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Efficient Groupcast Schemes for Vehicle Platooning in V2V Network

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ABSTRACT Recently, groupcast has taken a lot of attention for vehicle platooning in vehicle-to-vehicle (V2V) network. In general, a traditional groupcast scheme by retransmission where source vehicle user equipment (S-VE) repeatedly transmits the same packet to destination VEs (D-VEs) is implemented in two ways; repetitive transmission for a predetermined number of times without receiving hybrid automatic repeat request (HARQ)-ACK/NACK from the D-VEs, and retransmission based on the HARQ-ACK/NACK. Although the former scheme is very easy to implement, it may lead to inefficient resource utilization due to excessive retransmissions. For the latter, the same problem arises when link quality between S-VE and D-VE is constantly poor. Hence, in this paper, we first investigate a heuristic scheme that can yield the superior performance of groupcast success rate with low computational complexity. Then, a groupcast scheme with the joint control of retransmission VE (R-VE) selection and time domain resource allocation is investigated by formulating a Markov decision process (MDP). The goal of the second proposed scheme is to find an optimal joint strategy for R-VE selection and time domain resource allocation that can minimize total time consumption while satisfying desired performance in terms of groupcast success rate. Simulation results validate that the proposed schemes significantly improve the groupcast success rate and the efficiency of time domain resource utilization, and greatly reduce the completion time of groupcast as compared with the two traditional groupcast schemes.

INDEX TERMS V2V communications, groupcast, vehicle platooning, MDP.

I. INTRODUCTION

Vehicle-to-everything (V2X) communications has recently attracted considerable attention as a facilitator of intelligent transportation system (ITS). V2X is expected to enable various emerging automotive applications such as road safety improvement, efficient traffic management, autonomous driving and broadband in-vehicle infotainment services, which will provide safer and more efficient driving experience in our future daily lives. In particular, long term evolution (LTE) V2X, also known as cellular V2X (C-V2X), is emerging rapidly and being considered as an alternative to 802.11p owing to its longer communication ranges and higher data rates [1]–[4]. Meanwhile, the 3rd Generation Partnership Project (3GPP) launched a new study item (SI)

for standardization of new radio (NR)-based V2X from the RAN1#94 meeting in August 2018 after the completion of 5G NR release 15 (Rel-15) specification in June 2018 [5]. The NR V2X aims to support a wide range of advanced V2X services specified in technical report (TR) 22.886 [6] beyond services supported in LTE Rel-15 V2X by interworking with LTE V2X.

Vehicle platooning is one of the four major use case categories considered for the advanced V2X services [6]. In vehicle platooning, vehicles dynamically formed into a platoon are able to accelerate or brake simultaneously, which can eliminate the distance needed for human reaction and allow a closer headway between vehicles [7], [8]. Hence, it has recently emerged as a promising strategy that can enable the road capacity enhancement preventing traffic jams [9] and raise the fuel efficiency of vehicles in the platoon [10].

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To offer such advanced V2X services with key requirements in technical specification (TS) 22.186 [11], the current NR V2X standardization is primarily focused on sidelink design. The sidelink, first defined in 3GPP Rel-12 device-to-device (D2D) standardization, is a direct communication link between user equipments (UEs) including vehicle-to-vehicle (V2V) link and vehicle-to-pedestrian (V2P) link. In a recent 3GPP RAN1 meeting, additional sidelink operations, groupcast and unicast, were introduced along with the broadcast that is basically supported in LTE V2X. The groupcast, a type of communications similar to multicast, is a way to distribute information from a vehicle to multiple intended vehicles in the same group.

Unlike the existing LTE V2X, it has been agreed in RAN1#94-Bis meeting [12] that sidelink feedback control information (SFCI) is defined in NR V2X to include hybrid automatic repeat request (HARQ)-ACK. Subsequently, in RAN1#95 meeting, it was further agreed to define a new sidelink channel called physical sidelink feedback channel (PSFCH) to convey SFCI for unicast and groupcast. Obviously, the simplest implementation of groupcast is to perform blind retransmission in which source vehicle UE (S-VE) repeatedly transmits the same packet for a pre-determined number of transmissions without the necessity of receiving HARQ-ACK feedbacks from destination VEs (D-VEs). Although it can minimize implementation complexity, it is inefficient in terms of resource efficiency caused by excessive retransmissions. That's the main reason why the HARQ-ACK feedback is introduced for groupcast in NR V2X, and the retransmission can be performed with the HARQ-ACK feedback received from D-VEs to prevent the excessive retransmissions. However, in vehicle platooning, the link quality between S-VE and D-VE may not be good enough to deliver high-rate packets due to signal blockage caused by vehicle body of other VEs located between them, especially in the case of carrier frequency higher than 6 GHz (e.g., frequency range 2 (FR2) in 5G NR), which makes the groupcast susceptible to communication failures and results in an increase in the number of retransmissions.

Hence, in this paper, we investigate efficient groupcast schemes for vehicle platooning in a V2V network. The prominent feature of this work is that the problem of groupcast for vehicle platooning is formulated as a Markov decision process (MDP) to find an optimal policy of joint retransmission VE (R-VE) selection and time domain resource allocation that can minimize total time consumption while achieving a satisfactory groupcast success rate performance. Furthermore, we present a heuristic groupcast scheme that can yield superior performance in terms of groupcast success rate with low computational complexity. The rest of this paper is organized as follows. We first summarize related works in Section II. In Section III, we present the system model and channel model, and the basic problem formulation is presented in Section IV. Then, two traditional groupcast schemes and two proposed groupcast schemes that are designed based on heuristic approach and MDP formulation are presented

in Section V. In Section VI, extensive simulations have been conducted to analyze performance. Finally, we draw conclusions of the paper with brief discussions of future work in Section VII.

II. RELATED WORK

Recently, many studies have been done on designing multicast schemes assisted by user cooperation. [13]–[16]. Wang *et al.* [13] investigated a cooperative multicast technique that allows users to function as relays by studying its secure outage behavior and deriving the analytical expression of secure outage probability. Lee *et al.* [14] proposed a novel selective relay control-based multicast scheme capable of reducing unnecessary relay power consumption. The relay selection of this scheme is performed with consideration of the condition of nearby users. Similar to our work, Uddin *et al.* [15] investigated the joint problem of relay selection and optimal sharing of relay power in wireless cellular networks with multicast traffic. The authors formulated the combinatorially complex problem as a mixed Boolean-convex optimization problem and solved it using the branch and bound technique.

Moreover, multicast schemes have been researched for many years in efforts to enhance various target system performances such as throughput, outage and transmission completion time (TCT). The research by Zhang *et al.* [16], which is one of the most relevant studies to our paper, studied the optimal selection of broadcast relay vehicles in a multi-hop broadcast. The authors combined the sender-based and receiver-based selection schemes and proposed a Broadcast scheme based on the Prediction of Dynamics in order to minimize broadcast delay and maximize broadcast efficiency. They further proposed metrics called the estimated remaining delay and expected rebroadcast efficiency respectively for reducing the broadcast delay and maximizing broadcast efficiency, and proved that proposed protocols outperform conventional protocols and achieve the least delay and the highest dissemination efficiency.

Besides the work [16], many studies have been done on minimizing TCT and multicast retransmissions. First of all, Chi *et al.* in [17] studied TCT minimization for the uplink transmission of a given number of bits per node in wireless powered communication network, in which one hybrid access point with constant power supply coordinates the wireless energy/information transmissions to/from a set of one-hop nodes powered by the harvested RF energy only. The authors verified that the harvest-then-transmit transmission strategy is one of the transmission strategies for minimizing TCT. Secondly, Zhou *et al.* in [18] formulated the problem of finding an optimal number of retransmitters in D2D retransmissions in terms of resource utilization efficiency. The authors derived a closed-form expression for the probability density function (PDF) of an optimal number of retransmitters, and then proposed an intracluster D2D retransmission scheme, where the number of retransmitters adaptively changes to instantaneous D2D channel conditions. Thirdly,

Chi *et al.* [19] presented the subcluster based single-channel D2D retransmission method where the ACK-devices operating in the time division multiple access (TDMA) mode in the same channel, and formulated the joint optimization of NACK-devices' association and retransmitters' transmission powers as an mixed integer nonlinear programming problem, minimizing the total energy consumption of retransmitters. Then, they also proposed an algorithm for this problem and proved that the proposed algorithm greatly reduces the total energy consumption of retransmitters as compared with conventional schemes with a fixed number of retransmitters.

