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Research Article

Beacon Transmission Rate Allocation Optimization under Synchronized P-Persistent Repetition MAC Protocol for Platooning

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Platooning, which is enabled by vehicle-to-vehicle (V2V) communication, is one of the most potential frameworks in the intelligent transport system (ITS) to enhance driving safety and improve traffic capacity. In a platoon, vehicles interact with each other by broadcasting beacons via Dedicated Short Range Communication (DSRC). In this work, we explore the impact of beacon transmission rate allocation on the network utility which involves not only network performance but also traffic safety and efficiency for the vehicular ad hoc network (VANET) composing of a single platoon. An optimization problem aiming at searching for an optimal beacon transmission rate allocation for platoon management is developed based on a network utility maximization framework. Particularly, adopting a synchronized P-persistent repetition (SPR) medium access control (MAC) protocol, an optimal beacon transmission rate allocation to achieve the network utility maximization, is obtained for a platoon at a certain cruise velocity. In the simulation, the correctness of the proposed approach is validated, and its advantages over the benchmark are demonstrated by comparisons.

1. Introduction

Nowadays, time is money. However, commuters waste a great amount of time on the road every day due to the traffic jams; even some of them get injured or lose their life owing to the accidents [1]. Intelligent Transport System (ITS) is an indispensable component to realize the target of smart transportation and cities to provide an easier life [2–4]. Platooning, identified as one of the potential frameworks in ITS, is a promising approach to alleviate the problem of traffic jams, which has drawn substantial attention recently by industrial and academic [5]. By exchanging status information with each other periodically and then leading to vehicular ad hoc network (VANET), self-driving vehicles traveling on the same lane are self-organized into a platoon and kept one after another with a constant velocity and a small constant gap ahead, like a train [6, 7]. The platoon is led by a leading vehicle, and the rest are member vehicles that are indistinctive and regulated in a centralized mode. Platooning can not only enhance safety and comfort by reducing manual operations but also improve road utilization efficiency and fuel economy by shortening the intervehicle space to reduce aerodynamic drag [8]. Despite the potential advantages, platooning has put forward a higher demand for vehicle-to-vehicle (V2V) communication, especially on the design of medium access control (MAC) protocol. How the limited radio spectrum resources are allocated among vehicles in the platooning is an urgent problem to be solved so that it not only meets the needs of the promptness and reliability of beacon propagation but also guarantees traffic safety and improves efficiency.

The quality of MAC protocols on resource allocation among nodes in wired/wireless networks is judged based on the network utility function. The best MAC protocol can always maximize network utility [9]. Synchronous P-persistent Repetition (SPR) MAC protocol was initially proposed by Xu et al. [10] for Quality-of-Service (QoS) provision within vehicular safety communication. Thereafter, SPR has been extensively applied in general wireless networks for performance optimization [11–13]. When designing for the VANETs, the transportation aspect especially the traffic capacity should be taken into consideration since the nodes in the networks are the high-speed mobile vehicles on the road. Some literature has discussed the utility functions and their maximization problems for VANETs. In [14], the network utility was specified as the negative weighted sum of the expected delay. Then, a rate-adaptation problem formulation to maximize the network utility employing an SPR and its convergence properties were studied. In [15], an optimal beacon rate was recommended to maximize the messaging utility which accounts for the safety messages reliability requirements and neighbourhood information accuracy collected by beacons. The authors in [16] established an optimal resource allocation problem using the TDMA protocol where a limited resource condition and the danger coefficient of rear-end collision were considered. In these works, different MAC protocols were adopted, and the corresponding utility functions were defined where traffic safety was incorporated. However, they did not consider traffic capacity which is also an important indicator of transportation systems. Moreover, they only inspected the network utility maximization problems in the scenario of general VANETs.

