Time-Dependent Performance Modeling for Platooning Communications at Intersection

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Abstract—With the development of Internet of Vehicles, the platooning strategy has been widely studied as the potential approach to ensure the safety of autonomous driving. Vehicles in the form of platoon adopt 802.11p to exchange messages through vehicle-to-vehicle (V2V) communications. When multiple platoons arrive at an intersection, the leader vehicle of each platoon adjusts its movement characteristics to ensure that it can cross the intersection, and thus the following vehicles have to adjust their movement characteristics accordingly. In this case, the time-varying connectivity among vehicles leads to the significant nonstationary performance change in platooning communications, which may incur safety issues. In this article, we construct the time-dependent model to evaluate the platooning communication performance at the intersection based on the initial movement characteristics. We first consider the movement behaviors of vehicles at the intersection, including turning, accelerating, decelerating, and stopping as well as the periodic change of traffic lights to construct a movement model and then establish a hearing network to reflect the time-varying connectivity among vehicles. Afterward, we adopt the pointwise stationary fluid flow approximation (PSFFA) to model the nonstationary behavior of the transmission queue. Then, we consider four access categories (ACs) and continuous backoff freezing of 802.11p to construct the models to describe the time-dependent access process of 802.11p. Finally, based on the time-dependent model, the packet transmission delay (PTD) and packet delivery ratio (PDR) are derived. The accuracy of our proposed model is verified by comparing the simulation results with analytical results.

Index Terms—Intersection, platooning communication, time dependent.

I. INTRODUCTION

As the number of vehicles keeps increasing rapidly, road safety remains to be a critical issue. The world health organization (WHO) reports that around 1.25 million people die from traffic accidents each year in the world [1]. With the advent of artificial intelligence and cloud computing, autonomous driving has attracted the attention of many researchers due to its potential in improving road safety and travel experience [2]–[5]. Platooning is an important strategy to manage autonomous vehicles on a common lane. A platoon is composed of a leader vehicle and several follower vehicles. The leader vehicle controls the movement characteristics of the platoon, e.g., velocity and acceleration. The follower vehicles are autonomous vehicles that follow the leader vehicle one by one. The critical task of the platoon is to maintain its stable formation, i.e., each vehicle in the platoon keeps driving with a similar velocity and intraplatoon spacing. A platoon with a stable formation can save fuel consumption and avoid traffic accidents with high probability [6], [7].

Each platoon adopts the cooperative adaptive cruise control (CACC) system to maintain the stable formation, which relies on onboard sensors. Specifically, each vehicle in the platoon is equipped with sensors, e.g., radar or stereo cameras, to distinguish the preceding vehicle in the platoon from the nearby vehicles and detect the distance toward the preceding vehicle [8], [9]. Once the detected distance is not the safety intraplatoon spacing, the vehicle will automatically adjust its velocity and acceleration to ensure the distance to be the safe value [10]. However, sensors may be adversely affected by their own hardware problems and the external environment, e.g., rainy and foggy weather [11], which may prevent the vehicle from exactly distinguishing the preceding vehicle from the nearby vehicles. In this case, these sensors may fail in the target detection and yield an inaccurate detected distance [12], so it is far from enough to solely rely on the onboard sensor to maintain the stable platoon formation. Therefore, the CACC system further utilizes vehicle-to-vehicle (V2V) communications to maintain the stable platoon formation. IEEE 802.11p and cellular-vehicle-to-everything (C-V2X) Mode 4 are two important technologies to realize V2V communications without any infrastructure support [13]. However, C-V2X Mode 4 incurs a higher average delay than 802.11p [14]. Meanwhile, C-V2X Mode 4 lacks the mechanism to support the four kinds of data streams with different priorities defined by the European telecommunications standard institute (ETSI) [15], while 802.11p uses the enhanced distributed coordination function (EDCA) mechanism at the medium access control (MAC) layer to support the messages of the four access categories (ACs), where the ACs of messages are classified according to safety levels of vehicles [16]. Thus, C-V2X Mode 4 is limited to support V2V communications for the autonomous vehicles in platoons [13]. Therefore, in this article, we consider each vehicle adopts 802.11p to communicate with each other. Specifically, each vehicle exchanges messages with the vehicles within its communication range [17].

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The messages have to be received successfully within a limited time interval to ensure that all vehicles in the platoon can react in time to maintain the stable platoon formation. Therefore, the packet transmission delay (PTD) and packet delivery ratio (PDR) are very important metrics for platooning communications.

The characteristics of vehicles in platoons change dynamically when the platoons drive across the intersection. Specifically, when a platoon enters an intersection area, the leader vehicle will accelerate to pass through the intersection or decelerate to stop before the stop line according to the status of the traffic light, i.e., red or green, which incurs dramatic change of intraplatoon spacing toward its follower vehicles. In this case, the follower vehicles of the platoon will adjust their acceleration to maintain the intraplatoon spacing between adjacent vehicles, thus the formation of the platoon will be changed dynamically. Especially, when the platoon is turning at the intersection, the moving direction of the leader vehicle is time varying. In this case, each follower vehicle will sense the varying distance toward the preceding vehicle and adjust its moving direction and acceleration accordingly to maintain the safe intraplatoon spacing. In addition, when the distance between two adjacent platoons, i.e., interplatoon spacing, is smaller than the safe intraplatoon spacing, the leader vehicle of the following platoon will also adjust its acceleration to ensure the safe spacing, thus the formation of the following platoon will also change dynamically. As a result, when multiple platoons on different lanes with different directions enter the intersection, the distances between vehicles change obviously, which imposes the network connectivity to change dynamically. In this case, the PTD and PDR will be time dependent, thus the vehicles in the platoons may be unable to receive messages successfully within the limited time duration and further react in time to maintain the stable formation. It is critical to establish an analytical time-dependent model to evaluate the complex system scenario of vehicular platooning. However, the dynamic network connectivity leads to the nonstationary change of the PTD and PDR of platooning communications, which poses a challenge to establish the time-dependent model. To the best of our knowledge, no work has constructed the time-dependent model to evaluate the performance of platooning communications in the complex intersection scenario, which motivates us to investigate it.

In this article, we construct a time-dependent model to evaluate the performance of vehicular platooning communications at an intersection. The main contribution of this article is summarized as follows.

1) Considering the movement behaviors of platoons at the intersection (including turning, accelerating, decelerating, and stopping) as well as the periodic change of traffic lights, we construct a movement model of platoons at the intersection to calculate the time-dependent position of each vehicle. We further construct a hearing network to calculate the time-varying connectivity among vehicles according to the vehicles’ positions.

2) The pointwise stationary fluid flow approximation (PSFFA) is adopted to model the nonstationary dynamic behavior of the transmission queue. Moreover, we consider the four ACs and continuous backoff freezing of 802.11p to construct the models to describe the time-dependent access process of 802.11p. Then, the PTD and PDR are derived based on our proposed time-dependent model.

3) The accuracy of our proposed model is verified by comparing the analytical results with the simulation results. Moreover, the time-dependent performance of platooning communications at the intersection has been evaluated based on our model.

The remainder of this article is organized as follows. Section II reviews related works on the performance modeling of V2V communications. Section III describes the system scenario and overview the 802.11p EDCA mechanism. Section IV constructs the movement model to derive the time-dependent position of each vehicle and then establishes the hearing network to reflect the time-varying connectivity among vehicles. Section V constructs a time-dependent model for platooning communications at the intersection and then derives the PTD and PDR. We present simulation and analytical results in Section VI and then conclude them in Section VII.

II. RELATED WORK

In this section, we have reviewed the existing works on the performance modeling of V2V communications, including 802.11p and C-V2X Mode 4.

Many works have focused on the performance modeling of 802.11p and C-V2X Mode 4 in vehicular ad hoc networks (VANETs). Kim et al. [18] constructed multidimensional Markov chains to model the performance of 802.11p in intelligent transportation systems and then evaluated the successful delivery probability and the delay distribution. Shah et al. [19] presented a Markov chain model to derive the throughput and average delay of the 802.11p and further verified whether the 802.11p can satisfy the criteria of VANETs. Almohammedi and Shpelev [20] derived the transmission probability and system throughput of 802.11p based on a nonsaturated 2-D Markov chain model to evaluate the performance of vehicular networks. Yao et al. [21] presented a performance analysis model to evaluate the probability distribution, deviation, and mean of the MAC access delay for the single-hop broadcast under the 802.11p protocol. Togou et al. [22] proposed a Markovian analytical model to describe the process of collecting time-dependent channel state information and analyzed the throughput of the 802.11p for unsafety applications in V2V communications. Zheng and Wu [16] considered the factors (such as saturation condition, backoff counter freezing, and standard parameters) that affect the transmission probability, collision probability, and delay of 802.11p and constructed a 1-D and a 2-D Markov chain to model the 802.11p. Gonzalez-Martín et al. [23] presented the models to analyze the average PDR of C-V2X Mode 4 and then quantified the four different types of packet errors that affect C-V2X Mode 4. Schiegg et al. [24] considered the physical (PHY) and MAC layer of C-V2X Mode 4,
while developing a comprehensive analytical model to evaluate the communication performance. Although the above works have studied the modeling of the 802.11p and C-V2X Mode 4 in VANETs, they have not considered the platooning scenario.