In addition to the studies [13]–[16], many studies have been conducted to consider routing selection in various multi-hop cognitive radio network (CRN) scenarios [20]–[22]. Banerjee *et al.* [21] formulated an optimization problem in multi-hop CRN minimizing the end-to-end secondary outage probability under the constraints of energy causality and primary user cooperation rate. The authors explored the optimal route selection for total power consumption minimization and network lifetime enhancement. Similarly, He *et al.* [22] modeled the energy harvesting multi-hop CRN communication problem as a partially observable MDP and the Q-learning reinforcement learning algorithm was used to find a routing strategy aimed at maximizing transmission rate and minimizing energy consumption.

Similar to the approach of our study, Ali and Taha [23] formulated the problem of finding the best relay that meets the QoS data rate requirements of the connections' traffic given the allocated subcarriers as an MDP and solved it using the Gauss-Seidel value iteration algorithm. In addition, vehicle platooning in a C-V2X network was studied by Wang *et al.* [24]. The authors investigated the platoon cooperation in the multi-lane platoons scenario where platoons communicate with each other through C-V2X communications, and proposed a two-step subchannel allocation strategy that platoon head performs the intra-platoon subchannel allocation based on the subchannel resources allocated by base station (BS). They also designed a subchannel allocation and power control algorithm for the joint optimization of platoon formation, subchannel allocation, and power control based on distributed dynamic programming (DP).

In this paper, we focus on the problem of groupcast for vehicle platooning in a V2V network. To the best of our knowledge, little research has been done so far on formulating this problem as an MDP and exploring the optimal joint strategy of R-VE selection and time domain resource allocation that can minimize total time consumption, which differentiates our work from the aforementioned studies. More specifically, the main contributions of this paper are summarized as follows.

- Unlike most previous research on multicast scenarios operating under the support of network, we consider a groupcast scenario for vehicle platooning without network assistance, which is one of vehicle platooning scenarios (e.g., in rural highways).

- To better capture the channel characteristics of groupcast for vehicle platooning, Nakagami-*m* fading channel is considered and signal penetration loss by vehicles is further taken into account.

- We assume a relatively realistic environment where transmitter has no knowledge of the instantaneous channel state information (CSI) of V2V links considering the CSI at the time of transmission may differ from the estimated CSI due to the rapid channel variation in typical vehicular communications, which is one difference from the assumption in [19] that BS has knowledge of the instantaneous channel power gains of D2D links.

- We formulate the problem of V2V groupcast for vehicle platooning as a finite-horizon MDP and propose a groupcast scheme with the optimal joint policy of R-VE selection and time domain resource allocation that can minimize time consumption while achieving a desired groupcast success rate performance.

- A new design of state space and action space is proposed for the MDP-based proposed scheme to reduce computational complexity, which makes the proposed scheme feasible in implementation.

III. V2V GROUPCAST FOR VEHICLE PLATOONING

In this section, we first describe the system model and channel model of groupcast for vehicle platooning in a V2V network.

A. SYSTEM MODEL

As illustrated in Fig. 1, we consider V2V groupcasts for vehicle platooning without network assistance in highway environments (e.g., rural highways) where vehicles are out of coverage or data rate of vehicle-to-network (V2N) link is insufficient to support vehicle platooning. In this system, a group of vehicles that are composed of a head vehicle and a number of followers, called vehicle platoon, drive cooperatively by continuously coordinating their speed and distance through V2V communications. A single-lane vehicle platooning scenario, where all vehicles in the platoon driving at the same speed are deployed in the same lane with the same separation distance, is considered. Specifically, this paper assumes that the vehicles in the platoon move according to the intelligent driver model (IDM) [25], and each vehicle in the platoon reaches an equilibrium point prior to groupcast. The equilibrium intra-platoon spacing d_e, hereinafter referred to as vehicle separation distance (VSD), can be expressed as a function of the equilibrium velocity denoted by v_e as follows [26]

$$d_e = \frac{d_0 + v_e T_0}{\sqrt{1 - (\frac{v_e}{v_0})^4}}, \tag{1}$$

where T_0 represents the desired time headway in seconds, and d_0 and v_0 denote the minimum VSD [m] and the maximum velocity [m/s], respectively. It is very intuitive to see from (1) that the VSD is mainly determined by the velocity of the platoon, and as velocity v_e increases, d_e should be increased to
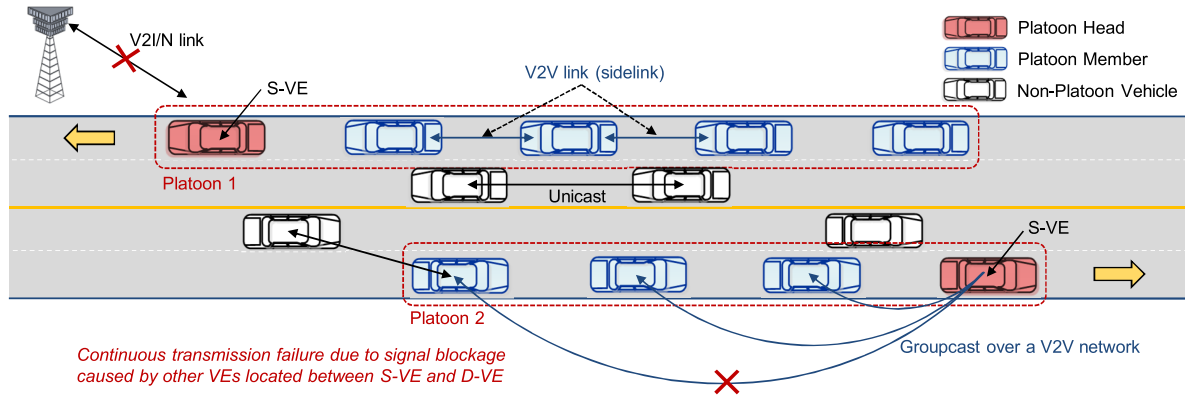
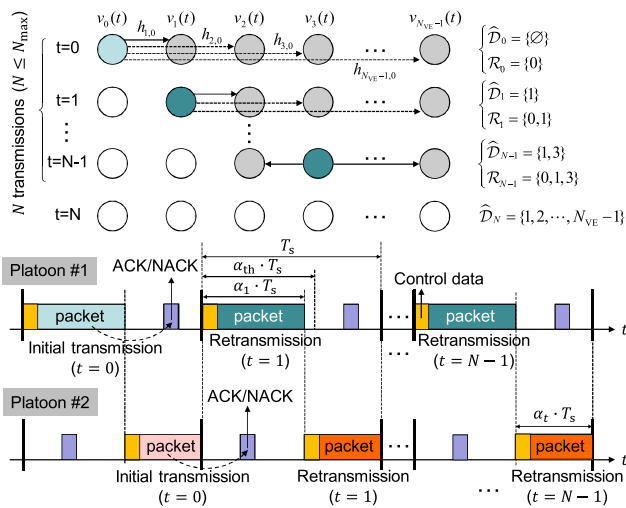**FIGURE 1.** Illustration of system model for vehicle platooning.

FIGURE 2. Illustration of system model where a packet is transmitted over *N* transmissions.

deploy the vehicles in the platoon at a larger VSD in order to ensure vehicle safey. Then, the distance between i-th VE and j-th VE can be expressed as

$$d_{i,j} = |i - j| \cdot d_e. \qquad (2)$$

In the considered groupcast scenario, a platoon is formed by a group of VEs $\mathcal{G} = \{0, 1, \cdots, N_{VE} - 1\}$, and the groupcast performed by VEs over V2V links is basically divided into two transmission phases: *initial transmission phase* and *retransmission phase*. In the *initial transmission phase*, S-VE $j' \in \mathcal{G}$ delivers a packet to a group of D-VEs $\mathcal{D} = \mathcal{G} \setminus j'$ over V2V channels. After the *initial transmission*, some of the D-VEs may not successfully receive the packet due to signal loss caused by channel fading. Therefore, as shown in Fig. 2, the *retransmission phase* can be initiated to retransmit the packet within the maximum allowable number of retransmissions N_{ret} (equivalently, the maximum number of transmissions allowed N_{max} is $N_{ret} + 1$). To prevent excessive retransmission, each D-VE

can be configured to send HARQ-ACK/NACK to inform the transmitting VE of whether retransmission is required. By receiving the HARQ-ACK/NACK, the transmitting VE can retransmit the packet until it is received by all D-VEs in the platoon within the allowable number of transmissions. Therefore, the actual number of transmissions (initial transmission + retransmission) N is less than or equal to N_{max} (i.e. $N \leq N_{max}$).