Platoon-based VANET is also an attraction in the academic society where [4] provided a comprehensive survey on it from the cyber-physical interaction aspect. As a special kind of VANET, it might consist of platoons and individual vehicles [17, 18] or it only contains platoons running on a dedicated lane without the interruption of other private vehicles [19] [20], which are like the Bus Rapid Transit (BRT) operating on the BRT corridor [21]. There also some results concerning traffic capacity in the context of platoon-based VANET such as [22, 23], but they considered different problems exploiting different wireless technology and evaluated the traffic capacity qualitatively but not quantitatively.

In our work, we develop a beacon rate optimization problem for platoon-based VANETs where the platoon travels on a single dedicated lane. Specifically, we adopt the SPR MAC protocol and define the network utility function of a certain beacon transmission rate allocation as the reciprocal of expected delay of each sender-receiver pair multiplied by the weight of traffic efficiency. An optimization problem is formulated to maximize the network utility, and the corresponding optimal beacon transmission rate allocation is found. To the best of the authors' knowledge, the results about incorporating traffic capacity into the network utility definition and exploiting its maximization problem in the context of platoon-based VANET are absent in the literature.

2. System Model and Background

2.1. Background. Dedicated Short-Range Communication (DSRC) is a key technology to provision vehicle-to-vehicle (V2V) communication. The PHY layer and MAC sublayer of DSRC utilize the IEEE 802.11p standard [24]. It operates at a 5.9 GHz band ranging from 5.850 GHz to 5.925 GHz including one 10 MHz Control Channel (CCH) which is responsible for the transmission of high-priority safety-critical information, i.e., periodic message (also called beacons, e.g., speed, acceleration/deceleration, location) and event-driven messages, and the transmission of control information (e.g., service advertisements) and six 10 MHz Service channels (SCHs) [25]. Beacons advertised by the vehicle tend to be broadcast on the CCH since they are usually beneficial to all neighbouring vehicles to know its presence and status information. Due to the nature of life-critical, beacon propagation has stringent reliability and delay requirements. To improve broadcast reliability, repetitions are added for two reasons: one is that the size of a beacon is small; the other is that when 802.11p operates in broadcast mode, there is no acknowledgment feedback mechanism. Moreover, the absence of an RTS/CTS mechanism forces nodes to pin their hope on temporal diversity in their repetition pattern, so that a successful transmission within a lifetime can be guaranteed.

From the above, the repetition-based SPR protocol, which is proved to work very well on the top of DSRC and be able to provide a warranted beacon broadcasting reliability at the expense of promptness [10], is projected to serve as the MAC protocol in our work. Thus, only the aspect of timeliness needs to be considered in the later sections.

As for the detail of SPR, the CCH duration is divided into several timeslots and the interval of each equals the packet transmission time μ. The maximum delay, *i.e.*, the lifetime of a beacon, defines a transmission frame of L timeslots. In SPR MAC protocol, nodes are synchronized to a global clock (which is easily achieved using GPS), and each node i attempts to transmit a repetition of the latest generated packet in each slot with a probability of $\alpha_i \, (i = 1, 2, \dots, n)$, where $\alpha_i \in [\alpha_{\min}, \alpha_{\max}]$ is a configurable parameter.

2.2. System Model. Consider a VANET consist of a platoon formed by several moving vehicular nodes. Vehicles in the platoon travel on the same dedicated lane and contact with each other through DSRC radios, which is depicted in Figure 1.

Let $G(V, E)$ be an n ordered directed graph, where $V = \{1, 2, \dots, n\}$ is the set of nodes and $E \subset V \times V$ is the set of edges. Then, we use $G(V, E)$ to represent the VANET, where all vehicular nodes transmitting beacons at the same and certain transmission power P_t is assumed, and the corresponding common transmission range is denoted as R_t. For any two distinct vehicular nodes i and j, if the distance between them satisfies $d_{ij} < R_t$, then $E_{ij} = 1$; $E_{ij} = 0$, otherwise. The set of neighbors of node i is denoted by $N_i = \{j \in V \mid j \neq i, d_{ij} \leq R_t\}$.

