


# Resource Allocation for Cellular-based Inter-Vehicle Communications in Autonomous Multiplatoons

Haixia Peng , *Member, IEEE*, Dazhou Li, Qiang Ye, *Member, IEEE*, Khadige Abboud, Hai Zhao, Weihua Zhuang, *Fellow, IEEE*, and Xuemin Shen, *Fellow, IEEE*

**Abstract**—With the significant population growth in megacities everywhere, traffic congestion is becoming a severe impediment, leading to long travel delays and large economic loss on a global scale. Platooning is a promising intelligent transportation framework that can improve road capacity, on-road safety, and fuel efficiency. Furthermore, enabling inter-vehicle communications within a platoon and among platoons (in a multiplatoon) can potentially enhance platoon control by keeping constant inter-vehicle and inter-platoon distances. However, an efficient resource allocation (RA) approach is required for the timely and successful delivery of inter-vehicle information within multiplatoons. In this paper, subchannel allocation scheme and power control mechanism are proposed for LTE-based inter-vehicle communications in a multiplatooning scenario. We jointly consider the evolved multimedia broadcast multicast services and device-to-device (D2D) multicast communications to enable intra- and inter-platoon communications such that a desired tradeoff between the required cellular resources and the imposed communication delay can be achieved. Simulation results are given to demonstrate that the proposed approaches can reduce the communication delay comparing to D2D-unicast based RA scheme, especially in a multiplatoon scenario with a large number of vehicles.

**Index Terms**—Autonomous vehicle, cellular network, device-to-device (D2D) communication, multiplatooning, resource allocation (RA).

## I. INTRODUCTION

THE fast growing of metropolitan areas has caused an increasing influx of vehicular traffic to and from big cities. As a result, urban roads and highways are plagued by traffic accidents, resulting in serious socio-economic problems. Platooning has been identified as a promising vehicle traffic management

strategy to increase road traffic capacity, improve traffic safety, and reduce fuel consumption and exhaust emissions [1]–[4]. In platooning, autonomous/semi-autonomous vehicles on the same lane are grouped into a *platoon*<sup>1</sup>, such that each vehicle moves at the same speed and maintains a constant small inter-vehicle distance from a head<sup>2</sup>. Recently, the popularization of autonomous vehicles (e.g., the Google’s driveless car [8]) and the mature advanced traffic management system (ATMS) introduce new prospects for platooning. They have motivated the establishment of several projects dedicated to research and development (R&D) in platooning, including both state-funded pilot deployment projects [9], [10] and privately-funded projects by auto-mobile manufacturers [6], [11].

Despite the potential benefits of platooning, controlling the platoon (i.e., controlling the speed and acceleration of the vehicles in the platoon) to maintain a constant speed and inter-vehicle spacing is a very challenging task, especially in highly dynamic highway scenarios [12], [13]. The key of platoon control is to maintain *string stability*, i.e., ensure that the inter-vehicle spacing error does not amplify upstream from vehicle to vehicle within the platoon [14]. The inter-vehicle spacing error amplifies significantly when the number of vehicles increases in the platoon [14], which result in maintaining string stability becomes more challenging and, therefore only small number of vehicles are allowed in a platoon [6]. A *multiplatoon*, i.e., a chain of platoons that follow one-another, is considered when the number of vehicles on the road is large [7], [15]. Each platoon is led by a leader vehicle, enabling a lower management complexity and a higher road traffic capacity [7], [16]. In a multiplatoon, both intra- and inter-platoon control are required. Maintaining the string stability in a multiplatoon becomes more challenging as the inter-vehicle spacing error propagates among vehicles and across platoons. Enabling the prompt exchange of vehicle information within a multiplatoon through wireless communications is a promising approach to assist platoon control in maintaining string stability [2], [6], [17]–[19]. Sharing the leader and preceding vehicles’ velocity and acceleration information is a necessary condition for intra-platoon control [17]. Furthermore, when a vehicle leaves/enters a platoon, sending a message to alert its following vehicles in the multiplatoon can allow

Manuscript received January 8, 2017; revised May 26, 2017; accepted June 30, 2017. Date of publication July 4, 2017; date of current version December 14, 2017. This work was supported in part by the Natural Science and Engineering Research Council (NSERC) of Canada research grants, in part by the Science and Technology Project supported by Liaoning Province (approve number: No.2015401039) in China. This paper was presented in part at the IEEE International Conference on Communications, Paris, France, May 21-25, 2017. The review of this paper was coordinated by Jiajia Liu. (*Corresponding author: Hai Zhao.*)

H. Peng, Q. Ye, K. Abboud, W. Zhuang, and X. (S.) Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: h27peng@uwaterloo.ca; q6ye@uwaterloo.ca; khabboud@uwaterloo.ca; wzhuang@uwaterloo.ca; sshen@uwaterloo.ca).

H. Zhao is with the School of Computer Science and Engineering, Northeastern University, Shenyang 110004, China (e-mail: zhaoh@mail.neu.edu.cn).

D. Li is with the College of Computer Science and Technology, Shenyang University of Chemical Technology, Shenyang 110142, China (e-mail: lidazhouzaku@gmail.com).

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Digital Object Identifier 10.1109/TVT.2017.2723430

<sup>1</sup>The platooning considered here is different from vehicle clustering. The latter is a network management strategy, in which near-by vehicles are grouped into different *clusters* [5].

<sup>2</sup>The inter-vehicle distance in a platoon can be kept at a value much smaller than the suggested safety distance corresponding to the 2-second rule [6], [7].

simultaneous reactions, thus preventing an increase in spacing error and enhancing platoon control [2].

In this paper, we study how to efficiently combine the evolved multimedia broadcast multicast services (eMBMS) and device-to-device (D2D) communications to support multiplatooning of autonomous vehicles. In a multiplatoon, the information required for platoon control includes not only that in a basic safety message, such as velocity and acceleration, but also platoon-specific information, such as join/leave the platoon and platoon membership information. Therefore, multiplatooning communications of platoon-specific information can benefit from wide-range and low-latency multicast/broadcast LTE services. On the other hand, preceding vehicle's velocity and acceleration information is needed only by its following vehicle and can, therefore, be shared via D2D communications. With D2D communications, vehicles communicate directly and effectively with each other over the D2D links while remaining under the control of the Evolved Node B (eNB) [20]–[22]. The transmit power of the D2D link can be adjusted according to the distance between the two vehicles [23], [24]. As a result, the same cellular radio resources (allocated subchannels) can be reused by different D2D links, increasing the spectral efficiency [25]. However, the higher the spatial reuse of the allocated subchannels, the higher the interference among concurrent D2D links. This trade-off calls for a resource allocation (RA) method for efficient multiplatooning communications while minimizing the burden of multiplatoon data traffic on the cellular network, such that it can accommodate the existing data traffic load from its legacy cellular users. Considering the potential data traffic overload in the cellular network and the requirement for communication delay in a multiplatoon scenario [2], we present efficient RA approaches for LTE-based inter-vehicle communications in a multiplatooning scenario, to balance the trade-off between the needed cellular resources and the communication delay. The main contributions of this paper are summarized as follows:

- 1) Using eMBMS and D2D communications, the communication models required for sharing vehicle and platoon information within the multiplatoon are proposed to reduce the number of required transmission hops;
- 2) Leveraging the trade-off between the number of required subchannels and the interference of concurrent D2D links, subchannel allocation scheme is proposed to increase the amount of spatial reuse of cellular radio resources while maintaining low interference;
- 3) Power control scheme is presented to guarantee the transmission rate of each D2D link while minimizing the transmission power of each vehicle.

The rest of this paper is organized as follows. Section II studies the literature of inter-vehicle communications in platoons, and Section III describe the system model. Section IV presents the subchannel allocation scheme for the communication links in the considered multiplatoon. Power control for each vehicle is designed in Section V. Then, the multiplatoon communication performance in terms of transmission rate and communication delay is analyzed in Section VI. Section VII is devoted to simulation results of the proposed subchannel allocation and power control schemes. Finally, in Section VIII, we conclude this work and highlight our future research.

## II. RELATED WORK

To enable inter-vehicle communications in platooning, two potential technologies, i.e., dedicated short range communications (DSRC) and cellular technologies [26], can be utilized. The DSRC technology uses the IEEE 802.11p amendment of the legacy WiFi standard [27]. Due to its low cost, the DSRC technology has been proposed for platoon communications in both academia ([17]–[19], [28]) and industry [6]. For example, an IEEE 802.11p-based model was proposed for multiplatooning scenario in [28], in which intra- and inter-platoon communication models were designed for information sharing within one platoon and among platoons. However, for vehicles that are within different and far platoons, more communication hops are needed when DSRC technology is applied, and therefore, resulting in long communication delay which is against to the requirement for communication delay in a multiplatoon scenario.

Recently, much attention has been paid to the feasibility of utilizing the cellular technology for enabling inter-vehicle communications [29]–[31]. Cellular networks provide an off-the-shelf potential solution for inter-vehicle communications, which can make use of a high capacity, large cell coverage range, and widely deployed infrastructure [26]. Furthermore, there is more appetite from auto-mobile industry to deploy a mature technology, such as cellular networks, which eases the implementation and accelerates the deployment of connected vehicle services in such lucrative and competitive global market [26]. The 3rd generation partnership project (3GPP) group has recently established a new working item specifically to study the feasibility of LTE support for inter-vehicle communications and to investigate enhancements to existing cellular services, e.g., eMBMS and D2D communications, to enable reliable inter-vehicle communications [32]. Furthermore, [2] indicates that cellular technology can be used for sharing information in multiplatooning scenarios. However, [2] focuses on discussing which kinds of communication information structure and content should be shared among vehicles in platooning, and very few works have studied how to utilize cellular technology to enable inter-vehicles communications in multiplatooning.

## III. SYSTEM MODEL

This section describes the multiplatooning scenario, the proposed communication models, and the channel model. The important symbols defined in this work are summarized in Table I.

### A. Multiplatooning

Consider a multiplatoon on one of the highway lanes located within the coverage area of an eNB, as illustrated in Fig. 1. The eNB is positioned with distance  $D_o$  from the middle point of the highway segment, which is defined as the origin of three-dimensional coordinates,  $O$ . The origin point divides the highway segment to two halves, where the length of each half is defined by  $D_a$  (i.e., the length of the highway segment within the coverage area of the eNB is  $2D_a$ ). Let  $R$  denote the communication range of the eNB in meters and  $D_e$  the height of the eNB. Therefore, the position of the top point on the eNB,

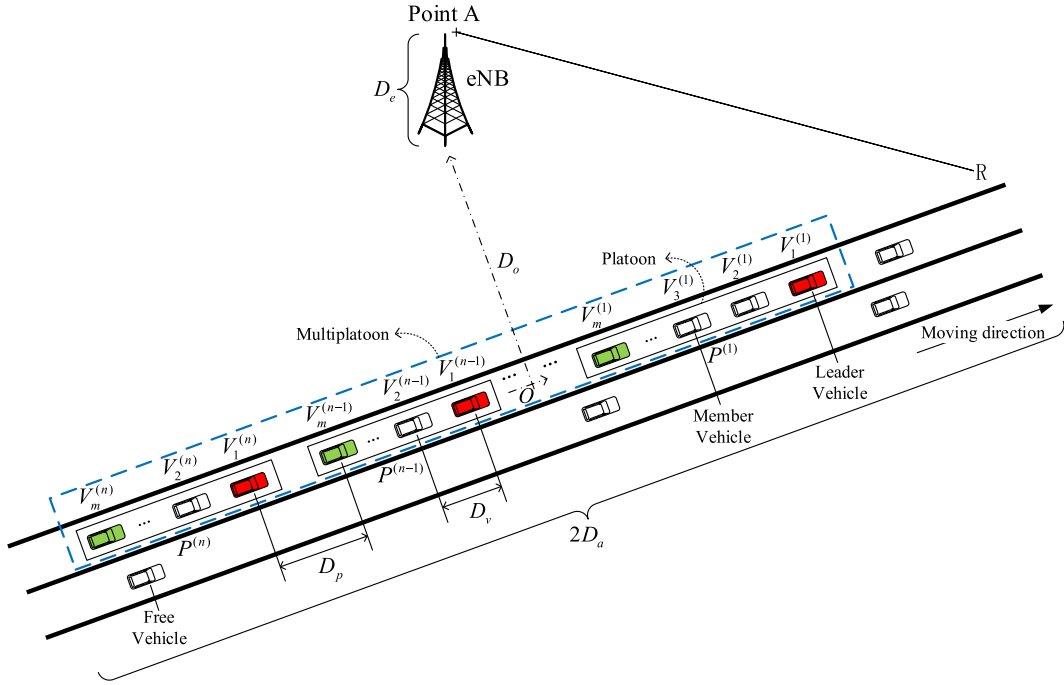


Fig. 1. Illustration of a multiplatoon on one of the highway lanes.

