L-Platooning: A Protocol for Managing a Long Platoon with DSRC

Myounggyu Won
Department of Computer Science
University of Memphis, TN, United States
mwon@memphis.edu

Abstract—Vehicle platooning is a new driving technology that enables vehicles to form a road train autonomously. It has great potential to improve traffic congestion, environmental pollution, and driver safety. As such, it received significant attention from governments, industry, and academics. It is especially beneficial for logistics companies that can take advantage of a long platoon consisting of large trailer trucks. Existing platooning solutions, however, may not work properly for a long platoon due to the limited range of dedicated short range communication (DSRC). In this paper, we present L-Platooning, the first platooning protocol that enables seamless, reliable, and rapid formation of a long platoon. A novel concept called Virtual Leader is developed to effectively manage a long platoon; a distributed algorithm based on a novel model called the Virtual Leader Quality Index (VLQI) is designed to effectively extend the coverage of the platoon leader and to support the vehicle join and leave maneuvers for a long platoon. Extensive simulation is performed using combination of Veins (Plexe) and SUMO. The results demonstrate that L-Platooning enables vehicles to form a long platoon rapidly and reliably, maintain the desired inter-vehicle distances precisely, and handles elegantly the vehicle join and leave maneuvers.

I. INTRODUCTION

With rapid development of automotive industry and urban growth, we witnessed an explosive increase in the number of vehicles on the highway that links cities. There are more than 1 billion registered vehicles and the number is on the significant rise. It is expected that the number will be doubled within the next 20 years. While a vehicle is a convenient tool for transportation, such a huge number of vehicles on the highway causes numerous social problems. In U.S. alone, traffic congestion not only caused drivers waste more than $100 billion per year [1], but also had detrimental effects on environment and driver safety.

A new driving technology based on platooning has been developed to address these problems [2]. Vehicle platooning is a new concept in which a group of vehicles drive as a single unit, enabled by systematic coordination of a vehicle control system, sensor system, and vehicle to vehicle (V2V) communication system. The development of platooning dates back to 1970 [3] and received significant attention in U.S. in 1990s when the California Partners for Advanced Transit and Highways (PATH) program was initiated [4]. Since then, platooning has been of significant interests to governments, industry, and academics all over the world [5]. It has been shown that platooning has huge benefits to address numerous transportation problems [6]. For example, platooning has potential to reduce traffic congestion and increase the road capacity because in platooning, vehicles drive together with very small inter-vehicle distances. It can also alleviate the environmental effect and enhance energy efficiency due to minimized air drag which leads to reduced CO2 emissions. Furthermore, since a vehicle in a platoon autonomously follows the preceding vehicle, driving can be much more comfortable and safer.

The vehicle control system [7][8][9][10] and the V2V communication system such as IEEE 802.11p (DSRC) [11] and 3GPP/LTE-based C-V2X [12] are two key enabling technologies for vehicle platooning. The vehicle control system automatically adjusts the acceleration of a vehicle to maintain a constant inter-vehicle distance from the preceding vehicle. The V2V communication system supports the control system by allowing it to receive the kinematic information of other vehicles in the platoon. A problem is that advanced control systems may not work correctly if messages from other vehicles, in most cases the platoon leader, are not received reliably since the speed and acceleration of other vehicles in the platoon are needed to calculate the acceleration of the vehicle. Especially, it becomes problematic for a long platoon in which some vehicles fail to receive a message due to the limited range of DSRC.

In this paper, we present L-Platooning, the first platooning protocol that is specifically designed to effectively manage a long platoon. A novel concept of Virtual Leader is introduced which refers to a platoon member that acts like the platoon leader in order to virtually extend the coverage of the platoon leader. A new model called Virtual Leader Quality Index (VLQI) is developed to select the most effective platoon member as the virtual leader which is capable of extending the coverage most while maintaining good connectivity with the platoon leader. Additionally, a distributed algorithm is developed to allow platoon members agree on a selected virtual leader and to effectively handle the vehicle join and leave maneuvers for a long platoon.

Through extensive simulations based on the combination of the OMNeT++ based vehicular network simulation framework (Veins [13]) and a roadway traffic simulator (SUMO [14]), we show that L-Platooning is capable of allowing vehicles to form a long platoon autonomously, rapidly and effectively. It is also demonstrated that L-Platooning allows vehicles to maintain the inter-vehicle distance very precisely with the mean error of 6cm, and it elegantly handles the vehicle join and leave
maneuvers for a long platoon.

This paper is organized as follows. In Section III, we present the problem of current platooning technology in Section. And then, the proposed protocol is presented in Section IV. We evaluate the performance of L-Platooning in Section V, and conclude in Section VI.

II. BACKGROUND

Platooning depends on longitudinal drive control and V2V communication to constantly maintain short inter-vehicle distances. In this section, we present background on these two key components of platooning.