Furthermore, for retransmission, the S-VE and the D-VEs that successfully decoded the data over past transmissions are considered as candidates of R-VE, and a R-VE can be dynamically selected at each slot from the R-VE candidates which can significantly increase the efficiency of retransmission. For the sake of simplifying analysis, we assume that a negligible amount of resources, which doesn't overlap with the resource for packet transmission in the frequency domain, is allocated to carry HARQ-ACK/NACK information, and the HARQ-ACK/NACK is received without error. For time domain resource allocation at each slot, the scheduling granularity is OFDM symbol. At each transmission slot t, groupcast can be carried out by controlling the number of OFDM symbols K_t for delivering a packet, and K_s is the maximum number of OFDM symbols that can be allocated within a slot, i.e., $K_t \leq K_s$. Although this paper only focuses on the groupcast of one platoon, symbol-level TDMA may be allowed in this V2V network. For instance, as depicted in Fig. 2, by receiving the control data of platoon 1 containing its resource allocation information K_t, the remaining $K_s - K_t$ OFDM symbols in slot t can be utilized by other platoons or VEs (e.g., platoon 2 and unicast VEs) using the same V2V channel.

In addition, as illustrated in Fig. 2, we define α_t as the ratio of allocated OFDM symbols in slot t, which can be expressed as a fraction below

$$\alpha_t = \frac{K_t}{K_s}. \qquad (3)$$

T_s is the slot duration (e.g., $T_s = 250\mu s$ in 5G NR with subcarrier spacing of 60 kHz), which corresponds to the length of K_s OFDM symbols, and $\alpha_t T_s$ represents the length of time resource allocated to slot t. $\alpha_{th} T_s$, which is equivalent

to the length of K_{th} OFDM symbols, indicates the maximum time duration allowed for V2V groupcast schemes with HARQ-ACK feedback at each slot. By determining an appropriate value of K_{th} such that $\alpha_{th}T_s = \frac{K_{th}}{K_s}T_s < T_s$ is short enough to cover the processing time required for the packet reception and associated HARQ-ACK/NACK transmissions as well as the preparation for retransmission within a slot duration, groupcast can be performed over consecutive slots as shown in Fig. 2, which enables to support low-latency V2X applications. Since in NR V2X, a total of 14 OFDM symbols can be used for each slot, we consider $K_s = 14$, and for groupcast schemes with HARQ-ACK feedback, we assume up to 10 OFDM symbols in each slot can be used, i.e., $K_t \leq K_{th} = 10$.

B. CHANNEL MODEL

We consider the V2V groupcast network operating at mmWave frequencies, which is capable of supporting a wide range of broadband and low-latency V2X services by allowing the utilization of a vast amount of spectrum and the reduction of transmission slot duration as compared with sub-6 GHz systems. We also consider the case where all vehicles in the platoon travel on the same lane, and the S-VE, which is the preceding vehicle running in front of the other vehicles (i.e., $j' = 0$), shares V2X information (e.g., safety critical information) to the other VEs. In this case, the obstruction of the vehicles located between S-VE and D-VE has a substantial influence on the performance of groupcast due to the serious penetration loss caused by the body of the vehicles, and it is obvious that the greater the number of VEs located between them is, the worse the performance is. In particular, blockage loss is known to be very severe in the high frequency band, and according to a field measurement conducted by AT&T [27], the blockage loss by a vehicle in the 39-GHz band was found to be approximately 5-7 dB.

For this reason, to capture the channel characteristics of vehicle platooning scenario as accurately as possible, the impact of signal blockage is taken into account for the channel model, and the signal blockage loss between i-th VE and j-th VE is given as follows

$$L_{i,j}^{dB} = \begin{cases} (|i-j|-1) \cdot \overline{L}_{blk}, & \text{if } i \neq j \\ 0, & \text{otherwise} \end{cases}, \quad \text{for } i, j \in \mathcal{G}, \quad (4)$$

where $\overline{L}_{blk}$ denotes the blockage loss caused by one vehicle. Furthermore, since the channel measurement results presented in [28] showed that a Nakagami distribution well describes the statistics of the small-scale fading in V2V communications and it was also used for the channel model in the work [29], we model the V2V groupcast channel for vehicle platooning as independent Nakagami-m fading channel with parameter m to characterize a wide range of fading environments for V2V links. Then, the channel coefficient of small-scale fading between i-th VE and j-th VE is defined as an independent and identically distributed (i.i.d.) random variable, $\bar{h}_{i,j} = |\bar{h}_{i,j}|e^{j\phi}$, where ϕ is assumed to be uniformly

distributed over $(0, 2\pi]$ [30], and $|\bar{h}_{i,j}|$ follows Nakagami-m distribution, $|\bar{h}_{i,j}| \sim \text{Nakagami}(m_{i,j}, \Omega_{i,j})$, whose PDF is given as follows

$$f_{|\bar{h}_{i,j}|}(x) = \frac{2m_{i,j}^{m_{i,j}} x^{2m_{i,j}-1}}{\Gamma(m_{i,j})\Omega_{i,j}^{m_{i,j}}} \exp\left(-\frac{m_{i,j}}{\Omega_{i,j}}x^2\right) U(x), \quad (5)$$

where $U(\cdot)$ signifies the unit step function and $\Gamma(\cdot)$ is the gamma function. The Nakagami-m channel model is a well-known general statistical fading channel model, where the parameter $m_{i,j}$ signifies the fading severity and smaller values of $m_{i,j}$ represent more fading in the channel. The special case of $m_{i,j} = 1$ yields the Rayleigh distribution, and $m_{i,j} < 1$ implies more severe fading. In the V2V groupcast channel, the Nakagami parameter $m_{i,j}$ is set differently depending on the presence of blocking vehicles between the transmitting and receiving VEs, which can be represented as follows

$$m_{i,j} = \begin{cases} 5, & \text{if } |i-j| = 1 \\ 1, & \text{otherwise} \end{cases}, \quad \text{for } i, j \in \mathcal{G}. \quad (6)$$

In case there is at least one blocking VE between the transmitting and receiving VEs, $m_{i,j}$ is set to 1 to assume a Rayleigh fading channel without a dominant line-of-sight (LoS) path. Otherwise, the Nakagami-m fading channel with $m_{i,j} = 5$ having a LoS path is assumed. Since it is noted that $m_{i,j} = \frac{\mathbb{E}[|\bar{h}_{i,j}|^2]^2}{\text{Var}[|\bar{h}_{i,j}|^2]}$, we assume that each VE is able to perfectly estimate $m_{i,j}$ by estimating $\mathbb{E}[|\bar{h}_{i,j}|^2]^2$ and $\text{Var}[|\bar{h}_{i,j}|^2]$, where $\mathbb{E}(\cdot)$ and $\text{Var}(\cdot)$ denote expectation and variance operators respectively. In addition, it is assumed that the average channel power is equal to 1, $\mathbb{E}[|\bar{h}_{i,j}|^2] = \Omega_{i,j} = 1$, and we consider the quasi-static fading channel whose fading channel coefficient $\bar{h}_{i,j}$ remains constant over one slot duration.

The groupcast channel matrix $\mathbf{H}(t) \in \mathcal{C}^{N_{VE} \times N_{VE}}$ at t slot is given as

$$\mathbf{H}(t) = \begin{bmatrix} 0 & h_{0,1}(t) & \cdots & h_{0,N_{VE}-1}(t) \\ h_{1,0}(t) & 0 & \cdots & h_{1,N_{VE}-1}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_{VE}-1,0}(t) & h_{N_{VE}-1,1}(t) & \cdots & 0 \end{bmatrix},$$
$$(7)$$

where the channel coefficient $h_{i,j}$ is given by $\sqrt{a_{i,j}} \cdot \bar{h}_{i,j}$, and we assume that channel reciprocity holds such that $h_{i,j}(t) = h_{j,i}(t)$ for $t \in \{0, 1, \cdots, N_{max} - 1\}$. $a_{i,j}$ is the coefficient containing large-scale fading (only path loss is considered), transmit (Tx) power and blockage loss, and it can be expressed in dB as follows

$$a_{i,j}^{dB} = P_{Tx,dBm} - PL_{dB}(d_{i,j}) - L_{i,j}^{dB}, \quad (8)$$

where path loss (PL) in dB is given as $PL_{dB}(d_{i,j}) = 92.4 + 20 \cdot \log_{10}(f_{c,GHz}) + 20 \cdot \log_{10}(\frac{d_{i,j}}{1000})$ [31].