Some existing works have studied the performance modeling of 802.11p and C-V2X Mode 4 for platooning communications. Peng et al. [25] presented an 802.11p-based communication model in multiplatooning scenario to improve the effectiveness of information sharing for platoon controlling. Jornod et al. [26] constructed a prediction model to guarantee the packet interreception time in the 802.11p-based VANETs where the vehicles cooperate as a platoon. Thunberg et al. [27] proposed an analytical framework considering the characteristics of V2V communication, i.e., packet loss probabilities and PTDs, to guarantee the string stability of platoon in the 802.11p-based VANETs. Yu et al. [28] adopted the Markov process and M/G/1/K queuing theory to propose the platoon structure model, vehicle control model, and communication model in a single platoon scenario and demonstrated that the 802.11p-based intravehicle communication can guarantee the stability of platoon. Lekidis and Bouali [29] presented a novel C-V2X Mode 4 network framework for platooning applications and constructed models to demonstrate the improvement of computing latency. Fu et al. [30] considered the C-V2X Mode 4 and proposed a prediction-assisted platooning mechanism to optimize the communication performance of platoons. They constructed a model for each vehicle based on the information received from the platoons to reduce information latency and then designed a detection algorithm to protect the platoons from malicious vehicles. However, these works only studied the time-independent performance model of vehicular platooning communications, which is not suitable to evaluate the dynamic vehicular environment when multiple platoons are crossing the intersection area.

A few papers have presented a time-dependent performance model of vehicular communications in VANETs. Xu et al. [31] established a time-varying communication network and evaluated the 802.11p-based V2V communication network. Tong et al. [32] adopted a continuous-time Markov chain to investigate the transmission behavior of 802.11p-based V2V safety communications. Awad et al. [33] considered the impact of a time-varying channel on V2V communications and proposed training-based, blind, and semiblind algorithms to evaluate the 802.11p-based V2V communications. Wu et al. [34] considered the disturbance in platoons and established a time-varying communication connectivity network to evaluate the PTD and PDR of the 802.11p in platoons. However, these works constructed the time-dependent model of vehicular communications in VANETs without considering platooning communications at the intersection, which inspires us to conduct this work.

### III. SYSTEM MODEL

In this section, we will introduce the system scenario at the intersection. Specifically, we describe the platoon behaviors at the intersection and then introduce the 802.11p EDCA mechanism. The notations in this article are summarized in Table I.

| Symbol | Description |
|--------|-------------|
| \( A_m \) | the number of additional time slots that must be waited to detect the channel idle for \( AG_m \) compared with \( AG_0 \) |
| \( AIPSN_m \) | the Arbitration Inter Frame Space Number of \( AG_m \) |
| \( a_{SN}\) | the maximum acceleration in the IDM model |
| \( b \) | the acceleration of \( V_s \) at time \( t \) |
| \( B_{k}^{\text{traffic}}(t) \) | the PGF of the traffic at the backoff counter of \( AG_m \) in vehicle \( V_{k} \) decreases to 0 when the number of retransmissions is \( j \) |
| \( c_{k,m}(t) \) | the squared coefficient variation of service time |
| \( D \) | the distance from the border of intersection area to stop line |
| \( D_s \) | the distance from the stop line to the center line |
| \( E[P_i] \) | the packet size |
| \( F_{k}(x) \) | the PGF of the backoff round time |
| \( f_{k,1}^{	ext{re}}(t) \) | the number of successfully received packets for \( AG_m \) of \( V_{k} \) at time \( t \) |
| \( f_{k,1}^{	ext{re}}(t) \) | the number of packets arriving at \( AG_m \) of \( V_{k} \) at time \( t \) |
| \( H_{k,m}(x) \) | the PGF of the time that the backoff counter of \( AG_m \) in vehicle \( V_{k} \) decreases one |
| \( L_0 \) | the length of each vehicle |
| \( MAC_{H} \) | the header length of MAC layer |
| \( M_{m} \) | the maximum number of retransmissions that the contention can be doubled |
| \( M_{r}^l \) | the retransmission limit |
| \( N_{k,m}(t) \) | the total number of vehicles in the communication range of \( V_{k} \) at time \( t \) |
| \( N_{k,m}(t) \) | the average number of packets in \( AG_m \) queue at time \( t \) |
| \( N_{k,m}(t) \) | the change rate of \( N_{k,m}(t) \) |
| \( N_{v}(t) \) | the number of vehicles of platoon \( P_k \) |
| \( P \) | the number of platoons |
| \( P_{k} \) | the kth platoon |
| \( P_{D_{k,m}}(t) \) | the time-dependent packet transmission delay |
| \( P_{D_{k,m}}(t) \) | the time-dependent packet delivery ratio |
| \( P_{k} \) | the PGF of service time of \( V_{k} \) in \( AG_m \) |
| \( P_{k} \) | the header length of physical layer |
| \( p_{k} \) | the probability that a packet arrives at the \( AG_m \) queue of vehicle \( V_{k} \) |
| \( p_{k}^{\text{loss}}(t) \) | the backoff freezing probability of \( AG_m \) in vehicle \( V_{k} \) |
| \( p_{k}^{\text{coll}}(t) \) | the internal collision probability of \( AG_m \) that multiple \( AG_m \) including \( AG_m \) transmit packets at the same time |
| \( p_{k}^{\text{coll}}(t) \) | the probability that the vehicle \( V_{j} \) successfully receives a packet transmitted from the target vehicle \( V_{k} \) |
| \( p_{k}^{\text{coll}}(t) \) | the collision probability caused by hidden vehicles |
| \( r_{k,m}(t) \) | the left-turn radius |
| \( R_{k} \) | the right-turn radius |
| \( R_{k} \) | the basic rate |
| \( R_{k} \) | the communication range of each vehicle |
| \( R_{d} \) | the data rate |
| \( s_{0} \) | the minimum intra-platoon spacing |
| \( s_{c} \) | the inter-platoon spacing at the equilibrium point \( e \) in the IDM model |
| \( \Delta S_{k,m}(t) \) | the intra-platoon spacing between \( V_{k} \) and \( V_{k-1} \) at time \( t \) |
| \( \Delta S_{k,m}(t) \) | the driving distance of \( V_{k} \) from time \( t \) to time \( t + \Delta t \) |
| \( S_{k,m}(t) \) | the maximum velocity allowed on the road |
| \( T_{0} \) | the desired gap of \( V_{k} \) to \( V_{k-1} \) at time \( t \) |
| \( T_{0} \) | the time duration of the green traffic light |
| \( T_{r} \) | the time duration of the red traffic light |
| \( T_{s} \) | the remaining time of green light when the leader vehicle enters the intersection area |
| \( T_{c}(x) \) | the PGF of the transmission time |
| \( T_{k,m}(t) \) | the MAC service time of \( AG_m \) in vehicle \( V_{k} \) |
| \( T_{k,m}(t) \) | the average residence time of a packet in \( AG_m \)’s queue |
| \( v_{c}(t) \) | the velocity at the equilibrium point \( e \) |
| \( v_{c}(t) \) | the velocity of \( V_{k} \) at time \( t \) |
| \( V_{k,m}(t) \) | the velocity of \( V_{k} \) at time \( t \) |
| \( V_{k,m}(t) \) | the velocity difference between \( V_{k} \) and \( V_{k-1} \) |
| \( W_{m,j} \) | the transmission probability of \( AG_m \) in vehicle \( V_{k} \) |
| \( W_{m,j} \) | the internal transmission probability of \( AG_m \) in vehicle \( V_{k} \) |
| \( (x_{k},y_{k}(t)) \) | the position of vehicle \( V_{k} \) at time \( t \) |
| \( \theta_{k}(t) \) | the angle of \( V_{k} \)’s heading deviating from the X-axis |
| \( \sigma_{k}^2(t) \) | the variance of the service time in \( AG_m \) of \( V_{k} \) |
| \( \lambda_{m} \) | the packet arrival rate at the \( AG_m \) queue |
| \( \mu_{k} \) | the service rate of \( AG_m \) |
| \( \mu_{k} \) | the probability of non-empty transmission queue of \( AG_m \) in vehicle \( V_{k} \) |
| \( \tau_{k}(t) \) | the transmission probability of \( V_{k} \) to \( V_{k} ") |
| \( \tau_{k,m}(t) \) | the external transmission probability of \( AG_m \) |
| \( \gamma \) | the propagation delay |
The coverage of the RSU is a circle with radius $R_u$. Consider the initial movement characteristics of vehicles. A roadside unit (RSU) which is connected to the vehicles within its communication range. 802.11p to broadcast its movement characteristics, i.e., position, velocity, and acceleration, to the vehicles within its communication range. The square area within the stop lanes is the center of the intersection. Four traffic lights are deployed at the intersection to control the traffic flow of each direction. Each traffic light keeps green for duration $T_G$ and red for duration $T_R$. Consider the transceiver is placed at the front bumper of each vehicle. The leader vehicle of each platoon adjusts its movement according to the traffic light when it enters the intersection area, i.e., the distance of its front bumper toward the stop line is smaller than $D_s$, where $D$ is the distance from the border of the intersection area to stop line. Within each time slot $Δt$, each vehicle in a platoon employs a car-following model widely adopted by platoons until the platoon passes the stop line. Thus, $V_k$ first observes the remaining time of green light and then estimates whether it can accelerate with the maximum acceleration $a$ specified in [25] to ensure it passes the stop line before the due time of the green light [36]. If $V_k$ can pass the stop line, $V_k$ makes a uniform acceleration linear motion with acceleration $a$ until it passes the stop line; otherwise, it reduces its acceleration in real time, similar to its operation under the red light. Note that if its velocity exceeds the maximum velocity allowed on the road $v_0$, it would keep moving with the velocity $v_0$.

