Performance Analysis of IEEE 802.11p DCF for Multiplatooning Communications With Autonomous Vehicles

Haixia Peng, *Student Member, IEEE*, Dazhou Li, Khadige Abboud, Haibo Zhou, *Member, IEEE*, Hai Zhao, Weihua Zhuang, *Fellow, IEEE*, and Xuemin (Sherman) Shen, *Fellow, IEEE*

***Abstract*—Platooning has been identified as a promising framework to improve road capacity, on-road safety, and energy efficiency. Enabling communications among vehicles in platoons is expected to enhance platoon control by keeping constant intervehicle and interplatoon distances. Characterizing the performance of intra- and interplatoon communications in terms of throughput and packet transmission delays is crucial for validating the effectiveness of information sharing on platoon control. In this paper, we introduce an IEEE 802.11p-based communication model for multiplatooning (a chain of platoons) scenarios. We present a probabilistic performance analysis of distributed-coordination-function-based intra- and interplatoon communications. Expressions for the transmission attempt probability, collision probability, packet delay, packet-dropping probability, and network throughput are derived. Numerical results show that the performance of interplatoon communications is affected by the transmissions of the first and last vehicles in a multiplatoon. This effect is reduced with an increase of the platoon number in the multiplatoon. In addition, the communication performance for three typical multiplatooning application scenarios is investigated, indicating that the IEEE 802.11p-based communication can support the timely delivery of vehicle information among platoons for diverse on-road applications.**

***Index Terms*—Autonomous vehicles, intervehicle communication, multiplatooning, performance analysis, 802.11p distributed coordination function (DCF).**

Manuscript received December 31, 2015; revised April 2, 2016; accepted May 17, 2016. Date of publication May 23, 2016; date of current version March 10, 2017. This work was supported in part by NSERC, by the National Natural Science Foundation of China under Grant 60973022, and by the China Scholarship Council. This paper was presented in part at the IEEE Global Communications Conference, San Diego, CA, USA, December 6–10, 2015. The review of this paper was coordinated by Dr. P. Lin.

H. Peng is with the School of Information Science and Engineering, Northeastern University, Shenyang 110004, China, and also with the University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: penghaixiauw@gmail.com).

D. Li is with the College of Computer Science and Technology, Shenyang University of Chemical Technology, Shenyang 110142, China (e-mail: lidazhouzaku@gmail.com).

K. Abboud, H. Zhou, W. Zhuang, and X. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: khabboud@uwaterloo.ca; h53zhou@uwaterloo.ca; wzhuang@uwaterloo.ca; sshen@uwaterloo.ca).

H. Zhao is with the School of Information Science and Engineering, Northeastern University, Shenyang 110004, China (e-mail: zhaoh@mail.neu.edu.cn).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2016.2571696

I. Introduction

Traffic jams represent a serious problem for commuters every day, leading to long traveling delays and economic losses [2]. A potential approach to solving traffic jams on highways is platooning [3]. Platooning is a vehicle traffic management strategy in which autonomous/semiautonomous vehicles organize themselves, on the same lane, into a set called a *platoon*.[1] Each platoon is led by a leader vehicle (detailed definition of leader vehicle is given out in Section II-A). Grouping vehicles in the same lane into a platoon can keep them moving at a constant speed, following one another in a train-like manner, and having small constant intervehicle spacing ahead [5]–[7]. In the future, the autonomous platooning system in each vehicle is expected to take over steering, braking, and accelerating, allowing the driver to carry out other activities, such as reading books, using laptops, and chatting with friends. Platooning has been identified as a promising framework in intelligent transportation systems (ITS) [8]. In addition to reducing traffic jams, platooning helps improve on-road safety and reduce fuel consumption and exhaust emissions [7]. Furthermore, recent technological advances in vehicle automation (e.g., Google's driveless car [9]) are opening a new prospect for platooning and multiplatooning. When the number of vehicles increases, a chain of platoons that follow one another, which is referred to as *multiplatooning*, as shown in Fig. 1, is considered instead of one big platoon [3], [10]. With the help of the leader vehicle in each platoon, a multiplatoon enables higher vehicle traffic flow and lower management complexity than a single large platoon, particularly in a highly dynamic scenario [3], [11].

Despite the potential benefits of platooning, forming and maintaining a multiplatoon, as vehicles join and leave it, are not easy tasks. Maintaining constant intraplatoon/interplatoon spacing is a key issue in platoon control. When a vehicle moves in/out of a platoon, the platoon control system (such as the autonomous cruise control (ACC) system [12] and cooperative ACC [13]) in the following vehicle causes it to accelerate/decelerate to account for the spacing change (error). However,

[1]The platooning considered here is different from node clustering. The latter is a network management strategy that groups nearby vehicles into different *clusters* as they appear in vehicle traffic patterns [4].

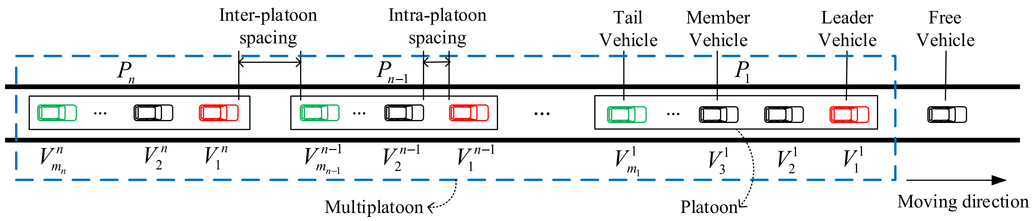


Fig. 1. Multiplatoon in a single lane.

a serious problem called *string instability*[2] can occur. String instability becomes more significant in a multiplatoon as the spacing error propagates among multiple platoons. A promising solution to this problem is to enable communications among vehicles, leading to a potential for vehicular ad hoc networks (VANETs) [6], [14]–[21]. In a platoon, a vehicle can wirelessly transmit its velocity and acceleration information (acquired from on-board sensors) to the leading and/or following vehicle in the same/preceding platoon. Existing studies show that the information exchange within a platoon and among platoons can help in preventing the spacing error from amplifying [6] and, hence, maintaining string stability [16]. Additionally, sharing braking information (from the vehicle's autonomous system) among vehicles in the multiplatoon can enhance platoon control [20]. When a vehicle leaves/enters a platoon, it sends a message to alert its platoon members and other platoons, thus allowing simultaneous reactions that enhance platoon control and road safety. A successful and timely delivery of the platoon messages (containing velocity, acceleration, braking, and/or leaving information) is critical in platoon control [6], on-road safety [20], and platooning applications. This calls for an efficient method of communications among vehicles in a multiplatoon.

In October 1999, the U.S. Federal Communications Commission allocated 75 MHz of radio spectrum in the 5.9-GHz band to be used for dedicated short-range communication (DSRC) by ITS. There are seven 10-MHz channels in the DSRC spectrum, i.e., one control channel (CCH) and six service channels (SCHs). An amendment of the IEEE 802.11 Wi-Fi standard has been approved for wireless access in vehicular environment [22]. Currently, the IEEE 802.11p medium access control (MAC) protocol is the only standard MAC for VANETs, which uses an enhanced distributed coordination function (DCF). For a road scenario that lacks roadside infrastructure support, DSRC becomes the only way for intervehicle communications. However, the dynamic nature of vehicular traffic on a highway can affect the communication performance [23]. The DCF operation in a vehicular environment can result in packet transmission failures, increasing packet transmission delay, and inducing low throughput. The analysis of communication performance determines the effectiveness of VANETs to support platoons [6], [20]. This calls for an analytical model that studies the DCF performance (in terms of the transmission collision probability, transmission attempt probability, packet delay, packet-dropping probability, and throughput) for multiplatooning communications. Despite the importance of the analytical model, ideal communication performance has been assumed in providing timely delivery of all required information for platoon control and road safety [6], [17], or the performance has been evaluated through simulations [20].

In this paper, we present an IEEE 802.11p-based communication model for multiplatooning, including the intraplatoon/interplatoon communications. To evaluate whether the DSRC can support platoons, a general probabilistic performance analysis of multiplatooning communications is proposed. The performance of DCF for intraplatoon/interplatoon communications is analyzed based on Markov chains. Specifically, for interplatoon communications, we derive expressions for the transmission attempt probability, packet transmission collision probability, packet delay, packet-dropping probability, and network throughput. Numerical results show that the performance of interplatoon communications is affected by the first and last vehicles in the multiplatoon, and the effect reduces with an increase of the platoon number in the multiplatoon. Additionally, the average end-to-end delay of a packet transmitted from the first platoon to the last platoon in a multiplatoon can be reduced by adjusting the contention window size and maximum backoff stage. Furthermore, we analyze the end-to-end delay of the multiplatoon communication for three different application scenarios. Numerical results indicate that multiplatooning communications based on DCF can satisfy the delay requirements of platoon control and on-road safety.

II. System Model

A. Multiplatooning Scenario

Consider a multiplatoon, i.e., a chain of n connected platoons, traveling on the same lane in a multilane highway. Fig. 1 shows the multiplatooning scenario under consideration. Label the n platoons with platoon IDs $P_1, P_2, \ldots, P_{n-1}, P_n$, where P_1 is the leading platoon, and P_n is the last following platoon in the chain. Denote V_i^j as the vehicle ID of the ith vehicle in the jth platoon, i.e., P_j, and m_j as the number of vehicles in platoon P_j, where $1 \leq j \leq n$. Let $m_{\max}$ be the maximum number of vehicles in a platoon, i.e., $m_j \leq m_{\max}$, and the value of $m_{\max}$ should be determined to soft guarantee one-hop communications among any two vehicles in the same platoon (further discussed in Section III-A). This is to reduce the influence from uncertain transmission delays within one platoon [24] and the disturbance between any two adjacent platoons [25].

[2]The string instability of a multiplatoon refers to the problem of amplification of the spacing error in intervehicle distances within the multiplatoon. This amplification occurs as the spacing error propagates toward the tail of the platoon and the end of the multiplatoon [6].

A vehicle in the considered multiplatooning scenario can be one of three types: a leader vehicle, a tail vehicle, and a member vehicle. A *leader vehicle* is the vehicle that leads other vehicles in one platoon, e.g., vehicle V_1^j is the leader vehicle of platoon P_j. A leader vehicle can 1) create and manage the platoon with the help of an advanced traffic management system, e.g., control the number of vehicles in its platoon and inform a newly joined vehicle to use which SCH for data transmission, and 2) collect and transmit information to and from other vehicles (vehicles in the same platoon and in other platoons). A *tail vehicle* is the last following vehicle in a platoon, which is responsible for communicating with the leader vehicle in the following platoon. The tail vehicle of platoon P_j is vehicle $V_{m_j}^j$. We refer to the set of leader and tail vehicles in the multiplatoon as *backbone vehicles*. A *member vehicle* is a vehicle within the platoon that is a nonleader vehicle. Vehicles within platoons follow a specified driving strategy. The vehicle that does not belong to any platoon and in the same lane is regarded as a candidate for the multiplatoon, and we call it as a free vehicle. As shown in Fig. 1, define the intraplatoon spacing as the distance between two consecutive vehicles in a platoon, i.e., the distance from the bumper of one vehicle to the rear of its preceding vehicle. Interplatoon spacing is the distance between the bumper of the leader vehicle in a platoon and the rear of the tail vehicle in the preceding platoon, e.g., the distance between V_1^{j+1} and $V_{m_j}^j$, where $1 \le j < n$.