Then the signal-to-noise ratio (SNR) of a link between i-th VE and j-th VE is written as $\gamma_{i,j} = \frac{|h_{i,j}|^2}{\sigma^2} = \xi_{i,j}|\bar{h}_{i,j}|^2$, where $\xi_{i,j} = \frac{a_{i,j}}{\sigma^2}$ and $\sigma^2 = 10^{N_{dBm}/10}$. N_{dBm} denotes noise floor in dBm, which is the minimum equivalent input noise,

and it is given by $N_{\text{dBm}} = -174 + N_{\text{F,dB}} + 10 \cdot \log_{10}(W)$, where $N_{\text{F,dB}}$ is the noise figure in the case of a receiver at temperature (290K), and W is the bandwidth allocated for the V2V groupcast.

Since it is noticed that the channel power denoted by $|\bar{h}_{i,j}|^2$ follows Gamma distribution, the corresponding cumulative distribution function (CDF) is given as follows

$$F_{i,j}(g) = F_{|\bar{h}_{i,j}|^2}(g) = \frac{\hat{\Gamma}\left(k_{i,j}, \frac{g}{\theta_{i,j}}\right)}{\Gamma(k_{i,j})}, \qquad (9)$$

where parameters $k_{i,j}$ and $\theta_{i,j}$ are the shape and scale parameters respectively, and can be represented by the Nakagami-*m* distribution parameters as $k_{i,j} = m_{i,j}$ and $\theta_{i,j} = \frac{1}{m_{i,j}}$. $\hat{\Gamma}(\cdot, \cdot)$ denotes the incomplete Gamma function defined as equation (8.350.1) in [32]. Hence, the average SNR of a link between *i*-th VE and *j*-th VE is given as $\mathbb{E}[\gamma_{i,j}] = \xi_{i,j}\mathbb{E}[|\bar{h}_{i,j}|^2] = \xi_{i,j}k_{i,j}\theta_{i,j} = \xi_{i,j}$.

In typical vehicular communications, the perfect knowledge of instantaneous CSI at the transmitter may not be a reasonable assumption considering that the channel at the time of transmission may differ from the estimated channel due to rapid channel variation. Hence, we consider the case where the platoon only knows long-term CSIs (e.g., RSRP) of VEs, $\mathbb{E}[\gamma_{i,j}] = \xi_{i,j}$, which can be obtained by a similar sensing procedure as in LTE / NR V2X. The detailed sensing mechanism is beyond the scope of this paper. It is also assumed that the platoon knows that the fading channel follows the Nakagami-*m* distribution.

IV. BASIC PROBLEM FORMULATION

First the condition of communication failure between *i*-th VE and *j*-th VE is defined as

$$C_{i,j}(t) = W \cdot \log_2\left(1 + \gamma_{i,j}(t)\right) < \frac{B_{\text{pkt}}}{\alpha_t T_{\text{s}}}, \qquad (10)$$

where B_{pkt} is the packet size in bits and (10) can be rewritten as

$$|\bar{h}_{i,j}(t)|^2 < \bar{g}_{i,j}(t) = \frac{2^{\frac{R_{\text{pkt}}K_{\text{s}}}{WK_t}} - 1}{\xi_{i,j}}, \qquad (11)$$

where R_{pkt} is the minimum data rate $R_{\text{pkt}} = \frac{B_{\text{pkt}}}{T_{\text{s}}}$ [bit/s] required to transmit a packet of B_{pkt} bits, and $\bar{g}_{i,j}(t)$ is the minimum channel gain required to decode this packet.

Then the problem of V2V groupcast for vehicle platooning is interpreted as a finite-horizon MDP in which the packet reception status of each VE in the platoon changes at each slot after packet reception and the maximum number of transmissions is limited to N_{max}. In general, an MDP consists of five distinct elements [23], [33] which are decision epochs $t \in \{0, 1, \cdots, N_{\text{max}} - 1\}$, states s, actions a, transition probabilities $\Pr(s'|s, a)$ and rewards $r(s, a)$. More specifically, $r(s, a), r : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$, is the average reward given that action $a \in \mathcal{A}$ is taken in state $s \in \mathcal{S}$, and $\Pr(s'|s, a)$ is the probability distribution over the next state $s' \in \mathcal{S}$ given that action $a \in \mathcal{A}$

is taken in state $s \in \mathcal{S}$, where $\mathcal{S}$ and $\mathcal{A}$ denote state space and the set of all possible actions respectively.

Since the considered finite-horizon MDP problem, a tuple $\langle \mathcal{S}, \mathcal{A}, \Pr(s'|s, a), r \rangle$, is characterized by a deadline at time and focuses on the sum of the rewards up to that time, the optimization objective can be expressed as the expected total cumulative reward shown below

$$V^\pi(s) = \mathbb{E}_\pi\left[\sum_{t=0}^{N_{\text{max}}} r(s_t, a_t) \,|\, s_0 = s\right], \qquad (12)$$

where $\pi = (\pi_0, \pi_1, \cdots, \pi_{N_{\text{max}}-1})$, which is a non-stationary control policy, represents a sequence of decision rules, and each action at each decision epoch a_t, which is implemented by $a_t = \pi_t(s_t)$, corresponds to the joint decision of R-VE selection and time domain resource allocation at time slot t performed by the platoon. The expected cumulative reward $V^\pi(s)$ is also known as a state value function, and our goal is to maximize $V^\pi(s)$ over all control policies and find an optimal policy π^* that achieves the maximal value function $V^*(s) \triangleq V^{\pi^*}(s) = \max_{\pi \in \Pi} V^\pi(s)$.

To solve the above optimization problem, the celebrated "principle of optimality", which is at the heart of DP, can be applied. As a general principle, the "principle of optimality", states that *the tail of an optimal policy is optimal for the "tail" problem*. More specifically, the state value function of a state s' in (12) can be rewritten as follows

$$V_t^\pi(s')$$

$$= \mathbb{E}_\pi\left[\sum_{t'=t}^{N_{\text{max}}} r(s_{t'}, a_{t'}) \,|\, s_t = s'\right] \qquad (13)$$

$$= \sum_{a_t \in \mathcal{A}_t} \pi_t(a_t|s_t)\left[r(s_t, a_t) + \sum_{s_{t+1} \in \mathcal{S}_{t+1}} \Pr(s_{t+1}|s_t, a_t)V_{t+1}^\pi(s_{t+1})\right], \qquad (14)$$

where $r(s_t, a_t) = \sum_{s_{t+1} \in \mathcal{S}_{t+1}} \Pr(s_{t+1}|s_t, a_t) \cdot r(s_t, a_t, s_{t+1})$, and $\pi_t(a_t|s_t)$ denotes the probability of taking action a_t at state s_t at time t. It can be observed in (13) that when $t = 0$, $V_0^\pi(s) = V^\pi(s)$, and the objective function in (14) has the form of a Bellman equation, that is, a DP equation, which in general can be solved in several ways, such as value iteration, policy iteration, Q-learning, SARSA, etc. In our case, since it is a finite-horizon MDP problem, the backward recursion algorithm is used to recursively compute the optimal value functions $V_t^*(s_t)$ starting from $t = N_{\text{max}} - 1$ to $t = 0$ as shown below

$$V_t^*(s_t) = \max_{a_t \in \mathcal{A}_t}\left[r(s_t, a_t) + \sum_{s_{t+1} \in \mathcal{S}_{t+1}} \Pr(s_{t+1}|s_t, a_t)V_{t+1}^*(s_{t+1})\right], \qquad (15)$$

where $V_{N_{\text{max}}}^*(s_{N_{\text{max}}}) = R(s_{N_{\text{max}}})$, and $R(s_{N_{\text{max}}})$ is the reward function of the final state $s_{N_{\text{max}}}$, which is a state-only function. Equation (15) is known as the optimal Bellman equation, and

an optimal policy at time t can be chosen as

$$\pi_t^*(s_t) \in \underset{a_t \in \mathcal{A}_t}{\operatorname{argmax}} \Big[r(s_t, a_t) + \sum_{s_{t+1} \in \mathcal{S}_{t+1}} \Pr(s_{t+1}|s_t, a_t) V_{t+1}^*(s_{t+1}) \Big],$$
(16)

where $\pi_t^*(s_t) \in \operatorname{argmax}(\cdot)$, which is not $\pi_t^*(s_t) = \operatorname{argmax}(\cdot)$, is due to the fact that the MDP problem may admit more than one optimal policy. With the obtained optimal policy, groupcast can be performed at each time slot t by taking the optimal action $a_t^* = \pi_t^*(s_t)$. In MDP problem, the design of reward function plays a pivotal role, and thus the reward function should be designed to well capture the target system objective of groupcast for vehicle platooning in order to avoid undesired behavior by the obtained policy.