 TABLE I  
 SUMMARY OF IMPORTANT SYMBOLS

Symbol	Description
$2D_a$	The length of the highway segment within the coverage area of the eNB
$D_e$	The height of the eNB
$m$	Platoon size
$n$	The number of platoons in the multiplatoon
$P^{(i)}$	Platoon ID of the $i$ th platoon
$V_i^{(j)}$	Vehicle ID of the $i$ th vehicle in the platoon $P^{(j)}$
$(x_i^{(j)}, 0, 0)$	The position of vehicle $V_i^{(j)}$
$D_v$	Distance headway
$D_p$	Inter-platoon spacing
$V_i^{(j)}$	Boundary vehicle in platoon $P^{(j)}$
$\mathcal{F}^k$	Subchannel set
$\alpha$	Path-loss exponent for links between the eNB and vehicles
$\beta$	Path-loss exponent for D2D links
$\mathcal{H}_{e,i}$	Channel gain for a link between the eNB and vehicle $i$
$\mathcal{H}_{g,w}$	Channel gain for the D2D link between vehicles $g$ and $w$
$h_0$	The complex Rayleigh fading channel coefficient
$l_{g,w}^{(j)}$	Communication link from $V_g^{(j)}$ to $V_w^{(j)}$
$l_{1,e}^{(j)}$	Communication link from $V_1^{(j)}$ to eNB
$f_{g,w}^{(j)}$	The subchannel allocated to link $l_{g,w}^{(j)}$

point A, has the coordinates  $(0, D_o, D_e)$ . The multiplatoon under consideration is composed of  $n$  equal-sized connected platoons, traveling on the same lane in a straight multi-lane highway. Let  $m$  denote the platoon size in terms of the number of vehicles in the platoon. The  $n$  connected platoons in the multiplatoon are labeled with platoon IDs  $P^{(1)}, P^{(2)}, \dots, P^{(n-1)}, P^{(n)}$ , where  $P^{(1)}$  is the leading platoon and  $P^{(n)}$  is the last following platoon. A vehicle in the multiplatoon can be either a leader vehicle or a member vehicle. A *leader vehicle* is the first vehicle in a platoon which is responsible of

- forming and managing the platoon with the help of ATMS, such as controlling the number of vehicles in its platoon;
- collecting information from and transmitting information to its member vehicles;
- relaying information to or from the eNB.

A *member vehicle*, on the other hand, is a non-leader vehicle within the platoon. Vehicles within platoons follow a specified driving strategy [16]. Vehicles not belonging to any platoon are referred to as *free vehicles*, and are regarded as candidates for joining the multiplatoon.

Let  $V_i^{(j)}$  denote the vehicle ID of the  $i$ th vehicle in the platoon  $P^{(j)}$ , for  $1 \leq i \leq m$  and  $1 \leq j \leq n$ . That is,  $V_1^{(j)}$  is the ID of the leader vehicle in platoon  $P^{(j)}$  for  $1 \leq j \leq n$ . Note that, the ATMS has the multiplatoon's membership information, i.e., platoon ID and vehicle ID, collected during the platoon formation period. The position of vehicle  $V_i^{(j)}$  is defined as the middle point on vehicle with coordinates  $(x_i^{(j)}, 0, 0)$ , where  $-D_a \leq x_i^{(j)} \leq D_a$ . All vehicles in the multiplatoon are assumed to be identical autonomous vehicles. Let  $D_v$  be the vehicle's distance headway, which is the distance between the middle points on two consecutive vehicles on the same lane. Let  $D_p$  be the inter-platoon spacing defined as the distance between the middle points on the leader vehicle in a platoon and the last following vehicle in the preceding platoon. We assume that the position of a vehicle is the same as the position of its transceiver, and the eNB's transceiver is located at point A.

### B. Communication Model

In a multiplatoon, vehicles share two types of information: velocity and acceleration (VaA), and braking and leaving (BaL) information.

- a) *VaA information*: When the constant-spacing policy is used [17], VaA information from the leader and member vehicles needs to be shared to guarantee the string stability of each platoon. In a platoon, the leader vehicle shares its VaA information with all member vehicles, and each member vehicle shares its VaA information only with its following vehicle. For example, in platoon  $P^{(j)}$ ,  $V_1^{(j)}$  shares its VaA information with vehicles  $\{V_2^{(j)}, V_3^{(j)}, \dots, V_i^{(j)}, \dots, V_m^{(j)}\}$ , while  $V_i^{(j)}$  shares its VaA information with vehicle  $V_{i+1}^{(j)}$ ,  $\forall 2 \leq i < m$ .
- b) *BaL information*: Platoon control and road safety can be enhanced if a vehicle shares its BaL information with its following vehicles in the multiplatoon [2].

The eNB is utilized to multicast leader vehicle's VaA information within one platoon or relay BaL information among platoons, while only D2D unicast communications are utilized for sharing member vehicle's VaA information. This can be explained as follows:

- a) When only LTE unicast transmissions are utilized, every member vehicle needs to communicate with the eNB directly, thus limiting the spatial reuse of the orthogonal subchannels within a multiplatoon;
- b) For short range communications, such as that required within a platoon, D2D communications can improve the utilization of the cellular radio resources due to spatial reuse within the multiplatoon [33];
- c) The eNB can be utilized to relay information among different platoons, thus reducing the number of required transmission hops for both VaA and BaL information.

We refer to a direct transmission between two nodes (vehicle or eNB) as one-hop transmission. A vehicle shares its BaL information with vehicles in the following platoons by transmitting it to the leader vehicle and the eNB first, which then relay the BaL information to the vehicles in the following platoons. Consider the transmission of BaL information of vehicle  $V_i^{(j)}$  to vehicles in platoon  $P^{(j+1)}$  ( $1 \leq j < n$ ). The transmission includes the following steps:

- a)  $V_i^{(j)}$  transmits its BaL information to  $V_1^{(j)}$  via D2D communications;
- b)  $V_1^{(j)}$  delivers this BaL information to the eNB using LTE unicast communication or D2D multicast communication;
- c) the eNB delivers this BaL information to  $V_{i'}^{(j')}$ ,  $\forall 1 \leq i' \leq m$  and  $j < j' \leq n$ , using eMBMS, or delivers this BaL information to  $V_1^{(j')}$ ,  $\forall j < j' \leq n$ , using LTE-unicast first, which is then relayed by every leader vehicle  $V_1^{(j')}$ ,  $j < j' \leq n$ , to every member vehicle  $V_{i'}^{(j')}$ ,  $\forall 1 < i' \leq m$ , via D2D multicast communications.

In addition to relaying the BaL information to the eNB, a leader vehicle also needs to share its VaA information with all member vehicles in the same platoon. Two communication models are established for the eNB and the leader vehicle to reduce the number of required transmission hops for transmitting the vehicle's VaA and BaL information, as shown in Fig. 2(a) and (b). The first model is an eMBMS based model, where the eMBMS technology is used by the eNB to multicast aggregated

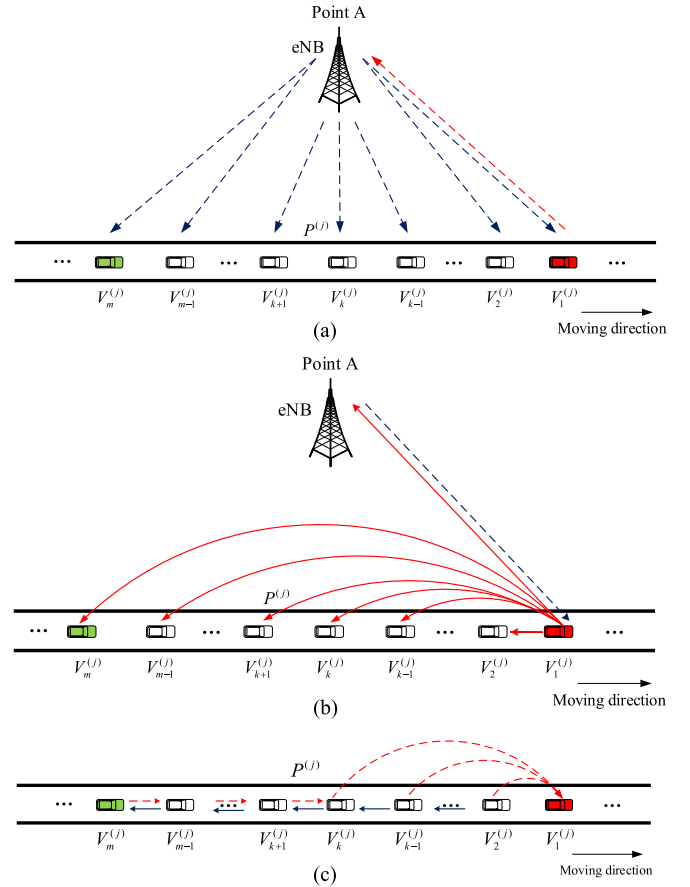


Fig. 2. Illustration of communication models in platoon  $P^{(j)}$ . (a) eMBMS based model for the eNB and leader vehicle in platoon  $P^{(j)}$ . (b) D2D-multicast based model for the eNB and leader vehicle in platoon  $P^{(j)}$ . (c) Communication model for member vehicles in platoon  $P^{(j)}$ .

information to member vehicles as illustrated in Fig. 2(a) [34]. The aggregated information received by member vehicles from the eNB includes VaA information of the leader vehicle and the BaL information of vehicles in other platoons. We assume that the member vehicles have already subscribed to the multicast service during the platoon formation, and do not consider latency and control signaling overhead associated with the join and leave procedures of creating a multicast group in the eMBMS service<sup>3</sup>. The second model is D2D-multicast based model as illustrated in Fig. 2(b). Each leader vehicle shares information with the eNB and its member vehicles via D2D multicast communications. Upon receiving the BaL information of vehicles in other platoons from the eNB, the leader vehicle aggregates the BaL information with its VaA information and multicasts the aggregated information to the member vehicles.

