A Decentralized Network with Fast and Lightweight Autonomous Channel Selection in Vehicle Platoons for Collision Avoidance

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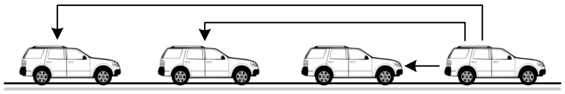
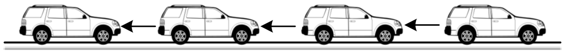
***Abstract*—Always keeping a certain distance between vehicles in a platoon is important for collision avoidance. Centralized platoon systems let the leader vehicle determine and notify the velocities of all the vehicles in the platoon. Unfortunately, such a centralized method generates high packet drop rate and communication delay due to the leader vehicle's limited communication capability. Therefore, we propose a decentralized platoon network, in which each vehicle determines its own velocity by only communicating with the vehicles in a short range. However, the multiple simultaneous transmissions between different pairs of vehicles may interfere with each other. Directly applying current channel allocation methods for interference avoidance leads to high communication cost and delay in vehicle joins and departures (i.e., vehicle dynamics). As a result, a challenge is *how to reduce the communication delay and cost for channel allocation in decentralized platoon networks?* To handle this challenge, by leveraging a typical feature of a platoon, we devise a channel allocation algorithm, called the Fast and Lightweight Autonomous channel selection algorithm (FLA), in which each vehicle determines its own channel simply based on its distance to the leader vehicle. We conduct experiments on NS-3 and Matlab to evaluate the performance of our proposed methods. The experimental results demonstrate the superior performance of our decentralized platoon network over the previous centralized platoon networks and of FLA over previous channel allocation methods in platoons.**

1. Introduction

Vehicle platoon systems, as a type of next-generation of land transportation systems, have received much attention during recent few years. In a platoon, one leader vehicle and several follower vehicles drive in a single lane, where each vehicle maintains a distance from its preceding vehicle. Since the platoon system allows for a shorter distance between vehicles, it provides higher traffic throughput and better traffic flow control [1], [2]. In addition, it helps to reduce energy consumption by avoiding unnecessary changes of acceleration. However, the shorter distance between vehicles leaves less time for each vehicle to react when its preceding vehicle decreases speed, which may cause collisions and impair vehicle safety. Therefore, it is critical to build a well-connected communication network for a platoon so that vehicles can quickly adjust their velocities through fast communication.



(a) Centralized platoon network



(b) Decentralized platoon network

Figure 1. Centralized vs. Decentralized platoon networks.

Several centralized platoon systems [3]–[6] have been proposed, where the leader vehicle is exclusively responsible for maintaining the entire platoon. That is, the leader vehicle determines the velocities and the trajectories for all follower vehicles and notifies them by direct communication. Also, most of these systems use static formation and do not allow vehicle joins or departures during run time. Fig. 1(a) shows a centralized platoon system, where the leader vehicle sends the information to three follower vehicles directly. It means that the leader vehicle plays a critical role and it must be capable of communicating with all vehicles. Usually, the leader vehicle is equipped with a special communication device, e.g., the DSRC (Dedicated Short Range Communication) based wireless device, to communicate with other vehicles. The limited communication range of such devices (i.e., 300-500 meters [7]) constrains the active platoon length (i.e., the number of vehicles in the platoon). For example, in a centralized platoon system, when the speed limit is 20 meters/second and the safety distance between vehicles is 35 meters according to the traffic policy [8], then the platoon can only support $\lfloor 300/35 \rfloor - \lfloor 500/35 \rfloor = 8-14$ vehicles. Moreover, during the running time, a higher velocity increase requires longer inter-vehicle distance for collision avoidance but leads to fewer vehicles that can be connected with the leader vehicle. In addition, the long distance between the leader vehicle and other follower vehicles significantly increases the packet drop rate in communication due to signal's propagation losses [9] and multipath fading effect [10], especially in the urban transportation environment. Furthermore, to avoid contentions between follower vehicles, the communication procedures between the leader and follower vehicles are scheduled separately, which lead to high packet delay in the network. Hence, due to high packet drop rate and delay in communication network, the vehicles' safety cannot be guaranteed in the centralized platoon networks. In current centralized platoon systems, IEEE Wireless Access in Vehicular Environment (WAVE) is based on DSRC technology and it defines the architecture and services for multi-channel DSRC/WAVE devices. WAVE combines IEEE 802.11p and IEEE 1609 protocol suite, covering from physical layer to application layer. On the physical layer, DSRC is operated at 5.9GHz band and there are seven channels for control and service operations. On the MAC layer, DSRC extends the basic service set with the Enhanced Distributed Channel Access (EDCA) mechanism for classifying different data flow into different access categories. To deal with the hidden terminal problem, IEEE 802.11p utilizes the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, the signal overhead on the control channel due to the handshaking procedures could penalize the safety-critical messages, especially in platoon systems and which may show poor performance with heavy packet loss and average delay in coarse traffic scenario [11]. Besides, CSMA/CA may exhibit exposed terminal problem for vehicles inside platoon. Moreover, DSRC is pushed to the limit if different application scenarios (e.g., information and warning function, longitude control, safety, cooperative assistance, etc) which create contradictory constraints under heavy traffic condition. To overcome such drawbacks of the centralized platoon networks, we propose a decentralized platoon network with the objective to *guarantee individual vehicle safety and increase the number of vehicles in a platoon*. We consider that each vehicle is equipped with a mobile communication device capable of communicating within a short distance (e.g., IEEE 802.11a/b enabled mobile device which covers 70m-80m [12]). In our proposed decentralized platoon network, each vehicle is only required to communicate with its neighbor vehicles and there is no explicit centralized control. Also, all vehicles are independent and can join in or leave from the platoon any time. As shown in Fig. 1(b), each vehicle periodically transmits a message composed of its own velocity and location to the next vehicle in the platoon, and each vehicle calculates its own velocity based on its current velocity and received information from its preceding vehicle. As the leader vehicle does not need to communicate with all the vehicles, the platoon length is no longer limited by the leader vehicle's communication capability. Besides, the decentralized network has much lower packet drop rate since each vehicle only needs to communicate with the vehicles in a short range. Furthermore, different from the centralized platoon networks, the decentralized network allows multiple transmissions to be active simultaneously, which reduces the packet delay. Therefore, the decentralized network is more effective for collision avoidance.

