

RESEARCH

Open Access



A hybrid access method for broadcasting of safety messages in IEEE 802.11p VANETs

Xiaoying Lei¹ , Xiangjin Chen¹ and Seung Hyong Rhee^{2*}

*Correspondence:
rhee@kw.ac.kr

² Department of Electronics
Convergence Engineering,
Kwangwoon University,
Seoul, Korea
Full list of author information
is available at the end of the
article

Abstract

Vehicular Ad-hoc Networks (VANETs) can improve the road safety by transmitting safety-critical messages such as beacons and emergency messages. IEEE 802.11p VANETs have adopted the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism for the multiple access control. The 802.11p media access control (MAC) protocol, however, can not guarantee the reliability of broadcasting data, since the reception of transmitted messages are not acknowledged. Moreover, the backoff scheme of the 802.11p MAC utilizes a fixed-size contention window for safety message broadcasting, which causes high collision probabilities especially in dense environments. In order to improve such drawbacks, we propose a hybrid access method as follows: Nodes are equipped to reserve time slots for the next round of broadcasting, while unoccupied time slots are preserved for those which have emergency needs. In addition, implicit feedbacks are enabled for detecting collisions incurred during random channel accesses in preserved time slots. We devise a mathematical model which optimally controls the parameters of our scheme while minimizes the cost caused by idle channels and collisions. Extensive simulations show that our mechanism can remarkably improve the performance of VANETs in broadcasting of the safety messages.

Keywords: VANETs, IEEE 802.11p, MAC protocol, Broadcasting of safety message, Resource reservation

1 Introduction

Vehicular Ad-hoc Networks (VANETs) provide safety services by allowing vehicles to transmit safety-critical messages periodically [1]. The Wireless Access in Vehicular Environments (WAVE) standard which consists of the IEEE 1609 family and IEEE 802.11p [2–4] specifies most of the key technologies adopted by the VANETs. According to the IEEE 1609 standard, seven channels are allocated to VANETs, including one control channel (CCH) and six service channels (SCHs). The channel access time is divided into consecutive synchronization intervals, called Synchronization Intervals (SIs). Each SI has a fixed length of 100 ms and splits into two alternating 50 ms intervals - control channel interval (CCHI) and service channel interval (SCH). During the CCHI, vehicles broadcast safety messages periodically for the purpose of advertisement, beacons, cooperative awareness, and etc.

The IEEE 802.11p standard focuses on the technologies adopted by the physical (PHY) as well as the media access control (MAC) layers of the VANETs. The media access method of the 802.11p MAC is basically the same as the 802.11 distributed coordination function (DCF), which is a CSMA/CA mechanism [5]. In order to provide prioritized channel access, the 802.11p MAC protocol is extended by incorporating enhanced distributed channel access (EDCA) mechanism, where the nodes with higher priority traffics contend to access channel by adopting a smaller contention window. However, the 802.11p MAC protocol loses efficiency in broadcasting of safety messages. First, the EDCA is known to be ineffective in providing strict prioritization, particularly, it becomes useless when the traffic has only one type of safety messages [6]. Second, since the reception of transmitted messages are not acknowledged, the reliability of the safety message broadcasting cannot be guaranteed. Finally, the MAC protocol adopts a random backoff scheme that may cause a high collision probability due to the fixed contention window, i.e., in dense networks vehicles tend to choose the same backoff-counters (BCs).

Many previous works have proposed solutions to enhance the performance of the backoff mechanism adopted by the 802.11 MAC protocol [7–11]. In [7], stations are equipped to piggyback randomly selected BCs in ongoing packets, in order to reserve BCs for following transmissions. However, since the values of the reserved BCs haven't been optimized, this scheme can bring in long idle channels. Authors in [8] present a Semi-random backoff scheme, where a station can set its BC to a deterministic value after a successful transmission and continually uses the same BC. In case the station encounters a failure at any of its transmissions, e.g., due to packet loss or etc., the station will randomly choose a new BC according to the 802.11 backoff method. It can be observed that collisions may occur in case some of the stations accidentally choose a same BC. Moreover, since the stations tend to reserve BCs with relatively large values, their scheme can cause long convergence times and idle channel periods in large-size networks. Researchers in [9] propose to use sequence numbers such that stations having chosen the same BCs are able to access channel at different time slots, via following their assigned sequences. Aiming at mitigating the successive collisions, literature [10] reports the semi-distributed backoff (SDB) mechanism where a receiver-side backoff process will be triggered if a station suffers from collisions in sender-side backoff procedures. A point worth noting is that this approach only works in unicast transmissions. In [11], a BC reservation scheme is presented to enhance the reliability of the broadcasting of safety messages: Nodes are enabled to reserve BCs according to a given rule which is able to provide implicit feedbacks on whether transmitted messages experiencing collisions. However, their scheme cannot be adaptively implemented in fast-varying topologies. The time slot reservation method has also been investigated in literature [12], where a dynamic framed slotted Aloha based method is proposed for collision avoidance in RFID systems.

In this work, we present a hybrid channel access method to enhance the performance of 802.11p VANETs in broadcasting of safety messages, such that the safety critical messages can be transmitted with shorter transmission delays and higher reliabilities. Our proposal is inspired by the following observation: Under the IEEE 802.11p MAC protocol, a SI is divided into discrete time slots with varying durations, depending on whether

a transmission has occurred in a time slot or not. Since nodes (we use the terms node and vehicle interchangeably) are able to count the time slots due to the carrier sensing process as well as the backoff mechanism, if we consider one CCHI as a sequence of numbered time slots, those nodes that are connected to a same controller can share the sequence information of the time slots without exchanging additional information. Note that the controller can be a leading vehicle in the platoon/group based VANETs or a road side unit (RSU), i.e., the node plays the role of initiating the CCHI periodically. On the other hand, the IEEE 1609 standard states that CCHIs are allocated to nodes for periodically broadcasting of safety messages. One can expect that if a node is able to store a time slot number in the safety message, through successfully broadcasting the packet the node can reserve a time slot for the next round of the safety message transmission.

Given the aforementioned observation, our main contributions in this work are the following:

- Considering one CCHI as a sequence of numbered time slots, we propose to equip nodes to reserve time slots for broadcasting of safety messages for the next round. Moreover, configuring BCs using the sequence numbers of reserved time slots enables nodes to adopt unique BCs, which can efficiently reduce the collision probability.
- For those nodes which are unable to reserve a time slot, or have any emergency needs and may need to access the channel immediately, unoccupied time slots are available between any adjacent reserved time slots. Those nodes can access channel by randomly selecting an unoccupied time slot. We furthermore provide a mechanism to prevent nodes from selecting the reserved time slots.
- Regarding multiple access methods, there is a tradeoff between reliability and delay: I.e., the higher reliability is possible through delays due to reservations, and removing reservation delays would cause collisions. Considering such a tradeoff, we devise a mathematical model to optimally control the applied parameters such that it minimizes the cost caused by idle time slots and collisions. Extensive simulations are performed to evaluate the performances of IEEE 802.11p [2], Semi-random backoff [8], and our hybrid access scheme.