To share the information of a member vehicle, only D2D communication is applied since a member vehicle needs to transmit its VaA and BaL information only to the following vehicle and

<sup>3</sup>Since platoon dynamics are relatively low compared to that of regular vehicle traffic, the platoon membership remains constant for a relatively long time and, hence, the effect of joining/leaving the multicast eMBMS group is neglected [35].

its leader vehicle, respectively. Fig. 2(c) illustrates the proposed communication model within platoon  $P^{(j)}$  for each member vehicle to share its VaA information with the following vehicle (the blue solid arrows) and its BaL information with the leader vehicle (dashed arrows). Within a platoon  $P^{(j)}$ , only member vehicles  $V_2^{(j)}, V_3^{(j)}, \dots, V_k^{(j)}$  communicate directly with the leader vehicle, the rest of member vehicles communicate in a multi-hop fashion. We refer to vehicle  $V_k^{(j)}$  as the platoon's *boundary vehicle* and indicates the boundary between the vehicles communicating with the leader vehicle in multi-hops and the vehicles communicating with the leader vehicle directly. The calculation of the value  $k$  is discussed in details in Section IV.

The wireless communication links established among vehicles share a subchannel set,  $\mathcal{F} = \{1, 2, \dots, F\}$  with  $F = |\mathcal{F}|$  orthogonal subchannels. The  $F$  subchannels are assigned to these communication links by the eNB using a standard packet scheduling procedure. Full-duplex (FD) communications are applied in each vehicle and the eNB to enable simultaneous multiple transmissions and/or receptions over the same or different subchannels [33], [36]. The self-interference, experienced at the eNB or a vehicle resulting from their transmission to their reception over the same subchannel, can be sufficiently suppressed by using existing self-interference cancellation methods, such as the distributed linear convolutional space-time coding (DLC-STC) scheme proposed in [36]. The eNB assigns the subchannels based on the received BaL information and the membership information, and then sends the radio resource control (RRC) connection setup to each communication link on the physical downlink control channels [37]. To meet communication delay requirements, subchannel allocation scheme and power control scheme are proposed in Sections IV and V, respectively.

### C. Channel Model

Consider a large scale fading channel model [38]. Since the eNB and vehicles can have different antennas types and different line-of-sight (LOS) components of radio propagation may be experienced at the receivers [25], two types of path-loss exponents are considered. Let  $\alpha$  and  $\beta$  denote the path-loss exponents for a link between the eNB and a vehicle and for a D2D link, respectively. Let  $\mathcal{H}_{e,i}$  denote the channel gain for a link between the eNB and vehicle  $i$ , and  $\mathcal{H}_{g,w}$  denote the channel gain of the D2D link between vehicle  $g$  and vehicle  $w$ . The channel gains are given by

$$\mathcal{H}_{e,i} \triangleq |h_0|^2 \cdot (d_{e,i})^{-\alpha} \quad (1)$$

and

$$\mathcal{H}_{g,w} \triangleq |h_0|^2 \cdot (d_{g,w})^{-\beta} \quad (2)$$

where  $d_{e,i}$  is the distance between the eNB and vehicle  $i$ ,  $d_{g,w}$  is the distance between vehicle  $g$  and vehicle  $w$ , and  $h_0$  is the complex Rayleigh fading channel coefficient. All channel gains under consideration are assumed to be reciprocal [38], i.e.,  $\mathcal{H}_{e,i} = \mathcal{H}_{i,e}$  and  $\mathcal{H}_{g,w} = \mathcal{H}_{w,g}$ .

## IV. SUBCHANNEL ALLOCATION

For the communication models discussed in Section III, the end-to-end transmission delay of a packet carrying member vehicle's VaA information is the delay of a one-hop D2D unicast communication<sup>4</sup>. On the other hand, the end-to-end transmission delay of a packet carrying the leader vehicle's VaA information is the delay of a two-hop communication in the eMBMS based model and that of a one-hop communication in the D2D-multicast based model. For a packet carrying the BaL information, the end-to-end transmission delay is the delay to transmit this packet from the source to the destination in the multiplatoon and is proportional to the number of transmission hops for a given transmission rate. Since a stable transmission rate depends on the signal-to-interference-and-noise-ratio (SINR) [39], we have the following two objectives:

- a) reducing the number of transmission hops for transmitting BaL information;
- b) reducing interference caused by subchannel reuse and minimizing the transmission power of each vehicle while guaranteeing the received signal power and SINR at each receiver.

Fig. 2(c) indicates that the maximum number of transmission hops for the BaL information occurs in the last vehicle of platoon  $P^{(j)}$ , and the value of the maximum transmission hops depends on the position of its boundary vehicle,  $V_k^{(j)}$ . Thus, to achieve the first objective,  $k$  is restricted to the second half of the  $m - 1$  member vehicles in each platoon, i.e.,  $\lceil \frac{m+2}{2} \rceil \leq k \leq m$ . Then, combining subchannel allocation and power control schemes to achieve the second objective. It should be noted that, in proposed subchannel allocation scheme, the global view of the network (with all the communication links) is considered while the link-level local view is considered in our power control approach.

### A. Subchannel Allocation for Leader Vehicles

Let  $l_{g,w}^{(j)}, l_{1,e}^{(j)}, l_{e,1}^{(j)}$  denote the communication links from  $V_g^{(j)}$  to  $V_w^{(j)}$ , from  $V_1^{(j)}$  to eNB, and from eNB to  $V_1^{(j)}$ , respectively, where  $1 \leq j \leq n$  and  $1 < g, w \leq m$ . For the two communication models described in Section III-B, the leader vehicles in the multiplatoon apply the following subchannel allocation methods:

- 1) *eMBMS based model*: The leader vehicle  $V_1^{(j)}$  communicates with the eNB in one subchannel, and the eNB multicasts the aggregated VaA and BaL information to  $V_i^{(j)}$  ( $1 \leq i \leq m$ ) in another subchannel;
- 2) *D2D-multicast based model*: The communication links, established when the eNB unicasts a packet to a leader vehicle or when this leader vehicle multicasts a packet to its member vehicles and the eNB (i.e., links  $l_{1,i}^{(j)}, l_{1,e}^{(j)}$  and  $l_{e,1}^{(j)}$ , where  $1 < i \leq m$ ), use only one subchannel. Since each leader vehicle multicasts a packet to the eNB and its member vehicles, and the packet transmitted in

<sup>4</sup>In this work, the packet arrival rate is modeled as constant and less than the transmission rate in each communication link. Thus, the queuing and access delays are neglected.

$l_{1,i}^{(j)}$  ( $1 < i \leq m$ ) is the same as that in  $l_{1,e}^{(j)}$ . Therefore, there is no co-channel interference between these two communication links.

To reduce co-channel interference experienced at each vehicle, the subchannels occupied by communication links in the eMBMS based model and D2D-multicast based model cannot be reused by any other links. Thus, for  $n$  leader vehicles,  $2n$  and  $n$  subchannels are needed for the eMBMS based and the D2D-multicast based models, respectively.

### B. Subchannel Allocation for Member Vehicles

Denote  $F_1$  as the number of subchannels that can be reused by the  $n \times (2m - 3)$  intra-platoon communication links shown in Fig. 2(c). Due to the inter-platoon spacing,  $D_p$ , there is at least  $D_p$  spatial separation between two intra-platoon communication links in one platoon and in another platoon. Thus, the subchannel allocated to an intra-platoon communication link in a platoon can be reused in other platoons. Scheme 1 is designed for allocating the minimum number of  $F_1$  subchannels among the  $2m - 3$  intra-platoon communication links in a platoon, and scheme 2 is designed for allocating these  $F_1$  subchannels in the multiplatoon. Let  $f_{g,w}^{(j)}$  denote the subchannel that is allocated to link  $l_{g,w}^{(j)}$  where  $1 \leq g, w \leq m$  and  $1 \leq j \leq n$ .

*Scheme 1 intra-platoon subchannel allocation:* For the intra-platoon communication links in platoon  $P^{(j)}$ , the subchannel allocation is given by

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

From (3), links  $l_{i-1,i}^{(j)}$  and  $l_{i,1}^{(j)}$  use the same subchannel when  $2 < i \leq k$ ; and links  $l_{i-1,i}^{(j)}$  and  $l_{i,i-1}^{(j)}$  use the same subchannel when  $k < i \leq m$ . This design can be explained as follows. First, suppose that the DLC-STC scheme is used in each transmitter [36], and then the self-interference experienced at a vehicle can be sufficiently suppressed and neglected [40]. The co-channel interference (due to subchannel reuse by other links) depends on the transmission power of and the distance to the interfering source. Reducing co-channel interference experienced at a receiver always affects the transmission in its interfering source. Thus, in addition to scheme 1, the following choice can be considered: when  $2 < i \leq k$ ,  $l_{i-1,i}^{(j)}$  and  $l_{i,i+1}^{(j)}$  use one subchannel, and  $l_{i,1}^{(j)}$  uses another subchannel; and when  $k < i < m$ ,  $l_{i-1,i}^{(j)}$  and  $l_{i,i+1}^{(j)}$  use one subchannel while  $l_{i+1,i}^{(j)}$  and  $l_{i,i-1}^{(j)}$  use another subchannel. However, it is clear that the number of required subchannels in scheme 1 is fewer than that in this choice. Furthermore, due to interference experienced at  $V_{i+1}^{(j)}$  generated by  $l_{i-1,i}^{(j)}$  ( $2 \leq i < m$ ) and interference experienced at  $V_{i-1}^{(j)}$  generated by  $l_{i+1,i}^{(j)}$  ( $k \leq i < m$ ), the total interference experienced at vehicles in this choice is larger than that in scheme 1.

Based on scheme 1, we can get the subchannel allocation results for member vehicles in platoon  $P^{(j+1)}$ , i.e.,  $f_{g,w}^{(j+1)}$ , where  $1 \leq g, w \leq m$ . Then, scheme 2 can be described as follows.

*Scheme 2 inter-platoon subchannel allocation:* The subchannels allocated for the intra-platoon communication links in platoon  $P^{(j)}$  are related to those in platoon  $P^{(j+1)}$  according to

$$f_{2,1}^{(j)} = f_{k-1,k}^{(j+1)} \quad (4)$$

and

$$f_{i-1,i}^{(j)} = \begin{cases} f_{(k+2)-i,1}^{(j+1)}, & \text{if } 2 < i \leq 2k - m \\ f_{i+(m-k),i+(m-k)-1}^{(j+1)}, & \text{if } 2k - m < i \leq k \\ f_{(m+2)-i,1}^{(j+1)}, & \text{if } k < i \leq m. \end{cases} \quad (5)$$

Based on scheme 2,  $l_{2,1}^{(j)}$  and  $l_{k-1,k}^{(j+1)}$  use one subchannel when  $i = 2$ ;  $l_{i-1,i}^{(j)}$  and  $l_{(k+2)-i,1}^{(j+1)}$  use one subchannel when  $2 < i \leq 2k - m$ ;  $l_{i-1,i}^{(j)}$  and  $l_{i+(m-k),i+(m-k)-1}^{(j+1)}$  use one subchannel when  $2k - m < i \leq k$ ; and  $l_{i-1,i}^{(j)}$  and  $l_{(m+2)-i,1}^{(j+1)}$  use one subchannel when  $k < i \leq m$ . Scheme 2 can be explained by the following theorem, proved in Appendix A.

