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SPECIAL SECTION ON ADVANCES IN STATISTICAL CHANNEL MODELING
FOR FUTURE WIRELESS COMMUNICATIONS NETWORKS

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The Vehicle-To-Vehicle Link Duration Scheme Using Platoon-Optimized Clustering Algorithm

ZUFAN ZHANG, KUN XU, AND CHENQUAN GAN
School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

Corresponding author: Kun Xu (xukun1993628@163.com)

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ABSTRACT In the scenario of the vehicle network, the unstable vehicle to vehicle (V2V) connectivity caused by a high-speed vehicle movement is improved through efficient clustering algorithm to some extent. However, in view of the insufficient consideration of the variation of cluster stability in existing clustering algorithms, the V2V connectivity needs to be further enhanced. To this end, in this paper, a V2V link duration scheme using platoon-optimized clustering algorithm is proposed, which consists of three aspects: system model, a platoon-optimized clustering algorithm, and the analysis of link duration. Specifically, the second-order nonlinear dynamic system for platoon is analyzed to initialize the network scene. Then, a platoon-optimized clustering algorithm is performed, which combines the platoon leader (PL) selection based on motion consistency and the updated algorithm based on the dynamically stable cluster to reduce the randomness caused by the dynamic change of network topology. In addition, the V2V link duration based on the proposed scheme is quantitatively implemented through specific mathematical formulas. Finally, the extensive simulation results show that the proposed scheme can effectively guarantee the cluster stability and prolong the V2V link duration.

INDEX TERMS V2V connectivity, link duration, clustering algorithm, platoon stability.

I. INTRODUCTION

With the advent of 5G communication era, the premise of realizing diverse data services in vehicle network is to ensure efficient connectivity between vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) [1]. Especially the vehicles in V2V communication scenarios that are independent on infrastructure assistance, and the dissemination of real-time information is directly affected by the performance of connectivity [2]. Therefore, the research on V2V connectivity is of great significance to promote the further development of vehicle network [3].

Generally, one main problem of V2V connectivity is that the high-speed or random movement of vehicles results in a short link duration [4]. However, due to the limitation of traffic roads, vehicle network is controllable and the trajectory of vehicle nodes can be predicted. Substantial communication schemes have been proposed to improve the connectivity of vehicle network, which can be divided into contention-free and contention-based. The main idea for typical contention-free solutions is to group vehicles into a cluster [5].

Clustering technology in vehicle network usually aims to simplify routing and improve network connectivity through the similar metrics of vehicle nodes [6]–[9]. However, in the dynamic maintenance stage of clusters, the specific vehicle movements are ignored in previous work, leading to the lack of group stability. To improve the cluster stability and ensure the connectivity of vehicles in the group, the dynamic behavior of vehicles based on platoon stability is studied in this paper.

Although the current clustering algorithms show the dynamic characters of clusters, the variation of cluster stability in time domain was rarely considered, which results in the limitations of cluster stability and the effects on the V2V connectivity. Inspired by the moving state of platoon, vehicles

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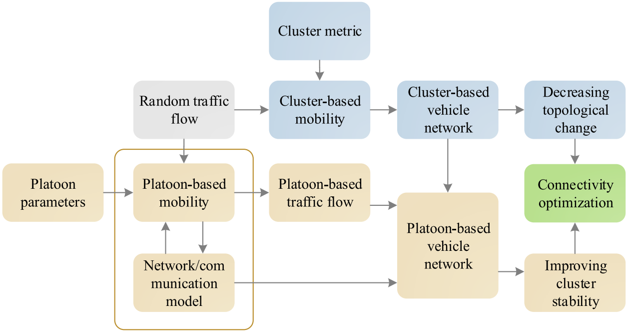


FIGURE 1. **A comprehensive structure of clustering and platoon-based network.**

with some common interests on the road can cooperatively form a platoon-based driving pattern, in which small and almost constant distances are maintained between vehicles. It has been proved that such a platoon-based driving pattern can significantly improve road capacity and communication efficiency compared with driving individually [10]. Furthermore, platoon stability can further shorten the wireless transmission distance of vehicles in the cluster and maintain relatively stable wireless communication state. Hence, this paper proposes a platoon-based traffic as a complementary method to the cluster network.

The vehicles inside platoon achieve stable moving state through consistency protocol under ideal conditions. However, in real road scenarios, vehicle density, mobility model and the displacement of platoon leader (PL) may break the relatively stable equilibrium state. To improve cluster stability and prolong the link duration of V2V, the V2V link duration scheme using platoon-optimized clustering algorithm is proposed in this paper, as shown in Fig. 1, which focuses on the influence of platoon-based traffic to cluster-based networks. Specifically, the main contributions of this paper lie in the following aspects:

- A platoon-optimized clustering algorithm by analyzing the platoon-based system model is designed, and the detailed mathematical quantitative analysis of V2V link duration is given. This improves the link duration and V2V connection reliability of dense vehicle networks.
- The whole platoon-optimized clustering process is considered from the proposed algorithm. Based on platoon stability, the evolutionary states of the cluster in the update process are supplemented, so as to strengthen the stability of the cluster in the maintenance phase and establish the stability of the cluster in the reconstruction phase. The dynamically stable cluster is realized by considering the randomness and consistency of vehicle motion.

The rest of this paper is organized as follows. The related work is introduced in Section II. In Section III, the V2V link duration scheme using platoon-optimized clustering algorithm is proposed, which analyzes the relationship between platoon stability and the variation of cluster stability to prolong the V2V link duration. The analysis of extensive simulation experiments is given in Section IV. In Section V, the contributions are concluded.

II. RELATED WORK

The research of vehicle network connectivity aims at achieving efficient inter-connection such as V2V and V2I. Different from other hardware systems, the vehicles can supply power for each module, which reduces the limitation of communication module size and energy consumption [11]–[13]. Due to complex radio environment of V2V short-range communications, the main factors affecting the connectivity of V2V and V2I are communication channel fading, vehicle moving speed, and network dimension, to name a few [14], [15]. Due to the received signal envelope suffering severe attenuation and fluctuation, the fading characteristics should be represented accurately by the channel models for vehicular environments. The Nakagami distribution is generally adopted to describe severe fading [16]. Besides, some other distributions can also be represented by Nakagami depending on specific model parameters, including Rayleigh and Rician fading. In addition, the Nakagami distribution fits well with the fading analysis based on channel measurement results in [17]. For instance, Zarei *et al.* [18] built a mathematical model for the mobility of connected vehicles based on variable vehicle speed. In particular, a new closed calculation formula of the probability density function was proposed through the long tail probability of the vehicles in multi-lane highway. The simulation results show that the V2V connectivity performance is improved. Backelli *et al.* [19] analyzed the transmission rate of V2V information on two-way highways. The results show that the information transmission rate is stable at the average rate under the threshold of vehicle density. When the vehicle density exceeds this threshold, the information transmission rate may increase exponentially with the vehicle density. Unlike most studies on sparse traffic scenarios, Shao *et al.* [20] studied the V2V connectivity subjected to Poisson distribution under different traffic densities. The analysis shows that a platoon-based vehicle network can significantly improve the network connection performance in V2V and V2I communication scenarios compared with the vehicle network without platoons. H. Peng *et al.* [21] proposed a multi-objective communication subchannel allocation scheme to realize intra-platoon and inter-platoon communications, which jointly considered the evolution of multimedia broadcasting services and equipment-to-equipment multicast communications. The simulation results show that the proposed scheme can reduce the communication delay in dense traffic. However, most of the current studies on V2V connectivity are devoted to deriving connectivity probability through mathematical models, the influence of clustering on V2V connectivity and the interaction between vehicles in the dynamic time domain are ignored.

