Lei and Rhee *EURASIP Journal on Wireless Communications and Networking* (2019) 2019:61
https://doi.org/10.1186/s13638-019-1381-9

EURASIP Journal on Wireless Communications and Networking

RESEARCH Open Access

Performance analysis and enhancement of IEEE 802.11p beaconing

Xiaoying Lei[1*] and Seung Hyong Rhee[2]

Abstract

Previous work on the performance analysis of IEEE 802.11p beaconing protocol has paid little attention to the varying number of contending nodes and the restricted channel access: Since each node is allowed to broadcast only one beacon frame per control channel (CCH), the number of contending nodes decreases as the CCH elapses. Thus, the performance of 802.11p MAC protocol varies with the number of contending nodes, and the expiration of CCH may cause the beacon messages to drop. In this paper, we propose a new mathematical model to analyze the performance of 802.11p MAC, which considers both the effects of changing number of contending nodes and the restricted channel access. Based on the analytic results, a *random contention window* scheme is proposed. Through conducting extensive simulations, we verify that the proposed scheme considerably outperforms the legacy 802.11p protocol.

Keywords: IEEE 802.11p, Beaconing, Control channel, Performance analysis, Random contention window

1 Introduction

Dedicated short-range communication (DSRC) is considered as one of the most crucial technologies for intelligent transportation systems (ITS). Operating at 5.9-GHz frequency band, DSRC can provide wireless communication capabilities for transportation applications within a 1000-m range typically at highway speeds [1]. Wireless access in vehicular environment (WAVE) is a key protocol for DSRC, which consists of the IEEE 1609 family and IEEE 802.11p. The IEEE 1609 family includes resource manager (1609.1), security services (1609.2), network layer services (1609.3), multi-channel operation (1609.4), and electronic payment (1609.11)[2]. And IEEE 802.11p, which is a modified version of the IEEE 802.11 standard, is adopted for standardization of the physical (PHY) and media access control (MAC) layers.

IEEE 1609.4 standard splits the allocated spectrum into seven channels, including one control channel (CCH) and six service channels (SCHs). And the channel access time is divided into consecutive synchronization intervals (SIs)[3], where each SI has a fixed length of 100 ms and consists of two alternating 50-ms intervals—CCH interval (CCHI) and SCH interval (SCHI). During CCH, nodes can broadcast status messages (beacons), like car position, speed, and heading, as well as safety messages, including any accident ahead, sudden brake, and poor road condition detected.

IEEE 802.11p MAC applies enhanced distributed channel access (EDCA) scheme for channel access control, where nodes access channel basically according to the distribution coordination function (DCF), while priorities are considered [4]. Accordingly, nodes sense the channel before starting a transmission: If the channel is idle for a period of arbitration inter-frame space (AIFS, the duration varies according to nodes' priorities), the node can access channel immediately. Else if the channel is busy, after waiting for a period of AIFS, the node enters into the backoff process by randomly selecting a backoff counter (BC) from the range of $(0, w)$, where w is the node's current contention window (CW) size. Initially, w is set to its minimum value, $CW_{\min}$, and it doubles each time a collision occurs till it reaches to the maximum value, $CW_{\max}$. However, because feedback is not allowed in broadcast communications, 802.11p beaconing adopts a constant CW size, i.e. $CW_{\min}$.

In 802.11p vehicular ad hoc network (VANET), since the nodes broadcast only one beacon frame per CCHI, the number of contending nodes decreases as CCHI elapses. Thus, the nodes suffer from the highest collision probability at the beginning of CCHI. Also, as CCHI switches

*Correspondence: xylei@yzu.edu.cn
[1]College of Information Engineering, Yangzhou University, Yangzhou, Jiangsu, China
Full list of author information is available at the end of the article

to SCHI every 50 ms, in a dense network, the expiration of CCH may cause heavy dropping of beacon messages. So far, previous work pays little attention to these factors, or investigates them separately, which is unable to disclose how these factors jointly affect the performance of 802.11p beaconing. In light of the above inadequacies, we develop a new mathematical model in this paper and then propose a random contention window scheme to enhance the performance of 802.11p MAC. Our contributions are as follows: (1) A mathematical model considering the effects caused both by channel expiration and varying numbers of contending nodes is built. Based on this new model, the time slots where CCH expiration occurs are counted. And the successful transmission probability of beacon messages upon different network size and $CW_{\min}$ is calculated. (2) A random contention window mechanism is presented to improve the reliability of beacon message broadcasting: Instead of utilizing a constant *CW*, arrays of minimum and maximum CWs ($CW_{\min}$ and $CW_{\max}$) are provided. Nodes can randomly select a pair of $CW_{\min}$ and $CW_{\max}$, based on which they can form groups. (3) Proposed scheme is implemented on the ns-3 simulator. By performing extensive simulations, the performance gain of our proposal comparing with the legacy protocol can be verified.

The remainder of this paper is organized as follows. Section 2 reviews the related works. Section 3 presents our new analytical model, which counts the *BC* time slots where CCH expiration occurs and evaluates successful transmission probabilities. Section 4 describes the details of our proposed *random contention window* scheme, while Section 5 shows and discusses the simulation results. Finally, Section 6 gives some concluding remarks.