*Theorem 1:* In a random platoon, the transmission power of an intra-platoon communication link, required to guarantee an SINR threshold  $\lambda$  at its receiver, is proportional to the distance of this link, i.e.,

$$p_1 - p_0 = \frac{\lambda I_1}{|h_0|^2} (d_{g,w})^\beta \quad (6)$$

where  $p_0$  is the transmission power of vehicle  $g$  in the presence of a background additive white Gaussian noise (AWGN),  $p_1$  is the transmission power of vehicle  $g$  in the presence of a background AWGN of the same power spectral density and interference  $I_1$  generated by other transmissions that use the same subchannel.

Theorem 1 indicates that the power efficiency of multiplatooning communications can be improved if the interference experienced at a vehicle (which is the receiver of multiple links) is largely corresponding to the transmission over the shorter link. According to scheme 1 and scheme 2, the value of  $F_1$  can be reduced to  $m - 1$ . An example for reusing subchannels within two consecutive platoons,  $P^{(j)}$  and  $P^{(j+1)}$ , is illustrated in Fig. 3, where  $m = 7$ ,  $k = 6$ ,  $F_1 = 6$ , and the numbers on the arrows indicate the subchannel IDs of the  $F_1$  subchannels. It should be noted that, when  $F_1 > m - 1$ , the impact of co-channel interference on the multiplatooning communication performance is reduced and the designed subchannel allocation scheme can be adjusted accordingly. On the other hand, when  $F_1 < m - 1$ , we can combine scheme 1 and scheme 2 with the subchannel allocation scheme proposed in [25] to support multiplatooning communications.

## V. POWER CONTROL

To guarantee fairness among different links that share the same subchannel, a minimum received signal power threshold,  $\eta$ , and a minimum received SINR threshold,  $\lambda$ , are set for each receiver. In order to achieve a received signal power over  $\eta$  and an SINR over  $\lambda$  at the receiver while minimizing the transmission power, a power control scheme is proposed in this section. Taking platoons  $P^{(j)}$  and  $P^{(j+1)}$  as an example, the proposed

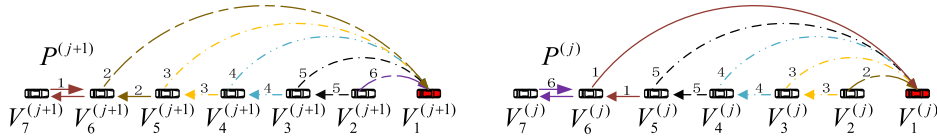


Fig. 3. An illustration for subchannel reuse when employing scheme 1 and scheme 2 for intra-platoon communication links within two consecutive platoons with  $m = 7$  and  $k = 6$ .

power control schemes for the eNB, leader vehicles, and member vehicles are as follows.

#### A. Power Control for eNB

- 1) *eMBMS based model*: Denote  $p_e^{(j)}$  as the transmission power of the eNB when it multicasts a packet to the vehicles in platoon  $P^{(j)}$ . The received signal power and the SINR at vehicle  $V_i^{(j)}$  ( $1 \leq i \leq m$ ) are given by

$$\mathcal{R}_{e,i}^{(j)} = p_e^{(j)} \cdot |h_0|^2 \cdot \left(d_{e,i}^{(j)}\right)^{-\alpha} \quad (7)$$

and

$$\mathcal{S}_{e,i}^{(j)} = \frac{p_e^{(j)} \cdot |h_0|^2 \cdot \left(d_{e,i}^{(j)}\right)^{-\alpha}}{\sigma}. \quad (8)$$

In (7) and (8),  $\sigma$  is the value of AWGN,  $d_{e,i}^{(j)}$  is the distance between point A and vehicle  $V_i^{(j)}$  and is given by

$$d_{e,i}^{(j)} = \sqrt{\left[x_1^{(j)} - (i-1)D_v\right]^2 + (D_o)^2 + (D_e)^2} \quad (9)$$

where  $(x_1^{(j)}, 0, 0)$  is the position of vehicle  $V_1^{(j)}$ . Among the  $m$  vehicles in platoon  $P^{(j)}$ ,  $\max d_{e,i}^{(j)} = d_{e,1}^{(j)}$  when  $\frac{1}{2}(m-1)D_v \leq x_1^{(j)} \leq D_a$ , and  $\max d_{e,i}^{(j)} = d_{e,m}^{(j)}$  when  $-D_a \leq x_1^{(j)} < \frac{1}{2}(m-1)D_v$ . Thus, to guarantee the received signal power and SINR for each vehicle in platoon  $P^{(j)}$ , i.e.,  $\mathcal{R}_{e,i}^{(j)} \geq \eta$  and  $\mathcal{S}_{e,i}^{(j)} \geq \lambda$  ( $1 \leq i \leq m$ ), the minimum  $p_e^{(j)}$  in the eMBMS based model can be expressed as (10).

$$p_e^{(j)'} = \begin{cases} \max \left\{ \frac{\eta \left(d_{e,1}^{(j)}\right)^\alpha}{|h_0|^2}, \frac{\lambda \sigma \left(d_{e,1}^{(j)}\right)^\alpha}{|h_0|^2} \right\}, & \text{if } \frac{1}{2}(m-1)D_v \leq x_1^{(j)} \leq D_a \\ \max \left\{ \frac{\eta \left(d_{e,m}^{(j)}\right)^\alpha}{|h_0|^2}, \frac{\lambda \sigma \left(d_{e,m}^{(j)}\right)^\alpha}{|h_0|^2} \right\}, & \text{if } -D_a \leq x_1^{(j)} < \frac{1}{2}(m-1)D_v. \end{cases} \quad (10)$$

- 2) *D2D-multicast based model*: The eNB only unicasts packets to leader vehicle  $V_1^{(j)}$  in this model. To guarantee the received signal power and the SINR at  $V_1^{(j)}$ , the minimum  $p_e^{(j)}$  can be expressed as

$$p_e^{(j)'} = \max \left\{ \frac{\eta \left(d_{e,1}^{(j)}\right)^\alpha}{|h_0|^2}, \frac{\lambda \sigma \left(d_{e,1}^{(j)}\right)^\alpha}{|h_0|^2} \right\}. \quad (11)$$

#### B. Power Control for Leader Vehicles

- 1) *eMBMS based model*: Denote  $p_1^{(j)}$  as the transmission power of  $V_1^{(j)}$ . As mentioned in Section III-C, all channel gains are assumed to be reciprocal. Thus, based on eMBMS, the minimum  $p_1^{(j)}$  to guarantee the received signal power and the SINR at the eNB, i.e.,  $p_1^{(j)'}$ , is the same as  $p_e^{(j)'}$  in the D2D-multicast based model and is given by (11).
- 2) *D2D-multicast based model*: As mentioned in Section IV, for platoon  $P^{(j)}$  ( $1 \leq j \leq n$ ), same packets are transmitted over  $l_{1,i}^{(j)}$  ( $1 < i \leq m$ ) and  $l_{1,e}^{(j)}$ , and the self-interference in each vehicle can be neglected. Thus, for vehicle  $V_i^{(j)}$  ( $1 < i \leq m$ ), only interference generated by the transmission in  $l_{e,1}^{(j)}$  is considered. When receiving packet from  $V_1^{(j)}$ , the received signal power and SINR at  $V_i^{(j)}$  ( $1 < i \leq m$ ) can be expressed as

$$\mathcal{R}_{1,i}^{(j)} = p_1^{(j)} |h_0|^2 \left(d_{1,i}^{(j)}\right)^{-\beta} \quad (12)$$

and

$$\mathcal{S}_{1,i}^{(j)} = \frac{\mathcal{R}_{1,i}^{(j)}}{\sigma + p_e^{(j)} |h_0|^2 \left(d_{e,i}^{(j)}\right)^{-\alpha}} \quad (13)$$

respectively, where  $p_e^{(j)}$  is given by (11),  $p_1^{(j)}$  is the transmission power of  $V_1^{(j)}$ , and  $d_{1,i}^{(j)}$  is the distance between  $V_1^{(j)}$  and  $V_i^{(j)}$  and can be calculated by

$$d_{1,i}^{(j)} = (i-1)D_v. \quad (14)$$

Let  $\widehat{p}_1^{(j)}$  denote the minimum transmission power of  $V_1^{(j)}$  to guarantee the signal power threshold,  $\eta$ , at each member vehicle. Since  $\beta > 0$ , according to (12) and (14),  $\widehat{p}_1^{(j)}$  is given by

$$\widehat{p}_1^{(j)} = \frac{\eta [(m-1)D_v]^\beta}{|h_0|^2}. \quad (15)$$

Let  $\widetilde{p}_1^{(j)}$  denote the minimum  $p_1^{(j)}$  to guarantee the SINR threshold,  $\lambda$ , at each member vehicle. Equations (9) and (13) show that the value of  $\mathcal{S}_{1,i}^{(j)}$  is related to  $x_i^{(j)}$  and is different from member vehicles when  $V_1^{(j)}$  multicasts a packet to its member vehicles with transmission power  $p_1^{(j)}$ . For a given  $x_1^{(j)}$ , the

power control problem for leader vehicles is formulated as

$$\min_i \mathcal{S}_{1,i}^{(j)} = \frac{p_1^{(j)} |h_0|^2 \left(d_{1,i}^{(j)}\right)^{-\beta}}{\sigma + p_e^{(j)} |h_0|^2 \left(d_{e,i}^{(j)}\right)^{-\alpha}}$$

subject to

$$x_i^{(j)} = x_1^{(j)} - (i-1)D_v \quad (16a)$$

$$d_{1,i}^{(j)} = (i-1)D_v \quad (16b)$$

$$d_{e,i}^{(j)} = \sqrt{\left(x_i^{(j)}\right)^2 + (D_o)^2 + (D_e)^2} \quad (16c)$$

$$-D_a \leq x_i^{(j)} \leq D_a \quad (16d)$$

$$1 < i \leq m. \quad (16e)$$

By solving the above power control problem, the minimum  $\mathcal{S}_{1,i}^{(j)}$  among the  $m-1$  member vehicles can be obtained.

From the above discussion, the minimum transmission power of  $V_1^{(j)}$  to guarantee the received signal power and SINR at the eNB and member vehicles is given by

$$p_1^{(j)'} = \max \left\{ p_e^{(j)}, \widehat{p}_1^{(j)}, \widetilde{p}_1^{(j)} \right\}. \quad (17)$$

### C. Power Control for Member Vehicles

Subchannels are reused among intra-platoon communication links within a single platoon and among that within multiple platoons. In platoon  $P^{(j+1)}$ , scheme 1 indicates that  $l_{i,i-1}^{(j+1)}$  and  $l_{i-1,i}^{(j+1)}$  use subchannel  $f_i^{(j+1)}$  when  $k < i \leq m$ ; and  $l_{i,i-1}^{(j)}$  and  $l_{i,i-1}^{(j)}$  reuse subchannel  $f_i^{(j+1)}$  when  $1 < i \leq k$ . Among the intra-platoon communication links in platoon  $P^{(j)}$ ,  $l_{i-1,i}^{(j)}$  ( $1 < i \leq k$ ) is a link between two consecutive vehicles with link distance  $D_v$ , which is small compared to that of  $l_{i,i-1}^{(j)}$ . Hence, the transmission power of the transmitter in  $l_{i-1,i}^{(j)}$  ( $1 < i \leq k$ ) is relatively small. Therefore, for the transmissions in intra-platoon communication links in  $P^{(j)}$  which reuse  $f_i^{(j+1)}$  ( $1 < i \leq k$ ), only interference generated by  $l_{i,i-1}^{(j)}$  is considered.