Cooperative driving pattern was proposed in generous V2V connection schemes to improve the link performance between vehicles [22]. As mentioned above, vehicles grouped into a cluster through the similarity of geographic location and motion state can reduce the movement difference and randomness of the whole network to a certain extent, in which the cluster header (CH) is responsible for allocating time division multiple access (TDMA) slots to other cluster members (CMs) [23]. In this way, the V2V connectivity of intra-cluster can be effectively improved. The crucial parts of cluster are the selection methods of CHs and the maintenance of cluster stability. Therefore, numerous algorithms have been proposed to achieve efficient cluster. Hassanabadi *et al.* [24] proposed a distributed clustering algorithm based on neighborhood propagation to improve connectivity robustness. The authors in [25] selected the frontest vehicle as the temporary CH which assigns the vehcile closest to the center of the cluster as the new CH. However, the mechanism is only suitable for simple road topology. In addition, the authors in [26] proposed a cluster-based routing protocol, which attempted to select a small number of mobile nodes as dominating nodes to form a stable backbone in the vehicle network. The authors in [27] provided a new multi-hops clustering scheme to achieve more stable clusters and reduce the number of CHs under realistic traffic scenario. Recently, the authors in [28] proposed a unified framework of clustering approach in Vehicular Ad Networks (VANETs), which shows steady performance under different traffic scenarios. Also, the methods of social-aware are implemented to mine the social attributes of various devices [29]. The authors in [30] proposed a social-aware cluster algorithm in the 5G-VANET system, which exploited a social pattern prediction model to enhance the stability of clusters. The authors in [31] proposed a novel passive multi-hop clustering algorithm, which aims at ensuring the coverage and stability of the cluster. Although some cluster work mentions the importance of cluster stability, there is a lack of description of the specific movement behavior of vehicles within the cluster.

To improve the cluster stability and ensure the connectivity of vehicles, the dynamic behavior of vehicle is described in detail based on platoon stability. Vehicle platoon can be regarded as a dynamic system, in which multiple single vehicle nodes interact with each other through control information and couple to form a consistent behavior. Consistency as the basis of cooperative control has been widely used in many research fields, such as formation control, aggregation, and synchronization [32]–[35]. Di Bernardo *et al.* [36] proposed a distributed control protocol for vehicle platoons to solve the problem of high heterogeneous delay. S. Li et al. [37] enhanced platoon control based on vehicle longitudinal prediction technology. Wu *et al.* [38] proposed a traffic control algorithm for vehicular physical system to describe platoon behavior at isolated intersections. The simulation results show that the algorithm has better performance than the traditional signal timing strategy. Cruz-Morales *et al.* [39] considered the control of discrete-time mobile robots based on the monitoring of virtual leader. Shao *et al.* [40] studied the convergence performance of self-cycling platoon systems under different topologies. With the help of binary relation theory, a new sufficient condition was given to enable the motion agreement based on transforming the topology structure. Zegers *et al.* [41] proposed a distributed cooperative control scheme to improve the aggregation performance of vehicles in the platoon and evaluated the exponential stability of platoon dynamics. The simulation validates the robustness of the platoon stability control under the three-lane highway scenario. Recently, Li *et al.* [42] studied the influence of the initial state on vehicle platoon control under different communication topologies. In addition, the neural networks have been widely used in many fields such as feature learning [43], automatic modulation classification [44], and textual sentiment analysis [45]. Considering that the neural networks have the excellent performance of parameters learning, Chebyshev neural networks (CNN) are implemented to approximate the unknown nonlinear functions for vehicle-following platoon [46]. The simulation results show the string stability and desired spacing are further ensured.

The previous studies show that the basic characteristic of cluster in time domain is establishment-maintenance-break. Some researchers believe that the division and merging behavior exists under the influence of CHs with different capabilities. By considering these behaviors, cluster stability is improved. However, due to the lack of analysis of the specific movement characteristics of vehicles, the change of cluster stability do not show a certain regularity, resulting in a vulnerable maintenance of cluster stability. Inspired by platoon stability, the characteristic of dynamic stability in cluster is found in this paper.

III. PROPOSED SCHEME

To solve the insufficient consideration of the variation of cluster stability of vehicles in existing clustering algorithms, the V2V link duration scheme using platoon-optimized clustering algorithm will be introduced in this section, which includes the system model, the platoon-optimized clustering algorithm and the analysis of link duration.

A. SYSTEM MODEL

It is assumed that there are N vehicles on the current road L, including $M \leq N$ platoons, each platoon is denoted as S_k, $k = 1, 2, ..., M$, and the vehicles in the platoon S_k are represented as $c_{k,j}$, $j = 1, ..., w_k$. The platoon-based vehicular system is normally complex and nonlinear, including the engine, brake system, aerodynamic drag, tire friction, rolling, and resistance. To facilitate modeling, three reasonable assumptions are used in this paper to obtain a concise model for analysis:

(1) The vehicle platoon is formed by the vehicles with the same dynamics;

(2) The vehicle platoon moves within a straight-line lane and takes no lane-shifting maneuver in a freeway scenario;

(3) The acceleration and deceleration of each vehicle in the platoon are controllable.

Based on the above assumptions, the second-order nonlinear dynamic system for the platoon S_k is expressed as:

$$\begin{cases} x_{c_{k,j}}^{\prime S_k}(t) = v_{c_{k,j}}^{S_k}(t) \\ v_{c_{k,j}}^{\prime S_k}(t) = u_{c_{k,j}}^{S_k}(t) + f_{c_{k,j}}^{S_k}(x_{c_{k,j}}^{S_k}(t), v_{c_{k,j}}^{S_k}(t), t) \end{cases} \tag{1}$$

where, $(x_{c_{k,1}}^{S_k}(t), v_{c_{k,1}}^{S_k}(t)) \in R^2$ denotes the position and velocity of PL, and $j = 2, \ldots, w_k$, $(x_{c_{k,j}}^{S_k}(t), v_{c_{k,j}}^{S_k}(t)) \in R^2$ denotes the position, velocity of the PMs. $u_{c_{k,j}}^{S_k}(t)$ denotes the control input. $f_{c_{k,j}}^{S_k}(x_{c_{k,j}}^{S_k}(t), v_{c_{k,j}}^{S_k}(t), t)$ is the unknown nonlinear effect, which is assumed to be smooth continuous bounded on a compact set, and models vehicle acceleration disturbances, wind gust, parameters uncertainties, and intermediate uncertainties induced by networks. The platoon-based vehicular systems are shown in Fig. 2.

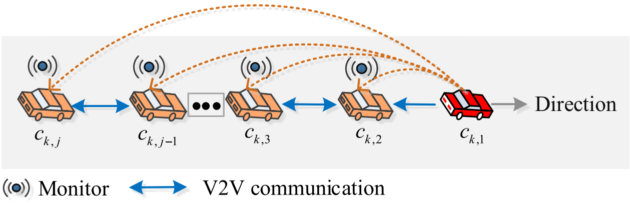


FIGURE 2. The platoon-based vehicular systems.

