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A new delay-based broadcast suppression mechanism for efficient emergency messages dissemination in CAVs environment

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ABSTRACT

Network congestion is a major issue affecting communications in Connected and Autonomous Vehicles (CAVs) under high vehicle density scenarios. The common idea used by emergency message broadcast protocols to overcome this challenge is to reduce the number of retransmissions. This is achieved by suppressing redundant retransmissions while maintaining broadcast reliability. In this paper, we analyze the problem of inaccurate suppression of redundant retransmissions in delay-based broadcast protocols and propose uHBS (unHurried Broadcast Suppression), a new more efficient broadcast suppression mechanism. uHBS avoids inaccurate decisions to suppress or forward an emergency message by considering the occurrence of duplicate receptions of this message and using an indication about the channel's busy status. Next, we use the proposed uHBS mechanism as a basis for designing uHBS-DP (uHBS based Dissemination Protocol), a novel delay-based protocol for broadcasting emergency messages in urban vehicular networks. The simulation results show that uHBS-DP, using the proposed broadcast suppression mechanism, significantly improves the efficiency of emergency message broadcasting by ensuring high reliability with low broadcasting overhead, compared to two other variants of uHBS-DP that use conventional suppression mechanisms. Furthermore, the results show a substantial improvement, compared to a well known protocol, in terms of reduced collision ratio (up to 36.57%), lower dissemination delay (up to 19.17%) and reduced broadcast overhead (up to 19.28%).

1. Introduction

Smart transport is one of the main pillars of smart cities that aims to leverage collected real-time traffic data to efficiently manage traffic flow, improve road safety and support sustainable mobility [1]. By combining connectivity and automation technologies, the emerging Connected and Autonomous Vehicles (CAVs) (a.k.a. connected and automated vehicles) technology promises to revolutionize the development of smart transport [2,3]. CAVs use various wireless technologies to communicate with other vehicles (V2V), the infrastructure (V2I), and everything else including smart devices (V2X) [4]. This combination of communication technologies, used depending on the operating context and the target application, allows CAVs to operate safer and smarter by sharing information or alerts on congestion and road safety risks.

Besides improving the traffic efficiency and providing comfort services to users, safety-related applications, which concern human lives, remain the most important applications of smart transport [5]. These applications are mainly based on protocols for distributing or sharing information between vehicles. Certain information, such as traffic density, vehicle position and speed, etc., are shared with neighboring vehicles using periodic messages often called Beacons Messages (BM). Other information, such as emergency reports and post-crash alerts, are carried in messages that need to be forwarded to reach as many vehicles as possible within the region of interest (RoI) with strict low latency and low packet loss requirements [6]. These event-driven messages are called emergency messages (EM). Due to the limited bandwidth available for vehicular communications, these broadcast protocols suffer from higher packet collision rates as the network load increases [7].

To overcome the above congestion problem, EM broadcast protocols use broadcast suppression mechanisms to reduce the additional load due to EMs' retransmissions. This is achieved by suppressing redundant retransmissions while maintaining high reliability level [8]. For this purpose, upon receipt of an EM, these suppression mechanisms manage the contention between forwarding candidates (FCs) to become EM forwarders. Each FC is assigned a priority value to become a forwarder, expressed as either a probability or as a timeout before retransmission [7]. In probabilistic-based suppression mechanisms

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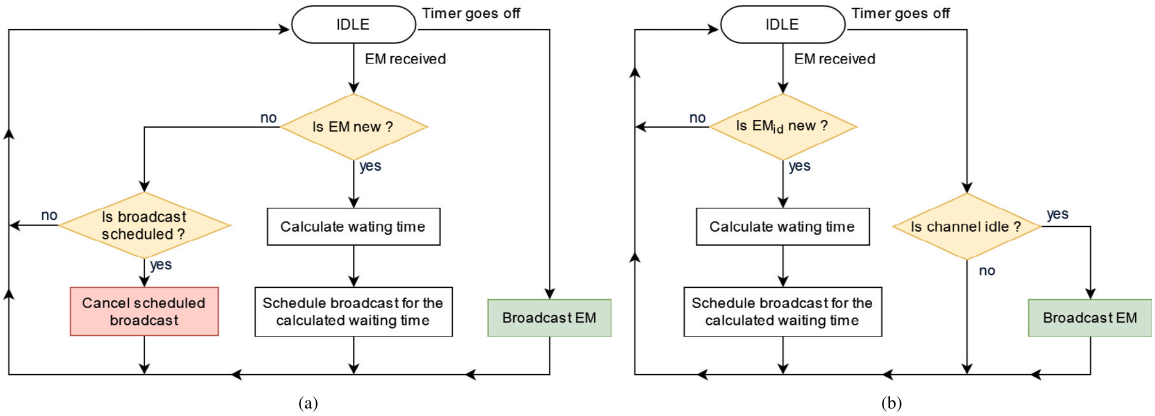


Fig. 1. Broadcast suppression mechanisms. (a) Emergency message broadcast suppression mechanism based on duplicate reception of the same message. (b) Emergency message broadcast suppression mechanism based on channel status.

[9–11], each FC rebroadcasts the received EM according to its assigned retransmission probability. Since the probabilities assigned to the FCs are different, not all of these FCs will rebroadcast the EM. This reduces the number of retransmissions and thus reduces the network congestion. However, delay-based suppression mechanisms [12–14] manage the contention between FCs by assigning them different waiting times before retransmission. Basically, the FC with the shortest timeout gets the highest priority of becoming an EM forwarder. To avoid redundant retransmissions, each FC interrupts its waiting process and cancels the EM retransmission as soon as it considers that this EM has already been rebroadcast.

We can distinguish two cases considered by the existing delay-based broadcast suppression mechanisms that allow an FC to detect the rebroadcast of the EM by a forwarder: (i) after receiving the same message again [8,12,15–18]; (ii) after the expiry of the timeout, if the channel is found busy then a retransmission of the EM is assumed [14,19]. In this work, we first analyze the disadvantages of considering each of these cases in delay-based broadcast suppression mechanisms. Then, we propose a new broadcast suppression mechanism (uHBS: unHurried Broadcast Suppression) that avoids inaccurate decisions to suppress or forward the EMs. In our proposed mechanism, suppression or forwarding decisions take into account the occurrence of duplicate reception of an EM, and an indication, received from the lower layer, about the busy status of the channel. This allows improving retransmission suppression to better control the network congestion without affecting the reliability of the broadcast protocol. Next, we use the proposed broadcast suppression mechanism as a basis for designing a new delay-based protocol (uHBS-DP: uHBS based Dissemination Protocol) for broadcasting EMs in urban vehicular networks. Performance evaluation based on simulation showed that the new broadcast suppression mechanism allows uHBS-DP achieving high reliability with low overhead compared to its variants CSBS-var and EMRBS-var (CSBS-var uses a suppression mechanism based on channel status, whereas in EMRBS-var the suppression decision is made only based on detecting duplicate reception of the same EM). The simulation results also highlight that uHBS-DP is more efficient, in terms of the achieved collision ratio, broadcast overhead and dissemination delay, compared to the well known protocol AddP [12].