According to scheme 2, the value of  $k$  impacts the subchannel allocation results among intra-platoon communication links in platoons  $P^{(j)}$  and  $P^{(j+1)}$ . In (4) and (5), links  $l_{i+(m-k),i+(m-k)-1}^{(j+1)}$  and  $l_{i,i-1}^{(j)}$  are between two consecutive vehicles when  $2k-m < i \leq k$  and  $k < i \leq m$ . Furthermore, the transmission power in these two links are small and the proposed subchannel allocation scheme avoids allocating a subchannel to two adjacent communication links. Thus, interference experienced at  $V_1^{(j)}$ , generated by the transmission in  $l_{i+(m-k),i+(m-k)-1}^{(j+1)}$  ( $2k-m < i \leq k$ ), and interference experienced at  $V_1^{(j+1)}$ , generated by the transmission in  $l_{i,i-1}^{(j)}$  ( $k < i \leq m$ ), are negligible. Considering the distance between a receiver and its interfering source, the largest interference experienced at  $V_1^{(j+1)}$  is generated by the transmission in  $l_{2k-m,1}^{(j)}$  when  $V_{m-k+2}^{(j+1)}$  transmits a packet to  $V_1^{(j+1)}$  ( $2 \leq i \leq 2k-m$ ).

This is also the largest interference experienced at a platoon, which is generated by its preceding platoon.

From the above discussion, a large  $k$  means a short distance between  $V_{2k-m}^{(j)}$  and  $V_1^{(j+1)}$ , i.e., a small  $2(m-k)D_v + D_p$ , which indicates large interference experienced at  $V_1^{(j+1)}$ , that is generated by the transmission in  $l_{2k-m,1}^{(j)}$ . Thus, resulting in high transmission powers of  $V_{m-k+2}^{(j+1)}$  and  $V_{2k-m}^{(j)}$  to guarantee the signal power and SINR thresholds at their receivers. However, a large  $k$  can reduce the number of member vehicles communicating with the leader vehicle in multi-hops, and therefore, reduce the delay for transmitting the BaL information of these member vehicles. Thus, the power control problem for member vehicles is formulated to minimize the transmission powers of  $V_{m-k+2}^{(j+1)}$  and  $V_{2k-m}^{(j)}$  while guaranteeing the received signal powers at  $V_1^{(j+1)}$  and  $V_1^{(j)}$  over the threshold  $\eta$ , and the received SINR at  $V_1^{(j+1)}$  over the threshold  $\lambda$ . The power control problem for member vehicles can be represented as follows,

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

subject to

$$p_{2k-m}^{(j)} |h_0|^2 [(2k-m-1)D_v]^{-\beta} \geq \eta \quad (18a)$$

$$p_{m-k+2}^{(j+1)} |h_0|^2 [(m-k+1)D_v]^{-\beta} \geq \eta \quad (18b)$$

$$\frac{p_{m-k+2}^{(j+1)} |h_0|^2 [(m-k+1)D_v]^{-\beta}}{\sigma + p_{2k-m}^{(j)} |h_0|^2 [2(m-k)D_v + D_p]^{-\beta}} \geq \lambda \quad (18c)$$

$$\frac{m+2}{2} \leq k \leq m \quad (18d)$$

where (18a) and (18b) guarantee the signal power thresholds at  $V_1^{(j+1)}$  and  $V_1^{(j)}$ , (18c) guarantees the SINR threshold at  $V_1^{(j+1)}$ , and (18d) indicates that fewer than half of member vehicles communicate with the leader vehicle in multi-hops. The optimal  $k$ ,  $k_{opt}$ , can be obtained by solving the above power control problem, which minimizes the sum of the transmission powers of  $V_{m-k+2}^{(j+1)}$  and  $V_{2k-m}^{(j)}$ .

As proved in Appendix B, the above power control problem can be simplified according to the following theorem.

*Theorem 2:* The power control problem for member vehicles can be simplified to the following

$$\min_{k^*, k'} \{ \Lambda(k^*), \Omega(k') \}$$

subject to

$$\Lambda(k^*) = \Gamma_1(k^*) + \Gamma_2(k^*) \quad (19a)$$

$$\Omega(k') = \Gamma_1(k') [1 + \Gamma_3(k')] + \Gamma_4(k') \quad (19b)$$

$$\Gamma_2(k^*) \geq \Gamma_1(k^*) \Gamma_3(k^*) + \Gamma_4(k^*) \quad (19c)$$

$$\Gamma_2(k') < \Gamma_1(k') \Gamma_3(k') + \Gamma_4(k') \quad (19d)$$

$$\frac{m+2}{2} \leq k^*, k' \leq m \quad (19e)$$



where  $\Gamma_1(k)$ ,  $\Gamma_2(k)$ ,  $\Gamma_3(k)$ , and  $\Gamma_4(k)$  are

$$\begin{aligned}\Gamma_1(k) &= \frac{\eta}{|h_0|^2 [(2k - m - 1)D_v]^{-\beta}} \\ \Gamma_2(k) &= \frac{\eta}{|h_0|^2 [(m - k + 1)D_v]^{-\beta}} \\ \Gamma_3(k) &= \frac{\lambda [2(m - k)D_v + D_p]^{-\beta}}{[(m - k + 1)D_v]^{-\beta}} \\ \Gamma_4(k) &= \frac{\sigma\lambda}{|h_0|^2 [(m - k + 1)D_v]^{-\beta}}.\end{aligned}\quad (20)$$

## VI. MULTIPLATOONING COMMUNICATION ANALYSIS

In Sections IV and V, we have proposed subchannel allocation and power control schemes for vehicles in a multiplatoon, which can guarantee the received signal power and SINR of each communication link. In this section, the multiplatooning communication performance, in terms of the transmission rate and transmission delay, is analyzed.

- 1) *Transmission rate*: Section V shows that the received SINR in each communication link is guaranteed to reach the SINR threshold. Thus, the achievable transmission rate in a communication link, denoted by  $r$ , satisfies

$$r \geq W \log_2(1 + \lambda) \quad (21)$$

where  $W$  is the subchannel bandwidth.

- 2) *Transmission delay*: Define  $E[L]$  as the average size of the packet carrying the VaA or BaL information. As mentioned in Section III-B, each leader vehicle needs to share its VaA information with all member vehicles in the same platoon and each member vehicle needs to share its VaA information with its following member vehicle. According to the communication model and the proposed subchannel allocation and power control schemes, the end-to-end transmission delay for a packet carrying the member vehicle's VaA information is the delay of a D2D link and can be expressed as

$$\mathcal{T}_{V_{aA_M}} = \frac{E[L]}{r} \leq \frac{E[L]}{W \cdot \log_2(1 + \lambda)}. \quad (22)$$

- i) *In the eMBMS based model*: As illustrated in Fig. 2(a), the leader vehicle unicasts its VaA information to the eNB first, then the eNB multicasts this information using eMBMS to the member vehicles in the same platoon. Thus, the end-to-end transmission delay for a packet carrying the leader vehicle's VaA information,  $\mathcal{T}_{V_{aA_1}}$ , is the delay of the two-hop communication, which can be expressed as

$$\mathcal{T}_{V_{aA_1}} = 2 \frac{E[L]}{r} \leq \frac{2E[L]}{W \cdot \log_2(1 + \lambda)}. \quad (23)$$

When a member vehicle in a platoon shares its BaL information with the member vehicles in other platoons, the BaL information needs to be relayed by the leader vehicle and the eNB. Thus, when  $k = k_{opt}$ , the end-to-end transmission delay for a packet carrying the BaL information

TABLE II  
SYSTEM PARAMETERS VALUES

Parameter	Value	Parameter	Value
$R$	500 m	$D_e$	50 m
$D_o$	100 m	$D_a$	487.34 m
$D_v$	8 m	$D_p$	40 m
$m$	20	$n$	5
$F$	24	$\alpha$	3
$\beta$	4	$\eta$	-100 dBm
$\lambda$	100	$E[L]$	2048 bits
$\sigma$	-110 dBm	$W$	2 MHz

in the eMBMS based model is proportional to the number of transmission hops and can be expressed as

$$2 \frac{E[L]}{r} \leq \mathcal{T}_{BaL_1} \leq (m - k_{opt} + 3) \frac{E[L]}{r} \quad (24)$$

where  $\mathcal{T}_{BaL_1} = 2 \frac{E[L]}{r}$  when vehicle  $V_1^{(n)}$  shares its BaL information with the member vehicles in platoon  $P^{(n)}$  and  $\mathcal{T}_{BaL_1} = (m - k_{opt} + 3) \frac{E[L]}{r}$  when vehicle  $V_m^{(j)}$  shares its BaL information with the vehicles in platoon  $P^{(u)}$ ,  $j \leq u \leq n$ .

- ii) *In the D2D-multicast based model*: As illustrated in Fig. 2(b), a leader vehicle multicasts its VaA information aggregated with the BaL information from other platoons to its member vehicles directly. Thus, based on a D2D multicast communication, the end-to-end transmission delay for a packet carrying the leader vehicle's VaA information,  $\mathcal{T}_{V_{aA_2}}$ , is the delay of a D2D link, same as  $\mathcal{T}_{V_{aA_M}}$ . As in the eMBMS based model, when a member vehicle in a platoon shares its BaL information with member vehicles in other platoons, this BaL information needs to be relayed by the leader vehicle and the eNB. Thus, the end-to-end transmission delay for a packet carrying BaL information in the D2D-multicast based model can be expressed as

$$\frac{E[L]}{r} \leq \mathcal{T}_{BaL_2} \leq (m - k_{opt} + 4) \frac{E[L]}{r}. \quad (25)$$

## VII. SIMULATION RESULTS

To demonstrate the multiplatooning communication performance with the proposed subchannel allocation and power control schemes, this section presents the simulation results for the proposed power control scheme, evaluates the end-to-end transmission delay of vehicle's VaA/BaL information, and compares the results with the performance of a D2D-unicast based RA approach (proposed in [25]).

We consider a multiplatooning communication scenario with a set of parameters listed in Table II. For the D2D-unicast based RA approach proposed in [25], only communication links between two adjacent vehicles are considered. In addition, the communication links within the multiplatoon are divided into  $n$  individual groups, where the  $n$  groups reuse  $m$  subchannels and each group represents the communication links within the same platoon (including that from the leader vehicle to the last

member vehicle in the preceding platoon). For a fair comparison, FD mode is considered at each vehicle when it shares its VaA/BaL information using the approach in [25], and links between two adjacent vehicles, i.e.,  $l_{i,i+1}^{(j)}$  and  $l_{i+1,i}^{(j)}$ , are allocated the same subchannel.

#### A. Power Control Results

Fig. 4(a) shows the transmission powers of the eNB when it multicasts packet to  $V_i^{(j)}$  based on eMBMS and unicasts packet to  $V_1^{(j)}$  in the D2D-multicast based model. The transmission power of the eNB can be adjusted according to the position of the leader vehicle to guarantee a received SINR threshold at each vehicle. From the red curve in Fig. 4(a), it can be seen that the smaller the value of  $|x_1^{(j)}|$  is, the less transmission power the eNB needs in the D2D-multicast based model. That is because on the highway segment within the coverage area of the eNB, a smaller  $|x_1^{(j)}|$  implies a shorter distance between the leader vehicle and the eNB, and the eNB only needs to guarantee the received signal power and SINR at the leader vehicle in the D2D-multicast based model. However, in the eMBMS based model, the eNB needs to guarantee the received signal power and SINR at the vehicle with the largest distance to the eNB in each platoon, i.e., the leader vehicle when  $x_1^{(j)} > 77.5$  m or the last member vehicle when  $x_1^{(j)} \leq 77.5$  m. Furthermore, when  $x_1^{(j)} \leq 77.5$  m, the distance between the eNB and the last member vehicle in one platoon is always longer than that between the eNB and this platoon's leader vehicle. Thus, the transmission power of the eNB in the D2D-multicast based model is less than that in the eMBMS based model when  $x_1^{(j)} \leq 77.5$  m, as shown in Fig. 4(a).