B. Communication Model

We assume that all vehicles within a platoon are one-hop neighbors, and vehicles communicate with vehicles in other platoons via one-hop or multihop communications. To reduce the interference between intraplatoon and interplatoon communications, each vehicle in the multiplatoon is equipped with two radio-frequency transceivers, i.e., transceiver 1 and transceiver 2. Transceiver 1 is used for one-hop intraplatoon communications, and transceiver 2 is used for multihop interplatoon communications, as shown in Figs. 2(a) and 3(a). Based on IEEE 1609.4 [26], which is a standard for wireless access in vehicular multichannel environments, let transceiver 1 and transceiver 2 synchronously alternate operation on the CCH and one SCH, respectively. Here, the common time base used in the synchronization function is the coordinated universal time, which can be obtained from the vehicle's global positioning system receiver [27]. We assume that each transceiver is allocated one of the SCHs, such that the SCH used for interplatoon communication is different from that used for intraplatoon communications. This can be achieved by a channel negotiation process during the CCH (i.e., when the transceiver is tuned to the CCH) that can select which SCH to be used for data transmission [28]. Data transmissions among vehicles in the multiplatoon occur during the SCH interval of each transceiver. In the rest of this work, we will focus on the analysis of communication during an SCH interval. Time is divided into equal time slots with duration ρ.

We focus on analyzing the communication performance in a multiplatoon, including the single-hop intraplatoon communications and the multihop interplatoon communications. An

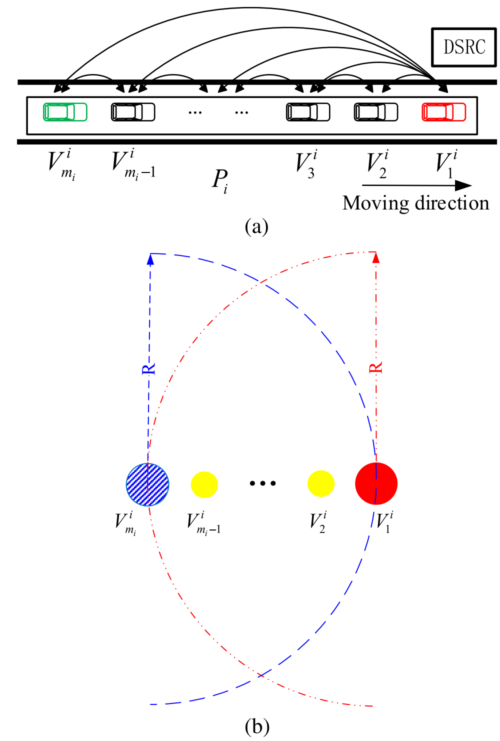


Fig. 2. Intraplatoon communication model in multiplatooning. (a) Intraplatoon communications. (b) Single-hop intraplatoon communications.

intraplatoon communication model of platoon P_i is shown in Fig. 2(b), and the interplatoon communication model for a multiplatoon with n platoons is shown in Fig. 3(b). Note that only the backbone vehicles in the multiplatoon engage in interplatoon communications. For convenience, we relabel the $2n$ backbone vehicles (n leader vehicles and n tail vehicles) with IDs 1 to $2n$, as shown in Fig. 3(b), and refer to the *backbone vehicle* i as *vehicle* i for short, where $1 \le i \le 2n$. In addition to providing each vehicle with the required information for platoon control and road safety, information sharing among vehicles in the multiplatoon can support other applications.

Take the interplatoon communications as an example. Transceiver 2 is used to access an SCH according to the IEEE 802.11p DCF protocol [29]. To reduce data packet transmission collisions, DCF uses a backoff mechanism before attempting retransmission, where the backoff time is uniformly chosen from $(0, \omega - 1)$, and ω is the *contention window size*. At the first transmission attempt of a packet, ω is set to the *minimum contention window* $W = CW_{\min}$. After each unsuccessful transmission, ω is doubled, up to a maximum value $CW_{\max} = 2^M CW_{\min}$, and M is the *maximum backoff stage*. The retransmission limit is reached when the number of transmission failures of a packet reaches $M + 1$ and the packet is dropped. Here, we analyze the multiplatooning communications under a practical SCH condition, i.e., a packet can encounter transmission errors caused by channel impairments with probability p_e. The data traffic condition is unsaturated. Let q_p be the probability that a vehicle has at least one packet waiting to be transmitted on transceiver 1 in a given time slot and q_i be the probability that vehicle i has at least one packet waiting to be transmitted on transceiver 2 in a given time slot.

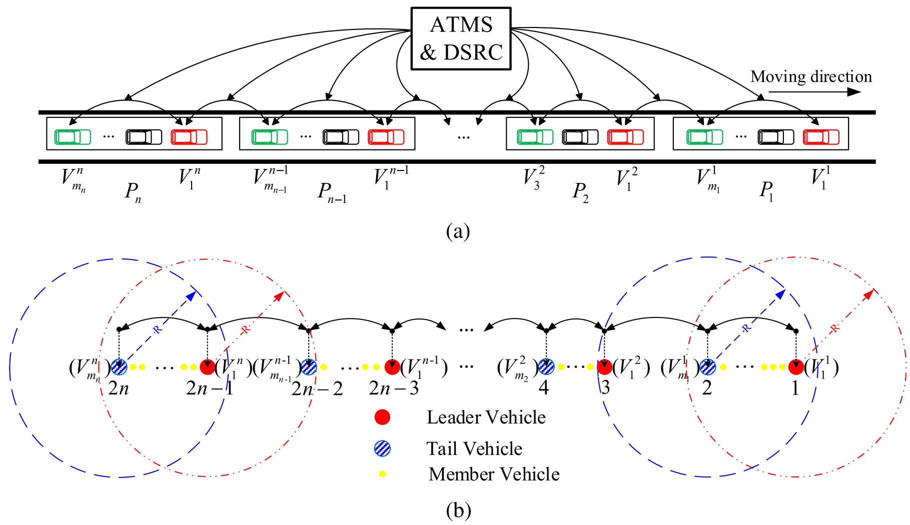


Fig. 3. Interplatoon communication model in multiplatooning. (a) Interplatoon communications. (b) Multihop interplatoon communications.

C. Vehicle Mobility Model

Vehicles in the multiplatoon move according to the intelligent driver car-following model (IDM) [30]. Consider the ith vehicle, i.e., V_i, in a platoon at a certain time slot t. Denote $S_i^*(t)$ and T_0 as the desired gap to the preceding vehicle V_{i-1} and the desired time headway.[3] At time slot t, let $S_i(t)$, $v_i(t)$, $a_i(t)$, and $\Delta v_i(t)$ be the intraplatoon spacing, the velocity, the acceleration, and the velocity difference to V_{i-1} for vehicle V_i, respectively. The IDM can be expressed by the following two relations [30]:

$$S_i^*(t) = s_0 + v_i(t)T_0 + \frac{v_i(t)\Delta v_i(t)}{2\sqrt{ab}} \tag{1}$$

$$a_i(t) = a\left[1 - \left(\frac{v_i(t)}{v_0}\right)^4 - \left(\frac{S_i^*(t)}{S_i(t)}\right)^2\right] \tag{2}$$

where v_0 and s_0 are, respectively, the maximum speed and minimum intraplatoon spacing, a is the maximum acceleration, and b is a comfortable deceleration.

III. Multiplatooning Communications Analysis

Here, we first present platoon analysis, and then, based on the multiplatooning communication model shown in Figs. 2(b) and 3(b), we study the performance of DCF in each vehicle's SCH interval for unsaturated data traffic. The performance analysis focuses on transmission attempt probability, collision probability, packet delay, packet-dropping probability, and throughput for both intraplatoon communications and interplatoon communications. Here, *the transmission delay of a packet* is referred to as *packet delay*. Some related definitions are as follows: *Transmission attempt probability* is the probability that a vehicle transmits a packet in a randomly chosen time slot. *Collision probability* is the probability that a packet transmission collides on the SCH. The packet collisions are assumed to be independent of transmission errors. *Transmission failure probability* is the probability of a transmission failure seen by a packet due to a collision or a transmission error. Important notations in multiplatooning communications are summarized in Table I.

TABLE I
Notations in Multiplatooning Communications

Description of notations	intra-platoon communications	inter-platoon communications
transmission attempt probability	τ_p	τ
maximum backoff stage	M_p	M
minimum contention window	W_p	W
collision probability	$p_{c,p}$	$p_{c,i}$ for vehicle i
transmission failure probability	$p_{f,p}$	$p_{f,i}$ for vehicle i
average packet delay	$E[D_p]$	$E[D_i]$ for vehicle i

A. Platoon Analysis

Based on the system model, the intraplatoon spacing, platoon size, and interplatoon spacing are analyzed as follows.

1) Intraplatoon Spacing: According to (1) and (2), the intraplatoon spacing is given by [11]

$$S_i(t) = \frac{s_0 + v_i(t)T_0 + \frac{v_i(t)\Delta v_i(t)}{2\sqrt{ab}}}{\sqrt{1 - \left(\frac{v_i(t)}{v_0}\right)^4 - \frac{a_i(t)}{a}}}. \tag{3}$$

In the rest of this paper, we consider that each vehicle in the multiplatoon is at equilibrium point e [11] at a single time slot, where $a_i(t) = 0$, $\Delta v_i(t) = 0$. Let v_e and s_e be the equilibrium velocity and equilibrium intraplatoon spacing, respectively; then, the intraplatoon spacing can be rewritten as [11]

$$s_e = \frac{s_0 + v_e T_0}{\sqrt{1 - \left(\frac{v_e}{v_0}\right)^4}}. \tag{4}$$

2) Platoon Size: The number of vehicles in one platoon is defined as the platoon size. To guarantee single-hop communications among any two vehicles in one platoon, the maximum number of vehicles in one platoon, i.e., $m_{\max}$, should satisfy

[3]The time headway is the elapsed time of the passage of identical points on two consecutive vehicles, e.g., V_i and V_{i-1}.

$m_{\max} L_0 + (m_{\max} - 1)s_e \leq R_T$, where L_0 is the length of each vehicle, and R_T is the fixed minimum transmission range of each vehicle. Therefore

$$m_{\max} \leq \left\lfloor \frac{R_T + s_e}{L_0 + s_e} \right\rfloor. \tag{5}$$

To facilitate further discussion, we assume that the sizes of all these n platoons are equal to m_v, that is, $m_1 = m_2 = \cdots = m_{n-1} = m_n = m_v \leq \lfloor (R_T + s_e)/(L_0 + s_e) \rfloor$.

3) Interplatoon Spacing: Since each vehicle is at equilibrium point e, the interplatoon spacing is constant, which is denoted by D_p. A constant D_p is guaranteed by adopting the constant-spacing controller [6]. Considering that the constant-spacing controller depends on the velocity and acceleration information of the tail vehicle in the preceding platoon, D_p should not be too large to guarantee connectivity between two consecutive platoons. On the other hand, the value of D_p cannot be too small to avoid collision between V_1^{i+1} and $V_{m_i}^i$. Based on these two constraints, we set the interplatoon spacing, i.e., D_p, range to

$$R_T - (m_v - 1)(s_e + L_0) \leq D_p \leq R_T. \tag{6}$$

B. Performance Metrics of Intraplatoon Communications

We focus on the performance evaluation of the 802.11p DCF in the intraplatoon communications in this section.

