a set $N_i \subseteq N$. The ROI of p_i is determined by the broadcast source.

TABLE II
SUMMARY OF NOTATIONS AND SYMBOLS

Notation	Description
v_r, v_s, v_j	receiver, sender, an one-hop neighbor of the receiver
n_r	the number of packets successfully received by the receiver within a fixed time
P	a set of packets received by the receiver
N	a set of one-hop neighbors
p	a particular broadcast packet
Be, Re	benefit set and redundancy set
R_v	V2V transmission range
s	link quality
N_{max}	maximum number of one-hop neighbors
N_{non}	maximum number of one-hop neighbors at non-intersection in urban area
b	benefit
r	redundancy
α, β	adjustment parameters
T_{bi}, T_{di}	basic probability assignments
Pri	priority
BT	backoff time

Secondly, v_r calculates the Euclidean distance between the sender v_s and all neighbors $v_j \in N_i$. To simplify the discussion, we set the location of a vehicle as a two-dimensional coordinate (x, y). Generally, v_r obtains neighbors' location information from beacons. Therefore,

$$e_{sj}^2 = (x_s - x_j)^2 + (y_s - y_j)^2, v_j \in N_i. \tag{1}$$

Thirdly, v_r divides all neighbors $v_j \in N_i$ into a benefit set Be_i and a redundancy set Re_i according to whether they are in the benefit zone or redundancy zone. As shown in Fig.3, for a definite sender v_s, the transmission range of v_r is divided into two zones:

- **Benefit zone.** The benefit zone indicates the zone belongs to the transmission range of the receiver but outside the transmission range of the sender. Neighbors in this zone cannot receive the packet from the sender. Therefore, when the receiver rebroadcasts the packet, these neighbors receive the packet for the first time.
- **Redundancy zone.** The redundancy zone indicates the intersection zone of the transmission range between the sender and the receiver. All neighbors of the receiver in this zone can receive packets from the sender when the packet delivery ratio

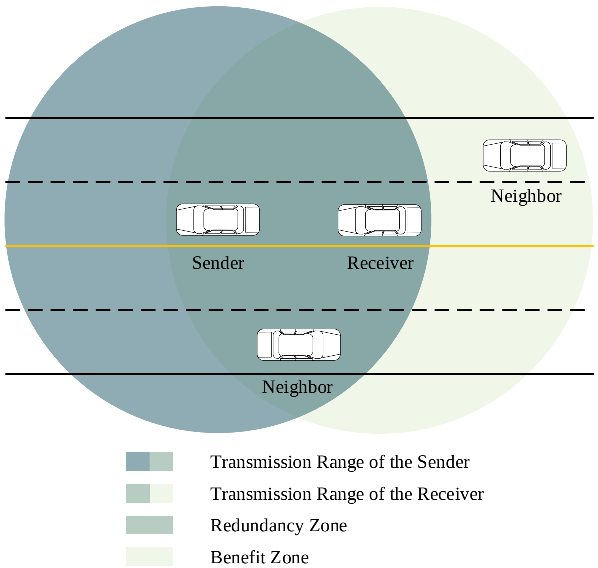


Fig. 3. **Distribution of neighbors.**

(PDR) is 100% [14]. Therefore, these neighbors receive the packet repeatedly if the receiver rebroadcasts the packet.

Therefore, if $e_{sj}^2 > R_v^2$, where R_v is the V2V transmission range, v_j is added to Be_i; otherwise, v_j is added to Re_i.

$$Be_i = \{v_j | v_j \in N_i, e_{sj}^2 > R_v^2\}, \tag{2}$$

$$Re_i = \{v_j | v_j \in N_i, e_{sj}^2 \le R_v^2\}. \tag{3}$$

In conclusion, these two sets indicate the distribution of neighbors relative to p_i.

B. Benefit and Redundancy

After obtaining the distribution of neighbors, the receiver combines the link quality with neighbors to quantify the expected *benefit* and *redundancy*.

1) Quantification of Benefits and Redundancy: Firstly, the original *benefit* and *redundancy* of v_r are defined as

$$b_i' = \sum_{v_j \in Be_i} s_j, \tag{4}$$

$$r_i' = \sum_{v_j \in Re_i} s_j, \tag{5}$$

where $s_j \in [0, 1]$ is the link quality between v_r and v_j, which is defined as

$$s_j = \frac{n_{b_j}}{f_j}, \tag{6}$$

where n_{b_j} is the number of beacons v_r received from v_j in unit time; f_j is the frequency of beacons, which is unified globally or determined by an application.