2 Related works

IEEE 802.11 VANET adopts the EDCA scheme for channel access control, which can provide prioritized services by enhancing the legacy DCF. Many researchers have investigated the performance of the 802.11p EDCA protocol through simulations or mathematical modeling. Eichler [5] and Martelli et al. [6] conducted extensive simulations: [5] proved that, while EDCA can prioritize messages, it can significantly degrade network performance in a dense environment. Martelli et al. [6] studied two important performance parameters of beaconing—beacon delivery rate (PDR) and beacon inter-reception time (PIR). Their results showed that PIR time distribution is heavy-tailed, while PIR and PDR are loosely correlated metrics. Qiu et al. [7] adopted verified stochastic traffic models, which incorporate the effect of urban settings (such as traffic lights and vehicle interactions) in order to study the broadcasting performance of 802.11p VANET. Utilizing stochastic geometry and queuing theory, [8] studied the transmission behavior of vehicle-to-vehicle (V2V) safety communications with non-saturated data traffic. Also, [9] investigated the connectivity properties of VANET under the impact of fading and path losses, by modeling the road systems as random line process and vehicle locations as Poisson point process.

Bianchi [10] pioneered to build a 2-D Markov chain model for the performance analysis of the 802.11 DCF protocol, focusing on a saturated network deployed under an ideal wireless channel. Zheng and Wu, Han et al., Ma et al., Li et al., Gallardo et al., Khabazian et al., Campolo et al., Stanica et al., Yang et al., Fallah et al., Yao et al., and Wang et al. [11–22] extended the Markov chain model in [10] and evaluated the performance of the 802.11p MAC protocol. In [11], 2-D and 1-D Markov chains are built in order to study the channel access performance under the factors such as saturation condition and standard parameters. Similarly, [12] studied the impact of standard parameters like CW size and AIFS duration.

Ma et al., Li et al., Gallardo et al., Khabazian et al., Campolo et al., Stanica et al., Yang et al., Fallah et al., Yao et al., and Wang et al. [13–22] devoted to investigate the performance of 802.11p MAC in the control channel (CCH), i.e., performance of broadcasting safety messages and beacons. Ma et al. [13] combined Markov chain-based models with simulations, taking hidden terminal, non-saturation traffic, and mobility into account. Li et al. [14] built a 2-D Markov chain model with finite buffers and finite loads, which includes modeling the backoff process and queueing process. Assuming CCH is continually available, both [15] and [16] evaluated the performance of broadcasting safety messages with different priorities. In contrast, [17] analyzed the effects caused by restricted channel access of CCH, i.e., switching CCHI and SCHI periodically. Stanica et al. [18] suggested a non-ergodic Markov chain for periodic beaconing, while [19] utilized a discrete time D/M/1 queue. Since transmission reliability is very important for broadcasting of message, [20] suggested a model for the broadcast-based VANET network on a highway topology and studied the effect of transmission rate and transmission range. Also, [21] analyzed the reliability of safety-critical data under both non-saturated and saturated conditions. Wang et al. [22] provided a more comprehensive model, which includes MAC protocol operations, PHY layer wireless channel conditions, and mobility of vehicles.

However, the previous models suggested for analyzing the 802.11p beaconing have paid little attention to the varying number of contending nodes [13, 14, 21], and the restricted channel access of CCH [15, 16], or investigated them separately [17]. Since the 802.11p MAC protocol is a contention-based scheme, the joint effect of the varying number of contending nodes and the restricted channel access may lead the network to perform quite differently.

In this work, we develop a new mathematic model that integrates those two factors. And based on the analysis results, we propose a random contention window scheme to improve the performance of 802.11p beaconing.

3 Analysis model

In this section, we describe our model for the performance analysis of beaconing in 802.11p vehicular networks. We assume that the network consists of N nodes and the one-hop neighbors of each node are not changed due to node mobility. CCH channel is slotted into S_M slots, and the duration of each slot varies according to the events that occur in the slot. At the ith time slot, the busy probability of the medium is denoted by p^i. Also, the nodes use a constant contention window, $CW_{\min}$, which is denoted by W. Then, based on [10], the probability τ that a tagged node transmits in a randomly chosen time slot is given by

$$\tau = \frac{2}{W+1}. \tag{1}$$

Let N_i be the number of nodes which have beacons buffered at ith time slot. Based on the 802.11p standard, each node can broadcast only one beacon frame per CCH, and retransmission is not allowed in case of collisions. Therefore, the number of contending nodes is a non-increasing function of the ith slot:

$$N_i = N_{i-1} - \begin{cases} 0 & (i-1)\text{th slot is idle} \\ 1 & (i-1)\text{th slot is busy and} \\ & \text{only one node broadcasts a beacon} \\ j & (i-1)\text{th slot is busy and} \\ & j \text{ nodes broadcast beacons} \end{cases} \tag{2}$$

Since N_i nodes have beacon frames to send at the ith time slot, the busy probability p^i of ith slot is

$$p^i = 1-(1-\tau)^{N_i}. \tag{3}$$

At the ith time slot, if the channel is busy and N_i nodes are contending, then the probability of a successful transmission p_s^i is given by

$$p_s^i = \frac{N_i\tau(1-\tau)^{N_i-1}}{1-(1-\tau)^{N_i}}. \tag{4}$$

Then, at the ith time slot, the idle probability is $1-p^i$ and the collision probability $1-p_s^i$. Note that N_1, the number of contending nodes at the first time slot, equals to N. Since j is the number of nodes which experience collisions, combining (2) $\sim$ (4) gives the value of N_i as follows: $\forall i,\ 2 \le i \le N$,

$$\begin{aligned} N_i &= N - \sum_{k=1}^{i-1}\left[p^k p_s^k + j p^k\left(1-p_s^k\right)\right] \\ &= N - \sum_{k=1}^{i-1}\left[(1-j)N_k\tau(1-\tau)^{N_k-1} + j(1-(1-\tau)^{N_k})\right] \\ &= N - j(i-1) + \sum_{k=1}^{i-1}(1-\tau)^{N_k-1}\left[\left(jN_k - N_k - j\right)\tau + j\right] \end{aligned} \tag{5}$$