In this paper, we design two groupcast schemes respectively aimed at the objectives as follows

- *Objective 1: maximization of groupcast success rate,*
- *Objective 2: minimization of time consumption,*

and the MDP formulation is only considered for *objective 2*. The performance of the proposed schemes are compared with two traditional groupcast schemes, *groupcast based on blind retransmission* (GC-BR) and *groupcast based on HARQ-ACK feedback* (GC-HF) schemes, under the groupcast model described in section III. To help better understand the equations to be described below, some sets of VE groups are defined as follows:

$\hat{\mathcal{D}}_t$: The set of D-VEs that correctly received the packet over t transmission slots.

$\mathcal{F}_t$: The set of D-VEs that failed to receive the packet over t transmission slots, which can be also represented by $\mathcal{F}_t = \mathcal{D} \setminus \hat{\mathcal{D}}_t$.

$\mathcal{H}_t$: The set of HARQ-ACK/NACK feedback VEs (H-VEs) that are designated to feed back HARQ-ACK/NACK information corresponding to the packet received at t-th transmission slot.

$\mathcal{R}_t$: The set of R-VEs that are the candidates for the retransmission of packet at t-th transmission slot.

V. GROUPCAST SCHEMES FOR VEHICLE PLATOONING

This section describes two traditional groupcast schemes (GC-BR and GC-HR) and two proposed groupcast schemes.

A. TRADITIONAL GROUPCAST SCHEMES

Similar to LTE V2V communications, GC-BR initiates retransmission without receiving HARQ-ACK from D-VEs, $\mathcal{H}_t = \emptyset$. As a result, there is no way to inform S-VE of whether a packet is successfully received by D-VEs, and thus the S-VE repeats transmissions ($\mathcal{R}_t = j'$) for a predetermined number of times $N_{\max}$ to achieve a higher link reliability. For this reason, in some cases, it may significantly waste radio resources due to excessive retransmissions, which is a fatal disadvantage of this scheme. Nevertheless, since the processing time required for HARQ-ACK/NACK feedback procedure and preparation for associated retransmission is not needed in the GC-BR, it also has some benefits such as

the significant reduction of implementation complexity and signalling overhead and the full utilization of OFDM symbol resources in each slot for groupcast (i.e., $\alpha_t = 1$).

In contrast to the GC-BR, GC-HF configures the D-VEs in the platoon to feed back HARQ-ACK/NACK signal to S-VE, $\mathcal{H}_t = \mathcal{F}_t$. If a packet is received and decoded successfully by a D-VE, the D-VE reports an HARQ-ACK to the S-VE. Otherwise, a HARQ-NACK is reported to the S-VE. The number of transmissions in the GC-HF does not exceed $N_{\max}$.

B. GROUPCAST SCHEME FOR MAXIMIZING GROUPCAST SUCCESS RATE

As mentioned previously, in the considered vehicle platooning scenario, some D-VEs may experience a constantly poor channel due to the signal blockage by other VEs, which may be insufficient to receive the packet from S-VE and may result in frequent communication failure, and the performance degradation of groupcast becomes more acute as the platoon size increases. To this end, a heuristic groupcast scheme for *objective 1* aimed at maximizing groupcast success rate (GSR), hereinafter referred to as GC-GSR, is proposed by finding an optimal control of joint R-VE selection and time domain resource allocation. The R-VE is dynamically selected among the S-VE j' and the D-VEs $\hat{\mathcal{D}}_t$ that successfully received the packet over t slots, which can be represented by $\mathcal{R}_t = j' \bigcup \hat{\mathcal{D}}_t$.

The basic idea of GC-GSR is to find an optimal VE j_t^* and the optimal number of OFDM symbols K_t^* for each slot t that can maximize the average number of VEs $\mathcal{F}_t$ that successfully receive the packet at slot t, which can be derived as

$$(j_t^*, K_t^*) = \underset{(j \in \mathcal{R}_t, K_t)}{\operatorname{argmax}} \mathbb{E}_{|\bar{h}_{i,j}(t)|^2} \Big[\sum_{i \in \mathcal{F}_t} 1_{|\bar{h}_{i,j}(t)|^2 \geq \bar{g}_{i,j}(t)} \Big]$$

$$= \underset{(j \in \mathcal{R}_t, K_t)}{\operatorname{argmin}} \sum_{i \in \mathcal{F}_t} \Pr\left(|\bar{h}_{i,j}(t)|^2 < \bar{g}_{i,j}(t) \right)$$

$$= \underset{(j \in \mathcal{R}_t, K_t)}{\operatorname{argmin}} \sum_{i \in \mathcal{F}_t} F_{i,j}\Big(\frac{2^{\frac{R_{\text{pkt}}K_s}{WK_t}} - 1}{\xi_{i,j}} \Big),$$
(17)

where $1_{|\bar{h}_{i,j}(t)|^2 \geq \bar{g}_{i,j}(t)}$ represents the indicator function defined as

$$1_{|\bar{h}_{i,j}(t)|^2 \geq \bar{g}_{i,j}(t)} = \begin{cases} 1, & \text{if } |\bar{h}_{i,j}(t)|^2 \geq \bar{g}_{i,j}(t) \\ 0, & \text{otherwise} \end{cases}.$$
(18)

Since the first derivative of incomplete Gamma function $\hat{\Gamma}(\alpha, x)$ is positive as shown below

$$\frac{d}{dx}\hat{\Gamma}(\alpha, x) = -\frac{d}{dx}\Gamma(\alpha, x) = x^{\alpha-1}e^{-x} > 0,$$
(19)

$F_{i,j}(\cdot)$, which is the CDF of Gamma distribution given in (9), is an increasing function of x. Hence, obviously, $F_{i,j}(\cdot)$ is an increasing function of K_t, and the optimal number of OFDM symbols K_t^* is simply given as

$$K_t^* = K_{\text{th}}.$$
(20)

Thus (17) can be rewritten as

$$j_t^* = \operatorname*{argmin}_{j \in \mathcal{R}_t} \sum_{i \in \mathcal{F}_t} F_{i,j}\left(\frac{2^{\frac{R_{\text{pkt}}K_s}{WK_{\text{th}}}} - 1}{\xi_{i,j}}\right), \qquad (21)$$

which provides the criterion for the optimal R-VE selection of GC-GSR.

C. GROUPCAST SCHEME FOR MINIMIZING TIME CONSUMPTION

In this subsection, the design of the proposed groupcast for the *objective 2* aimed at minimizing total time consumption (TC) is presented, and the proposed groupcast scheme is hereinafter referred to as GC-TC.