Then, v_r obtains the expected *benefit* and *redundancy* by normalizing b_i' and r_i', which ensures that their value range

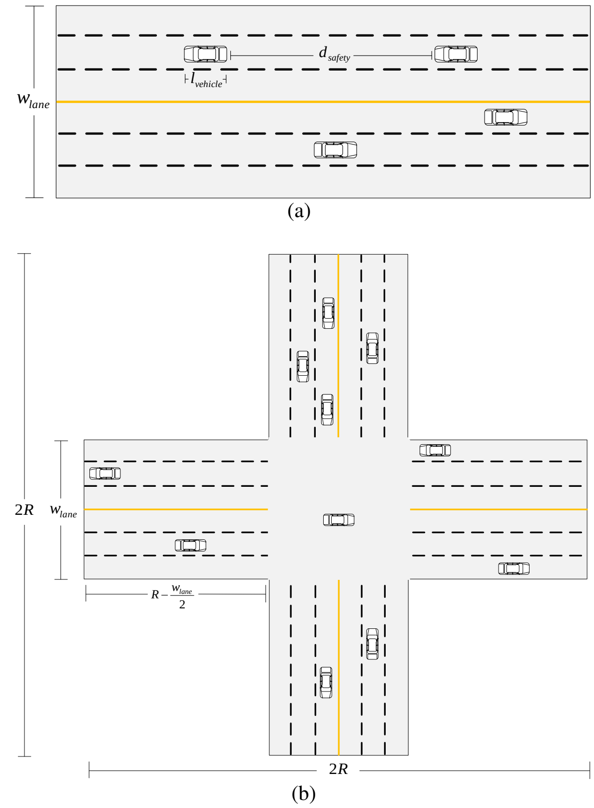


Fig. 4. **Two types of roads in urban areas.** (a) Non-intersection; (b) Intersection.

are in $[0, 1]$. The normalized results are $b_i = \frac{b_i' - b_{min}'}{b_{max}' - b_{min}'}$, $r_i = \frac{r_i' - r_{min}'}{r_{max}' - r_{min}'}$, respectively.

According to Eq.(4) and Eq.(6), $b_{max}' = N_{max} \cdot s_{max} = N_{max}$ and $b_{min}' = N_{min} \cdot s_{min} = 0$, where N_{max} is the maximum number of one-hop neighbors, which is synchronized between vehicles through beacons. In the same way, we can get $r_{max}' = N_{max}$ and $r_{min}' = 0$. Therefore, the normalized result can be simplified as $b_i = \frac{b_i'}{N_{max}}$, $r_i = \frac{r_i'}{N_{max}}$.

2) Estimation of N_{max}: In ABM-V, all vehicles share their stored N_{max} in beacons. For instance, a vehicle stores N_{max} and receives N_{max}' shared by a neighbor. If $N_{max}' > N_{max}$, the vehicle updates $N_{max} = N_{max}'$. Additionally, ABM-V sets the reset time $Time_{reset}$ to avoid the situation that N_{max} does not change for a long time due to its immense value. If N_{max} does not change until the end of the timer, the vehicle updates it to the number of current neighbors.

In VANETs, N_{max} is directly related to the type of road. For instance, roads in urban areas are mainly divided into non-intersections (Fig.4(a)) and intersections (Fig.4(b)). The estimation equation for N_{max} can given by

$$N_{max} = \kappa_{loc} \cdot N_{non}, \tag{7}$$

where N_{non} is the maximum number of one-hop neighbors of vehicles at non-intersection in urban areas, which can be estimated by

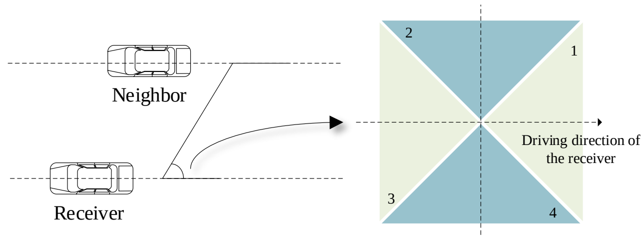


Fig. 5. **Angle between the receiver and its neighbors.** The coordinate system is established with the traveling direction of v_r as the positive direction of the x-axis.

$$N_{non} = [2R_v/(l_{vehicle} + d_{safety})] \cdot n_{lane}, \tag{8}$$

where $l_{vehicle}$ is the length of vehicles, d_{safety} is the safety following distance between vehicles, and n_{lane} is the number of lanes on urban main roads. The intuition of this equation is to use the space occupied by each vehicle at a safe distance to estimate the number of vehicles. Similar to the reference in [14, 31], we can set R_v = 300m, $l_{vehicle}$ = 5m, d_{safety} = 2s × 60km/h = 34m (according to the 2 second rule), and $n_{lane} = 6$. Therefore, the value of N_{non} can be approximately estimated to be 92.

κ_{loc} is the position parameter, and its subscript loc indicates the position of a vehicle. A receiver v_r determines loc by the angles between its driving direction and the driving direction of its neighbors. As illustrated in Fig.5, if all the included angles are in area 1 and area 3, the driving directions of all neighbors are the same as or opposite to v_r. From this, v_r determines that it is driving at a non-intersection and sets $loc = 1$. If any angle is in area 2 or area 4, v_r determines that it is at an intersection and sets $loc = 2$.

