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

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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 a constant inter-vehicle and inter-platoon distances. Characterizing the performance of intra- and inter-platoon 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 probabilistic performance analysis of distributed coordination function (DCF) based intra- and inter-platoon 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 inter-platoon 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—Multiplatooning; Performance analysis; Autonomous vehicles; 802.11p DCF; Inter-vehicle communication.

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 solve traffic jams on highways is platooning [3]. Platooning is a vehicle traffic management strategy in which autonomous/semi-autonomous vehicles organize themselves, on the same lane, into a set called a platoon1. Each platoon is led by a leader vehicle (detailed definition of leader vehicle is given out in the Subsection 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 a small constant inter-vehicle 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 to improve on-road safety, and reduce fuel consumption and exhaust emissions [7]. Further, recent technological advances in vehicle automation (e.g., the 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, referred to as multiplatooning, as shown in Figure 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, especially 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 intra/inter-platoon spacings, is a key issue in platoon control. When a vehicle moves in/out of a platoon, the platoon control system (such as autonomous cruise control (ACC) system [12], cooperative ACC [13]) in the following vehicle causes it to accelerate/decelerate in order to account for the spacing change (error). However, a serious problem called string instability2 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 of vehicular ad hoc networks (VANETs) [6], [14]–[21]. In a platoon, a vehicle can wirelessly transmit its velocity and

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

2 The string instability of a multiplatoon refers to the problem of amplification of the spacing error in inter-vehicle distances within the multiplatoon. This amplification occurs as the spacing error propagates towards the tail of the platoon and the end of the multiplatoon [6].
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 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 to 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 (FCC) 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 10MHz 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 (WAVE) [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 which lacks roadside infrastructure support, DSRC becomes the only way of inter-vehicle communications. However, the dynamic nature of vehicular traffic on 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 intra/inter-platoon communications. To evaluate whether the DSRC can support platoons, a general probabilistic performance analysis of multiplatooning communications is proposed. The performance of DCF for intra/inter-platoon communications is analyzed based on Markov chains. Specifically, for inter-platoon 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 inter-platoon communications is affected by the first and the 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 multi-lane highway. Figure 1 illustrates 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 \( i \)th vehicle in the \( j \)th platoon, \( P_j \), and \( m_j \) as the number of vehicles in platoon \( P_j \), where \( 1 \leq j \leq n \). Let \( m_{\text{max}} \) be the maximum number of vehicles in a platoon, i.e., \( m_j \leq m_{\text{max}} \) and the value of \( m_{\text{max}} \) should be determined so as to soft guarantee one-hop communications among any two vehicles in the same platoon (further discussed in subsection 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].

A vehicle in the considered multiplatooning scenario can be one of three types: a leader vehicle, tail vehicle, and member vehicle. A leader vehicle is the vehicle that leads other vehicles in one platoon, e.g., vehicle \( V_1^1 \) is the leader vehicle of platoon \( P_1 \). A leader vehicle can: (i) create and manage the platoon with the help of an advanced traffic management system (ATMS), e.g., control the number of vehicles in its
platoon, inform a newly joined vehicle to use which SCH for data transmission; and (ii) 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 non-leader 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 Figure 1, define the intra-platoon 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. The inter-platoon 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 \( V_{i}^{j+1} \) and \( V_{m_j}^j \), where \( 1 \leq j < n \).

### 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 multi-hop communications. To reduce the interference between intra-platoon communications and inter-platoon communications, each vehicle in the multiplatoon is equipped with two RF transceivers, i.e., transceiver 1 and transceiver 2. Transceiver 1 is used for one-hop intra-platoon communications, and transceiver 2 for multi-hop inter-platoon communications, as illustrated in Figure 2(a) and Figure 3(a). Based on the IEEE 1609.4 [26], a standard for wireless access in vehicular multi-channel 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 (UTC), which can be obtained from the vehicle’s global positioning system (GPS) receiver [27]. We assume that each transceiver is allocated one of the SCHs, such that the SCH used for inter-platoon communication is different from that used for intra-platoon 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 \( \rho \).