For simplicity, we assume collisions are caused by no more than two nodes. Then, (5) can be simplified as, $\forall i,\ 2 \le i \le N$,

$$N_i = N - 2(i-1) + \sum_{k=1}^{i-1}(1-\tau)^{N_k-1}(N_k\tau - 2\tau + 2). \tag{6}$$

Now, we compute the duration of the ith time slot T_i. First, let us define T_s and T_c as the time durations for a successful transmission of one beacon frame and a failed transmission due to a collision, respectively:

$$\begin{aligned} T_s &= T_h + L/R + AIFS \\ T_c &= T_h + L/R + EIFS, \end{aligned} \tag{7}$$

where L is the packet length, R the data rate, and T_h the duration of the physical layer convergence protocol (PLCP) preamble and header. Using the idle probability and collision probability of the ith slot, we have

$$T^i = (1-p^i)\delta + T_s p^i p_s^i + T_c p^i\left(1-p_s^i\right), \tag{8}$$

where δ is the duration of one idle time slot which is defined in the 802.11p standard. Using (8), we can compute the duration of totally exhausted channel, T_e, which is the summation of all time slots before the CCH expires. If we assume the expiration occurs at the mth time slot, then

$$\begin{aligned} T_e &= T_g + \sum_{i=1}^{m} T^i \\ &= (mT_c + T_g) + \sum_{i=1}^{m}(1-\tau)^{N_i-1}\left[\,(\delta - T_c)(1-\tau) - \tau\alpha N_i\right], \end{aligned} \tag{9}$$

where T_g is the guard interval. The second equality of (9) is derived by denoting $T_c = T_s + \alpha$, where $\alpha = EIFS - AIFS$, and also from (3) and (4).

We then define the satisfactory ratio R as follows:

$$R = \frac{\text{Number of provided time slots}}{\text{Number of expected time slots}},$$

where the numerator counts how many time slots have been generated before CCH expiration occurs. Since it equals to m, we can obtain its value by solving (9) under the condition that $T_e \le T_{CCH}$, i.e., the broadcasting of beacons cannot exceed T_{CCH}. Similarly, the number of expected time slots indicates the time slots required for all the nodes to transmit one beacon on a continually available channel: Its value can be obtained through (9) by replacing the parameter m with N, which is the number of nodes in the current network.

Table 1 shows the parameters which are used in our analysis. For different values of the number of nodes and the contention window sizes, we can find m, the time slot where a CCH timeout occurs, and R, the satisfactory ratio, as in Table 2. In the network of 20 nodes and $CW_{\min} = 32$, one can see that the maximum number of time slots provided by the CCH channel is 36.9. Also, the satisfactory ratio reaches 100% in small size networks, such as networks with less than 60 nodes. However, as the number of nodes or the contention window size increases, the number of available time slots is reduced, e.g., in the 100-node network with $CW_{\min} = 128$, the number of provided BC time slots is only 31.9. Moreover, the satisfactory ratio R in dense networks degrades more severely, e.g., in the network with 80 nodes, only 80% nodes can obtain slots for broadcasting beacon messages, and in the network with 100 nodes, the ratio is reduced to 64%.

Now, using the parameters given in Table 1, we compute the successful transmission probability of beacons by (4), while varying the network size and the contention window size. The obtained results are presented in Fig. 1a–d. One can find that, since sufficient time slots are provided in small size networks, nodes can complete their broadcasting of beacons before the CCH expires: In the networks with 20 and 60 nodes in Fig. 1a and b, the successful transmission probability drops to 0 at the 20th and 30th time slot, respectively, because the nodes complete their beacon broadcasting. On the contrary, dense networks suffer from severe channel resource starvation: As shown in Fig. 1c and d, the nodes' probabilities are still considerably high at the time slot where the CCH expiration occurs, e.g., at the 32th time slot with a contention window of 128, the successful transmission probabilities are 18% and 31%, respectively, for networks with 80 and 100 nodes.

Table 1 Parameters in analysis

Parameters	Value
Packet size	500 bytes
Channel period (CCH+SCH)	100 ms
Beacon generation rate	10 Hz
Data rate	3 Mbps
Slot time	16 μs
SIFS time	32 μs
AIFSN	2
EIFS	188 μs
Header duration (T_h)	40 μs
Packet generation rate	10 Hz

Table 2 Provided time slots and satisfactory ratio

CW_{min}	No. of nodes							
	20		60		80		100	
	m	R	m	R	m	R	m	R
32	36.9	1.0	32.8	1.0	32.6	0.8	32.6	0.64
64	33.1	1.0	32.1	1.0	32.1	0.8	32.1	0.64
128	33.8	1.0	31.9	1.0	31.9	0.79	31.9	0.63

In summary, although increasing the contention window size can reduce the collision probability, a large CW size may increase the channel access delay and cause dropping of beacons due to the channel expiration. Therefore, it is important to adopt a proper size of contention window in order to enhance the reliability of the 802.11p beaconing.