Fig. 4(b) shows the transmission power of a leader vehicle when it communicates with the eNB or its member vehicles according to the eMBMS and D2D-multicast based models. Regardless of the leader vehicle's position, the leader vehicle's transmission power  $p_1^{(j)}$  in the D2D-multicast based model is always larger than that in the eMBMS based model. This is because the leader vehicle needs to multicast packets to its member vehicles in the D2D-multicast based model while unicast packets to the eNB in the eMBMS based model. Moreover, due to the increase of the distance between the leader vehicle and the eNB,  $p_1^{(j)}$  increases with the value of  $|x_1^{(j)}|$  in the eMBMS model. In the D2D-multicast based model,  $p_1^{(j)}$  tends to decrease first, then increase, and then decrease again.  $p_1^{(j)}$  tends to decrease because  $p_e^{(j)}$  decreases with  $x_1^{(j)}$  when  $x_1^{(j)} < 0$ ; since  $p_e^{(j)}$  increases with  $x_1^{(j)}$  when  $x_1^{(j)} > 0$ ,  $p_1^{(j)}$  increases to guarantee the received SINR at  $V_m^{(j)}$ . However, the distance between the eNB and the last member vehicle  $V_m^{(j)}$  increases with  $x_1^{(j)}$ , resulting in interference reduction that gradually counteracts the increased  $p_e^{(j)}$  and eventually decreases the value of  $p_1^{(j)}$ .

Fig. 5(a) plots the transmission powers of vehicles  $V_{m-k+2}^{(j+1)}$  and  $V_{2k-m}^{(j)}$ , and the sum of them, i.e.,  $p_{m-k+2}^{(j+1)}$ ,  $p_{2k-m}^{(j)}$ , and  $p_{m-k+2}^{(j+1)} + p_{2k-m}^{(j)}$ , for different  $k$  values ( $\frac{m+2}{2} \leq k \leq m$ ). A large  $k$  means a large distance between  $V_{2k-m}^{(j)}$  and  $V_1^{(j)}$ ,

thus resulting in a high transmission power of  $V_{2k-m}^{(j)}$ . Since  $d_{m-k+2,1}^{(j+1)} = (m-k+1)D_v$  decreases with  $k$ , the transmission power of vehicle  $V_{m-k+2}^{(j+1)}$ , required to guarantee the received signal power and SINR at  $V_1^{(j+1)}$ , decreases when  $k$  increases from 11 to 15. On the other hand, the value of  $2(m-k)D_v + D_p$  decreases with  $k$ , resulting in the increasing of the interference experienced at  $V_1^{(j+1)}$  generated by  $V_{2k-m}^{(j)}$ , and therefore,  $p_{m-k+2}^{(j+1)}$  increases when  $k$  increases from 15 to 18. When  $18 \leq k \leq 20$ ,  $p_{m-k+2}^{(j+1)}$  decreases again, which can be explained by Theorem 1. The optimal  $k$  values for different platoon sizes,  $5 \leq m \leq 20$ , are shown as in Fig. 5(b).

#### B. Transmission Delay

In this section, the performance of our proposed approaches in terms of the transmission delay is compared with that in [25]. We focus on BaL information and leader vehicle's VaA information transmissions only, since the transmission delay for sharing member vehicle's VaA information is the delay of a D2D communication link. On the other hand, when one vehicle shares its BaL or VaA information with different destination vehicles, the number of transmission hops may differ, resulting in different transmission delays. Since the transmission delay of each transmission between the source and destination vehicles is important to multiplatooning applications, the maximum end-to-end delay of BaL/VaL information, which defined as the end-to-end delay between two vehicles which need the maximum number of transmission hops for a packet carrying BaL/VaA information, are analyzed in this section. According to the communication models shown in Fig. 2, the maximum end-to-end delay of BaL information can be defined as the interval between the time that a packet carrying BaL information is dispatched from the  $m$ th member vehicle and the time that it is received by the  $m$ th member vehicle in one of the following platoons. The maximum end-to-end delay of VaA information can be defined as the interval between the time that a packet carrying VaA information is dispatched from a leader vehicle and the time it is received by the member vehicles in the same platoon.

Fig. 6 shows the effect of the platoon size,  $m$ , on the maximum end-to-end transmission delays for sharing VaA and BaL information. Considering  $3 \leq m \leq 20$ , we can see that the end-to-end transmission delays of the proposed approaches are always less than that in [25], especially the one according to the D2D-multicast based model. The reasons can be summarized as follows: (i) the numbers of transmission hops required for sharing the leader vehicle's VaA and BaL information are reduced by applying the utilized D2D multicast and eMBMS communication technologies in our proposed approaches; and the intra-platoon communication model shown in Fig. 2(c) further reduces the number of transmission hops required for member vehicles' BaL information; (ii) the numbers of transmission hops for both VaA and BaL information are proportional to  $m$  in [25], since only the communication links between two adjacent vehicles are considered. Furthermore, the value of  $k_{opt}$  increases with  $m$ , resulting in more vehicles communicating with the leader vehicle directly (single-hop). Moreover, from Fig. 6,

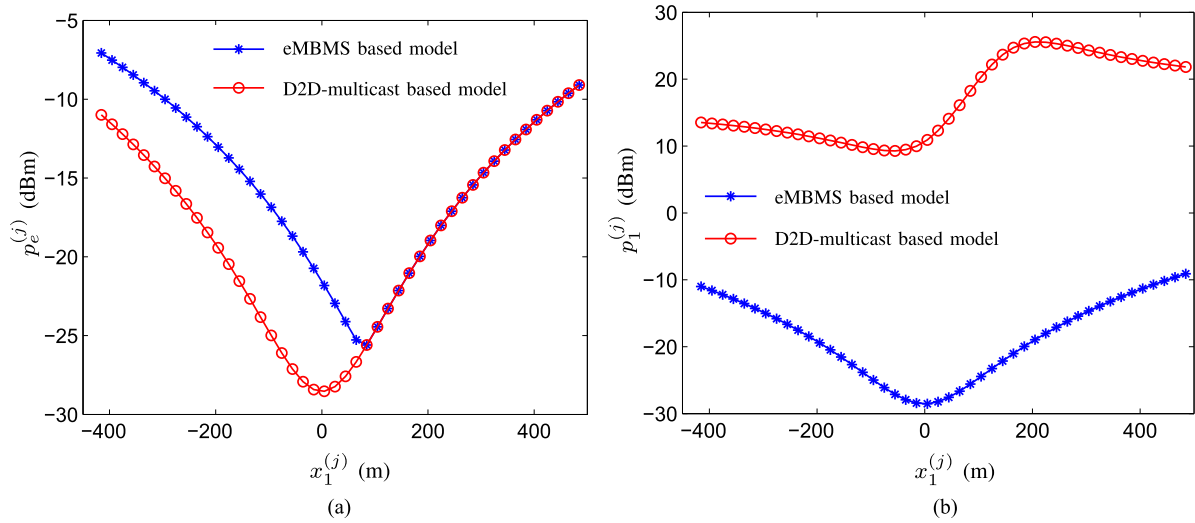


Fig. 4. The power control results for the eNB and leader vehicles. (a) The power control results for eNB. (b) The power control results for leader vehicles.

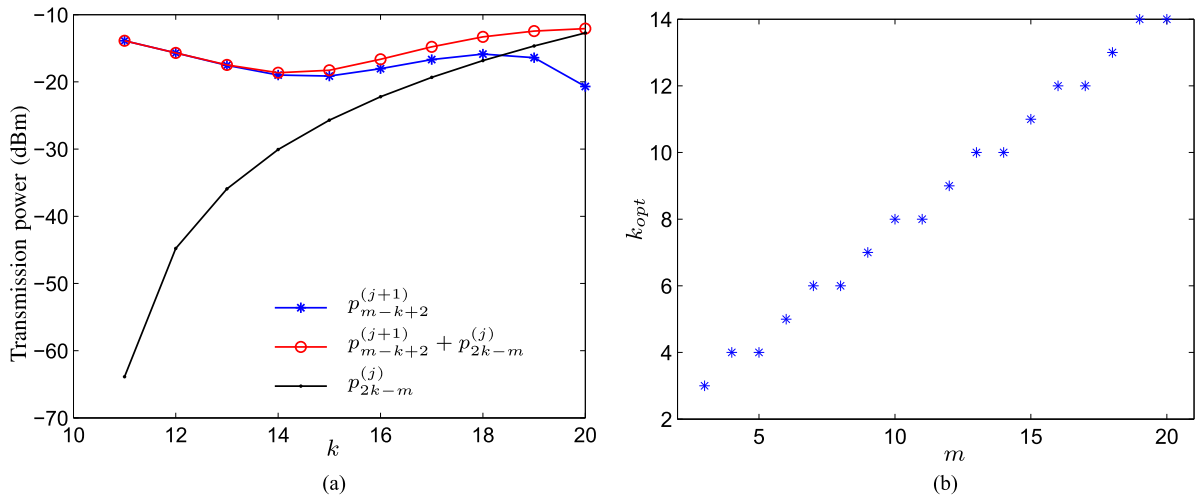


Fig. 5. The  $k_{opt}$  for different platoon size. (a) The transmission powers of vehicles  $V_{m-k+2}^{(j+1)}$  and  $V_{2k-m}^{(j)}$  with different  $k$ . (b) The  $k_{opt}$  vs. platoon size.

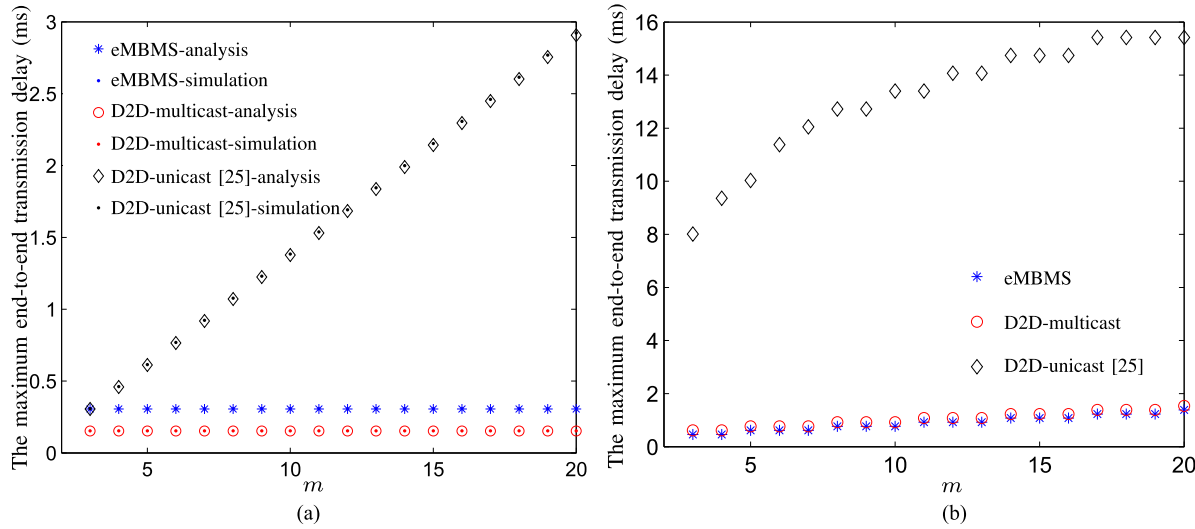


Fig. 6. Effect of the platoon size  $m$  on the maximum end-to-end transmission delay for VaA and BaL information. (a) For leader vehicle's VaA information. (b) For member vehicle's BaL information.