The main contributions of this paper can be summarized as follows:

- Analyzing the problem of inaccurate suppression of redundant retransmissions in delay-based broadcast protocols.
- Designing a new broadcast suppression mechanism that improves the suppression of redundant retransmissions compared to conventional mechanisms.
- Developing a novel protocol, based on the proposed new suppression mechanism, for broadcasting emergency messages in urban vehicular networks.
- Performing a rigorous performance evaluation of our proposed broadcast protocol through simulation experiments.

The rest of the paper is organized as follows: In the following Section, we present the main works related to the different delay-based diffusion suppression mechanisms. Section 3 provides a detailed description of our proposed solution. Then, the simulation results are presented in Section 4. Finally, we conclude the work in Section 5.

2. Related work

Reducing congestion in vehicular networks under high vehicle densities scenarios, without affecting application performance, is still a challenging problem. To overcome this challenge in safety-related applications, the state-of-the-art EM broadcast protocols suppress supposedly redundant retransmissions using broadcast suppression mechanisms [8,20]. In this section, we briefly review a selection of delay-based protocols which are directly related to our proposed solution. These protocols can be divided into three main categories:

- EMRBS-based protocols: built upon EM Reception-based Broadcast Suppression mechanism;
- CSBS-based protocols: built upon Channel Status-based Broadcast Suppression mechanism;
- Broadcast protocols based on the RTB/CTB (Request-To-Broadcast/Clear-To-Broadcast) handshake mechanism.

2.1. EMRBS-based protocols

In EMRBS-based protocols (see Fig. 1(a)), when a vehicle receives an EM, it verifies whether the received EM is a duplicate. If the vehicle receives the EM for the first time, and thus becomes an FC, it calculates a waiting time before retransmission, then it schedules the broadcast according to the calculated waiting time. Otherwise, the vehicle returns to the IDLE state after suppressing the already scheduled broadcast, if any. When the waiting time expires, the vehicle broadcasts the EM directly and returns to the IDLE state [8,12,15–18].

To address scalability in vehicular networks, the Efficient multi-directional Data Dissemination Protocol (EDDP) [8] relies on traffic conditions estimation, which is based only on speed data to exploit the speed-density relationship in most traffic flow models: average speed decreases as density increases. This estimation, without relying on BMs, enables EDDP to scale well under high-density scenarios. In the Adaptive Data Dissemination Protocol (AddP) [12], the candidate selection mechanism for message rebroadcast is based on the local density and distance from neighboring nodes. Moreover, AddP uses a disseminated messages monitoring mechanism to detect if a selected forwarder did not rebroadcast a message, and an adaptive beacon congestion control algorithm to reduce the beacon load in high-density scenarios.

In addition to a distance factor, the Road-Casting Protocol (RCP) [15] also considers the link quality when selecting forwarders to avoid choosing vehicles with poor link quality. Its selection mechanism deals with the non-line of sight problem by giving vehicles crossing an intersection more chances of being selected as a next forwarder. In [16], the authors propose a novel broadcast scheme called REMD (Reliable Emergency Message Dissemination scheme). The objective of REMD is to ensure predefined broadcast reliability requirements at each hop. To this end, REMD selects multiple forwarders based on their reception link quality and positions. Furthermore, the forwarders cooperatively perform an optimal number of broadcast repetitions which is determined based on the estimated reception quality of links in the transmission range.

Intelligent Forwarding Protocol (IFP) [17] is built upon a contention window based mechanism. Such a mechanism allows an FC to adjust its own maximum contention window size rather than using a timer that determines the waiting time before rebroadcasting. IFP exploits handshake-less communication, introduces an improved collision resolution mechanism, and uses an acknowledgment process totally independent and decoupled from the message propagation progress. In the clustering-based scheme proposed in [18], the cluster head immediately rebroadcasts the received EM, and a time barrier-based broadcast suppression technique is used by cluster members to handle the broadcast storm problem. This technique gives the farthest vehicle from the sending vehicle more chances of rebroadcasting the received EM.

2.2. CSBS-based protocols

In CSBS-based protocols (see Fig. 1(b)), when a vehicle receives an EM, it verifies whether the received EM is new. In the case of a duplicate reception of the same EM, the vehicle simply discards it and returns to the IDLE state. Otherwise, it becomes an FC, and therefore calculates a waiting time before retransmission, then it schedules the broadcast according to the calculated waiting time. When the timer is triggered, if the channel is detected busy, the vehicle simply returns to the IDLE state considering the channel busy status is due to EM rebroadcasting by another forwarder. Otherwise, it broadcasts the EM and returns to the IDLE state [14,19].

The RObust and Fast Forwarding (ROFF) protocol [14] uses a bitmap that describes the distribution of empty spaces between FCs to avoid unnecessary delays in the contention process. ROFF also avoids collisions due to the wait time difference between adjacent vehicles which may be too short by preventing this difference from being shorter than a lower limit. In [19], the authors propose a sender-based broadcast protocol called AFB (Adaptive Fast Broadcast). To minimize the size of the control information piggybacked in the broadcast message to the FCs, AFB uses an index-based control structure and a street segment of interest partition algorithm.

2.3. RTB/CTB based protocols

In broadcast protocols based on the RTB/CTB handshake mechanism, before transmitting the EM, the current forwarder broadcasts an RTB message. The receiving vehicle of this message, whose location is in the broadcast direction, becomes an FC and therefore participates in a contention phase to be selected as a next forwarder. The portion of road in the broadcast direction and within the transmission range of the current forwarder is divided into segments. Various mechanisms are used to select a potential segment and finally allow a selected vehicle located within that segment to reply to the current forwarder by sending a CTB message [13,21–24].

In the Urban Multi-hop Broadcast (UMB) protocol [21], each FC participates in the contention phase by emitting the black-burst signal (a jamming signal) for a period of time proportional to the distance between its segment and the current forwarder. At the end of this period, the FC verifies the channel status. If the channel is detected idle, then it sends the CTB message. Otherwise, the vehicle exits the contention phase. When several CTB messages are sent, the vehicles that have sent those messages must join a collision resolution phase which finally allows only one vehicle to be selected. After successfully receiving the CTB message, the current forwarder transmits the EM and waits for an acknowledgment (ACK) from the newly selected forwarder. Unlike UMB, the Smart Broadcast (SB) protocol [22] uses a contention resolution phase based on contention windows dimensioning to reduce the rebroadcast delay. The FCs, in each segment, randomly pick a backoff value in the contention window assigned to that segment.

The Binary-Partition-Assisted Broadcast (BPAB) protocol [23] attempts to make the latency constant by introducing a binary partition-based approach. BPAB iteratively partitions the area inside the transmission range. In each iteration, the black-burst is used to eliminate a non-potential segment from further consideration. After a fixed number of iterations, a vehicle in a farthest narrow segment is chosen at random as the next forwarder.

