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Resource Allocation for D2D-Enabled Communications in Vehicle Platooning

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ABSTRACT Recent studies have shown that traffic safety and efficiency can be substantially improved by vehicle platooning, in which the platoon' stability is ensured through the exchange of control information among vehicles. So, it is a key issue to share control information efficiently and timely. Proximity-based device-to-device (D2D) communications with high transmission rate, can provide a promising solution to the above issue. In this paper, a platoon leader evaluation-based two-stage platoon formation algorithm is proposed to form stable platoons, which can significantly reduce the spectrum resource overhead and improve the safety of vehicle platooning. After that, we propose a predecessor-following communication mode-based on D2D, ensuring high-rate transmission of control information. Moreover, we propose time division-based intra-platoon and minimum rate guaranteed inter-platoon resource allocation mechanisms, which aims at allocating resources for D2D users efficiently within the platoon and optimize cellular users' rate, respectively. Numerical results show that the proposed mechanism and algorithm can not only significantly improve spectrum resource utilization, but also guarantee the platoon stability.

INDEX TERMS D2D communications, vehicle platooning, resource allocation, PL evaluation, platoon formation.

I. INTRODUCTION

Nowadays traffic efficiency and safety have become very serious problems [1]. Global status report on road safety-2015 by World Health Organization (WHO) indicates total death toll of almost 1.25 million per year in road accidents, while the number of light duty vehicles will grow to 2 billion in 2050 compared to 850 million in 2013 [2]. Platooning, as a vehicular traffic management strategy, has been identified as a promising framework in intelligent transportation systems (ITS) [3]–[7]. Grouping autonomous vehicles on the same lane into a platoon, i.e., keeping each vehicle moving at a constant speed and following one another in a train-like manner with a small constant inter-vehicle spacing ahead, can improve the driving safety of autonomous vehicles, reduce traffic congestion, fuel consumption, and exhaust emissions. Compared with transportation infrastructure construction and new energy vehicle development, platooning is a more sustainable and less costly way to alleviate above problems [8]–[11].

The platoon's stability is ensured through the high-rate and high-reliability exchange of control information among vehicles about their current kinematics status. So, the inter-vehicle communication performance in the platoon will greatly affect its stability and safety [12], [13]. Dedicated short range communications (DSRC) adopts the IEEE 802.11p standard, also known as wireless access for vehicular environments (WAVE), which is the de facto standard for vehicular communications [14]. However, recent studies [15], [16] show that DSRC's physical and medium access control (MAC) layers are designed primarily to optimize wireless local area networks (WLANs) with lower mobility. So, it suffers from several challenges, such as scalability issues, potentially unbounded channel access delay, lack of quality-of-service (QoS) guarantees and so on. Moreover, due to its limited radio range and the lack of pervasive road side infrastructure, DSRC can only provide intermittent and short-lived inter-vehicle communications. In contrast, cellular networks provide wide coverage and exercise flexible centralized control over network resources, which guarantees optimal performance of the networks [17], [18]. Better still, proximity-based D2D links, complementing the centralized cellular architecture, will provide direct local message dissemination with substantially reduced latency and power consumption, thus it is suitable for delay-sensitive inter-vehicle communications. As a result, the proximity-based D2D represents a promising solution to enable high-rate and high-reliability communications in vehicle platooning [19]–[21].

In recent years, there have been some works [22]–[24] studying resource allocation for D2D-enabled communications in vehicle platooning, but these works do not comprehensively analyze the three interaction aspects of platoon formation, platoon communication mode and resource allocation. In addition, the above works do not consider the following problems: (1) Some badly-behaved or malicious PLs may jeopardize the platoon by providing low-quality services or even put the platoon members (PMs) in dangerous situations, how to distinguish and avoid them. (2) Frequent entry and departure of PMs will significantly increase the signaling overhead and affect the safety of vehicular platooning, how to form stable platoons as the basis for following work to improve the vehicle platooning's performance. (3) In particular, an appropriate communication mode can only be designed on the basis of the information transmission's requirements in vehicle platooning, how to design an efficient model, combined with D2D technology to meet these requirements. (4) The platoon communication mode and resource allocation mechanism correspond one by one, how to propose efficient allocation mechanisms to optimize CUEs' rate while ensuring the performance of D2D-enabled communications within the platoon.

To solve the above problems, we propose a trust-based PL evaluation mechanism to distinguish and avoid malicious PLs. Based on this, a two-stage platoon formation algorithm is proposed to fully consider the subjective intention of PMs and PLs to form stable platoons. Besides, by considering the characteristics of information transmission in vehicle platooning, a predecessor-following communication mode based on D2D is designed to ensure high-rate transmission of control information. At last, time division based intra-platoon and minimum rate guaranteed inter-platoon resource allocation mechanisms are proposed to fit the previously designed platoon communication model and optimize CUEs' rate respectively. The main contributions are as follows:

(1) A trust-based PL evaluation mechanism is proposed by utilizing historical feedback provided by trusted PMs, to recommend the most reliable PLs for undertaking autonomous driving services. Moreover, a trust score update algorithm is designed to exclude those malicious feedback. Based on the above works, a two-stage platoon formation algorithm is proposed to form stable platoons, by comprehensively analyzing the similar interests, habitual destinations, service needs and service benefits.

(2) Facing complicated road conditions such as curves and intersections, a predecessor-following communication mode based on D2D is designed. In this mode, vehicle only communicates with the preceding one to know its kinetic status to maintain relative speed and distance stability.

(3) A time division based intra-platoon resource allocation mechanism is proposed, which allocates resources for DUEs efficiently within the platoon to ensure high-rate transmission of control information. Furthermore, a minimum rate guaranteed inter-platoon resource allocation mechanism is proposed to optimize CUEs' rate while guaranteeing the minimum transmission rate for each platoon.

The rest of this paper is organized as follows. The related works are introduced in Section II. The vehicle platooning mode and platoon communication mode are designed in Section III. Section IV introduces how to choose reliable PLs and form stable platoons. Resource allocation mechanisms are proposed in Section V. Simulation results are analyzed in Section VI. Lastly, the conclusions are given in Section VII.

II. RELATED WORK

Recently, there are few researches on platoon formation algorithms for D2D-enabled vehicle platooning architecture. However, the works on clustering algorithms for D2D and vehicle network are relatively mature. So, we can learn from these works to solve our problems. A pair of algorithms, namely, sociological pattern clustering (SPC) and route stability clustering (RSC) are proposed in [25], which solves the broadcast storm problem by coping with the rapidly changing vehicle-network topology. The work in [26] proposes a region-based clustering mechanism to divide the network topology into multiple spatial units. Each unit strictly limits the number of vehicle nodes, so that the number of nodes participating in channel competition is greatly reduced, thereby improving data transmission efficiency. Gunter *et al.* [27] present a medium access scheme for vehicular ad-hoc networks based on clustering of vehicles. The cluster head node is the manager of intra-cluster communication and responsible for scheduling time-division resources for cluster members. In [28], a distributed D2D architecture is proposed based on the hybrid clustering approach to organize vehicles into several dynamic clusters. The cluster head acts as a gateway for uplink data stream, and the vehicles in the cluster adopt D2D communications to improve the resource utilization of the uplink. Zhang *et al.* [29] propose a cluster formation scheme to categorize a group of users into multiple D2D clusters. Within each cluster, highly spectrum-effcient D2D multicasting is enabled. However, existing clustering algorithms neither consider optimizing cluster heads' benefits nor meet cluster members' service needs as much as possible.