3) Enter the Center Area of the Intersection: When $V_k$ enters the center area of the intersection, it would change the movements as follows until it leaves the center area of the intersection. If its velocity is larger than $v_s$, it decelerates its velocity with the suitable deceleration $b$ specified in [25]. Otherwise, if its velocity is smaller than $v_s$, it accelerates its velocity with acceleration $a$. In the deceleration or acceleration process, if its velocity reaches $v_s$, it will keep the constant velocity. Similar with [37], the moving directions of $V_k$ would be different when it moves on different lanes before entering the center area. If it is on the straight lane, it does not change its direction. If it is on the left-turn/right-turn lane, it takes a quarter circular motion until it reaches the target lane.

4) Leave the Center Area of the Intersection: When $V_k$ leaves the center area of the intersection, it drives along a straight line and makes the same acceleration or deceleration process as it enters the center area of the intersection.
The follower vehicles in $P_k$ adjust their velocities according to the IDM model, thus the formation of the platoon is dynamic in different areas.

B. 802.11p EDCA Mechanism

We will overview the access mechanism of the 802.11p protocol in this section. The 802.11p protocol adopts the EDCA access mechanism at the MAC layer to satisfy the requirements of different services. It defines four ACs, i.e., AC_{m} (m = 0, 1, 2, 3), to support the packets with various priorities to access channel. Each AC has a separate transmission queue. To distinguish the priorities of different ACs, the 802.11p EDCA mechanism defines different contention parameters for each AC, including the minimum contention window $CW_{min}^m$, maximum contention window $CW_{max}^m$, and arbitration interframe space AIFS_{m}. Here, AIFS_{m} is a channel’s idle duration before obtaining transmission opportunities, which is determined by arbitration interframe space number AIFSN_{m}. The relationship between AIFS_{m} and AIFSN_{m} of AC_{m} is expressed as follows:

$$AIFS_{m} = AIFSN_{m} \times \delta + SIFS$$  \hspace{1cm} (1)

where SIFS is the short interframe space and $\delta$ is one time slot.

In this article, we adopt the broadcast mechanism of the 802.11p to access channel. The detailed access process is described as follows. The backoff process is initialized once an AC_{m} in a vehicle has to transmit a packet. First, the backoff counter of AC_{m} is set as a random value within $[0, W_{m,0} - 1]$. Here, $W_{m,0}$ is the contention window size of AC_{m} when the number of retransmissions is 0 and $W_{m,0} = CW_{min}^m + 1$. Then, if the channel is detected to be idle within one time slot $\delta$, the backoff counter of AC_{m} would decrease by one. Otherwise, the backoff counter will be frozen until the channel keeps idle for the duration of AIFS_{m}. Note that continuous backoff freezing occurs when the channel is sensed to be busy for continuous slots. Therefore, the backoff counter would be frozen continuously until the channel keeps idle for AIFS_{m}. When the backoff counter of AC_{m} decreases to 0, AC_{m} attempts to transmit a packet. If no other ACs with higher priorities in the vehicle are transmitting at the same time, the packet of AC_{m} will be transmitted, and then the backoff counter will be reset as a random value within $[0, W_{m,0} - 1]$. Otherwise, an internal collision occurs and the packet will be retransmitted. At this time, the number of retransmission pluses one and a new backoff process is initialized with the contention window $W_{m,1}$ to retransmit the packet. The relationship between $W_{m,j}$ ($j = 0, 1, \ldots, M_{m}'$) and $CW_{min}^m, CW_{max}^m$ is expressed as follows:

$$W_{m,j} = \begin{cases} 2^j(CW_{min}^m + 1), & j \in [0, M_{m}] \\ CW_{max}^m + 1, & j \in (M_{m}, M_{m}') \end{cases}$$  \hspace{1cm} (2)

where $M_{m}'$ is the maximum number of retransmissions that the contention window can be doubled, $M_{m}$ is the retransmission limit, and the $CW_{max}^m$ is calculated as follows:

$$CW_{max}^m = 2^{M_{m}}(CW_{min}^m + 1) - 1.$$  \hspace{1cm} (3)

Let $M_{m}' = M_{m} + L_{m}$. If the number of retransmissions exceeds $M_{m}'$, the packet will be discarded. The detailed access process is shown in Fig. 2.

IV. MOVEMENT MODELING AND HEARING NETWORK

In this section, we first consider the movement behaviors of platoons at the intersection, such as turning, accelerating, decelerating, and stopping as well as the periodic change of traffic lights to construct the movement model of vehicles and derive the time-dependent position of each vehicle. Then, we establish the hearing network according to the time-dependent position of each vehicle to reflect the time-varying connectivity among vehicles.

A. Movement Modeling

The position of each vehicle is represented by a rectangular coordinate system, where the center of the intersection is set as the origin, the direction of the $x$-axis is east and the direction of the $y$-axis is north. The RSU is located at the origin point. At the initial time $t_0$, $V_{k,1}$ arrives at the coverage of the RSU and sends the movement characteristics of each vehicle in platoon $P_k$ to the RSU. Consider $V_{k,1}$ is driving toward east at $t_0$. Let $V_{k,i}$ be the target vehicle. During each time interval $\Delta t$, we assume that each vehicle follows the uniformly accelerated motion. Denote $v_{k,i}(t)$ as the velocity of $V_{k,i}$ at time $t$ and $a_{k,i}(t)$ as its acceleration rate. When $V_{k,i}$ is driving along the $x$-axis, $x_{k,i}(t)$ is fixed and $x_{k,i}(t)$ is calculated as follows:

$$x_{k,i}(t + \Delta t) = x_{k,i}(t) + v_{k,i}(t)\Delta t + \frac{1}{2}a_{k,i}(t)\Delta t^2.$$  \hspace{1cm} (4)

When $V_{k,i}$ is driving along the $y$-axis, $x_{k,i}(t)$ is constant and $y_{k,i}(t)$ can be calculated as follows:

$$y_{k,i}(t + \Delta t) = y_{k,i}(t) + v_{k,i}(t)\Delta t + \frac{1}{2}a_{k,i}(t)\Delta t^2.$$  \hspace{1cm} (5)

