IEEE Access Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 17 September 2023, accepted 17 November 2023, date of publication 28 November 2023, date of current version 14 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3335838

RESEARCH ARTICLE

A Hypergraph Matching-Based Subchannel Allocation for Multi-Platoon's Communications

CHUNG-MING HUANG[1], (Senior Member, IEEE), **DAN-NGUYEN LAM**[1], **AND DUY-TUAN DAO**[2]

[1]Department of Computer Science and Information Engineering, National Cheng Kung University, Tainan 70101, Taiwan

[2]Faculty of Electronics and Telecommunications Engineering, The University of Danang-University of Science and Technology, Da Nang 50000, Vietnam

Corresponding author: Duy-Tuan Dao (ddtuan@dut.udn.vn)

This work was supported in part by the Ministry of Science and Technology (MOST), Taiwan, under Grant MOST 111-2221-E-006-077-MY3; and in part by the Funds for Science and Technology Development of the University of Danang under Project B2021-DN02-06.

ABSTRACT In a platoon communication scenario, the Platoon Leader (PL) vehicle interacts with the gNodeB (gNB) to obtain some assigned radio resources and then the obtained radio resources are allocated to the PL vehicle and its Platoon Member (PM) vehicles. The high transmission delay in the platoon network affects the quality of vehicles' connectivity. Therefore, the issues of improving radio resource's spectral efficiency and stability of the vehicle platooning with limited radio resources need to be tackled. This work proposes the 2-STage Resource Allocation (2-STRA) method for multi-platoon communication to reduce the transmission latency of platoon vehicles, i.e., it can improve the data transmission rates of platoon vehicles for the conditions of various speeds and various numbers of subchannels. In the 1st stage, a greedy algorithm that jointly considers subchannel allocation and power control for PL vehicles' resource allocation is devised. In the 2nd stage, the resource allocation for PM vehicles, which is based on the subchannels that are not allocated to PL vehicles, is resolved. A tripartite hypergraph, in which a tripartite hyperedge links:I 1) cluster of PM vehicles that use the same subchannel; 2) individual cellular user; and 3) subchannel, is adopted to devise the PM vehicles' resource allocation algorithm. The simulation results show that the proposed 2-STRA method can have better performance in terms of spectral efficiency and the sum of data transmission rate comparing with the other methods.

INDEX TERMS Autonomous vehicle, graph theory, multi-platoon communications, communication, resource allocation, V2X, vehicle platoon.

I. INTRODUCTION

In the platooning environment, a platoon is a group of vehicles that are moving together by constantly coordinating their speeds and distances. Platooning vehicles has been highlighted as a promising way for reducing communication delay and saving energy of vehicles in Intelligent Transportation Systems (ITS) [1], [2]. A platoon consists of a Platoon Leader (PL) vehicle, which is in the lead position of the platoon, and some Platoon Member (PM) vehicles, which follow PL vehicle's driving orders [3], [4]. Normally, PL vehicle is the first vehicle of a platoon, which is responsible for managing and forming the platoon with the help of the gNodeB (gNB), e.g., adjusting platoon speed, modifying message's broadcasted range and accepting/declining requests from free vehicles that do not join any platoon. Thus, PL vehicle is responsible for relaying information from or to the gNB. Each PM vehicle can also relay the driving information delivered from the PL vehicle to its subsequent vehicles. PL vehicle not only receives information from the gNB but also collects Cooperative Awareness Messages (CAMs) sent from PM vehicles and then extract information from CAMs and send the extracted information to the gNB. Each PM vehicle also can send its own data to the PM vehicle that follows it.

The potential benefits of platooning are available when platoons are stable. Platoon's stability is heavily influenced by the platoon's communication effectiveness, such as high

The associate editor coordinating the review of this manuscript and approving it for publication was Jie Gao.

data rate and high reliability [5]. Large communication latency, which results in wireless network's poor quality of service (QoS) for vehicles, may cause the platooning system to become unstable. In other words, platoon's stability is ensured through the high-rate and high-reliability of exchanging control information among platoon vehicles about their current kinematics status. However, as the intra-platoon information exchange has strict requirements on the communication performance, such as delay and packet collision, it is difficult to ensure the platoon's stability. Some factors that affect platoon's stability are as follows. According to the traffic rule, it has the minimum intra-platoon V2V distance depending on vehicle's velocity, i.e., the higher/lower vehicle velocity it is, the longer/shorter intra-platoon V2V distance it needs to have. Additionally, the development of the 5G C-V2V technique enriches the types of information flow topologies, which brings benefits as well as challenges to the analysis and design of platoon systems [7]. Inter-platoon PM vehicles' distance is normally larger than intra-platoon PM vehicles' distance for safety; the shorter distance between two intra-platoon's adjacent PM vehicles and the platoon's speed can affect the communication link's channel gain [5], [8].

In order to guarantee low latency communication to meet the predetermined communication quality requirements, platoon vehicles must be allocated a specific amount of spectrum resources. Since the spectrum and bandwidth allocated for the vehicle networking are limited, it is necessary to make full use of the limited spectrum resource as much as possible to ensure the realization of vehicle platooning. Many platoon's resource allocation methods for platooning communication have been proposed in the past. Some technical concerns are as follows:

- The assigned subchannels of PL vehicles for broadcasting messages (i) should be orthogonal to the assigned subchannels for PM vehicles, i.e., each PL vehicle's allocated subchannel cannot be reused by other PM vehicles [9], [10], [11], but (ii) can be reused by the uplinked subchannels of mobile nodes, e.g., cellular phones or free vehicles that do not join any platoon [12]. Thus, it needs a feasible scheme for selecting good subchannels for PL vehicles.
- The assigned subchannel for the V2V link of two directly connected intra-platoon PM vehicles can be (i) reused by intra-platoon PM vehicles but can not be reused by other platoons' PM vehicles [7], [11], (ii) reused by other inter-platoon PM vehicles but cannot be reused by other intra-platoon PM vehicles [9], [13], (iii) reused by intra-platoon and/or inter-platoon PM vehicles [10], [14], [15]; additionally, subchannel allocated for cellular phone users and/or free vehicles can be reused by PM vehicles [13], [16], [17].
- Velocity's changing of a platoon, which results in the changing of intra-platoon's minimum V2V distance, will significantly affect the resource allocation and utilization of vehicular platooning and communication delay.

A. MOTIVATIONS

Several works [7], [9], [10] have presented many technical issues related to resource allocation to improve the resource utilization of platooning's communication. However, there is a lack of research studying resource allocation efficiency in 5G NR C-V2X that can satisfy the low latency and high reliable requirements of platooning. Since the Generation Partnership Project (3GPP) standard just briefly pinpoints some new key issues, but do not state any particular resource allocation scheme for multi-platoon communication [18], an efficient resource allocation scheme for multiple platoons is quite necessary to guarantee the service requirement of vehicle platooning using 5G NR C-V2X.