1) STATE

As previously mentioned, since the maximum number of transmissions is limited to N_{max}, the V2V groupcast problem can be simply modeled as a finite-horizon MDP. In this model, a state $s_t \in \mathcal{S}_t$ consisting of two sub-states, which are the packet reception state of platoon at slot t represented by a vector $\mathbf{v}_t$ and the sub-state representing the cumulative sum of the number of allocated OFDM symbols in addition to δ_{ref} symbols of each slot over t consecutive transmissions denoted by e_t, is defined, and the state space is given as

$$\mathcal{S}_t = \mathcal{V}_t \times \mathcal{E} = \{(\mathbf{v}_t, e_t) | \mathbf{v}_t \in \mathcal{V}_t, e_t \in \mathcal{E}\}, \qquad (22)$$

where $\times$ is the Cartesian product operator. More specifically, the packet reception state $\mathbf{v}_t \in \mathcal{V}_t$ at transmission slot $t \in \{0, 1, \cdots, N_{\text{max}} - 1\}$, which indicates whether VEs in the platoon receive the packet over t slots, is given as below

$$\mathbf{v}_t = [v_0(t), v_1(t), \cdots, v_{N_{\text{VE}}-1}(t)]^T, \qquad (23)$$

where each element $v_i(t)$ is a binary variable indicating the packet reception state of i-th VE at t slot. If the i-th VE has failed to receive data over t transmissions, $v_i(t) = 0$. Otherwise $v_i(t) = 1$. For example, suppose a platoon is formed by five VEs, $N_{\text{VE}} = 5$, and VE 0 is S-VE, $v_0(t) = 1$. In this case, if VE 1 and VE 3 in the platoon correctly received the packet over the past two transmissions, the sub-state $\mathbf{v}_2$ is $[1, 1, 0, 1, 0]^T$. Since $e_t \in \mathcal{E}$ represents the cumulative sum of the number of allocated OFDM symbols in addition to δ_{ref} symbols of each slot over t consecutive transmissions, it can be generally expressed as

$$e_t = \begin{cases} 0, & \text{if } t = 0 \\ e_{t-1} + \delta_{t-1}, & \text{if } t > 0 \end{cases}, \qquad (24)$$

where $\delta_t \in [-\delta_{\text{ref}}, K_{\text{th}} - \delta_{\text{ref}}]$ is the number of allocated OFDM symbols in addition to the reference number of OFDM symbols δ_{ref} at slot t, i.e., $K_t = \delta_{\text{ref}} + \delta_t$. Suppose $\delta_{\text{ref}} = 5$ and 7 OFDM symbols are allocated for the initial transmission ($t = 0$), then $\delta_0 = 2$ which is the additional number of allocated OFDM symbols and thus the cumulative sum of the additional number of allocated OFDM symbols after the transmission is $e_1 = e_0 + \delta_0 = 2$. After the initial

transmission, if the first retransmission at $t = 1$ slot is done by allocating four OFDM symbols (i.e., $\delta_1 = -1$), then the cumulative sum of the additional number of allocated OFDM symbols over the two slots can be obtained by $e_2 = e_1 + \delta_1 = 2 - 1 = 1$. The rationale for the definition of sub-state e is explain in Section V-C.3.

In this paper, since we assume the head VE is S-VE, the initial state $s_0 = (\mathbf{v}_0, e_0)$ is given as $([1, 0, \cdots, 0, 0]^T, 0)$, and the groupcast is terminated when the state $\mathbf{v}_t$ reaches terminal state $[1, 1, \cdots, 1, 1]^T$ or the number of transmissions N reaches N_{max}.

2) ACTION

The policy of GC-TC is defined as a sequence of joint decision rules for R-VE selection and time domain resource allocation, and the action space $\mathcal{A}_t$, a set of possible actions at slot t, can be generally defined as

$$\mathcal{A}_t = \mathcal{R}_t \times \mathcal{K} = \{(j_t, K_t) \mid j_t \in \mathcal{R}_t, K_t \in \mathcal{K}\}, \qquad (25)$$

where $j_t \in \mathcal{R}_t \subset \mathcal{G}$ is a VE chosen for transmitting packet and $\mathcal{K}$ is the set of the allocable number of OFDM symbols per slot. However, instead of the action space in (25), we redesign the action space with a slight modification as follows

$$\tilde{\mathcal{A}}_t = \mathcal{R}_t \times \tilde{\mathcal{K}} = \{(j_t, \delta_t) \mid j_t \in \mathcal{R}_t, \delta_t \in \tilde{\mathcal{K}}\}, \qquad (26)$$

where $\tilde{\mathcal{K}} = \{\delta \mid \delta + \delta_{\text{ref}} \in \mathcal{K}\}$, and then $\mathcal{A}_t$ in (15) and (16) is replaced by $\tilde{\mathcal{A}}_t$ in (26). The reason for this modification is also explained in Section V-C.3.

3) REWARD

Since the problem of minimizing time consumption while satisfying desired groupcast success rate can be equivalently interpreted as the problem of maximizing transmission efficiency of groupcast, the reward function at slot t is defined as the groupcast efficiency over $t + 1$ slots, which can be expressed as follows

$$r(s_t, a_t, s_{t+1})$$
$$= \begin{cases} \dfrac{\{\|\mathbf{v}_{t+1}\|_1 - 1\}^+}{K_{\text{tot},t+1}}, & \text{if } t = N_{\text{max}} - 1 \\[3mm] \dfrac{\|\mathbf{v}_{t+1}\|_1 - 1}{K_{\text{tot},t+1}}, & \text{if } t < N_{\text{max}} - 1, \|\mathbf{v}_{t+1}\|_1 = N_{\text{VE}} \\[3mm] 0, & \text{otherwise,} \end{cases}$$
$$\qquad (27)$$

where $\{\cdot\}^+ \triangleq \max\{\cdot, 0\}$, and $\|\cdot\|_1$ denotes L_1-norm. $\{\|\mathbf{v}_{t+1}\|_1 - 1\}^+$ represents the number of D-VEs that successfully received the packet over $t + 1$ slots and the cumulative sum of the number of OFDM symbols allocated over $t + 1$ transmissions denoted by $K_{\text{tot},t+1}$ can be written as

$$K_{\text{tot},t+1} = \sum_{t'=0}^{t} K_{t'} \qquad (28)$$
$$= K_{\text{tot},t} + K_t, \qquad (29)$$

and as can be seen from (29), $K_{\text{tot},t}$ increases over time slot t. Hence, if $K_{\text{tot},t}$ is defined as a sub-state instead of e_t in (22)

and K_t is defined as a sub-action in (25) to obtain the reward in (27), this will result in an increase in the size of state space $\mathcal{S}_t$, and thus significantly increase the computational complexity of MDP problem. By contrast, as explained in Section V-C.1, e_t is likely to be offset by δ_t as t increases, and thus $e_t \in \mathcal{E}$ can have a smaller sub-state space than $K_{\text{tot},t}$ as t increases. This is the reason why the sub-state $e_t \in \mathcal{E}$ and the sub-action $\delta_t \in \tilde{\mathcal{K}}$ are defined instead of $K_{\text{tot},t}$ and $K_t \in \mathcal{K}$ so as to reduce the size of state space. Nevertheless, there still exists a tradeoff between system performance and computational complexity, which is determined by the definition of $\mathcal{E}$. In other words, increasing the value range of e_t increases system performance while the computational complexity is increased due to the increased size of the sub-state. Therefore, the value range should be determined according to the target performance with the consideration of acceptable computation complexity.

Given that $K_t = \delta_{\text{ref}} + \delta_t$ and (24), $K_{\text{tot},t+1}$ in (28) can be rewritten as

$$K_{\text{tot},t+1} = \sum_{t'=0}^{t} (\delta_{\text{ref}} + \delta_{t'}) \qquad (30)$$

$$= (t+1)\delta_{\text{ref}} + \sum_{t'=0}^{t} \delta_{t'}$$

$$= (t+1)\delta_{\text{ref}} + (e_1 - e_0) + (e_2 - e_1) + \cdots$$
$$+ (e_t - e_{t-1}) + (e_{t+1} - e_t)$$

$$= (t+1)\delta_{\text{ref}} + e_{t+1}. \qquad (31)$$

Then by substituting (31) for $K_{\text{tot},t+1}$ in (27), the proposed reward function in (27) can be rewritten as follows

$$r(s_t, a_t, s_{t+1})$$
$$= \begin{cases} \dfrac{\{\|\mathbf{v}_{t+1}\|_1 - 1\}^+}{(t+1)\delta_{\text{ref}} + e_{t+1}}, & \text{if } t = N_{\max} - 1,\, e_t + \delta_t \in \mathcal{E} \\[2ex] \dfrac{\|\mathbf{v}_{t+1}\|_1 - 1}{(t+1)\delta_{\text{ref}} + e_{t+1}}, & \text{if } t < N_{\max} - 1,\, e_t + \delta_t \in \mathcal{E}, \\ & \quad \|\mathbf{v}_{t+1}\|_1 = N_{\text{VE}} \\[2ex] 0, & \text{otherwise} \end{cases}$$
$$(32)$$

where $R(s_{N_{\max}}) = 0$.