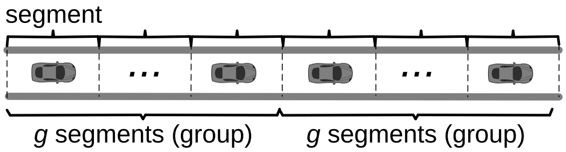


Figure 2. Partition of a platoon.

However, the decentralized platoon network brings about the transmission interference problem. Different from the centralized systems, where only one transmission (between the leader vehicle and any other follower vehicle) is allowed in a single time slot, the decentralized platoon network allows multiple transmissions to be active simultaneously. The multiple simultaneous transmissions between different vehicle pairs may interfere with each other. To avoid interference, we need *channel allocation* to schedule different channels to vehicles. Using the previous channel allocation algorithms [13]–[18], to select a channel to use, a vehicle must estimate the sum interference from all other vehicles, which requires the knowledge of their locations. Then, if some vehicles' locations in the platoon are changed when a vehicle enters or leaves the platoon [19], they must send messages to all other vehicles to update their locations, which generates high communication cost. Since vehicles in platoon may change their locations [19], directly employing the previous channel allocation algorithm to the platoon network would lead to much higher communication cost and longer transmission delay. Considering the poor channel capacity for the vehicle to vehicle (V2V) communication [14], a challenge is *how to conduct channel allocation with low delay and low communication cost in a decentralized platoon network?*

In this paper, we aim to resolve the channel interference problem arisen in the decentralized platoon network. To handle this problem, we propose a Fast and Lightweight Autonomous channel allocation algorithm (FLA) that takes advantage of a typical feature of the platoon. Different from general wireless networks, where the nodes are arbitrarily distributed, in the platoon, vehicles drive in a single lane and the distance between neighboring vehicles is equal to the safety distance [8]. Based on this feature, to avoid interference, we let vehicles use the same channel only when their distance is beyond the interference range and let vehicles within the interference range use different channels. *Interference range* is the distance range that makes the interference upper bounded by an acceptable value for packet decoding. Specifically, as shown in Fig. 2, we geometrically partition the platoon into segments of the same length δ such that each segment contains at most one vehicle and the length of a segment is lower bounded by the interference range. Then, we consider every g consecutive segments as a group of vehicles and allocate g different channels to the segments in each group of vehicles. Here, g is the current minimum number of channels needed to avoid the interference. The aforementioned platoon feature also enables a vehicle to locate its segment position in a group and then autonomously decide its channel accordingly. As a result, the vehicles using the same channel have a distance equals to the interference range in between. Finally, we evaluate our decentralized platoon network through simulation in both Matlab [20] and Network Simulator 3 (NS-3) [21]. The simulation results demonstrate the superior performance of our decentralized platoon network over the traditional centralized platoon network in both aspects of packet drop rate and platoon size. The simulation results also show the efficiency of our channel allocation method compared to the previous methods [16], [22]. The rest of this paper is organized as follows. Section 2 presents the aforementioned channel interference problem in detail. Section 3 presents our methods to solve the previously mentioned problem and Section 4 evaluates the performance our methods. Section 5 presents the related work. Section 6 concludes this paper with our remarks on the future work.

2. Problem Statement

In this section, we first discuss the channel allocation problem in wireless communication network. Then, we introduce the channel allocation problem in vehicular platoon network.