This work proposed a resource allocation method for platooning using the 5G NR C-V2X technique to reduce the transmission latency using the graph-based approach. The proposed resource allocation method for platooning adopts Mode 1's C-V2V communication way defined in the 5G NR standard [25]. Mode 1 is a signified mechanism that allows direct C-V2V communications within the gNodeB coverage where the gNodeB schedules sidelink resources for vehicles that are having C-V2V communications [26]. Since platoons need to co-exist with many free vehicles, which do not join any platoon, and smartphone users, it needs to design a resource allocation method that can (1) increase spectral efficiency, minimize the intra-platoon transmission latency, and satisfy the QoS requirement of individual cellular network users, which include both smart phone users and free vehicles that do not join any platoon. Since the higher transmitted power results in the higher energy consumption, it needs to have the lower transmitted power for PL. On the other hand, it is expected to have the higher number of PM vehicles, i.e., as many as possible, to be able to receive PL's broadcasted messages to achieve the purpose of platooning. Nevertheless, it needs to have the higher PL's transmitted power in order to cover more PM vehicles. Thus, one of the goals of this work is to reduce PL's transmitted power to reduce energy consumption and to increase the number of PM vehicles that can effectively receive PL vehicle's broadcasted messages. To have the higher transmission rate and reliability, it needs to acquire more allocated resources. On the other hand, since the resource is limited, it needs to have some resource sharing among communicating entities, i.e., vehicles and smart phone users, as more as possible. Nevertheless, the more resource sharing among communicating entities, the higher interference it has, which results in the higher transmission delay and lower transmission reliability. Thus, the other goal of this work is to have the suitable resource sharing principle among communicating entities such that it can minimize intra-platoon transmission latency and satisfy the QoS requirement of individual cellular network users, i.e., free vehicles and smart phone users.

The proposed method adopts the following ways to achieve the aforementioned goals: (1) the resource allocation for PL vehicles is mathematically formulated as an optimization problem that maximizes the transmission range of PL vehicles with the minimum transmitted power; (2) the resource allocation for PM vehicles is mathematically formulated as an optimization problem that minimizes the total transmission latency of PM vehicles based on the corresponding resource sharing principle. For the resource allocation of PL vehicles, in order to reduce the co-channel interference, which significantly affects the effectiveness of vehicles' connectivity, the subchannels assigned to PL vehicles can not be reused by any other vehicle. Thus, the optimization problem considers subchannel allocation and power control for PL vehicles, which are modeled as an optimization problem aiming to maximize PL vehicle's broadcasted range. The transmitted power can be adjusted to maximize the number of PM vehicles that can successfully receive PL vehicle's broadcasting messages. For the resource allocation of PM vehicles, it can be regarded as a problem of minimizing the total transmission latency of PM vehicles. To improve spectrum utilization efficiency, PM vehicles can share their allocated subchannels with inter-platoon PM vehicles and/or individual cellular network users, which include both smart phone users and free vehicles that do not join any platoon. Therefore, the optimization problem of resource allocation for PM vehicles is formulated with the objective of minimizing the total transmission latency of PM vehicles, which is based on the constraints of communication reliability and QoS requirement.

To solve the aforementioned two defined optimization problems of resource allocation, a 2-STage Resource Allocation (2-STRA) method using the k-partite graph, which has been widely used to solve the problems of wireless resource allocation [15], [19], [20], [21], for multi-platoon communication is proposed in this work. The proposed 2-STage Resource Allocation (2-STRA) method for multi-platoon communication is based on the following criteria: (i) a PL vehicle can use a unique subchannel, i.e., no sharing with other entities, to reduce the co-channel interference; (ii) the subchannel used by a PM vehicle can be reused by inter-platoon PM vehicles and/or one individual cellular network user, which can be a cellular phone user or a free vehicle that does not join any platoon; (iii) there is no spectrum sharing among intra-platoon PM vehicles to eliminate the intra-platoon PM vehicles' interference impact; (iv) no spectrum sharing among individual cellular network users in order to guarantee the QoS requirements of individual cellular network users. In the first stage of the proposed 2-STRA method, a Joint Subchannel and Power Allocation for Platoon Leaders (JSPA-PLs) scheme, which jointly considers subchannel allocation and power control for PL vehicles, is devised. The role of JSPA-PLs algorithm is for selecting the suitable pairing of the subchannel and the transmitted power for each platoon's PL vehicle. In the second stage of the proposed 2-STRA method, the resource allocation for PM vehicles, which is based on the subchannels that are not allocated to PL vehicles, is resolved. In order to efficiently model the complicated interference scenario and reduce resource allocation complexity, the PM Vehicles' Partitioning (PMVP) algorithm was devised to group PM vehicles into clusters, for which those PM vehicles use the same subchannel belong to the same cluster. Then, the Tripartite Hypergraph Construction (TPHC) algorithm was proposed to construct a tripartite hypergraph, in which (1) there are three different types of vertices to denote (i) individual cellular network users, (ii) subchannels and (iii) clusters respectively, and (2) each hyperedge comprises three vertices, for which one vertex denotes an individual cellular network user, another vertex denotes a subchannel, and the other vertex denotes a cluster. After that, the Greedy Hypergraph-based Subchannel Allocation for Platoon Members (GHSA-PMs) algorithm was proposed to assign subchannels for PM vehicles based on the constructed tripartite hypergraph. In this way, the proposed 2-STRA method can increase spectral efficiency by minimizing the intra-platoon transmission latency, while satisfying the QoS requirement of individual entities in the conditions of various speeds and various numbers of subchannels.

B. CONTRIBUTIONS

The main contributions of this work can be summarized as follows:

- We define and mathematically formulate the optimization problem of resource allocation for PL and PM vehicles.
- We first propose the 2-STage Resource Allocation (2-STRA) method, including (i) the resource allocation for PL vehicles that is resolved the 1st stage and (ii) the resource allocation for PM vehicles that is resolved in the 2nd stage, to improve spectrum efficiency. In the 1st stage, a JSPA-PLs algorithm has been designed to maximize PL vehicle's broadcasted range using the minimum transmitted power of PL vehicles. In the 2nd stage, PMs' vehicles are clustered using the proposed PMVP algorithm, for which those PMs' vehicles that use the same subchannel are put into a cluster.
- To solve the problem of platoon resource allocation, a tripartite hypergraph is formulated using the proposed TPHC algorithm. Then, the GHSA-PMs algorithm was proposed to solve the problem of resource allocation for PM vehicles based on the constructed tripartite hypergraph.
- The simulation results show that the performance of the proposed 2-STRA method can have better performance in terms of spectral efficiency, transmission latency and the sum of transmission rate comparing with the other methods.

The remaining part of this paper is organized as follows. Related works are presented in Section II. Section III introduces the proposed system model of the considered NR-V2X platoon-based network. The resource allocation problems for

PL vehicles and PM vehicles are mathematically formulated in Section IV. Section V presents details of the proposed 2-STRA method. Section VI presents the simulation results of the proposed method. Section VII has the conclusion remarks and potential future research.

II. RELATED WORK

In this Section, related works for the proposed resource allocation method are presented.

In [9], the authors proposed a resource allocation method for sharing information within multi-platoons to reduce the required number of transmission hops in each platoon. The proposed method can ensure the transmission rate of each V2V link while minimizing the transmission power of each vehicle. The proposed method jointly considered the evolved multimedia broadcast multicast services (MBMS) and V2V multicast communication ways to enable intra-platoon communications, for which a subchannel allocation scheme and a power control mechanism were proposed. In the proposed V2V multicast communication scenario, the allocated subchannels for PL vehicles cannot be reused by any other vehicle; but in each platoon, the communications of (i) PL vehicle's broadcasting messages to PM vehicles, (ii) PL vehicle's communication with BS (Base Station) and (iii) BS's communication with the PL vehicle use only one subchannel. The allocated subchannel of a PM vehicle can be reused by other PM vehicles in different platoons. In each platoon, PL vehicle's broadcasting messages to PM vehicles may be affected when BS is using the same subchannel to communicate with PL vehicle and vice versa.