When $V_{k,i}$ is turning at the center area of the intersection, it would make a quarter circular motion after passing the stop lane until it arrives at the target lane. As shown in Fig. 3, circle center is the junction between the stop lane of the current lane and the target lane, and the radius is the distance from the center of stop line to the junction. Let $R_l$ and $R_r$ be the radius of the circle when $V_{k,i}$ is turning left and right, respectively, and $\theta_{k,i}(t)$ be the angle between $V_{k,i}$’s driving direction and the direction of the $x$-axis at time $t$. Here, $\theta_{k,i}(t)$ is 0 when $V_{k,i}$ begins to take a turn. We first consider the case when it is turning left. As shown in Fig. 3, the time-dependent angle
of $V_{k,i}$ can be expressed as follows:

$$\theta_{k,i}(t + \Delta t) = \theta_{k,i}(t) + \frac{\Delta L_{k,i}(t)}{R_l} + o(\Delta t)$$  \hspace{1cm} (6)

where $\Delta L_{k,i}(t)$ is the driving distance of $V_{k,i}$ from time $t$ to $t + \Delta t$, which can be expressed as follows:

$$\Delta L_{k,i}(t) = v_{k,i}(t)\Delta t + \frac{1}{2}a_{k,i}(t)\Delta t^2 + o(\Delta t^2).$$  \hspace{1cm} (7)

Based on $\theta_{k,i}(t)$ and $\Delta L_{k,i}(t)$, the time-dependent position of $V_{k,i}$ is calculated as follows:

$$\begin{cases} x_{k,i}(t + \Delta t) &= x_{k,i}(t) + \Delta L_{k,i}(t)\sin(\theta_{k,i}(t + \Delta t)) \\ y_{k,i}(t + \Delta t) &= y_{k,i}(t) + \Delta L_{k,i}(t)\cos(\theta_{k,i}(t + \Delta t)). \end{cases}$$  \hspace{1cm} (8)

Similarly, when turning right, the time-dependent position of $V_{k,i}$ can be calculated according to (8) by replacing $R_l$ with $R_r$ in (6).

According to (4)–(8), we need to further derive $v_{k,i}(t)$ and $a_{k,i}(t)$ to determine the time-dependent position. Based on the uniformly accelerated motion equation, $v_{k,i}(t)$ is represented as follows:

$$v_{k,i}(t + \Delta t) = v_{k,i}(t) + a_{k,i}(t)\Delta t + o(\Delta t).$$  \hspace{1cm} (9)

In (9), $v_{k,i}(t)$ is a function of $a_{k,i}(t)$. Therefore, we also need to derive $a_{k,i}(t)$ of leader vehicle and follower vehicles to determine the time-dependent position of $V_{k,i}$.

1) Leader Vehicle: If the interplatoon spacing of leader vehicle $V_{k,1}$ toward its preceding vehicle is smaller than the safe intraplatoon spacing $s_e$, it would act as a follower vehicle to adjust its acceleration according to the IDM model, which will be introduced in the accelerations of follower vehicles. Otherwise, $V_{k,1}$ would select different accelerations when it reaches different areas, i.e.: 1) enter the coverage of RSU; 2) enter the intersection area; 3) enter the center area of the intersection; and 4) leave the center area of the intersection.

According to the IDM model which is a car-following model widely adopted by platoons [38], $s_e$ is determined by $v_e$ and is calculated as follows:

$$s_e = \frac{s_0 + v_e T_0}{\sqrt{1 - \left(\frac{v_e}{v_0}\right)^4}}$$  \hspace{1cm} (10)

where $v_0$ is the maximum velocity allowed on the road, $s_0$ is the minimum intraplatoon spacing, and $T_0$ is the desired time headway. The time-dependent acceleration of leader vehicle $V_{k,1}$ is calculated as follows.

\begin{enumerate}
  \item \textit{Enter the coverage of RSU:} At the initial time $t_0$, $V_{k,1}$ enters the coverage of the RSU and sends the movement characteristics of each vehicle in $P_k$ to the RSU. Then, $V_{k,1}$ keeps moving with constant velocity $v_e$ before it enters the intersection area, thus the time-dependent acceleration of $V_{k,1}$ is given as follows:

$$a_{k,1}(t) = 0$$  \hspace{1cm} (11)

thus $x_{k,1}(t)$ is calculated according to (4) and $y_{k,1}(t)$ keeps $y_{k,1}(t_0)$.

  \item \textit{Enter the intersection area:} When $x_{k,1}(t) = -(D + D_s)$, $V_{k,1}$ enters the intersection area. At this time, $V_{k,1}$ observes the state of the traffic light and adjusts its acceleration accordingly.

1) Red Light: When the traffic light is red, $V_{k,1}$ slows down in real time until stopping at the stop line. Specifically, at the beginning of each time interval $\Delta t$, $V_{k,1}$ adjusts its deceleration based on a uniformly accelerated motion until reaching the stop line, thus the speed gradually becomes zero to avoid emergency braking. The time-dependent acceleration of $V_{k,1}$ is calculated as follows:

$$a_{k,1}(t) = \frac{v_{k,1}(t)^2}{2(D + x_{k,1}(t))}.$$  \hspace{1cm} (12)

Then, it will predict whether it can pass the stop line within $T_{G}^{\text{rem}}$. Note that if the velocity of $V_{k,1}$ exceeds the maximum velocity $v_0$, it would keep moving with the velocity $v_0$ [39]. In other words, the acceleration of $V_{k,1}$ is as follows:

$$a_{k,1}(t) = \begin{cases} a, & v_{k,1}(t) < v_0 \\ 0, & v_{k,1}(t) = v_0. \end{cases}$$  \hspace{1cm} (14)

$V_{k,1}$ calculates $x_{k,1}(t + T_{G}^{\text{rem}})$ according to (4)–(9). Note that the computation capacity of $V_{k,1}$ is powerful and it can calculate its position within a short time that can be neglected. Then, $V_{k,1}$ takes different actions according to the prediction result. Specifically, if $x_{k,1}(t + T_{G}^{\text{rem}}) < -D_s$, $V_{k,1}$ cannot pass the stop line. In this case, it has to slow down in real time based on the acceleration in (12). If $x_{k,1}(t + T_{G}^{\text{rem}}) \geq -D_s$, $V_{k,1}$ can pass the stop line by adjusting the acceleration based on (14).

In this area, $x_{k,1}(t)$ is calculated according to (4) and $y_{k,1}(t)$ keeps $y_{k,1}(t_0)$.

  \item \textit{Enter the center area of the intersection:} When $x_{k,1}(t) = -D_s$, $V_{k,1}$ enters the center area of the intersection. At this time, it decelerates its velocity with the suitable deceleration $b$. Otherwise, it accelerates with acceleration $a$. In the deceleration or acceleration process, the velocity of $V_{k,1}$ would
keep $v_e$ after it reaches $v_e$. Thus, the acceleration of $V_{k,1}$ is calculated as follows:

$$a_{k,1}(t) = \begin{cases} 
- b, & v_{k,1}(t) > v_e \\
0, & v_{k,1}(t) = v_e \\
\alpha, & v_{k,1}(t) < v_e.
\end{cases} \quad (15)$$

In this area, $x_{k,1}(t)$ and $y_{k,1}(t)$ are calculated according to (6)–(8) if $V_{k,1}$ is turning left. If $V_{k,1}$ is turning right, $x_{k,1}(t)$ and $y_{k,1}(t)$ can be calculated according to (8) by replacing $R_l$ with $R_r$ in (6). If $V_{k,1}$ is driving straightly, $x_{k,1}(t)$ is calculated according to (4) and $y_{k,1}(t)$ keeps $y_{k,1}(t_0)$.

d) Leave the center area of the intersection: When $|y_{k,1}(t)| = D_o$ or $x_{k,1}(t) = D_c$, $V_{k,1}$ leaves the center area of the intersection. At this time, $V_{k,1}$ would decelerate or accelerate with an acceleration calculated by (15).

In this area, when $V_{k,1}$ turns left and right, $y_{k,1}(t)$ is calculated according to (5) and $x_{k,1}(t)$ keeps constant. When it drives straightly, $x_{k,1}(t)$ is calculated according to (4) and $y_{k,1}(t)$ keeps constant.

Note that the movement models are similar when $V_{k,1}$ drives toward other directions within the coverage of the RSU at $t_0$. In addition, the movement behaviors may be different at different intersections, but the movement model can be generically constructed in different cases if each vehicle follows the uniformly accelerated motion in each time interval $\Delta t$.