2.1. Background

We consider a platoon with n communication links among vehicles: $(s_1, r_1), ..., (s_n, r_n)$, where (s_i, r_i) represents a transmission link from vehicle sender s_i to vehicle receiver r_i. Let $\mathcal{S} = \{s_1, ..., s_n\}$ and $\mathcal{R} = \{r_1, ..., r_n\}$ represent the set of vehicle senders and vehicle receivers. Let x_{s_i} and x_{r_i}denote the location of vehicle sender s_i and vehicle receiver r_i, respectively. We calculate the Euclidean distance between s_i and r_j by $d_{s_i,r_j} = |x_{s_i} - x_{r_j}|$, $\forall s_i \in \mathcal{S}$ and $\forall r_j \in \mathcal{R}$. We assume that the mobile devices in vehicles have the same communication range R and any sender, say s_i, can communicate with its receiver r_i iff $d_{s_i,r_i} \leq R$. We use δ to denote the sum of the safety distance and vehicle's general length, called vehicle distance. Here, we assume all vehicles have the same length. That is, if there are m vehicles in the platoon, the platoon length is approximately δm. Accordingly, we require $d_{s_i,r_j} \geq \delta$, $\forall s_i \in \mathcal{S}$ and $\forall r_j \in \mathcal{R}$ for collision avoidance. Table 1 presents the main notations used in this paper. As we indicate in Section 1, the decentralized platoon network can overcome the drawbacks of the centralized platoon network by increasing the platoon length and vehicle safety, but it also brings the interference problem. In the following, we will explain the problem in more detail.

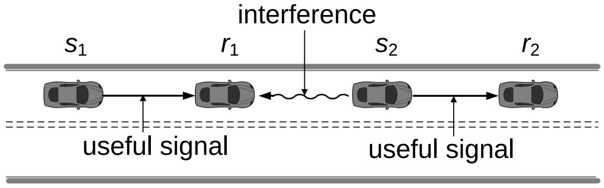


Figure 3. Vehicle signal interference.

In the centralized platoon network, only one transmission is allowed in a single time slot between the leader vehicle and a follower vehicle. The decentralized platoon network allows multiple transmissions between each pair of consecutive vehicles to be active at the same time, which reduces packet drop rate caused by long communication distance and packet transmission delay. However, when multiple vehicles transmit their packets at the same time with the same channel, their signals interfere with each other. As Fig. 3 shows, vehicle s_1 sends a packet to vehicle r_1, and vehicle s_2 sends a packet to vehicle r_2. Because vehicle r_1 is within the communication range of vehicle s_2, vehicle r_1 will be interfered by vehicle s_2, which may corrupt the packet received from vehicle s_1. Therefore, we need to allocate different channels to vehicles within the interference range to overcome interference among multiple transmissions.

TABLE 1. NOTATIONS AND DEFINITIONS.

Symbol	Description
s_i	The vehicle sender i
r_i	The vehicle receiver i
$SINR_{s_i,r_i}$	SINR received by r_i from vehicle s_i
N_0	Noise power received by each vehicle
(s_i, r_i)	The link between s_i and r_i
P	The transmission power
R	The transmission range
n	The number of links
δ	The sum of the safety distance and vehicle's general length
$\mathcal{S}$	The set of senders
$\mathcal{R}$	The set of receivers
$\mathcal{U}(i)$	The set of vehicle senders with the same channel as vehicle sender s_i
α	Path loss exponent
γ_{th}	The decoding threshold
d_{s_i,r_j}	The Euclidean distance between vehicles s_i and r_j
x_{s_i} (x_{r_i})	The location of s_i (r_i)

Since the interference among transmissions is the main factor to be considered for channel allocation, the selection of the interference model is important. In this paper, we select the Signal-to-Interference-plus-Noise Ratio (SINR) model [13], [23] to describe the interference among transmissions, which is more realistic than the traditional graph-based interference model [16], [24]–[26]. The SINR received by receiver r_i from node s_i is defined as:

$$SINR_{s_i,r_i} = \frac{P d_{s_i,r_i}^{-\alpha}}{N_0 + \sum_{s_j \in \mathcal{U}(i) \setminus s_i}^{\infty} P d_{s_j,r_i}^{-\alpha}}, \qquad (1)$$

where $\mathcal{U}(i)$ represents the set of vehicle senders that use the same channel as vehicle sender s_i, P represents the transmission power, N_0 represents the whole noise power, and α represents the path loss exponent, which reflects the reduction of signal power as the signal propagates through space. The SINR model considers the interference received by each vehicle receiver, say r_i, as the sum of all of its received noise (N_0) and undesired transmissions' signals ($\sum_{s_j \in \mathcal{U}(i) \setminus s_i}^{\infty} P d_{s_j,r_i}^{-\alpha}$). r_i can successfully receive the packet from vehicle s_i iff its received SINR is higher than the decoding threshold γ_{th}.