To lower EM transmission delay and reduce message redundancy, Urban Multi-hop Broadcast Protocol (UMBP) [24] includes a novel forwarding vehicle selection scheme that utilizes iterative partition, mini-slot, black-burst, and asynchronous contention mechanisms. UMBP selects remote neighboring vehicles, and then a single forwarding vehicle is successfully chosen by the asynchronous contention among them. Moreover, three broadcast strategies (bidirectional broadcast, multi-directional broadcast, and directional broadcast) are designed according to the positions of the EM senders to quickly select a single forwarder in each road direction to disseminate the received EM. In [13], the complete relay node selection method on the curve road is proposed for fast message delivery and complete coverage of the curve road. Moreover, a metric of the curving rate is defined to describe the bending degree of the curve road quantitatively.

To account for redundant retransmissions problem, the above protocols handle it by using broadcast suppression mechanisms which are based on RTB/CTB hand-shaking, or one of two cases allowing an FC to detect the rebroadcast of the same EM by another forwarder (i.e., simply after receiving the same EM again, or detecting the busy status of the channel after the timeout expires is considered to be due to a retransmission of the EM). Therefore, the focus of this work is to propose a new handshake-free broadcast suppression mechanism (uHBS) that benefits from the two cases mentioned above to avoid inaccurate suppressions. The proposed suppression mechanism will be the basis of a new broadcast protocol (uHBS-DP) for EM dissemination in CAVs environment.

3. Proposed solution

In this section, we analyze the problem of inaccurate suppression of redundant retransmissions. Based on this analysis, we propose a new broadcast suppression mechanism which forms the basis of our new EM broadcast protocol described in detail below. The most important notations used in this paper are also summarized in Table 1.

3.1. Analysis of inaccurate suppression of redundant retransmissions

In delay-based broadcast suppression mechanisms, each FC calculates its delay before forwarding the EM according to a predefined priority. The FC suppresses its scheduled retransmission when it detects a retransmission of the same EM from another forwarder. Therefore, an FC v must wait for WT_v, referring to the waiting time of the FC vehicle v, before forwarding the EM. When two neighboring vehicles f and v (i.e., the distance that separates them is less than the vehicles' transmission range denoted as R) receive an EM for the first time from the sender s, they determine their respective delays (WT_f and WT_v)

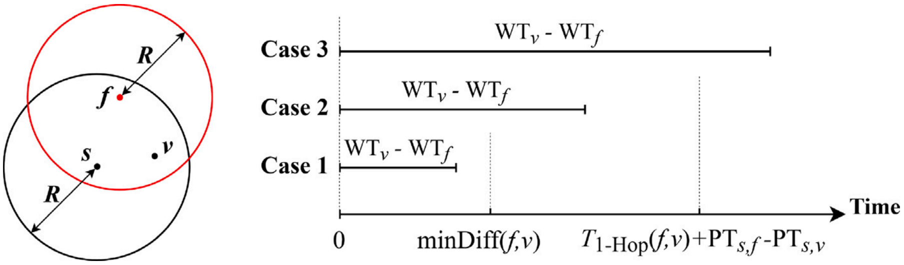


Fig. 2. Illustration of the waiting time difference between adjacent vehicles.

Table 1
Summary of notations.

Notations	Description
BM	Beacon message
CAVs	Connected and autonomous vehicles
CBR	Channel Busy Ratio
CSBS-var	Variant of uHBS-DP that uses the channel status-based broadcast suppression mechanism
EM	Emergency message
EMRBS-var	Variant of uHBS-DP that uses the EM reception-based broadcast suppression mechanism
FC	Forwarding Candidate
IWT_f	The initial waiting time of the FC f before rebroadcasting the EM
$\mathrm{minDiff}(f, v)$	The minimum waiting time difference between neighboring FCs f and v
NB	One-hop neighbors' base
NSB_f	The suitability of the neighboring FC f for broadcasting
$\mathrm{PT}_{s,v}$	The propagation delay between two vehicles s and v
R	Vehicle's transmission range
RoI	Region of interest
$T_{1-\mathrm{Hop}}(s, v)$	The one-hop transmission time between two vehicles s and v
uHBS	unHurried Broadcast Suppression
uHBS-DP	uHBS based Dissemination protocol
VD	Vehicle density
$\mathrm{WT}_{\mathrm{diff}}$	The maximum value of the minimum waiting time difference between neighboring FCs
WT_v	The waiting time of the FC v before rebroadcasting the EM

before forwarding the EM. We assume that $\mathrm{WT}_f \leq \mathrm{WT}_v$, f will not suppress its scheduled rebroadcast and v will receive the retransmission made by f. In order that v detects the transmission signal from f before switching its interface to the transmission mode to forward the EM, a minimum difference of the waiting time between f and v is required. It is denoted $\mathrm{minDiff}(f, v)$ and it is thoroughly studied in [14]. In general, by looking at the difference in waiting times between f and v, we can distinguish the following three cases (see Fig. 2):

- **Case 1** ($\mathrm{WT}_v - \mathrm{WT}_f < \mathrm{minDiff}(f, v)$):
  In this case, the difference in waiting time between f and v does not allow the vehicle v to detect the transmission signal from f before the expiry of its waiting time. In other words, WT_v expires and the vehicle v switches its interface to the transmission mode to forward the EM before the transmission signal of f being detectable. Therefore, v will not suppress its scheduled retransmission.
- **Case 2** ($\mathrm{WT}_v - \mathrm{WT}_f \geq \mathrm{minDiff}(f, v)$) and

  $(\mathrm{WT}_v - \mathrm{WT}_f < T_{1-\mathrm{Hop}}(f, v) + \mathrm{PT}_{s,f} - \mathrm{PT}_{s,v})$:

  where, $T_{1-\mathrm{Hop}}(f, v)$ denotes the one hop delay between f and v (i.e., the time interval separating the transmission of the EM by f and its successful reception by v), $\mathrm{PT}_{s,f}$ is the propagation time between s and f (i.e., the time required for a signal to travel from the source s to the destination f) and $\mathrm{PT}_{s,v}$ is the propagation time between s and v.

  In this second case, when its waiting time expires, v could detect the transmission signal from f by checking the status of the channel, which should be shown as busy. At this time, the reception of the EM by v has not been completed yet. Therefore, relying on the busy status of the channel only does not allow a vehicle to affirm that it is receiving the same EM previously received, thus it cannot accurately suppress the scheduled rebroadcast.
- **Case 3** ($\mathrm{WT}_v - \mathrm{WT}_f \geq (T_{1-\mathrm{Hop}}(f, v) + \mathrm{PT}_{s,f} - \mathrm{PT}_{s,v})$):
  In this third case, the vehicle v completes the reception of the EM rebroadcast by f before the expiry of its waiting time. Thus, the scheduled rebroadcast of the EM by v will be suppressed.