In [10], the authors considered the platoon size and power consumption of multi-platoons for platooning's resource allocation. In the proposed method, gNB allocates the resource to PL vehicles and each PL vehicle assigns the allocated resources to their PM vehicles. In the proposed method, the subchannel allocated for PM vehicles in each platoon (i) should be orthogonal to the broadcasting subchannels assigned to PL vehicles and (ii) can be reused by other PM vehicles that belong to the same platoon and/or different platoons; any two adjacent vehicles in a platoon can not use the same subchannel. A two-step resource allocation strategy was proposed to improve multi-platoon cooperation, maximize platoon size, and reduce power consumption in the C-V2X network. (i) In the 1st step, the brand and bound algorithm, which is generally used for solving combinatorial optimization problems, was adopted to solve the problem of subchannel allocation for each platoon. (ii) In the 2nd step, a Dynamic Programming based PM vehicles' subchannel allocation and power control algorithm for the joint optimization of platoon formation, subchannel allocation, and power control was proposed based on each platoon's allocated subchannels derived in the 1st step. However, the intra-platoon communication performance will be degraded without some feasible control of intra-platoon and inter-platoon link interferences.

In [11], the authors proposed a collaborative platoon communication and control design for a platoon. Two communication phases in each platoon are as follows: the 1st phase is the leader's information dissemination and the 2nd phase is the followers' information dissemination. Three types of vehicles defined in the proposed method are PL vehicles, relay vehicles and PM vehicles. To extend the communication range of the PL vehicle, the proposed method uses relay vehicles to forward PL vehicle' messages in the 1st phase, for which, if a platoon vehicle is configured as a relay vehicle, it will keep forwarding PL vehicle' information to its follow-up vehicles, including both relay vehicles and PM vehicles, using the broadcast way. In the proposed method, the PL vehicle and each relay vehicle broadcast the messages over the whole bandwidth because no other simultaneous transmissions of PM vehicles. In the 2nd phase, PM vehicles use the same timeslots to exchange information with neighboring PM vehicles. When the number of subchannels is smaller than the number of wireless links for PM vehicles' communication, it has intra-platoon PM vehicles' resource sharing, i.e., one subchannel is allowed to be allocated to multiple intra-platoon PM vehicles, to improve spectrum utilization. The relay vehicle's selection was formulated as an integer programming and a dynamic programming method was proposed to solve the problem of relay vehicle's selection. An adaptive distributed model predictive control performance downgrading. Additionally, this work only considered a single platoon's scenario.

In [12], the authors proposed a method to minimize the intra-platoon groupcast latency. Instead of the PL vehicle, a platoon manager serves as the platoon's control vehicle in this work. The authors proposed a dynamic platoon manager selection algorithm to improve the communication performance. In the proposed method, the uplinked subchannels of free vehicles can be reused by platoon manager' vehicles for broadcasting messages. A joint resource allocation and coding rate optimization algorithm was proposed. Since the spectrum resource of broadcasting messages are allowed to be reused by free vehicles, it results in the unsatisfactory system throughput and longer broadcasting transmission may get severe interference due to co-channel interference.

In [15], the authors investigated the joint optimization problem of spectrum sharing and interference management in the multi-platoon scenario. The dedicated resource is allocated to a P L vehicle for transmitting messages to BS and broadcasting messages to its PM vehicles. PM vehicles shared resources with other PM vehicles belonging to the same platoon and/or different platoons to forward their messages to the intra-platoon adjacent PM vehicles behind them. The resource allocation problem was transformed into a hypergraph coloring problem to maximize the resource utilization efficiency. A Hypergraph-based Resource Allocation and Interference Management (HRAIM) scheme was proposed to assign resources for PM vehicles based on the required SINR threshold. However, the authors did not consider the resource allocation for PL vehicles in this work.

The authors in [22] proposed (i) a handover method to have the cooperative multipoint transmission (CoMP)-based seamless handover between roadside units (RSUs) and (ii) the resource allocation (C-SHRA) algorithm for platoon handover between RSUs. A cooperative spectrum resource allocation scheme was designed for intra-platoon V2V links to mitigate both intra-platoon and inter-RSU interferences to avoid ping-pong handover and enhance the effective throughput in 5G NR C-V2X based communications. Additionally, a joint block length and transmission power optimization (JBLTPO) algorithm was proposed to achieve the optimal performance in terms of effective throughput of the RSU-to-platoon (R2P) link in the CoMP mode.

In [23], the authors proposed the method for the joint platoon partition, power control and spectrum allocation to maximize the V2I capacity while satisfying the reliability requirement of intra-platoon communication. Considering that the resource allocation is built on the platoon partition result, the formulated problem is decomposed into a resource allocation problem and a platoon partition problem. The proposed multicast cluster based intra-platoon communication achieves the better performance on V2I throughput than other general models. However, this paper did not focus on multi-platoons communications scenario.

Some work adopted the D2D communication mechanism/technique for resolving the platooning problems [8], [9], [24]. The authors in [8] proposed (i) a platoon leader evaluation based two-stage platoon formation algorithm to form stable platoons and (ii) a predecessor following communication mode based on V2V communications to reduce platoon delay. The authors in [24] examine the secure radio resource sharing problem in D2D enabled multi-platoon vehicular communications to achieve efficient communications. The authors in [9] proposed the resource allocation method based on the evolved multimedia broadcast multicast services (eMBMS) capability and D2D communications to enhance the reliability and reduce the transmission latency in a scenario with a chain of platoons. Some technical concerns of our work are similar to the aforementioned papers. However, our work proposed a new resource allocation method for platooning to reduce the transmission latency using the graph-based approach. As a result, the proposed 2-STRA method has the better performance on (i) the transmission latency of platoon vehicles, (ii) the power control for PL vehicles and (iii) the transmission rates of platoon vehicles under the conditions of various speeds and various numbers of subchannels.

III. THE SYSTEM MODEL

This Section presents the system model, including network model, mobility model, communication model and channel model. Table 1 depicts symbols that are used in this work.

A. NETWORK MODEL

The network model is 5G-V2X-based. The network model includes (i) one gNB in the center of the cell, (ii) M platoons with varying sizes on the road and (iii) C individual cellular network users, including both smartphone users and those free vehicles that do not join any platoon, that are distributed randomly in the cell's signal coverage. An exemplary configuration is depicted in Fig. 1. Vehicles are capable of forming multiple platoons on their own. Vehicles within a platoon operate cooperatively. The PL vehicle is responsible for managing and forming the platoon with the help of the 5G base stations-gNodeB(gNB), e.g., adjust platoon speed, broadcasting range and accepting/declining requests from free vehicles.

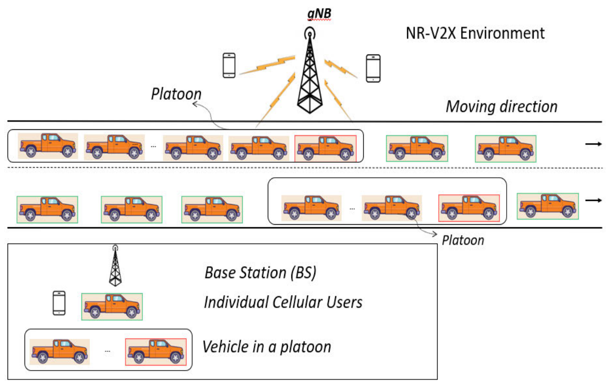

FIGURE 1. An exemplary configuration of the system model.