When $loc = 1$, it indicates that the vehicle is at a non-intersection, so we can set $\kappa_{loc} = 1$ and estimate N_{max} is about 92; when $loc = 2$, it indicates that the vehicle is at an intersection, so we can set $\kappa_{loc} = [2R_v + 2(R_v - w_{lane}/2)]/2R_v = 1.965$ and estimate N_{max} is about 180, where w_{lane} is the width of the road and is set to 21m [32]. In conclusion,

$$N_{max} = \begin{cases} N_{non}, & \text{if } loc = 1; \\ 1.965 \cdot N_{non}, & \text{if } loc = 2. \end{cases} \tag{9}$$

C. Backoff Time

In ABM-V, the vehicle utilizes Dempster-Shafer evidence theory to fuse *benefit* and *redundancy* to quantify relay *priority*. Then, the vehicle calculates the backoff time.

The normalized *benefit* and *redundancy* can be viewed as evidence or belief functions for the vehicle to judge its relay priority. The Dempster-Shafer evidence theory can combine pairs of evidence or belief functions to derive a new evidence or belief function [33]. Compared with the Bayesian theory of probability, this method does not rely on prior knowledge, so it is often regarded as an extension of the Bayesian theory and is widely used to deal with uncertain data [34].

1) Construction of Basic Probability Assignments: Basic probability assignments (BPAs) indicate the impact of *benefit* and *redundancy* on relay priority, which are determined by the following three steps.

Firstly, the receiver v_r ascertains a reference value. Specifically, v_r records the number of packets it successfully received as n_r within a fixed time. If $n_r > 1$, it calculates multiple sets of benefit and redundancy and divides them into two sets $\{b_1, b_2, ..., b_{n_r}\}$ and $\{d_1, d_2, ..., d_{n_r}\}$, where $d_i = 1 - r_i$ ($i \in \{1, ..., n_r\}$). This ensures that the relevance of the *benefit* and *redundancy* to *priority* is consistent [35]. Then, v_r gets b_{max}, b_{min}, d_{max}, and d_{min} from the above two sets. If $n_r = 1$, we set $b_{max} = d_{max} = 1$ and $b_{min} = d_{min} = 0$ to prevent the value of *priority* from being fixed at 0.5.

Secondly, v_r ascertains the frame of discernment. For simplicity, in ABM-V, there are two evaluation indices for the influence of *benefit* and *redundancy*: $high$ and low. Thus, the universe $U = (high, low)$ and the frame of discernment $P(U) = \{high, low, high\ or\ low\}$.

Thirdly, v_r creates BPAs for *benefit* and *redundancy*. We define $t_{bi}(h)$ as the degree of trust that v_r has a high priority for packet p_i with *benefit* as evidence. On the contrary, $t_{bi}(l)$ represents the degree of trust that v_r has a low priority for p_i with *benefit* as evidence. Similarly, we define $t_{di}(h)$ and $t_{di}(l)$ with *redundancy* as evidence. Specifically,

$$t_{bi}(h) = \frac{|b_i - b_{min}|}{b_{max} - b_{min} + \alpha}, \tag{10}$$

$$t_{bi}(l) = \frac{|b_i - b_{max}|}{b_{max} - b_{min} + \alpha}, \tag{11}$$

$$t_{di}(h) = \frac{|d_i - d_{min}|}{d_{max} - d_{min} + \beta}, \tag{12}$$

$$t_{di}(l) = \frac{|d_i - d_{max}|}{d_{max} - d_{min} + \beta}, \tag{13}$$

where α and β are adjustment parameters, satisfying $0 < \alpha, \beta \leq 1$. Adjustment parameters ensure that the denominators in the above formulas are not 0. In addition, they can be used to control the influence of the *benefit* and *redundancy* on fusion results. Then, BPAs are obtained as

$$T_{bi} = (t_{bi}(h), t_{bi}(l), t_{bi}(\theta)), \tag{14}$$

$$T_{di} = (t_{di}(h), t_{di}(l), t_{di}(\theta)), \tag{15}$$

where

$$t_{bi}(\theta) = 1 - t_{bi}(h) - t_{bi}(l), \tag{16}$$

$$t_{di}(\theta) = 1 - t_{di}(h) - t_{di}(l), \tag{17}$$

where $\theta = high\ or\ low$; $t_{bi}(\theta)$ and $t_{di}(\theta)$ indicate the degree to which the receiver is not sure whether its relay priority of p_i is high or low.