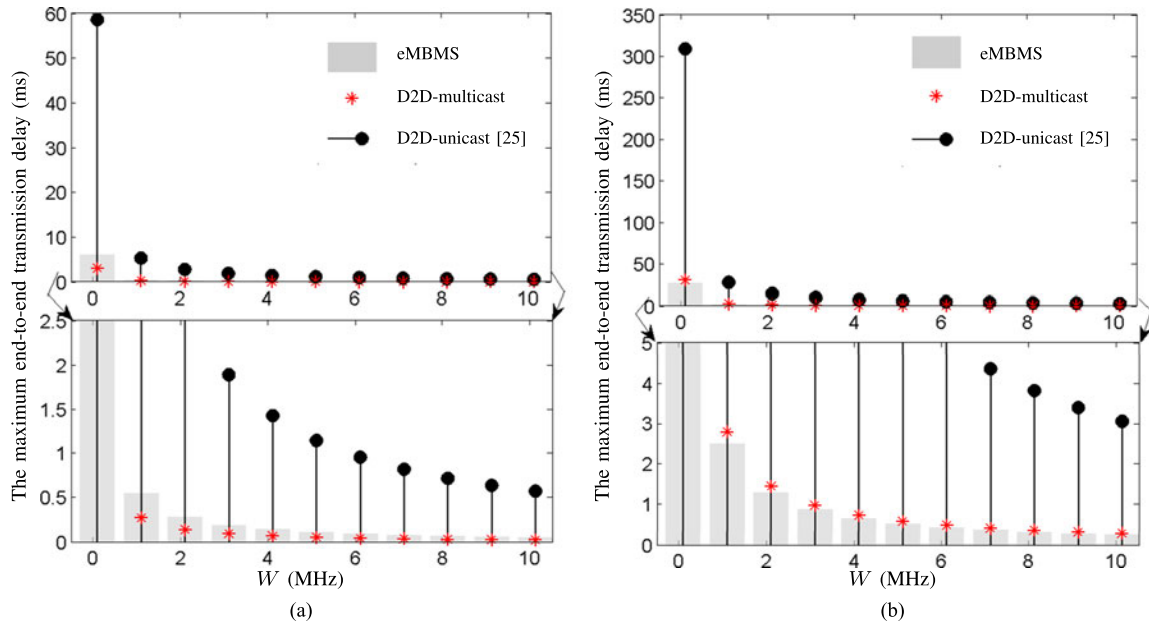


Fig. 7. Effect of the subchannel bandwidth  $W$  on the maximum end-to-end transmission delay for VaA and BaL information. (a) For leader vehicle's VaA information. (b) For member vehicle's BaL information.

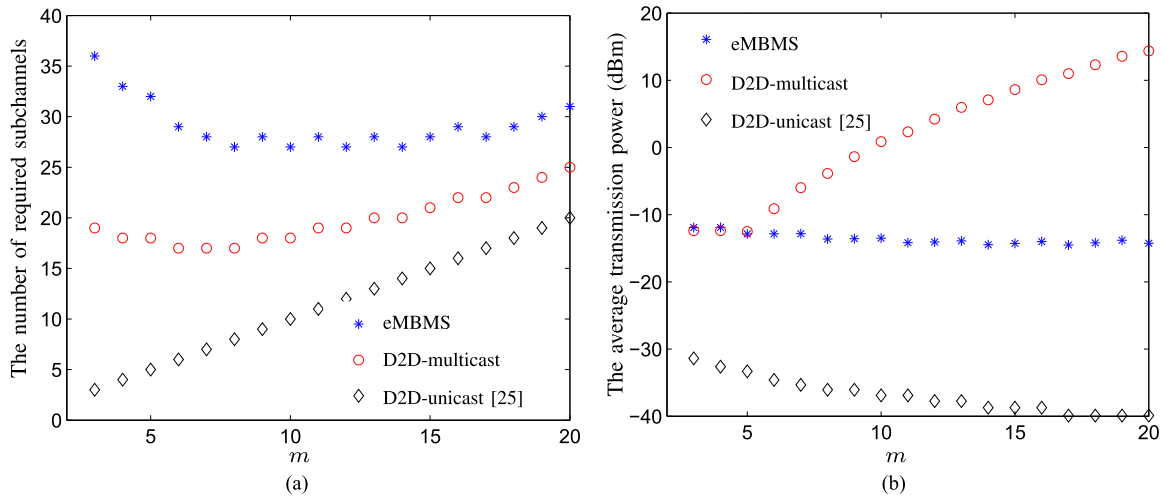


Fig. 8. Effect of the platoon size  $m$  on the number of required subchannels and the average transmission power for BaL information. (a) The number of required subchannels. (b) The average transmission power for BaL information.

it can be seen that the transmission delay in the D2D-multicast based model is less than that in the eMBMS based model when sharing the leader vehicle's VaA information, while the eMBMS based model outperforms the D2D-multicast based model when sharing BaL information. Note that since the difference between the analysis result and simulation result is very small, as shown in Fig. 6, only simulation results are discussed in the remainder of this section.

Fig. 7 shows the effect of the subchannel bandwidth  $W$  on the delay performance for the three approaches. As the subchannel bandwidth  $W$  increases, the maximum end-to-end transmission delays of these three approaches decrease. However, with the same subchannel bandwidth  $W$ , the maximum end-to-end transmission delays of our proposed approaches are smaller than that of the approach in [25]. Furthermore, Figs. 6 and 7 show that

the proposed approaches outperform the approach in [25], especially for a large platoon size and a small subchannel bandwidth.

The benefits of our proposed approaches come at the cost of the amount of subchannels and transmission power needed. This is shown in Fig. 8. More subchannels are needed in our proposed approaches compared to that of [25], especially in the eMBMS based model. However, the difference in the number of required subchannels among these three approaches decreases with  $m$ . On the other hand, the results in Fig. 8(b) show that more transmission power is needed in the proposed approaches, especially in the D2D-multicast based model. This is due to the longer-distance single-hop transmissions utilized in the intra-platoon communication model (in Fig. 2(c)), which leads to a relatively higher transmission powers on some vehicles, and therefore, resulting in a higher average transmission power.

## VIII. CONCLUSION

In this paper, we have proposed subchannel allocation and power control schemes that utilize D2D multicast and eM-BMS communications to support inter-vehicle communications in a highway multiplatooning scenario. We have analyzed the achievable transmission rate and delay of the proposed RA approaches. In order to evaluate the performance of the proposed RA approaches, we compare them to an existing D2D-unicast based RA scheme. The simulation results have demonstrated that the proposed RA approaches outperform the existing one, in terms of transmission delay for sharing vehicle and platoon information. For the future work, we will investigate the impact of communication delay on the multiplatoon control, compare the multiplatooning communication performance between the DSRC and the LTE technologies, and ultimately design an efficient DSRC-LTE hybrid approach for multiplatooning communications.

 APPENDIX A  
 PROOF OF THEOREM 1

*Proof:* According to (2) in Section III-C, the received SINR at  $V_w$  can be expressed as

$$\mathcal{S}_{g,w} = \frac{p_0 |h_0|^2 (d_{g,w})^{-\beta}}{\sigma} = \lambda \quad (26)$$

and

$$\mathcal{S}'_{g,w} = \frac{p_1 |h_0|^2 (d_{g,w})^{-\beta}}{\sigma + I_1} = \lambda \quad (27)$$

respectively, where the (26) is the received SINR at  $V_w$  in presence of background AWGN  $\sigma$ , and (27) is the received SINR at  $V_w$  in presence of background AWGN  $\sigma$  and the interference  $I_1$ . Then, one can get the transmission powers  $p_0$  and  $p_1$  as follows,

$$p_0 = \frac{\lambda \sigma}{|h_0|^2} (d_{g,w})^\beta \quad (28)$$

$$p_1 = \frac{\lambda(\sigma + I_1)}{|h_0|^2} (d_{g,w})^\beta. \quad (29)$$

Thus, the value of  $p_1 - p_0$  can be calculated as,

$$\begin{aligned} p_1 - p_0 &= \frac{\lambda(\sigma + I_1)}{|h_0|^2} (d_{g,w})^\beta - \frac{\lambda \sigma}{|h_0|^2} (d_{g,w})^\beta \\ &= \frac{\lambda I_1}{|h_0|^2} (d_{g,w})^\beta. \end{aligned} \quad (30)$$

 APPENDIX B  
 PROOF OF THEOREM 2

*Proof:* According to the constraint equations (18a) and (20), the transmission power of  $V_{2k-m}^{(j)}$  can be given by

$$\begin{aligned} p_{2k-m}^{(j)} &\geq \frac{\eta}{|h_0|^2 [(2k-m-1)D_v]^{-\beta}} \\ &\geq \Gamma_1(k). \end{aligned} \quad (31)$$

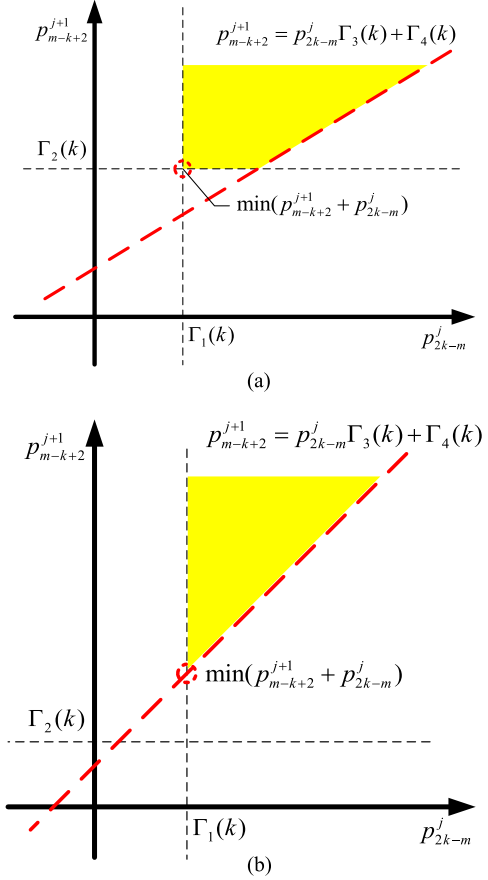


Fig. 9. Illustration of the relationship between the optimization objective function and constrain equations (31), (32) and (33). (a) When  $\Gamma_2(k^*) \geq \Gamma_1(k^*)\Gamma_3(k^*) + \Gamma_4(k^*)$ . (b) When  $\Gamma_2(k^*) < \Gamma_1(k^*)\Gamma_3(k^*) + \Gamma_4(k^*)$ .