A. Control System

A longitudinal control system is comprised of an upper controller and a lower controller (Fig. 1). The upper controller is a cruise controller that computes the desired acceleration in order to retain an inter-vehicle distance to the front vehicle using a set of inputs such as on-board sensor data and kinematic data of other vehicles in the same platoon received via V2V communication. The lower controller is used to control the actuation of the vehicle, i.e., throttle and brakes using the output of the upper controller.

![Fig. 1. A basic architecture of a driving control system.](image)

The adaptive cruise control (ACC) has long been a traditional drive control system that can be used for platooning. It automatically adjusts acceleration in order to achieve the desired time headway with respect to the front vehicle. Various kinds of input data are used for ACC such as RADAR and LIDAR to compute the time headway, based on which the desired acceleration is calculated. The calculated acceleration is provided as input to the lower controller which adjusts the throttle and brake.

A main problem with ACC is, however, that it is not capable of achieving string-stable performance [15]. The string stability refers to that any error occurred in controlling a platoon member does not amplify as it propagates towards the end of the platoon. For example, an error in braking of a vehicle in a platoon amplifies towards the end of the platoon and may cause complete stop or even a collision of a following vehicle. The reason for lack of string stability for ACC is because it is based on only the local sensor data and data received from only the preceding vehicle, not utilizing data received from other vehicles especially the platoon leader via V2V communication.

The cooperative adaptive cruise control (CACC) algorithm addresses the problem of ACC and ensures the string stability. It utilizes both the on-board sensor data, vehicle kinematic data received from the preceding vehicle and other vehicles in the platoon that are farther away. Different kinds of CACC algorithms have been proposed in the literature [7][8][9][10]. In this paper, we adopt a typical CACC algorithm based on a classical control theory that utilizes data received both from the front vehicle and the platoon leader [15]. For example, the PATH and SARTRE (Safe Road Trains for the Environment) projects [16][7] used this type of controller.

More specifically, the control law for the \(i\)-th platoon member that computes the desired acceleration denoted by \(\dot{x}_i\omega_{des}\) is given as follows [15].

\[
\dot{x}_i\omega_{des} = \alpha_1\dot{x}_{i-1} + \alpha_2\dot{x}_0 + \alpha_3\varepsilon_i + \alpha_4(\dot{x}_i - \dot{x}_0) + \alpha_5\varepsilon_i
\]

\[
\varepsilon_i = x_i - x_{i-1} + l_{i-1} + \text{gap}_{des}
\]

\[
\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1}
\]

\(\dot{x}_0\) and \(\dot{x}_0\) are the acceleration and speed of the platoon leader; \(\dot{x}_{i-1}\) is the acceleration of the preceding vehicle; \(l_{i-1}\) is the length of the preceding vehicle; \(x_i\) and \(x_{i-1}\) are the positions of the current vehicle and the preceding vehicle; \(\varepsilon_i\) is the distance error with respect to \(\text{gap}_{des}\) which is the desired inter-vehicle distance. The parameters \(\alpha_i\) are as follows.

\[
\alpha_1 = 1 - C_1; \quad \alpha_2 = C_1; \quad \alpha_3 = -\omega_n^2
\]

\[
\alpha_4 = -(2\xi - C_1(\xi + \sqrt{\xi^2 - 1}))\omega_n
\]

\[
\alpha_5 = C_1(\xi + \sqrt{\xi^2 - 1})\omega_n
\]

The default values are taken from [17] for a weighting factor between the accelerations of the preceding vehicle and the platoon leader \(C_1\), the damping ratio \(\xi\), and the controller bandwidth \(\omega_n\). The default values for the parameters are summarized in Table I.

B. Vehicle to Vehicle (V2V) Communication

Another critical component for platooning is the V2V communication system. There are two types of V2V technologies for platooning: IEEE 802.11p (DSRC) [11] and 3GPP/LTE-based C-V2X [12].

The MAC layer of IEEE 802.11p is a variation of the IEEE 802.11 standard to cope more effectively with dynamic vehicular environments [11]. It eliminates the need of establishing a basic service set (BSS), thereby it executes in the Outside the Context of a BSS (OCB) mode with CSMA/CA. The physical layer of IEEE 802.11p is similar to IEEE 802.11a, i.e., it is amended based on OFDM to facilitate communication among vehicles that move fast. More specifically, it introduces 10MHz channels rather than 20MHz channels in order to reduce the root-mean-squared delay spread in dynamic vehicular environments.
Another line of V2V technology is 3GPP/LTE-based C-V2X technologies [12]. The Third Generation Partnership Project (3GPP) introduced Release 14 in 2016 which included the V2V communication service. It supports both infrastructure-based, *i.e.*, using eNodB for resource allocation (Mode-3), and infrastructureless also called as the sidelink/PC5 like IEEE 802.11p, *i.e.*, using a direct communication link between vehicles (Mode-4). For more details on C-V2X, the reader is referred to the paper [18].