The information flow topology describes the way a member vehicle queries the state information of its neighbor vehicles, which is of great significance to the collective behaviors of the platoon. Typically, the types include predecessor following, predecessor-following leader, and so on [26]. In this paper, we assume the platoon adopts a predecessor-following leader type which indicates that vehicles in the platoon only need to communicate with their immediately preceding neighbor, the topology of which is demonstrated in Figure 2.

Meanwhile, we assume all vehicular nodes in the network have the same network settings, such as packet size s, data rate r, and $\alpha_1 = \dots \alpha_{\mathrm{i}} = \dots = \alpha$ which is a reasonable

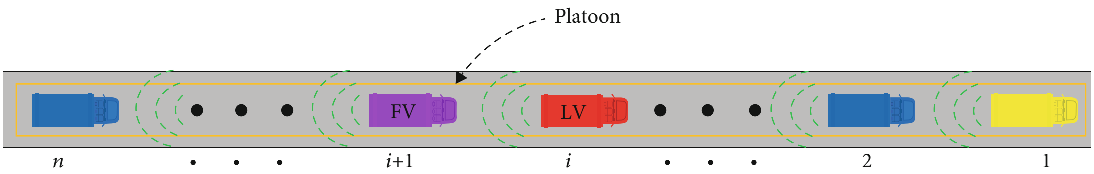

Figure 1: The schematic diagram of the VANET.

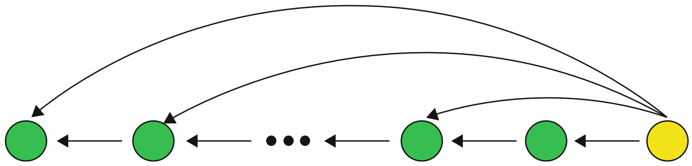

Figure 2: The demonstration of predecessor-following leader topology.

assumption for a platoon [27]. Our work aims to propose a method to find an optimal global transmission probability α for the system in the context of SPR MAC protocol.

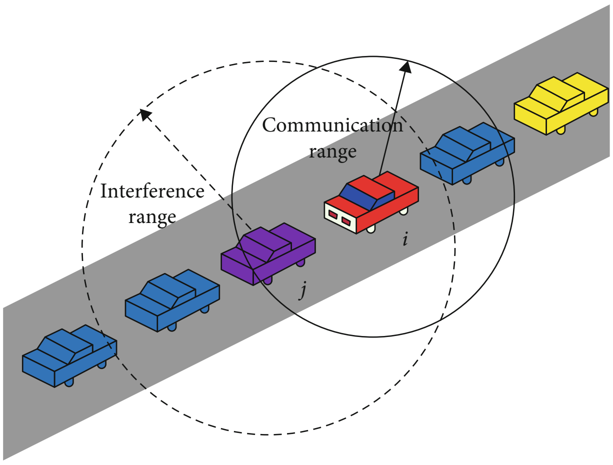

Figure 3: Communication range and interference range.

3. Network Performance Measure

Packet interreception time (also called packet delay), defined as the time interval between two consecutive successful packet reception on a given link, is a critical network metric to characterize active safety application performance [28]. To calculate the packet delay, we first derive the interference range and the number of interferer within it; then, the process of a successful transmission on the link $i \longrightarrow j$ is viewed as a *Bernoulli* distribution, the expected value of which is the delay.

3.1. Interference Range and Number of Interferers. As depicted in Figure 3, we denote the interference range of node j as R_I. If two or more nodes situated within R_I of the receiver node j transmit packets concurrently, then collisions will occur at node j, where the capture effect is neglected.