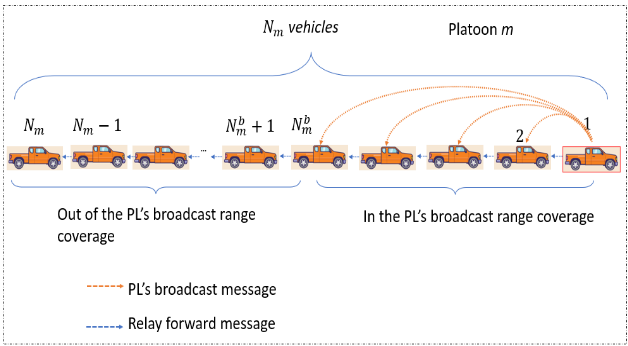

FIGURE 2. The communication configuration in a platoon.

In Fig.1, a PL vehicle interacts with the gNB such that the gNB can assign radio resources to the PL vehicle and then the PL vehicle allocates the obtained radio resources to its PM vehicles. Let (1) M $= \{1, 2, \ldots, M\}$ denote the set of platoons, (2) C $= \{1, 2, \ldots,$ C$\}$ denote the set of C individual cellular network users, and (3) $\mathrm{N_m} = \{1, 2, \ldots, N_m\}$ be the set of vehicles in each platoon m, m $= 1, 2, \ldots M$, where vehicles are numbered sequentially from 1 to N_m starting from the PL vehicle. The intra-platoon communication's configuration is depicted in Fig. 2.

Let there be N_m vehicles in platoon m. Let PL vehicle's broadcasted range of platoon m cover PM vehicles 2 *to* N_m^b, i.e., PM vehicles from 2 *to*N_m^b can successfully receive the broadcast messages sent from PL vehicle. If $N_m^b = N_m$, it means that the PL vehicle of platoon m can broadcast its messages to all of its PM vehicles; if $N_m^b < N_m$, it means that the PL vehicle of platoon m can not broadcast its messages to all its PM vehicles.

TABLE 1. List of the notation used in this paper.

Variable	Definition	Variable	Definition
d_0	The minimum intra-platoon spacing.	$h_{n-1,n}^{m,k}$	The channel gain between vehicle $n-1$ of platoon m and vehicle n of platoon m over subchannel k.
v_0	The maximum speed of a platoon.	$h_{c,j}^{m,k}$	The channel gain between individual cellular network user c and vehicle j of platoon m.
v_e	The equilibrium speed.	$h_{i',j}^{m',m,k}$	The channel gain between vehicle i' of platoon m' and vehicle j of platoon m.
T_0	The desired time headway.	$h_{c,BS}^{k}$	The channel gain between individual cellular network user c and gNB.
d_e	The intra-platoon spacing.	h_0^{k}	The complex gaussian variable representing the Rayleigh fading.
$d_{i,j}^{m}$	The distance between vehicle i of platoon m and vehicle j of platoon m.	G	The power gain constant introduced by communication equipment
$d_{c,BS}$	The distance from individual cellular network user c to gNB.	P_c^{k}	The transmission power of individual cellular network user c over subchannel k.
$d_{n,BS}^{m}$	The distance from vehicle n of platoon m to gNB.	$P_n^{m,k}$	The transmission power of platoon m's vehicle n over subchannel k.
$d_{n',n}^{m',m}$	The distance from vehicle n' of platoon m' to vehicle n of platoon m.	$P_1^{m,k}$	The transmission power of PL PL_m of platoon m over subchannel k.
$d_{c,n}^{m}$	The distance from individual cellular network user c to vehicle n of platoon m.	$SINR_{n-1,n}^{m,k}$	The SINR in the receiving vehicle n of platoon m from the transmitting vehicle $n-1$ of platoon m over subchannel k .
L_m	The length of platoon m.	$SINR_{1,N_m^b}^{m,k}$	The SINR in the receiving vehicle N_m^b of platoon m from the transmitting PL of platoon m over subchannel k.
ℓ	The length of a vehicle.	$R_{n-1,n}^{m,k}$	The data rate in the receiving vehicle n of platoon m from the transmitting vehicle $n-1$ of platoon m over subchannel k.
$\mathcal{K}$	The set of subchannels in the system.	$R_{1,N_m^b}^{m,k}$	The data rate in the receiving vehicle N_m^b of platoon m from the transmitting PL of platoon m over subchannel k.
$\mathcal{K}_C$	The subset of subchannels allocated to individual cellular network users.	$R_{c,BS}^{k}$	The data rate in the received BS from the transmitting individual cellular network user c over subchannel k .
$\mathcal{K}_m$	The subset of subchannels allocated to platoon m.	R_{thr}^{c}	The minimum data rate threshold for individual cellular network user c.
K	The total number of orthogonal subchannels of the system.	R_{thr}^{d}	The minimum data rate threshold for the V2V user.
K_m	The number of subchannels allocated to platoon m.	$T_{n,n+1}^{m,k}$	The data transmission latency from vehicle n of platoon m to vehicle $n+1$ of platoon m over subchannel k.
$\mathcal{M}$	The set of platoons.	T_{1,N_m}^{m}	The data transmission latency from platoon leader PL_m to the tail vehicle of platoon m.
M	The number of platoons in the system.	λ	The length of each data packet.
N	The maximum number of vehicles in the platoon.	σ^2	The power of the additive white Gaussian noise (AWGN).
$\mathcal{N}_m$	The set of vehicles of platoon m.	X^{k}	The matrix indicates the assignment of subchannel k to platoon vehicles.
N_m	The number of vehicles in platoon m.	$x_{m,n}^{k}$	The indicator shows whether subchannel k is allocated to vehicle n of platoon m or not.
N_m^b	The number of vehicles that are in the broadcasted range of the platoon leader PL_m of platoon m, i.e., there are $(N_m^b - 1)$ member vehicles inside the broadcasted range of PL_m, excluding PL_m.	y_c^{k}	The indicator shows whether subchannel k is allocated to individual cellular network user c or not.

Referring to Fig. 2, vehicle $V_{N_m^b}$ is the PM vehicle that is in the edge of PL vehicle's broadcasted range; $(N_m - 1)$ subchannels are allocated to PM vehicles of platoon m, for which one subchannel is allocated to the V2V link between V_i and $V_{i+1}, i = 1, \ldots, N_m - 1$. The intra-platoon subchannels are not reused by the corresponding platoon's PM vehicles, but these subchannels can be reused by other platoons' PM vehicles and/or one individual cellular network user.

B. MOBILITY MODEL

The intelligent driver car-following model (IDM) [14] is used in this work. It is assumed that all vehicles reach an equilibrium state where the acceleration and velocity difference are zero. The intra-platoon spacing (d_e), i.e., the equilibrium distance between two adjacent vehicles in a platoon, is denoted as follows [27]:

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

where d_0 denotes the minimum allowable intra-platoon spacing, $v_\mathbf{0}$ denotes the maximum allowable velocity, v_e denotes the equilibrium velocity and T_0 denotes the desired time headway.