It is expected that the two communication technologies will co-exist for some time. It is not only the automotive industry that is split in two, *e.g.*, Toyota, General Motors, and Volkswagen are the manufacturers of DSRC-equipped cars, while Ford, PSA Group, and Daimler have committed to the C-V2X technology. At the point of writing this paper, debates are going on in U.S., Europe, and China on determining the standard for V2V communication, and research on developing solutions that support both DSRC and C-V2X is very active. In the mean time, most practical platooning tests have been dominated by DSRC/WAVE [19], and its European counterpart ITS-G5 [20], [21].

III. PROBLEM STATEMENT

Recent measurement studies on DSRC demonstrated that the inter-vehicle distance and signal propagation environment determine the characteristics of DSRC [22] [23]. Especially the packet delivery rate (PDR) for DSRC decreases significantly as the inter-vehicle distance increases. For example, in an urban environment, PDR decreased from 93.6% at range of 0-50m to 39.1% at range of 450-500m.

We focus on the limited coverage problem of DSRC in which platoon members that are far from the platoon leader fail to receive a periodic beacon from the platoon leader. As described in Section II-A, failing to receive a beacon message from the leader results in disruption to the string stability (*i.e.*, $\dot{x}_o$ and $\ddot{x}_o$ are not available). To understand better the effect of the limited range of DSRC, we performed simulation using Veins [13] and SUMO [14]. Veins is a framework for vehicular network simulation which is based on OMNeT++ [24]. SUMO [14] is a road traffic simulator. In particular, we adopted Plexe [17] a platooning extension for Veins. In this simulation, a long platoon with 30 vehicles (trailer trucks with body length of 13m) with inter-vehicle distance of 20m was created, and the platoon leader changed its speed continuously in a sinusoidal fashion. Details on the simulation setup including V2V communication, vehicle mobility, and driving control system are presented in Section V-A.

We measured PDR of platoon members (Fig. 2). In this simulation, vehicles within the range of 0~350m from the platoon leader received a beacon message reliably from the leader with nearly 100% PDR. PDR decreased significantly starting from the 11th vehicle of the platoon which is about 400m away from the leader. The PDR of the 12nd and 13rd vehicles were only about 5.8% and 0.5%, respectively, and all other following vehicles that are farther away from the leader than these vehicles had nearly 0% PDR.

![Fig. 3. Speed of a following vehicle. The vehicle receives a beacon reliably from the leader, thus precisely adjusting the speed according to that of the leader.](image3)

The platoon members that do not receive a beacon message from the leader reliably due to the limited range of DSRC fail to adjust their acceleration correctly. Fig. 3 shows the speed of a vehicle with a high PDR that is close to the platoon leader. We notice that the vehicle adjusts its speed precisely according to the speed of the platoon leader that changes...
continuously in a sinusoidal fashion. On the other hand, the cumulative distribution function plot for 4 different platoon members (Fig. 4) shows that while the speed of vehicles 1, 7, and 9 (which had a high PDR) was accurately synchronized with the platoon leader, vehicle 17 with a 0% PDR had significantly large speed difference compared with that of the platoon leader.

Not accurately maintaining the vehicle speed and/or the inter-vehicle distance is not the only problem caused by the limited range of DSRC. Another critical problem is that standard approaches for handling the vehicle join and leave maneuvers will not simply work for a long platoon. More specifically, a vehicle may not be able to join a long platoon if it cannot communicate with the platoon leader to get permission from the leader for joining the platoon due to the limited range of DSRC.

IV. L-PLATOONING

A. Overview

We aim to develop a protocol that supports formation of a platoon regardless of the size while sustaining the string stability with minimum error in the inter-vehicle distance, and effectively handles the vehicle join and leave maneuvers. A naive solution would be to make vehicles piggyback the speed and acceleration information of the platoon leader on its beacon message, and broadcasts it in the next beacon interval. This naive solution, however, is not suitable for managing a long platoon. According to the DSRC standard [25], time is divided into 100ms sync period which consists of a 50ms control channel (CCH) interval and a 50ms service channel (SCH) interval. Thus, to broadcast a beacon with the piggybacked information, a vehicle has to wait up to 100ms. If a vehicle is \( n \) hops away from the platoon leader, the maximum latency would be \( 100 \times n \) ms. Considering the fast speed of a vehicle, and requirement of a short inter-vehicle distance for platooning, tolerating such a large delay every time a beacon message is sent is not acceptable.

To address the challenge, we introduce the concept of Virtual Leader. The virtual leader is a platoon member that is specifically selected to act as an intermediate platoon leader. More precisely, the following vehicles of the virtual leader consider the virtual leader as the platoon leader and use the speed and acceleration of the virtual leader instead of the original platoon leader, virtually extending the coverage of the platoon leader. Basically, the idea is to cluster and reorganize a long platoon into multiple manageable small platoons by electing the virtual leaders that serve each of the small platoon. In the following sections, we discuss how to select the virtual leader (Section IV-B), how to assign the selected virtual leaders to platoon members (Section IV-C), and how to handle the vehicle join and leave maneuvers (Section IV-D).