The remainder of this paper is structured as follows. Section 2 presents an overview of the IEEE 802.11p as well as the recent studies that are related to ours, and Sect. 3 gives the details of our proposed scheme. In Sect. 4, a mathematical model is devised for the optimal settings of the proposed scheme, while Sect. 5 conducts extensive simulations to evaluate the performance. Finally, Sect. 6 summarizes our work.

2 Preliminary

2.1 IEEE 802.11p

IEEE 802.11p standard specifies the technologies adopted by the PHY and the MAC layers in VANETs [13, 14]. Accordingly, the 802.11p PHY layer applies most technologies of the 802.11a such that it uses Orthogonal Frequency Division Multiplexing (OFDM) and offers data rates ranging from 3 to 27 Mbps. The 5.9 GHz spectrum is dedicated to 802.11p VANETs, while supported channel bandwidths include 10 MHz and 20 MHz.

The 802.11p MAC protocol applies the DCF mechanism, and the basic channel access procedure are the following: Upon the delivery of a packet, a node senses the channel for a period of distributed inter-frame space (DIFS). If an idle channel is detected the node accesses the channel immediately. Otherwise, the node starts a backoff process via randomly choosing a BC from the range of $(0, \omega)$, where ω denotes the node's current CW [15]. During the backoff process, the node continually senses the channel and reduces its BC by 1 for each detected idle time slot. Once the BC reaches 0 the node accesses channel to broadcast the packet.

In order to provide prioritized channel access, the 802.11p MAC protocol is extended by incorporating the EDCA mechanism. The EDCA scheme differentiates packets from the upper layer into four different access categories (ACs) according to the quality of service [6]. Each AC acts as an independent node and contends for the transmission opportunity (TXOP) using its own EDCA parameters, i.e., arbitration inter-frame space (AIFS), and the contention window size [16]. The AC with a higher priority applies the smaller AIFS and contention window size.

However, the 802.11p MAC protocol loses efficiency in broadcasting of safety messages: As nodes use a constant value for their contention windows (802.11p standard has defined a minimum value of contention window for each AC), the packets delivered under the same AC may encounter a high collision probability. Moreover, due to the lack of the acknowledgement in broadcasting of safety messages, the reliability cannot be guaranteed.

2.2 Related works

Contention-free channel access methods such as space division multiple access (SDMA) and time division multiple access (TDMA) have been investigated in the 802.11p MAC [3, 4, 6, 17–19]. The main idea of the SDMA based scheme is to divide the road into small cells/segments and each cell/segment is assigned to one time slot. The nodes located at the same segment contend to access channel according to the 802.11 DCF mechanism. On the other side, the TDMA based mechanisms split channels into identical time slots and allocate an unique time slot to each node for channel access.

In [6], a Congestion-Controlled-Coordinator-based (CCC) MAC protocol is presented where the network is virtually partitioned into a number of segments, and the vehicles access channels according to the time slotted schedule that is generated by the segment coordinator. In order for efficient bandwidth utilizations, inter-segment slot transfer is supported such that vehicles can utilize the unoccupied time slots of the adjacent segments.

In [17], a slotted structure is integrated with the MAC protocol, where each vehicle creates a frame information (FI) according to the status of the allocated time slot. The FI is then broadcast to the node's one-hop neighbors. Researchers in [3] propose to assign disjoint sets of time slots to the nodes moving into the opposite directions, in order to reduce collisions. Authors in [4] suggest to detect the potential collisions and to use the real-time traffic conditions together with the vehicles information to update the predication. The allocated time slots are then rescheduled in accordance with the updates. In [18], a time slot-sharing MAC protocol is proposed, which supports diverse periodical broadcasting rates. To enable the nodes to efficiently share

the time slots, a distributed time slot sharing algorithm as well as a random index first fit algorithms are designed. Literature [19] proposes a hybrid TDMA/CSMA multi-channel MAC protocol, where nodes use the ANC packet to reserve time slots and transmit safety messages in their reserved time slots.

Contention-free schemes like SDMA and TDMA cause low channel utilization: In SDMA schemes, cells/segments with sparse traffic are allocated to the same channel resources as those with heavy traffic, bringing in inefficient channel utilization. Similarly, TDMA schemes partition time horizon into identical time slots and allocate to the vehicles without consideration of their traffic loads.

Another array of works focus on the improvement of functions as well as the mechanisms adopted by the 802.11p MAC protocol [20–23]. Literature [20] reports a congestion control mechanism such that the CW size can be adjusted based on a joint measurement of the local transmission status and the network density. Authors in [21] provide a mathematical analysis of the 802.11p beaconing scheme to study the effects caused by the channel expiration as well as the varying numbers of contending nodes. Based on the obtained results, they present a random contention window scheme where arrays of minimum and maximum CWs (CW_{\min} and CW_{\max}) are introduced, such that nodes are enabled to randomly choose a pair of CW_{\min} and CW_{\max} to determine a CW, instead of applying a constant CW.

In [22], a variable CCHI-enabled multichannel medium access control scheme is proposed, where the intervals of both CCH and SCH can be dynamically adjusted. The optimal CCHI is derived to improve the saturation throughput of SCHs while ensures the transmissions of safety information and private service advertisements on CCH. In [23], an orthogonal frequency division multiple access-based (OFDMA-based, namely OBV) MAC protocol is proposed. Channel access duration is divided into contention-based negotiation phase and contention-free transmission phase. In any contention-based phase, vehicles access channel following the CSMA/CA mechanism, while in the contention-free phase, they conduct channel access based on the OFDMA. Although OBV protocol is able to provide high throughputs, especially in heavy-loaded environments, it causes long delays in light-loaded networks.

3 A hybrid channel access method

In this section, we report a hybrid channel access scheme exploiting the strengths of the TDMA scheme together with the 802.11p MAC protocol: Considering one CCHI as a sequence of numbered time slots, we propose to enable nodes to reserve time slots for broadcasting of safety messages while maintaining idle time slots available. During the backoff process, nodes set their BCs according to sequence numbers of their reserved time slots, thus can avoid applying the BCs that are identical to others. The nodes having an emergency requirement or being unable to reserve a time slot can access the channel through randomly selecting a unoccupied time slot. Since the reservation information is shared by nodes belonging to a same group, proposed scheme provides implicit feedbacks on whether a safety message has been transmitted successfully.