We focus on analyzing the communication performance in a multiplatoon, including the single-hop intra-platoon communications and the multi-hop inter-platoon communications. An intra-platoon communication model of the platoon \( P_i \) is illustrated in Figure 2(b), and the inter-platoon communication model for a multiplatoon with \( n \) platoons is shown in Figure 3(b). Note that only the backbone vehicles in the multiplatoon engage in inter-platoon communications. For convenience, we relabel the \( 2n \) backbone vehicles (\( n \) leader vehicles and \( n \) tail vehicles) with IDs 1 to \( 2n \) as illustrated in Figure 3(b), and refer to the backbone vehicle \( i \) as vehicle \( i \) for short, where \( 1 \leq i \leq 2n \). 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 inter-platoon 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 chosen uniformly from \((0, \omega - 1)\), and \(\omega\) is the contention window size. At the first transmission attempt of a packet, \(\omega\) is set to the minimum contention window \( W = CW_{\text{min}} \). After each unsuccessful transmission, \(\omega\) is doubled, up to a maximum value \( CW_{\text{max}} = 2^M CW_{\text{min}} \), and \( M \) is the maximum backoff stage. The retransmission limit is reached when the number of transmission failure 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 \( q_i \), the probability that vehicle \( i \) has at least one packet waiting to be transmitted on transceiver 2 in a given time slot.
C. Vehicle mobility model

Vehicles in the multiplatoon move according to the intelligent driver car-following model (IDM) [30]. Consider the $i$th vehicle, $V_i$, 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 intra-platoon 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]:

$$S^*_i(t) = s_0 + v_i(t)T_0 + \frac{v_i(t)\Delta v_i(t)}{2\sqrt{ab}}$$  \hspace{1cm} (1)

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

where $v_0$ and $s_0$ are respectively the maximum speed and minimum intra-platoon spacing, $a$ is the maximum acceleration, and $b$ is a comfortable deceleration.

III. MULTIPLATOONING COMMUNICATIONS ANALYSIS

In this section, we first present platoon analysis, then based on the multiplatoon communication model illustrated in Figure 2(b) and Figure 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 intra-platoon communications and inter-platoon 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 multiplatoon communications are summarized in Table I.

![Figure 3: Inter-platoon communication model in multiplatooning](image)

<table>
<thead>
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<th>Description of notations</th>
<th>intra-platoon communications</th>
<th>inter-platoon communications</th>
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<td>$\tau_p$</td>
<td>$\tau$</td>
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<tr>
<td>maximum backoff stage</td>
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<td>minimum contention window collision probability</td>
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<td>average packet delay</td>
<td>$E[D_p]$</td>
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A. Platoon analysis

Based on the system model, the intra-platoon spacing, platoon size and inter-platoon spacing are analyzed in the follows.

1) Intra-platoon spacing: According to (1) and (2), the intra-platoon spacing is given by [11]

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

In the rest of this paper, we consider that each vehicle in the multiplatoon is at the 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 intra-platoon spacing,
respectively, then the intra-platoon spacing can be rewritten as
\[ s_e = \frac{s_0 + v_e T_0}{\sqrt{1 - \left(\frac{s_0}{v_e}\right)^2}}. \] (4)

2) Platoon size: The number of vehicles in one platoon is defined as platoon size. To guarantee the single-hop communications among any two vehicles in one platoon, the maximum number of vehicles in one platoon, \( m_{\text{max}} \), should satisfy \( m_{\text{max}} L_0 + (m_{\text{max}} - 1) s_e \leq R_T \), where \( L_0 \) is the length of each vehicle, and \( R_T \) is the fixed minimum transmission range of each vehicle. Therefore,
\[ m_{\text{max}} \leq \left\lfloor \frac{R_T + s_e}{L_0 + s_e} \right\rfloor. \] (5)

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

3) Inter-platoon spacing: Since each vehicle is at the equilibrium point \( e \), the inter-platoon spacing is constant, 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 tail vehicle in the preceding platoon, \( D_p \) should not be too large in order to guarantee the connectivity between two consecutive platoons. On the other hand, the value of \( D_p \) cannot be too small in order to avoid collision between \( V^{i+1}_1 \) and \( V^{i}_{m_e} \). Based on these two constraints, we set the inter-platoon spacing, \( D_p \), range to
\[ R_T - (m_e - 1)(s_e + L_0) \leq D_p \leq R_T. \] (6)

B. Performance metrics of intra-platoon communications

We focus on performance evaluation of the 802.11p DCF in the intra-platoon communications in this subsection.