2) Follower Vehicles: Follower vehicles can adjust their accelerations to maintain the stable formation of platoons according to the IDM model. The accelerations of the follower vehicles are calculated according to the IDM model [25], i.e.,

$$a_{k,j}(t) = \alpha \left[ 1 - \left( \frac{v_{k,j}(t)}{v_0} \right)^4 - \frac{S_{k,j}(t)}{\Delta S_{k,j}(t)} \right]^2. \quad (16)$$

where

$$S_{k,j}(t) = s_0 + v_{k,j}(t)T_0 + \frac{v_{k,j}(t)\Delta v_{k,j}(t)}{2\sqrt{ab}}. \quad (17)$$

In (16) and (17), $a$ is the maximum acceleration, $b$ is the suitable deceleration, $\Delta S_{k,i}(t)$ is the intraplatoon spacing between $V_{k,j}$ and $V_{k,i-1}$ at time $t$, $S_{k,j}(t)$ indicates the desired gap toward the preceding vehicle at time $t$, and $\Delta v_{k,j}(t)$ is the velocity difference between vehicle $V_{k,j}$ and the preceding vehicle $V_{k,i-1}$ at time $t$. In (16) and (17), $a$, $b$, $v_0$, $s_0$, and $T_0$ are given, and $\Delta v_{k,j}(t)$ is calculated as follows:

$$\Delta v_{k,j}(t) = v_{k,j}(t) - v_{k,i-1}(t) \quad (18)$$

where $v_{k,j}(t)$ and $v_{k,i-1}(t)$ are calculated according to (9). In addition

$$\Delta S_{k,j}(t) = \sqrt{[x_{k,j-1}(t) - x_{k,j}(t)]^2 + [y_{k,j-1}(t) - y_{k,j}(t)]^2} - L_0 \quad (19)$$

where $L_0$ is the length of each vehicle, $x_{k,j-1}(t)$, $x_{k,j}(t)$, $y_{k,j-1}(t)$, and $y_{k,j}(t)$ are calculated based on (4)–(8), which are dependent on the areas where $V_{k,i}$ and $V_{k,i-1}$ are located.

According to the above analysis, given the initial movement characteristics of each vehicle, including position, velocity, and acceleration of each vehicle at $t_0$, RSU can determine the time-dependent position of each vehicle in the intersection.

B. Hearing Network

We denote $(x_{k,i}(t), v_{k,i}(t))$ as the position of $V_{k,i}$ at time $t$, $R_c$ as the communication range of each vehicle, and $M$ as the number of vehicles. Then, the hearing network matrix $H(t)$, which is an $M \times M$ square symmetric matrix, can be modeled as follows:

$$H(t) = \begin{bmatrix}
    h_{11}(t) & \cdots & h_{11,p}(t) \\
    \vdots & \ddots & \vdots \\
    h_{p1}(t) & \cdots & h_{p1,p}(t)
\end{bmatrix}
$$

where

$$h_{k,i}(t) = \begin{cases} 
1, & \sqrt{[x_{k,i}(t) - x_{k,j}(t)]^2 + [y_{k,i}(t) - y_{k,j}(t)]^2} \leq R_c \\
0, & \sqrt{[x_{k,i}(t) - x_{k,j}(t)]^2 + [y_{k,i}(t) - y_{k,j}(t)]^2} > R_c.
\end{cases} \quad (21)$$

In (20) and (21), if $h_{k,i}(t) = 1$, the distance between $V_{k,i}$ and $V_{q,l}$ is smaller than the communication range $R_c$ at time $t$, i.e., $V_{k,i}$ and $V_{q,l}$ could communicate with each other at $t$; otherwise, they cannot communicate with each other at $t$. The value of $h_{k,i}(t)$ can be calculated according to the time-dependent positions of $V_{k,i}$ and $V_{q,l}$, which has been obtained in the previous section, thus the hearing network can be determined to reflect the time-varying connectivity among vehicles.

V. MODELING OF 802.11P

In this section, we construct models of 802.11p for platooning communications at the intersection based on the hearing network. We first adopt the PSFFA to model the dynamic behavior of a transmission queue, then consider the continuous backoff freezing and adopt the z-domain linear model to describe the access process of the 802.11p with four ACs. Finally, based on the time-dependent model of 802.11p, the PTD and PDR are derived.

A. Dynamic Behavior of Transmission Queue

We adopt the single-server first-come–first-service (FCFS) queuing system with infinite capacity for each transmission queue of $V_{k,i}$. Packets arrive at the transmission queue $A_{k,i}$ according to a poisson process with the arrival rate $\lambda_m$, which is a constant. Let $N_{k,i,m}(t)$ be the average number of packet in transmission queue $A_{k,i}$ at time $t$, and $\hat{N}_{k,i,m}(t)$ be the average change rate of $N_{k,i,m}(t)$, $\mu_{k,i,m}(t)$ is the service rate of $A_{k,i}$ in vehicle $V_{k,i}$, and $\rho_{k,i,m}(t)$ be the server utilization, i.e., the probability of nonempty transmission queue of $A_{k,i}$ in $V_{k,i}$. Thus, $\hat{N}_{k,i,m}(t)$ can be calculated according to the fluid flow (FF) model, i.e.,

$$\hat{N}_{k,i,m}(t) = -\mu_{k,i,m}(t)\rho_{k,i,m}(t) + \lambda_m. \quad (22)$$

Similar to [31], the access process of $A_{k,i}$ obeys a general distribution and the service time at each time is independent and identically distributed. Let $T_{k,i,m}(t)$ and $\sigma_{k,i,m}^2(t)$ be...
the mean and variance of the service time in $AC_m$ of $V_{k,i}$ at time $t$, and thus we have $T_{k,i,m}(t) = (1/\mu_{k,i,m}(t))$. In this case, the transmission queue of $AC_m$ is regraded as an M/G/1 queue model, and the relationship between $N_{k,i,m}(t)$ and $\rho_{k,i,m}(t)$ can be obtained through Pollaczek–Khinchine (P-K) formula [40], i.e.,

$$N_{k,i,m}(t) = \rho_{k,i,m}(t) + \frac{\rho_{k,i,m}(t)^2 (1 + c_{k,i,m}^2(t))}{2(1 - \rho_{k,i,m}(t))}$$  \hspace{1cm} (23)

where $c_{k,i,m}^2(t)$ is the squared coefficient variation of service time in $AC_m$ of $V_{k,i}$ at time $t$. Based on (23), $\rho_{k,i,m}(t)$ is calculated as follows:

$$\rho_{k,i,m}(t) = N_{k,i,m}(t) + 1 - \sqrt{N_{k,i,m}(t)^2 + 2c_{k,i,m}^2(t)N_{k,i,m}(t) + 1}$$  \hspace{1cm} (24)

Substituting (24) into (22), $\dot{N}_{k,i,m}(t)$ can be derived according to PSFFFA [31], where the PSFFFA equation for $AC_m$ is as follows:

$$\dot{N}_{k,i,m}(t) = - N_{k,i,m}(t) + 1 - \sqrt{N_{k,i,m}(t)^2 + 2c_{k,i,m}^2(t)N_{k,i,m}(t) + 1}$$  \hspace{1cm} (25)

where $c_{k,i,m}(t)$ is the service time of $AC_m$ of $V_{k,i}$ at time $t$. The arrival rate $\lambda_m$ is determined by adopting the Runge–Kutta algorithm [41] to solve (25) in each time interval $\Delta t$ if both $c_{k,i,m}(t)$ and $\mu_{k,i,m}(t)$ are determined. Here, $c_{k,i,m}(t)$ is defined as follows [31]:

$$c_{k,i,m}(t) = c_{k,i,m}(t) \mu_{k,i,m}(t)$$  \hspace{1cm} (26)

and the relationship between $T_{k,i,m}(t)$ and $\mu_{k,i,m}(t)$ is as follows:

$$\mu_{k,i,m}(t) = \frac{1}{T_{k,i,m}(t)}$$  \hspace{1cm} (27)

Thus, the mean and variance of the service time, i.e., $T_{k,i,m}(t)$ and $\sigma_{k,i,m}^2(t)$, will be required to determine $c_{k,i,m}(t)$ and $\mu_{k,i,m}(t)$. Next, we will further model the access process of the 802.11p EDCA mechanism to derive $T_{k,i,m}(t)$ and $\sigma_{k,i,m}^2(t)$.

**B. Modeling of the 802.11p Access Process**

The access process of the 802.11p (i.e., the 802.11p EDCA mechanism) consists of transmission and backoff processes, thus the delay of vehicle $V_{k,i}$’s $AC_m$ is an aggregated time duration of the transmission and backoff processes. We will consider the continuous backoff freezing and adopt the z-domain linear model proposed in [42] to model the access process of the 802.11p.