According to the constraint equations (18b) and (20), the transmission power of  $V_{m-k+2}^{(j+1)}$  can be given by

$$\begin{aligned} p_{m-k+2}^{(j+1)} &\geq \frac{\eta}{|h_0|^2 [(m-k+1)D_v]^{-\beta}} \\ &\geq \Gamma_2(k). \end{aligned} \quad (32)$$

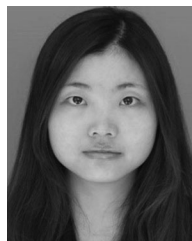
According to the constraint equations (18c) and (20), one can get

$$\begin{aligned} p_{m-k+2}^{(j+1)} &\geq p_{2k-m}^{(j)} \frac{\lambda [2(m-k)D_v + D_p]^{-\beta}}{[(m-k+1)D_v]^{-\beta}} 3 \\ &\quad + \frac{\sigma \lambda}{|h_0|^2 [(m-k+1)D_v]^{-\beta}} \\ &\geq p_{2k-m}^{(j)} \Gamma_3(k) + \Gamma_4(k). \end{aligned} \quad (33)$$

Substitute (31), (32), and (33) back into the optimization objective function and constrain equations (18a)–(18d) of the power control problem for member vehicles, then, the relationship among the optimization objective function and the constrain equations (31), (32), and (33) can be described as Fig. 9 for a given  $k$  ( $\frac{m+2}{2} \leq k \leq m$ ). Thus, the power control problem for member vehicles can be simplified. ■

## REFERENCES

- [1] P. A. Ioannou and C.-C. Chien, "Autonomous intelligent cruise control," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 657–672, Nov. 1993.
- [2] 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.
- [3] A. Ali, G. Garcia, and P. Martinet, "The flatbed platoon towing model for safe and dense platooning on highways," *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 1, pp. 58–68, Spring 2015.
- [4] 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.
- [5] K. Abboud and W. Zhuang, "Stochastic modeling of single-hop cluster stability in vehicular ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 226–240, Jan. 2016.
- [6] Mercedes Benz-Daimler, "Highway pilot connect: Networked trucks drive in a convoy for greater safety and lower fuel consumption," *Shaping Future Transportation: Campus Connectivity*, press article, Daimler Global Media Site, Mar. 2016.
- [7] 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.
- [8] Google, "Google-self driving car project," 2016. [Online]. Available: <https://www.google.com/selfdrivingcar/>
- [9] European Commission, "The safe road trains for the environment (SARTRE) project," 2016. [Online]. Available: <http://www.sartre-project.eu/>
- [10] USDOT, "The national automated highway system consortium (NAHSC) project," 2016. [Online]. Available: <https://www.fhwa.dot.gov/>
- [11] Volkswagen Group Research, "The cooperative mobility solution for supervised platooning (COMPANION) project," 2016. [Online]. Available: <http://www.companion-project.eu/>
- [12] 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.
- [13] G. Guo and S. Wen, "Communication scheduling and control of a platoon of vehicles in VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 6, pp. 1551–1563, Jun. 2016.
- [14] D. Swaroop, "String stability of interconnected systems: An application to platooning in automated highway systems," California Partners Adv. Transit Highways, Richmond, CA, USA, Tech. Rep. UCB-ITS-PRR-97-14., 1997.
- [15] P. Fernandes and U. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 91–106, Mar. 2012.
- [16] 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.
- [17] R. Rajamani, *Vehicle Dynamics and Control*. New York, NY, USA: Springer Science & Business Media, 2011.
- [18] 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 Trans. Intell. Transp. Syst.*, vol. 16, no. 1, pp. 102–112, Feb. 2015.
- [19] 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.
- [20] J. Liu, Y. Kawamoto, H. Nishiyama, N. Kato, and N. Kadowaki, "Device-to-device communications achieve efficient load balancing in LTE-advanced networks," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 57–65, Apr. 2014.
- [21] J. Liu, S. Zhang, N. Kato, H. Ujikawa, and K. Suzuki, "Device-to-device communications for enhancing quality of experience in software defined multi-tier LTE-A networks," *IEEE Netw.*, vol. 29, no. 4, pp. 46–52, Jul. 2015.
- [22] D. Feng, L. Lu, Y.-W. Yi, G.-Y. Li, G. Feng, and S. Li, "Device-to-device communications underlying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541–3551, Aug. 2013.
- [23] J. Liu, H. Nishiyama, N. Kato, and J. Guo, "On the outage probability of device-to-device-communication-enabled multichannel cellular networks: An RSS-threshold-based perspective," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 1, pp. 163–175, Jan. 2016.
- [24] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," *IEEE Commun. Surveys Tut.*, vol. 17, no. 4, pp. 1923–1940, Dec. 2015.
- [25] 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.
- [26] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, Dec. 2016.
- [27] Q. Ye, W. Zhuang, L. Li, and P. Vigneron, "Traffic-load-adaptive medium access control for fully connected mobile ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9358–9371, Nov. 2016.
- [28] H. Peng *et al.*, "Performance analysis of IEEE 802.11p DCF for multi-platooning communications with autonomous vehicles," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2485–2498, Mar. 2017.
- [29] J. Calabuig, J. Monserrat, D. Gozalvez, and O. Klemp, "Safety on the roads: LTE alternatives for sending ITS messages," *IEEE Veh. Technol. Mag.*, vol. 9, no. 4, pp. 61–70, Dec. 2014.
- [30] 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.
- [31] E. Yaacoub, F. Filali, and A. Abu-Dayya, "QoE enhancement of SVC video streaming over vehicular networks using cooperative LTE/802.11 p communications," *IEEE J. Sel. Top. Signal Process.*, vol. 9, no. 1, pp. 37–49, Feb. 2015.
- [32] 3GPP, "Study on LTE support for V2X services (release 14)," Technical Specification Group Services and System Aspects, Tech. Rep. 3GPP TR 36.885, 2016.
- [33] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for full-duplex relaying-based D2D communication underlying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4911–4916, Oct. 2015.
- [34] 3GPP, "The mobile broadband standard," 2016. [Online]. Available: <http://www.3gpp.org/DynaReport/23246.htm>
- [35] 3GPP, "Multimedia broadcast/multicast service (MBMS); architecture and functional description (release 13)," Technical Specification Group Services and System Aspects, Tech. Rep. 3GPP TS 23.246 V13.0.0, 2015.
- [36] 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.
- [37] 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.
- [38] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Energy efficiency and spectrum efficiency of multihop Device-to-Device communications underlying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 367–380, Jan. 2016.
- [39] 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.
- [40] S. T. Veetil, K. Kuchi, and R. K. Ganti, "Performance of PZF and MMSE receivers in cellular networks with multi-user spatial multiplexing," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 4867–4878, Sep. 2015.



**Haixia Peng** (S'15–M'17) received the M.S. and Ph.D. degrees in electronics and communication engineering and computer science from Northeastern University, Shenyang, China, in 2013 and 2017, respectively. She is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. Her current research focuses on vehicular networks and communication security in platoon. She was a TPC member in IEEE VTC-fall 2016&2017, IEEE Globecom 2016&2017, IEEE ICC 2017&2018 conferences.



**Dazhou Li** received the B.S. degree in electronic information science and technology from Liaoning University, Shenyang, China, in 2005, and the M.S. and Ph.D. degrees from Northeastern University, Shenyang, China, in 2008 and 2014, respectively. He is currently a Lecturer in the College of Computer Science and Technology, Shenyang University of Chemical Technology, Shenyang, China. His current research interests include wireless communication, network topology control and network performance analysis in vehicular ad hoc networks,

and body area network.



**Qiang Ye** (S'16–M'17) received the B.E. degree in network engineering, the M.E. degree in communication and information system from Nanjing University of Posts and Telecommunications, Nanjing, China, and the Ph.D. degree in electrical and computer engineering from University of Waterloo, Waterloo, ON, Canada, in 2009, 2012, and 2016, respectively. Since December 2016, he has been a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, University of Waterloo. His research interests include medium access control and performance

optimization in mobile ad hoc networks and Internet of Things, resource virtualization for 5G networks, and software-defined networking.



**Khadige Abboud** received the B.Sc. degree in electrical engineering from Kuwait University, Kuwait, in 2007, and the Ph.D. and M.A.Sc. degrees in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2009 and 2015, respectively. Her research interests include vehicle mobility modeling, node cluster stability, and cellular-DSRC interworking for vehicular communications. She received the Best Paper Award from the ACM MSWiM 2014. She was a TPC member in the IEEE ScalCom 2014, IEEE Globecom (2015–2016),

and IEEE VTC-fall 2016–2017 conferences. From 2015 to 2016, she was a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Waterloo. She is currently a Fellow at Insight Data-Science program in Boston, MA.



**Hai Zhao** received the B.S. degree in electrical engineering from Dalian Maritime University, Dalian, China, in 1982, the M.S. and Ph.D. degrees in computer science from Northeastern University, Shenyang, China, in 1987 and 1995, respectively. He is a Professor in the Department of Computer Science and Technology, Northeastern University. He is the Director of Liaoning Provincial Key Laboratory of Embedded Technology. His current research interests include embedded internet technology, wireless sensor network, vehicular ad hoc network, body area

network, pervasive computing, operating system, data and information fusion, and computer simulation and virtual reality. He received allowance of the State Council due to his special contributions to the development of education.



**Weihua Zhuang** (M'93–SM'01–F'08) has been with the Department of Electrical and Computer Engineering, University of Waterloo, Canada, since 1993, where she is currently a Professor and a Tier I Canada Research Chair in wireless communication networks. Her current research focuses on resource allocation and QoS provisioning in wireless networks, and on smart grid. She was a corecipient of several best paper awards from the IEEE conferences. She was the Editor-in-Chief of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY from 2007 to 2013, and the

Technical Program Co-Chair/Chair of the IEEE VTC 2016/2017. She is a Fellow of the Canadian Academy of Engineering, the Engineering Institute of Canada, an Elected Member of the Board of Governors, and the VP Publications of the IEEE Vehicular Technology Society.



**Xuemin (Sherman) Shen** (M'97–SM'02–F'09) received the B.Sc. degree from Dalian Maritime University, Dalian, China, in 1982, and the M.Sc. and Ph.D. degrees from Rutgers University, New Brunswick, NJ, USA, in 1987 and 1990, respectively, all in electrical engineering. He is a University Professor and Associate Chair for Graduate Studies, Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on resource management in interconnected wireless/wired networks, wireless network security,

social networks, smart grid, and vehicular ad hoc and sensor networks. He was an elected member of IEEE ComSoc Board of Governor, and the Chair of Distinguished Lecturers Selection Committee. He was the Technical Program Committee Chair/Co-Chair for IEEE GLOBECOM'16, INFOCOM'14, IEEE VTC'10 Fall, and GLOBECOM'07, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08, the General Co-Chair for ACM MobiHoc'15, CHINACOM'07 and QShine'06, the Chair for IEEE Communications Society Technical Committee on Wireless Communications, and P2P Communications and Networking. He was also the Editor-in-Chief of IEEE NETWORK, *Peer-to-Peer Networking and Application*, and *IET Communications*, and IEEE INTERNET OF THINGS JOURNAL, a Founding Area Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *Computer Networks*, and *ACM/Wireless Networks*, etc.; and the Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE WIRELESS COMMUNICATIONS, IEEE COMMUNICATIONS MAGAZINE, and *ACM Mobile Networks and Applications*, etc. He received the Excellent Graduate Supervision Award in 2006. He is a registered Professional Engineer in Ontario, Canada, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, a Royal Society of Canada Fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology Society and Communications Society.