Equ. (1) shows that the SINR received by each receiver r_i is determined not only by the distance between r_i and its sender vehicle s_i (i.e., d_{s_i,r_i}), but also by the distance between vehicle r_i and all other vehicles that share the same channel with vehicle s_i (i.e., d_{s_j,r_i}, $s_j \in \mathcal{U}(i) \setminus s_i$). Therefore, to determine whether a channel can be allocated to s_i, a straightforward channel allocation algorithm [13] is to collect the location information of all other vehicles, estimate their interference to vehicle r_i according to Equ. (1) and see whether the SINR received by vehicle r_i is higher than the decoding threshold γ_{th}. If the SINR is lower than γ_{th}, the transmission will be failed and vehicle s_i cannot use this channel. One the other hand, if the SINR is higher than γ_{th}, then the transmission will be successful and vehicle s_i can use this channel.

If we apply this approach to the platoon network, the leader node needs to function as the central node to calculate the channel allocation and notify all nodes about their allocated channels. However, this approach is impractical to be applied in the platoon network because vehicles in platoon may change their locations in vehicle dynamics, leading to the changes of distances between vehicles. The high computation time complexity of the recalculation of the channel allocation of all nodes leads to a long delay and the notification of allocated channels to all nodes leads to high communication cost and also communication delay.

2.2. Vehicle Channel Allocation Problem

Below, we first formulate the *Vehicle Channel Allocation (VCA) problem*.

Formally, the VCA problem is defined as follows:
Instance: A finite set of senders $\mathcal{S}$ and their respective receivers $\mathcal{R}$ in a geometric plane, decoding threshold γ_{th}, and a constant Λ.
Question: Using Λ channels, whether there exists a schedule (which allocates a channel to each vehicle sender), such that the SINR received by each vehicle receiver is higher than γ_{th}?

3. System Design

In this section, we introduce how to solve the Vehicle Channel Allocation (VCA) problem using a heuristic method in the decentralized platoon network.

As mentioned previously, vehicles may change their locations in the platoon. Such changes also lead to interference to change under the given channel allocation, which requires us to keep re-scheduling channels among vehicles whenever location change happens. Previous SINR based channel allocation methods [13]–[15] require each node to collect the location information of all the vehicles, which leads to high transmission delay, especially when re-scheduling of channels frequently happens. In addition, high computation time complexity of the recalculation of the channel allocation of all nodes leads to high computation delay. To solve the problem, we propose a Fast and Lightweight Autonomous channel allocation algorithm (FLA), where each vehicle autonomously determines its channel for transmission solely based on its distance from the leader vehicle, without the need to collect the location information of other vehicles. The idea of FLA is based on the platoon feature that the distance between vehicles equals the safety distance. Based on this feature, we can conduct the channel allocation to ensure that the distance between vehicles using the same channel is lower bounded by the interference range. Also, each vehicle can autonomously decide which channel it should use solely based on its distance from the leader vehicle, where the distance with the location of the leader vehicle is broadcasted from the leader vehicle. Here, the leader vehicle needs to periodically broadcast its location to the following vehicles. According to this information and its own location, each following vehicle can derive its distance from the leader vehicle. As Fig. 4 shows, we geometrically split the platoon to g segments with length equal to δ so that each segment contains at most one vehicle. Then, we consider every g consecutive segments as a group. Next, we allocate g channels to g segments in each group, and the vehicle in a segment chooses the channel allocated to this segment. As a result, at most one vehicle is contained in each segment and the vehicles sharing the same channel must have distance no less than the interference range, (i.e., $kg\delta$, $k = 1, 2, ...$), which avoids the interference. In the following, we will introduce how to determine g which is the minimum number of channels to avoid interference (Section 3.1) and how each node determines its channel in FLA (Section 3.2) in detail.

3.1. The Minimum Number of Channels

Now, we need to determine g, which denotes the least number of channels used to overcome interference. For any segment l, the distance between segment l and each segment that has the same channel as segment l is $kg\delta$ ($k = 1, 2, ...$). If the distance between two segments is $kg\delta$, then the safety distance between the vehicles in

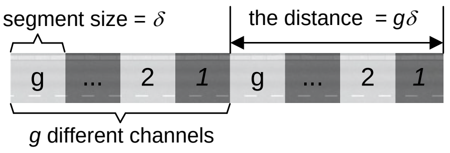


Figure 4. Channel allocation.

the two segments is $kg\delta - \delta$, which implies that the interference generated from the vehicle in one segment to the vehicle in the other segment is at most $P(kg\delta - \delta)^{-\alpha}$. Consequently, the sum interference received by each vehicle is upper bounded by

$$\begin{aligned} \sum_{k=1}^{\infty} P\left(gk\delta - \delta\right)^{-\alpha} &\leq P \sum_{k=1}^{\infty} \left((g-1)k\delta\right)^{-\alpha} \\ &\leq P(g-1)^{-\alpha}\delta^{-\alpha} \sum_{k=1}^{\infty} k^{-\alpha} \\ &= P(g-1)^{-\alpha}\delta^{-\alpha}\zeta(\alpha) \quad (2) \end{aligned}$$