The platoon-based vehicular systems provide a consistency view in describing the dynamic behavior of the vehicle. By analyzing the platoon consistency protocol, the continuous and stable connection state can provide a better communication environment for vehicles. Therefore, an dynamically stable clustering algorithm based on platoon will be proposed to solve the problem of the V2V unstable connectivity.

B. THE PLATOON-OPTIMIZED CLUSTERING ALGORITHM

In this Section, the platoon-optimized clustering algorithm is proposed from two aspects: the PL election based on motion consistency and the updated algorithm based on dynamically stable cluster. In particular, the evolution state of dynamically stable cluster will be presented in the updated algorithm.

1) PL ELECTION BASED ON MOTION CONSISTENCY

In the initial stage of the network, vehicle nodes do not belong to any platoons. The formation of the platoon is a dynamic process, which needs to consider not only the geographical location and mobility similarity of vehicles but also the platoon control to maintain the dynamic stability of platoon. The PLs, responsible for the safety and stability of all PMs, take full control of the whole platoon when driving on the road. Therefore, a PL election algorithm based on motion consistency is proposed to ensure the reliability of V2V communication between vehicles, in which the relative stable velocity, expected driving distance, and actual driving distance are considered.

Neighbor discovery is the premise of a cluster. When the relative distance $\Delta d_{i,j}$ between any vehicle i and j is less than communication range R, the two vehicles are called neighbors and the neighbor node of the marked node i is expressed as

$$N_i = \left\{ j \middle| \Delta d_{i,j} < R \right\} \tag{2}$$

Considering the system model mentioned in the first part is constructed on the basis of the two-dimensional coordinate axis, the primary clustering metric after the initial vehicle generation is calculated. The relative distance $\Delta d_{i,j}(t)$ and relative speed $\Delta v_{i,j}(t)$ in the time slot t between any two vehicles i, j are calculated as

$$\Delta d_{i,j}(t) = \left\| (x_i - x_j)^2 + (y_i - y_j)^2 \right\| \tag{3}$$

$$\Delta v_{i,j}(t) = v_i - v_j \tag{4}$$

As the lane width is small, the y-coordinate in formula 3 can be ignored. Moreover, the average velocity of vehicles reflects the relative stability of the nodes in the platoon. The average velocity $\overline{v_{S_k}}$ and average distance $\overline{d_i}$ of the platoon S_k are defined as follows:

$$\overline{v_{S_k}} = \frac{1}{w_k} \sum_{j=1}^{w_k} \Delta v_{i,j} \tag{5}$$

$$\overline{d_i} = \frac{1}{w_k} \sum_{j=1}^{w_k} \Delta d_{i,j} \tag{6}$$

In addition, the predicted driving distance of the vehicle reflects the continuity of the node movement in the platoon. The maximum driving distance in the platoon S_k is defined as

$$h_{S_k} = \arg\max(d_{c_{k,j}}), \quad c_{k,j} \in S_k \tag{7}$$

Selecting several suitable PLs to form a platoon set is the goal of the PL election. Based on the assuming for the network scene and the settings for the relative movement, the complete algorithm is presented in Table 1:

TABLE 1. PL election based on motion consistency.

```
Input: number of vehicles $N$, vehicle beacon information
Output: number of platoons $M$, PL set $\{c_{k,1}\}$
Begin
Initialization platoon: according to formula (2-6), vehicle $i$
  find the neighbors by broadcasting its beacon information,
  and the number of vehicles in each platoon is $w_k$
Calculating the average speed $\overline{v_{S_k}}$ of $k$ platoon
for $k = 1$ to $M$ do
    for $j = 1$ to $w_k$ do
        if $\left| \frac{v_j - \overline{v_{S_k}}}{\overline{v_{S_k}}} \right| \geq 0.5$
        $S_k \leftarrow S_k - \{c_{k,j}\}$
    end for
end for
for $k = 1$ to $M$ do
    $h_{S_k} = \arg\max(d_{c_{k,j}}), c_{k,j} \in S_k$
end for
```

Noticed that the vehicles of different lanes cannot form a platoon in the initial stage, the proposed algorithm initializes the platoon by electing PL as the vehicle with stable speed

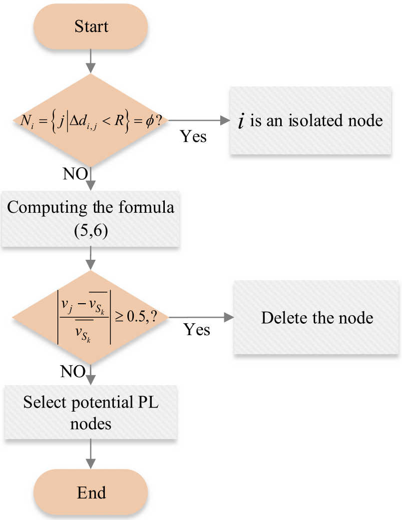


FIGURE 3. **The flow diagram of PL election.**

and relatively long driving distance. In addition, PL node needs to go through the platoon cluster firstly. Therefore, the computational complexity of the algorithm is expressed as $O(Mw_k)+O(M)$, which depends on the maximum number of nodes accommodated in the range of one-hop communication of vehicles. When the number of platoon clusters and PMs are similar in actual simulation, the algorithm complexity is approximated as $O(n^2)$. The flow diagram of PL election is shown in Fig. 3.

As mentioned earlier, CH directly affects cluster performance. PL is selected to as the CH of the whole platoon cluster through the designed algorithm in this section, which guarantees the performance of the platoon cluster. Based on this, the platoon updating and the maintenance of consistency is studied in the next section to improve group stability and extending V2V link duration.

2) UPDATED ALGORITHM BASED ON DYNAMICALLY STABLE CLUSTER

To achieve the updated algorithm based on dynamically stable cluster, the vehicle movement inside the platoon is analyzed firstly. To simplify the system analysis, the formula 1 is modeled as a second order equation.

$$\begin{cases} x'^{S_k}_{c_{k,j}}(t) = v^{S_k}_{c_{k,j}}(t) \\ v'^{S_k}_{c_{k,j}}(t) = u^{S_k}_{c_{k,j}}(t) \end{cases} \tag{8}$$

The objective of stable maintenance, which achieves a consensus of the platoon, is to ensure each member follow the leader asymptotically and maintain the identical inter-vehicle spacing d_1, and is expressed by

$$\begin{cases} x^{S_k}_{c_{k,j}}(t) \to x^{S_k}_{c_{k,1}}(t) - (j-1)\cdot d_1 \\ v^{S_k}_{c_{k,j}}(t) \to v^{S_k}_{c_{k,1}}(t) \end{cases} \tag{9}$$

The consensus control algorithms for the platoon is designed. To deal with the packet loss of leader, the last available state of leader to estimate the current state is adopted, which means the states of leader (velocity and position) are always globally reachable to all followers. The consensus algorithms are proposed as follows:

$$\begin{aligned} u^{S_k}_{c_{k,j}}(t) = \sum_{j=2}^{w_k} a_{ij} \Big\{ & \phi_1 \left[x^{S_k}_{c_{k,j}}(t) - x^{S_k}_{c_{k,i}}(t) \right] \\ & + \phi_1 \left[v^{S_k}_{c_{k,1}}(t) - \text{(j-i)} \cdot d_1 \right] \\ & + \phi_2 \left[v^{S_k}_{c_{k,j}}(t) - v^{S_k}_{c_{k,i}}(t) \right] \Big\} \\ & + \beta \Big\{ \phi_1 \left[x^{S_k}_{c_{k,1}}(t) - x^{S_k}_{c_{k,i}}(t) \right] \\ & + \phi_1 \left[v^{S_k}_{c_{k,1}}(t) - i \cdot d \right] \\ & + \phi_2 \left[v^{S_k}_{c_{k,1}}(t) - v^{S_k}_{c_{k,i}}(t) \right] \Big\} \end{aligned} \tag{10}$$

where, a_{ij} is the $(i, j)th$ entry of the adjacency matrix. β, ϕ_1 and ϕ_2 are the positive control parameters. The desired acceleration is determined by the state difference (position and velocity) between itself and neighbor. Accordingly, the system can be decoupled into two parts: the neighboring consensus system and the state error system of leader.