4 Random contention window selection

4.1 Overview

Based on the previously analyzed results, in this section, we propose a *random contention window scheme* to improve the performance of 802.11p MAC on broadcasting. Since the reliability of broadcasting message is a main concern of our work, we assume nodes compete channel under the same priority. The key idea of our proposal is as follows. Instead of applying a constant contention window, CW, where nodes randomly select a BC from range $(0, w)$, here w is the value of CW, they are supplied with minimum and maximum contention window ($CW_{\min}$ and $CW_{\max}$) arrays. During backoff process, nodes can select a pair of numbers, $CW_{\min}$ and $CW_{\max}$, from provided arrays, and the BC is determined by randomly choosing a number from range $(CW_{\min}, CW_{\max})$. The contention window array sizes can be tuned according to the network scale, i.e., with large-scale networks, arrays with more available numbers are provided, and with small-scale networks, arrays with fewer available numbers are supplied. Since the nodes adopting the same $CW_{\min}$ and $CW_{\max}$ form a group and channel access contentions only occur among nodes belonging to the same group, our scheme is expected to efficiently reduce the collisions occurred in CCH.

4.2 Determination of contention window

The details of the proposed scheme are the same as illustrated in Fig. 2. We assume the road site units (RSUs) are equipped along the road, let N denote the number of nodes associated with an RSU, n denote the group size, and k denote the number of groups, clearly $k = N/n$. Also, let $CW_{\min}[k]$ and $CW_{\max}[k]$ denote the arrays of

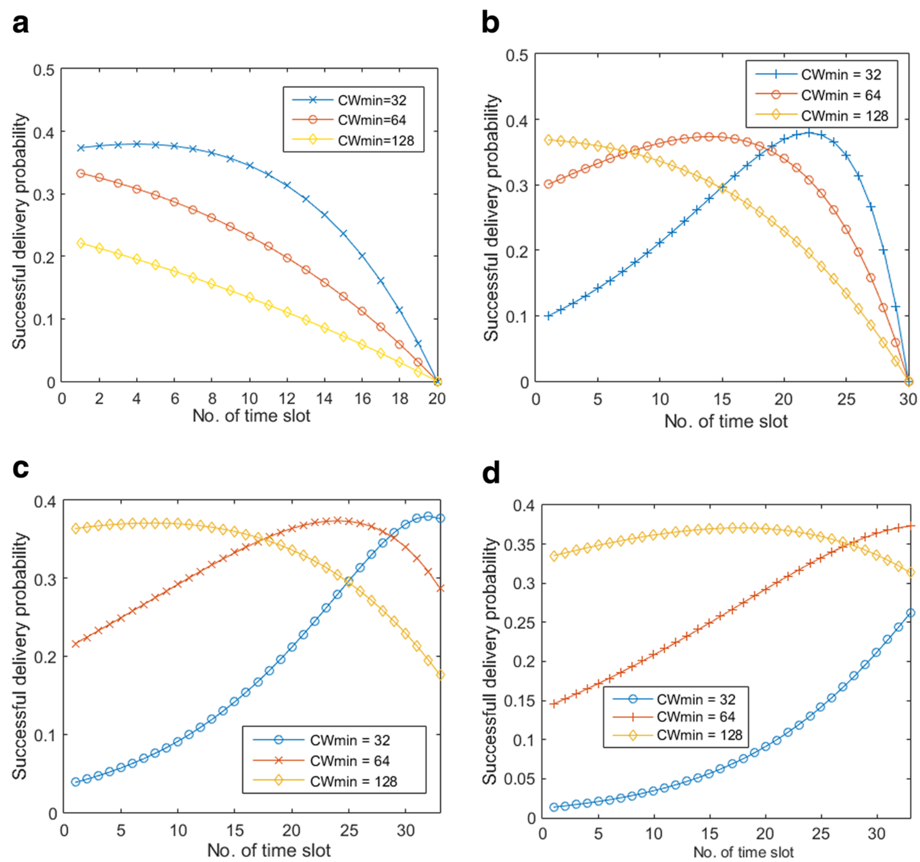

Fig. 1 a–d Successful transmission probability. **a** 40-node network, **b** 60-node network, **c** 80-node network, **d** 100-node network

$CW_{\min}$ and $CW_{\max}$, which can provide k values individually. Through randomly selecting an integer i from the range $(0, k)$, a node can obtain one pair of minimum and maximum contention windows, $CW_{\min}[i]$ and $CW_{\max}[i]$, the difference between which is ϵ. The nodes select the same number from $(0, k)$, i.e., i, applying the same minimum and maximum contention windows, $CW_{\min}[i]$ and $CW_{\max}[i]$, and they fall into a group. The nodes' backoff counters can be determined through randomly selecting a number from range $(CW_{\min}[i], CW_{\max}[i])$. Note that the value of ϵ, which is the difference between each pair of $CW_{\min}[i]$ and $CW_{\max}[i]$, determines the number of BC time slots that can be generated from the range $(CW_{\min}[i], CW_{\max}[i])$.