Much effort has been made in the literature to allocate resources under the framework of D2D and vehicular communications. A new interference management strategy is proposed in [30] to enhance the overall capacity of cellular networks and D2D systems. To help the base station in managing radio resources, an optimization method is proposed in [31]. In this context, the outage probability at the D2D receivers is derived first. Then, this derivation acts as the baseline while formulating the resource allocation problem as a linear assignment problem. Aiming at D2D communication in Vehicle-to-Everything (V2X), a heuristic resource allocation mechanism related to vehicle location information is proposed in [32]. The work in [33] proposes two different algorithms to effectively solve V2X resource allocation problem based on D2D technology. An overall framework including vehicle clustering, channel allocation, power control is proposed in [34]. However, these works do not have an integrated analysis of intra-platoon and inter-platoon resource allocation.

III. SYSTEM MODEL

A. VEHICLE PLATOONING MODE

As shown in Fig. 1, there are multiple platoons driving on the road, and the vehicles in platoons can be further divided into the following two categories: PL and PM vehicles. A PL is the first one in a platoon that leads its PMs. We denote $P = \{pl_1, pl_2, \cdots, pl_{m_i}\}$, $V = \{v_1, v_2, \cdots, v_{m_j}\}$ as the PLs set and PMs set, which including m_i PLs and m_j PMs respectively. Besides, we call the vehicles not belonging to any platoon as individual vehicles (IVs), which are regarded as candidates for the PMs. All of the IVs are assumed to be CUEs whose spectrum resources will be reused by other platoons.

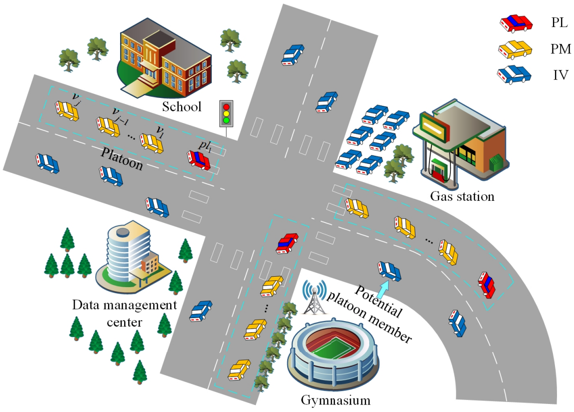
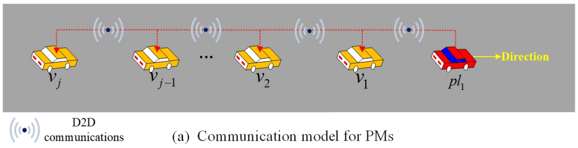


FIGURE 1. Vehicle platooning mode.

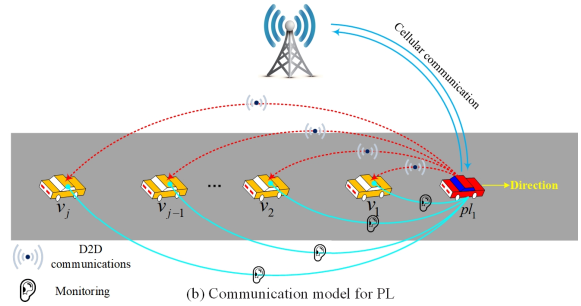
B. PLATOON COMMUNICATION MODE

Information shared among vehicles in vehicle platooning can be divided into two types: time-triggered control information and event-triggered information. The first one mainly includes velocity, acceleration, position and allocated spectrum resources, etc., which are periodically interacted between vehicles. By periodically interacting with the control information and then adjusting their own kinematics status, vehicles can move at a constant speed and following one another in a train-like manner with a small inter-vehicle gap; the second one includes safety and entertainment information: vehicle's braking, joining or leaving information, traffic accident, multimedia videos and so on. This type of information occurs randomly without regularity.

In practical traffic scenario, the road is not an ideal straight line, but full of numerous curves and intersections. As a typical platoon communication mode, the predecessor-leader communication mode has the advantage of high precision, in which the PMs periodically obtains PL's kinematics status to maintain a relatively stable distance and speed from it. In such mode, each vehicle is equipped with on-board sensors and global positioning system (GPS) to measure its absolute distance from the PL, which is less than the actual arc distance. Moreover, when the PM is far away from PL, the error will continue to be amplified, affecting vehicle platooning' safety and stability. To avoid the above disadvantages, a predecessor-following communication mode based on D2D is designed. In this mode, vehicle only communicates with the preceding one to get its kinetic status to maintain relative speed and distance stability. Due to the close distance between adjacent vehicles, the measurement error caused by curves can be minimized, as shown in Fig. 2(a). Besides, proximity-based D2D technology can provide direct local message dissemination with substantially reduced latency and power consumption, thus suitable for delay-sensitive inter-vehicle communications. Therefore, D2D communication is adopted in this paper to support vehicular platooning communications.



(a) Communication model for PMs



(b) Communication model for PL

FIGURE 2. Platoon communication mode.

Event-triggered safety information including vehicle's braking, joining or leaving alerts should be delivered to all PMs in the platoon to avoid traffic accidents. As shown in Fig. 2(b), the PL monitors all the information exchanged between adjacent vehicles. Once event-triggered safety information is monitored, it will be broadcast to all PMs of the platoon in time. Besides, the PL interacts with the base station based on a certain period or event trigger to upload all PMs' information. Then, according to the state of the whole network, the base station allocates spectrum resources for each platoon, and the resource allocation result is broadcasted by PL to all its members in time.

IV. PL-EVALUATION BASED PLATOON FORMATION

A. TRUST-BASED PL EVALUATION MECHANISM

The PLs take full control of the whole platoon when driving on the road; they are responsible for the services experience of all PMs. More importantly, their behaviors affect the whole platoon's safety. Therefore, it is the basic requirement of PMs to choose vehicles with rich driving experiences, good service attitude and reputation as the PLs. In this paper, we propose a trust-based PL evaluation mechanism by utilizing historical feedback provided by trusted PMs, to recommend the most reliable PLs for undertaking autonomous driving services.