Algorithm 1 Adaptive Backoff Mechanism

Input:
$P = \{p_1, p_2, ..., p_{n_r}\}$, N, R_v, $Time_{wait}$;
Output:
BT_i;

for p_i in P **do**
  Construct $N_i \subseteq N$ from the ROI of p_i;
  Initialize Be_i, Re_i;
  for v_j in N_i **do**
    Calculate e_{sj}^2 by Eq.(1);
    if $e_{sj}^2 > R_v^2$ **then**
      v_j is added to Be_i;
    else
      v_j is added to Re_i;
    end if
  end for
  Calculate b_i', r_i' by Eq.(4)-(6);
  Calculate b_i, r_i by normalizing b_i', r_i';
  $d_i \leftarrow 1 - r_i$;
end for
Construct two sets $\{b_1, b_2, ..., b_{n_r}\}$ and $\{d_1, d_2, ..., d_{n_r}\}$ from the calculation results;
if $n_r = 1$ **then**
  $b_{max} \leftarrow 1$, $d_{max} \leftarrow 1$, $b_{min} \leftarrow 0$, $d_{min} \leftarrow 0$;
else
  Select b_{max}, b_{min} from $\{b_1, b_2, ..., b_{n_r}\}$;
  Select d_{max}, d_{min} from $\{d_1, d_2, ..., d_{n_r}\}$;
end if
Calculate $t_{bi}(h)$, $t_{bi}(l)$, $t_{di}(h)$, $t_{di}(h)$ by Eq.(9)-(12);
Calculate $t_{bi}(\theta)$, $t_{di}(\theta)$ by Eq.(15)-(16);
Calculate $t_i(h)$, $t_i(l)$ by the Dempsters rule of combination;
$Pri_i \leftarrow t_i(h) - t_i(l)$;
$BT_i \leftarrow (1 - Pri_i) \cdot Time_{wait}$;

2) Calculation of Priority: The willingness of the vehicle to rebroadcast packet p_i is defined as

$$T_i = (t_i(h), t_i(l), t_i(\theta)), \tag{18}$$

where $t_i(h)$, $t_i(l)$ and $t_i(\theta)$ are obtained by the Dempster's rule of combination [35], which is defined as

$$t_i(A) = \frac{1}{1-K} \sum_{B \cap C = A} t_{bi}(B) t_{di}(C), \tag{19}$$

with

$$K = \sum_{B \cap C = \varnothing} t_{bi}(B) t_{di}(C), \tag{20}$$

where A, B, and C are elements of $P(U)$, and K is the conflict coefficient of BPAs. The BPAs and combined results corresponding to all elements in the frame of discernment are shown in Table III.

Referring to [33], we let $t_i(\theta)$ assign to $t_i(h)$ and $t_i(l)$ averagely. Therefore,

TABLE III
THE FUSION RESULTS OBTAINED FROM DEMPSTER-SHAFER EVIDENCE THEORY.

$P(U)$	t_{bi}	t_{di}	t_i
high	$t_{bi}(h)$	$t_{di}(h)$	$t_i(h)$
low	$t_{bi}(l)$	$t_{di}(l)$	$t_i(l)$
high or low	$t_{bi}(\theta)$	$t_{di}(\theta)$	$t_i(\theta)$

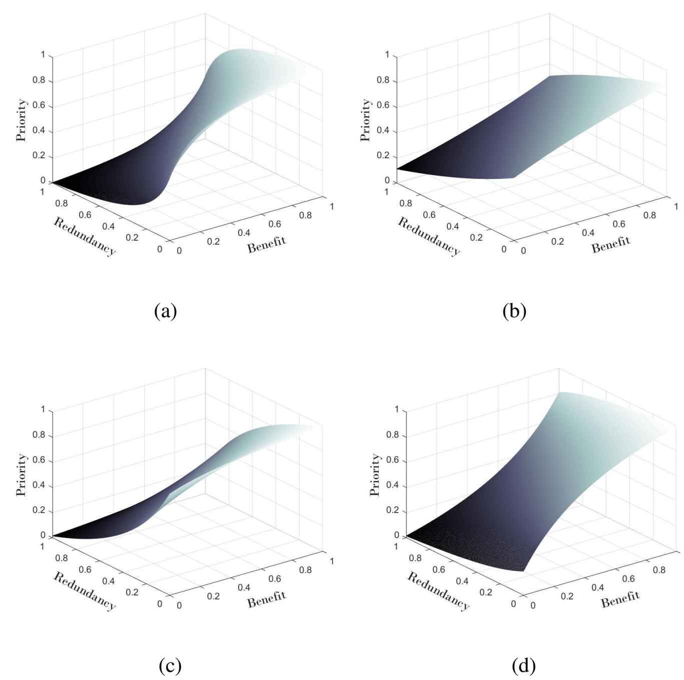


Fig. 6. **The influence of the benefit and redundancy on the priority.** (a) α = 0.1, β = 0.1; (b) α = 0.9, β = 0.9;(c) α = 0.5, β = 0.1; (d) α = 0.1, β = 0.5.

$$T_i(h) = t_i(h) + \frac{t_i(\theta)}{2}, \tag{21}$$

$$T_i(l) = t_i(l) + \frac{t_i(\theta)}{2}, \tag{22}$$

where $T_i(h)$ and $T_i(l)$ are the rebroadcast probability of *high* and *low* for the packet p_i, respectively. Thus, *priority* could be represented by a function associated with $T_i(h)$ and $T_i(l)$:

$$Pri_i = T_i(h) - T_i(l) = t_i(h) - t_i(l). \tag{23}$$

Then, the backoff time of v_r for p_i is defined as

$$BT_i = (1 - Pri_i) \cdot Time_{wait}, \tag{24}$$

where $Time_{wait}$ is the preset maximum backoff time.