where $\zeta(\alpha) = \sum_{k=1}^{\infty} k^{-\alpha}$. By definition (Equ. (1)), SINR is actually the quotient of the useful signal power to the sum interference. Because the distance between each pair of sender and receiver, say vehicles s_i and r_i, is upper bounded by the communication range R, the useful signal power received at vehicle r_i ($Pd^{-\alpha}_{s_i,r_i}$) is lower bounded by $PR^{-\alpha}$, i.e., $Pd^{-\alpha}_{s_i,r_i} \geq PR^{-\alpha}$. To guarantee that r_i can successfully receive a packet from s_i, we need to ensure that $SINR_{s_i,r_i} \geq \gamma_{\mathrm{th}}$. That is, we need to find a channel for s_i to upper bound the sum interference from the senders with the same channel with s_i by $\frac{PR^{-\alpha}}{\gamma_{\mathrm{th}}}$. Then, according to Equ. (2), we need to ensure

$$P(g-1)^{-\alpha}\delta^{-\alpha}\zeta(\alpha) \leq \frac{PR^{-\alpha}}{\gamma_{\mathrm{th}}} \quad (3)$$

from which we derive that

$$g \geq \lceil \left(R^{\alpha}\delta^{-\alpha}\zeta(\alpha)\gamma_{\mathrm{th}}\right)^{\frac{1}{\alpha}} + 1 \rceil \quad (4)$$

We hope we can use as fewer channels as possible, then:

$$g = \lceil \left(R^{\alpha}\delta^{-\alpha}\zeta(\alpha)\gamma_{\mathrm{th}}\right)^{\frac{1}{\alpha}} + 1 \rceil \quad (5)$$

That is, g can be pre-defined based on the transmission range of vehicles (R), path loss exponent (α), decoding threshold γ_{th}, and segment distance δ.

Theorem 3.1. (Feasibility) By setting the number of channels g by Equ. (5), the SINR received by each receivers is higher than the decoding threshold γ_{th}.

Proof: Without loss of generality, we examine any vehicle receiver r_i of which $(s_i, r_i) \in L_k$. Because $(s_i, r_i) \in L_k$, $2^{k-1}\delta \leq d_{s_i,r_i} < 2^k\delta$, the signal power received at r_i from its desired sender s_i is at least

$$P_{s_i,r_i} \geq \frac{P}{2^{\alpha k}\delta^{\alpha}}. \quad (6)$$

Now we consider the interference caused by the transmission from other requests. Suppose r_i is located in square Seg^k_m, since links are scheduled concurrently iff their receivers reside in the segment with the same color, the interference can only be caused by the links whose receivers are in $\mathrm{Seg}^k_{m\pm 2q}$, where $q \in \mathbb{N}$. We represent the set of links whose receivers are in the two segments by $\mathcal{Q}^k_q$. For any link $(s_j, r_j) \in \mathcal{Q}^k_q$, because the distance between r_i and s_j is at least $(2q(g_k - 1) - 2^k)\delta$, the useful signal on r_i is at most

$$P_{s_i,r_i} \leq \frac{P}{(2q(g_k - 1) - 2^k)^{\alpha}\delta^{\alpha}}. \quad (7)$$

and

$$\sum_{s_j:(s_j,r_j)\in L_k \setminus (s_i,r_i)} P_{s_j,r_i} = \sum_{q=1}^{\infty} \sum_{j:(s_j,r_j)\in \mathcal{Q}^k_q} P_{s_j,r_i}$$

Then,

$$\begin{aligned} SINR_{s_i,r_i} &= \frac{P_{s_i,r_i}}{\sum_{s_j:(s_j,r_j)\in L_k \setminus (s_i,r_i)} P_{s_j,r_i}} \quad (8) \\ &\geq \frac{(g_k - 1)^{\alpha}}{2^{\alpha k+1}\zeta(\alpha)} \geq \gamma_{\mathrm{th}}. \quad (9) \end{aligned}$$

which implies that r_i can successfully receive the packet. □

3.2. Autonomous Channel Determination

In one segment group, as shown in Figure 4, each segment has a segment ID ranging from 1 to g. Vehicles in the segment with ID i choose to use channel i among g channels. Below, we introduce our FLA algorithm in which each vehicle autonomously determines its segment ID and then the channel to use.

Definition 3.1. (Distance offset). The distance offset of a follower vehicle receiver r_i, denoted by Δ_i, is defined as the remainder of its distance from the leader vehicle (r_1) divided by $g\delta$:

$$\Delta_i = d_{r_i,r_1} \mod g\delta \quad (10)$$

Property 3.1. Given the distance offset of a receiver r_i, Δ_i, the segment ID of this vehicle is $\left\lceil \frac{\Delta_i}{g\delta} \right\rceil$.

TABLE 2. THE FLA TABLE.