1) Transmission Attempt and Collision Probabilities: A vehicle transmits its data packets to other vehicles in the same platoon via single-hop communications, as shown in Fig. 2(b). Packets generated from vehicles in the same platoon have the same transmission attempt probability, i.e., τ_p, and collision probability, i.e., $p_{c,p}$. The transmission failure probability for a packet transmitted via intraplatoon communications, i.e., $p_{f,p}$, can be calculated by

$$p_{f,p} = 1 - (1 - p_{c,p})(1 - p_e). \tag{7}$$

Based on the Markov chain model in [31], which is based on [32], while considering that the packet is dropped after the retransmission times reach the maximum backoff stage and considering an unsaturated data traffic condition, the transmission attempt probability for a packet generated from vehicle V_j^i in platoon P_j is given by

$$\tau_p = \frac{2(1 - 2p_{f,p})}{(1 - 2p_{f,p})(W_p + 1) + p_{f,p} W_p (1 - (2p_{f,p})^{M_p})}. \tag{8}$$

On the other hand, since the platoon size of P_j is m_v and the probability $p_{c,p}$ that a transmitted packet encounters a collision is the probability that at least one of the remaining vehicles in the platoon transmits packets in the same slot time on the same channel, then, for the intraplatoon communications in platoon P_j, we can get

$$p_{c,p} = 1 - (1 - q\tau_p)^{m_v - 1}. \tag{9}$$

According to (7), (8), and (9), we can obtain τ_p and $p_{c,p}$ in terms of the transmission attempt probability and collision probability.

2) Packet Delay: Let $E[X_p]$ be the average number of time slots required for successfully transmitting a packet and $E[s_i]$ be the average length of a time slot. Then, the packet delay of intraplatoon communications, i.e., $E[D_p]$, provided that this packet is not dropped during the intraplatoon communications, is given by

$$E[D_p] = E[X_p] \cdot E[s_i] \tag{10}$$

where $E[X_p]$ and $E[s_i]$ are given by [31]

$$\begin{cases} E[X_p] = \frac{W\left(1-(2p_{f,p})^{(M_p+1)}\right)(1-p_{f,p})+(1-2p_{f,p})\left(1-(p_{f,p})^{M_p+1}\right)}{2((1-2p_{f,p})(1-p_{f,p})} \\ \qquad - \frac{(p_{f,p})^{(M_p+1)}\left[W_p(2^{M_p+1}-1)+(M_p+1)\right]}{2} \\ E[s_i] = \rho\left(q(1-\tau_p) + (1-q)\right) + T_f \tau_p p_{f,p} \\ \qquad + T_s \tau_p (1 - p_{f,p}) \end{cases} \tag{11}$$

where T_f is the average time duration that the channel is sensed busy due to a packet transmission collision or a transmission error, and T_s is the average time period that the channel is sensed busy because of a successful transmission.

C. Performance Metrics of Interplatoon Communications

Consider an interplatoon communication model between two backbone vehicles, e.g., V_1^i and $V_{m_j}^j$, where $1 \leq i, j \leq n$, as shown in Fig. 3(b). Next, we analyze the performance of the IEEE 802.11p DCF in interplatoon communications.

1) Transmission Attempt and Collision Probabilities: Consider the multihop interplatoon communication model shown in Fig. 3(b). Packets from different backbone vehicles can be received by a different number of backbone vehicles. For example, only one vehicle can receive packets from vehicle 1 and vehicle $2n$. Denote by $\{\tau_1, \tau_2, \tau_3, \ldots, \tau_{2n}\}$ and $\{p_{c,1}, p_{c,2}, p_{c,3}, \ldots, p_{c,2n}\}$ the transmission attempt and collision probabilities for packet transmission from these $2n$ backbone vehicles, respectively. Then, the values of τ_i and $p_{c,i}$ can be calculated through the following steps, where $1 \leq i \leq 2n$.

First, by adjusting the bidimensional discrete-time Markov chain in [32] to model the behavior of the DCF backoff timer in interplatoon communications for these $2n$ backbone vehicles, we have (12), wherein $p_{f,i}$ is the transmission failure probability of packets from vehicle i, the relationship between $p_{f,i}$ and $p_{c,i}$ is $p_{f,i} = 1 - (1 - p_{c,i})(1 - p_e)$, and p_e is the transmission error probability. The following equations indicate that τ_i is related to $p_{c,i}$:

$$\begin{cases} \tau_1 = \frac{2(1-2p_{f,1})}{(1-2p_{f,1})(W+1)+p_{f,1}W(1-(2p_{f,1})^M)} \\ \tau_2 = \frac{2(1-2p_{f,2})}{(1-2p_{f,2})(W+1)+p_{f,2}W(1-(2p_{f,2})^M)} \\ \tau_3 = \frac{2(1-2p_{f,3})}{(1-2p_{f,3})(W+1)+p_{f,3}W(1-(2p_{f,3})^M)} \\ \qquad \vdots \\ \tau_{2n-2} = \frac{2(1-2p_{f,2n-2})}{(1-2p_{f,2n-2})(W+1)+p_{f,2n-2}W(1-(2p_{f,2n-2})^M)} \\ \tau_{2n-1} = \frac{2(1-2p_{f,2n-1})}{(1-2p_{f,2n-1})(W+1)+p_{f,2n-1}W(1-(2p_{f,2n-1})^M)} \\ \tau_{2n} = \frac{2(1-2p_{f,2n})}{(1-2p_{f,2n})(W+1)+p_{f,2n}W(1-(2p_{f,2n})^M)}. \end{cases} \tag{12}$$

Second, a vehicle can only communicate with up to two other vehicles via direct interplatoon communications, as shown in Fig. 3(b). Let T_p be the channel time that a transceiver spends on transmitting one packet over the air. For vehicle 1 (similar to vehicle $2n$), its packets can only be received by vehicle 2. If packets from vehicle 1 are successfully received at time t, vehicle 2 should not send any packet at the same time, which occurs with probability $(1 - q_2\tau_2)$. Meanwhile, to avoid the transmission collision of packets from vehicle 3, vehicle 3 should not send any packets to vehicle 2 in the duration $[t - T_p, t + T_p]$, which occurs with probability $(1 - q_3\tau_3)^{2T_p/\rho}$. Therefore, vehicle 1's packets are sent and received successfully with probability $(1 - q_2\tau_2)[(1-q_3\tau_3)^{2T_p/\rho}]$. For vehicle 2 [similar to vehicle $(2n - 1)$], it can send packets to vehicle 3 and vehicle 1. Let α be the probability that vehicle i is the destination of vehicle $i + 1$'s packet, where $3 \leq i \leq (2n - 2)$. The probability that vehicle 3 is the destination of vehicle 2's packet and this packet is successfully received by vehicle 1 is $\alpha(1 - q_1\tau_1)$. Consequently, the probability that vehicle 3 is the destination of vehicle 2's packet and this packet is successfully received by vehicle 3 is $(1 - \alpha)(1 - q_3\tau_3)[(1 - q_4\tau_4)^{2T_p/\rho}]$. For vehicle i, where $3 \leq i \leq (2n - 2)$, we assume that the destinations of its packets are vehicle $i - 1$ and vehicle $i + 1$ with probabilities α and $1 - \alpha$, respectively. Then, we can get the probabilities that vehicle i's packets are received successfully by these two backbone vehicles, being $\alpha(1-q_{(i-1)}\tau_{(i-1)})[(1 - q_{(i-2)}\tau_{(i-2)})^{2T_p/\rho}]$ and $(1 - \alpha)(1 - q_{(i+1)}\tau_{(i+1)})[(1 - q_{(i+2)}\tau_{(i+2)})^{2T_p/\rho}]$. As a result, we can get $2n$ equations, as shown below in (13).

Without loss of generality, we assume that $q = q_p = q_1 = q_2 = q_3 = \cdots = q_{2n-1} = q_{2n}$. Then, based on (12) and (13), we can find that the equations related to vehicles i and $2n + 1 - i$ are the same. That is, the interplatoon communication model has symmetry, and the performance of DCF in vehicles i and $2n + 1 - i$ (which have symmetrical positions in this model with respect to a virtual line that splits the multiplatoon into two halves with an equal number of platoons) is the same. Therefore, we have (14), shown below. According to (12)–(14), we can calculate the values of $\{\tau_1, \tau_2, \tau_3, \ldots, \tau_{2n}\}$ and $\{p_{c,1}, p_{c,2}, p_{c,3}, \ldots, p_{c,2n}\}$, respectively, as

$$\begin{cases} p_{c,1} = 1 - (1 - q_2\tau_2)\left[(1 - q_3\tau_3)^{\frac{2T_p}{\rho}}\right] \\ p_{c,2} = 1 - \alpha(1 - q_1\tau_1) - (1 - \alpha)(1 - q_3\tau_3) \\ \qquad \left[(1 - q_4\tau_4)^{\frac{2T_p}{\rho}}\right] \\ p_{c,3} = 1 - \alpha(1 - q_2\tau_2)\left[(1 - q_1\tau_1)^{\frac{2T_p}{\rho}}\right] - (1 - \alpha) \\ \qquad (1 - q_4\tau_4)\left[(1 - q_5\tau_5)^{\frac{2T_p}{\rho}}\right] \\ \qquad \vdots \\ p_{c,2n-2} = 1 - \alpha(1 - q_{2n-3}\tau_{2n-3})\left[(1 - q_{2n-4}\tau_{2n-4})^{\frac{2T_p}{\rho}}\right] \\ \qquad -(1 - \alpha)(1 - q_{2n-1}\tau_{2n-1})\left[(1 - q_{2n}\tau_{2n})^{\frac{2T_p}{\rho}}\right] \\ p_{c,2n-1} = 1 - \alpha(1 - q_{2n-2}\tau_{2n-2})\left[(1 - q_{2n-3}\tau_{2n-3})^{\frac{2T_p}{\rho}}\right] \\ \qquad -(1 - \alpha)(1 - q_{2n}\tau_{2n}) \\ p_{c,2n} = 1 - (1 - q_{2n-1}\tau_{2n-1})\left[(1 - q_{2n-2}\tau_{2n-2})^{\frac{2T_p}{\rho}}\right] \end{cases} \tag{13}$$

$$\begin{cases} p_{c,1} = p_{c,2n}, \ \tau_1 = \tau_{2n} \\ \qquad \vdots \\ p_{c,i} = p_{c,2n+1-i}, \ \tau_i = \tau_{2n+1-i} \\ \qquad \vdots \\ p_{c,n} = p_{c,n+1}, \ \tau_n = \tau_{n+1}. \end{cases} \tag{14}$$