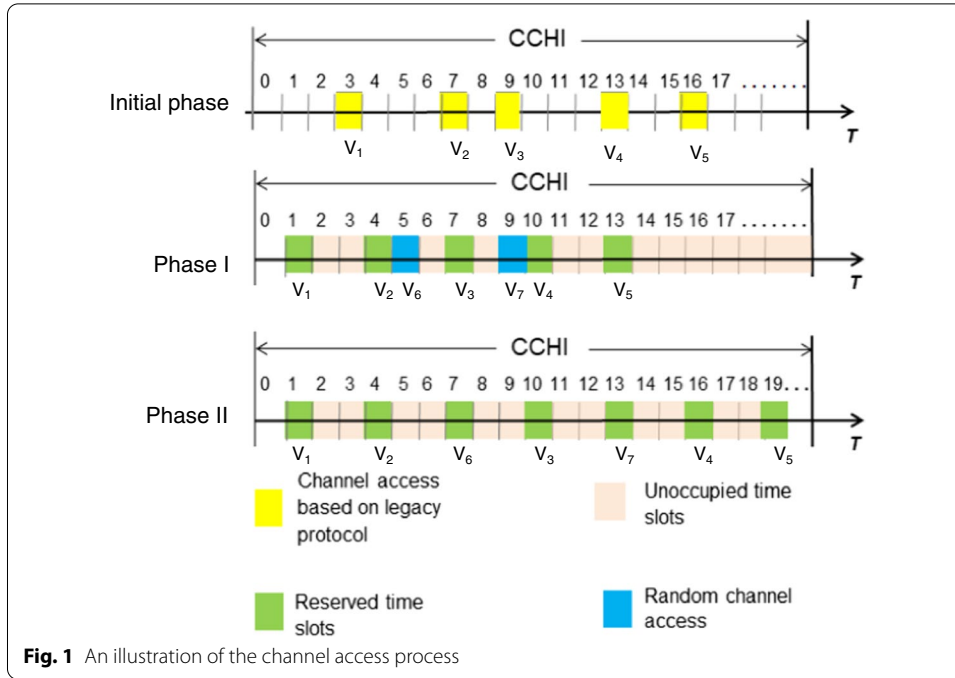
3.1 Time slot reservations

We assume that nodes are synchronized with each other, e.g., in 802.11p VANETs, the controller broadcasts beacon messages periodically based on which nodes synchronize their clocks. We equip nodes with a reservation table to save their neighbors' reserved sequence numbers both for current and the following CCHI. At the initial step, nodes access the channel according to the IEEE 802.11p standard, where the BC is determined through randomly choosing a number from $(0, CW_{\min}]$, here, CW_{\min} denotes the minimum backoff window, the value of which has been specified in the 802.11p standard. The sequence number of a chosen time slot is piggybacked by an ongoing safety message, which can be received by the other nodes in case the message is transmitted successfully. Note that the sequence number is a real number starting with 1 and increases additively, indicating the sequence of the reserved time slot in the corresponding CCHI. In order to preserve idle time slots unoccupied for nodes which are unable to make a reservation, we adopt a parameter to tune the interval of the sequence numbers of any adjacent reserved time slots. Let's denote by i the sequence number of the time slot reserved by a tagged node, and denote by θ the interval of any two adjacent reservations, accordingly, the sequence number of the next reservation becomes $i + (\theta + 1)$. One can observe that there exists θ unoccupied time slots between adjacent reserved time slots.

In the next CCHI, through setting its BC to $j + (j - 1)\theta$, the node that is the j th node having conducted time slots reservation can access channel at the time slot with a sequence number of $j + (j - 1)\theta$. Nodes which are unable to reserve a time slot choose an unoccupied time slot by setting their BCs according to $k(1 + \theta) - \varepsilon$, where k and ε are randomly selected while $k = 1, 2, \dots$ and $2 \leq \varepsilon < \theta + 1$. The value of the θ is broadcast by the controller node at the start of a CCHI. For the node having not received such information, i.e., nodes have missed the message from the controller, they either request the information from the controller or resolve by itself through overhearing the channel: The value of the θ can be resolved through calculating the interval of any two adjacent reservations.

3.2 An example of the channel access process

We specify the channel access process of the proposed hybrid method by a simple example illustrated in Fig. 1. Here, the sequence numbers of the time slots start with 0, and the 0th time slot is preserved intentionally. Either reservation based or random channel access proceeds from the 1st time slot. The time slots of a CCHI are presented with identical durations only for illustration purpose, their lengths differ from each other in the real system, depending on whether a transmission is incurred in that time slot or not. As it is shown, during the initial phase, nodes V_1, V_2, V_3, V_4 and V_5 have accessed channel according to the 802.11p MAC protocol, and they have broadcast a safety message in time slots 3, 7, 9, 13 and 16, respectively. Since their messages have been transmitted successfully, each of them has reserved a time slot for the second CCHI. The sequence numbers of reserved time slots are 1, 4, 7, 10, 13, i.e., we set θ to be 2 in this example. In the following CCHI, nodes access channel in their reserved time slots by setting their BCs to the sequence numbers of associated reserved time slots.

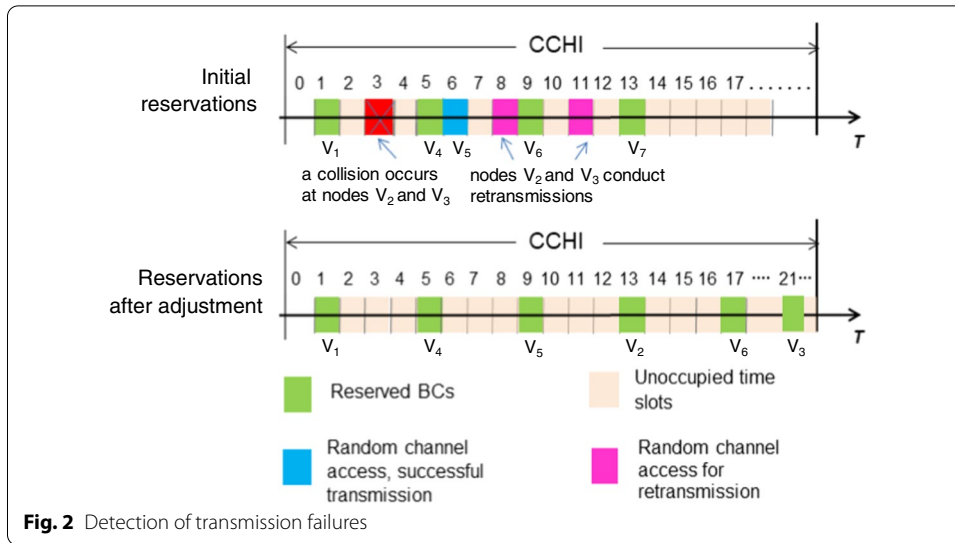


Meanwhile, another two nodes, let's say V_6 and V_7 , move into the area during the second CCHI. After overhearing at least two continuous transmissions of safety messages, they figure out that there exist two time slots between adjacent reservations, i.e., $\theta = 2$. Let's take V_6 as an example for channel access. Assuming that node V_6 moves in the area while V_1 is performing transmission, V_6 waits until V_2 completes transmission and finds out the current value of θ is 2. Accordingly, node V_6 can choose a BC based on $k(\theta + 1) - \varepsilon$, where $2 \leq \varepsilon \leq \theta + 1, k = 1, 2, \dots$. If k is set to 1, then the possible values of the BC include 0 and 1. Or if k is set to 2, the possible values of the BC include 3 and 4. We consider the case that node V_6 sets k to 1 and chooses 0 as its BC. As a result, V_6 can access channel right after V_2 's transmission. By following the similar steps, node V_7 accesses channel at the 9th time slot. While nodes delivering safety messages in the second CCHI (Phase I in the Fig. 1), they piggyback the sequence numbers of reserved time slots for the following CCHI in the safety messages. The consequences of the reservations are the same as it is shown in the Phase II in the Fig. 1.