1) Transmission attempt and collision probabilities: A vehicle transmits its data packets to other vehicles in the same platoon via single-hop communications as illustrated in Figure 2(b). Packets generated from vehicles in the same platoon have the same transmission attempt probability, \( \tau_p \), and collision probability, \( p_{c,p} \). The transmission failure probability for a packet transmitted via intra-platoon communications, \( p_{f,p} \), can be calculated by
\[ p_{f,p} = 1 - (1 - p_{c,p})(1 - p_e). \] (7)

Based on the Markov chain model in [31] which is based on [32] while considering the packet is dropped after the retransmission times reach the maximum backoff stage, and considering unsaturated data traffic condition, the transmission attempt probability for a packet generated from vehicle \( V^i_j \) in platoon \( P_j \) is given by
\[ \tau_p = \frac{2(1 - 2p_{f,p})}{(1 - 2p_{f,p})(W_p + 1) + p_{f,p} W_p (1 - (2p_{f,p})^W_p)}. \] (8)

On the other hand, since the platoon size of \( P_j \) is \( m_e \), 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 intra-platoon communications in platoon \( P_j \), we can get
\[ p_{c,p} = 1 - (1 - q \tau_p)^{m_e - 1}. \] (9)

According to (7), (8), and (9), we can obtain \( \tau_p \) 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 \( E[s_i] \) the average length of a time slot. Then, the packet delay of intra-platoon communications, \( E[D_p] \), provided that this packet is not dropped during the intra-platoon communications, is given by
\[ E[D_p] = E[X_p] \cdot E[s_i]. \] (10)

where \( E[X_p] \) and \( E[s_i] \) are given by [31]
\[ E[X_p] = \frac{W(1 - (2p_{f,p})^{W_p+1})(1 - p_{f,p})(1 - p_{c,p})^{M_p+1}}{2(1 - 2p_{f,p})(1 - p_{f,p})(1 - p_{c,p})^{M_p+1}} \]
\[ - \frac{(p_{f,p})^{M_p+1} [W_p(2p_{f,p})^{M_p+1} - 1]}{2} \tau_p \]
\[ + E[s_i] = \rho(q(1 - \tau_p) + (1 - q)) + T_f \tau_p p_{f,p} + T_s \tau_p (1 - p_{f,p}) \]
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 inter-platoon communications

Consider an inter-platoon communication model between two backbone vehicles, e.g., \( V^i_i \) and \( V^j_j \), where \( 1 \leq i, j \leq n \), as illustrated in Figure 3(b). Next, we analyze the performance of the IEEE 802.11p DCF in inter-platoon communications.

1) Transmission attempt and collision probabilities: Consider the multi-hop inter-platoon communication model shown in Figure 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 \( \tau_i \) and \( p_{c,i} \) can be calculated through the following steps, where \( 1 \leq i \leq 2n \).

Firstly, by adjusting the bidimensional discrete time Markov chain in [32] to model the behaviour of the DCF backoff timer in inter-platoon communications for these 2n backbone vehicles, we have equation (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. Equations in (12) indicate that \( \tau_i \) is related to \( p_{c,i} \).

