Resource Allocation for D2D-Enabled Inter-Vehicle Communications in Multiplatoons

Haixia Peng*†, Dazhou Li‡, Qiang Ye†, Khadige Abboud†,
Hai Zhao*, Weihua Zhuang†, Xuemin (Sherman) Shen†
*School of Information Science and Engineering, Northeastern University, Shenyang, China, 110819
†Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada, N2L 3G1
‡College of Computer Science and Technology, Shenyang University of Chemical Technology, Shenyang, China, 110142
Email: h24peng@uwaterloo.ca, lidazhouzaku@gmail.com, {q6ye, khabboud}@uwaterloo.ca,
zhaoh@mail.neu.edu.cn, {wzhuang, sshen}@uwaterloo.ca

***Abstract*—Platooning has been identified as a promising vehicular traffic management strategy to improve road capacity, energy efficiency, and on-road safety in intelligent transportation systems (ITS). Inter-vehicle communications within a platoon and among multiple platoons can assist platoon control by maintaining a constant inter-vehicle distance, which in turn enhances road safety. An efficient method of sharing inter-vehicle information successfully and timely is critical to many platooning applications. In this paper, a resource allocation (RA) approach is proposed to support inter-vehicle communications underlaying cellular network for a multiplatooning (a chain of platoons) scenario. By applying the evolved multimedia broadcast multicast services (eMBMS) in the Evolved Node B (eNB), the transmission delay for intra-platoon and inter-platoon communications can be reduced. Then, using the proposed subchannel allocation and power control schemes, the number of required subchannels and the transmission powers of each vehicle and the eNB can be minimized. Numerical results show that the proposed approach outperforms the candidate RA scheme in terms of transmission delay, especially in a multiplatooning scenario with a large number of vehicles.**

***Index Terms*—Multiplatooning; Inter-vehicle communication; Subchannel allocation; Power control; D2D communication.**

I. Introduction

Platooning, as a vehicular traffic management strategy, has been identified as a promising framework in intelligent transportation systems (ITS) [1]. Grouping autonomous vehicles on the same lane into a platoon, i.e., keeping each vehicle moving at a constant speed and following one another in a train-like manner with a small constant inter-vehicle spacing ahead [2], [3], can improve the driving safety of autonomous vehicles and reduce traffic congestion, fuel consumption, and exhaust emissions [3]. Instead of one big platoon, a *multiplatoon*, i.e., a chain of platoons that follow one-another, as illustrated in Fig. 1, is considered when the number of vehicles on the road is large [4]. In a multiplatoon, each platoon is led by a leader vehicle. With the help of leader vehicles, lower management complexity and higher traffic flow are achieved by a multiplatoon than by a single large platoon, especially in a highly dynamic highway scenario [4], [5].

Inspite of the potential benefits, forming and maintaining a multiplatoon, referred to as *platoon control*, is not an easy task and has drawn substantial attention from researches [6]. The most common objectives in platoon control are string stability and driving safety [1], [2], especially when a vehicle moves in or out of a platoon. The string stability refers to the amplification of the spacing error in inter-vehicle distances within a multiplatoon. This amplification occurs as the spacing error propagates towards the tail of each platoon and the end of the multiplatoon [2]. Due to the spacing error propagating among multiple platoons, maintaining the string stability in a multiplatoon becomes more challenging and significant. One promising solution is to enable communications among vehicles to assist platoon control based on the inter-vehicle information sharing [1], [2], [7]. It has been shown that the string stability of the multiplatoon can be guaranteed with a constant spacing policy [2], which is widely used in vehicular platoon control [7]. However, inter-vehicle communications are required for constant spacing policy, where the lead vehicle and each member vehicle need to share their velocity and acceleration information to all the vehicles in the platoon and to its following vehicle, respectively. Additionally, from [1], sharing each vehicle's braking information to the following vehicles in the multiplatoon can enhance on-road safety. When a vehicle leaves or enters a platoon, sending an alerting message to its following vehicles in the multiplatoon can allow simultaneous reactions, and thus enhance platoon control and on-road safety. An efficient method on inter-vehicle communications for sharing information, including vehicle's velocity, acceleration, braking, and/or leaving information, successfully and timely is critical to multiplatoons.