B. Selection of Virtual Leaders

In this section, we describe how a virtual leader is selected. We ensure that a virtual leader has good connection with both its platoon leader (which can be another virtual leader if already selected for this vehicle) and the following vehicles within the range. To this end, each vehicle keeps monitoring the quality of connection and piggybacks the connectivity information on its beacon message. Consequently, the platoon leader, upon receiving beacon messages from the following vehicles, makes a decision on which of the following vehicles should serve as the virtual leader.

To measure the quality of connection with the platoon leader, we adopt a real-time link quality estimator. There are numerous real-time link quality estimators [26][27]. In this protocol, the exponentially weighted average packet reception ratio (EWMPRR) [28] is adopted. EWMPR is very simple and memory efficient, requiring only 2 multiplications and 1 addition; thus it is adequate for vehicle platooning that requires very frequent message transmissions and rapid processing. However, it should be noted that it can be easily replaced with a different estimator depending on the needs of an application.

The quality of connection with the platoon leader for vehicle \( i \) is denoted by \( CON_i^L \) is EWMPR for the platoon leader denoted by \( PRR^L \), i.e., \( CON_i^L = PRR^L \).

Additionally, a virtual leader should have good connection with its followers. More specifically, to qualify as a virtual leader, a vehicle should be able to cover as many following vehicles that have poor connection with the platoon leader. The quality of connection for vehicle \( i \) with its following vehicles is thus modeled as follows.
\[ CON_i^F = \sum_{j \in \text{Followers}} (P RR_i^j - P RR_{i-1}^j). \] (7)

Here \( P RR_i^j \) is vehicle \( i \)'s EWMPR for a following vehicle \( j \), and \( P RR_{i-1}^j \) is vehicle \( j \)'s EWMPR for the platoon leader. In order for vehicle \( i \) to use \( P RR_i^j \) in calculating \( CON_i^F \), we ensure that \( P RR_i^j \) is piggybacked on a beacon message. We are ready to define the Virtual Leader Quality Indicator (VLQI) for vehicle \( i \) which is used to select a virtual leader as follows.

\[ VLQI_i = \gamma \times CON_i^F + (1 - \gamma) \times CON_{i}^L. \] (8)

After calculating VLQI, each vehicle piggybacks the calculated VLQI value on its beacon message. The platoon leader, receiving beacon messages from its following vehicles, selects a vehicle with the largest VLQI value as the virtual leader. Consider Fig. 5 for an example. The platoon leader selects a vehicle with the largest VLQI value as the virtual leader, receiving beacon messages from its following vehicles.

We examined how virtual leaders are selected under the same simulation setting as described in Section III. Fig 6 shows the results. As shown, the VLQI values of all vehicles quickly converged. In this simulation, vehicle 10 is selected as the virtual leader because it has the highest VLQI value. Although vehicle 11 had more followers with poor connection with the platoon leader than vehicle 10, in this case, \( P RR_i^{11} \) is too small compared with vehicle 10 (See Fig. 2). Similarly, vehicle 12 is not selected as the virtual leader because it has very poor connection with the platoon leader, thereby having very small VLQI value.

### C. Assignment of Virtual Leaders

Once a virtual leader is selected by the platoon leader, it should be assigned to the platoon members, i.e., the following vehicles of the newly selected virtual leader. More specifically, when a virtual leader is selected, the platoon leader notifies the selected virtual leader that it is selected as a virtual leader. It is implemented by adding a new 4 byte field \( \text{selectedVLID} \) in a beacon message. Thus, when a platoon member receives a beacon message from the platoon leader, it compares its ID with \( \text{selectedVLID} \) and if they are the same, the vehicle starts to act as the virtual leader. The selected virtual leader first notifies its following vehicles that their platoon leader has been changed. For this, we add another 4 byte field \( \text{newVLID} \) in the beacon message. The following vehicles, upon receiving this beacon message from the newly selected virtual leader, set the platoon leader to the new virtual leader and start to calculate the VLQI values with respect to the new virtual leader and report the values to the virtual leader. The virtual leader keeps receiving VLQI values from its following vehicles and selects another virtual leader if necessary. This way any platoon with arbitrary size can be effectively managed.

A challenge arises when we have to change the virtual leader. For example, the virtual leader may leave from the platoon, or a vehicle with a better VLQI value may appear. The beauty of L-Platooning is the capability of adaptively and rapidly updating the virtual leader by keeping monitoring the VLQI values of their following vehicles and selecting a new virtual leader if needed. When a virtual leader is changed, the original leader writes the ID of the previous virtual leader in the new 4 byte field \( \text{oldVLID} \) and the ID of the new virtual leader in the field \( \text{newVLID} \), and broadcast the beacon message. Upon receiving this beacon message, the old virtual leader becomes a regular platoon member stopping acting as the virtual leader, and the vehicle with the new virtual leader ID becomes the new leader. Both the newly selected virtual leader and the previous virtual leader keep broadcasting the beacon message with the ID of the previous virtual leader ID in the \( \text{oldVLID} \) field so that any following vehicles can update their leader to the new virtual leader.