4) TRANSITION PROBABILITY

The transition probability of obtaining a next state at slot $t+1$, $s_{t+1} \in \mathcal{S}_{t+1}$, when action $a_t = (j_t, \delta_t) \in \tilde{\mathcal{A}}_t$ is taken by the platoon in the current state at slot t, $s_t \in \mathcal{S}_t$ can be expressed as

$$\Pr(s_{t+1}|a_t, s_t) = \prod_{i \in \mathcal{F}_t \cap \hat{\mathcal{D}}_{t+1}} \Pr\big(|\bar{h}_{i,j_t}(t)|^2 \geq \bar{g}_{i,j_t}(t)\big)$$
$$\cdot \prod_{i' \in \mathcal{F}_t \cap \mathcal{F}_{t+1}} \Pr\big(|\bar{h}_{i',j_t}(t)|^2 < \bar{g}_{i',j_t}(t)\big), \quad (33)$$

and given that $K_t = \delta_{\text{ref}} + \delta_t$ and according to (9) and (11), the transition probability can be rewritten as

$$\Pr(s_{t+1}|a_t, s_t) = \prod_{i \in \mathcal{F}_t \cap \hat{\mathcal{D}}_{t+1}} \left(1 - F_{i,j_t}\left(\frac{2^{\frac{R_{\text{pkt}}K_s}{W(\delta_{\text{ref}}+\delta_t)}} - 1}{\xi_{i,j_t}}\right)\right)$$
$$\cdot \prod_{i' \in \mathcal{F}_t \cap \mathcal{F}_{t+1}} F_{i',j_t}\left(\frac{2^{\frac{R_{\text{pkt}}K_s}{W(\delta_{\text{ref}}+\delta_t)}} - 1}{\xi_{i',j_t}}\right). \quad (34)$$

Finally, by substituting the reward function and transition probability respectively obtained in (32) and (34) into (15), the backward recursion algorithm for GC-TC can be implemented, and then the joint optimal strategy for R-VE selection and time domain resource allocation can be obtained by (16).
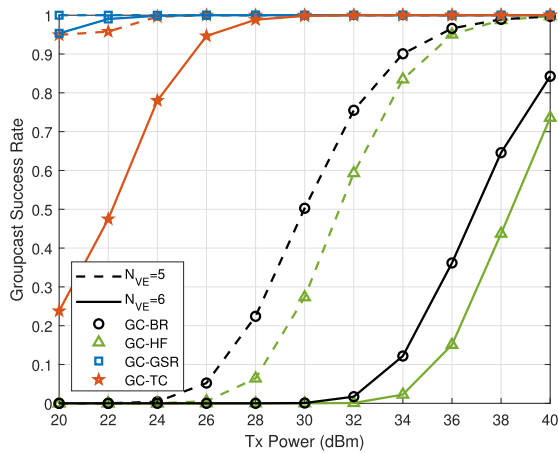
VI. NUMERICAL RESULTS

In this section, under the detailed simulation parameters listed in Table 1, computer simulation has been conducted to analyze the performance of our proposed groupcast schemes. We compare the proposed schemes with the traditional groupcast schemes, GC-BR and GC-HF, by mainly evaluating the groupcast success rate and total time consumption.
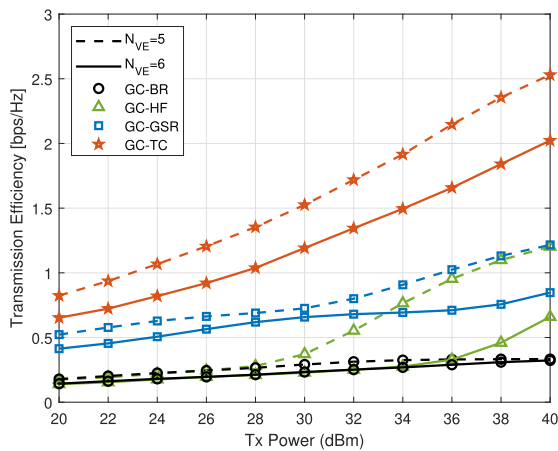
TABLE 1. Simulation assumptions for performance evaluation.

Parameters	Values
Carrier frequency [GHz], $f_{c,\text{GHz}}$	30
Tx power [dBm], $P_{\text{Tx,dBm}}$	$\{20, 22, \cdots, 40\}$
Bandwidth [MHz], W	100
Noise figure [dB], $N_{\text{F,dB}}$	8
Blockage loss [dB], $L_{\text{blk,dB}}$	5
Number of VEs in platoon, N_{VE}	$\{3, 4, 5, 6, 7, 8\}$
Initial group state, $\mathbf{v}_0$	$[1, 0, \cdots, 0, 0]^T$
Velocity [km/h], v_e	$\{30, 40, \cdots, 100\}$
Maximum velocity [m/s], v_0	30
Desired time headway [s], T_0	1.0
Minimum VSD [m], d_0	1.0
Number of transmitted packets, N_{pkt}	10^4
Target transmission rate [Mbps], R_{pkt}	100
Transmission limit (GC-BR), $N_{\max}$	3
Transmission limit (GC-HF), $N_{\max}$	4
Transmission limit (V-B, V-C), $N_{\max}$	4
Reference number of symbols, δ_{ref}	7
Sub-state space, $\mathcal{E}$	$\{-10, -9, \cdots, 10\}$
Sub-action space, $\tilde{\mathcal{K}}$	$\{-6, -5, \cdots, 3\}$

Fig. 3 shows the average groupcast success rate versus Tx power [dBm] with two different sizes of platoon, $N_{\text{VE}} = 5$ and $N_{\text{VE}} = 6$. According to [27], [34], Tx power implemented for mmWave-band V2V communications [27] and mmWave-band V2N communications [34] is around 20 dBm. Hence, Tx power of 20-40 dBm, in which transmitter and receiver antenna gains are taken into account, is considered

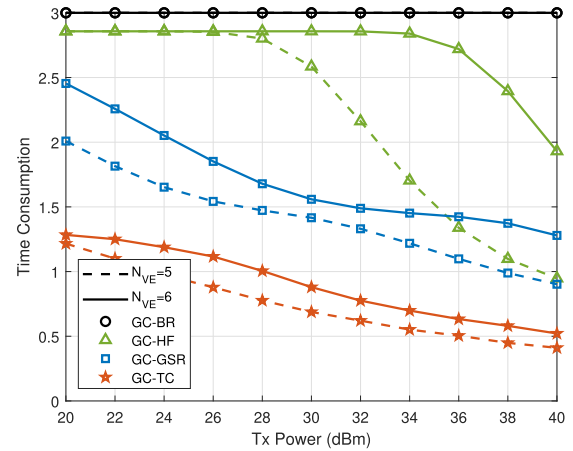**FIGURE 3.** Average groupcast success rate versus Tx power ($v_e = 80$ km/h).

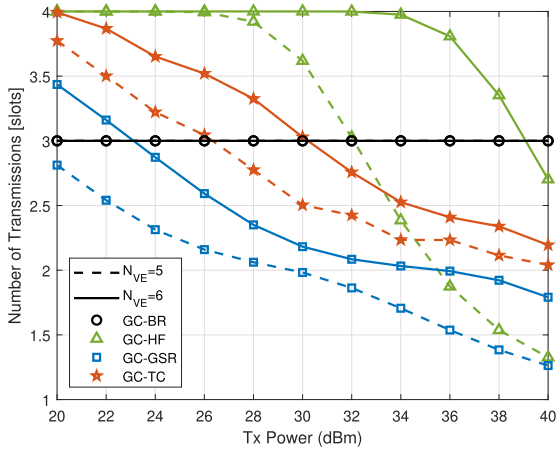**FIGURE 4.** Average groupcast efficiency versus Tx power ($v_e = 80$ km/h).