One potential technology that can enable inter-vehicle communications is cellular network, which can provide high data rate and low latency to vehicular users [8], [9]. Recently, much attention has been paid to the applicability of Long Term Evolution (LTE) to support communications in vehicular environments. The 3rd generation partnership project (3GPP) group has established a new working item to study the feasibility of LTE supporting inter-vehicle communications [10]. Different from general vehicular application scenarios, local information, such as velocity and acceleration, and global information, such as braking or leaving platoon, are simultaneously needed in the multiplatoon [1], [2]. Relaying by the eNB is better for reducing transmission delay of global inter-vehicle information exchange while it may also increase the transmission delay of local inter-vehicle information. On the other hand, a higher vehicle density is allowed in the multiplatooning scenario, resulting in a larger number of communication links, and therefore, more cellular resource is needed if each vehicle communicates with the eNB. Considering the rapid growth of mobile data traffic and the limited resources in cellular networks, device-to-device (D2D) communications have been extended to support vehicular communications [11]. With D2D communications, vehicles can communicate directly with each other over the D2D links while remaining controlled by the eNB [12], [13]. In [14], a resource allocation (RA) approach has been proposed by applying D2D-unicast communications underlaying cellular system to support inter-vehicle communications. However, only consecutive vehicles can communicate with each other in [14], which results in a higher transmission delay for sharing inter-vehicle information among multiple platoons.

In this paper, we study how to efficiently apply cellular network services to share inter-vehicle information in the multiplatooning scenario. Combining evolved multimedia broadcast multicast services (eMBMS) and D2D communication technologies, the communication models for inter-vehicle information sharing are proposed to reduce the number of communication hops. Then, a resource allocation approach, including subchannel allocation and power control, is proposed to reduce the number of required subchannels and minimize the transmission power of each vehicle. Numerical results show that, the proposed resource allocation approach achieves a shorter transmission delay, especially in the multiplatooning scenario with a large number of vehicles, compared with the existing resource allocation approach in [14].

The remainder of this paper is organized as follows. Firstly, the multiplatooning scenario and communication models are described in Section II. Then, Section III presents the resource allocation scheme, including subchannel allocation and power control schemes. Section IV is devoted to numerical results of the proposed resource allocation scheme. Finally, in Section V, we conclude this work and highlight our future research.

II. System Model

In this section, the multiplatooning scenario is described first, then we present the proposed communication models.

A. Multiplatooning

Consider a multiplatoon located within the coverage area of the eNB, as illustrated in Fig. 1. The length of the highway segment within the coverage area of the eNB is $2D_a$. The middle point of this highway segment, denoted by O, is the origin of the three-dimensional coordinates. The eNB, with the communication range of R, is located at the vertical center line of the highway segment. The distance between the eNB and the highway segment is D_o; and the height of the eNB is D_e. Assume the transceiver of the eNB is located on its top point, *point A*, which can be described as $(0, D_o, D_e)$. As shown in Fig. 1, the multiplatoon under consideration is a chain of n connected platoons, traveling on the same lane in a straight multi-lane highway. The n platoons are labeled with platoon IDs $P^{(1)}, P^{(2)}, \cdots, P^{(n-1)}, P^{(n)}$. Define platoon size, m, as the number of vehicles in one platoon.

A vehicle in the multiplatoon under consideration can be one of two types: a leader vehicle or a member vehicle. A *leader vehicle* is the first one in a platoon that leads its member vehicles. Denote $V_i^{(j)}$ as the ith vehicle in the platoon, $P^{(j)}$, and $V_1^{(j)}$ is the leader vehicle, where $1 \leq j \leq n$. The position of $V_i^{(j)}$ is described as $(x_i^{(j)}, 0, 0)$, then in the highway segment under consideration, $-D_a \leq x_i^{(j)} \leq D_a$. Define the intra-platoon space D_v as the distance between two consecutive vehicles in a platoon, i.e., the distance between the middle points of one vehicle and its preceding vehicle; D_p is denoted as the inter-platoon space, i.e., the distance between the middle points of the first vehicle in a platoon and the last vehicle in the preceding platoon, e.g., the distance between vehicles $V_1^{(j+1)}$ and $V_m^{(j)}$. Note that, the position of one vehicle is same as the position of its transceiver, which is located on its middle point. Vehicles within platoons follow a specified driving strategy [5]. We call the vehicles not belonging to any platoon as *free vehicles*, which are regarded as candidates for the multiplatoon. All of the vehicles in the multiplatoon are assumed to be identical autonomous vehicles.