Additionally, to prevent frequent changes of the virtual leader especially when VLQI values change significantly in the beginning of platoon formation due to the nature of EWMPR, we ensure that the platoon leader selects a virtual leader if the VLQI value of a vehicle is the greatest for \( \beta \) consecutively received beacons from the vehicle.

Once a vehicle sets its leader to a virtual leader, it starts to use the speed and acceleration of the virtual leader in computing the desired acceleration. For example, in Fig. 5, vehicle \( B \) is selected as the virtual leader, and its followers \( C \) and \( D \) use the speed and acceleration of vehicle \( B \) in calculating their desired acceleration.

We examined how virtual leaders are selected under the same simulation setting with \( \beta = 5 \) as described in Section III.
Fig. 7 shows that 3 virtual leaders are selected to serve a platoon consisting of 30 trailer trucks with body length of 13m and the desired inter-vehicle distance of 20m. It is interesting to note that there is a virtual leader near the tail of the platoon, i.e., 28th vehicle serving 29th vehicle and being ready to take any join request from vehicles that wish to join the platoon. We will discuss this great property of L-Platooning in more detail in Section V-1. Another notable observation is that selection and assignment of the virtual leader are completed very rapidly, in this example, within 10 seconds.

While L-Platooning is very effective and fast in managing a long platoon due to simple distributed mechanisms for selecting a virtual leader and assigning the virtual leader to following vehicles, it has some overhead in terms of the increased beacon message size. More specifically, the additional message overhead is 28 bytes to add the new fields, VLQI, PRR, selectedVLID, newVLID, and oldVLID. Empirical studies, however, show that a packet size increase of 100 bytes has only slight impact on performance [29]. We expect that an increase of only 28 bytes will have a very marginal effect. We analyze the impact of the increased packet size in more detail in Section V-D.

D. Managing Vehicle Join/Leave Maneuvers

In this section, we describe how L-Platooning handles the vehicle join and leave maneuvers. A standard approach for managing the vehicle join maneuver is to allow a joining vehicle to send a request message to the platoon leader; and then the platoon leader allows the joining vehicle to join by sending a reply message to the joining vehicle [17]. Similarly, when a vehicle leaves, a vehicle sends a request message to the platoon leader; and if the platoon leader permits, the vehicle can leave [17].

The problem is that when a joining vehicle or a leaving vehicle has poor connection with the platoon leader, then the request cannot be completed. The proposed L-Platooning elegantly addresses the problem. More specifically, even if a joining vehicle has poor connection with the platoon leader, it can still safely join as it maintains good connection with a virtual leader. A nice property of L-Platooning is that there is always a virtual leader near the tail of a platoon that can receive a request from a joining vehicle. This property can be simply proved based on proof by contradiction. Assume in contradiction that a joining vehicle does not have connection with a virtual leader, i.e., the joining vehicle is out of range of the virtual leader. This is contradiction because the virtual leader must have selected one of the following vehicles within its range as another virtual leader. Consider Fig. 5 for an example. Here vehicle E is a joining vehicle. Although vehicle E is close to vehicle D, it does not have connection with vehicle B which is the virtual leader. Since vehicle B would have selected vehicle D or C as the virtual leader according to the protocol, the joining vehicle E should be able to join the platoon.

L-Platooning manages nicely the vehicle leaving maneuver as well. There are two cases to consider: (1) a leaving vehicle is not a virtual leader, and (2) a leaving vehicle is a virtual leader. The first case can be handled simply. More specifically, when a vehicle leaves, the immediately following vehicle closes the gap based on the control system, and then its virtual leader recalculates the VLQI values for its following nodes and re-select a virtual leader if necessary. The second case is a little bit trickier because when a virtual leader leaves, its following vehicles no longer receive a beacon message from the leader which has left already. To address the challenge, L-Platooning ensures that if a leaving vehicle is a virtual leader, it first sends a leave request to its immediate follower and designate the follower as the new virtual leader. If it does not have a follower, it can just simply leave. After the vehicle leaves, the new virtual leader closes the gap starting to serve its following vehicles.

V. EVALUATION

A. Simulation setup

We consider a platoon consisting of 30 trailer trucks with body length of 13m led by a platoon leader which continuously changes its speed in a sinusoidal fashion. L-Platooning was implemented in a vehicular simulation framework Veins/Plexe [13] [17] incorporated with a traffic simulator SUMO [11]. The desired inter-vehicle distance is set to 20m with γ = 0.5 and β = 5. All other simulation parameters for V2V communication, car mobility, and driving controller are summarized in Table 1.