Let $P_{st}^{k,i,m}(z)$ be the probability generating function (PGF) of the service time of $V_{k,i}$’s $AC_m$, $T_{st}(z)$ be the PGF of the transmission time, $B_j^{k,i,m}(z)$ be the PGF of the backoff time of $AC_m$ when the number of retransmissions is $j$, and $p_{st}^{k,i,m}(t)$ be the internal collision probability of $AC_m$ in $V_{k,i}$, i.e., the probability that there are other ACs of $V_{k,i}$ with higher priority transmitting at the same time. Based on the z-domain linear model, we have

$$P_{st}^{k,i,m}(z) = B_0^{k,i,m}(z) T_{st}(z), \quad m = 0$$

$$+ \left(1 - p_{st}^{k,i,m}(t)\right) \left(1 - B_0^{k,i,m}(z) T_{st}(z) \sum_{m=0}^{M_b} \left(p_{st}^{k,i,m}(t)^m \prod_{j=0}^{m} B_j^{k,i,m}(z) \right) \right.$$  \hspace{1cm} (28)

Next, $T_{st}(z)$ and $B_j^{k,i,m}(z)$ are calculated as follows. Assuming the size of each packet in each AC is the same, the transmission time $T_{st}$ is calculated as follows:

$$T_{st} = \frac{PHY_H}{R_b} + \frac{MAC_H + E[P]}{R_d} + \gamma$$  \hspace{1cm} (29)

where $PHY_H$ is the header length at the physical layer, $MAC_H$ is the header length at the MAC layer, $R_b$ is the basic rate, $R_d$ is the data rate, $\gamma$ is the propagation delay, and $E[P]$ is the packet size. In (29), $PHY_H$, $MAC_H$, $R_b$, $R_d$, $\gamma$, and $E[P]$ are predefined, thus $T_{st}(z)$ can be expressed as follows:

$$T_{st}(z) = z^{-2} T_{st}.$$  \hspace{1cm} (30)

In addition, $B_j^{k,i,m}(z)$ can be expressed based on the z-domain linear model, i.e.,

$$B_j^{k,i,m}(z) = \left\{ \begin{array}{ll} \frac{1}{W_{0,0}} \sum_{k=0}^{W_{0,0}-1} \left[H_{k,i,m}(z)^m, \quad m = 0 \right] \\
\frac{1}{W_{1,0}} \sum_{k=0}^{W_{1,0}-1} \left[H_{k,i,m}(z)^m, \quad m = 1, 2, 3, j \in [0, M_b - 1] \right] \\
\frac{1}{W_{m,M_b}} \sum_{k=0}^{W_{m,M_b}-1} \left[H_{k,i,m}(z)^m, \quad m = 1, 2, 3, j \in [M_b, M_b'] \right] \end{array} \right.$$  \hspace{1cm} (31)

where $H_{k,i,m}(z)$ is the PGF of the average time that the backoff counter in $AC_m$ of $V_{k,i}$ takes to decrease by one. If the channel is sensed busy, i.e., it is occupied by other vehicles or other ACs of $V_{k,i}$ with higher priority, the backoff counter would be frozen for $T_{st} + AIFS_m$. Thus, the PGF of the backoff freezing time $F_m(z)$ can be expressed as follows:

$$F_m(z) = z^{-T_{st} + AIFS_m}.$$  \hspace{1cm} (32)

Let $p_{st}^{k,i,m}(t)$ be the probability that the channel is sensed busy. According to the z-domain linear model in [43], when the continuous backoff freezing is considered, $H_{k,i,m}(z)$ can be calculated by the mason formula, i.e.,

$$H_{k,i,m}(z) = \frac{1}{1 - p_{st}^{k,i,m}(t) F_m(z)} \times \left\{ (1 - p_{st}^{k,i,m}(t))^\delta \left[1 - p_{st}^{k,i,m}(t) F_m(z) \right] + p_{st}^{k,i,m}(t) F_m(z) \left(1 - p_{st}^{k,i,m}(t)^\delta \right) \right\} \hspace{1cm} (33)$$

Combining the above equations, we can find that $P_{st}^{k,i,m}(z)$ depends on $p_{st}^{k,i,m}(t)$ and $p_{st}^{k,i,m}(t)$. Thus, we will further derive $p_{st}^{k,i,m}(t)$ and $p_{st}^{k,i,m}(t)$. Let $w_{st}^{k,i,m}(t)$ be the internal transmission probability of $AC_m$, i.e., the probability that the backoff
counter of $A_m$, decreases to zero. Since $p_{V,i}^{k,i,m}(t)$ is the probability that there are other ACs of $V_{k,i}$ with higher priorities transmitting packets, $p_{V,i}^{k,i,m}(t)$ is expressed as follows:

$$p_{V,i}^{k,i,m}(t) = \begin{cases} 0 & m = 0 \\ 1 - \prod_{n=1}^{m-1} (1 - w_{k,i,n}(t)) & m = 1, 2, 3. \end{cases} \quad (34)$$

Since $p_{b}^{k,i,m}(t)$ is the probability that other vehicles in the communication range of $V_{k,i}$ or other ACs of $V_{k,i}$ are transmitting, $p_{b}^{k,i,m}(t)$ is calculated as follows:

$$p_{b}^{k,i,m}(t) = 1 - \left(1 - \tau_{k,i}(t)\right)^{N_{c}^{k,i}(t)-1} \prod_{n=1}^{m} (1 - w_{k,i,n}(t)) \quad (35)$$

where $N_{c}^{k,i}(t)$ is the number of vehicles in the communication range of $V_{k,i}$ and can be determined by the hearing network $H(t)$, which has been obtained in Section IV, i.e.,

$$N_{c}^{k,i}(t) = \sum_{q=1}^{P} \sum_{l=1}^{n_k} h_{k,i,q}(t). \quad (36)$$

For $A_m$, $A_m$ more slots needs to be detected than $A_0$, thus $A_m$ is calculated as follows:

$$A_m = \text{AIFS}_{m} - \text{AIFS}_{0}. \quad (37)$$

Meanwhile, $\tau_{k,i}(t)$ is calculated as follows:

$$\tau_{k,i}(t) = \sum_{i=0}^{3} \tau_{k,i,m}(t) \quad (38)$$

where $\tau_{k,i,m}(t)$ is the external transmission probability of $A_m$ for $V_{k,i}$, i.e., the probability that only the current $A_m$ of $V_{k,i}$ is transmitting while ACs with higher priorities of $V_{k,i}$ are not transmitting. Thus, $\tau_{k,i,m}(t)$ can be calculated as follows:

$$\tau_{k,i,m}(t) = \begin{cases} w_{k,i,m}(t) & m = 0 \\ w_{k,i,m} \prod_{n=1}^{m-1} (1 - w_{k,i,n}(t)) & m = 1, 2, 3. \end{cases} \quad (39)$$

According to (34)–(39), both $p_{V,i}^{k,i,m}(t)$ and $p_{b}^{k,i,m}(t)$ are determined by $w_{k,i,m}(t)$, which can be calculated as follows [44]:

$$w_{k,i,m}(t) = \begin{cases} \frac{w_{k,i,m+1}}{2(p_{b}^{k,i,m}(t))} + \frac{1-p_{b}^{k,i,m}(t)}{p_{b}^{k,i,m}(t)} & m = 0 \\ \frac{1-w_{k,i,m}(t)}{1-p_{b}^{k,i,m}(t)} - \frac{1-w_{k,i,m}(t)}{1-p_{b}^{k,i,m}(t)} + \frac{w_{m}^{k,i}(t)}{2(1-p_{b}^{k,i,m}(t))} & m = 1, 2, 3. \end{cases} \quad (40)$$

where $p_{a}^{k,i,m}(t)$ is the probability that a packet arrives at $A_m$. Since packets arrive at each AC according to the possion distribution with rate $\lambda_m(t)$, $p_{a}^{k,i,m}(t)$ is calculated as follows:

$$p_{a}^{k,i,m}(t) = \sum_{n=1}^{\infty} \frac{(\lambda_m(t))^{n}}{n!} e^{-\lambda_m(t)} = 1 - e^{-\lambda_m(t)}. \quad (41)$$

Substituting (41) to (40), it can be found that $w_{k,i,m}(t)$ is related to $\rho_{k,i,m}(t)$, thus $\tau_{k,i,m}(t)$ is determined by $\rho_{k,i,m}(t)$. According to the property of the PGF approach, the $T_{k,i,m}(t)$ is calculated as follows:

$$T_{k,i,m}(t) = \frac{dP_{k,i,m}(z)}{dz} \bigg|_{z=1} \quad (42)$$

and $\sigma_{k,i,m}(t)$ is calculated as follows:

$$\sigma_{k,i,m}(t) = \left[ \frac{d^2P_{k,i,m}(z)}{dz^2} + \frac{dP_{k,i,m}(z)}{dz} - \left( \frac{dP_{k,i,m}(z)}{dz} \right)^2 \right] \bigg|_{z=1} \quad (43)$$

As $T_{k,i,m}(t)$ and $\sigma_{k,i,m}(t)$ are related to $\rho_{k,i,m}(t)$, the calculation of $T_{k,i,m}(t)$ and $\sigma_{k,i,m}(t)$ is a nonlinear complex simulation process. Therefore, we use the iterative method to calculate $T_{k,i,m}(t)$ and $\sigma_{k,i,m}(t)$ step by step.