Under the constant spacing policy, each PM needs to track the trajectory of its preceding PM. Thus, several important indicators are introduced to evaluate the platoon control performance of each PM. Firstly, the spacing error and velocity error of PM $c_{k,j}, j = 2, \ldots, w_k$, with respect to the preceding one $c_{k,j\text{-}1}$ is defined as

$$\begin{cases} \delta_{c_{k,j}} = x^{S_k}_{c_{k,j-1}} - x^{S_k}_{c_{k,j}} - d_1 \\ e^{v}_{c_{k,j}} = v^{S_k}_{c_{k,j-1}} - v^{S_k}_{c_{k,j-1}} \end{cases} \tag{11}$$

To deal with the effect of current kinematic inputs in the later time slots, string stability is put forward to regulate the long-term behavior of the platoon. The string stability indicates the spacing errors caused by the disturbance at the PL should not enlarge from one PM to another downstream along with the platoon in the future, i.e., the spacing error of PM $\left|\delta_{c_{k,j}}(t)\right|$ should not be larger than the spacing error of its preceding PM $j-1$, $\left|\delta_{c_{k,j-1}}(t)\right|$.

Definition 1: A platoon is string stable if the spacing errors between consecutive vehicles do not amplify along the string

$$\left|\delta_{c_{k,j}}(t)\right| \leq \left|\delta_{c_{k,j-1}}(t)\right| < \varepsilon, \quad \textit{for any time slot } t \tag{12}$$

Because the whole network consists of multi-platoons, the sub-cluster consensus of the cooperative system is guaranteed by the following theorem.

Theorem 1: Suppose that the single platoon string is connected and the gain parameters ϕ_1 and ϕ_2 are positive. Then, the sub-cluster consensus of every single string is reached under the proposed control protocol 10 by

$$\begin{cases} \lim\limits_{t\to\infty} \left\| x_i(t) - x_j(t) - d_1 \right\| \leq \varepsilon \\ \lim\limits_{t\to\infty} \left\| v_i(t) - v_j(t) \right\| \leq \varepsilon \end{cases} \tag{13}$$

The proof of the string stability can be found in generous literature [47]–[49], which are valid by constructing

Lyapunov function and the Routh-Hurwitz stable criterion. In this paper, the specific process is no longer described in detail. It should be noted that such stability is bounded as the state errors between the vehicle and its neighbors are bounded by some factors, e.g., acceleration and time delay.

Although the PL election based on vehicle motion consistency is implemented to select the appropriate PL set, the variety of platoon may happen with the mobility state updating of PL. Therefore, in the process of platoon updating, it is necessary to consider not only the consistency of platoons but also the replacement behavior when different PLs meet and the potential PL attributes of isolated nodes appear. That is to say, when two neighboring PLs are moving in the same direction within the transmission range of each other, the cluster merging procedure will be triggered. The CH vehicle with less CMs will give up the leadership and another CH becomes the CH of the merged cluster and CMs in the dismissed cluster will be automatically included in the merged cluster. The average speed difference $\Delta\overline{v_{S_{i,j}}}$ and the average speed $\overline{v_{S_i}}$ of platoon S_i are expressed as

$$\Delta\overline{v_{S_{i,j}}} = \left|\overline{v_{S_i}} - \overline{v_{S_j}}\right| \tag{14}$$

$$\overline{v_{S_i}} = \frac{1}{w_k}\sum_{j=2}^{w_k}\left|v_{c_{k,1}}^{S_k} - v_{c_{k,j}}^{S_k}\right| \tag{15}$$

Based on the platoon consistency protocol and the replacement behavior of PLs during platoon movement, the system update behavior is guaranteed. The specific algorithm is shown in Table 2:

For the current time slot, the algorithm complexity is calculated as $O(M + N_i)$ because platoon update requires to traverse the number of platoons and isolated nodes. Further, the algorithm complexity is approximated as $O(n)$. In addition, PL responds for the maintenance of the current members and the updating of the members to join. The flow diagram of updated algorithm is shown in Fig. 4.

The whole platoon-optimized clustering algorithm can be obtained by combining the PL election and updated algorithm based on dynamically stable cluster, which takes into account consistency of vehicle motion with three important elements E_d, $\overline{v_{S_k}}$ as well as the control information, prolongs the continuous communication time of the vehicles in one platoon and provides a relatively reliable connection. The flow diagram of the complete clustering algorithm is shown in Fig. 5.

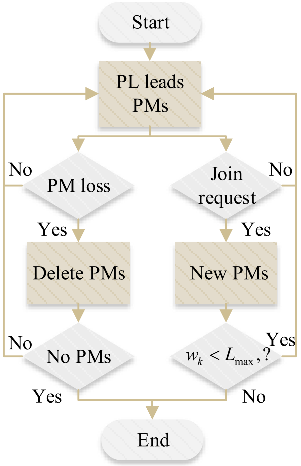


FIGURE 4. The flow diagram of updated algorithm.

TABLE 2. Updated algorithm based on dynamically stable cluster.

```
Input: number of PL Cluster $\{c_{k,1}\}$, beacon message $B$
       (control information added in)
Output: number of platoons M, Platoon set $S_k$
Begin
  Once the PL in each platoon is ensured
  for $i = 1$ to $M$ do
     The control information are added in the platoon,
  when $S_i$ enters into the communication range of $S_j$
      if $\frac{\Delta\overline{v_{S_{i,j}}}}{v_{S_i}} \geq 0.5$
          $S_i$ maintenance
      else
        if $\overline{d_i} \geq \overline{d_j}$
          $c_{i,1} \rightarrow S_j$, $S_i$ break
        PL $c_{j,1}$ in $S_j$ broadcasts its CH role to new
  joined members
        else $S_j$ break
        PL $c_{i,1}$ in $S_i$ broadcasts its CH role to new
  joined members
        end
      end
  end for
  Once the new merged cluster $S_k$ is trigged
  for $i = 1$ to the current isolated nodes $N_i$, do
     if $w_k < L_{\max}$
         $S_k \leftarrow S_k \cup \{N_i\}$
     else
         $S_{M+1} = \{N_i\}$
  end for
  end
```

C. THE ANALYSIS OF LINK DURATION

In this paper, the status of the link between the communication pair of vehicles will be connected, if the signal to interference plus noise ratio (SINR) at the receiver vehicle is greater than or equal to the threshold ζ. Hence, the inter-vehicle connectivity probability P_{iv} is defined as the probability that the received SINR γ is greater than or equal to the threshold ζ, and P_{iv} can be given by

$$P_{iv} = \Pr\{\gamma \geq \zeta\} = \Pr\left\{\frac{P}{I + N_0} \geq \zeta\right\} \tag{16}$$

where P, I and N_0 denote the received dominant power, total interference signal powers and noise power at the receiver, respectively. If the beacon information containing the motion state of the vehicle itself can be successfully received by other