The distance between platoon vehicle i and platoon vehicle j of platoon m can be expressed as follows:

$$d_{i,j}^m = |i - j| * d_e \tag{2}$$

The platoon's length is denoted as L_m, which is the length from the PL vehicle to the last PM vehicle of the platoon. Let all vehicles in platoon m have the same length ℓ, platoon m's length (L_m), which is composed of one PL vehicle and ($N_m - 1$) PM vehicles, is derived as follows:

$$L_m = (N_m - 1) * (d_e + \ell) \tag{3}$$

C. CHANNEL MODEL

To model the wireless channel, the free space path-loss model with loss coefficient and Rayleigh fading are used [28]. The channel power gain $h_{i,j}^{m,\Bbbk}$ from transmitting vehicle i to receiving vehicle j over subchannel $\Bbbk(\Bbbk \in K)$ in platoon m is calculated as follows:

$$\left|h_{i,j}^{m,\Bbbk}\right|^2 = G * (d_{i,j}^m)^{-\alpha} * \left|h_0^{\Bbbk}\right|^2 \tag{4}$$

where G denotes the power gain constant introduced by communication equipments, $h_0^{\Bbbk} \sim CN(0, 1)$ denotes a complex gaussian random variable representing Rayleigh fading, $d_{i,j}$ denotes the distance from platoon m's vehicle i to platoon m's vehicle j and α denotes the path loss exponent. Similarly, $h_{c,j}^{m,\Bbbk}$, $h_{i',j}^{m',m,\Bbbk}$ and $h_{c,BS}^{\Bbbk}$ are used to represent (i) the channel gain between individual cellular network user c and platoon m's vehicle j, (ii) the channel gain between vehicle i' of platoon m' and vehicle j of platoon m and (iii) the channel gain between individual cellular network user c and gNB, respectively. It is assumed that gNB can obtain the channel state information (CSI) of all links in the network.

Let $x_{m,n}^{\Bbbk}$ be the binary variable, for which $x_{m,n}^{\Bbbk} = 1$ indicates that subchannel $\Bbbk$ is assigned to platoon vehicle n of platoon m; $x_{m,n}^{\Bbbk} = 0$, otherwise. Then, the matrix $X^{\Bbbk} = \left[x_{m,n}^{\Bbbk}\right]_{\forall m,n} \in \{0, 1\}^{MxN}$ represents the assignment of subchannel $\Bbbk$ to platoon vehicles in the whole network. Let $y_c^{\Bbbk}$ be the subchannel allocation indicator for the assignment of subchannel $\Bbbk$ to individual cellular network user c ($c \in$ C). The matrix $Y = \left[y_c^{\Bbbk}\right] \in \{0, 1\}^{CxK}$ represents the assignment of subchannel $\Bbbk$ to individual cellular network users. $y_c^{\Bbbk} = 1$ indicates that subchannel $\Bbbk$ is assigned to individual cellular network user c; $y_c^{\Bbbk} = 0$ otherwise. The Signal to Interference plus Noise Ratio (SINR) in the receiving PM vehicle N_m^b from its PL_m over subchannel $\Bbbk$ is denoted as follows:

$$SINR_{1,N_m^b}^{m,\Bbbk} = \frac{P_1^{m,\Bbbk}\left|h_{1,N_m^b}^{m,\Bbbk}\right|^2}{\sigma^2} \tag{5}$$

where $\mathrm{P}_1^{m,\Bbbk}$ denotes the transmission power of the PL vehicle of platoon m over subchannel $\Bbbk$, $h_{1,N_m^b}^{m,\Bbbk}$ denotes the channel power gain from the transmitting PL vehicle to the receiving PM vehicle $N_m^b(2 \leq N_m^b \leq N_m)$ of platoon m over subchannel $\Bbbk$ and σ^2 denotes the power of the additive white Gaussian noise (AWGN).

Let (i) $I_{BS}^{\Bbbk}$ denote the interference from other platoons, which share the same subchannel $\Bbbk$; (ii) $\mathrm{P}_c^{\Bbbk}$ *and* $P_n^{m,\Bbbk}$ denote the power of individual cellular network user c and the power of PM vehicle n in platoon m over subchannel $\Bbbk$, respectively; (iii) $d_{c,BS}$ and $d_{n,BS}^m$ denote the distance from individual cellular network user c to gNB and the distance from PM vehicle n of platoon m to gNB, respectively. The SINR from the transmitting individual cellular network user c to gNB in subchannel $\Bbbk$ is represented as follows:

$$SINR_{c,BS}^{\Bbbk} = \frac{P_c^{\Bbbk}\left|h_{c,BS}^{\Bbbk}\right|^2}{\sigma^2 + I_{BS}^{\Bbbk}} = \frac{P_c^{\Bbbk}G(d_{c,BS})^{-\alpha}.\left|h_0^{\Bbbk}\right|^2}{\sigma^2 + I_{BS}^{\Bbbk}} \tag{6}$$

where

$$I_{BS}^{\Bbbk} = \sum_{m=1}^{M}\sum_{n=1}^{N_m} x_{m,n}^{\Bbbk} P_n^{m,\Bbbk}\left|h_{n,BS}^{m,\Bbbk}\right|^2 = \sum_{m=1}^{M}\sum_{n=1}^{N_m} x_{m,n}^{\Bbbk} P_n^{m,\Bbbk} G(d_{n,BS}^m)^{-\alpha}.\left|h_0^{\Bbbk}\right|^2$$

Let (i) $I_n^{m,\Bbbk}$ denote the total co-channel interference to receiving vehicle n of platoon m over subchannel $\Bbbk$; (ii) $h_{n-1,n}^{m,\Bbbk}$ represent the channel gain of the V2V link between transmitting vehicle $n-1$ of platoon m and receiving vehicle n platoon m over subchannel $\Bbbk$; (iii) $h_{n',n}^{m',m,\Bbbk}$ represent the channel gain between vehicle n' of platoon m' and vehicle n of platoon m over subchannel $\Bbbk$; (iv) $h_{c,n}^{m,\Bbbk}$ represent the channel gain between individual cellular network user c and platoon vehicle n of platoon m over subchannel $\Bbbk$. For intra-platoon communication, the SINR in the receiving PM vehicle $n(2 < n \leq N_m)$ of platoon m from the transmitting PM vehicle $n-1$ of platoon m over subchannel $\Bbbk$ is denoted as follows:

$$SINR_{n-1,n}^{m,\Bbbk} = \frac{P_{n-1}^{m,\Bbbk}\left|h_{n-1,n}^{m,\Bbbk}\right|^2}{\sigma^2 + I_n^{m,\Bbbk}} = \frac{P_{n-1}^{m,\Bbbk}G(d_{n-1,n})^{-\alpha}.\left|h_0^{\Bbbk}\right|^2}{\sigma^2 + I_n^{m,\Bbbk}} \tag{7}$$

where

$$
\begin{aligned}
I_n^{m,k} &= \sum_{m'=1,m'\neq m}^{M} \sum_{n'=1}^{N_{m'}} x_{m',n'}^{k} P_{n'}^{m',k} \left|h_{n',n}^{m',m,k}\right|^2 + \sum_{c=1}^{C} y_c^{k} P_c^{k} \left|h_{c,n}^{m,k}\right|^2 \\
&= \sum_{m'=1,m'\neq m}^{M} \sum_{n'=1}^{N_{m'}} x_{m',n'}^{k} P_{n'}^{m',k} G\left(d_{n',n}^{m',m}\right)^{-\alpha} \cdot \left|h_0^{k}\right|^2 \\
&\quad + \sum_{c=1}^{c} y_c^{k} P_c^{k} G\left(d_{c,n}^{m}\right)^{-\alpha} \cdot \left|h_0^{k}\right|^2
\end{aligned}
$$