\[
\begin{align*}
\tau_1 &= \frac{2(1-2p_{f,1})}{(1-2p_{f,1})(W+1) + p_{f,1}W(1-(2p_{f,1})^M)} \\
\tau_2 &= \frac{(1-2p_{f,2})W}{(1-2p_{f,2})(W+1) + p_{f,2}W(1-(2p_{f,2})^M)} \\
\tau_3 &= \frac{(1-2p_{f,3})W}{(1-2p_{f,3})(W+1) + p_{f,3}W(1-(2p_{f,3})^M)} \\
\tau_{2n-2} &= \frac{2(1-2p_{f,n-2})}{(1-2p_{f,n-2})(W+1) + p_{f,n-2}W(1-(2p_{f,n-2})^M)} \\
\tau_{2n-1} &= \frac{(1-2p_{f,n-1})W}{(1-2p_{f,n-1})(W+1) + p_{f,n-1}W(1-(2p_{f,n-1})^M)} \\
\tau_{2n} &= \frac{(1-2p_{f,n})W}{(1-2p_{f,n})(W+1) + p_{f,n}W(1-(2p_{f,n})^M)}.
\end{align*}
\]

(12)

Secondly, a vehicle can only communicate with up to two other vehicles via direct inter-platoon communications as illustrated in Figure 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 received successfully 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 \((1-q_{3\tau_3})\). Therefore, vehicle 1’s packets are sent and received successfully with probability \((1 - q_{2\tau_2}) (1 - q_{3\tau_3})\). For vehicle 2 (similar to vehicle \((2n - 1)\)), it can send packets to vehicle 3 and vehicle 1. Let \( \alpha \) 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 \( i \) is the destination of a vehicle’s 2 packet and this packet is received successfully by vehicle 1 is \( \alpha (1 - q_{1\tau_1}) \). Consequently, the probability that vehicle 3 is the destination of a vehicle’s 2 packet and this packet is received successfully by vehicle 3 is \((1 - \alpha)(1 - q_{3\tau_3}) (1 - q_{4\tau_4})\). For vehicle \( i \), where \( 3 \leq i \leq (2n - 2) \), we assume that the destination of its packets are vehicle \( i - 1 \) and vehicle \( i + 1 \) with probabilities \( \alpha \) and \( 1 - \alpha \), respectively. Then, we can get the probabilities that vehicle \( i \)'s packets are being received successfully by these two backbone vehicles being \( \alpha (1 - q_{(i-1)\tau_{(i-1)}}) (1 - q_{(i-2)\tau_{(i-2)}}) (1 - q_{(i+1)\tau_{(i+1)}}) (1 - q_{(i+2)\tau_{(i+2)}})\). As a result, we can get 2n equations, as shown in equation (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 vehicle \( i \) and vehicle \( 2n + 1 - i \) are the same. That is, the inter-platoon communication model has symmetry, and the performance of DCF in vehicle \( i \) and vehicle \( 2n + 1 - i \) (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). 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.

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

(13)

2) Packet delay: Consider vehicle \( i \) undergoing an inter-platoon 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

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

(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 \( E[X_i] \) and \( E[s_i] \) are given by

\[
\begin{align*}
E[X_i] &= \frac{W(1-(2p_{f,i})(M+1)+1-(2p_{f,i})(1-(p_{f,i})^{M+1}))}{2(1-2p_{f,i})(1-p_{f,i})} \\
E[s_i] &= \rho((1 - q_i) + q_i(1 - \tau_i)) + T_f \tau_i p_{f,i}q_i \\
&+ T_s q_i \tau_i(1 - p_{f,i}).
\end{align*}
\]

(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

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

(17)

The average packet dropping probability for a packet transmitted from the first backbone vehicle 1 to the last backbone
vehicle 2n via inter-platoon communications is defined as the average end-to-end packet dropping probability, \( p_d \), which is given by

\[
p_d = 1 - \prod_{i=1}^{2n} \left(1 - p_{d,i}\right)
= 1 - \prod_{i=1}^{2n} \left[1 - (1 - (1 - p_{c,i})(1 - p_c))^{\alpha+1}\right].
\]  

(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 \( 1 - q_i(1 - \tau_i) \). The probability that vehicle \( i \) fails to transmit a packet is \( q_i \tau_i p_{f,i} \) while 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 by (19).