To facilitate the demonstration of interferences range calculation, we use the free-space channel model, and the computation procedure can be easily extended to other channel models. According to [29], the reception power P_r of a signal at the receiver is given by:

$$\mathrm{Pr} = Pt \cdot \frac{A}{d^2}. \qquad (1)$$

Here, d denotes the distance between the transmitter node i and the receiver node j, $A = G_l \lambda^2 / 16\pi^2$ is a constant, λ is the signal wavelength, and $G_l = 1$ for omnidirectional antennas [30]. Given the signal-to-interference plus noise ratio (SINR) threshold β (in decibel) at a certain data rate and the communication range R_t, the transmission power P_t can be computed as

$$Pt = \mathrm{Pr} \cdot \frac{Rt^2}{A}. \qquad (2)$$

As the thermal noise is ignorable when compared with the interference signal, we have

$$10^{\beta/10} = \frac{Pr}{PI}, \qquad (3)$$

where P_I is the interference power at the receiver and can be written as

$$PI = Pt \cdot \frac{A}{RI^2}. \qquad (4)$$

Finally, the interference range R_I is obtained by

$$RI = \sqrt{APt/PI} = 10^{\beta/20} \cdot d. \qquad (5)$$

Let M_j denote the set of nodes whose packets may collide at node j and m denote the cardinality of M_j. According to equation (5), the number of interferers m is computed by

$$m = \frac{2 \cdot \text{Interference range}}{\text{Meters per vehicle}} \cdot \text{Lane number} = 2\rho d 10^{\beta/20}, \qquad (6)$$

where the lane number equals 1 and ρ is the vehicle density (in vehicles per meter).

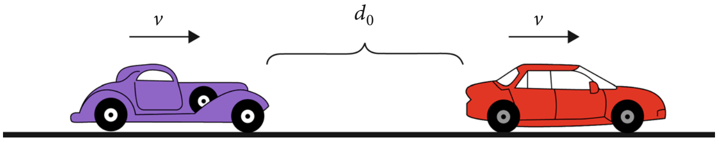

Figure 4: FV follows with LV normally.

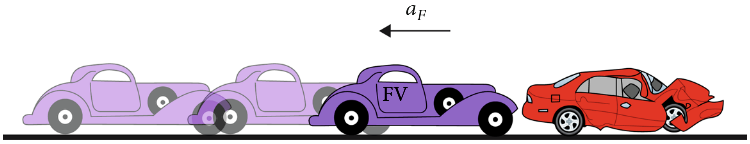

Figure 5: FV reacts to the accident of LV.

3.2. Packet Interreception Time. Let S_{ij} represent the probability of a message that is sent from node i and delivered to node j in a certain timeslot with interference. Recall that $\alpha_1 = \dots \alpha_i = \dots = \alpha$, then

$$Sij = \alpha i \Pi_{k \in Mj \backslash i} (1 - \alpha k) = \alpha (1 - \alpha)^{m-1}. \tag{7}$$

We count the number of timeslots to represent the packet delay using a random variable T_{ij}. The process of pursuing a successful transmission from $i \longrightarrow j$ can be seen as an independent *Bernoulli* distribution with probability S_{ij}. Then, T_{ij} follows a geometric distribution whose expectation is

$$E[Tij] = \frac{1}{Sij} = \frac{1}{\alpha (1 - \alpha)^{m-1}}. \tag{8}$$

And the packet interreception time can be easily gotten as

$$Td = \mu E[Tij] = \frac{\mu}{\alpha (1 - \alpha)^{m-1}} = \frac{\mu}{\alpha (1 - \alpha)^{2\rho d 10^{\beta/20} - 1}}. \tag{9}$$

4. Transportation Performance Measure

To achieve high traffic efficiency is the primary goal of transportation systems, which, however, on the premise of guaranteeing safety. Hence, in this section, we first deduce the prerequisites for traffic safety among vehicular nodes in VANET. Then, the traffic flow is defined to assess the efficiency of a transportation system.

4.1. Traffic Safety. Assume that in the platooning application, the average length of vehicles is l, the intervehicle spacing d_0 which is the distance from the rear of the Leading Vehicle (LV) to the bump of the Following Vehicle (*FV*) and the cruise speed $v \in [0, v_{\max}]$ at equilibrium point are the same and constant, where $v_{\max}$ is the maximum allowable speed on the lane. We choose the rear-end collision model, which is one of the most typical types of motor vehicle crashes, to investigate traffic safety. Randomly, we take two successive vehicles in the platoon as an example, such as FV and LV in Figure 1. LV runs ahead and FV follows behind, which is illustrated in Figure 4.