The Shannon capacity is adopted to evaluate the achievable data rate [10]. The receiving data rate in gNB from the transmitting individual cellular network user c over subchannel k can be expressed as follows:

$$R_{c,BS}^{k} = log_2\left(1 + SINR_{c,B\ S}^{k}\right) \tag{8}$$

The receiving data rate of vehicle N_m^b of platoon m, which is in the edge of $PL_m' s$ broadcasted range, from the transmitting PL vehicle of platoon m over subchannel k can be expressed as follows:

$$R_{1,N_m^b}^{m,k} = log_2\left(I + SINR_{1,N_m^b}^{k}\right) \tag{9}$$

The receiving data rate of PM vehicle n of platoon m from the transmitting PM vehicle $n-1$ of platoon m over subchannel k can be expressed as follows:

$$R_{n-1,n}^{m,k} = log_2\left(1 + SINR_{n-1,n}^{m,k}\right) \tag{10}$$

Let the data size of the data packet that the PM vehicle of platoon m needs to be forwarded to the tail PM vehicle of platoon m be $\lambda(\lambda \geq 0)$. The transmission latency from platoon m's transmitting platoon vehicle n to platoon m's receiving vehicle $n+1$ over subchannel k is expressed as follows:

$$T_{n,n+1}^{m,k} = \frac{\lambda}{R_{n,n+1}^{m,k}} \tag{11}$$

Let $k_0, k_1, \ldots, k_{N_m-N_m^b} \in K_m$ be the allocated subchannels to each transmission link, and K_m denote the subset of subchannels allocated to platoon m. Then, the data delivery latency from the PL vehicle of platoon m to platoon m's tail PM vehicle is expressed as follows:

$$T_{1,N_m} = \frac{\lambda}{R_{1,N_m^b}^{m,k_0}} + \frac{\lambda}{R_{N_m^b,N_m^b+1}^{m,k_1}} + \ldots + \frac{\lambda}{R_{N_m-1,N_m}^{m,k_{N_m-N_m^b}}} \tag{12}$$

IV. PROBLEM FORMULATION

In this Section, (1) the resource allocation problem for PL vehicles, which belongs to the 1st stage of the proposed method, and (2) the resource allocation problem for PM vehicles, which belongs to the 2nd stage of the proposed resource allocation method, are formulated.

A. THE OPTIMIZATION PROBLEM OF RESOURCE ALLOCATION FOR PL VEHICLES

The resource allocation problem for PL vehicles considers the subchannel allocation and power control of PL vehicles, which are modeled as an optimization problem aiming to maximize PL vehicle's broadcasted range. To reduce the co-channel interference, the subchannels assigned to PL vehicles cannot be reused by any other vehicle. Thus, for M platoons, there are M subchannels that need to be allocated to M PL vehicles. The goal is to reduce PL's transmitted power to reduce energy consumption and increase the number of PM vehicles that can effectively receive PL vehicle's broadcasted messages. As a result, the subchannel allocation and power control problem for PL vehicles can be mathematically formulated as follows:

$$\text{maximize} \left(\sum_{m=1}^{M}\left(x_{m,1}^{k} * \left(N_m^b - \frac{P_1^{m,k}}{P_{max}}\right)\right)\right) \tag{13}$$

$$\text{Subject to:}\quad P_1^{m,k} \leq P_{max} \tag{13a}$$

$$2 \leq N_m^b \leq N_m \tag{13b}$$

$$SINR_{1,N_m^b}^{m,k} \geq \text{SINR}_{\text{thr}} \tag{13c}$$

$$\sum_{m=1}^{M}\sum_{n=2}^{N_m} x_{m,n}^{k} + \sum_{c=1}^{C} y_c^{k} = 0 \tag{13d}$$

$$\sum_{m=1}^{M} x_{m,1}^{k} = 1 \tag{13e}$$

In the optimization problem, constraint (13a) denotes that the transmitted power of the PL vehicles should not exceed the maximum threshold, which is denoted as P_{max}. The last PM vehicle N_m^b inside PL vehicle's broadcasted range of platoon m is denoted in constraint (13b), i.e., PM vehicles $N_m^b + 1$ and after are outside PL vehicle's broadcasted range of platoon m. Constraint (13c) denotes the reliability requirement for each PM vehicle inside PL vehicle's broadcasted range, i.e., the long-term SINR of the allocated subchannel is larger than the SINR threshold, i.e., SINR_{thr}. Constraint (13c) is needed to establish reliable communication for the edge PM vehicle inside PL vehicle's broadcasted range. Constraints (13d) and (13e) correspond to the following restriction: the subchannel assignment for a PL vehicle can only be assigned to one PL vehicle. Note that, (i) N_m^b is an integer number, i.e., it is increased/decreased by 1, 2, …; (ii) $\frac{P_1^{m,k}}{P_{max}}$ is a real number that is between (0,1).

The optimization problem depicted in Equation (13) is explained as follows. Since N_m^b is an integer number and $\frac{P_1^{m,k}}{P_{max}}$ is a real number, it can get the maximum value of $\left(N_m^b - \frac{P_1^{m,k}}{P_{max}}\right)$ by making N_m^b as big as possible and making $P_1^{m,k}$ as small as possible. But the bigger N_m^b it is, the smaller $SINR_{1,N_m^b}^{m,k}$ it has. Thus, it needs to increase the transmitted power. Nevertheless, the value of $\left(N_m^b - \frac{P_1^{m,k}}{P_{max}}\right)$ will be decreased when the transmitted power is increased. Let N_m^b be equal to x_i, which is an integer number. Then, it has the smallest transmitted power of $P_1^{m,k}$ to satisfy constraint (13c).

Let N_m^b be equal to x_{i+1}, *where* $x_{i+1} > x_i$. Then, the smallest transmitted power for satisfying constraint (13c) is increased; but the corresponding $\left(N_m^b - \frac{P_1^{m,\kappa}}{P_{max}}\right)$ may be bigger or smaller than that for x_i. Since different platoons are in different locations, assigning different subchannels to the PL vehicle of platoon $m, m = 1, 2, \ldots, M$, results in different $(N_m^b, P_1^{m,k})$ to have different values of $\sum_{m=1}^{M}\left(x_{m,1}^{k} * \left(N_m^b - \frac{P_1^{m,k}}{P_{max}}\right)\right)$.

Thus, it needs to evaluate possible pairings between subchannels and PL vehicles to resolve the objective function.