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

(19)

According to [32], we define the multi-hop throughput of the inter-platoon communication model (from the first backbone vehicle to the last backbone vehicle) as \( \Phi = \sum_{i=1}^{2n} \Phi_i \). Hence, \( \Phi \) is given by (20).

D. Analysis of DCF parameters

Intra-platoon 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 subsection 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 inter-platoon 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 inter-platoon communications. In this case, (12) can be rewritten as

\[
\tau_1 = \tau_2 = \cdots = \tau_{2n-1} = \tau_{2n} = \frac{2}{(W + 1)}.
\]  

(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

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

(20)

\[p_{c,1} = p_{c,2n} = 1 - (1 - q_{W+1}^2) \left[1 - q_{W+1}^2 \frac{2 \rho}{W + 1}\right] = 1 - (1 - q_{W+1}^2) \left(1 + \frac{2 \rho}{W + 1}\right),
\]

\[p_{c,2} = p_{c,2n-1} = 1 - \alpha (1 - q_{W+1}^2 - (1 - \alpha)(1 - q_{W+1}^2)
= \left[1 - (1 - q_{W+1}^2) \left[1 - q_{W+1}^2 \frac{2 \rho}{W + 1}\right]\right]
= 1 - \left[\alpha (1 - q_{W+1}^2) + (1 - \alpha)(1 - q_{W+1}^2) \left(1 + \frac{2 \rho}{W + 1}\right)\right]
= p_{c,1} = p_{c,2n}.
\]  

(22)

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

\[
E[X_i] = \frac{1 - W}{2} \left[1 - (1 - p_{c,i})(1 - p_c)\right]
= \frac{1 - W}{2} \left[1 - (1 - q_{W+1}^2) \left(1 + \frac{2 \rho}{W + 1}\right)\right] \]  

(23)

\[
E[s_i] = (1 - \rho)_i \frac{2q_{W+1}^2}{W + 1} T_f + \frac{2q_{W+1}^2}{W + 1} (1 - p_{f,i}) T_s,\]  

(23)

For \( M = 0, i = 2, 2n - 1 \), (16) becomes

\[
E[X_i] = \frac{1 - W}{2} \left[1 - (1 - p_{c,i})(1 - p_c)\right]
= \frac{1 - W}{2} \left[1 - (1 - q_{W+1}^2) \left(1 + \frac{2 \rho}{W + 1}\right)\right] \]  

(24)

\[
E[s_i] = (1 - \rho)_i \frac{2q_{W+1}^2}{W + 1} T_f + \frac{2q_{W+1}^2}{W + 1} (1 - p_{f,i}) T_s,\]  

(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 \( \Phi \) for inter-platoon 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 backoff when they are undergoing an inter-platoon communication. For \( M = \infty \) and \( i = 1, 2, 3, \ldots, (2n - 1), 2n \), (12) becomes

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

(20)
When \( p_e = 0.2 \) to facilitate the following analysis, the expression of \( \tau_i \) for two cases of subsection, the performance analysis focuses on the following approaches (16), when \( M = 0 \), and the analysis of collision probability, packet delay, and throughput are the same as discussed previously.

(ii) When \( 0.5 \leq p_f,i \leq 1 \): From (27), \( \tau_i = 0 \) and \( p_{c,i} = 0 \), where \( i = 1, 2, 3, \cdots, (2n - 2), (2n - 1), 2n \). According to (16), when \( M = \infty \), \( \tau_i = 0 \), and \( p_{c,i} = 0 \), the value of \( E[X_i] \) approaches \( \infty \) and \( E[s_i] = \rho \), which means that the packet delay tends to \( \infty \) in such a situation. On the other hand, based on (19), the throughput \( \Phi_i \) of each vehicle in the inter-platoon communications tends to 0.

IV. NUMERICAL RESULTS

This section presents 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 IEEE 802.11p standard [29] and existing studies [24], [32]. The values of the related parameters are shown in Table II.