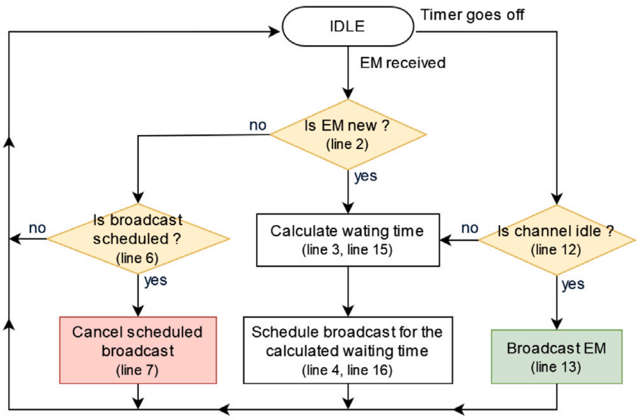
Therefore, the above analysis of the difference in waiting times between two adjacent FCs must be taken into consideration when designing an efficient suppression mechanism.

3.2. New broadcast suppression mechanism

In the existing broadcast suppression mechanisms, an FC assumes that a rebroadcast is performed by another forwarder either after having received once again the same EM [8,12,15–18], or it considers that the busy status of the channel after the expiry of its waiting time is due to a rebroadcast of the same EM [14,19]. However, using the duplicate reception of the same EM as the only criterion to suppress the scheduled rebroadcast makes the FCs hasty in their forwarding decision as the EM reception might still in progress. On the other hand, considering that the busy status of the channel is due to a rebroadcast of the same EM previously received is not always correct even with a channel fully dedicated to the transmission of EMs. This is because several EMs can be broadcast at the same time, which leads to inaccurate hasty broadcast suppression.

To avoid that the FCs are hasty in making the forwarding or the rebroadcast suppression decision of the EMs, we propose a new broadcast suppression mechanism (uHBS: unHurried Broadcast Suppression). Our proposed mechanism exploits the duplicate reception of the EM in addition to a channel-busy indication metric received from the MAC (Medium Access Control) layer.

The flowchart and algorithm shown in Fig. 3 highlight the operation of the proposed uHBS mechanism. When an FC receives an EM for the first time (line 2), it calculates an initial waiting time before retransmission (line 3), then it schedules the rebroadcast of this EM according to the calculated waiting time (line 4). Alternatively, if this EM is previously received (line 5), the receiver vehicle suppresses its already scheduled rebroadcast (line 7), if any (line 6). Moreover, an FC should not make a final decision to forward the EM when its waiting time expires, but instead it checks the channel status as well. Thus, if the channel is detected idle (line 12), the FC broadcasts the EM (line 13). Otherwise, it delays its rebroadcast (lines 15 and 16) and therefore postpones its forwarding decision. The purpose of this delay is to take into consideration the case where an EM reception has not been completed yet to avoid making inaccurate/wrong forwarding decisions. This will also further improves the broadcast suppression efficiency because delaying the retransmission increases the probability of receiving the same EM once again. The calculation of the initial waiting time



(a)

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Algorithm 1 Unhurried broadcast suppression mechanism
Notations:
EM: Emergency message received.
 1: procedure EM-Received(EM)
 2:     if $EM_{id}$ is new then
 3:         Calculate the initial waiting time
 4:         Schedule the EM broadcast   // Set a timer for the calculated waiting time
 5:     else
 6:         if EM broadcast is scheduled then
 7:             Cancel the EM broadcast   // Terminate the EM broadcast timer
 8:         end if
 9:     end if
10: end procedure