B. Communication Model

Information shared among vehicles in a multiplatoon can be one of two types: velocity and acceleration (VaA) information, and braking and leaving (BaL) information. To reduce the transmission delay of each vehicle's BaL information and leader vehicles' VaA information, we assume the eMBMS technology is applied in the eNB [15] for relaying information, as shown in Fig. 2(a). Then, member vehicles can get the multicast information from the eNB directly, including the VaA information of the leader vehicle and the BaL information of the vehicles in other platoons. Fig. 2(b) illustrates the communication model within platoon $P^{(j)}$ for sharing each member vehicle's VaA information to its following vehicle (the blue solid arrows) and for sharing member vehicle's BaL information to the leader vehicle (dashed arrows). In Fig. 2(b), vehicle k is the boundary vehicle in one platoon indicating the boundary between the vehicles communicating with the leader vehicle in multi-hops and the vehicles communicating with the leader vehicle directly.

Considering the limited spectrum resources and potential traffic overload issue in current cellular networks, we assume the wireless communication links established among vehicles used for sharing the above two types of information share a subchannel set, $\mathcal{F} = \{1, 2, ..., F\}$ with $|\mathcal{F}|$ orthogonal subchannels, where $|\cdot|$ denotes the cardinality of a set. The F subchannels are assigned to the above communication links by the eNB using a standard packet scheduling procedure [16]. To find a way to allocate the limited F subchannels to the above communication links and simultaneously to guarantee the delay performance for multiplatooning communications,

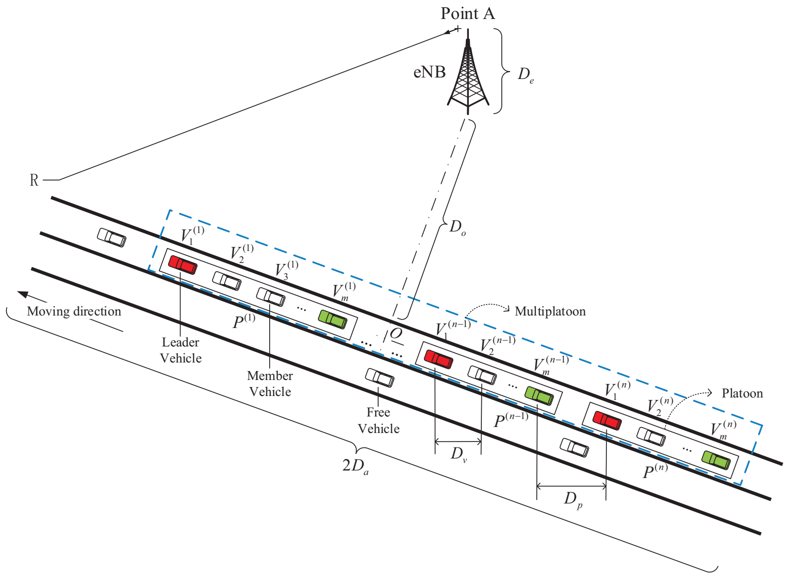
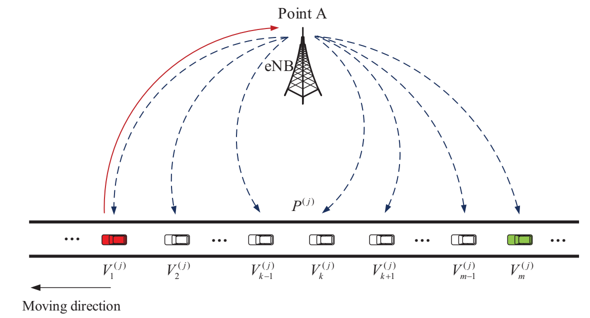
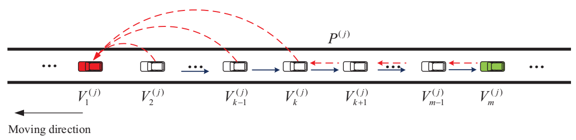


Figure 1: Illustration of a multiplatoon on one of the highway lanes



(a) Communication model for the eNB and leader vehicle in platoon $P^{(j)}$



(b) For member vehicles in platoon $P^{(j)}$

Figure 2: Illustration of communication models in platoon $P^{(j)}$

subchannel allocation and power control schemes will be both studied in Section III.