3) Fusion Result: Fig.6 illustrates the fusion results of the expected *benefit* and *redundancy* the impact of adjustment parameters on the results.

Firstly, we discuss the fusion results when adjustment parameters are equal. Fig.6(a) illustrates that when $\alpha = \beta = 0.1$, the value of *priority* is positively correlated with *benefit* and negatively correlated with *redundancy*, which means that the receiver with high-benefit and low-redundant will get a higher *priority* and a shorter backoff time. This is in line with the expectation of ABM-V. Then, we increase α and β to 0.9 gradually and find that the fusion results become flat and the value range of the *priority* is decreased (Fig.6(b)). Therefore, we can reduce the probability of vehicles having the same backoff time by setting smaller α and β, which is conducive to reducing V2V collisions.

Secondly, we discuss the fusion results when adjustment parameters are unequal. Fig.6(c) illustrates that when $\alpha = 0.5$ and $\beta = 0.1$, *priority* is more sensitive to changes in redundancy; Fig.6(d) illustrates that when $\alpha = 0.1$ and $\beta = 0.5$, the result is the opposite. Therefore, the influence of *benefit* and *redundancy* in the fusion are determined by α and β.

In the following simulation, we set $\alpha = \beta = 0.1$ to maximize the average difference in the backoff time between vehicles and guarantee that the *benefit* and *redundancy* have the same influence in the fusion.

V. Performance Evaluation

This section analyzes the broadcast performance and additional overhead of ABM-V.

A. Simulation Setup

Similar with the references [4, 8, 16], we use Python in conjunction with SUMO for simulation. SUMO is widely used to simulate realistic vehicle movement. The map in the simulation is Manhattan, New York imported by OpenStreetMap (Fig.7), and its size is 2km $\times$ 2km. In addition, we set the V2V transmission range to 300m [14] and the maximum velocity of vehicles to be 15km/h to 120km/h. In the simulation, a vehicle travels at a constant velocity after reaching the maximum velocity, and this is affected by traffic lights at intersections. If the vehicle encounters a red light, its velocity drops to 0 evenly. When the red light turns green, the vehicle accelerates to the maximum velocity evenly.

Each simulation starts with a random vehicle selected as the broadcast source and ends with no vehicle continuing to rebroadcast. We record the number of times each vehicle receives the packet and the number of times it rebroadcasts the packet. To avoid fluctuation, we get the average results from 200 times experiments and calculate the standard deviation to reflect the dispersion of the results.

We measure the performance from two dimensions: mitigation effect and broadcast reliability. The mitigation effect of the broadcast storm problem has two metrics, rebroadcast ratio and redundancy ratio [4], which measure the transmission overhead and reception overhead, respectively; Reachability measures the proportion of vehicles that receive the packet at the end of the simulation [23].

- **Rebroadcast ratio** = n_b/n_c, where n_b is the number of vehicles that rebroadcast the packet; n_c is the number of vehicles that received the packet.
- **Redundancy ratio** = $1 - n_c/n_p$, where n_p is the total number of the packet that received by vehicles.
- **Reachability** = n_c/n_v, where n_v is the total number of vehicles.

B. Broadcast Performance

We compare ABM-V with multiple existing receiver-based schemes, including GSP [20], DPB [15], and UV-CAST [4]. GSP is a classic fixed-probability scheme in which all vehicles rebroadcast received packets with a preset probability. Compared with GSP, we can analyze the performance difference between the fixed rebroadcast probability scheme and the dynamic rebroadcast probability scheme. DPB and UV-CAST utilize location to calculate the distance between vehicles and dynamically adjust the rebroadcast probability. In general, receivers further away from the sender have a higher rebroadcast probability. However, they only consider the *benefit* of the rebroadcast, ignoring the problem of repeating the same packets received by next-hop neighbors.

In VANETs, the broadcast performance is mainly affected by external and internal factors [2]. External factors include vehicle density and wireless transmission environment; internal factors include vehicle velocity and application requirements. Therefore, we compare the broadcast performance of ABM-V with other schemes from the above four aspects.

1) Impact of Vehicle Density: In VANETs, the vehicle density varies significantly over time and scenarios. For instance, in urban areas, the vehicle density in the morning/evening peaks is significantly higher than that in the early morning. Therefore, the proposed scheme should adapt to different vehicle densities [22]. In the simulation, we control the number of vehicles in the range of 50 to 200.

Fig.8(a) illustrates that as the vehicle density increases, the rebroadcast ratio of ABM-V drops from 52.41% to 31.43%.