When a platoon arrives at the PL's destination, it is recorded as completing a vehicle platooning service. Let S be the set of services with the total number of m_k so that $S = \{Se_1, Se_2, \cdots, Se_{m_k}\}$. After a PM $v_j \in V$ enjoys the autonomous driving service provided by a PL $pl_i \in P$ in service $Se_k \in S$, it is required to provide a feedback to the PL pl_i, which is denoted by $f_j^k (\in [0, 1])$. Each feedback includes the service ID Se_k, PL ID pl_i, PM ID v_j, feedback time f_j^k, PM's destination and preference vector, as shown in Fig. 3(a). Moreover, PM's destination and preference vector will be used and analyzed in the next subsection. The feedback is directly uploaded by the PMs to the data management center. The center is responsible for the storage and analysis of the feedback and dynamically updates the evaluation scores of each PL. In addition, in order to exclude the untruthful feedback provided by malicious PMs, it is necessary for the center to dynamically update each PM's trust scores table which stores each PM's ID and corresponding trust score $T_j^l (\in [0, 1])$ at present, as shown in Fig. 3(b). Those trust scores are used to describe the reliability and accuracy of their feedback. T_j^l indicates the trust score after lth feedback.

Service ID	PM ID	PL ID	Feedback Time	Feedback Value	PM's Destination	PM's Preference Vector
⋮	⋮	⋮	⋮	⋮	⋮	⋮
Se_k	v_j	pl_i	t_j^k	f_j^k	$loc_y \in Loc$	$\{x_{j1} \cdots x_{jm_a}\}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮

(a)

PM ID	Trust Score
⋮	⋮
v_j	T_j^l
⋮	⋮

(b)

PL ID	Service ID	Service End Time	The Truthful Score of This Service	PL's Destination	PL's Preference Vector
⋮	⋮	⋮	⋮	⋮	⋮
pl_i	Se_k	t_k	SE_k^{tru}	$loc_y \in Loc$	$\{x_{i1} \cdots x_{im_a}\}$
⋮	⋮	⋮	⋮	⋮	⋮

(c)

FIGURE 3. (a) PMs' feedback table. (b) PMs' trust table. (c) PLs' services evaluation scores table.

In order to obtain the truthful evaluation scores that the PL receives in service Se_k, it is necessary to filter out false and malicious feedback first. For this purpose, we first calculate the integrated feedback SE_k of the service Se_k, which could be regarded as the average score of the PL in this service by combining all PMs' feedback and corresponding trust scores. Then, SE_k will be compared with all PMs' feedback in this service. In a platoon, PMs' status and service quality are basically the same, so a greater difference leads to a malicious feedback. Therefore, the truthful evaluation score SE_k^{tru} obtained by the PL in this service can be calculated after removing malicious feedback.

Each service consists of multiple PMs, we use $PM_1, PM_2, \cdots, PM_{m_k}$ to represent the PMs set of service $Se_1, Se_2, \cdots, Se_{m_k}$, respectively. Combining all feedback and corresponding trust scores of PM_k in Se_k, we can calculate the integrated feedback SE_k of Se_k, as shown in Eq. (1). The higher the value, the better the driving experience acquired by PMs.

$$SE_k = \frac{\sum_{v_j \in PM_k} T_j^l \cdot f_j^k}{\sum_{v_j \in PM_k} T_j^l} \tag{1}$$

where f_j^k, T_j^l are the feedback value and the real-time trust score of v_j respectively. It can be seen that the higher the trust score, the greater the influence of the PM's feedback on integrated feedback. Making the feedback of PMs with higher trust scores plays a leading role can weaken the influence of false, malicious feedback on the truthful evaluation score.

The difference between the feedback f_j^k and integrated feedback SE_k is denoted as Dif_j^k, as shown in Eq. (2). When the Dif_j^k is higher than the threshold λ, the PM's feedback is judged to be false and malicious. By deleting all false, malicious feedback in the service and then getting the truthful PMs set PM_k^{tru}, we can calculate PL's truthful evaluation score SE_k^{tru} in the service, as shown in Eq. (3).

$$Dif_j^k = \left| f_j^k - SE_k \right| \tag{2}$$

$$SE_k^{tru} = \frac{\sum_{v_j \in PM_k^{tru}} T_j^l \cdot f_j^k}{\sum_{v_j \in PM_k^{tru}} T_j^l} \tag{3}$$

When PMs provide truthful or false feedback, their trust scores are increased or decreased accordingly. Especially when a PM continuous provides truthful or false feedback, the rate of increase and decrease in trust score is increased, to ensure that the truthful PM obtains a higher trust score faster and then plays a leading role in the evaluation mechanism. The update process of the trust score is expressed as

$$T_j^{l+1} = \begin{cases} T_j^l + 2^w \cdot 0.025, & if\ Dif_j^k \leq \lambda \\ T_j^l - 2^w \cdot 0.025, & if\ Dif_j^k > \lambda \\ 1, & if\ T_j^{l+1} \geq 1 \\ 0, & if\ T_j^{l+1} \leq 0.4 \end{cases} \tag{4}$$

where w is the number of times that a PM continuously provide truthful or false feedback. As w increases, the trust score changes faster. The upper bound of the trust score is 1. When the PM's trust score is lower than 0.4, it is determined to be a false and malicious one, and its feedback is invalid. In addition, the PM's initial trust score will not be given a high value to resist against newcomer attacks, which is set as 0.6. Combined with Eq. (4), it can be seen that when the newcomer provides false feedback for three consecutive times, the evaluation rights will be cancelled. So, the initial trust score setting gives the newcomer a certain evaluation opportunity, while limiting the impact of false feedback.

To calculate the evaluation score of a PL dynamically, a services evaluation scores table for each PL is maintained by data management center, as shown in Fig. 3(c). As mentioned above, the PL's destination and preference vector in Fig. 3(c) will be used and analyzed in the next subsection. Let $S_i \subset S$

indicates all service records of pl_i, then the evaluation score Sco_i of pl_i can be calculated by aggregating all truthful evaluation score in S_i, combined with forgetting factor, as shown in Eq. (5).

$$Sco_i = \frac{\sum_{S_i \subset S} \beta^{t-t_k} \cdot SE_k^{tru}}{\sum_{S_i \subset S} \beta^{t-t_k}} \tag{5}$$

where β ($\beta \in (0, 1)$) is the forgetting factor that reduces the impact of previous truthful evaluation scores. Dynamically setting the forgetting factor ensures that the evaluation score truly reflects the PL's current service status, to recommend the most reliable PLs for undertaking services.

B. TWO-STAGE PLATOON FORMATION ALGORITHM

As the high-scoring PLs will provide better services, PMs prefer to join their platoons. Moreover, the choice of vehicle platooning service is a two-stage process. In the process of PMs' selection of PLs, the PLs will also perform indirect selection of PMs according to their own wishes. The two-stage selection process actually completes the platoon formation. Vehicles are under the control of people, which can be seen as a microcosm of people in the traffic society. The social attributes of PMs and PLs greatly influence their behavior. In vehicle platooning, the main forms are similar interests and habitual destinations. People with similar interests are more likely to form a platoon, providing information sharing, collaborative driving and other services to each other, so as to improve their comfort and satisfaction in the process of platoon driving. The PL usually has habitual driving routes and destinations to avoid traffic jams, poor and complicated road conditions, so PLs are more inclined to select PMs who are on the habitual driving route. In addition, the autonomous driving services provided by PLs are not free, the PL will select the PMs with greater benefits. To sum up, the PL's choices of PMs need to consider three aspects: similar interests, habitual driving routes, destinations, and service benefits.