III. Resource Allocation

From Section II, the transmission delay of member vehicle's VaA information is the delay of one D2D link and the delay of leader vehicles' VaA information is two hop delay. For vehicle's BaL information, the transmission delay is proportional to the number of the communication hops from the source to the destination with a given transmission rate on each communication link. To guarantee the transmission delay of vehicle's BaL information, it is critical to reduce the number of transmission hops for vehicle's BaL information and minimize the transmission power while guaranteeing the signal power and signal-to-interference-and-noise-ratio (SINR) [17] at each receiver.

From Fig. 2(b), among vehicles within one platoon, the number of transmission hops of V_m's BaL information, which depends on the position of the boundary vehicle V_k, is the biggest one. Thus, we restrict k to the second half of the $m-1$ member vehicles in each platoon, i.e., $\lceil \frac{m+2}{2} \rceil \leq k \leq m$, and combine subchannel allocation and power control schemes to achieve the above two objectives.

A. Subchannel Allocation

1) Subchannel allocation for leader vehicles: Similar to [18], full-duplex (FD) communications are applied in each node (vehicles and the eNB) to enable simultaneously multiple transmissions and/or receptions over the same or different subchannels. Denote $l_{g,w}^{(j)}$ as the communication link from $V_g^{(j)}$ to $V_w^{(j)}$, $l_{1,e}^{(j)}$ as the communication link from $V_1^{(j)}$ to eNB, $l_{e,i}^{(j)}$ as the communication link from eNB to $V_i^{(j)}$, where $1 \leq j \leq n$ and $1 < g, w, i \leq m$. As shown in Fig. 2(a), assume the leader vehicle $V_1^{(j)}$ uses one subchannel to communicate with the eNB through $l_{1,e}^{(j)}$, and the eNB multicasts the information to $V_i^{(j)}$ in another subchannel through $l_{e,i}^{(j)}$ $(1 \leq i \leq m)$. Due to the long distance between $V_i^{(j)}$ and the eNB, the subchannel occupied by $l_{1,e}^{(j)}$ and $l_{e,i}^{(j)}$ can not be reused by any other links. Thus, $2n$ subchannels are needed for the n leader vehicles in a multiplatoon with n platoons.

2) Subchannel allocation for member vehicles: The communication links among member vehicles and leader vehicles are called as intra-platoon communication links. There are $n \times (2m-3)$ intra-platoon communication links in the multiplatoon under consideration. Assume F_1 subchannels are shared by these links. Due to the inter-platoon space, D_p, there is at least D_p spatial separation between intra-platoon communication links in one platoon and in another platoon. Thus, the subchannel allocated to the intra-platoon communication link in one platoon can be reused in other platoons. The two following schemes are designed for allocating these F_1 subchannels among the $2m-3$ intra-platoon communication links in one platoon and in the multiplatoon. They aim to reduce the number of required subchannels, F_1.

Self-interference experienced at a vehicle can be sufficiently suppressed by applying existing self-interference cancellation methods, such as the distributed linear convolutional space-time coding scheme proposed in [19]. However, co-channel interference depends on the transmission power of and distance to the interfering source. Therefore, the following scheme is designed to reduce co-channel interference experienced at a receiver by carefully arranging the transmission of interfering sources.

Scheme 1: Denote the subchannel that is allocated to $l_{g,w}^{(j)}$ $(1 \le g, w \le m,\ 1 \le j \le n)$ as $f_{g,w}^{(j)}$. For the intra-platoon communication links in platoon $P^{(j)}$, there is

$$f_{i-1,i}^{(j)} = \begin{cases} f_{i,1}^{(j)}, & \text{if } 2 < i \le k \\ f_{i,i-1}^{(j)}, & \text{if } k < i \le m. \end{cases} \tag{1}$$

Based on scheme 1, the subchannel allocation results for intra-platoon communication links in platoon $P^{(j+1)}$, $f_{g,w}^{(j+1)}$ $(1 \le g, w \le m)$, can be obtained. In order to improve the power efficiency of vehicles in the considered multiplatoon, scheme 2 is designed.