2) Packet Delay: Consider vehicle i undergoing an interplatoon communication and let $E[D_i]$ denote the average one-hop transmission delay of packets transmitted from vehicle i, then the average end-to-end packet delay for a packet transmitted from the first backbone vehicle 1 to the last backbone vehicle $2n$ is given by

$$E[D] = \sum_{i=1}^{2n} E[D_i] \tag{15}$$

where $E[D_i]$ can be calculated by $E[D_i] = E[X_i] \cdot E[s_i]$ [31], and $E[X_i]$ is the average number of time slots required for successfully transmitting a packet. The mean values $E[X_i]$ and $E[s_i]$ are given by

$$\begin{cases} E[X_i] = \frac{W\left(1-(2p_{f,i})^{(M+1)}\right)(1-p_{f,i})+(1-2p_{f,i})\left(1-(p_{f,i})^{M+1}\right)}{2((1-2p_{f,i})(1-p_{f,i})} \\ \qquad -\frac{(p_{f,i})^{(M+1)}\left[W(2^{M+1}-1)+(M+1)\right]}{2} \\ E[s_i] = \rho\left((1 - q_i) + q_i(1 - \tau_i)\right) + T_f\tau_i p_{f,i} q_i \\ \qquad +T_s q_i \tau_i (1 - p_{f,i}). \end{cases} \tag{16}$$

3) Packet-Dropping Probability: When a packet experiences a collision or a transmission error, it is retransmitted until reaching the retransmission limit. This packet is dropped after its last retransmission. Let $p_{d,i}$ be the probability that a packet from vehicle i is dropped. Since a packet is dropped if it encounters $M + 1$ failures, the value of $p_{d,i}$ can be described as

$$p_{d,i} = (p_{f,i})^{M+1} = [1 - (1 - p_{c,i})(1 - p_e)]^{M+1}. \tag{17}$$

The average packet-dropping probability for a packet transmitted from the first backbone vehicle 1 to the last backbone vehicle $2n$ via interplatoon communications is defined as the average end-to-end packet-dropping probability, i.e., p_d, which is given by

$$\begin{aligned} p_d &= 1 - \prod_{i=1}^{2n}(1 - p_{d,i}) \\ &= 1 - \prod_{i=1}^{2n}\left[1 - [1 - (1 - p_{c,i})(1 - p_e)]^{M+1}\right]. \end{aligned} \tag{18}$$

4) Throughput: Let $E[L]$ denote the average packet payload size. In a time slot, vehicle i does not send a packet if it has no packets or it has packets but does not attempt to transmit them. The probability of vehicle i not sending a packet is $(1 - q_i) + q_i(1 - \tau_i)$. The probability that vehicle i fails to transmit a packet is $q_i\tau_i p_{f,i}$, whereas the probability that vehicle i

transmits a packet successfully is $q_i\tau_i(1-p_{f,i})$. Therefore, the one-hop throughput of vehicle i can be calculated as

$$\Phi_i = \frac{q_i\tau_i(1-p_{f,i})E[L]}{[(1-q_i)+q_i(1-\tau_i)]\,\rho + q_i\tau_i p_{f,i}T_f + q_i\tau_i(1-p_{f,i})T_s}. \tag{19}$$

According to [32], we define the multihop throughput of the interplatoon communication model (from the first backbone vehicle to the last backbone vehicle) as $\Phi = \sum_{i=1}^{2n}\Phi_i$. Hence, Φ is given by (20), shown at the bottom of the page.

D. Analysis of DCF Parameters

Intraplatoon communications is similar to that in a star network, and there are many existing research works focused on their performance analysis [31], [33], [34]. Thus, the rest of the analysis in this section is focused on the impact of DCF parameters (specifically, the maximum backoff stage M and the minimum contention window W) on the packet delay and throughput in interplatoon communications.

1) $M = 0$: The backoff time for each packet is chosen from $(0, CW_{\min})$, and the $2n$ backbone vehicles are more likely to contend to access the SCH in interplatoon communications. In this case, (12) can be rewritten as

$$\tau_1 = \tau_2 = \cdots = \tau_{2n-1} = \tau_{2n} = \frac{2}{(W+1)}. \tag{21}$$

According to (21) and the previous assumption that $q_1 = q_2 = \cdots = q_{2n-1} = q_{2n} = q$, we can rewrite (13) as

$$\begin{cases} p_{c,1} = p_{c,2n} \\ \quad = 1-\left(1-q\frac{2}{W+1}\right)\left[\left(1-q\frac{2}{W+1}\right)^{\frac{2T_p}{\rho}}\right] \\ \quad = 1-\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)} \\ p_{c,2} = p_{c,2n-1} \\ \quad = 1-\alpha\left(1-q\frac{2}{W+1}\right)-(1-\alpha)\left(1-q\frac{2}{W+1}\right) \\ \qquad \times\left[\left(1-q\frac{2}{W+1}\right)^{\frac{2T_p}{\rho}}\right] \\ \quad = 1-\left[\alpha\left(1-q\frac{2}{W+1}\right)+(1-\alpha)\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)}\right] \\ p_{c,3} = p_{c,4} = \cdots = p_{c,2n-3} = p_{c,2n-2} \\ \quad = 1-\alpha\left(1-q\frac{2}{W+1}\right)\left[\left(1-q\frac{2}{W+1}\right)^{\frac{2T_p}{\rho}}\right]-(1-\alpha) \\ \qquad \times\left(1-q\frac{2}{W+1}\right)\left[\left(1-q\frac{2}{W+1}\right)^{\frac{2T_p}{\rho}}\right] \\ \quad = 1-\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)} \\ \quad = p_{c,1} = p_{c,2n}. \end{cases} \tag{22}$$

TABLE II
RELATED PARAMETER VALUES

Parameter	Value	Parameter	Value
$W = W_p$	64	$E[L]$	2048 bits
$M = M_p$	5	T_f	246.18 μs
ρ	13μs	T_s	297.63 μs
T_p	15 ρ	α	0.5

Combining (21) and (22), when $M = 0$, $i = 1, n$, or $i = 3, 4, 5, \ldots, (2n-3), (2n-2)$, (16) can be rewritten as

$$\begin{cases} E[X_i] = \frac{1-W}{2}\left(1-(1-p_{c,i})(1-p_e)\right) \\ \quad = \frac{1-W}{2}\left[1-(1-p_e)\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)}\right] \\ E[s_i] = \left(1-\frac{2q}{W+1}\right)\rho+\frac{2q}{W+1}p_{f,i}T_f+\frac{2q}{W+1}(1-p_{f,i})T_s \\ \quad = \left(1-\frac{2q}{W+1}\right)\rho+\frac{2q}{W+1} \\ \qquad \times\left[1-(1-p_e)\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)}\right]T_f+\frac{2q}{W+1} \\ \qquad \times\left[(1-p_e)\left(1-q\frac{2}{W+1}\right)^{\left(1+\frac{2T_p}{\rho}\right)}\right]T_s. \end{cases} \tag{23}$$

For $M = 0$, $i = 2{,}2n-1$, (16) becomes

$$\begin{cases} E[X_i] = \frac{1-W}{2}\left(1-(1-p_{c,i})(1-p_e)\right) \\ \quad = \frac{1-W}{2}\left[1-(1-p_e)\left[\alpha\left(1-\frac{2q}{W+1}\right) \right.\right. \\ \qquad \left.\left. +(1-\alpha)\left(1-\frac{2q}{W+1}\right)^{1+\frac{2T_p}{\rho}}\right]\right] \\ E[s_i] = \left(1-\frac{2q}{W+1}\right)\rho+\frac{2q}{W+1}p_{f,i}T_f+\frac{2q}{W+1}(1-p_{f,i})T_s \\ \quad = \left(1-\frac{2q}{W+1}\right)\rho+\frac{2q}{W+1} \\ \qquad \times\left[1-(1-p_e)\left[\alpha\left(1-\frac{2q}{W+1}\right) \right.\right. \\ \qquad \left.\left. +(1-\alpha)\left(1-\frac{2q}{W+1}\right)^{1+\frac{2T_p}{\rho}}\right]\right] \\ \qquad \times T_f+\frac{2q}{W+1}\left[(1-p_e)\right. \\ \qquad \left.\times\left[\alpha\left(1-\frac{2q}{W+1}\right)+(1-\alpha)\left(1-\frac{2q}{W+1}\right)^{1+\frac{2T_p}{\rho}}\right]\right]T_s. \end{cases} \tag{24}$$

When $M = 0$, the throughput can be calculated according to (19) and (20). For a given value of minimum contention window W, we can get the values of $E[D]$ and Φ for interplatoon communications.

2) $M = \infty$: Since the contention window is doubled before a packet is retransmitted and the new backoff time is chosen from the doubled contention window, vehicles tend to back off

$$\Phi = \frac{E[L]\sum_{i=1}^{2n}q_i\tau_i(1-p_{f,i})}{\rho\sum_{i=1}^{2n}[(1-q_i)+q_i(1-\tau_i)]+T_f\sum_{i=1}^{2n}q_i\tau_i p_{f,i}+T_s\sum_{i=1}^{2n}q_i\tau_i(1-p_{f,i})} \tag{20}$$

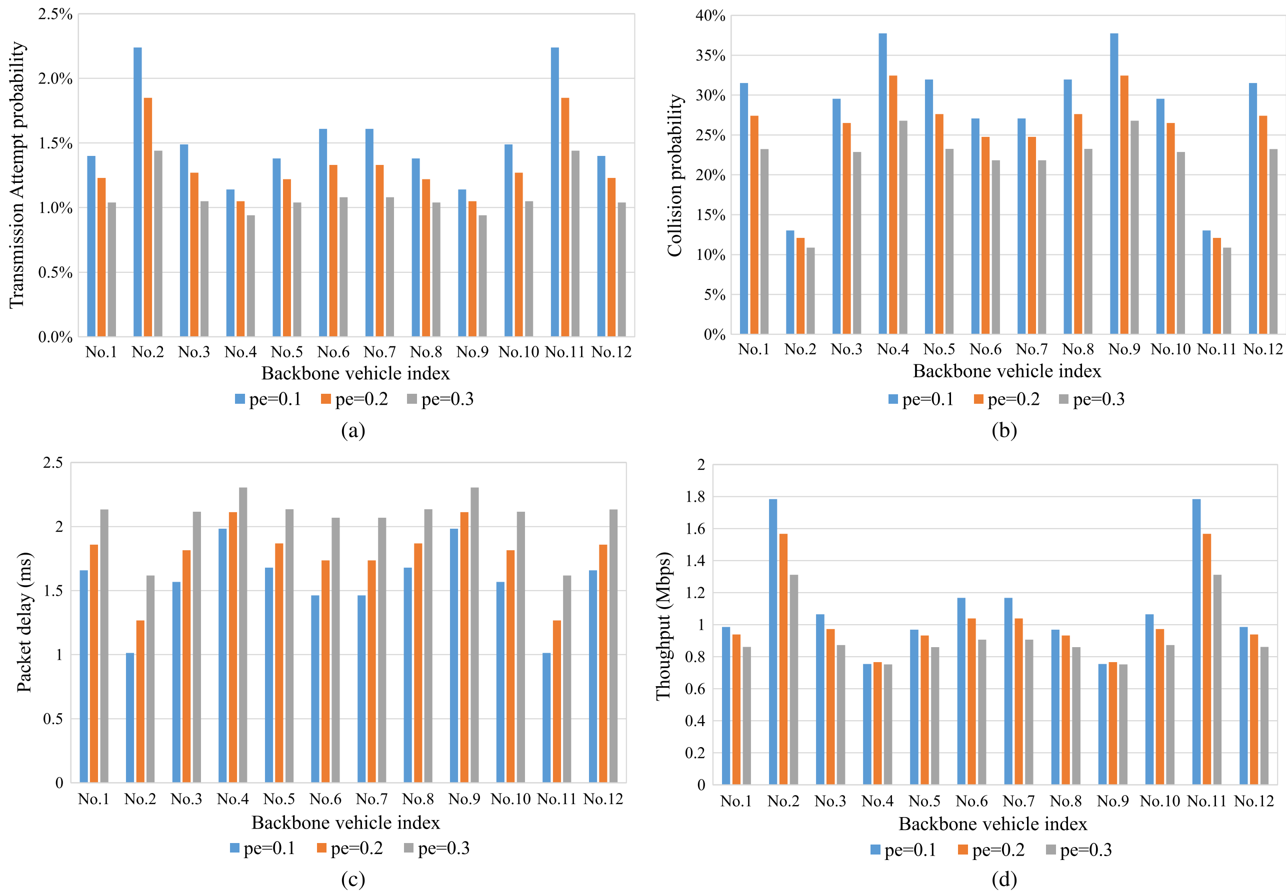


Fig. 4. Interplatoon communication performance of each vehicle with six platoons (12 vehicles). (a) Transmission attempt probability. (b) Collision probability. (c) Packet delay (μs). (c) Throughput (Mb/s).