Imagine an extreme case where LV knocks into a barrier in front and is blocked immediately. Acknowledging the abnormality from LV via DSRC, FV immediately reacts with maximum deceleration a_F after a delay of T_{d0} (by substituting $d = d_0$ into equation (9)), trying to avoid the impending rear-end collision, which is illustrated in Figure 5. According to the kinematic equations, FV drives a distance of

$$dF = vTd0 + \frac{v^2}{2aF}, \tag{10}$$

before it stops completely. For traffic safety, it requires that the initial gaps between any two successive vehicles should at least be d_F, i.e.,

$$d0 \geq dF, \tag{11}$$

where d_F is a function of α.

4.2. Traffic Efficiency. The traffic flow q is defined as the number of vehicles passing a reference point per unit of time, which can be expressed as

$$q = v\rho = \frac{v}{d0 + l}, \tag{12}$$

where $\rho = 1/(d_0 + l)$ is calculated as the spacing between the center of two cars [31]. Traffic flow is used to assess the efficiency of the platooning transportation system. The higher the traffic flow is, the more efficient the transportation system is.

5. Optimization of Beacon Transmission Rate Allocation

In this section, the definition of the utility function is first presented that both the packet interreception time between two consecutive neighbors and the traffic efficiency is incorporated into. Then, an optimization problem obtaining the optimal transmission rate allocation α^* is established based on utility maximization.

5.1. Utility Function. The definition of utility function under a certain beacon transmission rate allocation α is the reciprocal of packet interreception time with the traffic efficiency q as a multiplicative weight. Thus, the utility function $U(\alpha)$ can be written as

$$U(\alpha) = \frac{q}{Td0} = \frac{v\alpha(1-\alpha)^{m-1}}{\mu(d0+l)} = \frac{v\alpha(1-\alpha)^{2\rho d10^{\beta/20}-1}}{\mu(d0+l)}. \quad (13)$$

The value of α will not only affect the network performance such as the packet interreception time but also traffic safety and efficiency. Thus, α^* should minimize the packet delay and maximize traffic efficiency on the premise of safety.

5.2. Centralized Optimization Problem. We formulate the problem as a maximization of the utility function of any logical link $i \longrightarrow i+1$ in the network:

$$\max_{\alpha} U(\alpha) \text{s.t.} \begin{cases} dF(\alpha) \le d0, \\ \alpha \le \alpha \max, \\ \alpha \ge \alpha \min. \end{cases} \quad (14)$$

We rewrite the problem (14) into the problem of minimization of $-U(\alpha)$ and obtain the Lagrangian $\mathscr{L}$ as

$$\begin{aligned} \mathscr{L}(\alpha, \gamma 1, \gamma 2, \gamma 3) = {} & -q\frac{1}{Td0(\alpha)} + \gamma 1\left(vTd0(\alpha) + \frac{v^2}{2aF} - d0\right) \\ & + \gamma 2(\alpha - \alpha \max) + \gamma 3(\alpha \min - \alpha), \end{aligned} \quad (15)$$

where $\gamma_1, \gamma_2, \gamma_3 \ge 0$ are the Lagrangian multipliers related to the problem (14). According to the Karush-Kuhn-Tucker (KKT) conditions, the optimal transmission rate allocation α^* must satisfy the following inequalities:

$$\begin{aligned} & \alpha - \alpha \min \le 0, \alpha \max - \alpha \ge 0, \\ & \gamma 1\frac{d\mathscr{L}}{d\gamma 1} = \gamma 1\left(vTd0(\alpha) + \frac{v^2}{2aF} - d0\right) = 0, \\ & \gamma 2\frac{d\mathscr{L}}{d\gamma 2} = \gamma 2(\alpha - \alpha \max) = 0, \gamma 3\frac{d\mathscr{L}}{d\gamma 3} = \gamma 3(\alpha \min - \alpha), \\ & \frac{d\mathscr{L}}{d\alpha} = \frac{q}{T_{d0}^2}\frac{d}{d\alpha}Td0(\alpha) + \gamma 1 v\frac{d}{d\alpha}Td0(\alpha)(\gamma 2 - \gamma 3) = 0. \end{aligned} \quad (16)$$