11: procedure TimerGoesOff(EM)
12:     if The channel is detected idle then
13:         Broadcast EM
14:     else
15:         Calculate the added waiting time
16:         Schedule the EM broadcast   // Set a timer for the calculated waiting time
17:     end if
18: end procedure
```

(b)

Fig. 3. Illustration of the proposed uHBS mechanism. (a) Flowchart. (b) Algorithm.

and the delay value must take into account the analysis presented in Section 3.1. In the next section, we present the detailed operation of our broadcast protocol based on the new proposed suppression mechanism.

3.3. Emergency messages dissemination protocol

To ensure an efficient broadcast of EMs, we present in this section a new delay-based broadcast protocol (uHBS-DP: uHBS based Dissemination Protocol) that uses the new suppression mechanism proposed in the previous section (uHBS). We first present the design principles of uHBS-DP, then we describe in detail its next forwarder selection scheme.

3.3.1. Design principles

uHBS-DP is designed based on the following assumptions: (1) each vehicle is equipped with a GPS (Global Positioning System) receiver that allows it to get its position information. (2) The transmission range is the same for all the vehicles. (3) Each vehicle maintains a local knowledge base (neighborhood base, denoted as NB), that contains the information exchanged between neighbors using the BMs. These periodic messages contain the current GPS position, the local density perceived by neighboring vehicles (i.e. the size of its NB), and other relevant information for neighborhood awareness purpose.

In order to reduce redundant retransmissions and channel access conflicts, and thus address the problem of broadcast storm, uHBS-DP selects at each hop a limited number of vehicles to forward an EM. This selection mechanism is hybrid as it combines a selection made by the sender with a contention, based on a timeout, between the message receivers. In addition, uHBS-DP uses the uHBS mechanism described in the previous section. This mechanism allows any FC to delay its retransmission if it detects that the channel is busy when the timeout expires, and to make the final decision to suppress the rebroadcast only when it receives the same EM once again. Hereafter, we discuss the next forwarder selection scheme adopted in uHBS-DP.

3.3.2. Next-forwarders selection scheme

To reduce dissemination delays and improve the delivery ratio of the broadcast message, the sender vehicle of an EM uses the Euclidean distance and the local density of neighboring vehicles to select the most suitable next forwarder. The position of a vehicle, taken into account when calculating distances, and its local density are information shared between neighbors using BMs. For each neighbor vehicle f, the sender vehicle s calculates a Neighbor Suitability for Broadcasting value, denoted as NSB_f, using Eq. (1).

$$\mathrm{NSB}_f = \begin{cases} \frac{\min(d_{s,f}, R)}{R} + \mathrm{Dy}_f & \text{if}\left(d_{s,f} > \frac{R}{4}\right) \\ \frac{d_{s,f}}{R} & \text{otherwise} \end{cases} \tag{1}$$

where $d_{s,f}$ is the distance between s and f, and Dy_f is the local density perceived by the vehicle f.

The neighbor vehicle with the highest NSB value will be selected as the most suitable next forwarder. For neighbor vehicles with a distance greater than a quarter of the transmission range, the local density is the main factor in the calculation of their NSB_f values, while the distance, $d_{s,f}$, is used to prioritize the furthest vehicle among the vehicles with the same local density. However, the local density is not considered as a selection factor for other neighbor vehicles (i.e., vehicles with a distance less than a quarter of the transmission range). This avoids increasing the number of broadcast hops by selecting a very close neighbor, which in turn increases the broadcast delay. The result of this first selection phase is added to the EM before its retransmission.

In the second selection phase of uHBS-DP, each receiver of an EM is an FC. It rebroadcasts the message if it has not received it once again from another neighbor vehicle before the expiry of its waiting time. This latter consists of an initial waiting time to which are added eventual delays caused by the occupation of the channel. The initial waiting time of an FC f before rebroadcast, denoted as IWT_f, is calculated according to the result of the first selection phase using Eq. (2).

$$\mathrm{IWT}_f = \begin{cases} 0 & \text{if}(f = \mathrm{EM}_{\mathrm{SFC}}) \\ \mathrm{Random}[0, \mathrm{IWT}_{\max}] & \text{if}(\mathrm{EM}_{\mathrm{SFC}} = \mathrm{Null}) \\ \mathrm{Random}[\mathrm{WT}_{\mathrm{diff}}, \mathrm{IWT}_{\max}] & \text{otherwise} \end{cases} \tag{2}$$

uHBS-DP allows the FC selected by the sender ($\mathrm{EM}_{\mathrm{SFC}}$) to start the retransmission without any delay (i.e., the initial waiting time is zero). For other receivers, the initial waiting time is less than the $\mathrm{IWT}_{\max}$ parameter. It must also be, if another FC is selected by the sender, long enough so that the transmission signal of the selected forwarder can be detected before its expiry. The calculation of this minimum waiting time, denoted as $\mathrm{WT}_{\mathrm{diff}}$, is similar to that of the minimum difference of waiting time between two adjacent FCs (i.e., $\mathrm{minDiff}(f, v)$) [14]. The difference is that we want to compute a maximum threshold for two neighbor FCs. $\mathrm{WT}_{\mathrm{diff}}$ is calculated according to Eq. (3).