1. First, initialize $\rho_{k,i,m}(t)$ in the range (0, 1).
2. Second, calculate $p_{b}^{k,i,m}(t)$ and $p_{V,i}^{k,i,m}(t)$ according to (34) and (35).
3. Third, calculate the mean service time $T_{k,i,m}(t)$ according to (42) and calculate a new value of $\rho_{k,i,m}(t)$ according to the equation $\min(\lambda_m T_{k,i,m}(t), 1)$.
4. Fourth, compare the absolute error between the initial and new value of $\rho_{k,i,m}(t)$ with the predefined error bound $\epsilon$. If the absolute error is less than $\epsilon$, the iteration is terminated with the current $\rho_{k,i,m}(t)$ as an output. Otherwise, repeat the above iteration with the updated $\rho_{k,i,m}(t)$ as an initial value until the absolute error is less than $\epsilon$.
5. Finally, calculate the variance of service time $\sigma_{k,i,m}(t)$ according to (43).

Now, we have obtained $\tau_{k,i}(t)$, $\rho_{k,i,m}(t)$, $T_{k,i,m}(t)$, and $\sigma_{k,i,m}(t)$ based on which $c_{k,i,m}(t)$ and $\mu_{k,i,m}(t)$ can be calculated according to (26) and (27). Then, $N_{k,i,m}(t)$ in (25) can be further determined based on the PSFFA method [31].

C. PTD and PDR

Since the packets transmitted by $V_{k,i}$ should be received successfully within a short time duration at the intersection, PTD and PDR are very important for platooning communications.

1. Packet Transmission Delay: The PTD of vehicle $V_{k,i}$’s $A_m$ at time $t$ is defined as the time duration of a packet from entering the transmission queue $A_m$ of $V_{k,i}$ to being received successfully or discarded. According to Little’s law, the average number of packets in transmission queue $A_m$ of $V_{k,i}$ at time $t$ can be expressed as follows:

$$N_{k,i,m}(t) = \lambda_m \times T_{k,i,m}(t) \quad (44)$$

where $T_{k,i,m}(t)$ is the average residence time of the packet in $A_m$ of $V_{k,i}$ at time $t$. The change rate of $T_{k,i,m}(t)$ can be
expressed as follows:

$$\hat{P}_{k,i,m}(t) = \frac{\hat{N}_{k,i,m}(t)}{\lambda_m}.$$  \(45\)

Let \(PTD_{k,i,m}(t)\) be the PTD of \(V_{k,i}\)'s AC \(m\) at time \(t\). The PTD at time \(t + \Delta t\) can be calculated as the summation of \(PTD_{k,i,m}(t)\) and the change of average residence time of the packet in AC \(m\) within \([t, t + \Delta t]\), i.e., \(\frac{\Delta t}{\Delta t} P_{f_{k,i,m}(t)}\). Thus, according to \((45)\), \(PTD_{k,i,m}(t + \Delta t)\) is calculated as follows:

$$PTD_{k,i,m}(t + \Delta t) = \begin{cases} N_{k,i,m}(t), & t = t_0 \\ PTD_{k,i,m}(t) + f_{k,i,m}^{\Delta t} \frac{\hat{N}_{k,i,m}(t)}{\lambda_m} dt, & t > t_0 \end{cases} \tag{46}$$

where \(N_{k,i,m}(t_0)\) is given. Since \(\hat{N}_{k,i,m}(t)\) has been obtained in Section V, we can determine the time-dependent PTD according to \((46)\).

2) Packet Delivery Ratio: The PDR of AC \(m\) for \(V_{k,i}\) at time \(t\) [denoted as \(PDR_{k,i,m}(t)\)] is calculated as the ratio between the number of successfully received packets [denoted as \(f_{k,i,m}(t)\)] and the total number of packets arriving at AC \(m\) of \(V_{k,i}\) at time \(t\) [denoted as \(f_{a,k,i,m}(t)\)]. Thus, PDR\(_{k,i,m}(t)\) is expressed as follows:

$$PDR_{k,i,m}(t) = \frac{f_{k,i,m}(t)}{f_{a,k,i,m}(t)}.$$  \(47\)

Here, \(f_{a,k,i,m}(t)\) and \(f_{s,k,i,m}(t)\) are derived from the hearing network \(H(t)\). In particular, \(f_{a,k,i,m}(t)\) is calculated as follows:

$$f_{a,k,i,m}(t) = \sum_{q=1}^{P} \sum_{l=1}^{n_k} \lambda_m h_{k,i,q,l}(t).$$  \(48\)

Meanwhile, as the number of transmitted packets of AC \(m\) for \(V_{k,i}\) at time \(t\) is \(\mu_{k,i,m}(t)\rho_{k,i,m}(t)\), \(f_{s,k,i,m}(t)\) is expressed as follows:

$$f_{s,k,i,m}(t) = \sum_{q=1}^{P} \sum_{l=1}^{n_k} \mu_{k,i,m}(t)\rho_{k,i,m}(t) h_{k,i,q,l}(t) P_{k,i,q,l}^s(t)\tag{49}$$

where \(P_{k,i,q,l}^s(t)\) is the probability that \(V_{k,i}\) successfully receives a packet transmitted from \(V_{k,i}\). Since the physical layer has a much smaller impact on packet transmission compared to MAC layer, we consider this ideal channel in this article, similar to the related work [44], i.e., the packet loss is only incurred by the collisions at the MAC layer. Therefore, the successful transmission occurs when both conditions are satisfied. One is that no other vehicles in the communication range of \(V_{k,i}\) is transmitting at the same time, i.e., there is no collision caused by exposed vehicles. Another condition is that no other vehicle in the communication range of \(V_{k,i}\) but not in the communication range of \(V_{k,q}\) is transmitting at the same time, i.e., there is no collision caused by the hidden vehicles. Let \(P_{exposed}^{k,i,q,l}(t)\) be the collision probability that is caused by exposed vehicles, and \(P_{hidden}^{k,i,q,l}(t)\) be the collision probability that is caused by hidden vehicles. Thus, we have

$$P_{k,i,q,l}^s(t) = \left(1 - P_{k,i,q,l}^{exposed}(t)\right) \left(1 - P_{k,i,q,l}^{hidden}(t)\right).$$  \(50\)

The collision probability caused by exposed vehicles is the probability that there is at least one vehicle in the communication range of \(V_{k,i}\) transmitting at the same time. Therefore, \(P_{exposed}^{k,i,q,l}(t)\) is calculated as follows:

$$P_{exposed}^{k,i,q,l}(t) = h_{k,i,q,l} \times \left[1 - \prod_{r=1}^{P} \prod_{s=1}^{n_k} \left(1 - \tau_{r,s}(t)\right)\right]$$

\(\forall k, q, r = 1, \ldots, P; \forall l, s = 1, \ldots, n_k.\)  \(51\)

Denote \(T_d\) as the transmission delay. The collision probability caused by hidden vehicles is the probability that there is at least one vehicle outside the communication range of \(V_{k,i}\) transmitting to \(V_{q,l}\) within the time period \([t - T_d, t + T_d]\). Therefore, \(P_{hidden}^{k,i,q,l}(t)\) is calculated as follows:

$$P_{hidden}^{k,i,q,l}(t) = h_{k,i,q,l} \times \left[1 - \prod_{r=1}^{P} \prod_{s=1}^{n_k} \left(1 - \tau_{r,s}(t)\right)\right]$$

\(\forall k, q, r = 1, \ldots, P; \forall l, s = 1, \ldots, n_k.\)  \(52\)

Now, we have obtained the collision probability caused by exposed vehicle and hidden vehicles. Since \(\mu_{k,i,m}(t)\), \(\rho_{k,i,m}(t)\), and \(\tau_{r,s}(t)\) have been obtained in Section V-B, we can determine the time-dependent PDR according to \((47)\)–\((52)\).