After some algebra, $(d/d\alpha)Td0(\alpha)$, $d\mathscr{L}/d\gamma 1$, and $d\mathscr{L}/d\alpha$ in equation (16) are obtained as follows

Table 1: Parameter setup for the transportation system.

Parameters	Value
Road length	5 km
Road width	10 m
Speed	5 m/s~40 m/s
Vehicle length	4 m
Maximum deceleration a_F	5 m/s^2

$$\begin{aligned} \frac{d}{d\alpha}Td0(\alpha) &= \frac{d}{d\alpha}\left[\frac{\mu}{\alpha(1-\alpha)^{2\rho d010^{\beta/20}-1}}\right] \\ &= -\frac{\mu\left(1-\left(2\alpha d010^{\beta/20}/(d0+l)\right)\right)}{\alpha^2(1-\alpha)^{2d010^{\beta/20}/(d0+l)}}, \end{aligned} \quad (17)$$

$$\frac{d\mathscr{L}}{d\gamma 1} = \frac{\mu v}{\alpha(1-\alpha)^{\left(2d010^{\beta/20}(d0+l)\right)-1}} + \frac{v^2}{2aF} - d0, \quad (18)$$

$$\begin{aligned} \frac{d\mathscr{L}}{d\alpha} = {} & -\left[\alpha^2(1-\alpha)^{4d010^{\beta/20}/(d0+l)} + \gamma 1\mu^2(d0+l)\right] \\ & \times \frac{v\left(1-\left(2\alpha d010^{\beta/20}/(d0+l)\right)\right)}{\alpha^2\mu(d0+l)(1-\alpha)^{2d010^{\beta/20}/(d0+l)}} + \gamma 2 - \gamma 3. \end{aligned} \quad (19)$$

Applying equation (16), we can obtain α^* from the only four possibilities of α, that is, $\alpha_{\max}$, $\alpha_{\min}$, $\bar{\alpha}$, and $\tilde{\alpha}$ by comparing their corresponding objective function values, where $\bar{\alpha}$ is the root of equation (18) and $\tilde{\alpha}$ is the root of equation (19). In conclusion, we have

$$\alpha^* = \underset{\alpha \in \left\{\alpha \min, \alpha \max, \overline{\alpha}, \tilde{\alpha}\right\}}{\arg\max} U(\alpha). \quad (20)$$

6. Simulations

6.1. Model Validation. We implement the simulation using the parameters listed in Tables 1 and 2. Assume the platoon consisting of 50 vehicular nodes runs on a segment of a one-lane highway. Let nodes move at three cases of cruise velocity, which are low, medium, and high, respectively. The speed belongs to the sets {5, 10}, {15, 20}, and {25, 30, 35, 40}. Suppose that all vehicular nodes in the platoon are both synchronized in timeslots and transmission frame. By setting the intervehicle spacing as $d_0 = v + v^2/2a_F$ based on equation (10), we solve the optimization problem numerically and the analytical optimal α^* at different velocities is obtained, which is shown in Figure 6. The reason why the optimal α^* decreases with increasing data rate r is obvious.

Then, we obtain the simulation result which is driven by real traffic trace and compare it with the numerical result in Figure 7. The simulation results are in good agreement with the numerical analyses. So far, the model correctness is proved.

6.2. Performance Evaluation. PRR and packet delay are two important metrics to evaluate wireless network performance. To check the performance of SPR MAC protocol operating at

Table 2: Parameters setup for SPR protocol.