B. THE OPTIMIZATION PROBLEM OF RESOURCE ALLOCATION FOR PM VEHICLES

The resource allocation problem for PM vehicles mainly considers the subchannel allocation of PM vehicles. After the 1st stage is done, let K' denote the (minimum) number of the unassigned subchannels, where $K' \geq K - N$ and N is the maximum number of PM vehicles in the considered platoons. In the resource allocation for PM vehicles, which is the 2nd stage's resource allocation, a PM vehicle's assigned subchannel can be reused by other platoons' PM vehicles; additionally, the uplinked resource of individual cellular network users can be reused by PM vehicles to improve spectrum utilization efficiency. In the case of PM vehicles' sharing their allocated subchannels with individual cellular network users, the QoS requirements of individual cellular network users should be guaranteed. The QoS requirement is to guarantee the minimum data rate of each individual cellular network user in this work. The reliability of PM vehicles' communications is guaranteed using the minimum required SINR for PM vehicles. Thus, the subchannel allocation for PM vehicles can be regarded as a problem of minimizing the total transmission latency of PMs' vehicles. The optimization problem is mathematically modeled as follows:

$$\textit{minimize} \left(\sum_{m=1}^{M}\sum_{n=2}^{N_m} T_{n,n+1}^{m,k}\right) \tag{14}$$

$$\text{Subject to:} \quad \sum_{n=2}^{N_m} x_{m,n}^{k} \leq 1, \forall m \tag{14a}$$

$$\text{SINR}_{n,n+1}^{m,k} \geq \text{SINR}_{\text{thr}}, \forall x_n^{m,k} = 1 \tag{14b}$$

$$\sum_{c=1}^{C} y_c^{k} \leq 1 \tag{14c}$$

$$\sum_{s=1}^{K'} x_{m,n}^{s} \leq 1, \forall m, n \tag{14d}$$

$$\sum_{s=1}^{K'} y_c^{s} \leq 1, \forall c \tag{14e}$$

$$R_{c,BS}^{s} \geq R_{\text{thr}}^{c}, \forall y_c^s = 1 \tag{14f}$$

where $T_{n,n+1}^{m,k}$ in Equation (14) denotes the transmission latency from the transmitting PM vehicle n of platoon m to the receiving PM vehicle $n+1$ of platoon m over subchannel k. Constraint (14a) denotes that subchannel k is assigned to at most one PM vehicle in a platoon. Constraint (14b) denotes the SINR requirement of the receiving PM vehicle in a platoon over subchannel k. Constraint ta(14c) denotes that subchannel k can be assigned to at most one individual cellular network user. Constraint (14d) denotes that a PM vehicle can be allocated at most one subchannel. Constraint (14e) denotes that an individual cellular network user can be allocated at most one subchannel. The QoS requirement of each individual cellular network user that has been assigned with a subchannel is denoted in constraint (14f).

V. THE PROPOSED 2-STAGE RESOURCE ALLOCATION METHOD

This Section presents resource allocation algorithms that are used in the proposed 2-Stage Resource Allocation (2-STRA) method to solve the optimization problems formulated in Section IV.

Fig. 3 depicts the flowchart of the proposed 2-STRA method. The proposed 2-STRA method is divided into the following two stages:

1) The 1st stage contains the Greedy Resource Allocation Algorithm for PL vehicles. In the 1st stage, a Joint Subchannel and Power Allocation for Platoon Leaders (JSPA-PLs) algorithm has been designed to maximize PL vehicle's broadcasted range using the PL vehicle's minimum transmitted power. The JSPA-PLs algorithm can select the pairing of (i) the subchannel and the transmitted power and (ii) the platoon's PL vehicle that can have the maximum utility, and then assigns the corresponding subchannel and transmitted power to the selected platoon's PL vehicle; then, update the subchannels that can be used for the other platoons' PL vehicles.

2) In the 2nd stage, the resource allocation for PM vehicles, which is based on the subchannels that are not allocated to PL vehicles, is resolved. The second stage includes the following three phases:

a) In order to efficiently model the complicated interference scenario and reduce resource allocation complexity, the PM Vehicles' Partitioning (PMVP) algorithm is devised to group PM vehicles into clusters, for which those PM vehicles use the same subchannel belong to the same cluster. The PMVP algorithm assigns PMs of each platoon to a cluster to minimize the increased intra-cluster interference step by step.

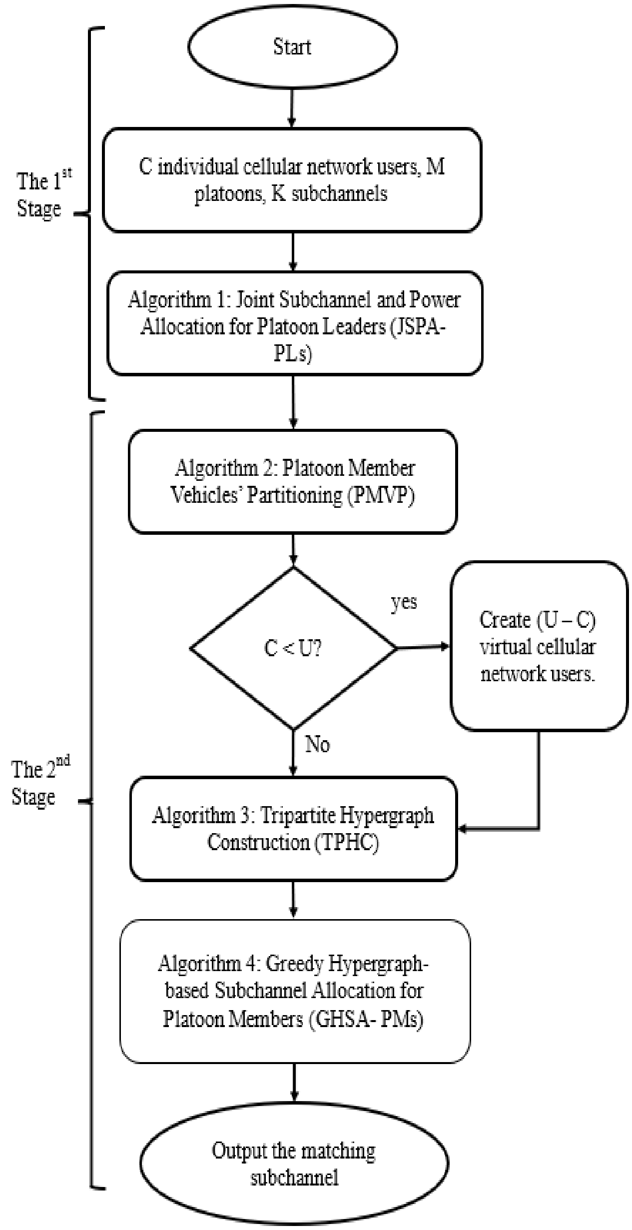

FIGURE 3. The control flowchart of the proposed 2-STRA method.

b) Then, the Tripartite Hypergraph Construction (TPHC) algorithm is proposed to construct a tripartite hypergraph, in which (1) there are three different types of vertices to denote (i) individual cellular network users, (ii) subchannels and (iii) clusters, and (2) each hyperedge comprises three vertices, for which one vertex denotes an individual cellular network user, another vertex denotes a subchannel, and the other vertex denotes a cluster.

c) After that, the Greedy Hypergraph-based Subchannel Allocation for Platoon Members (GHSA-PMs) algorithm is proposed to assign subchannels for PM vehicles based on the constructed tripartite hypergraph. The goal of the GHSA-PMs algorithm is to sequentially select the hyperedge that has the minimum weight as part of matching based the sorting of all hyperedges in the weight ascending list.

Notations used in this Section are depicted in Table 2.

TABLE 2. Notations used in the proposed 2-stra method.