$$\mathrm{WT}_{\mathrm{diff}} = 2\mathrm{PT}_{\max} + T_{\mathrm{Rx/Tx}} + T_{\mathrm{CCA}} \tag{3}$$

where $\mathrm{PT}_{\max}$ is the maximum propagation time between two neighbor vehicles, i.e., the propagation time between two vehicles where the distance between them is the transmission range R; $T_{\mathrm{Rx/Tx}}$ is the transition time of the PHY layer from the receiving state to the transmitting state (called Rx/Tx turnaround time); and T_{CCA} is the required time to access the transmission channel and determine if it is available (CCA: Clear Channel Assessment).

When delaying a rebroadcast due to channel occupancy, the FCs postpone its rebroadcast by a delay of $T_{1-\mathrm{Hop}}$. $T_{1-\mathrm{Hop}}$ denotes the delay of a hop between two vehicles separated by a distance equals to R [25]. This delay value allows, before its expiry, completing the reception of the message in progress. Consequently, this message will be taken into consideration in the EM's forwarding decision.

4. Performance evaluation

In order to evaluate the performance of our uHBS-DP protocol, we conducted a series of simulation experiments. The performance evaluation takes place in two stages. First, we show the gain obtained by using the proposed new suppression mechanism. In this step, uHBS-DP is compared to two of its variants that use conventional broadcast suppression mechanisms. The first variant, named CSBS-var, uses a Channel Status-based Broadcast Suppression mechanism, whereas the suppression mechanism of the second variant, named EMRBS-var, is based only on receiving once again the same EM (EM Reception-based Broadcast Suppression mechanism). In the second step, we compare uHBS-DP to a state of the art protocol known to be efficient, i.e., AddP [12]. In addition to its efficiency, the choice of the AddP protocol is also motivated by its design characteristics which are similar to those of our uHBS-DP protocol. Both protocols are beacon-assisted, use hybrid selection mechanisms (i.e., the decision on the priority to become a forwarder is shared between the sender and receiver), and are designed to work in urban scenarios. In what follows, Section 4.1 presents the simulation environment and parameters. The performance metrics considered for the evaluation are presented in Section 4.2. Finally, Section 4.3 describes and analyzes the obtained simulation results.

4.1. Simulation setup

To conduct our evaluation in a realistic simulation environment, we used the road traffic simulator SUMO (Simulation of Urban Mobility) [26] with a 3.6 km^2 portion of the Manhattan road network (Fig. 4) imported from OpenStreetMap.[1] We also used the vehicle network simulation framework Veins (Vehicles in Network Simulation) [27], which bi-directionally couples the road traffic simulator SUMO with the network simulator OMNeT++ [28], allowing them to communicate at runtime via the TraCI (Traffic Control Interface) protocol. We kept the specified speed limits for each lane or road in the network imported into SUMO from OpenStreetMap. SUMO uses Krauss' car-following model by default to calculate the safe speed for each vehicle to avoid car-to-car collisions [29]. Veins includes IEEE 802.11p DSRC/WAVE stack models designed for use in vehicular networks. In our simulations, we activated an obstacle shadowing model that was calibrated and validated against real measurements [30]. Also, the Nakagami-m fading model is enabled to reflect multipath propagation in urban environments [14]. We further adjusted the transmit power and receiver sensitivity to obtain a transmission range of approximately 330 meters which is representative of vehicular networks [31].

Usually, the Channel Busy Ratio (CBR) is seen as the result of the different densities of vehicles without taking into account the exchanged traffic load, other than the BMs. In our simulations, we decoupled the Vehicle Density (VD) and CBR parameters by simulating the network load of exchanged messages. This allowed us to evaluate scenarios where vehicle density is low while the CBR is high and also scenarios where vehicle density is high but not necessarily with high CBR. Table 2 outlines the main simulation parameters and their corresponding values.

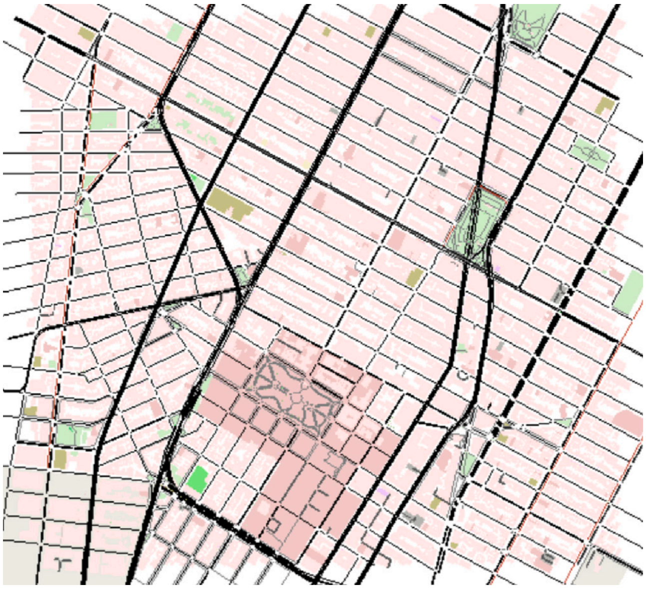

Fig. 4. Illustration of the Manhattan road map used in the evaluation.

Table 2
Simulation setting.

	Parameter	Value
IEEE 802.11p	Channel data rate	6 Mbps
	Transmission power	16 mW
	Receiver sensitivity	−88 dBm
	Noise	−98 dBm
	Path loss model	Free-space
	Shadowing model	Obstacle model
	Multi-path propagation	Nakagami-m fading
	CCAThreshold	−65 dBm
	Maximum interference distance	1000 m
DSRC/WAVE	EM size	128 bytes
	BM size	32 bytes
	Beacon interval	0.1 s
uHBS-DP	T_{1-Hop}	247 μs
	WT_{diff}	15 μs
	WT_{max}	2 ms
Scenario	Urban area scenario	Manhattan city
	Region of interest	1900 m × 1900 m
	Vehicle density	250, 500 and 750 veh./km^2
	Channel busy ratio	10%, 20%, 30% and 40%
	Simulation time	0.3 s with a warm-up period
	Number of repetitions	10
	Confidence level	95%

4.2. Performance metrics