Parameters	Value
Transmission power P_t	20 dBm
Data rate r	6, 12, 24 Mbps
SINR threshold β	6, 9 14 dB
Timeslot μ	1 ms
Transmission frame L	250
Packet size s	400 bytes
$\alpha_{\min}$, $\alpha_{\max}$	0.01, 0.33 [10]

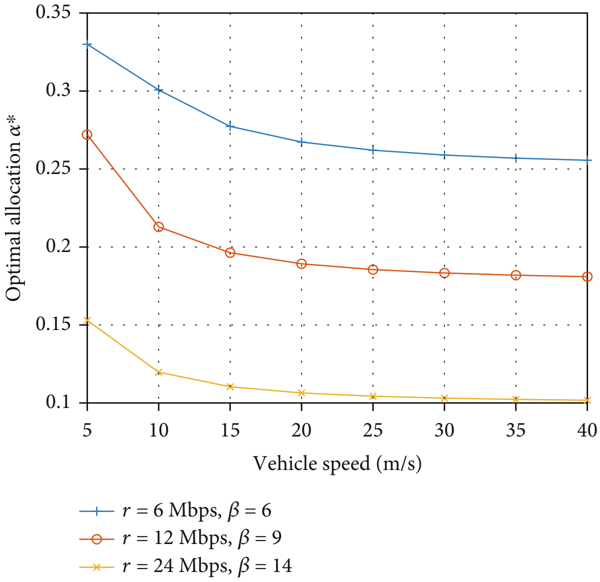

Figure 6: Optimal allocation α^* by numerical analyses at various data rates r.

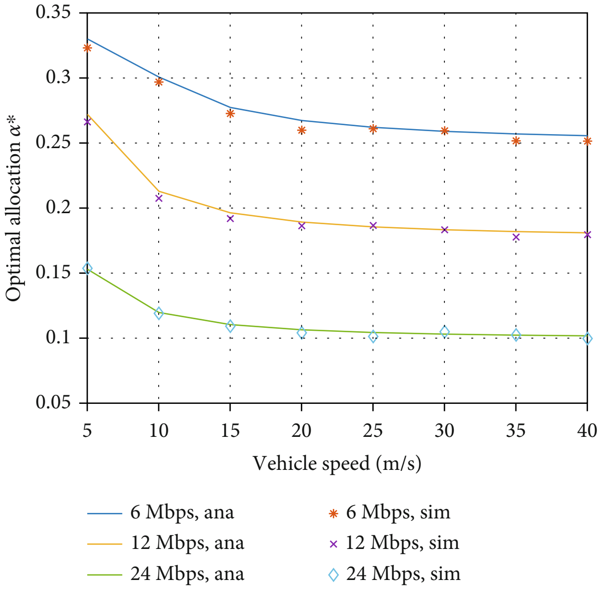

Figure 7: Comparison between numerical and simulation results in α^*.

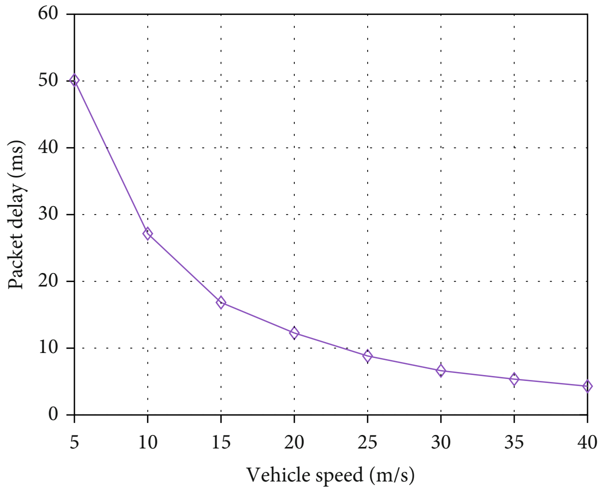

Figure 8: Packet delays at various optimal α^* with data rate $r = 6$ Mbps.