Scheme 2: Subchannel $f_{g,w}^{(j+1)}$ $(1 \le g, w \le m)$ can be allocated to the intra-platoon communication links in platoon $P^{(j)}$ according to

$$f_{2,1}^{(j)} = f_{k-1,k}^{(j+1)} \tag{2}$$

and

$$f_{i-1,i}^{(j)} = \begin{cases} f_{(k+2)-i,1}^{(j+1)}, & \text{if } 2 < i \le 2k-m \\ f_{i+(m-k),i+(m-k)-1}^{(j+1)}, & \text{if } 2k-m < i \le k \\ f_{(m+2)-i,1}^{(j+1)}, & \text{if } k < i \le m. \end{cases} \tag{3}$$

Note that, the communication links from the leader vehicle to member vehicles are already considered in the subchannel allocation for leader vehicles, thus, $f_{1,2}^{(j)}$ is not considered in this scheme.

For the transmission in $l_{g,w}$ in a random platoon, denote both p_0 and p_1 as the transmission powers of vehicle g to guarantee the received SINR at vehicle w over λ, in presence of background additive white Gaussian noise (AWGN) σ only and in presence of background AWGN σ and interference I_1 generated by other co-channel transmission. Then the following theorem, the proof of which is omitted here, demonstrates the property of Scheme 2.

Theorem 1: The value of $(p_1 - p_0)$ is proportional to the length of this link, $d_{g,w}$, and

$$p_1 - p_0 = \frac{\lambda I_1}{|h_0|^2}(d_{g,w})^{\beta}, \tag{4}$$

where, β is the path-loss exponent over a D2D link between two vehicles, λ is the received SINR threshold.

Theorem 1 indicates that the power efficiency of vehicles can be improved if larger interference experienced at a vehicle, which is the receiver of multiple links, corresponds to the transmission over the shorter link.

B. Power Control

A received signal power threshold, η, is set for each vehicle with the SINR threshold, λ. In order to guarantee the received signal power and the SINR at the receiver over their thresholds while minimizing the transmission power of each vehicle, power control should be performed. Taking vehicles in platoons $P^{(j)}$ and $P^{(j+1)}$ as examples, the power control schemes for the eNB and each vehicle are as follows.

1) Power control for the eNB: When multicasting packets to $V_i^{(j)}$ $(1 \le i \le m)$, the transmission power of the eNB is denoted by $p_e^{(j)}$. Then the received signal power and SINR at vehicle $V_i^{(j)}$ $(1 \le i \le m)$ are given as follows,

$$\mathcal{R}_{e,i}^{(j)} = p_e^{(j)} \cdot |h_0|^2 \cdot (d_{e,i}^{(j)})^{-\alpha}, \tag{5}$$

and

$$\mathcal{S}_{e,i}^{(j)} = \frac{p_e^{(j)} \cdot |h_0|^2 \cdot (d_{e,i}^{(j)})^{-\alpha}}{\sigma}, \tag{6}$$

respectively, where $|h_0|^2 \cdot (d_{e,i}^{(j)})^{-\alpha}$ is the channel gain of the communication link from the eNB to vehicle $V_i^{(j)}$ [14]; $d_{e,i}^{(j)}$ is the distance between point A and $V_i^{(j)}$, which can be given by

$$\begin{aligned} d_{e,i}^{(j)} &= \sqrt{(x_i^{(j)})^2 + (D_o)^2 + (D_e)^2} \\ &= \sqrt{[x_1^{(j)} - (i-1)(C_v + D_v)]^2 + (D_o)^2 + (D_e)^2}, \end{aligned} \tag{7}$$

where $(x_i^{(j)}, 0, 0)$ represents the position of vehicle $V_i^{(j)}$.

Among the m vehicles in platoon $P^{(j)}$, $\max d_{e,i}^{(j)} = d_{e,1}^{(j)}$ when $\frac{1}{2}[mC_v + (m-1)D_v] \le x_1^{(j)} \le D_a$, and $\max d_{e,i}^{(j)} = d_{e,m}^{(j)}$ when $-D_a \le x_1^{(j)} < \frac{1}{2}[mC_v + (m-1)D_v]$. Thus, to guarantee the received signal power and SINR at each vehicle in platoon $P^{(j)}$, the minimum $p_e^{(j)}$ can be expressed as equation (8).