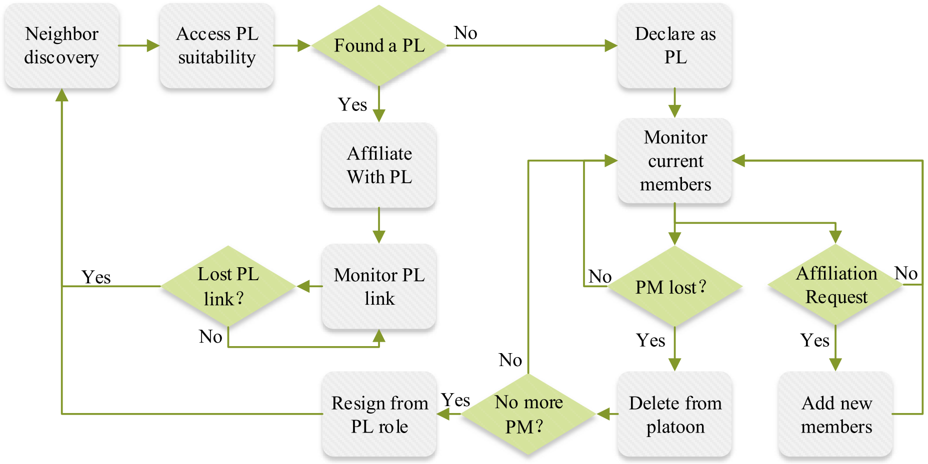


FIGURE 5. The flow diagram of the whole clustering algorithm.

vehicles in each time slot, the proposed clustering algorithm is triggered.

In addition, link duration describes the ability to maintain the connection of two vehicles, which also called link lifetime (LLT) [17]. When two vehicles are moving in the same or opposite directions, the equation (16) defines LLT calculation.

$$T_{i,j}^{LLT} = \frac{-\Delta v_{i,j} * \Delta d_{i,j} + \left|\Delta v_{i,j}\right| * R}{(\Delta v_{i,j})^2} \qquad (17)$$

As mentioned earlier, the basic characteristic of cluster change in time domain is generation-maintenance-destruction. In this section, to further show the time-demanding characteristics of cluster stability, the behaviors of platoon stability is implemented to the maintenance and reconstruction. The specific state evolution of dynamically stable cluster is shown in Fig. 6.

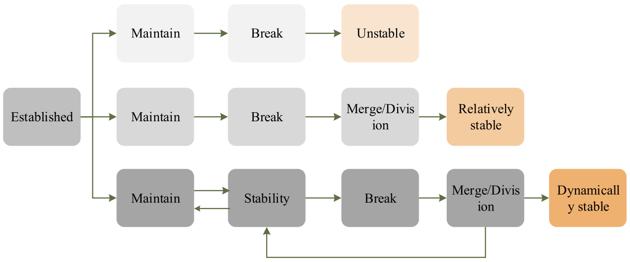


FIGURE 6. The specific state evolution of dynamically stable cluster.

Updated cluster will happen once PL enters the communication range of another PL. Define the difference of velocity and distance between any two PL as $v_{i,j}^{S_k}$, $d_{i,j}^{S_k}$. The actual driving distance for the platoon S_k is set as

$$d_k = \left(\frac{d_{k,i}^{S_k} - R}{v_{k,i}^{S_k}}\right), \quad k,\ i = 1, \ldots, M,\ k \neq i \qquad (18)$$

Define the time of motion convergence of all PMs with the PL as $T_{unstable}^{S_k}$, under the condition of the actual driving distance d_k. The stable link duration $T_{stable}^{S_k}$ of the platoon S_k is expressed as

$$T_{stable}^{S_k} = \frac{d_k}{v_{c_{k,1}}^{S_k}} - T_{unstable}^{S_k}, \quad k = 1, \ldots, M \qquad (19)$$

If the update of PL leads to platoon changes before the PMs of the platoon reach a consistency with the PL, there is no stable link duration. Hence, the $T_{stable}^{S_k}$ is further expressed as

$$\begin{cases} T_{stable}^{S_k} = \dfrac{d_k}{v_{c_{k,1}}^{S_k}} - T_{unstable}^{S_k}, & T_{stable}^{S_k} > 0 \\ T_{stable}^{S_k} = 0, & T_{stable}^{S_k} \leq 0 \end{cases} \qquad (20)$$

Finally, the average stable link duration of the whole network can be expressed as

$$\overline{T} = \sum\nolimits_{S_k} T_{stable}^{S_k} / M, \quad \text{for any time slot}$$
$$s.t \sum_{k=1}^{M} c_{k,j} \leq N, \quad j = 1, \ldots, w_k \qquad (21)$$

where the time of motion convergence of all PMs with the PL $T_{unstable}^{S_k}$ and actual driving distance are decided by the platoon control and the designed algorithm.

IV. EXPERIMENTS

The performance of the proposed scheme is shown in this section. The simulation tool is MATLAB. The experiments mainly focus on the performance in average platoon size, average platoon number, average platoon link duration, and average platoon stability lifetime. In particular, the average link duration based on the proposed scheme will be analyzed in detail. Considering the varying V2V environments, the Nakagami distribution is used to characterize realistic and accurate channel model in this paper. The experimental parameters are shown in Table 3.

TABLE 3. Parameters setting.

Parameters	Value
Vehicle numbers N	200
Road length L	$10km$
Expected driving distance E_d	$(0, 10)km$
Communication range R	$(100, 150, ..., 300)\ m$
Safety distance d_1	$10m$
Maximum PMs $L_{\max}$	20
Beacon interval B_i	$100ms$
Beacon size B_s	$50 - 500bytes$
Frequency bandwidth	$5.9GHz/10MHz$
Positive control parameter β	1
Space error control parameter ϕ_1	0.6
Speed error control parameter ϕ_2	0.75
Stability error ε	10^{-2}
SINR threshold ζ	$3dB$
Noise power N_0	$0.01w$
channel fading model	$Nakagami - m$

Before highlighting the performance of the algorithm, the connectivity performance of PLs under each slot is analyzed firstly. Considering the small-scale clusters in this paper, the effects of both channel parameters and the number of interferences are investigated. Particularly, the number of interference is set to $I = [5, 15]$, and the fading parameters of interference signal is $m = [0.5, 3]$, the mean power of interference signal Ω is fixed at 0.1. The fading parameters of receiver signal m_r is fixed at 5 and the mean received power Ω_r is set to 1.

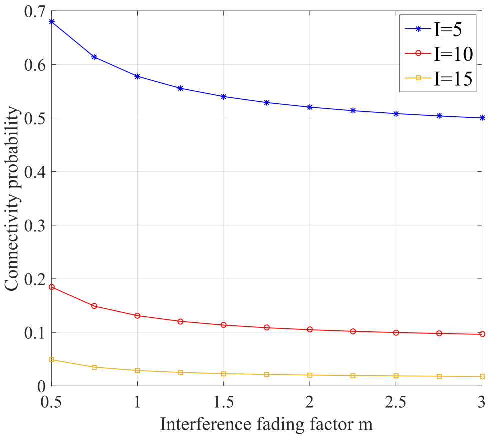


FIGURE 7. **The influence of interferences on inter-vehicle connectivity.**

The analytical and simulation results of inter-vehicle connectivity probability P_{iv} with different number of interferences are illustrated in Fig. 7. When $\Omega_r = 1$, the values of P_{iv} in $I = 15$ are evidently lower than the connectivity probability with less interference signals. It indicates of interference seriously deteriorates the reliability of inter-vehicle communications. considering the interference signals obey the gamma distribution at the receiver, according to its factorial characteristics, the value of gamma function increases with the number of interference signals. When the number of interference is small, the changing degree of probability is obvious. As the number of interference increases to a certain number, the inter-vehicle probability decrease to a very low level, so the change is relatively insignificant.