We focus on measuring the inter-vehicle distance of each platoon member in evaluating the performance of L-Platooning. More specifically, we examine if each vehicle accurately maintains the desired inter-vehicle distance (20m) when the speed of the platoon leader continuously changes (Section V-B). We then measure the time that L-Platooning takes to select virtual leaders and assign them to platoon members (Section V-C). We also analyze the effect of the increased packet size considering that L-Platooning requires a few additional fields in the DSRC beacon message (Section V-D). Finally, we study the effectiveness of L-Platooning in terms of handling the vehicle join and leave maneuvers (Sections V-E and V-F) focusing on the delay for completing the vehicle join and leave requests.
TABLE I  
SIMULATION PARAMETERS FOR V2V COMMUNICATION, MOBILITY, AND CONTROLLER

| Parameter                | Value                          |
|--------------------------|-------------------------------|
| Path loss model          | Free space                    |
| PHY model                | IEEE 802.11p                  |
| MAC model                | IEEE 1609.4                   |
| Frequency                | 5.89GHz                       |
| Bitrate                  | 6 Mbit/s (QPSK R = $\frac{1}{2}$) |
| Access category          | A_C-VI                        |
| Thermal noise            | -85dBm                        |
| Packet size              | 228Byte                       |
| TX power                 | 20dBm                         |
| Leader’s average speed   | 100km/h                       |
| Oscillation frequency    | 0.2Hz                         |
| Oscillation amplitude    | $\simeq$ 95 km/h to 105 km/h  |
| Platoon size             | 30 cars                       |
| Car length               | 13m (Truck)                   |
| Engine lag $\tau$        | 0.5s                          |
| Weight factor $C_1 \tau$ | 0.5                           |
| Controller bandwidth $\omega_n$ | 0.2Hz                      |
| Damping factor $\xi$     | 1                             |
| Desired gap $d_{des}$    | 20m                           |
| Headway time $T$         | 0.3s and 1.2s                 |
| ACC parameter $\lambda$  | 0.1                           |
| Distance gain $k_d$      | 0.7                           |
| Speed gain $k_s$         | 1.0                           |
| Desired speed $\hat{x}_{d,des}$ (followers) | 130km/h                     |

B. Inter-Vehicle Distance

In this section, we evaluate the performance of L-Platooning in terms of the inter-vehicle distances maintained by platoon members of a long platoon. Ideally, the protocol should enable platoon members to maintain precisely the inter-vehicle distance of 20m.

Fig. 8 illustrates the measured inter-vehicle distances of vehicles 1, 11, and 12 over time before applying L-Platooning. Vehicles 1 and 11 successfully accelerated to reduce the inter-vehicle distance to 20m and accurately maintained the desired inter-vehicle distance because these vehicles reliably received beacon messages from both the preceding vehicle as well as the platoon leader (Vehicle 0). In particular, since vehicle 1 is geographically closer to the platoon leader, it was able to achieve the desired inter-vehicle distance earlier than vehicle 11; more precisely, vehicle 11 could only reach the desired inter-vehicle distance after all of its front vehicles have reached it. An interesting observation is that while other vehicles were accelerating to reduce the inter-vehicle distance, vehicle 12 failed to receive a beacon message from the platoon leader and it did not accelerate while keeping the same speed based on the default cruise control mode. As a result, the inter-vehicle distance for vehicle 12 increased until all vehicles finished adjusting their inter-vehicle distances to 20m. And then, the speed of the front vehicles 1~11 is synchronized with that of the platoon leader. Consequently, the inter-vehicle distance of vehicle 12 fluctuated in a sinusoidal fashion as the speed of the front vehicles continuously changes according to that of the platoon leader.

We then applied L-Platooning and measured the inter-vehicle distances. The results are displayed in Fig. 9. All vehicles successfully adjusted their inter-vehicle distances to 20m. In particular, vehicle 12 was also able to adjust its distance to 20m because the virtual leader (vehicle 10) was selected and assigned to vehicle 12 at about 15sec. Note that the inter-vehicle distance of vehicle 12 increased in the beginning of the simulation because of the delay to select and assign the virtual leader. Overall, L-Platooning allowed all vehicles to precisely keep the inter-vehicle distance of 20m, although the distance fluctuated slightly because the leader continuously changed its speed. Despite the continuous speed change of the platoon leader, the inter-vehicle distance was kept nearly constant with the mean and max error of only 6cm and 22cm, respectively.

C. Delay for Selection and Assignment of Virtual Leader

We have demonstrated that once virtual leaders are selected and assigned to platoon members, the platoon members could maintain the desired inter-vehicle distances accurately. However, there is a delay to complete this process. In this section, we measure and analyze the delay. We repeated experiments for 100 times with different random seeds and recorded the delay for each vehicle.

Figure 10 shows the cumulative distribution function (CDF) of the delay. In particular, we compared the results for two different platoon sizes. The simulation results show that the
delay for a platoon with more vehicles was greater than the smaller platoon. It is quite straightforward because the virtual leader is selected one after another starting from the ones that are close to the platoon leader (Vehicle 0). As such, the vehicles near the tail of the platoon takes more time to get assigned a virtual leader. More accurately, the average delay for the platoon with 30 vehicles was 7.2s, while that for the platoon with 40 vehicles was 7.9s. Despite the differences, it is noticed that L-Platooning completes the virtual leader selection and assignment process very quickly.