![Figure 4: Inter-platoon communication performance of each vehicle with 6 platoons (12 vehicles)](image)

### Table II: Related parameters values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W = W_p )</td>
<td>64</td>
<td>( E[L] )</td>
<td>2048 bits</td>
</tr>
<tr>
<td>( M = M_p )</td>
<td>5</td>
<td>( T_f )</td>
<td>246.18 ( \mu ) s</td>
</tr>
<tr>
<td>( \rho )</td>
<td>13 ( \mu ) s</td>
<td>( T_s )</td>
<td>297.63 ( \mu ) s</td>
</tr>
<tr>
<td>( T_p )</td>
<td>15 ( \mu ) s</td>
<td>( \alpha )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A. Communication performance

Figure 4 and Figure 5 show the inter-platoon communication performance metrics of each vehicle in the multiplatoon for \( q = 0.8, p_e = 0.1, p_c = 0.2 \) and \( p_c = 0.3 \) with 6 and 12 platoons, respectively. According to the analysis in Section III-C, the values of the transmission attempt probability, \( \tau_i \), and the collision probability of a packet from backbone vehicle
Throughput (Mbps)

(d) Throughput (Mbps)

Collision probability

40%
35%
30%
25%
20%
15%
10%
5%
0%

(b) Collision probability

Transmission Attempt probability

40%
35%
30%
25%
20%
15%
10%
5%
0%

(a) Transmission Attempt probability

Packet delay (µs)

2.5
2
1.5
1
0.5
0

(c) Packet delay (µs)

Throughput (Mbps)

2.5
2
1.5
1
0.5
0

(d) Throughput (Mbps)

Figure 5: Inter-platoon communication performance results of each vehicle with 12 platoons (24 vehicles)

The effect of the channel condition variabilities, represented by $p_e$ on the inter-platoon communication performance is also shown in Figure 4 and 5, respectively. A larger $p_e$ results in more transmission errors and, hence, the following: (i) an increased backoff times of a packet transmission, leading to a lower value of $\tau_i$; (ii) fewer packets can be received by backbone vehicles, due to a reduced impact from hidden nodes and a decrease in $p_{c,i}$; and (iii) a longer packet delay and a lower throughput.

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

B. The impact of platoon number

Figure 7 shows the average end-to-end packet delay, $E[D]$, and the throughput, $\Phi$, for different platoon number, $n$, in the inter-platoon 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 inter-platoon communication model, which results in a larger number of

$i, p_{c,i}$, are different from other backbone vehicles, resulting in different values of packet delay, $E[D_i]$, and throughput, $\Phi_i$.

From Figure 4, we observe the following: (i) For the first and the 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 inter-platoon communications (i.e., vehicle 2 and vehicle 11), the packet collisions from vehicle 2 and 3 increase the collision probability of packets transmitted from vehicle 1 (as illustrated in Figure 4(b)); (ii) For some backbone vehicles at the two ends of the multiplatoon (such as vehicle 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, shown as in Figure 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 (Figure 4(a), 4(c), 4(d)); (iii) 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; (iv) It is noted that the first and last backbone vehicles of the multiplatoon have significant impact on the communication performance metrics of other backbone vehicles. However, from Figure 4, with an increase of the platoon number in the multiplatoon, this impact wears off for the middle backbone vehicles in the inter-platoon communication model. As a result, the backbone vehicles from 7 to 18 in the multiplatoon have similar performance, as shown in Figure 5.
packets successfully transmitted in one time slot and, therefore, a higher $\Phi$. 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. The impact of DCF parameters

In this subsection, we consider a multiplatoon with $p_{c,i} = 0.2$, $q = 0.8$, and $n = 12$. Figure 8 shows the average end-to-end packet delay of the whole inter-platoon communication system, $E[D]$. In line with the analysis results in Section III-D, for a fixed $M$, the relationship between $E[D]$ and $W$ is non-linear. It can be seen that $E[D]$ increases with the increasing of $W$ and $M$. For example, $E[D] = 79.8\mu s$ when $W = 2$ and $M = 0$, while $E[D] = 98.87ms$ for $W = 256$ and $M = 7$. This is because a smaller $W$ and $M$ reduces the average backoff time for one packet transmission, resulting in a smaller $E[D]$. The above analysis results indicate that, via adjusting $W$ and $M$ values, $E[D]$ can be minimized.