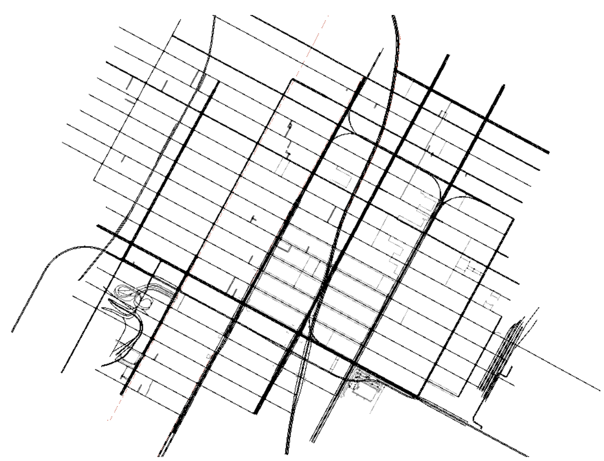
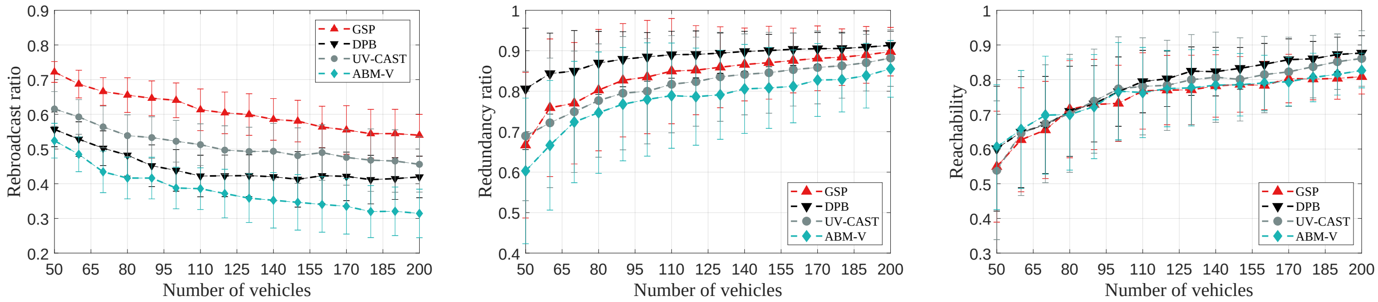
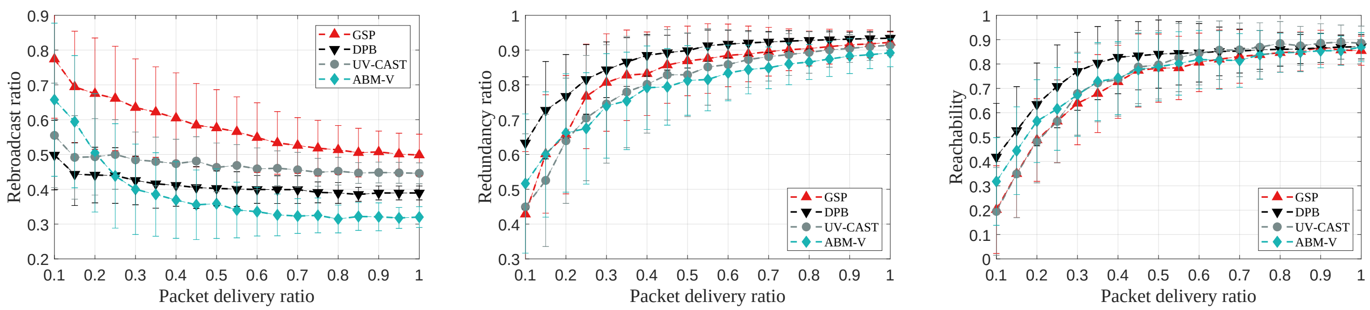


Fig. 7. **The map used in the simulation is Manhattan, New York.**



(a) (b) (c)

Fig. 8. **The impact of vehicle density on broadcast performance.**



(a) (b) (c)

Fig. 9. **The impact of wireless transmission environment on broadcast performance.**

Compared with other three schemes, ABM-V reduces the rebroadcast ratio by at least 2.25%, and this value can reach up to 10.52%, which reduces the transmission overhead. The main reason is that ABM-V is a local optimal relay strategy in which the receiver utilizes a adaptive backoff mechanism to determine that it has the highest relay priority within its transmission range. Therefore, the number of relay vehicles in ABM-V is hardly affected by vehicle density, which makes the rebroadcast ratio drop rapidly with the increase of density.