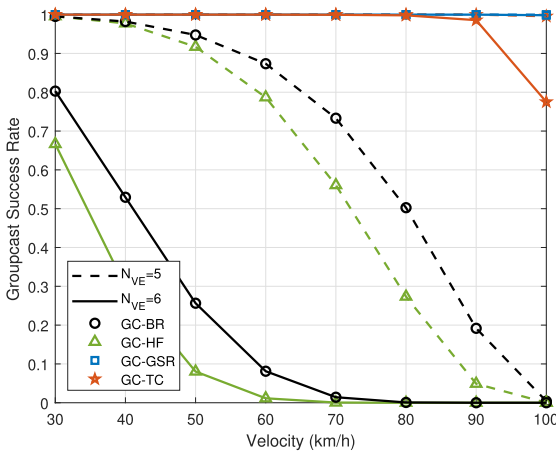**FIGURE 5.** Average total time consumption versus Tx power ($v_e = 80$ km/h).

comparison with the completion time of groupcast, N. As shown in Fig. 5, GC-TC can achieve a significantly lower time consumption while maintaining a similar groupcast success rate performance to that of GC-GSR as observed in Fig. 3 (when Tx power is larger 30 dBm). It is also observed that as Tx power increases, the time consumption of proposed schemes decreases gradually, which can avoid the excessive resource consumption in the time domain and thus allow other platoons or VEs to utilize for their V2V communications.

In simulations, we also evaluate the average number of transmissions to investigate the influence of minimizing the time consumption on the completion time of groupcast. Fig. 6 shows that GC-TC and GC-GSR outperform GC-HF and GC-BR in terms of groupcast completion time in most cases, and both proposed schemes drastically reduce the number of transmissions as Tx power increases. This is mainly due to the fact that by selecting an appropriate R-VE, both GC-TC and GC-GSR can minimize the blockage loss caused by vehicles and optimize the communication distance between the R-VE and the D-VEs for groupcast, which enables the reduction of unnecessary retransmissions and eventually contributes to the early termination of groupcast. Also, it is noticed in the figure that in some Tx power regions, GC-HF and GC-BR achieve better performance than GC-TC in terms of groupcast completion time, but it can be seen from Fig. 3 that both GC-HF and GC-BR in the Tx power regions cannot achieve reliable groupcast success rate performance. In addition, Fig. 6 shows that GC-TC increases the average number of transmissions as compared with GC-GSR. Hence, it is worth noting that at the cost of increasing the number of transmissions, the joint strategy of GC-TC for R-VE selection and time domain resource allocation contributes to the reduction of total time consumption, which allows another platoon or VEs to perform any type of V2X communications (i.e., broadcast, groupcast, unicast) by utilizing the rest of time-domain resources at each slot.

In V2V groupcast for vehicle platooning, the vehicle deployment, i.e., VSD, is one of key factors affecting groupcast performance, which motivates us to further investigate

in this simulation. In Fig. 3, it can be observed that the two proposed groupcast schemes yield far superior performance over the traditional groupcast schemes. In the figure, it is also observed that performance degrades as N_{VE} increases. In particular, in the case of $N_{VE} = 6$, although GC-GSR can provide better performance than the GC-TC in the low Tx power region, the same performance can be achieved in the reasonable Tx power region over 30 dBm.

Fig. 4 shows the average groupcast efficiency versus Tx power [dBm]. Since GC-TC is designed to maximize groupcast efficiency, as shown in Fig. 4, it can perform even better than the GC-GSR, the groupcast success rate-maximized transmission strategy, and as Tx power increases, the performance gain of GC-TC gradually increases.

In addition, Fig. 5 shows the total time consumption $\alpha_{tot,N}$ versus Tx power. The total time consumption in this paper is defined as the ratio of "the total number of OFDM symbols taken to complete groupcast" to "the maximum number of OFDM symbols per slot", which can be expressed as $\alpha_{tot,N} = \sum_{t=0}^{N-1} \alpha_t = \frac{K_{tot,N}}{K_s}$. The reason for using $\alpha_{tot,N}$ as a metric for total time consumption rather than $K_{tot,N}$ is to facilitate

FIGURE 6. Average number of transmissions versus Tx power ($v_e = 80$ km/h).

FIGURE 8. Average total time consumption versus velocity ($P_{Tx,dBm} = 30$ dBm).

FIGURE 7. Average groupcast success rate versus velocity ($P_{Tx,dBm} = 30$ dBm).

FIGURE 9. Average groupcast success rate and total time consumption versus the number of VEs in the platoon ($P_{Tx,dBm} = 30$ dBm, $v_e = 80$ km/h).
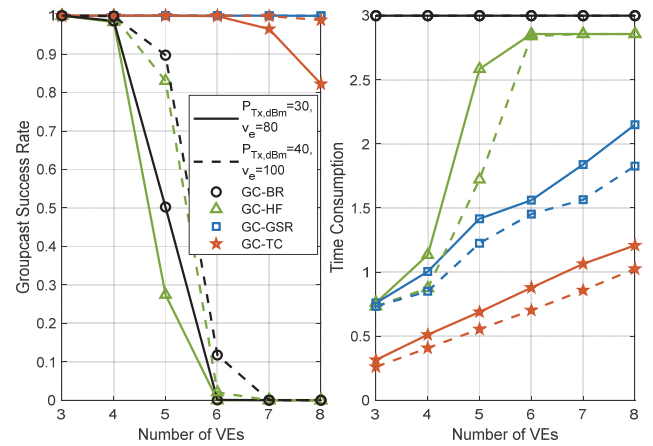
the influence of VSD on the performance of groupcast. As mentioned previously, since the VSD is proportional to the velocity of vehicle, the main performances are evaluated under different velocities as shown in Fig. 7 and Fig. 8.

In Fig. 7, simulation result shows that in general, the performance of groupcast success rate deteriorates with the increase of velocity. In particular, it is also found that the performance degradation of traditional groupcast schemes with Tx power of 30 dBm is so severe in most velocity ranges that the requirement of groupcast success rate cannot be satisfied, and to achieve the target requirement, the transmission power higher than 40 dBm is required as shown in Fig. 3. It is also observed that while GC-GSR can achieve the groupcast success rate of 1 for all valid velocity ranges, the performance of GC-TC degrades in the velocity range exceeding 80km/h.

Similarly, Fig. 8 shows that the larger velocity is, the more time-domain resources are required for groupcast. In the case of GC-HF, when velocity exceeds a certain velocity value (around 60 km/h in this case), it can be seen that the consumed time-domain resources reaches its maximum time-domain resource allowed.

In simulation, the performance of average groupcast success rate and time consumption is evaluated with different platoon sizes. As can be seen from the Fig. 9, in general, the performance of both groupcast success rate and time consumption deteriorates with the increase of platoon size and the proposed schemes outperform the traditional schemes. In particular, the two traditional groupcast schemes do not work when the platoon size is larger than 4, and the performance degradation of GC-TC with the Tx power of 30 dBm is also observed when the platoon size is larger or equal to 7. In this case, the platoon can either use a higher Tx power for groupcast or be formed with fewer vehicles, for example, by dividing the platoon into two separate platoons operating independently, which is beyond the scope of this paper and left for the future study.

VII. CONCLUSION

In this paper, we studied the problem of groupcast for vehicle platooning, where vehicles of a platoon moving in the single lane communicate with each other through V2V group-

cast without network assistance. We proposed two groupcast schemes. The first groupcast scheme called GC-GSR is a heuristic scheme that aims to maximize groupcast success rate and the second groupcast scheme called GC-TC is designed by formulating as an MDP to obtain a joint optimal strategy for R-VE selection and time domain resource allocation that can minimize total time consumption while maintaining a satisfactory groupcast success rate performance. Simulation results showed that the proposed schemes, GC-GSR and GC-TC with the designed strategies for joint R-VE selection and time domain resource allocation can achieve far superior performance over conventional groupcast schemes, GC-BR and GC-HF, especially in terms of groupcast success rate and total time consumption, which enables a highly reliable and efficient groupcast for vehicle platooning and enhances the efficiency of radio resource utilization. In addition, it was shown that the proposed schemes are capable of reducing the completion time of groupcast by preventing excessive retransmissions, which is essential for supporting latency-sensitive V2X applications. Also, it was observed that when both platoon size and velocity are very large, the performance degradation of GC-TC is observed. In this case, to apply the GC-TC to vehicle platooning, it may be necessary to consider reducing the platoon size, by dividing the platoon into two separate platoons operating independently, which is worth further investigating as a future study.

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