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

Figure 10 shows the throughput of the whole inter-platoon communication system, $\Phi$. The results show that $\Phi$ reaches a peak value of 37.99Mbps when $n = 12$, $M = 5$, and $W = 16$, wherein $E[D] = 21.68ms$. For a fixed $W$, $\Phi$ first increases and then decreases with an increase of $M$. For a fixed $M$, when $W$ increases, $\Phi$ first increases and then decreases. These results indicate that (i) a higher $\Phi$ can be achieved by adjusting $W$ and $M$; (ii) a smaller $W$ leads to a higher
collision probability for packets transmitted from each vehicle in the system and, therefore, a lower $\Phi$; and (iii) for a small $W$, a larger $M$ increases the number of retransmission times for each packet and, therefore, $\Phi$ increases.

D. Results for different multiplatooning application scenarios

In Subsections III-A and III-C, we have calculated the packet delay of intra-platoon communications, $E[D_p]$, and the end-to-end packet delay of the inter-platoon communication between the first and last backbone vehicles, $E[D]$. In this subsection 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 $V_1^n$, until this packet is received by $V_j^p$, 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 equation (10) and (15). Consider the following three multiplatoon application scenarios: (i) braking/leaving information [20], (ii) velocity and acceleration (V&A) information [6], and (iii) other information, e.g., vehicle destination information. Since $E[D_m]$ is important to multiplatooning applications, we present numerical results to evaluate whether the DSRC can satisfy the delay requirements for these applications. In the following, we set $s_0 = 3m$, $v_e = 25m/s$, $T_0 = 1.5s$, $v_0 = 30m/s$, $L_T = 450m$, $L_0 = 3m$ [11], and $s_e = 56.3m$, $m_{max} = 8$ (based on the analysis in Subsection 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 $\alpha$ in the inter-platoon communication model is equal to 1. Figure 11 shows the value of $E[D_m]$ versus the platoon size, $m_v$, and the platoon number, $n$, 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 $E[D_m] = 46.21ms$ which is a small fraction of the tolerable delay 6.72s (with braking force 10000, vehicle weight 1800kg, intra-platoon spacing 56.3m) from the braking force perspective [20].

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 $V_1^n$ is the V&A information from tail vehicle $V_{m_1}^p$, the value of $\alpha$ here
is 1. The value of average packet delay is dependent on vehicle’s role in the platoon. For a leader or member vehicle $i$, it transmits its V&A information to other vehicles via intra-platoon communications; for a tail vehicle $i$, it transmits its V&A information to the leader vehicle in its following platoon via inter-platoon communications which can be calculated according to the analysis in Subsection III-B and Subsection III-C.

Figure 12 shows the average packet delay for transmitting the V&A information by a tail vehicle in the multiplatoon. 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 inter-platoon communication model, the impact from the first and last backbone vehicles is weakened when $n$ increases. Figure 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 $m_v$ means that more vehicles contend for accessing the same SCH for intra-platoon 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 6.7ms (the average delay of DSRC in [10]), while continuing to ensure the string stability of platoons. The numerical results in this subsection 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 6.7ms. Furthermore, according to the analysis results in [35], the string stability can be guaranteed for $T_0 > 0.1s$ when the communication delay less than 2.5ms, which means the intra-platoon spacing can be reduced to $s_v = 7.64m$ 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. Figure 14 shows the $E[D_m]$ 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 $E[D_m] = 46.21ms$ for braking/leaving information and $E[D_m] = 45.71ms$ for other information.

It should be noted that, in our analysis, we have only considered inter-platoon 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 non-backbone 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 intra-platoon and inter-platoon 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. CONCLUSIONS

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 inter-platoon 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 the future work, we will investigate the multi-hop intra-platoon communications to find the optimal platoon size that can balance the road capacity and end-to-end packet delay; ultimately, we will design an effective IEEE 802.11p-based platoon communication protocol for autonomous vehicles.

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