3.3 Collision detection

Proposed scheme provides implicit feedbacks on whether broadcast messages encountered collisions. It becomes possible because in case a packet encounters collision the transmitting node fails in reservation. Consequently, other nodes may try to reserve the same time slot which the previous transmitting node fails in reservation, based on which the transmitter can be acknowledged that the packet has encountered collision.

Figure 2 shows the collision detection process of the proposed scheme by an example. As it is presented, a collision occurs at the 3th time slot where both nodes V_2 and V_3 have selected the same time slot, consequently, they fail in reserving a time slot. The following nodes V_4 and V_5 which transmit a packet at time slots 5 and 6 try to reserve the same time slots as nodes V_2 and V_3 have conducted in their transmissions. Overheard the



messages, nodes V_2 and V_3 are acknowledged that their transmissions have failed, therefore, they perform retransmissions via randomly selecting an idle time slot. As it is given in Fig. 2, they have chosen time slots 8 and 11 individually, and have reserved time slots with sequence numbers 13 and 21. Note that in this example the parameter θ is set to 3.

4 Optimizing parameters for time slot reservations

The hybrid channel access method equips nodes to access channel either through reserving a time slot in advance or through contending with other nodes by randomly selecting an idle (unoccupied) time slot. Accessing channel through reserving a time slot in advance guarantees a successful transmission if channel is in a good state, but it may bring in long delays in case nodes have reserved time slots near the tail of a CCHI. In contrast, random channel access brings in lower delays, but may cause collisions.

Let's denote by D the transmission range of a controller, and assume that nodes associating with the same controller can overhear each other, i.e., no hidden terminals. We also assume that vehicles are distributed according to a Poisson distribution with the average rate of β vehicles/m in each direction of the road. Accordingly, there are $N = 2\beta D$ nodes existing within the range of the controller. If there are n nodes having reserved time slots in a CCHI, and the interval between any adjacent reservations is θ , then $n\theta$ unoccupied time slots are available for m nodes, where $m = N - n$. It can be observed that the number of unoccupied time slots is determined by n and θ , i.e., more unoccupied time slots can be preserved in case either more nodes conduct reservations or the interval θ adopts a larger value. The problem is if a large number of nodes chooses to access channel through reserving a time slot, only a few nodes remain to perform random channel access with lots of idle time slots are available. As a result, the collision probability is reduced but introduces the large channel access delay, due to the preserved idle time slots between adjacent reservations. On the other hand, if a large number of nodes conduct random channel access, high collision probability will be incurred. In order to investigate the characteristics of our proposed scheme regarding parameters n , m , and the interval θ , we devise a mathematical model in this section. Modifying the mathematical model given in [24], we first provide

an observation of our model's behavior, and then suggest an optimal control of associated parameters.

4.1 Performance analysis

In the following analysis, we assume the duration of a CCHI is sufficient enough for all nodes to broadcast their safety messages. We also assume that each node reserves only one time slot in a given CCHI. Both of the assumptions are made for analysis purpose, in real system, however, some of the nodes may not transmit their messages due to the termination of the CCHI. And nodes are able to reserve more than one time slots. Since the channel access contention only occurs during the unoccupied time slots (m nodes contend to access channel in $n\theta$ time slots), we apply the mathematical model given in [24] to represent the channel access contention process as a discrete time stochastic process evolving between three states. Those states are as follows: an idle time slot where none of the nodes transmitted in the slot, a time slot where only one node accessed channel (the transmission proceeds successfully), and a time slot where more than two nodes accessed channel (collision occurs).

We denote the attempt probability of a node to access channel in an unoccupied time slot as p . Since there are $n\theta$ time slots available and a node can randomly choose any of the time slots, we have that

$$p = \frac{1}{n\theta}, \quad (1)$$

where n denotes the number of nodes having reserved a time slot and θ denotes the interval between the sequence numbers of any adjacent reservations. At a given time slot, a node can conduct a successful transmission with the probability

$$P_s = mp(1 - p)^{m-1}, \quad (2)$$

and the probability that the given time slot is idle is follows.

$$P_i = (1 - p)^m. \quad (3)$$

At the time slot, a collision occurs with a probability of

$$P_c = 1 - P_s - P_i. \quad (4)$$

The average system throughput $S(p)$ can be obtained by

$$S(p) = \frac{P_s E[P]}{P_s T_s + P_c T_c + P_i T_{\text{slot}}}, \quad (5)$$

where $E[P]$ denotes the average packet payload of a safety message, T_s denotes the duration of a successful transmission of a safety message, T_c denotes the duration of a collision, and T_{slot} denotes the duration of an idle slot. Since a broadcast communication can not provide any feedbacks, we have that $T_s = T_c = T_{\text{Preamble}} + T_{\text{Data}}$ where T_{Preamble} denotes the time for transmitting preambles, and has been specified by the 802.11p standard. Also T_{Data} denotes the transmission time for sending a safety message, and is

determined by the transmission rate as well as the packet length. We use T to denote both T_s and T_c , then Eq. (5) can be rewritten as

$$S(p) = \frac{P_s E[P]}{(P_s + P_c)T + P_i T_{\text{slot}}}. \quad (6)$$

Our objective is to find the optimal value of the attempt probability p , i.e., the attempt probability which can maximize the throughput through minimizing the collisions and the idle time slots. Note that maximizing Eq. (6) is equivalent to minimizing the following cost function [24]:

$$\text{Cost}(p) = \frac{\frac{T_c}{T_{\text{slot}}} P_c + P_i}{P_s}. \quad (7)$$

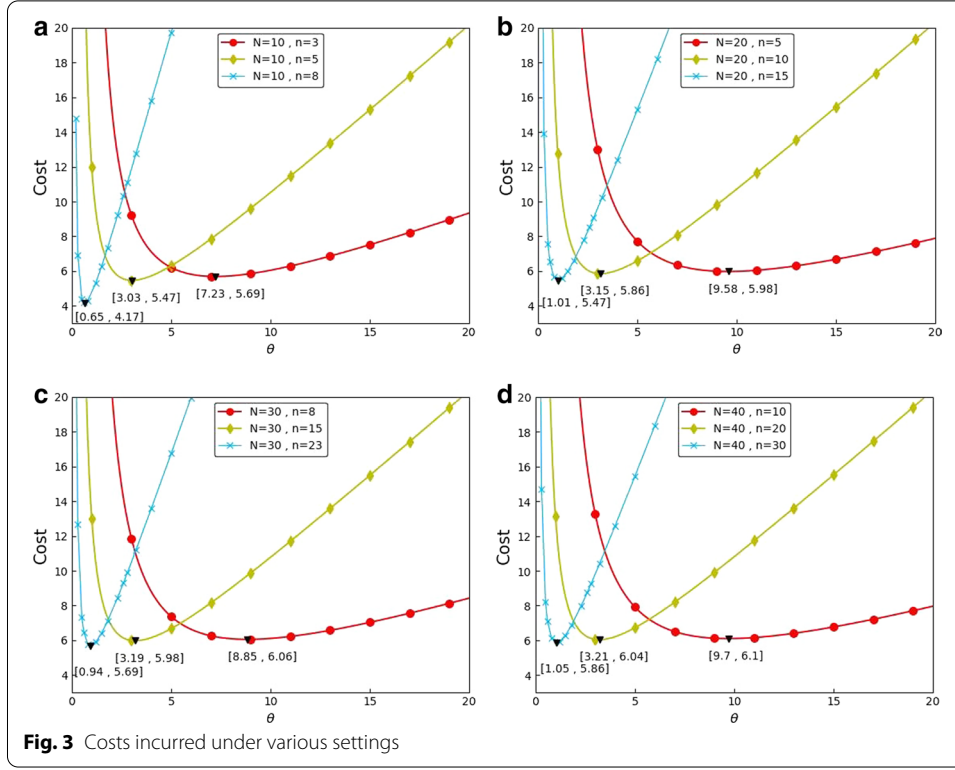
We first plot $\text{Cost}(p)$ by varying parameters n and m , i.e., the numbers of nodes having reserved time slots as well as the nodes contending to access channel, respectively, and the interval θ . The parameters applied in this analysis are given in Table 1.