The data management center stores the historical records of all PLs and PMs' destinations $Loc = \{loc_1 \cdots loc_y \cdots\}$, as shown in Fig. 3(a) and Fig. 3(c). Through data management center's statistical analysis, the times of pl_i to a certain destination loc_y is denoted as $m^i_{loc_y}$, and the preference degree of the PL to the destination can be calculated as

$$Ploc^i_{loc_y} = \frac{2}{\pi} \arctan m^i_{loc_y} \tag{6}$$

According to the nature of inverse trigonometric function, when $m^i_{loc_y} \geq 1$, with the increase of the independent variable, the preference degree $Ploc^i_{loc_y}$ increases monotonously and approaches 1 infinitely, which conforms to the rule that the degree of destination preference increases as the visits times increases. Moreover, when $m^i_{loc_y}$=7, according to Eq. (6), the degree of destination preference is $Ploc^i_{loc_y}$=0.9, which is consistent with life experience. Specifically, when the visits times to a destination reaches a certain level, the destination will be assigned to the habitual driving routes and destinations by the PL. As a result, the degree of preference to the destination has approached 1. With the visits times continue to increase, the degree of preference increases less.

PLs and PMs as individuals in the society have their own interests. People with similar interests are more likely to form a platoon, providing information sharing, collaborative driving and other services to each other, so as to improve their comfort and satisfaction. Therefore, similar interests significantly affect the PL's choices of PMs.

The classical algorithms for calculating interest similarity include Cosine similarity, Euclidean distance, and Jaccard coefficient. Different algorithms are suitable for different data analysis models. Euclidean distance can reflect the absolute difference of individual numerical characteristics, so it is more used to analyze the numerical difference from multidimensional vector; the numerical value in the vector is simply treated as 0 and 1 by Jaccard coefficient, which improves the computational efficiency, but completely ignores the function of numerical value; Cosine similarity focuses on distinguishing differences in direction, but not in absolute values, which is more used to analyze the interest similarity based on users' scores. At the same time, the problem of inconsistent evaluation metrics that may exist between different users has been corrected, since Cosine similarity is insensitive to absolute values.

As shown in Fig. 3(a) and Fig. 3(c), the data management center stores an n-dimensional list of interest tags including sports, entertainment, food, shopping, education, etc., with PLs and PMs' preference vectors for the list, denoted as $\{x_{i1} \cdots x_{im_a}\}$, $\{x_{j1} \cdots x_{jm_a}\}$ respectively. Besides, $x_{ia}, x_{ja} \in [0, 1]$ and higher values indicate more interest in the tag. The preference vectors in this paper are subjectively given by PMs and PLs, so there may be the problem of inconsistent evaluation metrics. The Cosine similarity is insensitive to absolute values and can be used to better correct the problem. Therefore, we calculate the similarity of interests between the PL pl_i and PM v_j by Cosine similarity as

$$Sim^i_j = \frac{x_{i1}x_{j1} + x_{i2}x_{j2} \cdots x_{im_a}x_{jm_a}}{\sqrt{x_{i1}^2 + x_{i2}^2 \cdots x_{im_a}^2} \cdot \sqrt{x_{j1}^2 + x_{j2}^2 \cdots x_{jm_a}^2}} \tag{7}$$

The autonomous driving services provided by PLs are not free, the PL will select PMs with greater benefits, which are mainly related to the PM's traveled distance and additional tips in the platoon. After v_j joins the platoon, the benefit obtained by the PL pl_i can be modeled as

$$Pro^i_j = Bf + \eta \left|loc_y\right| + tip^i_j \tag{8}$$

where $\left|loc_y\right|$ denotes the distance that the v_j is expected to travel, which can be calculated from the PM's destination, PL's destination and estimated routes. η is the fee charged by the PL per kilometer. tip^i_j is the additional tip for a higher probability of being served, and Bf is the base fare.

In summary, we comprehensively consider the three aspects of similar interests, habitual destinations, and service benefits, which are quantified by Eq. (6), (7) and (8), to define the entry factor as shown in Eq. (9). The higher the entry factor of PM v_j, the higher the priority of joining platoon pl_i .

$$\alpha_j^i = Pro_j^i \cdot Ploc_{loc_y}^i \cdot Sim_j^i \tag{9}$$

Based on the above analysis of influencing factors in platoon formation, we propose a two-stage platoon formation algorithm, as shown in algorithm 1. Lines 3) to 9) implement the choice of the PLs, cancel the service qualification of badly-behaved PLs, and obtain the candidate PLs set. Lines 10) to 30) enable PMs and PLs to choose each other, and finally get the platoon formation results. Lines 12) to 13) publish the destinations, estimated routes and remaining platoon quotas of remaining candidate PLs. And then, remaining PMs are applied to join the PLs' platoon according to their destinations and evaluation scores. Finally, a number of initial platoons are formed. Lines 14) to 23) rank the PMs in each initial platoon, according to the entry factors from high to low, and then the PL will give priority to PMs with higher ranks entering the platoon. When the number of PMs reaches the upper bound in a platoon, the platoon will not participate in the next round of PMs' selection; otherwise, it will participate in the next round and dynamically update the remaining platoon quotas x. Lines 24) to 28) judge whether it is still necessary to carry out the next round of selection so as to optimize the PLs' benefits and meet PMs' service needs as much as possible. Lines 29) to 30) output the final platoon formation result.

The algorithm makes full use of the feedback provided by trusted PMs, to recommend the most reliable PLs for undertaking services. At the same time, the subjective intention of PMs and PLs has been fully considered to form stable platoons, which comprehensively analyzes the similar interests between PMs and PLs, PLs' habitual destinations to optimize the PLs' benefits and meet PMs' service needs as much as possible.