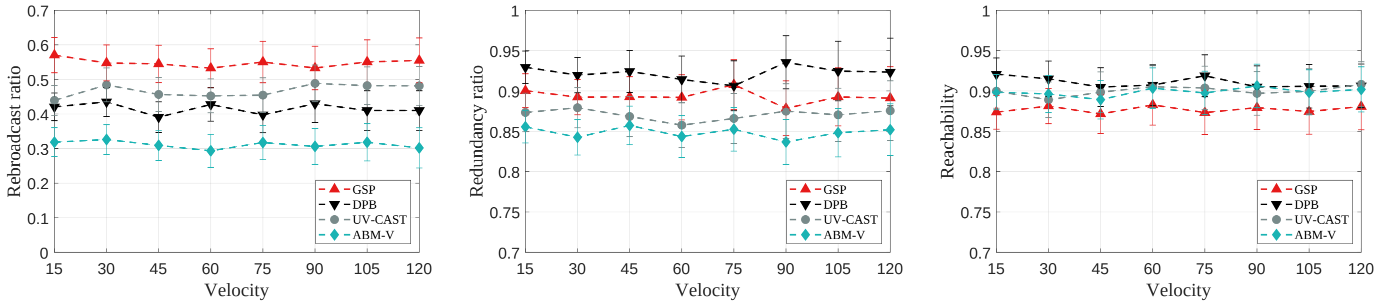
Fig.8(b) illustrates that as the vehicle density increases, the redundancy ratio of ABM-V increases from 60.30% to 85.53%. In a high-density scenario, there may be multiple senders around a vehicle, which increases the probability that the vehicle receives the broadcast packet repeatedly. However, compared with the other three schemes, ABM-V reduces the redundancy ratio by at least 2.53%, and this value can reach up to 6.65%. This is because ABM-V considers the reception status of neighbors, and only receivers with low expected *redundancy* can rebroadcast the packet, which reduces the reception overhead of neighbors.

Fig.8(c) illustrates that as the vehicle density increases, the reachability of ABM-V rises from 60.56% to 82.63%. The main reason is that the average distance between vehicles in high-density scenarios is small, which reduces the probability of link disconnection. The broadcast reachability of the four schemes is similar, which means that ABM-V does not reduce the reliability of broadcasting while reducing transmission overhead and reception overhead.

2) Impact of Transmission Environment: Trees and buildings beside roads in urban areas may cause the non-line-of-sight (NLOS) conditions [14]. Therefore, the proposed scheme should adapt to the complex transmission environment. We set the range of packet delivery ratio (PDR) to be [0.1,1] to simulate different transmission environments.

Fig.9(a) and Fig.9(b) illustrate that as the PDR increases, the rebroadcast ratio of ABM-V decreases from 65.73% to 31.47%, and the redundancy ratio of ABM-V increases from 51.65% to 89.20%. When PDR ≥ 0.25, the performance of ABM-V in these two aspects is the best among all schemes. Fig.9(c) illustrates that as the PDR increases, the reachability of ABM-V rises from 31.78% to 86.95%. Compared with other three schemes, ABM-V does not sacrifice the reachability of broadcasting while reducing the rebroadcast ratio and redundancy ratio. The main reason is that the relay in ABM-V implements a monitoring mechanism and rebroadcasts the packet repeatedly when the link is disconnected.

3) Impact of Vehicle Velocity: Mobility is the most critical property of VANETs [10]. Therefore, we need to ensure that ABM-V can maintain stable performance in different vehicle velocity scenarios. We control the maximum vehicle velocity

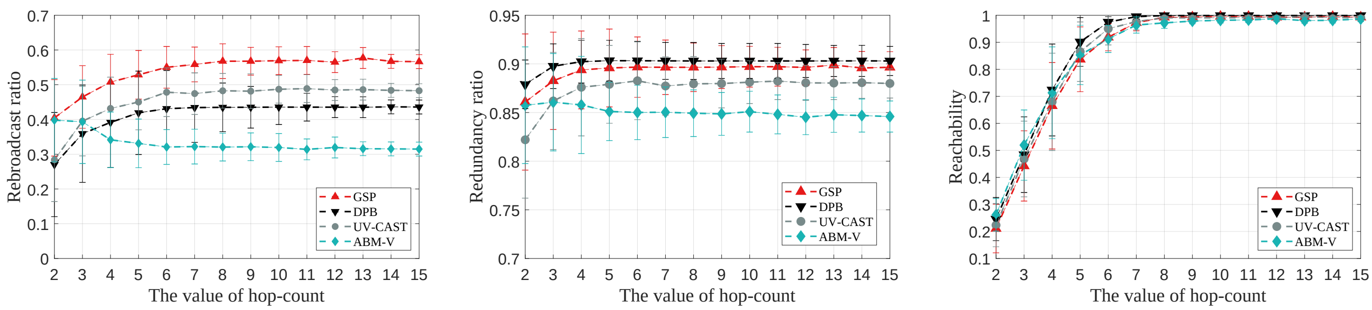


(a)

(b)

(c)

Fig. 10. **The impact of vehicle velocity on broadcast performance.**



(a)

(b)

(c)

Fig. 11. **The impact of application requirements on broadcast performance.**

in the simulation from 15km/h to 120km/h.

Fig.10 illustrates that the overall trend of the average broadcast performance of ABM-V remains stable under different vehicle velocity scenarios. This is due to the fact that the moving speed of vehicles is much lower than the transmission speed of data packets between vehicles. The fluctuations of the results are caused by the different initialization positions of all vehicles in each simulation. Compared with other schemes, ABM-V reduces the broadcast ratio and redundancy ratio by at least 10.38% and 2.21% while only losing 1.15% of reachability at most.