To evaluate uHBS-DP in terms of its scalability, reliability, generated overhead, and efficiency, we evaluated the following four performance metrics under different CBRs and vehicle densities:

- Collision Ratio (CR): CR is used to measure the channel contention level. It is defined as the ratio of the total number of packets lost during transmission to the overall number of packets transmitted by all vehicles. The minimization of CR aims to solve or minimize the negative effect of the broadcast storm problem.

$$\mathrm{CR} = \frac{\text{number of Rx/Tx lost packets}}{\text{number of transmitted packets by all vehicles}} \tag{4}$$

- Delivery Ratio or success ratio (DR): this metric measures the proportion of vehicles in the region of interest that successfully receive the EM [7]. Reliable protocols for broadcasting EMs must

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[1] openstreetmap.org.

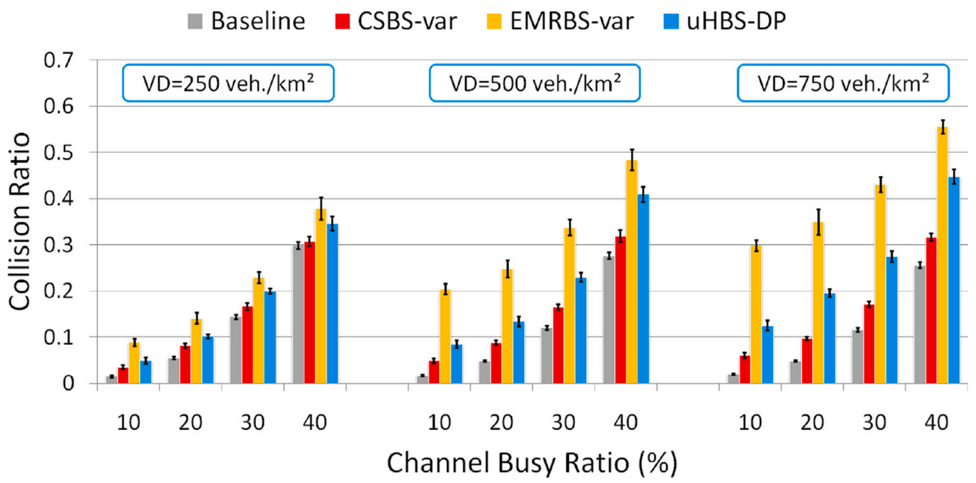

Fig. 5. Comparison of the achieved collision ratio by the uHBS-DP protocol and its two variants: EMRBS-var and CSBS-var.

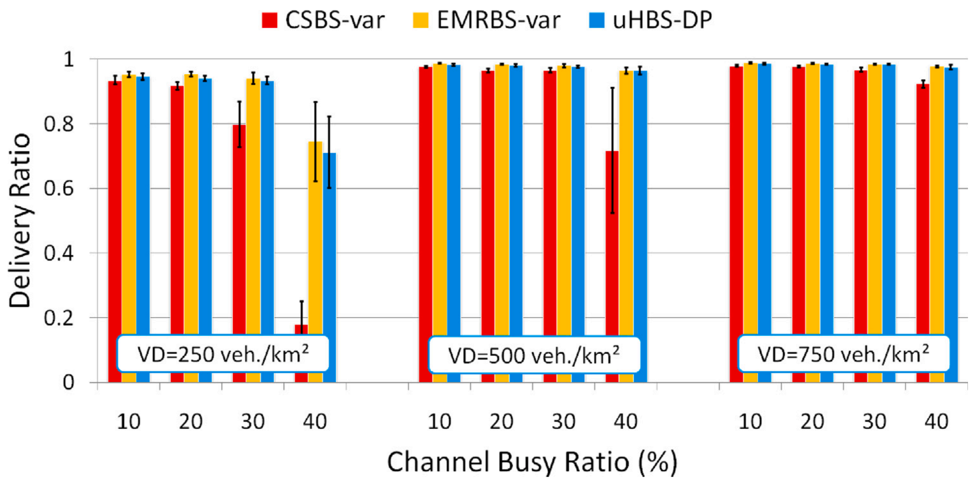

Fig. 6. Comparison of the achieved delivery ratio by the uHBS-DP protocol and its two variants: EMRBS-var and CSBS-var.

achieve a high delivery ratio.

$$DR = \frac{\text{number of vehicles successfully receiving EM}}{\text{number of vehicles in the RoI}} \quad (5)$$

- Broadcast Overhead (BO): for a source EM broadcast in the network, BO calculates the ratio of the total number of EMs inserted in the network to the number of vehicles that successfully received the message. This metric enables measuring the average cost for informing a single vehicle.

$$BO = \frac{\text{number of EM transmitted by all vehicles}}{\text{number of vehicles successfully receiving EM}} \quad (6)$$

- Dissemination Delay (DD): this is the average time required for an EM to travel from the origin vehicle to other vehicles in the region of interest [12]. Efficient broadcast of EMs requires a short dissemination delay.

$$DD = \text{average}(\text{EM reception time} - \text{EM initial time}) \quad (7)$$

4.3. Simulation results

In this section, we first analyze the comparison results of our uHBS-DP protocol against its two variants CSBS-var and EMRBS-var according to CR, DR, and BO metrics (Figs. 5–7), then we discuss the comparison results of uHBS-DP against the AddP protocol according to CR, DR, BO, and DD metrics (Figs. 8–11).

Fig. 5 shows the collision ratio for different CBRs and different vehicle densities. This ratio gives, for each vehicle, the average number of packets that are not successfully decoded for each transmitted packet, which indicates the channel contention level. In addition to the collision ratio of uHBS-DP and its two variants, Fig. 5 also shows the collision ratio without EM broadcast which represents the baseline for comparing the collision ratios of the other protocols. We can clearly observe an increasing trend in the collision ratio of all protocols (i.e., uHBS-DP, CSBS-var, and EMRBS-var) as a function of vehicle density for a given CBR, as well as an upward trend as a function of CBR for a given vehicle density. The vehicle density in the network is proportional to the average one-hop neighbor density observed by a single vehicle (i.e., the local vehicle density), and the CBR reflects the message load caused by neighboring vehicles, so increasing either parameter increases the collision ratio due to channel contention.

The EMRBS-var variant uses a suppression mechanism based solely on the duplicate reception of the same EM, which makes FCs' forwarding decision hasty because a duplicate reception might be still in progress and not terminated yet. Therefore, the collision ratio of EMRBS-var is the highest among all protocols, regardless of the CBR and network vehicle density. In our uHBS-DP protocol, an FC does not make the final decision to forward the EM when its waiting time expires if it detects that the channel is busy at that time. Instead, the FC defers its forwarding decision to take into account the message whose reception has not completed yet. This allows uHBS-DP to improve broadcast suppression and thus leads to an average collision rate

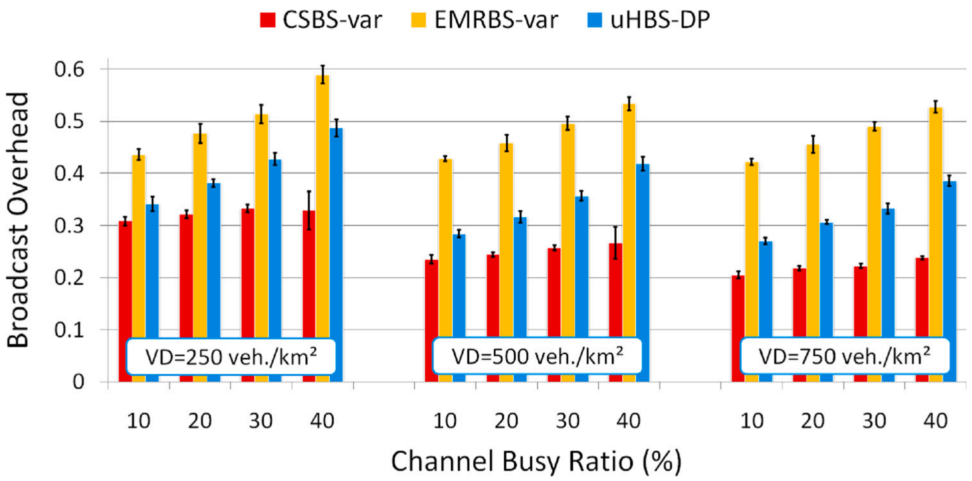

Fig. 7. Comparison of the achieved broadcast overhead by the uHBS-DP protocol and its two variants: EMRBS-var and CSBS-var.

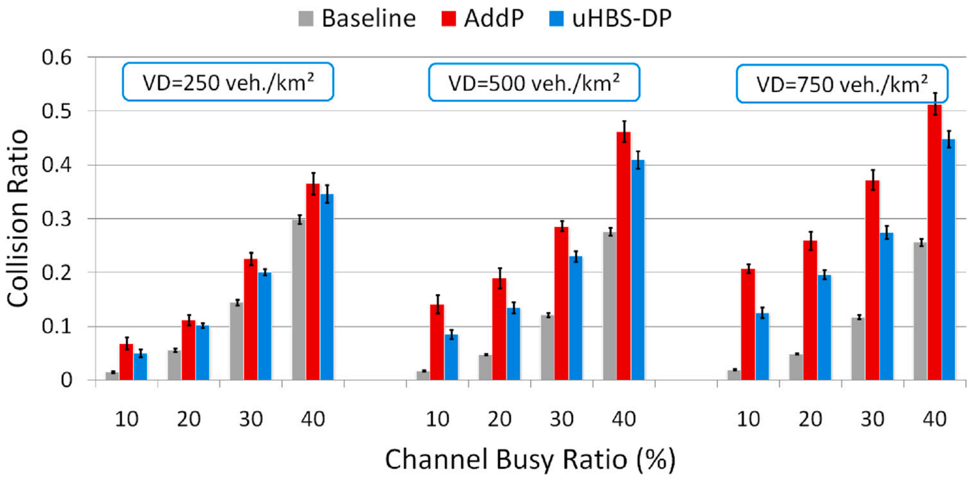

Fig. 8. Collision ratio: AddP vs. uHBS-DP.

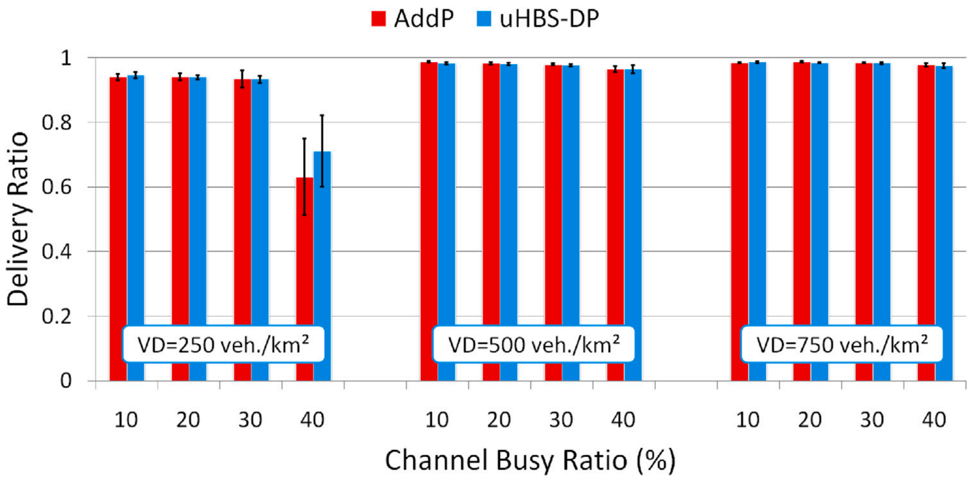

Fig. 9. Delivery ratio: AddP vs. uHBS-DP.

reduction, compared to EMRBS-var, of 43.86%, 51.50% and 49.72% at densities of 250, 500 and 750 veh/km^2 respectively.

In the CSBS-var variant, the suppression mechanism is based on the channel status. Each FC suppresses its scheduled rebroadcast if, after the expiry of its timeout, the channel status is detected to be busy. Therefore, compared to EMRBS-var and uHBS-DP protocols, CSBS-var has the lowest collision ratio. However, assuming that the busy channel status is always due to a rebroadcast of the same EM leads to inaccurate broadcast suppression. These hasty suppressions affect the reliability of the broadcast, which is reflected by the achieved low delivery ratio

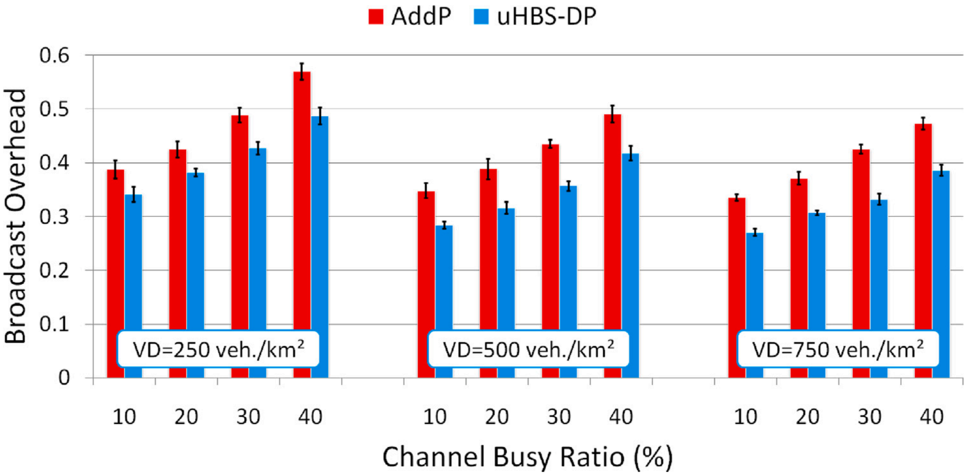

Fig. 10. Broadcast overhead: AddP vs. uHBS-DP.