Algorithm 1 Two-Stage Platoon Formation Algorithm

```
1: Input: $P$, $V$, $Sco_i$
2: output: $\rho$
3: Platoon leaders selection phase
4: for $pl_i \in P$ do
5:     if $Sco_i < Sco_{threshold}$ then
6:         Remove $pl_i$ from $P$
7:     end if
8: end for
9: Obtain the set of candidate platoon leaders $P_{candidate} = \{pl_1, pl_2, \cdots, pl_{m_n}\}$
10: Platoon member selection phase
11: Initialization: $\rho = \emptyset, x = 6$
12: Publish the destination and expected route of each candidate platoon leader
13: Form the initial platoons $\rho_{initial} = \{P_x^{(1)}, P_x^{(2)}, \cdots, P_x^{(m_n)}\}$ between the remaining candidate PLs and PMs according to the $Sco_i$ and destination similarity
14: for $P_x^{(n)} \in \rho_{initial}$ do
15:     for $v_j \in P_x^{(n)}$ do
16:         Sort the $v_j$ by $\alpha_j^i$ in descending order
17:         if $\left|P_x^{(n)}\right| \geq x$ then
18:             Remove the top $x - 1$ PMs, $P_x^{(n)}$ from $V$, $\rho_{initial}$ separately, and $\rho \leftarrow \rho \cup P_x^{(n)}$
19:         else if $\left|P_x^{(n)}\right| < x$ then
20:             Remove all $k$ PMs from $V$, and $x \leftarrow x - k$, $\rho \leftarrow \rho \cup P_x^{(n)}$
21:         end if
22:     end for
23: end for
24: if $V = \emptyset$ or $\rho_{initial} = \emptyset$ or no similar destination between PL and PM exists then
25:     end
26: else if $V \neq \emptyset$ and $\rho_{initial} \neq \emptyset$ and similar destination between PL and PM exists then
27:     return line 12
28: end if
29: Obtain the final platoon formation result and the remaining vehicles are treated as individual vehicles
30: END
```

V. RESOURCE ALLOCATION

A. TIME DIVISION BASED INTRA-PLATOON RESOURCE ALLOCATION MECHANISM

In order to gurantee the reliable and high-rate transmission of control information in platoons, a time division based intra-platoon resource allocation mechanism is proposed in this section. After dedicated CUE's spectrum resource is allocated to a platoon, it is divided into equal-length time slots and periodically assigned to the PMs for D2D communication to avoid co-channel interference caused by multiplexing the same spectrum resource. The control information to be transmitted by PMs in each time slot mainly includes vehicle's velocity T_s, acceleration T_a, braking T_b and so on. In addition, the PL also needs to broadcast resource allocation information to all PMs, including the start time of time slot T_t, the slot sequence T_n assigned to each PM and so on. Besides, each time slot includes a data segment. When a PM detects an unexpected event such as a traffic accident, the corresponding event-triggered information will be transmitted in the data segment. Entertainment information can also be transmitted in this data segment when there is no safety information transmission, as shown in Fig. 4.

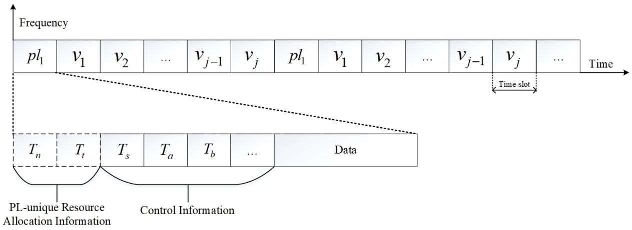


FIGURE 4. Time division based intra-platoon resource allocation.

This mechanism can efficiently allocate the required spectrum resources for the platoon communication shown in Fig. 2. Interference-free time slot resources are used to transmit control information; once event-triggered safety information is monitored in data segment, it will be broadcast to all PMs by the PL to improve road safety. In addition, the drawback of time division techniques is that the time slot is allocated fixedly. When there is no data transmission, the time slot resource is wasted. However, in the vehicle platooning strategy of this paper, periodic transmission of control information is required between vehicles. Therefore, no time slots are wasted in our proposed mechanism, so that the drawback can be better avoided.

B. MINIMUM RATE GUARANTEED INTER-PLATOON RESOURCE ALLOCATION MECHANISM

In vehicle platooning, the typically gap between adjacent vehicles is 10m, and the range of D2D communication is 50m. In order to ensure that all vehicles in the platoon can communicate with each other by D2D, the maximum number of vehicles in a platoon is set to 6, and the maximum length of the entire platoon is 50m. Visible, the size of the platoon is relatively small. Besides, as mentioned above, time-division based D2D communication is used to transmit control information for each PM. Therefore, the whole platoon can be treated as a node to continuously multiplex dedicated CUE's spectrum resource in time domain. In summary, each platoon can be treated as a node to reuse CUEs' spectrum resources for D2D communication. The co-channel interference caused by one CUE to all PMs in the platoon are considered the same. On the other hand, the co-channel interference caused by PMs in different time slots to the CUE can be equivalent to the PL's interferences in the continuous time domain. After dedicated CUE's spectrum resource is allocated to a platoon, the PL allocates corresponding time slots for each PMs. This paper mainly studies the resources allocation inter platoon nodes, without considering the specific process of time slot allocation intra platoon.

The platoon nodes (DUEs) obtained by algorithm 1 are denoted as $\rho = \{P^{(1)}, P^{(2)}, \cdots, P^{(m_n)}\}$. In order to meet the communication performance's requirements, each node can multiplex the uplink spectrum resources of multiple IVs (CUEs) at the same time; for the purpose of maximizing the spectrum utilization, spatial reuse of spectrum resources is adopted. That is, CUEs' resources can also be reused by multiple distant platoon nodes without co-channel interference. This way of allocating resources is called "M+N" resources multiplexing, which has higher flexibility and spectrum utilization. However, the interference model caused by this way is more complex, so that the computational complexity of resource allocation is higher. In order to reduce the computational complexity, the interference-free platoons are grouped into several platoon clusters. The platoon cluster is treated as a resource allocation node to reuse multiple CUEs' resources. Besides, one CUE's resource can only be multiplexed by one platoon cluster node, which is called "1+M" resources multiplexing. Since the platoon cluster contains multiple interference-free platoons, the "1+M" strategy essentially achieves the "M+N" strategy's effect and reduces the computational complexity.

By using vertex coloring algorithm in graph theory, the platoon clustering problem can be better solved. First, the base station constructs an undirected graph $G = (\rho, E)$ based on the interference relationship between different platoons, in which ρ is the vertices set, each vertex represents a platoon, and E is the adjacent edges set between vertices. If there is co-channel interference between two platoons, the adjacent edges will exist between the corresponding vertices. Then the undirected graph is colored by the vertex coloring algorithm, and vertices (platoons) will be grouped into different clusters according to their coloring later. Vertices with the same color can multiplex the same spectrum resources, and there are co-channel interferences between vertices of different colors, resulting in the inability to reuse the same resource. In summary, the vertices of the same color are divided into one cluster, in which these vertices can reuse the same resource without interference, and the coloring number is the number of final clusters.