2) Power control for the leader vehicles: In the considered multiplatoon, each leader vehicle needs to unicast packets to the eNB over one subchannel. Denote $p_1^{(j)}$ as the transmission power of $V_1^{(j)}$ when it unicasts packets to the eNB. To guarantee the received signal power and SINR at the eNB, the minimum $p_1^{(j)}$ can be expressed as

$$p_1^{(j)\prime} = \max\left\{ \frac{\eta \left(d_{1,e}^{(j)}\right)^{\alpha}}{|h_0|^2}, \frac{\lambda\sigma \left(d_{1,e}^{(j)}\right)^{\alpha}}{|h_0|^2} \right\}. \tag{9}$$

$$p_e^{(j)\prime} = \begin{cases} \max\{\frac{\eta(d_{e,1}^{(j)})^\alpha}{|h_0|^2}, \frac{\lambda\sigma(d_{e,1}^{(j)})^\alpha}{|h_0|^2}\}, & \text{if } \frac{1}{2}[mC_v + (m-1)D_v] \le x_1^{(j)} \le D_a, \\ \max\{\frac{\eta(d_{e,m}^{(j)})^\alpha}{|h_0|^2}, \frac{\lambda\sigma(d_{e,m}^{(j)})^\alpha}{|h_0|^2}\}, & \text{if } -D_a \le x_1^{(j)} < \frac{1}{2}[mC_v + (m-1)D_v]. \end{cases} \tag{8}$$

3) Power control for the member vehicles: Due to the short distance of the link between two consecutive vehicles, only interference generated by the transmission in $l_{i,1}^{(j)}$ $(1 < i \le k)$ is considered when sharing the F_1 subchannels among the intra-platoon communication links in $P^{(j)}$. In the considered multiplatoon, the value of k impacts the subchannel allocation results among the intra-platoon communication links in platoons $P^{(j)}$ and $P^{(j+1)}$. The interference experienced at $V_1^{(j+1)}$, generated by the transmission in $l_{2k-m,1}^{(j)}$ when $V_{m-k+2}^{(j+1)}$ transmitting packets to $V_1^{(j+1)}$ $(2 \le i \le 2k-m)$, is the largest interference experienced at vehicles in one platoon generated by its preceding platoon. A small k means a small number of member vehicles that communicate with their leader vehicle with multi-hops, and therefore, increasing the transmission delay of these member vehicles' BaL information. However, a small k can reduce the distance between $V_{2k-m}^{(j)}$ and $V_1^{(j+1)}$ which decreases interference experienced at $V_1^{(j+1)}$, and therefore, resulting in low transmission powers of $V_{m-k+2}^{(j+1)}$ and $V_{2k-m}^{(j)}$ to guarantee their receivers' received signal power and SINR thresholds. In order to get an optimal k which minimizes the transmission powers of $V_{m-k+2}^{(j+1)}$ and $V_{2k-m}^{(j)}$ while guaranteeing signal power thresholds at $V_1^{(j+1)}$ and $V_1^{(j)}$ and SINR threshold at $V_1^{(j+1)}$, a power control problem for member vehicles, PCM, is formulated as follows,

$$\min_k \; p_{2k-m}^{(j)} + p_{m-k+2}^{(j+1)}$$

subject to

$$p_{2k-m}^{(j)}|h_0|^2[(2k-m-1)(C_v+D_v)]^{-\beta} \ge \eta, \tag{10a}$$

$$p_{m-k+2}^{(j+1)}|h_0|^2[(m-k+1)(C_v+D_v)]^{-\beta} \ge \eta, \tag{10b}$$

$$\frac{p_{m-k+2}^{(j+1)}|h_0|^2[(m-k+1)(C_v+D_v)]^{-\beta}}{\sigma + p_{2k-m}^{(j)}|h_0|^2[2(m-k)(C_v+D_v)+D_p]^{-\beta}} \ge \lambda, \tag{10c}$$

$$\frac{m+2}{2} \le k \le m, \tag{10d}$$

Through solving PCM, the optimal k, k_{opt}, can be obtained, which minimizes the total transmission power of $V_{m-k+2}^{(j+1)}$ and $V_{2k-m}^{(j)}$.

IV. Numerical Results

In the considered multiplatooning communication scenario, the values of all related parameters are given in Table I.