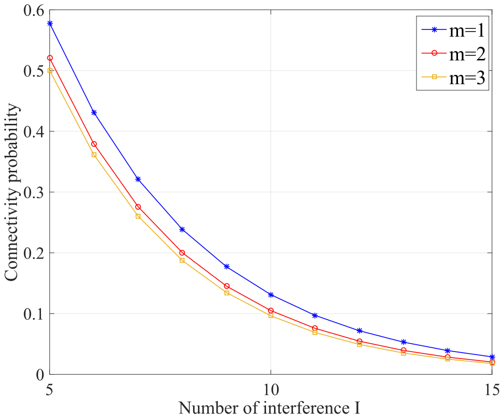


FIGURE 8. **The effect of the shading parameters on inter-vehicle connectivity.**

Fig. 8 shows the effect of the shading parameters m on connectivity performance. As depicted in the figure, increasing number of m can negatively affect connectivity performance. Note that Rayleigh fading can be represented as a special case of Nakagami distribution when $m_r = 1$. It indicates of fading factors seriously deteriorates the reliability of inter-vehicle communications and reduces the connectivity probability.

To highlight the performance of the proposed algorithm, several comparison algorithms are briefly introduced, including the lowest-ID clustering algorithm (LID), the vehicular multi-hop algorithm for stable clustering (VMASC) and the unified framework of clustering approach (UFC). Each node in the LID algorithm has an ID, and the vehicle periodically broadcasts its ID to all nodes in the two-hop communication range. The CH role will be declared or abandoned if a higher ID node is searched. VMASC is a new clustering algorithm based on metric of vehicle relative mobility to improve cluster stability and reduce the number of CH. This algorithm measured the average relative speed of vehicles to establish direct connections with existing CH or CM neighbors. UFC algorithm is composed of three important parts: neighbor sampling, backoff-based CH selection and cluster maintenance based on alternative CH. In different traffic scenarios, three cluster indicators are considered, including vehicle relative position, relative speed and link duration. In addition, the UFC algorithm carries out detailed parameter optimization analysis, especially in the case of high dynamic traffic flow with high cluster stability.

Considering the direct performance comparison of UFC algorithm with LID and VMASC algorithm in link duration, the speed variety covers four different comparison scenarios numbered A1, A2, B1 and B2. The similarities and

TABLE 4. Comparison of speed parameter settings in two scenarios.

Scenarios	Maximum acceleration	Maximum acceleration	Speed deviation	Maximum speed
A	$2.9m/s^2$	$7.5m/s^2$	0.7	$20m/s$
B	$2.9m/s^2$	$7.5m/s^2$	0.7	$35m/s$

differences of UFC settings are summarized into A and B in this paper, in which the case B is unstable relative to the case A, as shown in Table 4.

Based on the speed parameters settings of scenarios A and B in Table 4, to facilitate the analysis of V2V link duration, the performance of the design algorithm will be demonstrated from three aspects: average platoon size, average platoon number and average platoon link duration.

A. AVERAGE PLATOON SIZE

Figs. 9 and 10 show the impact of the changeable communication range on the average platoon size, which correspond to scenarios A and B, respectively. The simulation results show that the size of a single platoon increases with the increase of vehicle communication range. Due to the fact that vehicle motion consistency and expected driving distance are two important cluster indicators in proposed scheme, the average platoon size in scenario B is higher than that in scenario A. Although the speed of scene B has a large upper limitation and fluctuation, the expected driving distance of each vehicle is also increased in the specific simulation. A reasonable explanation is that scenario A is similar to the real urban roads, where vehicles have smaller speed deviation and upper limitation but the greater purpose driving variability. However, scenario B is similar to the real freeway, which achieve higher speeds and longer driving distances. Therefore, there are more PMs within the communication range in scenario B. In addition, compared with the general clustering algorithms without platoon partitioning, the PMs are reduced to some extent, which help PL to ensure the information transmission of PM and prevent the loss of data packets due to the excessive number of PM.

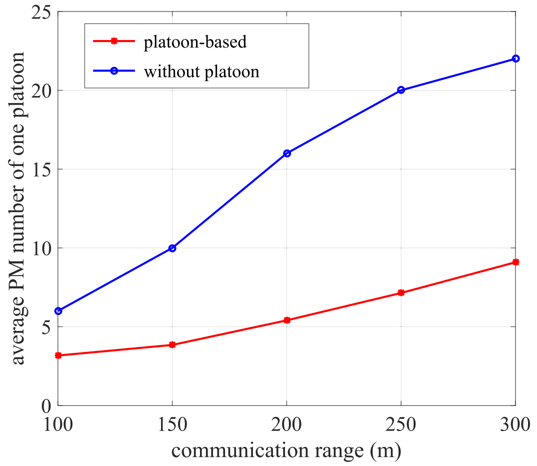


FIGURE 9. The average platoon size in scenario A.

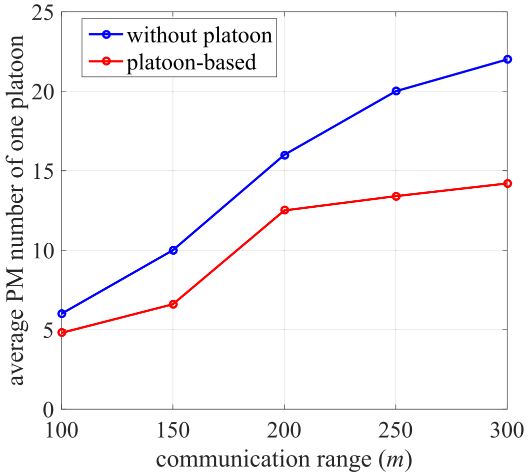


FIGURE 10. The average platoon size in scenario B.