when they are undergoing an interplatoon communication. For $M = \infty$ and $i = 1, 2, 3, \ldots, (2n-1), 2n$, (12) becomes

$$\tau_i = \begin{cases} \frac{2(1-2p_{f,i})}{(1-2p_{f,i})(W+1)+p_{f,i}W}, & \text{if } p_{f,i} < 0.5 \\ 0, & \text{if } p_{f,i} \geq 0.5. \end{cases} \quad (25)$$

To facilitate the following analysis, the expression of τ_i for $p_{f,i} < 0.5$ can be rewritten as

$$\tau_i = \frac{2}{\frac{1}{2-\frac{1}{1-p_{f,i}}}W + 1}. \quad (26)$$

When $p_{f,i}$ changes from 0 to 0.5, the value of $1/(2-(1/(1-p_{f,i}))$ is in $[1, \infty)$, and τ_i ranges in $(0, 2/(W+1)]$. Therefore, in the rest of this section, the performance analysis focuses on the following two cases of τ_i:

$$\tau_i = \begin{cases} \frac{2}{W+1}, & \text{if } 0 \leq p_{f,i} < 0.5 \\ 0, & \text{if } 0.5 \leq p_{f,i} \leq 1. \end{cases} \quad (27)$$

Similarly, substituting (27) and $q_1 = q_2 = \cdots = q_{2n-1} = q_{2n} = q$ into (13), we can analyze $p_{c,i}$ based on (13), as well as the analysis results of $E[D]$ and Φ.

i) *When* $0 \leq p_{f,i} < 0.5$: The value of τ_i is the same as that when $M = 0$, and the analysis of collision probability, packet delay, and throughput is the same as previously discussed.
ii) *When* $0.5 \leq p_{f,i} \leq 1$: From (27), $\tau_i = 0$, and $p_{c,i} = 0$, where $i = 1, 2, 3, \ldots, (2n-2), (2n-1), 2n$. According to (16), when $M = \infty$, $\tau_i = 0$, and $p_{c,i} = 0$, the value of $E[X_i]$ approaches ∞, and $E[s_i] = \rho$, which means that the packet delay tends to ∞ in such a situation. On the other hand, based on (19), the throughput Φ_i of each vehicle in the interplatoon communications tends to 0.

IV. Numerical Results

This section presents the numerical results of multiplatooning communication performance in terms of the transmission attempt probability, collision probability, packet-dropping probability, packet delay, and throughput. We consider a multiplatooning scenario with parameters set based on the DCF in the IEEE 802.11p standard [29] and existing studies [24], [32]. The values of the related parameters are shown in Table II.

A. *Communication Performance*

Figs. 4 and 5 show the interplatoon communication performance metrics of each vehicle in the multiplatoon for $q = 0.8$, $p_e = 0.1$, $p_e = 0.2$, and $p_e = 0.3$ with 6 and 12 platoons, respectively. According to the analysis in Section III-C, the values of the transmission attempt probability, i.e., τ_i, and the collision probability of a packet from backbone vehicle i, i.e., $p_{c,i}$, are different from other backbone vehicles, resulting in different values of packet delay $E[D_i]$ and throughput Φ_i.

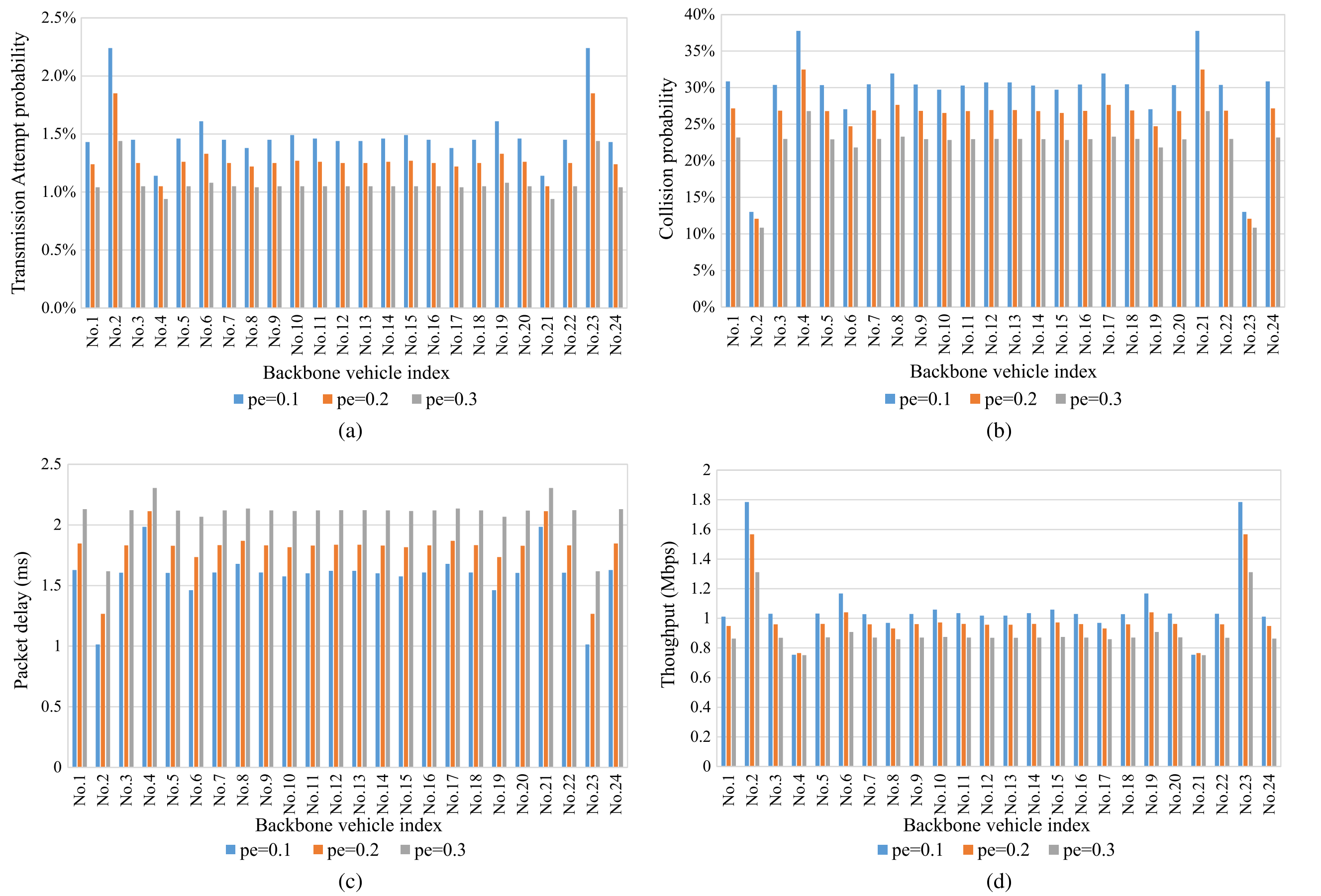


Fig. 5. Interplatoon communication performance results of each vehicle with 12 platoons (24 vehicles). (a) Transmission attempt probability. (b) Collision probability. (c) Packet delay (μs). (d) Throughput (Mb/s).

From Fig. 4, we observe the following: 1) For the first and last backbone vehicles in the multiplatoon (vehicle 1 and vehicle 12), since they can only send their packets to their only neighboring backbone vehicle via interplatoon communications (i.e., vehicle 2 and vehicle 11), the packet collisions from vehicles 2 and 3 increase the collision probability of packets transmitted from vehicle 1 [as shown in Fig. 4(b)]. 2) For some backbone vehicles at the two ends of the multiplatoon (such as vehicles 2 and 11), their packet collision probabilities are lower since there is no collision from hidden vehicles when they send their packets to vehicle 1 or vehicle 12, as shown in Fig. 3(b). On the other hand, a small $p_{c,i}$ leads to a shorter backoff time and, therefore, higher transmission attempt probabilities, smaller packet delays, and higher throughputs [see Fig. 4(a)–(d)]. 3) For middle backbone vehicles (vehicles 3, 4, 5, 8, 9, and 10), their packet collision probabilities are high, due to the impact from the first and last backbone vehicles in the multiplatoon. 4) It is noted that the first and last backbone vehicles of the multiplatoon have a significant impact on the communication performance metrics of other backbone vehicles. However, in Fig. 4, with an increase of the platoon number in the multiplaoon, this impact wears off for the middle backbone vehicles in the interplatoon communication model. As a result, the backbone vehicles from 7 to 18 in the multiplatoon have similar performance, as shown in Fig. 5.

The effect of the channel condition variabilities, represented by p_e, on the interplatoon communication performance is also shown in Figs. 4 and 5, respectively. A larger p_e value results in more transmission errors and, hence, the following: 1) increased backoff times of a packet transmission, leading to a lower value of τ_i; 2) fewer packets being received by backbone vehicles, due to a reduced impact from hidden nodes and a decrease in $p_{c,i}$; and 3) a longer packet delay and a lower throughput.

Fig. 6 shows the interplatoon communication performance metrics of each vehicle in a multiplatoon with six platoons for $p_e = 0.2$, $q = 0.7$, $q = 0.8$, and $q = 0.9$. A smaller q value leads to a lesser number of transmissions, which reduces the communication load for SCH, decreases the collision probability [as shown in Fig. 6(b)], and, therefore, increases the transmission attempt probability [as shown in Fig. 6(a)]. The higher attempt probability and lower collision probability decreases the packet delay, as shown in Fig. 6(c). On the other hand, a smaller q value results in a lower payload in SCH, which decreases the throughput [as shown in Fig. 6(d)].