D. Effect of Packet Size

The only cost for L-Platooning is the overhead due to the increased packet size since we add several new fields in the beacon message. In this section, we evaluate the effect of the increased packet size, more specifically additional 28bytes, focusing on the packet delivery rate for the beacon messages transmitted from the platoon leader. Fig. 11 shows the packet delivery rates for different packet sizes. The results indicate that there is no statistically significant difference between the two packet sizes in terms of the packet delivery rate. In fact, research has shown that even an increase of 100bytes for a DSRC beacon message does not have significant impact on performance [29].

E. Vehicle Join Maneuver

In this section, we evaluate the performance of L-Platooning in terms of how it handles the vehicle join maneuver. We created a scenario where a new vehicle joins 15 seconds after the formation of a long platoon is completed, i.e., all virtual leaders are selected and assigned to platoon members. The speed of the joining vehicle was set to be fast enough so that it can catch up with the platoon quickly. When the vehicle is close to the tail of the platoon, the vehicle sends a join request to the virtual leader of the platoon. We varied the distance between the joining vehicle (i.e., 100m, 150m, 200m, 250m) and the front vehicle when the joining request is sent, and measured the time it takes for the joining process to be completed.

To understand how L-Platooning handles the vehicle join maneuver, we recorded the speed and inter-vehicle distance of the joining vehicle. Fig. 12 shows the speed of the joining vehicle. It reduces the speed once it catches up with the platoon.

Fig. 12. Speed of the joining vehicle. It reduces the speed once it catches up with the platoon.

Fig. 13. Inter-vehicle distance of the joining vehicle. The inter-vehicle distance of the joining vehicle is successfully adjusted to 20m.

To understand how L-Platooning handles the vehicle join maneuver, we recorded the speed and inter-vehicle distance of the joining vehicle. Fig. 12 shows the speed of the joining vehicle. It shows that the joining vehicle increases the speed to catch up with the platoon in the beginning of the simulation. Once the vehicle is close enough to the tail of the platoon, it sends a request message to the closest virtual leader. The figure also shows that after the request message is sent, the speed of the joining vehicle is decreased to adjust the inter-vehicle distance to 20m. After the desired inter-vehicle distance is reached, the speed of the joining vehicle changes according...
to the platoon leader’s speed change in a sinusoidal fashion. The inter-vehicle distance of the joining vehicle is displayed in Fig. 13. It shows that the inter-vehicle distance quickly drops as the joining vehicle is increasing its speed to catch up with the platoon. Once the vehicle is close enough to the front vehicle, i.e., at about 25sec, it starts to gradually reduce the inter-vehicle distance and then finishes adjusting the gap to 20m.

![Fig. 13](image1.jpg)

**Fig. 13.** The inter-vehicle distance of the joining vehicle is displayed in Fig. 13. It shows that the inter-vehicle distance quickly drops as the joining vehicle is increasing its speed to catch up with the platoon. Once the vehicle is close enough to the front vehicle, i.e., at about 25sec, it starts to gradually reduce the inter-vehicle distance and then finishes adjusting the gap to 20m.

We measured the time it takes for completing the vehicle join maneuver, i.e., from the point when the request message is sent by the joining vehicle and to the point when the desired inter-vehicle distance is achieved. For this experiment, we varied the distance to the front vehicle when the request message is sent. Results are depicted in Fig. 14. It takes slightly longer to complete the join maneuver when the request message was sent early, i.e., when the distance to the front vehicle is larger because the joining vehicle needs more time to reduce the inter-vehicle distance to 20m. We also notice that the average delay for completing the vehicle join maneuver was 38sec in our simulation settings.

**F. Vehicle leaving**

In this section, we evaluate the performance of L-Platooning in terms of how it handles the vehicle leaving maneuver. To simulate the vehicle leaving maneuver, a vehicle to leave was randomly selected after 60sec when formation of the long platoon has been completed, i.e., all virtual leaders have been selected and assigned to platoon members. The leaving vehicle changes the lane, and then sends a leave request to the immediate follower if necessary (i.e., if it is a virtual leader) to leave from the platoon in accordance with the proposed protocol. If the request is approved the leaving vehicle accelerates and leaves the platoon.

Fig. 16 shows the speed of the immediate follower of the leaving vehicle. At 100sec, the speed is increased to reduce the inter-vehicle distance to 20m.

![Fig. 15](image2.jpg)

**Fig. 15.** Speed of the immediate follower of the leaving vehicle. At 100sec, the speed is increased to reduce the inter-vehicle distance to 20m.

![Fig. 16](image3.jpg)

**Fig. 16.** Inter-vehicle distance of the immediate follower of the leaving vehicle. The distance increases sharply as the vehicle leaves but is quickly readjusted to 20m.

Then, when the front vehicle left the platoon at 100sec, the immediate follower increased the speed to reduce the gap caused by the left vehicle quickly. Once the desired inter-vehicle distance is adjusted back to 20m, the speed of the immediate follower again fluctuated according to the speed of the platoon leader. Fig. 14 shows the inter-vehicle distance of the follower. When its front vehicle left at 100sec, the inter-vehicle distance increased sharply because the front vehicle no longer exists in the platoon. To reduce the gap quickly and adjust the inter-vehicle distance back to 20m, the vehicle increased the speed and consequently reached 20m.