B. AVERAGE PLATOON NUMBER

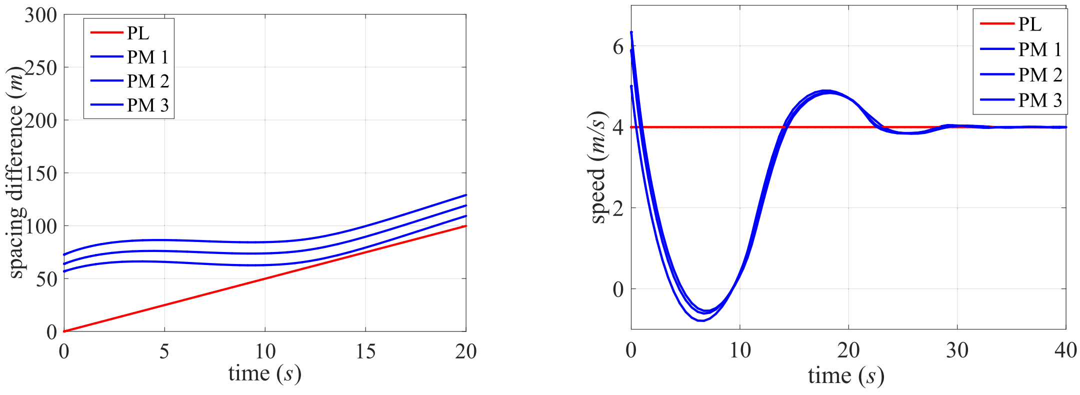
Table 5 shows the average number of clusters generated by the network when the vehicle communication range is 300 *m*. In this situation, the isolated nodes potentially with PL attributes in parentheses are considered. Compared with the mentioned clustering algorithms, the average number of clusters is implemented on a relatively balanced level in proposed algorithm. In addition, if isolated nodes are regarded as PL in each update time slot, the average number of platoon clusters will increase accordingly. The algorithm shows a good balance between the total number of vehicles and the average platoon size. Furthermore, the proposed algorithm presents fewer clusters and more isolated nodes in scenario B due to the fluctuation of speed. Therefore, the stability of the cluster is affected by the vehicle motion characteristics, as shown in Table 5.

TABLE 5. Comparison of the average number of clusters.

Scenarios	Algorithms			
	LID	VMASC	UFC	Proposed
A	15.72	62.71	58.56	24(+8)
B	17.68	47.1	63.95	15(+10)

C. AVERAGE LINK DURATION

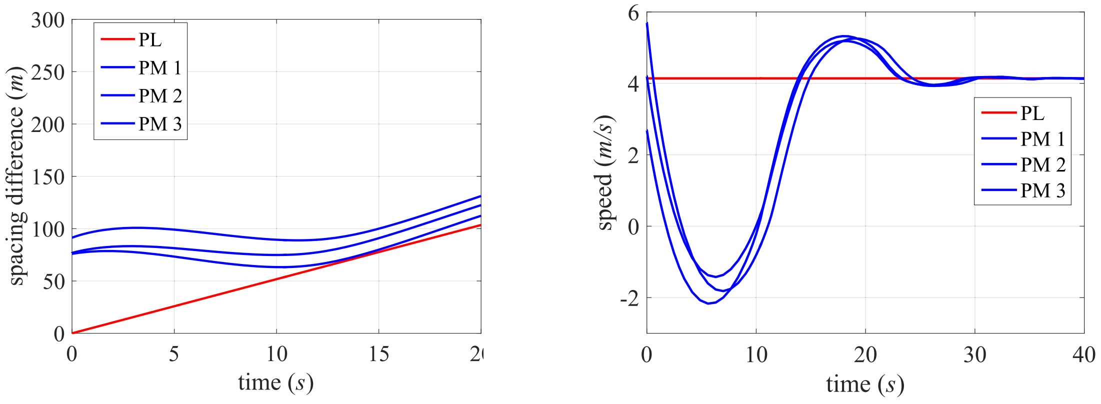
Figs. 11 to 15 show the impact of vehicle communication range on the average platoon size and the approaching time of platoon stability in scenario A. The process of platoon approaching stable connection is carried out in two aspects: relative distance and relative speed in the platoon. Specifically, Figs. 11(a) to 15 (a) corresponds to the process that the vehicle spacing within the platoon gradually reaches the preset constant value under the current communication range. Considering that the average platoon size (3, 3, 5, 7, 9) directly affects the platoon stabilization time, the detailed



(a)

(b)

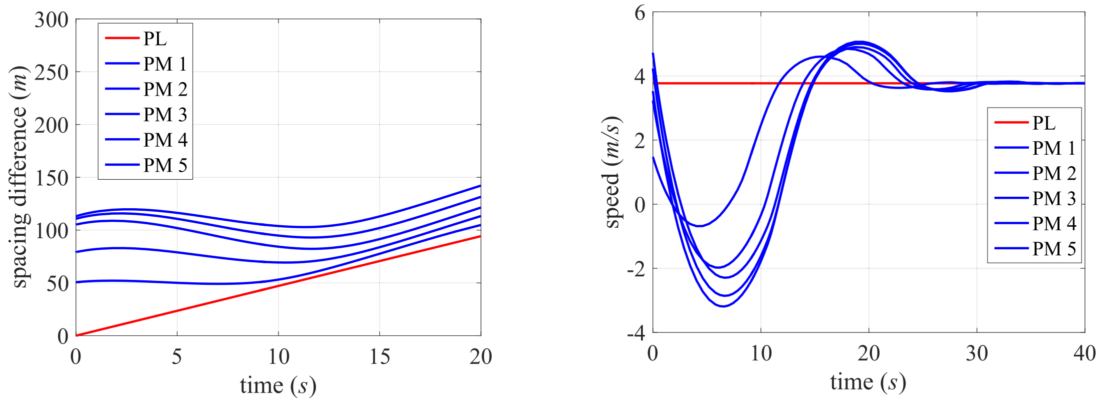
FIGURE 11. **Average approaching time of platoon stability under $R = 100m$ (a) Spacing difference. (b) Speed difference.**



(a)

(b)

FIGURE 12. **Average approaching time of platoon stability under $R = 150m$ (a) Spacing difference. (b) Speed difference.**

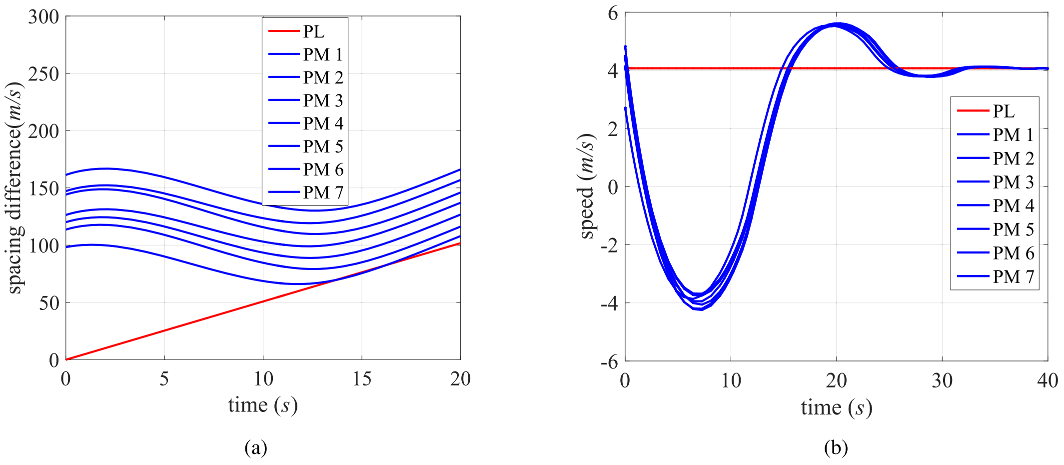


(a)

(b)