Figure 3a–d depicts the costs occurred in a platoon/group with 10, 20, 30, 40 nodes, respectively, while varying the number of nodes having reserved time slots. As it is shown, given the number of nodes performing reservation based channel access, if we increase the interval θ , the cost decreases first and then increases once it reaches the lowest point. The reason behind it is that the cost incurred in our analysis model is caused both by the idle channels and collisions, if the number of nodes having reserved time slots stays constant, adopting a small value of θ may generate a few unoccupied time slots. Therefore, if there is a large number of nodes contending to access channel, with only a few idle time slots available it will cause a high collision probability. On the other hand, adopting a large value of θ may preserve lots of idle time slots, and cause large idle channels. Figure 3a–d also show that there exists a minimum cost for each pair of (N, n) . For instance, as it is given in Fig. 3a if $N = 10, n = 3$, the minimum cost is 5.69, and can be achieved by setting θ to 7.23. Similarly, Fig. 3b presents the case $N = 20, n = 10$, and the minimum cost is 5.86 which can be achieved by setting θ to 3.15. The same goes to the the cases with $N = 30$ and $N = 40$, and the obtained minimum costs are illustrated in Fig. 3c, d.

We next investigate the optimal reservation interval $\hat{\theta}$ while the number of nodes of a platoon/group and the number of nodes accessing channel through reserving a time slot are known. As in [24], by setting the first derivation of the cost function given by Eq. (7) to zero, we have that:

Table 1 Parameters applied by the analysis model

Parameter	Value
Channel capacity	11 Mbps
Preamble	24 bytes
Packet size	200 bytes
Slot time	10 μ s



$$1 - m\hat{p} = \left(1 - \frac{T_{\text{SLOT}}}{T_c}\right)(1 - \hat{p})^m, \quad (8)$$

where \hat{p} denotes the attempt probability obtained under the optimal settings of n and θ . Denoting $\xi = m\hat{p}$ and $C = 1 - \frac{T_{\text{slot}}}{T_c}$ gives

$$1 - \xi = C\left(1 - \frac{\xi}{m}\right)^m, \quad (9)$$

combining with $m \rightarrow \infty$, we have that

$$1 - \xi = Ce^{\xi}. \quad (10)$$

Using the fact that $\hat{p} = \frac{1}{n\hat{\theta}}$ we obtain the optimal value of $\hat{\theta}$ given \hat{n} , i.e., the number of nodes having reserved a time slot. Table 2 provides an example of the optimal settings, where \hat{n} is set to $\frac{N}{4}$, $\frac{2N}{4}$, and $\frac{3N}{4}$. We observe that if $N = 10$, $\hat{n} = 3$, the optimal value of $\hat{\theta}$ is 5.69, which is identical to Fig. 3a. The same goes to the setup where $N = 20$, $\hat{n} = 10$.

In the next scenario, we fix $N = 60$ and compute the optimal $\hat{\theta}$ under different setups. Table 3 shows the results: While fewer nodes performing reservation based channel access, a large value $\hat{\theta}$ is required to reach the minimum cost. E.g., if \hat{n} is set to 3, the optimal value of $\hat{\theta}$ is 35.74. It is reasonable because in case only a small number of nodes performing reservation based channel access, a large number of nodes are remained to contend to access channel, thus requires a large number of idle time slots. On the other side, if there exists a large number of nodes accessing channel by reserving time slots, e.g., $\hat{n} = 45$, only fewer nodes are remained to contend to access channel, therefore, a

Table 2 Minimum cost I

N	(\hat{n}, m)	$\hat{\theta}$	Cost
10	(3, 7)	7.23	5.69
10	(5, 5)	3.03	5.47
10	(8, 2)	0.65	4.17
20	(5, 15)	9.58	5.98
20	(10, 10)	3.15	5.86
20	(15, 5)	1.01	5.47
40	(10, 30)	9.69	6.10
40	(20, 20)	3.21	6.04
40	(30, 10)	1.05	5.86

Table 3 Minimum cost II

N	(\hat{n}, m)	$\hat{\theta}$	Cost
60	(5, 55)	35.74	6.16
60	(10, 50)	16.24	6.15
60	(15, 45)	9.73	6.14
60	(20, 40)	6.48	6.13
60	(25, 35)	4.53	6.12
60	(30, 30)	3.23	6.1
60	(35, 25)	2.3	6.08
60	(40, 20)	1.61	6.04
60	(45, 15)	1.06	5.98

smaller number of unoccupied time slots is required, accordingly, the optimal value of $\hat{\theta}$ is small, i.e., $\hat{\theta}$ equals to 1.06.

4.2 Implementation of optimal parameters

In this subsection, we give a solution to implement optimal parameters of the proposed scheme. In the platoon/group based VANETs, a leading node plays the role of organizing the whole group, e.g., initiating a group, broadcasting parameters by beacon frames, etc.. In the case that the platoon/group is not supported, the parameters can be piggy-backed by the beacon frames broadcast periodically by an RSU. Therefore, we propose to equip the leading nodes or the RSUs to compute the optimal parameters at each start of a CCHI based on current network environments, and to broadcast the optimal parameters by beacon frames.

The results obtained in previous analysis show that given a pair of (n, m) , an optimal θ can be derived. It is observed that the leading node/RSU has the knowledge of N , and if it determines a value for \hat{n} , i.e., the maximum number of nodes that can reserve a time slot in next CCHI, an optimal $\hat{\theta}$ under the setup can be derived, where $\hat{\theta}$ denotes the interval between any two adjacent reservations. After each CCHI, the leading node/RSU adjusts the values of $(\hat{n}, \hat{\theta})$ according to the channel utilization in previous CCHI: It increases \hat{n} to allow more nodes to access channel through time slot reservations, or increases $\hat{\theta}$ to preserve more time slots for the nodes to contend to access channel.