Algorithm 2 Platoon Clustering Algorithm Based on Sequential Coloring

```
Input: $G = (\rho, E)$, $\rho = \{P^{(1)}, P^{(2)}, \cdots, P^{(m_n)}\}$, coloring function $\Omega$, $Co = \{color_1, color_2, \cdots\}$
output: $C = \{c_1, c_2, \cdots c_{m_t}\}$
Initialization:
$\Omega\,(P^{(1)}) = color_1, n = 1$
end Initialization:
for $P^{(n)} \in \rho$ do
    if $n \leq m_n$ then
        Obtain all the colors $Co(P^{(n)})$ of the adjoining nodes around $P^{(n)}$, make $b = \min\{Co \backslash Co(P^{(n)})\}$, then $\Omega\,(P^{(n)}) = color_b$
    else if $n > m_n$ then
        end
    end if
end for
Obtain the final platoon clustering result $C = \{c_1, c_2, \cdots c_{m_t}\}$ by grouping vertices of the same color into a cluster
END
```

In this paper, the undirected graph G is stained by sequential coloring algorithm to get the final clustering result, as shown in algorithm 2. Ω is the coloring function, which outputs the coloring result of each vertex; all vertices (platoons) of the same color are grouped into one cluster and then the final clustering result is obtained as $C = \{c_1, c_2, \cdots c_{m_t}\}$. The main idea of the algorithm is as follows: the vertices of G and the colors that may be used are randomly ordered to get the colors set $Co = \{color_1, color_2, \cdots\}$. Then, the vertices are colored from small to large by their orders, using the color with smallest order that is not used by all adjacent vertices. Besides, the sequential coloring is a heuristic algorithm with low computational complexity. Specifically, the complexity of determining the adjacency edges set E is $O(m_n * (m_n + 1)\big/2)$; based on this, vertex coloring is performed on the graph G, and the maximum complexity of this process is $O({m_n}^2)$. Therefore, the time complexity of the algorithm is $O({m_n}^2)$, in which m_n is the number of platoon nodes.

By platoons clustering, the resource allocation problem is simplified to "1+M" resources multiplexing between m_t platoon clusters (DUEs) $C = \{c_1, c_2, \cdots c_{m_t}\}$ and m_m individual vehicles (CUEs) $\{IV^{(1)}, IV^{(2)}, \cdots, IV^{(m_m)}\}$. Their subscript sets are represented as $\overline{m_t} = \{1, 2, \cdots, m_t\}$, $\overline{m_m} = \{1, 2, \cdots, m_m\}$. Based on the vehicle platooning system, we first guarantee the minimum transmission rate of each platoon and then optimize CUEs' sum transmission rate.

We suppose taht there are m_g platoons $\{P^{(1)}, P^{(2)}, \cdots, P^{(m_g)}\}$ in platoon cluster c_t. Each platoon comprises a PL and several PMs. As mentioned above, each platoon can be treated as a node to reuse CUEs' spectrum resources. The co-channel interferences caused by the CUE to all PMs in the platoon are treated as the same. On the other hand, the co-channel interferences caused by PMs in different time slots to the CUE can be equivalent to the PL's interferences in continuous time domain. Furthermore, for D2D communication in platoon $P^{(g)}$, the signal to noise ratio (SNR) between the PL pl_i and the farthest PM v_j is the worst. If the worst SNR meets the requirements of communication performance, the whole platoon can meet the requirements. To simplify the calculation, this worst one is taken as the SNR of D2D communication for the whole platoon. According to the Shannon formula, the transmission rate obtained by platoon $P^{(g)}$ after reusing the resource of CUE $IV^{(m)}$ is shown in Eq. (10).

$$\gamma_g = W \log(1 + \frac{h_{i,j}p_i}{\delta_j + h_{m,j}p_m}) \tag{10}$$

Where p_i, p_m are the transmit power of the PL pl_i and CUE $IV^{(m)}$ respectively. $h_{i,j}$, $h_{m,j}$ are the channel gain from the PL and CUE to the farthest PM v_j respectively. δ_j is the additive noise received by v_j, and W is the transmission bandwidth.

Similarly, there are m_g platoons in the c_t multiplexing the uplink resources of the CUE $IV^{(m)}$, causing co-channel interference to it. The transmission rate obtained by the $IV^{(m)}$ is given as

$$\gamma_m = W \log(1 + \frac{h_{m,B}p_m}{\delta_B + \sum\limits_{c_t} h_{i,B}p_i}) \tag{11}$$

Where $h_{m,B}$, $h_{i,B}$ are the channel gain from the PL pl_i and CUE $IV^{(m)}$ to the base station respectively. δ_B is the additive noise received by the base station. $\sum\limits_{c_t} h_{i,B}p_i$ represents the sum of co-channel interference of all platoons in platoon cluster c_t to the CUE $IV^{(m)}$.

In summary, platoon cluster c_t multiplexing the resource of $IV^{(m)}$ is defined as once match, and the transmission rate acquired by $IV^{(m)}$ is recorded as the matching weight $\tau_{t,m}$, as shown in Eq. (12). Besides, when the transmission rate obtained by any platoon in platoon cluster c_t is lower than the threshold γ_{th}, the matching weight is 0 to guarantee the minimum transmission rate of each platoon.

$$\tau_{t,m} = \begin{cases} 0 & if\ \gamma_g \leq \gamma_{th} for any P^{(g)} \in c_t \\ \gamma_m & else \end{cases} \tag{12}$$

In this paper, CUEs' sum rate is taken as the optimization target, and the minimum transmission rate of each platoon is taken as the constraint condition. Then, the optimization objective function is as follows:

$$\max \Psi_1 = \sum_{t=1}^{m_t} \sum_{m=1}^{m_m} \tau_{t,m}\omega_{t,m} \tag{13}$$

$$\sum_{t=1}^{m_t} \omega_{t,m} \leq 1, \quad \forall m \in \overline{m_m} \tag{14}$$

$$\sum_{m=1}^{m_m} \omega_{t,m} = M, \quad \forall t \in \overline{m_t} \tag{15}$$

$$\omega_{t,m} = 0 \quad or\ 1, m \in \overline{m_m}, t \in \overline{m_t} \tag{16}$$

Where Eq. (13) is the objective function that maximizes the transmission sum rate of all individual vehicles (CUEs) while guaranteeing the minimum transmission rate of each platoon. Eq. (14) and (15) are constraints to ensure that each CUE's resource is multiplexed by at most one platoon cluster and each platoon cluster reuses M CUEs' resources. In Eq. (16), $\omega_{t,m} = 0$ indicates that the resource of c_t is not multiplexed by $IV^{(m)}$, and multiplexed when the value is 1.