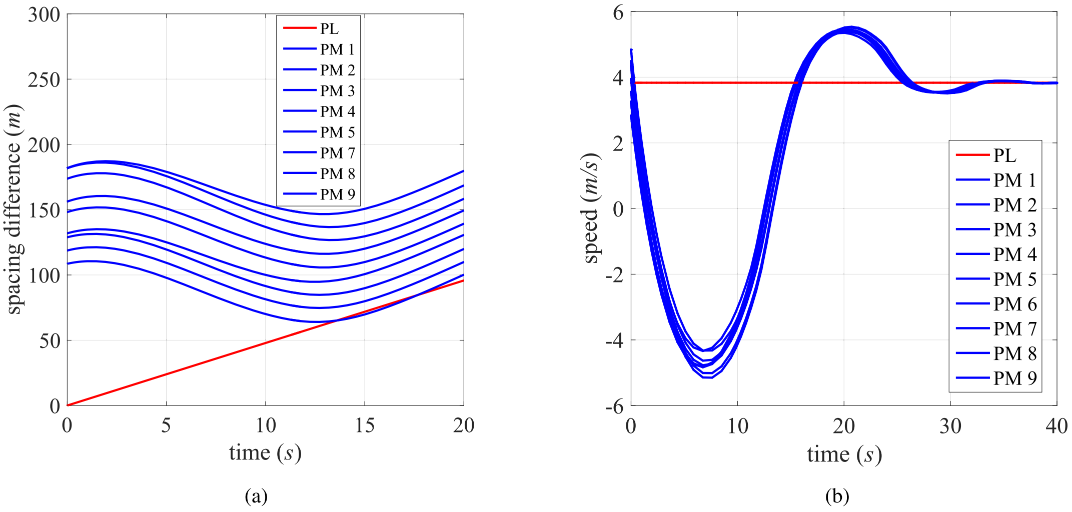
FIGURE 13. **Average approaching time of platoon stability under $R = 200m$ (a) Spacing difference. (b) Speed difference.**

process of the approaching time of platoon stability under different platoon sizes is given. It can be seen intuitively that each platoon PM gradually converges to the desired distance with PL through the proposed algorithm and achieves a relatively stable motion state. In addition, the consistency process of scenario B is the same as that of scenario A, and the final values of average V2V link duration will be presented in the table 6.



(a) (b)

FIGURE 14. **Average approaching time of platoon stability under $R = 250m$ (a) Spacing difference. (b) Speed difference.**



(a) (b)

FIGURE 15. **Average approaching time of platoon stability under $R = 300m$ (a) Spacing difference. (b) Speed difference.**

Figs. 16 and 17 show the performance of V2V link duration based on proposed scheme under scenarios A and B. The red line represents PL lifetime, that is, average platoon-based connectivity time. The blue line represents the average maintenance time of platoon stability. The green line represents the average approaching time of platoon stability. In general clustering algorithm, the increase of vehicle communication range leads to the corresponding increase of the number of adjacent vehicles, and the candidate range of CH reselection is greater. For example, LID algorithm updates CH periodically in any scenario so that the lifetime of each selected CH decreases gradually with the increase of communication range. However, the PL nodes are selected according to the consistency of vehicle motion and driving target. In addition, the PL features are maintained by the platoon stable maintenance algorithm on the straight road. Therefore, the PL lifetime is almost not affected by the communication range, and the probability of cluster destruction and reconstruction greatly reduced.

TABLE 6. **Comparison of average V2V link duration.**

Scenarios	Algorithms			
	LID	VMASC	UFC	Proposed
A	53.164	167.801	173.645	198.412
B	64.2	178.243	176.57	192.608

Table 6 summarizes the average cluster link duration of the comparison algorithm. It can be seen intuitively that LID algorithm presents lower connectivity time performance in both scenarios. The V2V link duration performance of VMASC algorithm is better than that of LID algorithm but slightly weaker than that of UFC algorithm. Compared with UFC algorithm under different scenarios, the proposed scheme increased by 14.3% and 9.1%, respectively.

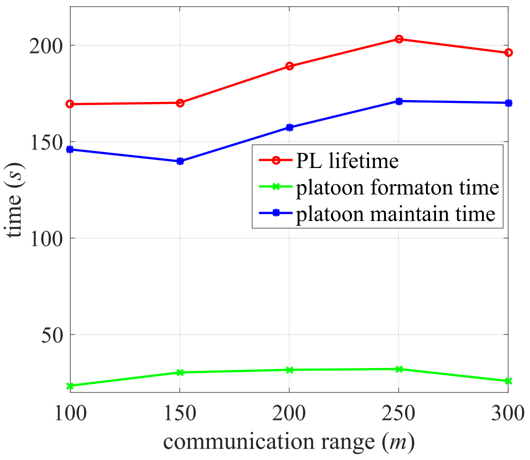


FIGURE 16. **The performance of link duration in scenario A.**

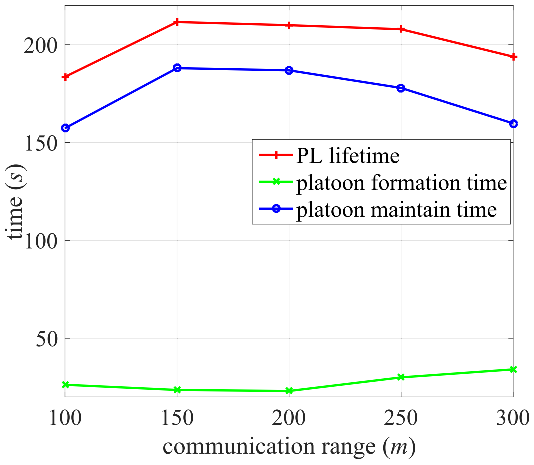


FIGURE 17. **The performance of link duration in scenario B.**

V. CONCLUSIONS

In this paper, the V2V link duration scheme using platoon-optimized clustering algorithm has been proposed, which comprehensively considers the clustering of vehicle movement and the consistency of intra-cluster motion. According to the characteristics of the platoon-based vehicular system, the platoon-optimized clustering algorithm is implemented in the proposed scheme that takes into account the characteristics of vehicle movement and the dynamically stable cluster. In particular, potential PL nodes on the road are selected to initialize the platoon cluster, then the PL characteristics are maintained in the process of cluster update and non-cluster nodes choose to join the platoon according to the similarities with the intra-cluster vehicles. Therefore, not only the stability of the cluster in the maintenance phase has been strengthen but also the stability of the cluster in the reconstruction phase has been established. Moreover, the quantitative analysis of V2V link duration is given in the proposed scheme. The simulation results show the superiority of the proposed scheme over the existing algorithms in terms of average platoon size, average platoon number, and average V2V link duration. In the future, the relationship between the dynamically stable cluster and the statistical distribution will be addressed by combining the analysis of actual road data.

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ZUFAN ZHANG received the B.Eng. and M.Eng. degrees from the Chongqing University of Post and Telecommunications (CQUPT), Chongqing, China, in 1995 and 2000, respectively, and the Ph.D. degree in communications and information systems from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2007. He was a Visiting Professor with the Centre for Wireless Communications (CWC), Oulu of University, Finland, from 2011 to 2012. He is currently a Professor with the School of Communication and Information Engineering, CQUPT. His current main research interests include wireless communications, mobile social networks, and machine learning.

KUN XU received the B.Sc. degree from the Chongqing University of Posts and Telecommunications, in 2015, Chongqing, China, where he is currently pursuing the master's degree in information and communication engineering. His research interests include vehicle to vehicle communications and machine learning.

CHENQUAN GAN received the B.Sc. degree from the Department of Mathematics, Inner Mongolia Normal University, in 2010, and the M.Sc. and Ph.D. degrees from the Department of Computer Science, Chongqing University, in 2012 and 2015, respectively. He has published over 10 research papers in international journals. His research interests include difference equations, computer virus propagation dynamics, and deep learning.

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