Δ_i	$[0, \delta)$	$[\delta, 2\delta)$	...	$[(k-1)\delta, k\delta)$
Channel	1	2	...	g

According to Property 3.1, each vehicle's distance offset determines its segment ID, and then determines its channel. Hence, we can build a table (Table 2), namely the *FLA* table, which associates each distance offset with each channel in g channels. A vehicle receives this table from its preceding vehicle after it joins the platoon. This table is kept in each vehicle's storage. Since the partition is static over time, once the table is built, each vehicle does not need to change the FLA table anymore. Using the FLA table, each vehicle only needs to know its distance from the leader vehicle to determine its channel without the need to collect location information of other follower vehicles. To let all the follower vehicles know the leader vehicle's location, the leader vehicle's current location is periodically propagated to all the follower vehicles by piggybacking the location information on the packet periodically sent from a preceding vehicle to its succeeding vehicle. According to the leader vehicle's location, each follower vehicle can calculate its distance from the leader vehicle. To implement FLA, each vehicle only needs to calculate the distance offset based on its current distance from the leader vehicle by Equ. (10). Then, it checks the FLA table by the calculated distance offset and finds the corresponding channel. For example, suppose the safety distance is 30 meters, and the number of channels is $g = 5$. Vehicle i estimates that the distance between the leader vehicle and itself is 195 meters. Using Equ. (10), vehicle i's distance offset equals 195 $\mod (30 \times 5) = 45$ meters. Since $45 \in [30, 60)$, it chooses channel 2 based on the FLA table.

4. Performance Evaluation

In the following subsections, we evaluate the performance of proposed distributed platoon network with several state-of-the art methods. For the simulation study, we use both Network Simulator-3 (NS-3) [21] and MatLab [20]. In the case of channel allocation method, we implemented several methods in Matlab and in the case of platoon networks, we use NS-3 for evaluating the performance of different methods.

For the simulation, we fixed one leader vehicle with other thirty follower vehicles where each vehicle was capable of communicating with its neighbor vehicles within a communication range. We considered the communicator device was IEEE 802.11b enabled and its range was about 80m. Each vehicle was capable to change its velocity from 8m/s to 30m/s (17.89m/h--67.12m/h), independently. In addition, each vehicle maintained safety distance (47.5m–80m) based on the safety policy [8]. Thus, based on the safety distances and communication range of each vehicle, each vehicle was capable of communicating with almost two neighbor vehicles. Here, the communication range of each vehicle is larger than the one times of safety distance but smaller than the two times of safety distance. Besides, each vehicle changed its velocity at every 0.1 second if it was necessary. In the following, we compare our method with previous methods in two aspects explained below.

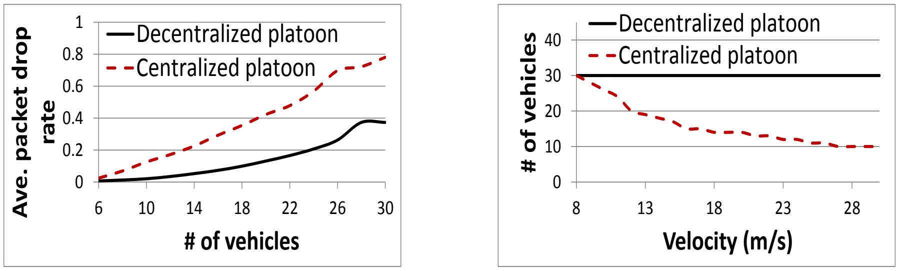
1) *Decentralized platoon network.* We chose an existing centralized vehicle network, called DynB [6], for comparison. In DynB, the leader vehicle continuously sends beacon messages to other vehicles. The leader vehicle requires a special device (802.11p DSCR device) to communicate with all other vehicles, and its transmission range is about 300–500 meters. We used NS-3 for this test.

2) *Channel allocation.* We chose two channel allocation methods, which are based on graph interference model [16] and SINR model [14] for comparison. Both methods require the location information from all nodes. Using the method for the platoon application, when allocating a channel, the method in [14] iteratively picks a sender and removes all the senders that have SINR smaller than the decoding threshold. This process is repeated until each sender is either picked or removed. In [16], for each pair of vehicles, a central node builds an edge between the two vehicles iff they are within each other's transmission range. Then, the central node partitions all the nodes into several subsets, where the vehicles in each subset are not connected by any edge. Finally, the central node allocates a channel to each subset. In this test, we used Matlab to evaluate different methods.