In order to set the values of n and ϵ, we first give a brief review on a work in [10]. Bianchi [10] proves that the optimal contention window size of the 802.11 DCF scheme can be obtained by $W_{\text{opt}} = N\sqrt{2T_c/\delta}$, where N is the number of contending nodes, δ the duration of an idle time slot, and T_c the time duration of a failed transmission due to collisions, as in Section 3. As [10] investigates the legacy protocol, where BC is selected from the range $(0, W_{\text{opt}})$, one can conclude that the optimum number of BC time slots required by N nodes is W_{opt}. As the number of BC time slots in our work depends on ϵ, we propose to set the value of ϵ to be $n\sqrt{2T_c/\delta}$, where n is the group size. In the numerical example given in Section 3, the 802.11p beaconing performs better in a network consisting of 20 nodes, we propose to set n to be 20. Using the parameters given in Table 1 while setting n to be 20, we can find the optimum value of ϵ is 32, which exactly corresponds with the analytic result shown in Fig. 1a.

In our proposal, nodes communicating with the same RSU utilize the same contention window arrays, the size of which are determined by k, and the values of the members are determined by ϵ. These parameters, k and ϵ, are broadcast by the RSU periodically, i.e., piggyback them into the beacon messages. For a node freshly moves into the RSU's coverage, the parameters can be sent to the node during its association process. Because 802.11p supports the Outside the Context of Basic service set (OCB) mode, nodes may transmit/receive data to/from a RSU without associating with it. In such a case, the node is enabled to perform the backoff process according to the legacy protocol.

N: number of nodes associated with an RSU

n: number of nodes per group

k: number of groups

$CW_{min}[k]$: the array of minimum contention windows for *k* groups

$CW_{max}[k]$: the array of maximum contention windows for *k* groups

ε: difference between each pair of CW_{min} and CW_{max}

BC_j : backoff counter of node *j*

Initial step:

$k = N/n$

$\varepsilon = n\sqrt{2T_c^*}$

$CW_{min}[k] = \{0, \varepsilon+1, 2\varepsilon+2, \ldots, (k-1)(\varepsilon+1)\}$

$CW_{max}[k] = \{\varepsilon, 2\varepsilon+1, 3\varepsilon+2, \ldots, k(\varepsilon+1)-1\}$

Backoff counter determination:

for (j=0; j<n; j++) {

Node *j* randomly selects a number *i* from $(0, k)$

Node *j* sets its CW_{min} and CW_{max}:

$CW_{min}[i] = (i-1)(\varepsilon+1)$, $CW_{max}[i] = i(\varepsilon+1)-1$

Node *j* set its backoff counter BC_j by randomly selecting a number from range ($CW_{min}[i]$, $CW_{max}[i]$):

$BC_j = (CW_{min}[i], CW_{max}[i])$

}

Fig. 2 Random contention window selection algorithm

4.3 Additional issues

Our proposal can improve the performance of 802.11p MAC on broadcasting as follows. Comparing with the legacy protocol, where only a constant contention window is available, our proposal provides nodes with contention window arrays, which makes the nodes form groups based on the chosen values. Since the configuration of group size as well as the contention window ranges are based on our analytical results, proposed scheme is expected to reduce collisions that occurred in CCH efficiently. In addition, our proposal totally works in a distributed fashion, although the parameters related to the contention window arrays are broadcast by the RSUs periodically, due to their small sizes, the involved overhead can be neglected.

5 Performance evaluation

In this section, we conduct simulations using *ns-3* to evaluate the performance of our proposed scheme. 802.11p MAC/PHY technologies and the channel switching schemes of IEEE 1609.4 standard are implemented in the ns-3 simulation environment. We consider a 300 $\times$ 1500 m^2 highway, where nodes are moving according to a random way-point mobility model with a speed of 20 m/s. Nodes are allowed to broadcast 500-byte beacon messages 10 times per second at 6 Mbps. The 10-MHz CCH is provided with a duration of 50 ms, and the two-ray ground model is adopted as a propagation model. Based on our analysis in the previous section, the group size n is set to 20, and the number of BC time slots available for each group is set to 32. More details on the simulation parameters can be found in Table 3.

We first evaluate the packet reception rate with regard to the safety ranges and the network sizes. The packet reception rate is defined as follows:

$$\text{Packet reception rate} = \frac{\text{Actual number of received packets within safety range}}{\text{Expected number of received packets within safety range}},$$

Table 3 Parameters in simulation

Parameters	Value
Road region	300*1500 m^2
Average speed	20 m/s
Packet size	500 bytes
Control channel period (CCH)	50 ms
Beacon generation rate	10 Hz
Data rate	6 Mbps
Group size (n)	20
Contention window step size (δ)	32

where the safety range is the length of the side of a predefined square. In the simulations, transmissions and receptions of beacons occurred in each square are recorded: Any two nodes can receive beacons from each other only if the euclidean distance between them is less than the safety range. A successful reception of the beacon also depends on whether the sender has successfully broadcast a beacon, i.e., the transmission collision as well as the CCH timeout will cause a reception failure. Therefore, the packet reception rate is a metric that shows how the performance of the 802.11p protocol is affected by factors like the varying number of contending nodes, the restricted channel access, and the mobility of nodes. We will use