B. Impact of Platoon Number

Fig. 7 shows the average end-to-end packet delay, i.e., $E[D]$, and the throughput, i.e., Φ, for different platoon numbers, i.e., n, in the interplatoon communication model with $p_e = 0.2$ and $q = 0.8$. The larger the platoon number in the multiplatoon, the larger the number of backbone vehicles in the interplatoon communication model, which results in more packets successfully

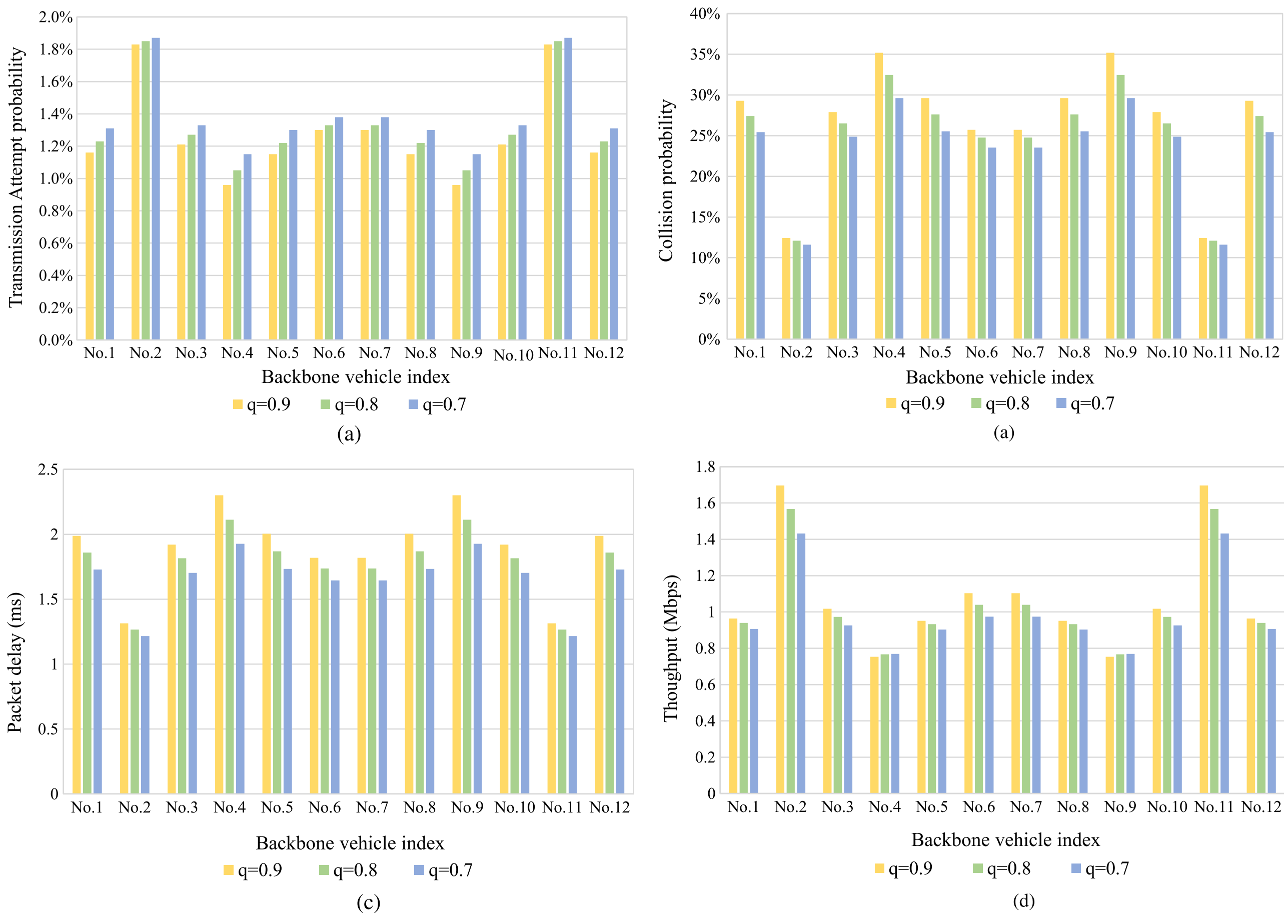


Fig. 6. Interplatoon communication performance of each vehicle with six platoons (12 vehicles). (a) Transmission attempt probability. (b) Collision probability. (c) Packet delay (μs). (d) Throughput (Mb/s).

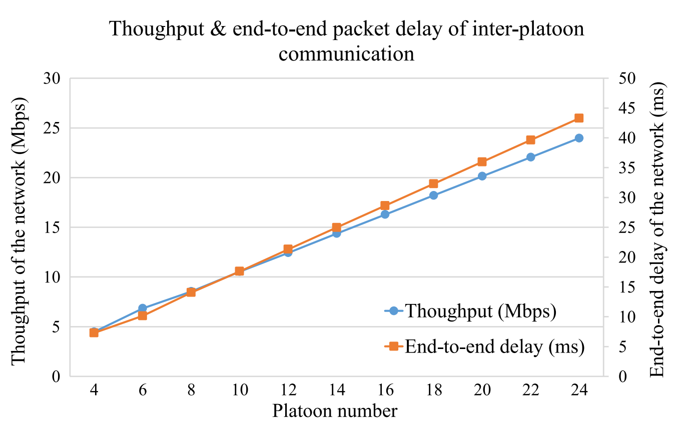


Fig. 7. Effect of the platoon number on interplatoon communication performance.

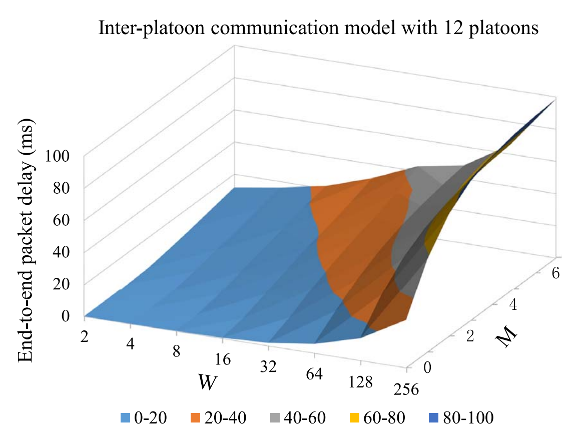


Fig. 8. End-to-end delay of interplatoon communication versus W and M.

transmitted in one time slot and, therefore, a higher Φ value. With an increase of n, the more hops that a packet needs to be transmitted from the first backbone vehicle to the last backbone vehicle and, therefore, the higher the end-to-end packet delay $E[D]$.

C. Impact of DCF Parameters

Here, we consider a multiplaoon with $p_e = 0.2$, $q = 0.8$, and $n = 12$. Fig. 8 shows the average end-to-end packet delay of the whole interplatoon communication system, i.e., $E[D]$. In line with the analysis results in Section III-D, for a fixed M, the relationship between $E[D]$ and W is nonlinear. It can be seen that $E[D]$ increases with increasing W and M. For example, $E[D] = 79.8$ μs when $W = 2$ and $M = 0$, whereas $E[D] = 98.87$ ms for $W = 256$ and $M = 7$. This is because smaller W and M values reduce the average backoff time for one packet transmission, resulting in a smaller $E[D_i]$ value. These analysis results indicate that, via adjusting W and M values, $E[D]$ can be minimized.

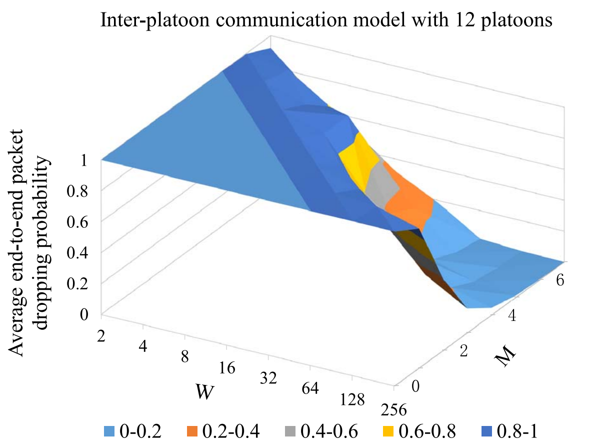


Fig. 9. Average end-to-end packet-dropping probability of interplatoon communication versus W and M.

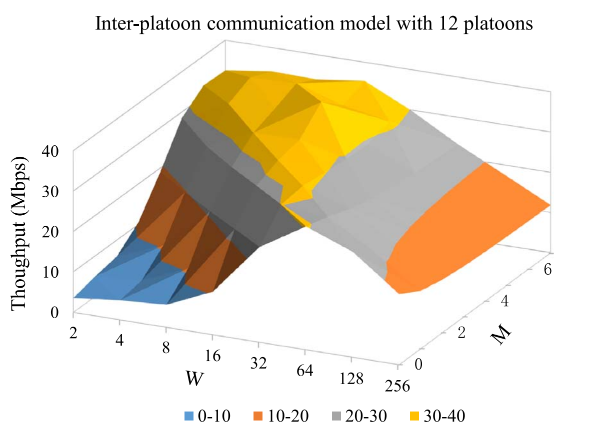


Fig. 10. Throughput of interplatoon communication versus W and M.

Fig. 9 shows the average end-to-end packet-dropping probability, i.e., p_d, for the interplatoon communications. The results show that small W and M values result in a larger p_d value, which is opposite to the impact on $E[D]$. As previously mentioned, a packet contending to access the SCH with smaller W and M values has a smaller average backoff time for one packet transmission and, therefore, a higher collision probability, i.e., $p_{c,i}$. According to Section III-C, the average end-to-end packet-dropping probability, i.e., p_d, increases with an increase of $p_{c,i}$. Figs. 8 and 9 show that, although smaller W and M values result in a lower $E[D]$ value, they also increase p_d. For a packet transmitted from the first platoon to the last platoon, to ensure it is successfully transmitted with a probability larger than 80%, for example, the shortest $E[D]$ is 43.38 ms when $W = 32$ and $M = 7$.

Fig. 10 shows the throughput of the whole interplatoon communication system, i.e., Φ. The results show that Φ reaches a peak value of 37.99 Mb/s when $n = 12$, $M = 5$, and $W = 16$, wherein $E[D] = 21.68$ ms. For a fixed W, Φ first increases and then decreases with an increase of M. For a fixed M, when W increases, Φ first increases and then decreases. These results indicate that 1) a higher Φ value can be achieved by adjusting W and M; 2) a smaller W value leads to a higher collision probability for packets transmitted from each vehicle in the system and, therefore, a lower Φ value; and 3) for a small W value, a larger M value increases the number of retransmission times for each packet, and therefore, Φ increases.

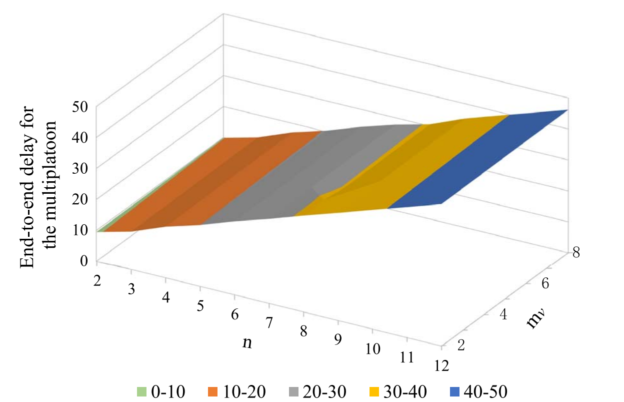


Fig. 11. Average end-to-end delay for transmitting the braking/leaving information in the multiplatoon.