4.1. Decentralized platoon network

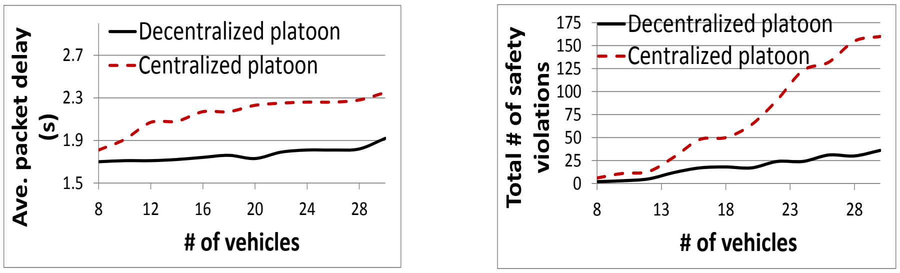
We measured the *average packet drop rate*, which is defined as the ratio of the number of packets dropped to the number of packets sent to all the vehicles in each second. Fig. 5(a) shows the average packet drop rates of the DynB centralized platoon network and our decentralized platoon network when the number of vehicles in the platoon is varied from 6 to 30. As expected, our method has much smaller packet drop rate than that of DynB. When the number of vehicles in Platoon is 30, the packet drop rate of DynB is approximately 0.8, whereas our method's packet drop rate is less than 0.37. It is because that DynB requires the leader vehicle to communicate with all the follower vehicles, in which the message signal will fade significantly over a long distance [13]. While in our method, each vehicle is only required to communicate with its preceding vehicle. A high packet drop rate seriously affects the vehicle safety. Therefore, our decentralized platoon network can support higher vehicle safety.

We also compared the number of vehicles that can be supported by the DynB centralized platoon network and our decentralized platoon network. Here, if a vehicle's packet drop rate (i.e., the ratio of its dropped packets in its sent packets in each second) is lower than 0.3, we consider that this vehicle can be supported by the platoon. Fig. 5(b) compares the number of vehicles that the centralized and decentralized platoon networks can support when the vehicle velocity is varied from 8m/s to 30m/s. We find that as the vehicle velocity increases, the number of vehicles decreases in the centralized platoon network, while it maintains the same level in the decentralized platoon network. It is because that in the centralized platoon network, the transmission range of the leader vehicle is limited but the inter-vehicle safety distance increases as the vehicle velocity increases [8]. Different from the centralized networks, in our decentralized platoon network, each vehicle only needs to send the packets to its succeeding vehicle. Hence, as long as the inter-vehicle distance



(a) Average packet drop

(b) The number of vehicles



(c) Average packet delay

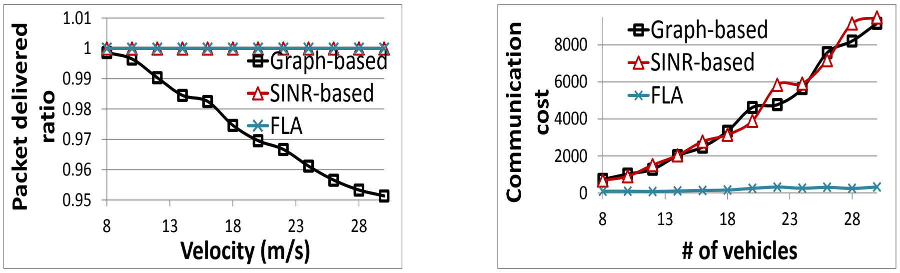
(d) Safety violation

Figure 5. Comparison of the centralized and the decentralized platoon networks.

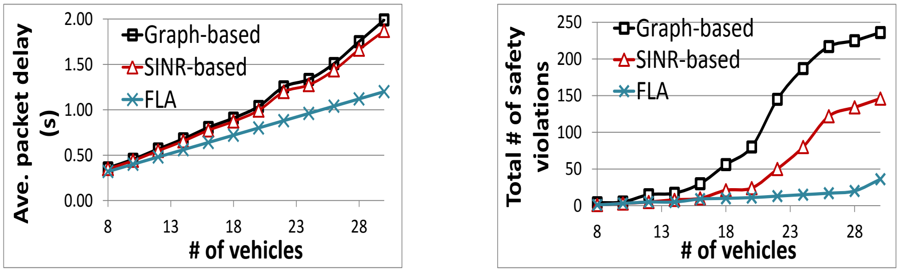
is smaller than the communication range, the platoon is always connected no matter how velocity changes. Consequently, the number of vehicles that platoon can support is not affected by the velocity changes. This result confirms that our decentralized platoon can support more vehicles than the existing centralized platoon networks. Fig. 5(c) compares the average packet delay of the decentralized and centralized platoon networks. We find that the average packet delay of the centralized platoon network is higher than that of the decentralized platoon network. This is because higher packet drop rate (as shown in Fig. 5(a)) generates more retransmissions, which leads to higher packet delay. Finally, we compared the total number of *safety violations* during the whole simulation time for the decentralized and centralized platoon networks in Fig. 5(d). A safety violation happens when there exist two consecutive vehicles in the platoon with the distance smaller than the safety distance. We find that the total number of safety violations of the centralized platoon network is lager than that of the decentralized platoon network. With a higher packet delay, vehicles are more likely to fail to adjust their velocities in time once their neighboring vehicles change their relative locations in the platoon, which causes more safety violations.