In the optimization problem of Eq. (13), it is necessary to allocate M CUEs' resources to each platoon cluster, which is an irregular assignment problem with high computational complexity. Therefore, we adopt a heuristic assignment algorithm to allocate only one CUE's resource for each platoon cluster in each assignment. Targeting local optimization, assigning M CUEs' resources to each platoon cluster by M times assignment to ensure the total optimization results. The value of M is determined by the number of cellular resources and the computational complexity requirements. The more resources are available, the greater the value space of M is, along with the higher computational complexity. As mentioned above, each CUE's resource can only be reused by one platoon cluster, so after one assignment is complete, the reused CUEs' resources are deleted. Each assignment is essentially to solve the max-weight matching problem based on the weighted bipartite graph. That is, in the remaining CUEs' resources pool, each platoon cluster is assigned a dedicated CUE's resource to maximize the total matching weight, which can be obtained from Eq. (12). The obtained max-weight matching is the resource allocation result in this assignment. Further, in order to facilitate the calculation, the matching weight $\tau_{t,m}$ is normalized as

$$\tau'_{t,m} = \tau_{t,m} \Big/ \max_{t,m} \tau_{t,m}, m \in \overline{m_m}, t \in \overline{m_t} \tag{17}$$

Then, this max-weight matching problem can be represented by the following maximum integer programming model:

$$\max \Psi_2 = \sum_{t=1}^{m_t} \sum_{m=1}^{m_m} \tau'_{t,m}\omega_{t,m} \tag{18}$$

$$\sum_{t=1}^{m_t} \omega_{t,m} \leq 1, \quad \forall m \in \overline{m_m} \tag{19}$$

$$\sum_{m=1}^{m_m} \omega_{t,m} = 1 \quad \forall t \in \overline{m_t} \tag{20}$$

$$\omega_{t,m} = 0 \quad or \ 1, m \in \overline{m_m}, t \in \overline{m_t} \tag{21}$$

Where Eq. (19) and (20) are constraints to ensure that each CUE's resource is multiplexed by at most one platoon cluster and each platoon cluster can reuses only one CUE's resource.

To solve this integer programming model, we add $m_m - m_t$ virtual nodes in $C = \{c_1, c_2, \cdots c_{m_t}\}$. The edges between virtual nodes $c_{m_t+1} \cdots c_{m_m}$ and CUEs are added and the weight of the newly added edge is 0, so as to construct a new matching weight function, as shown in Eq. (22).

$$\tau''_{t,m} = \begin{cases} \tau'_{t,m}, & t = 1, 2, \ldots, m_t; m = 1, 2, \ldots, m_m \\ 0 & , t = m_t + 1, \ldots, m_m; m = 1, 2, \ldots, m_m \end{cases} \tag{22}$$

The max-weight matching of the original bipartite graph can be obtained by removing the edge with weight of 0 in the obtained matching result. After adding virtual nodes, the above maximum integer programming model is further transformed into:

$$\max \Psi_3 = \sum_{t=1}^{m_m} \sum_{m=1}^{m_m} (\tau^*_{t,m} - \tau''_{t,m})\omega_{t,m} \tag{23}$$

$$\sum_{t=1}^{m_m} \omega_{t,m} = 1, \quad \forall m \in \overline{m_m} \tag{24}$$

$$\sum_{m=1}^{m_m} \omega_{t,m} = 1, \quad \forall t \in \overline{m_t} \tag{25}$$

$$\omega_{t,m} = 0 \quad or \ 1, m \in \overline{m_m}, t \in \overline{m_t} \tag{26}$$

Where $\underset{t,m\in(1,2,\ldots,m_m)}{\tau^*_{t,m}} = \max\{\tau''_{t,m}\}$ and the model is a common standard assignment model. Therefore, it can be solved by Hungarian algorithm whose worst time complexity is $O({m_m}^3)$ [35]. In order to save space, the solution process will not be described again.

The above process completes one assignment by assigning a dedicated CUE's resource to each platoon. By M times assignments, each platoon will be allocated M dedicated CUEs' resources, to achieve the optimization objective as shown in Eq. (13).

VI. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed two-stage platoon formation algorithm (TSPFA) and minimum rate guaranteed inter-platoon resource allocation mechanism (MRGRAM) in MATLAB. The TSPFA proposed in this paper is compared with two typical algorithms: direction-based propagation algorithm (DPA) [36] and adaptable mobility-aware clustering algorithm based on destination positions (AMACAD) [37]. The first one forms clusters based on individual vehicles' direction, to ensure that data transmission only occurs between vehicles in the same direction; the second one takes into account the destination of vehicles, including the current location, speed, and final destination as parameters to arrange the clusters. On the other hand, we compare the MRGRAM with two typical resource allocation mechanisms. The first one is cluster-based resource block sharing and power allocation mechanism (CROWN) [38], which takes into account the requirements of both vehicular users (VUEs) and CUEs, where resource sharing can take place not only between a VUE and a CUE but also among different VUEs; the second one is subchannel allocation and power control mechanism (SAPCM) [39], which allocates resources based on the distance between different vehicles to improve the resource utilization.

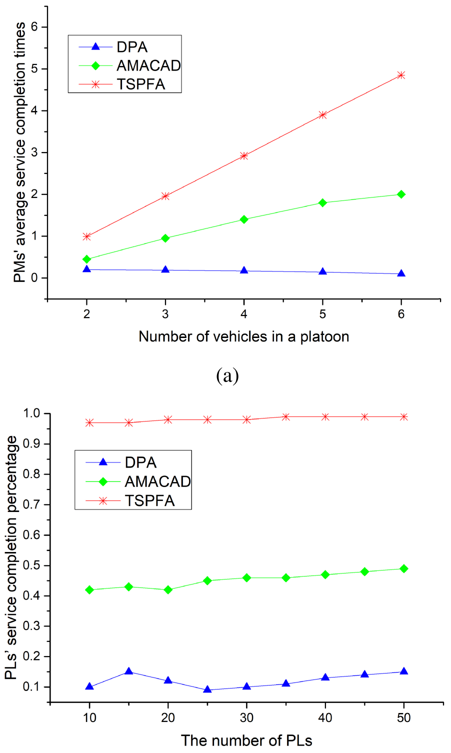
The performance metrics used in the evaluation of TSPFA are as follows: PMs' average service completion times, PLs' service completion percentage, the number of untruthful feedback and PLs' average benefits per service; of MRGRAM are as follows: CUEs' sum rate, D2D communication reliability and normalized spectrum utilization. We follow the simulation setup detailed in 3GPP TR 36.885 [40], and the main parameters used in our simulation are listed in Table 1.

TABLE 1. **Simulation parameters.**

Symbol	Quantity
Transmission bandwidth	10MHZ
Transmit power of DUEs	17dbm
Transmit power of CUEs	23dbm
Noise spectral density	-174dbm/Hz
MAX D2D transmission distance	50m
The number of platoon members	50-250
The number of malicious platoon members	20
The number of platoon leaders	10-50
The number of vehicles in a platoon	2-6
Difference threshold λ	0.2
Forgetting factorβ	0.5
Initial trust score	0.6
Trust threshold	0.4
Base fare	10
Fee charged per kilometer	3

A. PERFORMANCE OF THE PROPOSED TWO-STAGE PLATOON FORMATION ALGORITHM

PMs' average service completion times under various numbers of vehicles in a platoon are shown in Fig. 5(a); moreover, Fig. 5(b) shows the PLs' service completion percentage in different algorithms, as the number of PLs increases. Our proposed TSPFA has fully considered the similar destinations, PLs and PMs' subjective intention to form a platoon. So PLs are more inclined to provide good services and the destinations of the PMs are in the PLs' estimated driving routes,



(a)

(b)

FIGURE 5. **(a) PMs' average service completion times. (b) PLs' service completion percentage.**

which leads to the smooth completion of vehicle platooning services. AMACAD only considers the destinations without considering PLs' subjective intention, resulting in PLs' poor services and some PMs cannot reach their destination. What's more, due to the simple consideration of motion consistency, DPA can hardly guarantee PMs to reach their destinations. Numerical results show that the PMs' average service completion times and PLs' service completion percentage of TSPFA compared with AMACAD are improved by 121.5% and 116.7%on average.