D. Results for Different Multiplatooning Application Scenarios

In Section III-A and C, we have calculated the packet delay of intraplatoon communications, i.e., $E[D_p]$, and the end-to-end packet delay of the interplatoon communication between the first and last backbone vehicles, i.e., $E[D]$. Here, we investigate the end-to-end packet delay of the multiplatoon, denoted by $E[D_m]$ and defined as the transmission delay of a packet transmitted from a member vehicle in the first platoon to a member vehicle in the last platoon of the multiplatoon. That is, $E[D_m]$ is the average time interval from the time that the packet is transmitted from V_i^1 until this packet is received by V_j^n, where $2 \leq i \leq m_1$, $2 \leq j \leq m_n$. Hence, the end-to-end packet delay of the multiplatoon can be calculated by $E[D_m] = 2E[D_p] + E[D]$, where $E[D_p]$ and $E[D]$ can be got from (10) and (15). Consider the following three multiplatoon application scenarios: 1) braking/leaving information [20]; 2) velocity and acceleration (V&A) information [6]; and 3) other information, e.g., vehicle destination information. Since $E[D_m]$ is important in multiplatooning applications, we present numerical results to evaluate whether the DSRC can satisfy the delay requirements for these applications. In the following, we set $s_0 = 3$ m, $v_e = 25$ m/s, $T_0 = 1.5$ s, $v_0 = 30$ m/s, $R_T = 450$ m, $L_0 = 3$ m [11], and $s_e = 56.3$ m, $m_{\max} = 8$ (based on the analysis in Section III-A).

1) Braking/Leaving Information: A vehicle shares its braking/leaving information to its following vehicles in the multiplatoon [20], which means that the value of α in the interplatoon communication model is equal to 1. Fig. 11 shows the value of $E[D_m]$ versus the platoon size, i.e., m_v, and the platoon number, i.e., n, in the multiplatoon. The results show that, for a fixed m_v, $E[D_m]$ increases with the increase of n. For a fixed n, $E[D_m]$ also increases with the increase of m_v. At $m_v = m_{\max} = 8$ and $n = 12$, we have $E[D_m] = 46.21$ ms, which is a small fraction of the tolerable delay of 6.72 s (with braking force 10 000, vehicle weight 1800 kg, and intraplatoon spacing 56.3 m) from the braking force perspective [20].

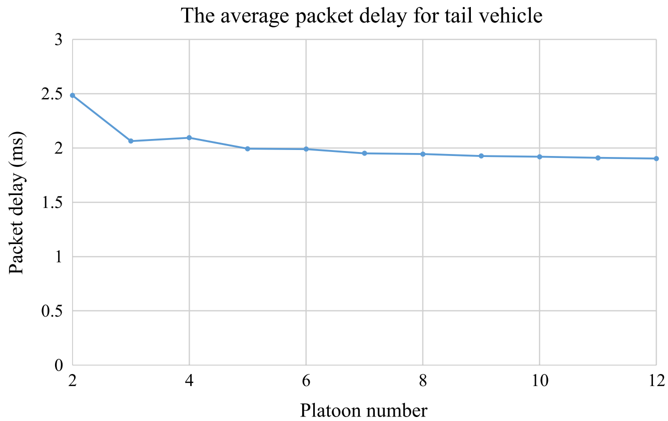


Fig. 12. Average packet delay for transmitting the V&A information by a tail vehicle in the multiplatoon.

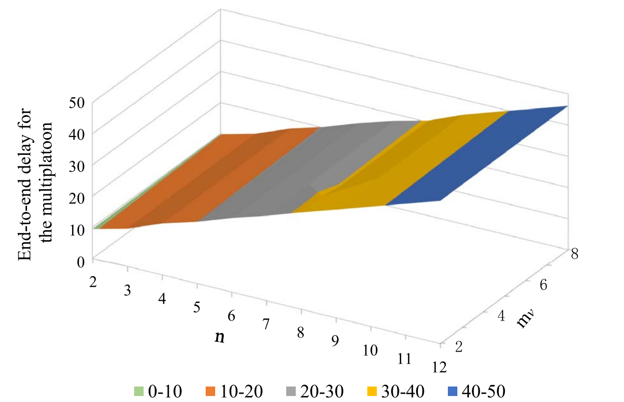


Fig. 14. Average end-to-end packet delay for transmitting other information in the multiplatoon.

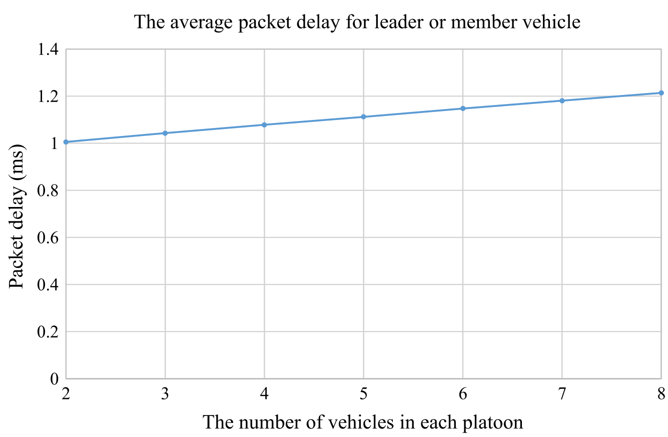


Fig. 13. Average packet delay for transmitting the V&A information by a leader or member vehicle in the multiplatoon.

2) Velocity and Acceleration (V&A) Information: The research results in [6] show that, using the constant-spacing policy to guarantee the string stability of each platoon in the multiplatoon, sharing V&A information between the lead and the following vehicles is needed. Each leader vehicle shares its V&A information with its member vehicles, and each vehicle shares its V&A information with its following vehicles. As the information for leader vehicle V_1^{j+1} is the V&A information from tail vehicle $V_{m_j}^j$, the value of α here is 1. The value of average packet delay is dependent on the vehicle's role in the platoon. For a leader or member vehicle i, it transmits its V&A information to other vehicles via intraplatoon communications; for a tail vehicle i, it transmits its V&A information to the leader vehicle in its following platoon via interplatoon communications, which can be calculated according to the analysis in Section III-B and C.

Fig. 12 shows the average packet delay for transmitting the V&A information by a tail vehicle. With the increase of n, the average packet delay of packets from the tail vehicles first decreases and then tends to remain constant. For the intermediate backbone vehicles in the interplatoon communication model, the impact from the first and last backbone vehicles is weakened when n increases. Fig. 13 shows the average packet delay for transmitting the V&A information by a leader (or a member) vehicle. The average packet delay is related to the value of m_v. A larger m_v value means that more vehicles contend for accessing the same SCH for intraplatoon communications, which results in a higher collision probability for each packet and, therefore, a longer packet delay. Additionally, based on the simulation results in [10], V&A updates can operate under an upper bound delay, which is much higher than 6.7 ms (the average delay of DSRC in [10]), while continuing to ensure the string stability of platoons. The numerical results in this section show that the packet delay for transmitting V&A is in the range of [1 2.5] ms, and the maximum delay under this situation is less than 6.7 ms. Furthermore, according to the analysis results in [35], the string stability can be guaranteed for $T_0 > 0.1$ s when the communication delay is less than 2.5 ms, which means that the intraplatoon spacing can be reduced to $s_e = 7.64$ m, and the platoon size increases to $m_v = 43$, considering the string stability of platoons.

3) Other Information: In a multiplatoon, via sharing destination information among vehicles, the vehicles that have the same destination can join the same platoon to maintain the platoon's membership. On the other hand, sharing each vehicle's available entertainment information and rejoining a new platoon, a vehicle can get the required entertainment information from another vehicle in the same platoon. This can enhance the effectiveness of resource sharing among vehicles in the multiplatoon. Fig. 14 shows $E[D_m]$ for transmitting such information when $\alpha = 0.5$. The results show that, comparing with the end-to-end packet delay for braking/leaving information, $E[D_m]$ for transmitting such information is slightly shorter. Under the condition $m_v = m_{\max} = 8$ and $n = 12$, we have $E[D_m] =$ 46.21 ms for braking/leaving information and $E[D_m] =$ 45.71 ms for other information.

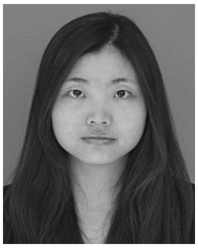
It should be noted that, in our analysis, we have only considered interplatoon communications among backbone vehicles on a single SCH. However, a more general communication for some multiplatooning scenarios is the end-to-end communication between a random source–destination vehicle pair (i.e., possibly nonbackbone vehicles). In this case, calculating the end-to-end throughput becomes very challenging. When the source and destination vehicles are not in the same platoon, data transmission from the source vehicle to the destination vehicle requires a mix of intraplatoon and interplatoon communications. As a result, analyzing the end-to-end throughput depends on the communications on two SCHs, rather than one, which requires further investigation.

V. CONCLUSION

In this paper, we have presented a probabilistic analysis of the communication performance with IEEE 802.11p DCF in a multiplatooning scenario. We have analyzed the communication performance in terms of the transmission attempt probability, collision probability, packet delay, packet-dropping probability, and throughput. The numerical results show that, when adopting IEEE 802.11p DCF for multiplatoon communications, the first leader vehicle and the last tail vehicle in the multiplatoon dominate the interplatoon communication performance, and the end-to-end delay can be reduced by adjusting the contention window size and maximum backoff stage. Additionally, we have analyzed the multiplatoon communication performance for three different application scenarios. Numerical results show that the IEEE 802.11p-based communication in multiplatooning can satisfy the delay requirement to improve road safety. For future work, we will investigate the multihop intraplatoon communications to find the optimal platoon size that can balance road capacity and end-to-end packet delay; ultimately, we will design an effective IEEE 802.11p-based platoon communication protocol for autonomous vehicles.