Specifically, substituting \((51)\) and \((52)\) into \((50)\), the successful receiving probability can be achieved. Furthermore, after substituting \((50)\) into \((49)\), the time-dependent PDR can be determined by substituting \((48)\) and \((49)\) into \((47)\).

VI. SIMULATION AND ANALYTICAL RESULTS

In this section, we present simulation experiments and compared the simulation results with the analytical results, i.e., the results obtained according to the analytically model, to verify the accuracy of the proposed analytical model. Furthermore, we evaluate the PTD and PDR of 802.11p for platooning communications at the intersection according to the analytical results. In order to investigate the affection of other vehicles on a target vehicle during the whole movements at different intersection areas, we initially set that all the platoons are randomly distributed in the coverage of RSU and outside the intersection area. The target vehicle is \(V_{1,1}\). The initial scenario is shown in Fig. 4. The initial traffic light is green at the beginning. The related parameters used in both the simulation experiments and analytical model are listed in Table II, where the parameters of 802.11p are set according to the 802.11p standard [45]. Note that we set the time interval \(\Delta t\) as the maximum delay limit defined by ETSI to ensure that a packet can be accepted successfully, i.e., 100 ms [46].

Fig. 5 shows the time-dependent number of vehicles in the communication range of \(V_{1,1}\) [i.e., \(N_{c,1}^v(t)\) in \((36)\)] when it initially drives on different lanes. It can be observed that the time dependent \(N_{c,1}^v(t)\) always increases first, then decreases, and finally keeps stable, which is independent of its initial lane. This is because platoons first enter the intersection from different directions, resulting in the increasing number of vehicles in the communication range of \(V_{1,1}\). Since the communication range is much larger than the intersection, \(N_{c,1}^v(t)\) will
keep stable for a period of time after all the vehicles enter the intersection. Then, the platoons that can pass the stop line within the remaining green light time will gradually drift away from the intersection, and thus $N_{1,c}(t)$ decreases accordingly. Finally, the platoons driving away from the intersection exit the simulation scenario while other platoons stop at the intersection, thus $N_{1,c}(t)$ keeps stable.

Fig. 6(a)–(c) shows the time-dependent mean service time of four ACs, i.e., $T_{k,i,m}(t)$ in (42), when $V_{1,1}$ initially drives on different lanes. It can be seen that the simulation results are very close to the analytical results, which indicates that the analytical model is accurate. Moreover, it is seen that the trend of each AC’s service time is consistent with that of $N_{1,c}(t)$. This is because the collision probability caused by the exposed vehicles and hidden vehicles increases with $N_{1,c}(t)$, and thus service time increases, which matches (35). In addition, we can find that the AC with lower priority will lead to a longer service time. This is because the contention window size of the AC with lower priority is larger, and thus the AC has a longer backoff time, incurring a longer service time.

Figs. 7(a)–(c) shows the time-dependent PTD of four ACs, i.e., $PTD_{k,i,m}(t)$ calculated by (46), when $V_{1,1}$ initially drives on different lanes, respectively. It is found that the simulation results almost match the analytical results. Moreover, we can see that the PDR first increases, and then the PDR reaches the maximum value and keeps for a short period. This is because the number of hidden vehicles of $V_{1,1}$ decreases when platoons enter the intersection, which results in the increasing PDR. Later, the target vehicle has no hidden terminal when all vehicles in the platoon enter the communication range of $V_{1,1}$. Afterward, the PDR first decreases, then increases, and finally keeps constant. It is because that several platoons will first leave the intersection within the remaining green light time and the hidden vehicles of $V_{1,1}$ appear and gradually increase. When the platoons are far away enough from the other platoons stopping at the intersection and exiting the communication range of $V_{1,1}$, the number of hidden vehicles of

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**TABLE II**

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $a$       | $2m/s^2$ | $b$       | $3m/s^2$ |
| $AIFS_{N_0}$ | 2 | $AIFS_{N_1}$ | 3 |
| $AIFS_{N_2}$ | 6 | $AIFS_{N_3}$ | 9 |
| $CW_{\text{min}}$ | 3 | $CW_{\text{max}}$ | 3 |
| $CW_{\text{min}}$ | 7 | $CW_{\text{max}}$ | 15 |
| $CW_{\text{min}}$ | 3 | $CW_{\text{max}}$ | 7 |
| $CW_{\text{max}}$ | 15 | $CW_{\text{max}}$ | 1029 |
| $D_0$ | 4m | $D_0$ | 100m |
| $D_1$ | 16.5m | $\lambda_0$ | 5 |
| $\lambda_1$ | 10 | $\lambda_2$ | 15 |
| $\lambda_3$ | 20 | $\nu_0$ | 50ms/s/m |
| $u_0$ | 25m/s/h | $T_0$ | 1.5s/Veh |
| $r_0$ | 3m | $r_0$ | 4m |
| $P$ | 24 | $n_0$ | 3 |
| $L_0$ | 3m | $R_e$ | 100m |
| $T_{\text{R}}$ | 150s | $T_R$ | 30s |
| $R_1$ | 7.75m | $R_e$ | 18.75m |
| $\Delta t$ | 0.1s | $\delta$ | 13$\mu$s |
| $\gamma$ | 3$\mu$s | $E[P]$ | 200bits |
| $R_4$ | 3Mbps | $R_k$ | 1Mbps |
| $PHY_{\text{MAC}}$ | 468bits | $MAC_{\text{MAC}}$ | 513bits |
| $SIFS$ | 32$\mu$s | $\text{Retransmission Limit (L}_{\text{num}}$ | 2 |

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**Fig. 5.** Time-dependent number of vehicles in the communication range of $V_{1,1}$. 

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**Fig. 8(a)–(c) shows the time-dependent PDR of four ACs, i.e., $PDR_{k,i,m}(t)$ calculated by (47), when $V_{1,1}$ initially drives on different lanes, respectively. It is found that the simulation results almost match the analytical results. Moreover, we can see that the PDR first increases, and then the PDR reaches the maximum value and keeps for a short period. This is because the number of hidden vehicles of $V_{1,1}$ decreases when platoons enter the intersection, which results in the increasing PDR. Later, the target vehicle has no hidden terminal when all vehicles in the platoon enter the communication range of $V_{1,1}$. Afterward, the PDR first decreases, then increases, and finally keeps constant. It is because that several platoons will first leave the intersection within the remaining green light time and the hidden vehicles of $V_{1,1}$ appear and gradually increase. When the platoons are far away enough from the other platoons stopping at the intersection and exiting the communication range of $V_{1,1}$, the number of hidden vehicles of
Fig. 6. Time-dependent mean service time. (a) Left turn. (b) Straight. (c) Right turn.

Fig. 7. Time-dependent PTD. (a) Left turn. (b) Straight. (c) Right turn.

Fig. 8. Time-dependent PDR. (a) Left turn. (b) Straight. (c) Right turn.

$V_{1,1}$ will gradually decrease until there is no hidden vehicle. In addition, the time-dependent PDR of each AC is high under different initial scenarios, which means that vehicles can receive most packets successfully.

VII. CONCLUSION

In this article, we have constructed time-dependent models of the 802.11p for platooning communications at the intersection. We first considered the movement behaviors of platoons at the intersection, including turning, accelerating, decelerating, and stopping as well as the periodic change of traffic lights to construct the movement model of the vehicles and then established the hearing network to reflect the time-varying connectivity among vehicles. After that, we adopted PSFFA to model the dynamic behavior of the transmission queue, then considered the continuous backoff freezing, and adopted the $z$-domain linear model to describe the access process of the 802.11p with four ACs. Finally, we derived the PTD and PDR based on the time-dependent model of the 802.11p. The accuracy of the analytical model was demonstrated by comparing the simulation results and analytical results. According to the analytical results, we can evaluate the PTD and PDR of 802.11p based on the time-dependent model and draw the following conclusions.
1) Since the maximum time-dependent PTDs of each AC is smaller than the maximum delay limit, i.e., 100 ms, the 802.11p can meet the requirement of platooning communications at the intersection.

2) The time-dependent PTD is primarily affected by the number of vehicles in the communication range of the target vehicle, and the time-dependent PDR is primarily affected by the hidden vehicles.

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