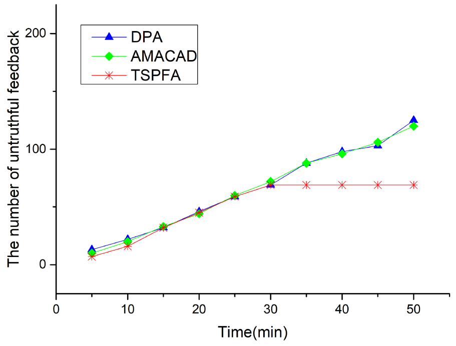


FIGURE 6. **The number of untruthful feedback.**

The number of untruthful feedback under various times is shown in Fig. 6. In this part of the simulation, 20 malicious platoon member vehicles who will provide untruthful feedback are added to the system. In our proposed TSPFA, trust score update algorithm has been designed to exclude those attackers. Specifically, PMs will lose eligibility for evaluation after three consecutive untruthful feedback are provided. As shown in Fig. 6, after 30 minutes, there is no untruthful feedback in TSMA, but it continues to rise in the other two algorithms.

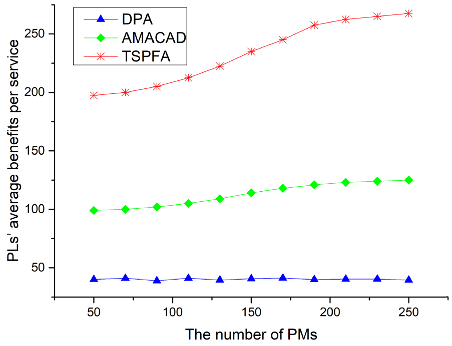


FIGURE 7. **PLs' average benefits per service.**

Fig. 7 demonstrates the change in PLs' average benefits per service with the increasing number of PMs. Apparently, the PLs' average benefits of TSPFA and AMCAD both increase with the growth of the number of PMs, because more candidate PMs can provide the PL more high-benefit options. However, when the number of candidate PMs is saturated, the revenue that the PL can obtain from the growth of the number of PMs gradually decreases. Obviously, our proposed algorithm TSPFA can better improve PLs' benefits, because it takes PMs' benefits as part of the optimization goal. Numerical results show that the average benefits of TSPFA is improved by 107.3% compared with AMCAD on average.

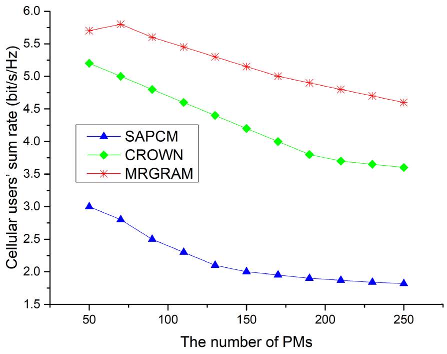


FIGURE 8. **CUEs' sum rate.**

B. PERFORMANCE OF THE PROPOSED MINIMUM RATE GUARANTEED INTER-PLATOON RESOURCE ALLOCATION MECHANISM

Fig. 8 illustrates the CUEs' sum rate under various numbers of PMs. Obviously, the sum rate decreases along with the growth of the number of PMs, because the growing PMs will cause more co-channel interference to CUEs. However, since our proposed MRGRAM adopts interference-free platoon clustering algorithm, the interference caused by DUEs to CUEs is reduced as much as possible. Numerical results show that the sum rate of TSPFA is improved by 21.4% compared with CROWN on average.

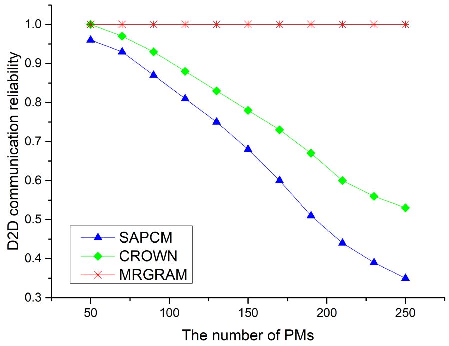


FIGURE 9. **D2D communication reliability.**

Fig. 9 reflects the D2D communication reliability of three mechanisms under various numbers of PMs. Obviously, the D2D communication reliability of our proposed mechanism is better than the other two contrasting mechanisms without using interference-free platoon clustering algorithm or guaranteeing the minimum transmission rate of DUEs.

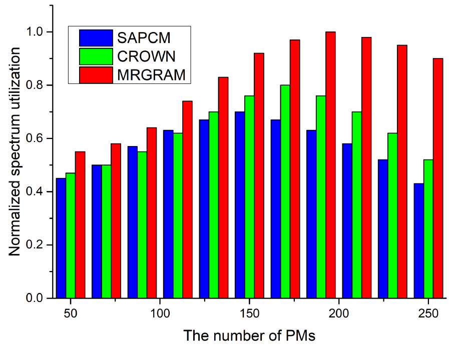


FIGURE 10. **Normalized spectrum utilization.**

Fig. 10 demonstrates the change in normalized spectrum utilization of different mechanisms with the increasing number of PMs. Spectrum resource utilization represents the content transmitted by the CUE and corresponding multiplexed DUEs in unit spectrum resource. With the growth of the number of PMs, the normalized spectrum utilization of the three programs rises first and then decreases. This is because as the number of users increases, resources can be more fully utilized in space domain. However, when the PM density is too high, co-channel interference will offset the benefits of resource reuse. Numerical results show that the normalized spectrum utilization of MRGRAM compared with CROWN and SAPCM is increased by 25% and 42.9% at least.

VII. CONCLUSION

In order to improve the efficiency and stability of vehicle platooning with limited spectrum resources, in this paper, we first propose a platoon communication mode based on D2D technology to share inter-vehicle control information efficiently and timely. And then, a two-stage platoon formation algorithm based on the PL evaluation mechanism is proposed to form stable platoons, as the basis for following work to improve the vehicle platooning' performance. Besides, a time division based intra-platoon resource allocation mechanism is proposed, which allocates resources for DUEs efficiently within the platoon to ensure the normal operation of the platoon communication function. Furthermore, a minimum rate guaranteed inter-platoon resource allocation mechanism is proposed to optimize CUEs' rate while guaranteeing the minimum transmission rate for each platoon. Numerical results show that the proposed mechanism and algorithm can not only significantly improve spectrum resource utilization and the stability of platoons but also optimize the PLs' benefits and meet PMs' service needs as much as possible.

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