4.2. Channel allocation

We define *packet delivery ratio* as the percentage of the packets successfully delivered to their destination vehicles in al the packets sent out during the whole simulation time (i.e, 15 minutes). We define *communication cost* as the total number of packets sent out during the whole simulation time. In both the graph-based and SINR-based methods, the communication cost includes 1) the packets that all the vehicles send to the leader vehicle to inform their initial locations, 2) the packets that the leader vehicle sends to notify each follower vehicle its allocated channels, and 3) the packets that each vehicle sends to the leader vehicle when its location changes. In FLA, the communication cost only refers to the number of packets that the leader vehicle sends to notify each vehicle the leader vehicle's updated location. For each packet, we define the packet delay as the time duration from the packet being sent to the packet being successfully delivered. And then, we calculate the average packet delay of all the packets sent during the simulation. In this test, in every minute, there is one vehicle entering the platoon and one vehicle leaving the platoon. Fig. 6(a),(b),(c), and (d) compare the packet delivery ratio (of each 10 seconds), the communication cost, the average packet delay, and the total number of safety violations of the three channel allocation methods with a different number of vehicles. Comparing the four figures, we find that FLA 1) produces the average packet delivery ratio almost the same as the SINR-based method but higher than the graph-based method, and 2) generates lower communication cost, average packet delay and a smaller number of safety violations than both the graph-based and SINR-based methods. FLA has much lower communication cost because when the relative location of a vehicle in the platoon changes so that its segment changes, the vehicle can change its own channel based on its scored FLA table without communicating with the leader vehicle. However, both graph-based and SINR-based methods require all vehicles to send to the leader vehicle their locations. Also, when a vehicle changes its relative location, it needs to send a notifi-



(a) Packet delivery ratio (b) Communication cost



(c) Average packet delay (d) Safety violation

Figure 6. Comparison of different channel allocation methods.

cation to the leader vehicle. Then, the leader vehicle recalculates the channel allocation and sends the new channel allocation to all the follower vehicles, which significantly increases the communication cost. More packets generate more interference and hence lower packet delivery ratio. Furthermore, when more packets are transmitted, each packet needs to wait longer time before other packets finish, leading to higher packet delay. Vehicles are less likely to adjust their velocities in time with higher packet delay when their neighboring vehicles' relative locations are changed in the platoon, leading to more safety violations. Hence, both graph-based method and SINR based method have higher packet delay more safety violations than our method. As a result, compared to the SINR-based method, FLA has lower communication cost, average packet delay and lager number of safety violations without compromising the packet delivery ratio, while compared to the graph-based method, our method has better performance in all aspects of communication cost, average packet delay, packet delivery ratio, and total number of safety violations.

5. Related Work

Vehicle networks. Several works proposed to improve the performance of vehicle networks by controlling channel congestion [27]–[29] or trying to decrease packet drop rates [30]–[32]. All of these works consider a centralized platoon network, where the leader vehicle can support a limited number of vehicles into the platoon and the number of vehicles inside the platoon is varied due to leader vehicle's limited communication capability and its performance is crucial for vehicle safety purpose. In contrast to the centralized platoon network, proposed decentralized platoon network can support more vehicles with lower packet drop rate and packet transmission delay, which provides better vehicle safety.

Channel allocation. Based on the choice of interference models, the current channel allocation methods can be classified to two groups: graph-based scheduling and SINR-based scheduling. In the graph-based scheduling methods [16], [24]–[26], for each pair of nodes, a central node builds an edge between the two nodes iff they are within each other's transmission range. Then, the central node partitions all the nodes into several subsets, where the nodes in each subset are not connected by any edge. Finally, the central node allocates a channel to each subset. These channel allocation methods are constrained by the limitations of the graph interference model that ultimately abstracts away the accumulative nature of wireless signals. The SINR model offers a more realistic representation of wireless networks. In the SINR-based scheduling method [13], [23], the central node allocates the same channel to the set of nodes such that, for each node, the accumulated interference from all other nodes is small enough for this node to decode packet. However, all these SINR-based scheduling requires the location information of all the senders in the network, which leads to high communication cost and long packet transmission delay if directly applied to the platoon network.

6. Conclusions

Centralized platoon networks cannot provide high vehicle safety or support a large number of vehicles due to the direct communication between the leader vehicle and each follower vehicle and the limited communication capacity of the leader vehicle. To overcome such problems, we proposed a decentralized platoon network where each vehicle only needs to communicate with its two neighbor vehicles. However, the decentralized platoon network brings the interference problem: reducing the signal interference in simultaneous multiple transmissions and maintaining the connectivity of platoons in vehicle dynamics. To handle the interference problem, we designed the Fast and Lightweight Autonomous channel selection algorithm (FLA), in which each vehicle determines its channel only based on its distance from the leader vehicle. Our simulation results show that the decentralized platoon network can scale out well with low packet drop rate, low packet delay, and low safety violation. Also, FLA outperforms the previous channel allocation methods for platoons in terms of packet delivery ratio, packet delay, communication cost, and safety violation. In our future work, we will study different channel allocation models for high-speed decentralized platoon network.

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