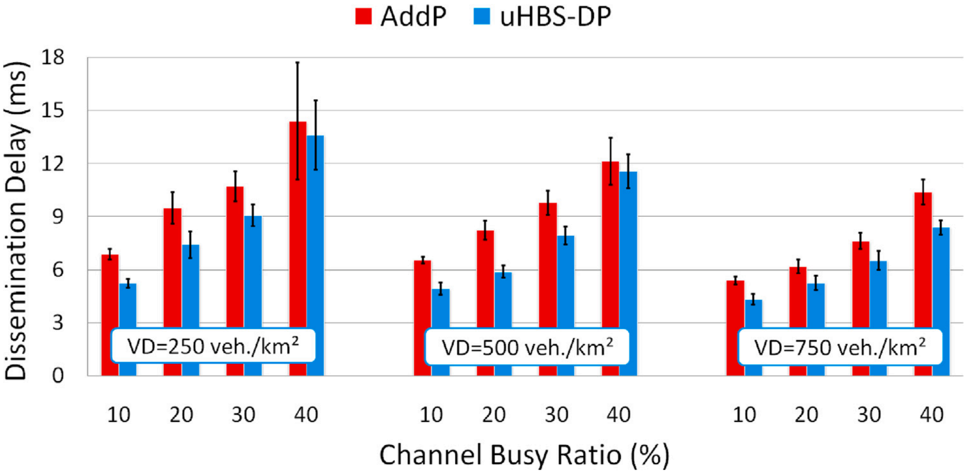

Fig. 11. Dissemination delay: AddP vs. uHBS-DP.

compared to other protocols (see Fig. 6), and it also explains the low broadcast overhead in terms of the number of retransmissions required to deliver an EM to a single vehicle (see Fig. 7).

We can also observe in Fig. 6 that the delivery ratios of EMRBS-var and uHBS-DP protocols are similar in all experiments with a small advantage for EMRBS-var. This can be explained by the very high broadcast overhead generated by EMRBS-var compared to that of uHBS-DP as shown in Fig. 7. The average improvement obtained by uHBS-DP in terms of broadcast overhead reduction compared to EMRBS-var is 18.99%, 28.56% and 31.95% at densities of 250, 500 and 750 veh./km^2 respectively.

From the results of these first simulation experiments, we can notice that CSBS-var has the lowest collision ratio, as well as the lowest broadcast overhead in terms of number of retransmissions compared to EMRBS-var and uHBS-DP. However, these performances were achieved at the expense of the protocol reliability. On the other hand, EMRBS-var guarantees high broadcast reliability similar to that of uHBS-DP but with the highest collision ratio and the highest broadcast overhead in terms of number of retransmissions. Thus, compared to its CSBS-var and EMRBS-var variants, uHBS-DP is the protocol that provides high reliability with low broadcast overhead, and thus the best reliability/overhead ratio.

Now, we analyze the comparison results of uHBS-DP protocol against the state-of-the-art AddP protocol [12]. In addition to the collision ratio of AddP and uHBS-DP, Fig. 8 also shows the collision ratio in a baseline test without broadcasting EMs. As with uHBS-DP, AddP's collision ratio has an increasing trend with vehicle density for a given CBR, and also with CBR for a given vehicle density. However, the suppression scheme used by uHBS-DP allows it to mitigate channel contention and thus reduce the collision ratio by avoiding hasty decisions to forward the EM. At densities of 250, 500 and 750 veh./km^2, uHBS-DP reduces the collision ratio on average compared to AddP by 28.42%, 36.57% and 34.36% respectively.

Fig. 9 depicts the delivery ratio of AddP and uHBS-DP for different CBRs and vehicle densities. We can observe that the achieved delivery ratio is negatively affected for both protocols as vehicle density decreases, and this effect becomes more significant when the CBR increases. This is expected, because the efficiency of the forwarders selection schemes, used in both protocols, decreases under low vehicle density scenarios as intermittent disconnections are more frequent in this case, resulting in poor EM delivery ratio. In addition, the high CBR in this case further deteriorates the performance of the selection schemes due to packet losses caused by the incurred collisions. We can also observe that the performance achieved by both protocols is similar in all experiments with a small advantage for uHBS-DP, despite its low broadcast overhead compared to that of AddP, as shown in Fig. 10. This means that our protocol suppresses redundant retransmissions more efficiently compared to AddP and thus ensures high broadcast reliability with low overhead. The average improvement obtained by uHBS-DP in terms of broadcast overhead reduction compared to AddP is 12.30%, 17.44% and 19.28% at densities of 250, 500 and 750 veh/km^2 respectively.

In addition to reliability, the broadcast of EMs also requires a short dissemination delay. Fig. 11 shows that the dissemination delay of our uHBS-DP protocol is better compared to AddP in all experiments, regardless of the CBR and vehicle density in the network. This improvement, achieved by uHBS-DP, is due to its more efficient redundant retransmission suppression mechanism that mitigates channel contention and thus reduces the number of hops to reach the intended receivers. At densities of 250, 500 and 750 veh./km^2, uHBS-DP reduces the dissemination delay on average compared to AddP by 16.65%, 19.17% and 17.21% respectively.

5. Conclusion

Due to the limited bandwidth available for vehicular communication, EM broadcasting requires an efficient mechanism to suppress redundant retransmissions to reduce channel congestion while ensuring reliable broadcasting. In this paper, we propose uHBS-DP, a new delay-based protocol for EM broadcasting. uHBS-DP is built upon a new redundant retransmission suppression mechanism (uHBS) that allows FCs to make the decision to forward the EM or to suppress the broadcast by exploiting both the duplicate reception of the same EM and an indication of the channel status received from the lower layer, and thus to avoid making hasty decisions. The performance evaluation results showed that the new broadcast suppression mechanism allows uHBS-DP to provide high reliability with low broadcast overhead compared to its CSBS-var and EMRBS-var variants. These results also highlight that uHBS-DP outperforms the state-of-the-art AddP protocol in terms of the achieved collision ratio, delivery ratio, broadcast overhead and dissemination delay.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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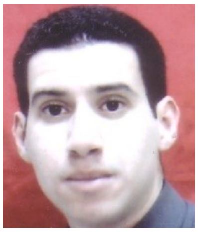

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