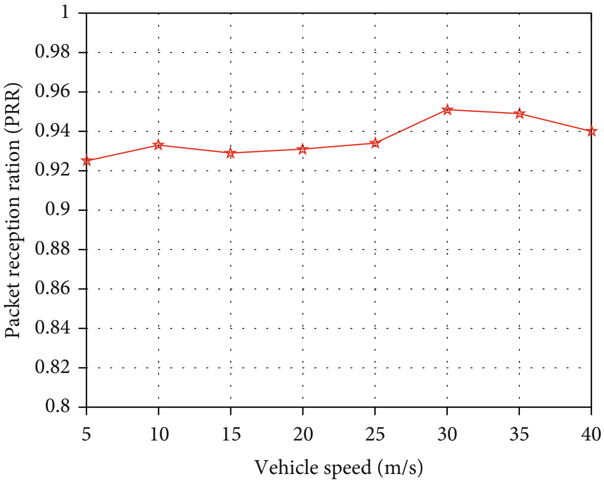

Figure 9: Packet reception ratio at various optimal α^* with data rate $r = 6$ Mbps.

different optimal α^*, we exhibit these two metrics in Figures 8 and 9 with data rate $r = 6$ Mbps which is generally accepted as the optimal data rate used in DSRC-based vehicular safety communications [32]. It is observed that both the packet delays (<100 ms) and PRRs (>90%) satisfy the safety application requirements.

Since IEEE 802.11p is the standardized MAC protocol in DSRC, it is usually set as the benchmark. So in the end, we display the comparison results of network utilities of platoon-based VANET using SPR and IEEE 802.11p separately in Figure 10, wherein the network parameters for IEEE 802.11p is listed in Table 3. We can easily find that SPR outperforms IEEE 802.11p in terms of network utility which indicates SPR is better at balancing both network and transportation aspects. Besides, with vehicle speed goes up, the vehicle density decreases and the gap between the two curves becomes smaller which illustrates that the performance of

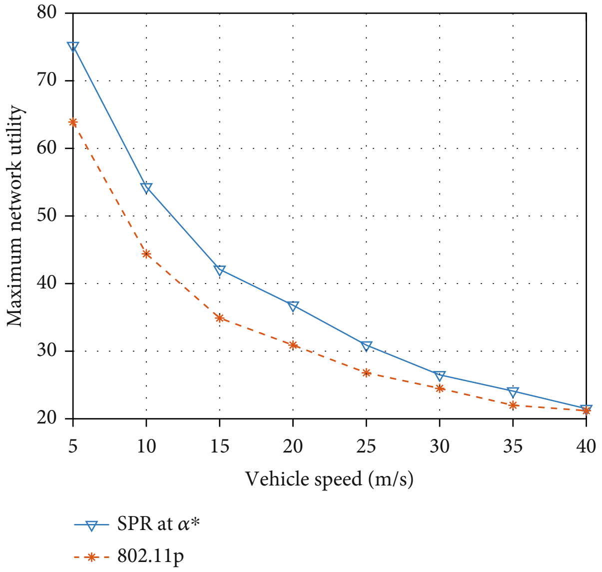

Figure 10: Maximum network utilities using SPR at α^* and IEEE 802.11p.

Table 3: Parameters setup for IEEE 802.11p.

Parameters	Value
Modulation	BPSK
Coding rate	1/2
OFDM symbol duration	8 μs
Contention window	31
DIFS	64 μs
SIFS	32 μs
Slot time	16 μs

IEEE 802.11p is comparable with SPR at low vehicle density but worsens at high vehicle density.

7. Conclusions

In this paper, we propose a framework to settle the optimal beacon transmission rate allocation for platoon-based VANET based on utility maximization under the SPR MAC protocol. The utility function takes packet interreception time, traffic safety, and efficiency into consideration. The network utility maximization problem is formulated, and the optimal solution is obtained analytically at any cruise velocity by applying the KKT conditions. The simulation results validate the accuracy of numerous analyses and evaluate the performance.

Data Availability

The simulation parameter data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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