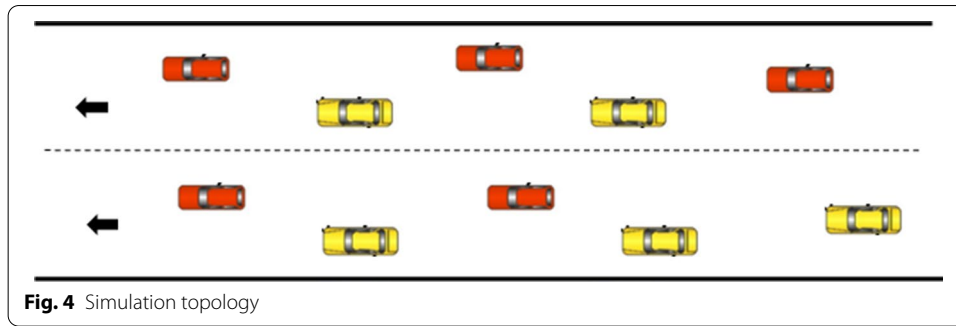


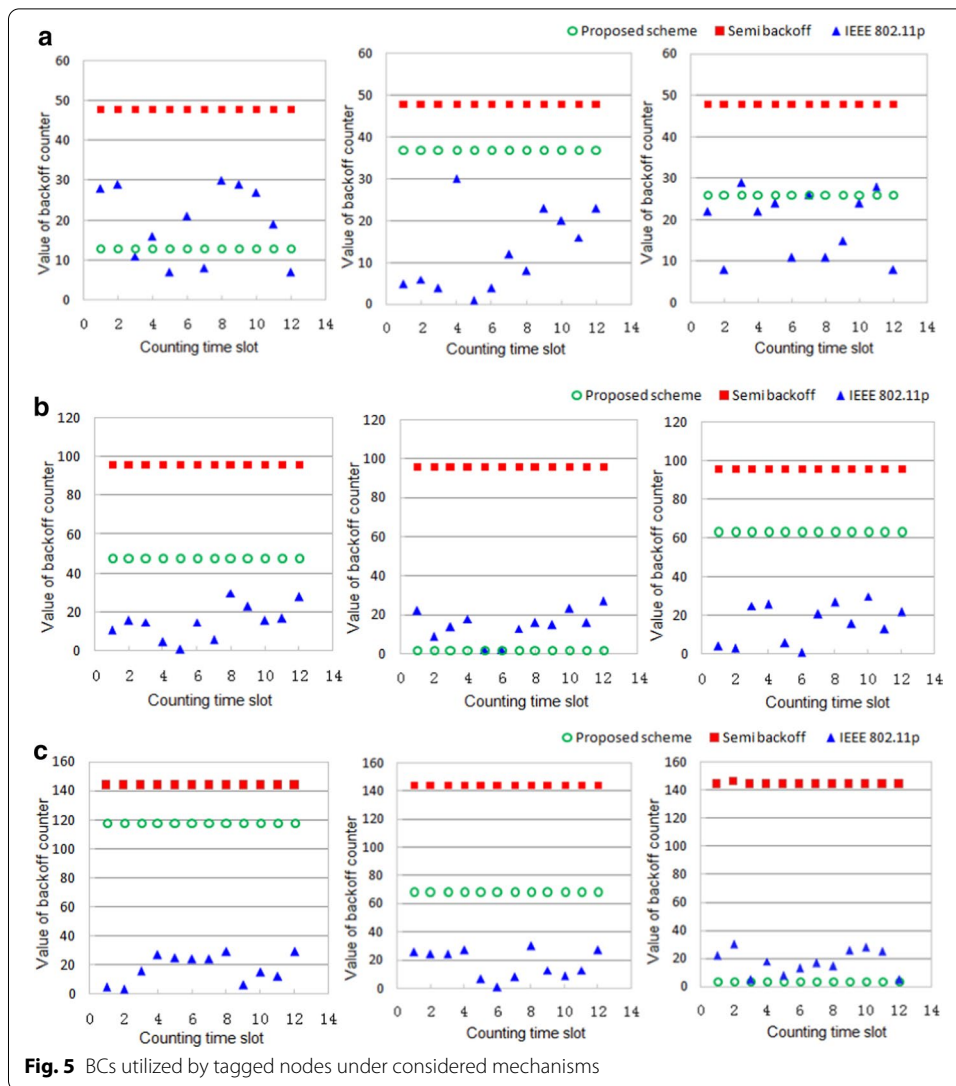
Table 4 System parameters

Parameter	Value	Parameter	Value
Channel capacity	11 Mbps	DIFS	20 μ s
CW _{min}	31	Slot time	10 μ s
Packet size	200 bytes	Number of vehicles	20–120

5 Results and discussion

In this section, we evaluate the performance of the proposed scheme by the OPNET simulator [25]. We have modified the *wlan_mac* process model of the OPNET in order to simulate the 802.11p MAC protocol, the Semi-random backoff protocol, and proposed hybrid channel access scheme. The *wlan_mac* process provides most functions related to the 802.11 MAC protocol, our modifications mainly focus on data transmission as well as the channel access associated functions. As it is illustrated in Fig. 4, the vehicular network topology considered in this work is a straight 2-lane highway with one-way traffic, nodes connecting with a controller from where they receive optimal parameters. We vary the number of nodes in one-hop from 20 to 120. Note that due to the space limitation (nodes should keep a certain distance between each other in VANETs) as well as the limitation in transmission range of the controller, nodes density becomes an important factor to the performance of the VANETs. We follow the setup given in [26] and set the transmission range of the controller to 300 m, the node density varies from 0.067 to 0.4 (vehicles/m). In conducted simulations, nodes broadcast safety messages with the same payloads (200 bytes) periodically, i.e., the interval of the SI equals to 100 ms. We compare the performance of our proposed reservation scheme to that of the Semi-random scheme, as well as of the IEEE 802.11p MAC protocol. We evaluate packet loss probabilities caused by collisions together with throughputs at the MAC layer under considered mechanisms. More details of the simulation parameters are presented in Table 4.

In the following simulations, we vary the value of N , i.e., the number of nodes consisting of one group, while setting the number of nodes having reserved a time slot as well as the nodes performing time slot reservations to half of the N , i.e., $(n, m) = (N/2, N/2)$. The optimal value of the θ can be resolved by the controller. We first study the BCs adopted by the vehicles under considered mechanisms. Figure 5a–c gives the BCs applied by vehicles based on proposed scheme, Semi-random backoff scheme, and the 802.11p MAC protocol. Three vehicles are tagged, denoted as V_1 , V_2 and V_3 . Since



vehicles select BCs from the range of $(0, CW_{\min})$ under 802.11p protocol, we observe that the BCs utilized by V_1 , V_2 and V_3 are distributed randomly in the range of $(0, 31)$. We expect a high collision probability to occur in the network with 120 nodes, as the range of the possible values of BCs is much smaller compared to the number of vehicles.