Table I: Related parameters values

Parameter	Value	Parameter	Value
D_e	50 m	R	500 m
D_o	100 m	D_a	487.34 m
D_v	5 m	C_v	3 m
m	20	D_p	40 m
F	24	n	5
β	4	α	3
η	-100 dBm	h_0	$\mathcal{CN}(0,1)$
$E[L]$	2048 bits	λ	100
W	2 MHz	σ	-110 dBm

Fig. 3 describes the values of $p_{m-k+2}^{(j+1)}$, $p_{2k-m}^{(j)}$, and $p_{m-k+2}^{(j+1)}+p_{2k-m}^{(j)}$ with different k, i.e., the transmission powers of vehicles $V_{m-k+2}^{(j+1)}$ and $V_{2k-m}^{(j)}$, and the sum of them. For vehicle $V_{2k-m}^{(j)}$, since the distance between it and its receiver $V_1^{(j)}$ increases with k, its transmission power $p_{2k-m}^{(j)}$ increases. For $V_{m-k+2}^{(j+1)}$, the value of $p_{m-k+2}^{(j+1)}$ decreases when k increases from 11 to 15 since $d_{m-k+2,1}^{(j+1)} = (m-k+1)D_v$ decreases with k. However, the distance between $V_1^{(j+1)}$ and $V_{2k-m}^{(j)}$ decreases with k, resulting in a larger interference experienced at $V_1^{(j+1)}$, and therefore, the value of $p_{m-k+2}^{(j+1)}$ increases when k increases from 15 to 18. When $18 \le k \le 20$, $p_{m-k+2}^{(j+1)}$ decreases again, which can be explained by theorem 1. Based on $p_{m-k+2}^{(j+1)} + p_{2k-m}^{(j)}$ as shown in Fig. 3, the optimal k equals 14 with platoon size 20.

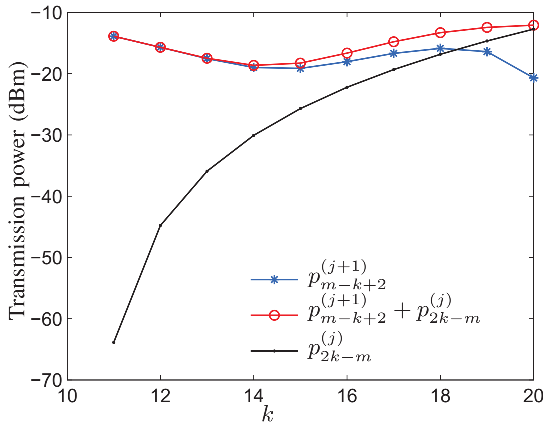


Figure 3: The transmission powers with different k.

We compare the transmission delay of the proposed RA approach with a candidate RA approach proposed in [14], in which only communication links between two adjacent vehicles are considered. For fair comparison, the FD mode is considered at each vehicle when it shares its VaA or BaL information as in [14], links between two adjacent vehicles, i.e., $l_{i,i+1}^{(j)}$ and $l_{i+1,i}^{(j)}$, are allocated one of the m subchannels.

Fig. 4 and Fig. 5 show the effect of the platoon size, m, on the delay for sharing leader vehicle's VaA information and member vehicle's BaL information. The considered transmission delay of member vehicle's BaL information is defined as the delay for sharing the mth member vehicle's BaL information to the mth member vehicle in one of its following platoons. From these two figures, the transmission delay in the proposed approach is always less than that in [14], for the following reasons, (i) for the proposed approach, the applied eMBMS technology maintains the number of transmission hops of leader vehicle's VaA information to be two; and the communication model shown in Fig. 2(b) further reduces the number of communication hops for member vehicle's BaL information; (ii) for the approach in [14], the numbers of transmission hops of both VaA and BaL information are proportional to m. Furthermore, the value of k_{opt} increases with m, resulting in more vehicles that communicate with the leader vehicle with multi-hops, and therefore, the transmission delay of member vehicle's BaL information increases with m in our approach.

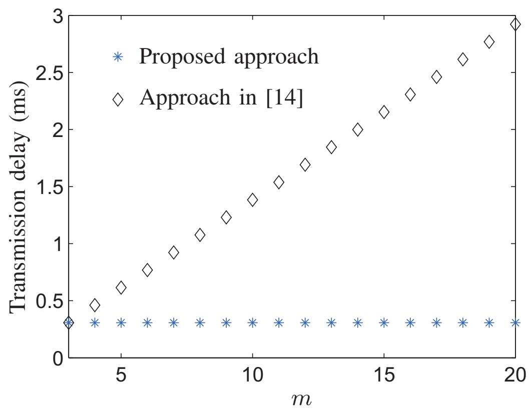


Figure 4: Effect of the platoon size m on the transmission delay of leader vehicle's VaA information.