We measured the time for L-Platooning to complete processing the vehicle leaving maneuver. More specifically, the time from the point when the leave request is initiated to the point when the immediate follower finished adjusting the inter-vehicle distance to 20m. We repeated simulation 10 times for each randomly selected leaving vehicle. We obtained that the average delay was 35.7sec with standard deviation of 0.2sec.

**VI. Conclusion**

We have presented L-Platooning, the first protocol that enables seamless, reliable, and rapid formation of a long platoon, effectively addressing the current problem of the limited range of DSRC. L-Platooning allows platoon members maintain precisely the desired inter-vehicle distance regardless of the
size of the platoon and elegantly handles both the vehicle join and leave maneuvers. As the first protocol specifically designed to support long platooning, we expect that this work will be significant assets to the research community and industry especially for logistics company that have vast interests in deploying a platoon of large trailer trucks.

REFERENCES

[1] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, “A survey on platoon-based vehicular cyber-physical systems,” IEEE communications surveys & tutorials, vol. 18, no. 1, pp. 263–284, 2015.

[2] R. Hall and C. Chin, “Vehicle sorting for platoon formation: Impacts on highway entry and throughput,” Transportation Research Part C: Emerging Technologies, vol. 13, no. 5-6, pp. 405–420, 2005.

[3] S. Dadras, R. M. Gerdes, and R. Sharma, “Vehicular platooning in an adversarial environment,” in Proceedings of the 10th ACM Symposium on Information, Computer and Communications Security. ACM, 2015, pp. 167–178.

[4] S. E. Shladover, “Path at 20history and major milestones,” IEEE Transactions on intelligent transportation systems, vol. 8, no. 4, pp. 584–592, 2007.

[5] E. Coelingh and S. Solym, “All aboard the robotic road train,” IEEE Spectrum, vol. 49, no. 11, pp. 34–39, 2012.

[6] B. Van Arem, C. J. Van Driel, and R. Visser, “The impact of cooperative adaptive cruise control on traffic-flow characteristics,” IEEE Transactions on intelligent transportation systems, vol. 7, no. 4, pp. 429–436, 2006.

[7] R. Rajamani, H.-S. Tan, B. K. Law, and W.-B. Zhang, “Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons,” IEEE Transactions on Control Systems Technology, vol. 8, no. 4, pp. 695–708, 2000.

[8] J. Ploeg, B. T. Scheepers, E. Van Nunen, N. Van de Wouw, and H. Nijmeijer, “Design and experimental evaluation of cooperative adaptive cruise control,” in 2011 IEEE International Conference on Intelligent Transportation Systems (ITSC). IEEE, 2011, pp. 260–265.

[9] M. Di Bernardo, A. Salvi, and S. Santini, “Distributed consensus strategy for platooning of vehicles in the presence of time-varying heterogeneous communication delays,” IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 1, pp. 102–112, 2014.

[10] S. Santini, A. Salvi, A. S. Valente, A. Pescap`e, M. Segata, and R. L. Cigno, “A consensus-based approach for platooning with inter-vehicular communications,” in 2015 IEEE Conference on Computer Communications (INFOCOM). IEEE, 2015, pp. 1158–1166.

[11] V. Vukadinovic, K. Bakowski, P. Marsch, I. D. Garcia, H. Xu, M. Sybys, P. Sroka, K. Wesolowski, D. Lister, and I. Thibault, “3gpp c-v2x and ieee 802.11 p for vehicle-to-vehicle communications in highway platooning scenarios,” Ad Hoc Networks, vol. 74, pp. 17–29, 2018.

[12] “3gpp,” TS 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2 (v14.3.0, Release 14), tech. Rep., Jun, 2017.

[13] C. Sommer, D. Eckhoff, A. Brummer, D. S. Buse, F. Hagenaue, S. Joerer, and M. Segata, “Vehins: The open source vehicular network simulation framework,” in Recent Advances in Network Simulation. Springer, 2019, pp. 215–252.

[14] M. Behrisch, L. Bieler, J. Erdmann, and D. Krajzewicz, “Sumo—simulation of urban mobility: an overview,” in Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind, 2011.

[15] R. Rajamani, Vehicle dynamics and control. Springer Science & Business Media, 2011.

[16] C. Bergenhem, Q. Huang, A. Benmiloun, and T. Robinson, “Challenges of platooning on public motorways,” in 17th world congress on intelligent transport systems, 2010, pp. 1–12.

[17] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. L. Cigno, “Plexa: A platooning extension for veins,” in 2014 IEEE Vehicular Networking Conference (VNC). IEEE, 2014, pp. 53–60.

[18] G. Naik, B. Choudhury, and J.-M. Park, “Ieee 802.11 bd & 5g nr v2x: Evolution of radio access technologies for v2x communications,” IEEE Access, 2019.