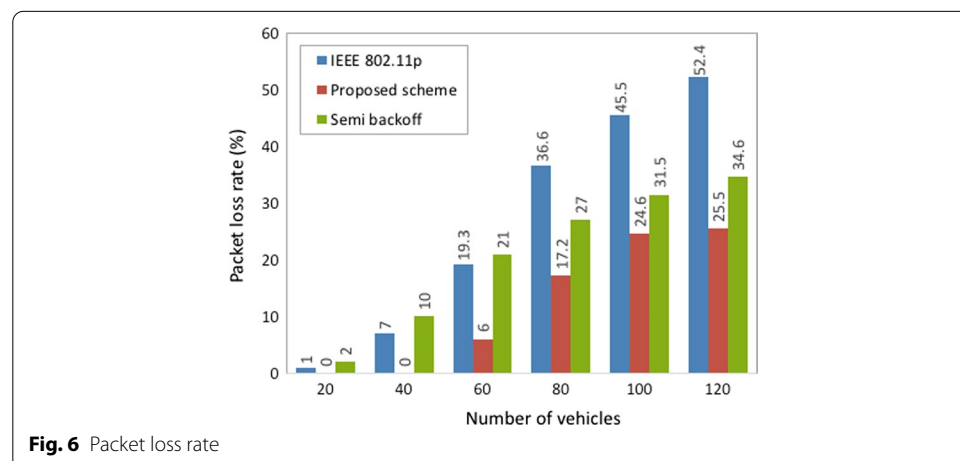
In the Semi-random backoff scheme, once the network reaches a steady state nodes adopt a deterministic number M , the value of which depends on the network size as their BCs. In our simulations, M is equal to $N + \mu$ where $\mu = 0.2 * N$. Consequently, as it is given in Fig. 5a in the network with 40 nodes, we observe that all the vehicles try to reserve a BC with a value of 48. As the network size increases, the possible values of the BC rise. It can be observed from Fig. 5b, c that in the network with 80 and 120 nodes, the possible values of BCs rise to 96 and 144, respectively.

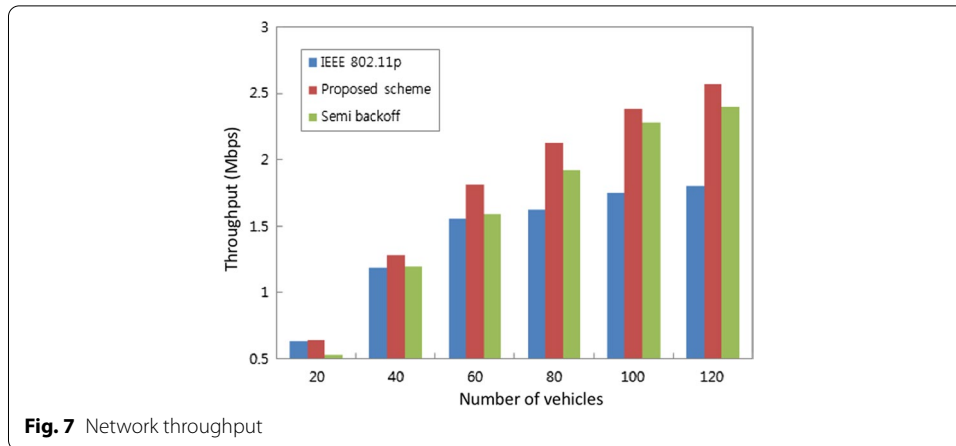
In our proposed scheme, however, nodes having reserved a time slot set their BCs to the sequence numbers of their reserved time slots. A node that has conducted a transmission at the time slot positioned near the head of a CCHI can reserve a time slot with

a smaller sequence number, thus adopts a smaller BC. As it is presented in Fig. 5a, nodes V_1 , V_2 , and V_3 which have reserved time slots 13, 37, and 26 set their BCs to be the corresponding values. The same goes to the scenarios where the network consists of 80 nodes and the network consists of 120 nodes, which can be confirmed from Fig. 5b, c. In the former case, nodes V_1 , V_2 , and V_3 have reserved time slots 48, 2, and 63 respectively, while in the later case tagged nodes have reserved time slots 118, 68 and 4. We observe that our scheme enables the vehicles to choose their BCs from a more adaptive range.

Next, we evaluate the packet loss rate and the network throughput while varying network sizes. In Fig. 6, note that the packet loss rate rises up fast as the network size increases under the 802.11p protocol. In the network with 120 nodes, the packet loss rate even reaches 52.4%. It coincides with our previous discussion: Under the 802.11p protocol, nodes randomly pick up a number from the range of $(0, CW_{\min})$ and set it to be its BC. In the network consisting of 120 nodes, a large number of nodes pick up the same number in a high probability, causing severe collisions. In contrast, both Semi-random backoff scheme and the proposed hybrid channel access scheme reduce the packet loss rate efficiently. Since the Semi-random backoff scheme hasn't adopted any solutions to prevent nodes from accessing the channel in time slots reserved by others, it introduces more collisions than our protocol, thus causes higher packet loss rate. In our proposal, based on the setups that $(n, m) = (N/2, N/2)$, the controller can obtain an optimal value of θ for each N according to the method suggested in Sect. 4. E.g., for $N = 40$ and $(n, m) = (20, 20)$ the controller can figure out that $\theta = 3.21$. Accordingly, for any two adjacent reservations our protocol keeps 3 time slots for nodes to conduct random channel access. The same goes to the scenarios with 60, 80, 100, 120 nodes. In such a way, proposed hybrid channel access method allows nodes to choose their BCs from an adaptive range, while it provides sufficient idle time slots for those performing randomly channel access. Both of these features efficiently reduce the collision probabilities thus cause less packet losses even in large size networks.

Figure 7 illustrates network throughputs achieved under considered mechanisms. Comparing against the 802.11p MAC protocol, throughputs incurred under both Semi-random backoff and our proposed mechanism grow fast as the network size increases. The throughput incurred under the 802.11p MAC increases fast before





the network size reaches 60, and then it rises very slowly. The main reason behind it is that once the network size increases to more than 60 nodes, the 802.11p MAC causes severe collisions which brings in high packet losses as it is suggested in Fig. 6. While on the other hand, due to the small size of the safety message, i.e., 200 bytes in our setup, the increment of the network size can only increase the throughput from a small scale. Comparing with the 802.11p mechanism which exhibits a poor throughput, both Semi-random backoff and our proposed scheme reduce collisions via time slot reservations, thus bring in high throughputs. As it is discussed previously, proposed hybrid channel access protocol eliminates collisions more efficiently, therefore it incurs the highest throughput.

6 Conclusions

In this paper, we have proposed a hybrid channel access method which exploits efficiencies of both reservation-based and random channel access schemes in 802.11p VANETs: The nodes are enabled to reserve time slots in advance, while unoccupied time slots are available for those which need to randomly access the channel. As a result, our proposed scheme provides low collision probabilities, low packet loss rates, and high throughputs, which are important features in dense VANETs. In addition, since the failed reservations can be observed, based on which nodes are able to confirm whether the safety messages has been transmitted successfully. Therefore, our proposed scheme can provide implicit feedbacks to the transmitters, which is hard to be realized in other broadcasting MAC protocols. Furthermore, a mathematical model is devised for the optimal control of our scheme, such that the cost due to idle channels and collisions can be minimized. By performing extensive simulations, we have shown our proposed scheme outperforms all the previous mechanisms.

Abbreviations

VANETs: Vehicular ad-hoc networks; WAVE: Wireless access in vehicular environments; MAC: Media access control; CSMA/CA: Carrier sense multiple access with collision avoidance; CCH: Control channel; SCH: Service channel; SI: Synchronization interval; CCHI: Control channel interval; SCHI: Service channel interval; DCF: Distributed coordination function; EDCA: Enhanced distributed channel access; BC: Backoff-counters; CW: Contention window; SDB: Semi-distributed backoff; RSU: Road side unit; PHY: Physical; OFDM: Orthogonal frequency division multiplexing; DIFS: Distributed inter-frame space; AC: Access category; TXOP: Transmission opportunity; AIFS: Arbitration inter-frame space; SDMA: Space division

multiple access; TDMA: Time division multiple access; CCC: Congestion-controlled-coordinator; FI: Frame information; CW_{min} : Minimum CW; CW_{max} : Maximum CW.