REFERENCES

[1] H. Peng *et al.*, "Performance analysis of IEEE 802.11p DCF for inter-platoon communications with autonomous vehicles," in *Proc. IEEE Globecom*, San Diego, CA, USA, 2015, pp. 1–6.
[2] D. Schrank, B. Eisele, and T. Lomax, "Urban mobility report," Texas A&M Transp. Inst., College Station, TX, USA, 2012.
[3] P. Fernandes and U. Nunes, "Multiplatooning leaders positioning and cooperative behavior algorithms of communicant automated vehicles for high traffic capacity," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1172–1187, Jun. 2015.
[4] K. Abboud and W. Zhuang, "Stochastic modeling of single-hop cluster stability in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 226–240, Jan. 2016.
[5] D. J. Stilwell, B. E. Bishop, and C. A. Sylvester, "Redundant manipulator techniques for partially decentralized path planning and control of a platoon of autonomous vehicles," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 35, no. 4, pp. 842–848, Aug. 2005.
[6] R. Rajamani, *Vehicle Dynamics and Control*. New York, NY, USA: Springer-Verlag, 2011.
[7] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 263–284, 1st Quart. 2016.
[8] P. A. Ioannou and C.-C. Chien, "Autonomous intelligent cruise control," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 657–672, Nov. 1993.
[9] CBC News, Google's newest self-driving cars hit public roads this summer, 2015. [Online]. Available: http://www.cbc.ca/news/technology/google-s-newest-self-driving-cars-hit-public-roads-this-summer-1.3069370
[10] P. Fernandes and U. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 91–106, Mar. 2012.
[11] D. Jia, K. Lu, and J. Wang, "A disturbance-adaptive design for VANET-enabled vehicle platoon," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 527–539, Feb. 2014.
[12] R. Rajamani and S. Shladover, "An experimental comparative study of autonomous and co-operative vehicle-follower control systems," *Transp. Res. C, Emerg. Technol.*, vol. 9, no. 1, pp. 15–31, 2001.
[13] G. J. Naus, R. P. Vugts, J. Ploeg, M. Van de Molengraft, and M. Steinbuch, "String-stable CACC design and experimental validation: A frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.
[14] P. Caravani, E. De Santis, F. Graziosi, and E. Panizzi, "Communication control and driving assistance to a platoon of vehicles in heavy traffic and scarce visibility," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 448–460, Dec. 2006.
[15] R. Sengupta, S. Rezaei, S. E. Shladover, D. Cody, S. Dickey, and H. Krishnan, "Cooperative collision warning systems: Concept definition and experimental implementation," *J. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 143–155, 2007.
[16] W. B. Dunbar and D. S. Caveney, "Distributed receding horizon control of vehicle platoons: Stability and string stability," *IEEE Trans. Autom. Control*, vol. 57, no. 3, pp. 620–633, Mar. 2012.
[17] L.-Y. Hsu and T.-L. Chen, "An optimal wheel torque distribution controller for automated vehicle trajectory following," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2430–2440, Jul. 2013.
[18] V. Milanés, S. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative adaptive cruise control in real traffic situations," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 296–305, Feb. 2014.
[19] J. Ploeg, D. P. Shukla, N. van de Wouw, and H. Nijmeijer, "Controller synthesis for string stability of vehicle platoons," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 2, pp. 854–865, Apr. 2014.
[20] L. Xu, L. Wang, G. Yin, and H. Zhang, "Communication information structures and contents for enhanced safety of highway vehicle platoons," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4206–4220, Nov. 2014.
[21] M. di Bernardo, A. Salvi, and S. Santini, "Distributed consensus strategy for platooning of vehicles in the presence of time-varying heterogeneous communication delays," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 1, pp. 102–112, Feb. 2015.
[22] N. Lu, N. Cheng, N. Zhang, X. Shen, J. Mark, and F. Ba, "Wi-fi hotspot at signalized intersection: Cost-effectiveness for vehicular Internet access," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3506–3518, May 2016.
[23] K. Abboud and W. Zhuang, "Stochastic analysis of single-hop communication link in vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2297–2307, Oct. 2014.
[24] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, "Analytical study of the IEEE 802.11p MAC sublayer in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 873–886, Jun. 2012.
[25] R. Pueboobpaphan, "Understanding the relationship between driver and vehicle characteristics and platoon and traffic flow stability for design and assessment of cooperative adaptive cruise control," in *Proc. TRB Annual Meeting*, Washington, DC, USA, 2010, pp. 873–886.
[26] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)-Multi-Channel Operation*, IEEE Std. 1609.4-2010, 2010.
[27] H. Omar, W. Zhuang, A. Abdrabou, and L. Li, "Performance evaluation of VeMAC supporting safety applications in vehicular networks," *IEEE Trans. Emerg. Topics. Comput.*, vol. 1, no. 1, pp. 69–83, Jun. 2013.
[28] G. Zhang, A. Huang, H. Shan, J. Wang, T. Q. Quek, and Y.-D. Yao, "Design and analysis of distributed hopping-based channel access in multi-channel cognitive radio systems with delay constraints," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 11, pp. 2026–2038, Nov. 2014.
[29] *IEEE Standard for Information Technology-Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements-Part 11: Wireless LAN, MAC and, PHY Specifications Amendment 6: WAVE*, IEEE Std. 802.11 Working Group, 2010.
[30] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Phys. Rev. E*, vol. 62, pp. 1805–1824, 2000.
[31] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "IEEE 802.11 packet delay—A finite retry limit analysis," in *Proc. IEEE Globecom*, San Francisco, CA, USA, 2003, pp. 950–954.
[32] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
[33] F.-Y. Hung and I. Marsic, "Access delay analysis of IEEE 802.11 DCF in the presence of hidden stations," in *Proc. IEEE Globecom*, Washington, DC, USA, 2007, pp. 2541–2545.
[34] D. Li and J. Pan, "Performance evaluation of video streaming over multi-hop wireless local area networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 338–347, Jan. 2010.
[35] G. Naus, R. Vugts, J. Ploeg, M. Van de Molengraft, and M. Steinbuch, "Towards on-the-road implementation of cooperative adaptive cruise control," in *Proc. 16th World Congr. Exhib. ITS World*, Stockholm, Sweden, 2009, pp. 1–12.



Haixia Peng (S'15) received the B.S. and M.S. degrees from Northeastern University, Shenyang, China, in 2011 and 2013, respectively.

She is currently a Visiting Scholar with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. Her current research focuses on communication performances analysis of vehicular ad hoc networks in platoon and wireless sensor networks.

Ms. Peng served as a Technical Program Committee Member for the 2016 IEEE Vehicular Technology Conference (Fall) and the 2016 IEEE Global Telecommunications Conference.

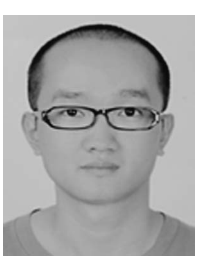
Dazhou Li received the B.S. degree in electronic information science and technology from Liaoning University, Shenyang, China, in 2005 and the M.S. and Ph.D. degrees from Northeastern University, Shenyang, in 2008 and 2014, respectively.

He is a Lecturer with the College of Computer Science and Technology, Shenyang University of Chemical Technology. His current research interests include wireless communication, network topology control, and network performance analysis in vehicular ad hoc networks and body area networks.

Khadige Abboud received the B.Sc. degree in electrical engineering from Kuwait University, Kuwait City, Kuwait, in 2007 and the M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2009 and 2015, respectively.

Since 2015, she has been a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Waterloo. Her research interests include vehicle mobility modeling, node cluster stability, and cellular dedicated short-range communications interworking for vehicular communications.

Dr. Abboud received the Best Paper Award at the 2014 ACM International Conference on Modeling, Analysis, and Simulation of Wireless and Mobile Systems. She has served as a Technical Program Committee Member for the 2014 IEEE International Conference on Scalable Computing and Communications, the 2015 and 2016 IEEE Global Telecommunications Conference, and the 2016 IEEE Vehicular Technology Conference (Fall).



Haibo Zhou (S'11–M'15) received the Ph.D. degree in information and communication engineering from Shanghai Jiao Tong University, Shanghai, China, in 2014.

He is a Postdoctoral Fellow with the Broadband Communications Research Group, Department of Electrical and Computer Engineering, Faculty of Engineering, University of Waterloo, Waterloo, ON, Canada. His current research interests include resource management and protocol design in cognitive radio networks and vehicular networks.

Hai Zhao received the B.S. degree in electrical engineering from Dalian Maritime University, Dalian, China, in 1982 and the M.S. and Ph.D. degrees in computer science from Northeastern University, Shenyang, China, in 1987 and 1995, respectively.

He is a Professor with the Department of Computer Science and Technology, Northeastern University. He is the Director of the Liaoning Provincial Key Laboratory of Embedded Technology. His current research interests include embedded Internet technology, wireless sensor networks, vehicular ad hoc networks, body area networks, pervasive computing, operating systems, data and information fusion, and computer simulation and virtual reality.

Dr. Zhao has received recognition from the State Council due to his special contributions to the development of education.

Weihua Zhuang (M'93–SM'01–F'08) received the B.Sc. and M.Sc. degrees from Dalian Maritime University, Dalian, China, and the Ph.D. degree from the University of New Brunswick, Fredericton, NB, Canada, all in electrical engineering.

Since October 1993, she has been with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. She is a Professor and a Tier I Canada Research Chair in Wireless Communication Networks. Her current research focuses on resource allocation and quality-of-service provisioning in wireless networks and on smart grids.

Dr. Zhuang co-received the Best Paper Awards at the 2007, 2013, and 2014 IEEE International Conference on Communications; the 2014 ACM International Conference on Modeling, Analysis, and Simulation of Wireless and Mobile Systems; the 2012 and 2013 IEEE Global Telecommunications Conference (Globecom); the IEEE Multimedia Communications Technical Committee in 2011; the 2010 IEEE Vehicular Technology Conference (Fall); the 2007 and 2010 IEEE Wireless Communications and Networking Conference; and the 2007 and 2008 International Conference on Heterogeneous Networking for Quality, Reliability, Security, and Robustness. She has also received the Outstanding Performance Award four times since 2005 from the University of Waterloo for her outstanding achievements in teaching, research, and service, as well as the Premier's Research Excellence Award in 2001 from the Ontario Government for having demonstrated excellence in scientific and academic contributions. She was the Editor-in-Chief of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY (2007–2013) and the Technical Program Committee Symposia Chair of IEEE Globecom in 2011. She is a Fellow of the Canadian Academy of Engineering, a Fellow of the Engineering Institute of Canada, and an elected member in the Board of Governors and VP Mobile Radio of the IEEE Vehicular Technology Society. She was an IEEE Communications Society Distinguished Lecturer during 2008–2011.

Xuemin (Sherman) Shen (M'97–SM'02–F'09) received the B.Sc. degree from Dalian Maritime University, Dalian, China, in 1982 and the M.Sc. and Ph.D. degrees from Rutgers University, New Brunswick, NJ, USA, in 1987 and 1990, respectively, all in electrical engineering.

He is a Professor and the University Research Chair with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He is also the Associate Chair for Graduate Studies. His research focuses on resource management in interconnected wireless/wired networks, wireless network security, social networks, smart grids, and vehicular ad hoc and sensor networks.

Dr. Shen is an elected member of the IEEE Communications Society Board of Governors and the Chair of the Distinguished Lecturers Selection Committee. He served as the Technical Program Committee Chair/Cochair for the 2007 and 2016 IEEE Global Telecommunications Conference, the 2014 IEEE International Conference on Computer Communications, and the 2010 IEEE Vehicular Technology Conference (VTC—Fall); the Symposia Chair for the 2010 IEEE International Conference on Communications (ICC); the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08; the General Cochair for the 2015 ACM International Symposium on Mobile Ad Hoc Networking and Computing, the 2007 International Conference in Communications and Networking in China, and the 2006 International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks; and the Chair for the IEEE Communications Society Technical Committee on Wireless Communications and Peer-to-Peer Communications and Networking. He also serves/served as the Editor-in-Chief for IEEE NETWORKS, *Peer-to-Peer Networking and Applications*, and *IET Communications*; a Founding Area Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *Computer Networks*, and *ACM/Wireless Networks*; and the Guest Editor for the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE WIRELESS COMMUNICATIONS, the IEEE COMMUNICATIONS MAGAZINE, and *ACM Mobile Networks and Applications*. He received the Excellent Graduate Supervision Award in 2006 and the Outstanding Performance Award in 2004, 2007, 2010, and 2014 from the University of Waterloo; the Premier's Research Excellence Award in 2003 from the Province of Ontario, Canada; and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. He is a registered Professional Engineer of Ontario, a Fellow of the Engineering Institute of Canada, a Fellow of the Canadian Academy of Engineering, a Fellow of the Royal Society of Canada, and a Distinguished Lecturer of the IEEE Vehicular Technology and IEEE Communications Societies.