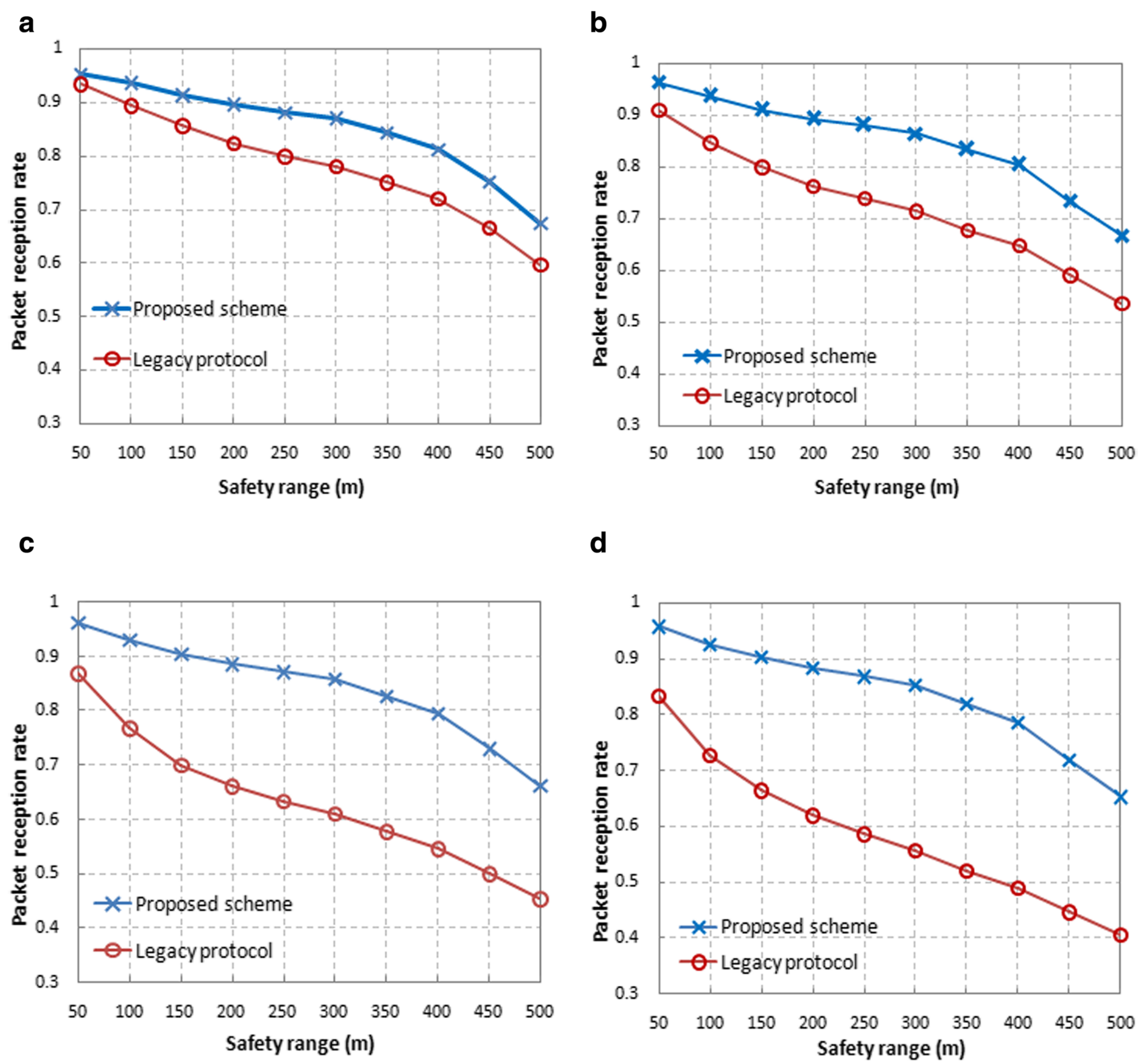

Fig. 3 a–**d** Packet reception rates. **a** 40-node network, **b** 60-node network, **c** 80-node network, **d** 100-node network the metric to compare the performances of our proposed protocol and the legacy one.

Figure 3 a–d show that, in both our protocol and the legacy one, the packet reception rate decreases as the safety range increases. However, our scheme maintains the rate at 68% even with the 500-m safety range. Also, the packet reception rate of the legacy protocol decreases more severely in large size networks: In the networks consisting of 80 and 100 nodes, the reception rates decrease to 45% and 40%, respectively. On the other hand, increasing the network size does not affect the packet reception rates in our protocol: Even in the 100-node network, the packet reception rate is identical to that of the 40-node network under the same safety range. Such a performance improvement is possible because our proposed scheme enables the nodes to form groups according to their selected contention windows. Note that the group size and the numbers of *BC* time slots available for each group are set to the optimum values which are obtained by the analysis model and that contentions occur only among the nodes belonging to the same group. Therefore, our protocol efficiently reduces the packet losses caused by collisions and the channel expiration.

Figure 4 a–d illustrate the end-to-end delays in our protocol and the legacy one. The end-to-end delays increase as the safety ranges grow up in both protocols, and they increase dramatically in large size networks, e.g., networks with 80 or 100 nodes. Compared with the legacy one, our proposed protocol shows 3-ms larger delays in average for the network of 60 nodes, and 5–6-ms larger delays in network of 80 or 100 nodes. Since the contention window sizes in the legacy protocol are normally small and