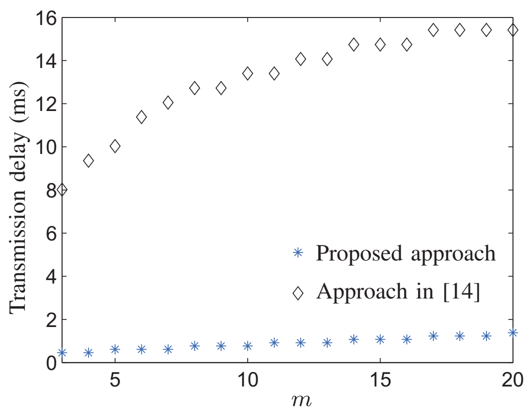


Figure 5: Effect of the platoon size m on the transmission delay of member vehicle's BaL information.

V. CONCLUSIONS

In this paper, we have proposed a RA approach to support inter-vehicle communications underlaying cellular networks for a multiplatooning scenario. Numerical results have demonstrated that the number of transmission hops for sharing vehicle's information can be reduced significantly while minimizing the transmission powers of vehicles. On the other hand, the proposed RA approach outperforms the existing approach, in terms of transmission delay for sharing two types of inver-vehicle information. The proposed approach can be used in a multiplatoon with a large platoon size to improve the road capacity. For our future works, we will investigate the impact of multiplatooning communication delay on the platoon control. Additionally, we will apply other communication technologies to support inter-vehicle communications for multiplatooning scenarios.

REFERENCES

[1] L. Xu, L. Wang, G. Yin, and H. Zhang, "Communication information structures and contents for enhanced safety of highway vehicle platoons," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4206–4220, Nov. 2014.

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

[3] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Commun. Surv. Tutor.*, vol. 18, no. 1, pp. 263–284, Jan. 2016.

[4] P. Fernandes and U. Nunes, "Multiplatooning leaders positioning and cooperative behavior algorithms of communicant automated vehicles for high traffic capacity," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1172–1187, Jun. 2015.

[5] D. Jia, K. Lu, and J. Wang, "A disturbance-adaptive design for VANET-enabled vehicle platoon," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 527–539, Feb. 2014.

[6] G. J. Naus, R. P. Vugts, J. Ploeg, M. Van de Molengraft, and M. Steinbuch, "String-stable CACC design and experimental validation: A frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.

[7] G. Guo and S. Wen, "Communication scheduling and control of a platoon of vehicles in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, pp. 1551–1563, Jun. 2016.

[8] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: a survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 148–157, May 2013.

[9] L. Lei, Y. Kuang, N. Cheng, X. Shen, Z. Zhong, and C. Lin, "Delay-optimal dynamic mode selection and resource allocation in device-to-device communicationsłpart i: Optimal policy," *IEEE Trans. on Veh. Technol.*, vol. 65, pp. 3474–3490, May 2016.

[10] 3GPP, "Study on LTE support for V2X services (release 14)," Technical Specification Group Services and System Aspects, Tech. Rep. 3GPP TR 36.885, 2016.

[11] Z. Su, Y. Hui, and S. Guo, "D2d-based content delivery with parked vehicles in vehicular social networks," *IEEE Wireless Communications*, vol. 23, pp. 90–95, 2016.

[12] D. Feng, L. Lu, Y.-W. Yi, G.-Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541–3551, Aug. 2013.

[13] K. Abboud, H. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, p. 15, to appear.

[14] Y. Ren, F. Liu, Z. Liu, C. Wang, and Y. Ji, "Power control in D2D-based vehicular communication networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5547–5562, Dec. 2015.

[15] 3GPP, "The mobile broadband standard," June 2016. [Online]. Available: http://www.3gpp.org/DynaReport/23246.htm

[16] L. Lei, Z. Zhong, C. Lin, and X. Shen, "Operator controlled device-to-device communications in lte-advanced networks," *IEEE Wireless Commun.*, vol. 19, no. 3, p. 96, Jun. 2012.

[17] D. To, H. X. Nguyen, Q.-T. Vien, and L.-K. Huang, "Power allocation for HARQ-IR systems under qos constraints and limited feedback," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1581–1594, Mar. 2015.

[18] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for full-duplex relaying-based D2D communication underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4911–4916, Oct. 2015.

[19] Y. Liu, X.-G. Xia, and H. Zhang, "Distributed space-time coding for full-duplex asynchronous cooperative communications," *IEEE Trans. Wireless Commun.*, vol. 11, no. 7, pp. 2680–2688, Jul. 2012.