4) Impact of Application Requirements: The expiration time of a packet determines its hop-count [2]. Therefore, the proposed scheme should adapt to the hop-count requirements of different applications, such as the time to live (TTL) in IPv6 packet or expiry time in WAVE short message (WSM) [28]. We discuss the performance of schemes with the value of hop-count in the range of 2-15.

Fig.11(a) illustrates that the rebroadcast ratio of ABM-V decreases and gradually stabilizes with the increase of the hop-count, and its lowest value is 31.40%, which is different from the results of the other three schemes. This is because the growth rate of the number of senders in ABM-V is lower than the number of receivers, but this difference decreases as the value of hop-count increases. Fig.11(b) illustrates that as the value of hop-count increases, the redundancy ratio of ABM-V stabilizes at 84.52% to 86.56%. When the value of hop-count is larger than 3, the performance of ABM-V is better than the other three schemes, because ABM-V avoids redundant reception by considering whether the next hop neighbor has received the same packet. Fig.11(c) illustrates that as the value of hop-count increases, the reachability of ABM-V rises from 26.13% to 98.62%. The reason is that an increase in the hop-count value makes more vehicles receive the packet.

C. Overhead Analysis

In ABM-V, the maximum number of one-hop neighbors N_{max} needs to be synchronized or shared through beacons, which causes additional overhead. In addition, vehicles in ABM-V need to calculate the distance between all neighbors, which increases the one-hop delay. In the following, we discuss that the additional beacon overhead and one-hop delay will not reduce the practicality of ABM-V.

1) Additional Beacon Overhead: According to the analysis in Section IV, the maximum value of N_{max} is about 180. Therefore, the length of the additional field required in the beacon can be calculated as $Add = \lceil log_2 N_{max} \rceil$ = 8 bits = 1 byte, which means that ABM-V can share N_{max} by only adding 1 byte to the beacon. The beacon is usually larger than 200 bytes, and the maximum payload of the MAC layer can

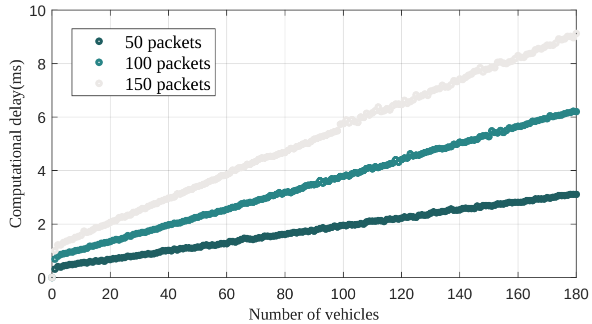


Fig. 12. **Computational delay of ABM-V.**

support is normally above 1,400 bytes [14], so the additional overhead caused by ABM-V is even negligible. In addition, adding extra information in beacons to achieve distributed protocol design is common in VANETs [36–38].

2) Additional Delay: The one-hop rebroadcast delay of the receiver in ABM-V consists of three parts: delivery delay, computational delay, and backoff time. Many studies have shown that the one-hop delivery delay caused by the DSRC protocol is usually less than 2ms [39, 40]. Calculational delay and backoff time is the additional time overhead caused by ABM-V. As similar with that in [3], the maximum backoff time does not exceed 3ms.

Then, we utilize Python to test the computational delay of ABM-V in the Windows environment with i7-9700 CPU and 16G RAM. We test the impact of the number of vehicles and the number of broadcast packets received by the receiver at the same time on the computational delay. Section IV discusses that the maximum number of one-hop neighbors is about 180. [2] indicates that the application of multi-hop broadcast in VANETs is far less frequent than that of one-hop broadcast. Therefore, we test the additional delay caused by ABM-V when the vehicle receives 50, 100 and 150 multi-hop broadcast packets concurrently. In order to avoid fluctuation, we get the average results from 1000 times experiments.

Fig.12 illustrates that the computational delay is proportional to the number of vehicles and the number of broadcast packets. When the number of vehicles is 180 and the number of broadcast packets is 150, the average computational delay for the receiver to execute ABM-V is 9.13ms. Therefore, the one-hop rebroadcast delay of the vehicle in ABM-V is less than 15ms. The minimum lifetime of packets in VANETs is about 500ms [5, 6], so ABM-V almost meets the requirements of all multi-hop-based safety applications and traffic efficiency applications [2].

VI. Conclusion

This paper proposes a broadcast storm mitigation scheme ABM-V in VANETs, in which the receiver comprehensively considers the link quality and the distribution of neighbors to estimate the expected *benefit* and *redundancy* and adjust its backoff time adaptively. To maintain reachability, the receiver records the rebroadcast behavior of the next-hop neighbors through the monitoring mechanism and rebroadcasts the packet again when the link is disconnected. Simulation results illustrate that ABM-V mitigates the broadcast storm by reducing the transmission and reception overheads and maintaining broadcast reachability. In addition, ABM-V adapts to the complex traffic conditions and transmission environment in VANETs and can be applied to most vehicular applications. In the future, we plan to utilize reinforcement learning to adjust parameters α and β to achieve a better fusion effect under different requirements.

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