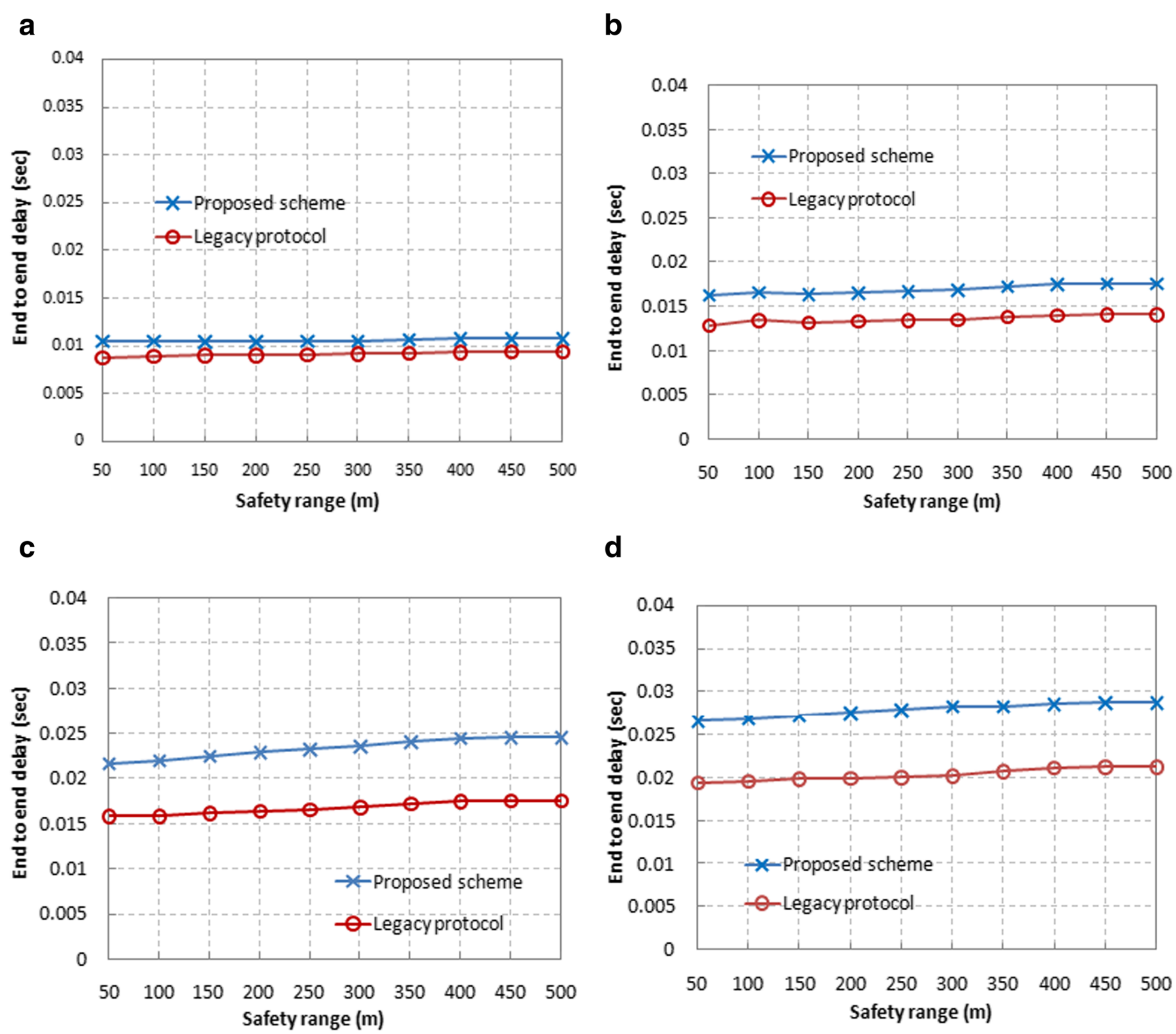

Fig. 4 a–**d** End-to-end delay. **a** 40-node network, **b** 60-node network, **c** 80-node network, **d** 100-node network constant, less delays are possible. In our proposed scheme, on the other hand, nodes are provided with minimum and maximum contention window arrays, and most of the provided values are larger than 32 (the constant contention window adopted by the legacy protocol). Note that, however, in return for the slight increment in the end-to-end delay, our protocol provides the considerable performance improvement in terms of the packet reception rate: For the 802.11p beaconing, reliability is one of the most important requirements.

6 Conclusion

In this work, we have proposed a new analytic model to investigate the performance of 802.11p MAC protocol on beaconing, especially regarding the effects caused both by varying numbers of contending nodes and by the restricted channel access. Based on the result of the analytic modeling, we presented a *random contention window* scheme to enhance the performance of 802.11p. Instead of adopting a constant contention window size, our scheme provides arrays of minimum and maximum contention windows, from which the nodes can randomly select a pair of $CW_{\min}$ and $CW_{\max}$. Nodes that select the same pair of $CW_{\min}$ and $CW_{\max}$ form a group, and they contend to access the channel. The optimal contention window size for the group is also discussed, and we can see that our analytic modeling is correct. Finally, we conducted extensive simulations using ns-3 to evaluate the performance of the proposed scheme, and the results show that our proposal efficiently enhances the broadcast performance of the 802.11p MAC protocol.

Abbreviations

AIFS: Arbitration interframe space; AIFSN: AIFS number; BC: Backoff counter; CCH: Control channel; CCHI: CCH interval; CW: Contention window; $CW_{\min}$: Minimum CW; $CW_{\max}$: Maximum CW; DCF: Distribution coordination function; DSRC: Dedicated short-range communication; EDCA: Enhanced distributed channel access; EIFS: Extended interframe space; ITS: Intelligent transportation systems; MAC: Media access control; OCB: Outside the context of basic service set; PHY: Physical; SI: Synchronization interval; RSU: Road site units; SCH: Service channel; SCHI: SCH interval; SIFS: Short interframe space; VANET: Vehicular ad hoc network; V2V : Vehicle to vehicle; WAVE: Wireless access in vehicular environment

Funding

This work was supported by Natural Science Foundation of the Jiangsu Higher Education Institutions (16KJB520044), Basic Science Research Program through the National Research Foundation of Korea (2017R1D1A1B03028184), and in part by the research grant of Kwangwoon University in 2017.