Acknowledgements

The work reported in this paper was conducted in part during the sabbatical year of Kwangwoon University in 2020.

Authors' contribution

X. Lei proposed the hybrid channel access scheme, derived the mathematical equations, and performed the simulations and manuscript writing. X. Chen performed the simulations for the Optimization reservation setting model. S. H. Rhee contributed in manuscript revision and correction. All authors read and approved the final manuscript.

Funding

This work was supported by Yangzhou University Innovation Fund (2017CXJ029), Basic Science Research Program through the National Research Foundation of Korea (2020R1F1A1069399).

Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that there is no competing interests regarding the publication of this paper.

Author details

¹ College of Information Engineering, Yangzhou University, Yangzhou, Jiangsu, China. ² Department of Electronics Convergence Engineering, Kwangwoon University, Seoul, Korea.

Received: 2 February 2020 Accepted: 24 February 2021

Published online: 01 April 2021

References

1. V. Nguyen, O.T.T. Kim, C. Pham, T.Z. Oo, N.H. Tran, C.S. Hong, E.N. Huh, A survey on adaptive multi-channel MAC protocols in VANETs using Markov models. *IEEE Access* **6**, 16493–16514 (2018)
2. Y.-J. Wu, W.-S. Wang, W.-S. Hwang, A modified backoff algorithm for safety message delivery in IEEE 802.11p/WAVE networks, in *Proceedings of the 2014 International Conference on Computer, Information and Telecommunication Systems*, pp. 1–5 (2014)
3. H.A. Omar, W. Zhuang, L. Li, VeMAC: a TDMA-based MAC protocol for reliable broadcast in VANETs. *IEEE Trans. Mob. Comput.* **12**(9), 1724–1736 (2013)
4. X. Jiang, D.H.C. Du, PTMAC: a prediction-based TDMA MAC protocol for reducing packet collisions in VANET. *IEEE Trans. Veh. Technol.* **65**(11), 9209–9223 (2016)
5. B. Cao, G. Feng, Y. Li, C. Wang, Cooperative media access control with optimal relay selection in error-prone wireless networks. *IEEE Trans. Veh. Technol.* **63**(1), 252–265 (2014)
6. J. Sahoo, E.H.-K. Wu, P.K. Sahu, M. Gerla, Congestion-controlled-coordinator-based MAC for safety-critical message transmission in VANETs. *IEEE Trans. Intell. Transp. Syst.* **14**(3), 1423–1437 (2013)
7. J. Choi, J. Yoo, S. Choi, C. Kim, EBA: an enhancement of the IEEE 802.11 DCF via distributed reservation. *IEEE Trans. Mobile Comput.* **4**(4), 378–390 (2005)
8. Y. He, J. Sun, X. Ma, A.V. Vasilakos, R. Yuan, W. Gong, Semi-random backoff: towards resource reservation for channel access in wireless LANs. *IEEE/ACM Trans. Netw.* **21**(1), 204–217 (2013)
9. P.V. Krishna, S. Misra, M.S. Obaidat, V. Saritha, Virtual backoff algorithm: an enhancement to 802.11 medium-access control to improve the performance of wireless networks. *IEEE Trans. Veh. Technol.* **59**(3), 1068–1075 (2010)
10. S. Misra, M. Khatua, Semi-distributed backoff: collision-aware migration from random to deterministic backoff. *IEEE Trans. Mob. Comput.* **14**(5), 1071–1084 (2015)
11. X. Lei, S.H. Rhee, A new backoff scheme with collision detection for IEEE 802.11p vehicular networks, in *Proceedings of the IEEE 86th Vehicular Technology Conference*, pp. 1–5 (2017)
12. J. Su, R. Xu, S. Yu, B. Wang, J. Wang, Idle slots skipped mechanism based tag identification algorithm with enhanced collision detection. *KSII Trans. Internet Inf. Syst.* **14**(5), 2294–2309 (2020)
13. IEEE, 802.11p-2010, IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks specific requirements part 11, in *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, pp. 1–51 (2010)
14. M. Amadeo, C. Campolo, A. Molinaro, Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs. *Ad Hoc Netw.* **10**(2), 253–269 (2012)
15. Y. Li, C. Wang, K. Long, W. Zhao, Modeling channel access delay and jitter of IEEE 802.11 DCF. *Wirel. Person. Commun.* **47**(3), 417–440 (2008)
16. J. Zheng, Q. Wu, Performance modeling and analysis of the IEEE 802.11p EDCA mechanism for VANET. *IEEE Trans. Veh. Technol.* **65**(4), 2673–2687 (2016)
17. F.A. Capone, M. Cesana, L. Fratta, ADHOCMAC: new MAC architecture for ad hoc networks providing efficient and reliable point-to-point and broadcast services. *Wireless Netw.* **10**(4), 359–366 (2004)

18. F. Lyu, H. Zhu, H. Zhou, W. Xu, N. Zhang, M. Li, X. Shen, SS-MAC: a novel time slot-sharing MAC for safety messages broadcasting in VANETs. *IEEE Trans. Veh. Technol.* **67**(4), 3586–3597 (2017)
19. V. Nguyen, T.Z. Oo, P. Chuan, C.S. Hong, An efficient time slot acquisition on the hybrid TDMA/CSMA multichannel MAC in VANETs. *IEEE Commun. Lett.* **20**(5), 970–973 (2016)
20. X. Shen, X. Cheng, R. Zheng, B. Jiao, Y. Yang, Distributed congestion control approaches for the IEEE 802.11p vehicular networks. *IEEE Intell. Transp. Syst. Mag.* **5**(4), 50–61 (2013)
21. X. Lei, S.H. Rhee, Performance analysis and enhancement of IEEE 802.11p beaconing. *EURASIP J. Wirel. Commun. Netw.* **2019**(1), 61 (2019)
22. Q. Wang, S. Leng, H. Fu, Y. Zhang, An IEEE 802.11p-based multichannel MAC scheme with channel coordination for vehicular ad hoc networks. *IEEE Trans. Intell. Transp. Syst.* **13**(2), 449–458 (2012)
23. A. Bazzi, A. Zanella, B.M. Masini, An OFDMA-based MAC protocol for next-generation VANETs. *IEEE Trans. Veh. Technol.* **64**(9), 4088–4100 (2015)
24. M. Heusse, F. Rousseau, R. Guillier, A. Duda, Idle sense: an optimal access method for high throughput and fairness in rate diverse wireless LANs, in *Proceedings of ACM SIGCOMM*, pp. 121–132 (2005)
25. OPNET Network Simulator, Riverbed, available at www.opnet.com
26. K.A. Hafeez, L. Zhao, B. Ma, J.W. Mark, Performance analysis and enhancement of the DSRC for VANET's safety applications. *IEEE Trans. Veh. Technol.* **62**(7), 3069–3083 (2013)

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)