Availability of data and materials

Not applicable.

Authors' contributions

XL proposed the analysis model as well as the random contention window scheme, derived the mathematical equations, and performed the simulations and manuscript writing. SHR contributed in the manuscript revision and correction. Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

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

Author details

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

Received: 27 April 2018 Accepted: 21 February 2019
Published online: 12 March 2019

References

1. S. Biswas, R. Tatchikou, F. Dion, Implementation and evaluation of scalable vehicle-to-vehicle safety communication control. IEEE Commun. Mag. **49**(11), 134–141 (2011)
2. C.-Y. Chang, H.-C. Yen, D.-J. Deng, V2V QoS guaranteed channel access in IEEE 802.11p VANETs. IEEE Trans. Dependable Secure Comput. **13**(1), 5–17 (2016)
3. S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, H. Zedan, A comprehensive survey on vehicular ad hoc network. J. Netw. Comput. Appl. **37**(9), 380–392 (2014)
4. IEEE, 802.11p-2010, IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks specific requirements part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 6: wireless access in vehicular environments, 1–51 (2010)
5. S. Eichler, in *Proceeding IEEE VTC*. Performance Evaluation of the IEEE 802.11 p WAVE Communication Standard (IEEE, 2007), pp. 2199–2203
6. F. Martelli, M. E. Renda, G. Resta, P. Santi, in *Proceeding IEEE Infocom*. A Measurement-based Study of Beaconing Performance in IEEE 802.11p Vehicular Networks (IEEE, 2012), pp. 1503–1511
7. H. J. F. Qiu, I. W.-H. Ho, C. K. Tse, Y. Xie, A methodology for studying 802.11p VANET broadcasting performance with practical vehicle distribution. IEEE Trans. Veh. Technol. **37**(9), 4756–4768 (2015)
8. Z. Tong, H. Lu, M. Haenggi, C. Poellabauer, A stochastic geometry approach to the modeling of DSRC for vehicular safety communication. IEEE Trans. Intell. Trans. Syst. **17**(5), 1448–1458 (2016)
9. D. H. Thuan, H. V. Cuu, H. N. Do, VANET modeling and statistical properties of connectivity in urban environment. REV J. Electron. Commun. **3**(1-2), 50–58 (2013)
10. G. Bianchi, Performance analysis of the IEEE 802.11 distributed coordination function. IEEE J. Sel. Areas Commun. **18**, 535–547 (2000)
11. 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)
12. C. Han, M. Dianati, R. Tafazolli, R. Kernchen, X. (S.). Shen, Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks. IEEE Trans. Intell. Transp. Syst. **13**(2), 873–886 (2012)
13. X. Ma, X. Chen, H. H. Refai, in *Proceeding IEEE VTC-2007 Fall*. Unsaturated Performance of IEEE 802.11 Broadcast Service in Vehicle-to-Vehicle Networks (IEEE, 2007), pp. 1957–1961
14. B. Li, B. Hu, R. P. Liu, S. Chen, in *Proceeding IEEE ICC, & quot*. Modeling and QoS Analysis of IEEE 802.11 Broadcast Scheme in Vehicular Ad Hoc Networks (IEEE, 2013), pp. 6444–48
15. J. R. Gallardo, D. Makrakis, H. T. Mouftah, Mathematical analysis of EDCA's performance on the control channel of an IEEE 802.11p WAVE vehicular network. EURASIP J. Wirel. Commun. Netw. **2010**(489-527), 1–15 (2010)
16. M. Khabazian, S. Aissa, M. Mehmet-Ali, Performance modeling of safety messages broadcast in vehicular ad hoc networks. IEEE Trans. Intell. Transp. Syst. **14**(1), 380–387 (2013)
17. C. Campolo, A. Vinel, A. Molinaro, Y. Koucheryavy, Modeling broadcasting in IEEE 802.11p/WAVE vehicular networks. IEEE Commun. Lett. **15**(2), 199–201 (2011)
18. R. Stanica, E. Chaput, A. Beylot, in *Proceeding IEEE ICC*. Enhancements of IEEE 802.11p Protocol for Access Control on a VANET Control Channel (IEEE, 2011), pp. 1–5
19. Q. Yang, J. Zheng, L. Shen, in *Proceeding IEEE Globecom*. Modeling and Performance Analysis of Periodic Broadcast in Vehicular Ad Hoc Networks (IEEE, 2011), pp. 1–5

20. Y. P. Fallah, C.-L. Huang, R. Sengupta, H. Krishnan, Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicle safety systems. IEEE Trans. Veh. Technol. **60**(1), 233–247 (2011)
21. Y. Yao, L. Rao, X. Liu, Performance and reliability analysis of IEEE 802.11p safety communication in a highway environment. IEEE Trans. Veh. Technol. **62**(9), 4198–4212 (2013)
22. H. Wang, R. P. Liu, W. Ni, W. Chen, I. B. Collings, VANET modeling and clustering design under practical traffic channel and mobility conditions. IEEE Trans. Commun. **63**(3), 870–881 (2015)