Symbol	Definition
$G(V, W)$	The graph used to represent the in/tra-cluster interference.
$w_{v,v'}$	The channel gain of the interference from the transmitting PM vehicle v to the receiving PM vehicle v'.
U	The amount of clusters.
$\mathcal{U}_u$	The set of PM vehicles of cluster u.
$H = (V, E)$	The tripartite hypergraph, in which V denotes the set of vertices and E denotes the set of hyperedges.
R	The min-weight tripartite matching in H, where $e_1 \cap e_2 = \emptyset, \forall e_1, e_2 \in R, R \subseteq E$.
$w(e)$	The weight of the hyperedge e.
$t(e)$	$t(e) = 1$ if the hyperedge e belongs to the matching, $t(e) = 0$ otherwise.
$\delta(v)$	The set of hyperedges containing vertex v.
$N[e]$	The set of H's hyperedges that intersect hyperedge e; note that $e \in N[e]$.

A. THE 1ST STAGE: A GREEDY RESOURCE ALLOCATION ALGORITHM FOR PL VEHICLES

To solve the problem of resource allocation for PL vehicles, the algorithm called Joint Subchannel and Power Allocation for Platoon Leaders (JSPA-PLs), which jointly considers subchannel allocation and power control for PL vehicles, is presented in this sub-Section.

Let subchannel $\mathscr{k}$ be allocated to a PL vehicle. Referring to Equation (5) and constraint (13b), constraint (13c) can be transformed into the following form:

$$SINR_{1,N_m^b}^{m,\mathscr{k}} \geq \mathrm{SINR_{thr}},\ 2 \leq N_m^b \leq N_m$$

$$\frac{\mathrm{P}_1^{m,\mathscr{k}} \left|\mathrm{h}_{1,N_m^b}^{m,\mathscr{k}}\right|^2}{\sigma^2} \geq \mathrm{SINR_{thr}}$$

$$\mathrm{P}_1^{m,\mathscr{k}} \geq \mathrm{SINR_{thr}} * \frac{\sigma^2}{\left|\mathrm{h}_{1,N_m^b}^{m,\mathscr{k}}\right|^2} \tag{15}$$

Combining Equation (15) with constraints (13a) and (13c), the transmitted power of a PL vehicle can be expressed as follows:

$$\mathrm{SINR_{thr}} * \frac{\sigma^2}{\left|\mathrm{h}_{1,N_m^b}^{m,\mathscr{k}}\right|^2} \leq \mathrm{P}_1^{m,\mathscr{k}} \leq P_{max} \tag{16}$$

Let $\sum_{m=1}^{M}\left(x_{m,1}^{\mathscr{k}} * \left(N_m^b - \frac{P_1^{m,\mathscr{k}}}{P_{\max}}\right)\right)$ be the *Utility*. Then, Equation (13), which solves the resource allocation problem of PLs, that jointly considers subchannel allocation and

Algorithm 1 Jointly Subchannel and Power Allocation for Platoon Leaders (JSPA-PLs)

- **Input**: $(\mathscr{M};\mathscr{K})$ // $\mathscr{M}$ denotes the set of M platoons, $\mathscr{K}$ denotes the set of K subchannels
- **Output:**Resource assignment for the PL vehicle of each platoon

1. **Repeat**
2. **Select** $m^* = argmax\ (L_m)\ , \forall m \in \mathscr{M}$ // select the longest platoon.
3. **Set** $N^b_{m^*} = N_{m^*}$
4. **For** $\mathscr{k} = 1 : k$ **do**
5. Compute the lowest bound $\mathrm{P}_1^{m^*,\mathscr{k}}$, which is $\mathrm{SINR_{thr}} * \frac{\sigma^2}{\left|h^{m^*,\mathscr{k}}_{1,N^b_{m^*}}\right|^2}$ according to Equation (17a), of the transmitted power for the PL vehicle of platoon m^*.
6. **If** it can not satisfy constraint (17a) **then**
7. **Set** $N^b_{m^*} = N^b_{m^*} - 1$
8. Go to Line 5.
9. **End if;**
10. Compute $\left(N^b_{m^*} - \frac{P_1^{m^*,\mathscr{k}}}{P_{max}}\right)$
11. **End for;**
12. **Select** $\left(\mathscr{k}^*, P_1^{m^*,\mathscr{k}^*}\right) = argmax \left(N^b_{m^*} - \frac{P_1^{m^*,\mathscr{k}}}{P_{max}}\right)$
13. Assign subchannel $\mathscr{k}^*$ and $P_1^{m^*,\mathscr{k}^*}$ for the PL vehicle of platoon m^*;
14. $\mathscr{K} = \mathscr{K} k^*$
15. $\mathscr{M} = \mathscr{M} m^*$
16. **Until:** $\mathscr{M} = \emptyset$ // assigning subchannels and power for all PL vehicles.

power control for PL vehicles is transformed to the following expression:

$$\text{maximize} \quad \left(\sum_{m=1}^{M}\left(x^{\mathscr{k}}_{m,1} * \left(N^b_m - \frac{P_1^{m,\mathscr{k}}}{P_{max}}\right)\right)\right) \tag{17}$$

$$\text{Subject to:} \quad \mathrm{SINR_{thr}} * \frac{\sigma^2}{\left|\mathrm{h}^{m,\mathscr{k}}_{1,N^b_m}\right|^2} \le \mathrm{P}_1^{m,\mathscr{k}} \le P_{max} \tag{17a}$$

$$2 \le N^b_m \le N_m \tag{17b}$$

$$\sum_{m=1}^{M}\sum_{n=2}^{N_m} x^{\mathscr{k}}_{m,n} + \sum_{c=1}^{C} y^{\mathscr{k}}_c = 0 \tag{17c}$$

$$\sum_{m=1}^{M} x^{\mathscr{k}}_{m,1} = 1 \tag{17d}$$

Three steps in JSPA-PLs are as follows: Step 1 (Lines 2-3) chooses the platoon with the longest length and sets N^b_m of the chosen platoon to be equal to the tail PM vehicle N_m. In other words, initially, it is assumed the PL vehicle of platoon m can broadcast its messages to all of its PM vehicles. Step 2 (Lines 4-11) selects the subchannel and has the corresponding power assignment for the PL vehicle of platoon m^* to maximize the objective function depicted in Equation (17). For each subchannel $\mathscr{k} \in K$, it computes the PL vehicle's lower bound transmitted power $\mathrm{P}_1^{m^*,\mathscr{k}}$, which is $\mathrm{SINR_{thr}} * \frac{\sigma^2}{\left|h^{m^*,\mathscr{k}}_{1,N^b_{m^*}}\right|^2}$. If the transmitted power is higher than the maximum transmitted power P_{max}, i.e., constraint (17a) is violated, then the value of $N^b_{m^*}$ is decreased by one and go to Line 5 to compute the transmitted power again; otherwise, the value of $\left(N^b_m - \frac{P_1^{m^*,\mathscr{k}}}{P_{max}}\right)$ is calculated. Step 2 is repeated until all of the utility, i.e., $\left(N^b_{m^*} - \frac{P_1^{m^*,\mathscr{k}}}{P_{max}}\right)$, of pairing (i) each of the subchannels that still can be used and (ii) the PL of platoon m^* has been derived. Step 3 (Lines 12-15) selects the pairing of the subchannel and the transmitted power for the PL vehicle of platoon m^* that can have the maximum *utility*, and assigns the corresponding subchannel and transmitted power for the PL vehicle of platoon m^*; then, update (i) the subchannels that can be used for the PL vehicles of other platoons and (ii) the platoons that are to be computed. Lines 1-16 are executed repeatedly until each PL vehicle of these M platoons has been assigned with a subchannel and the transmitted power respectively.

Algorithm 2 Platoon Member Vehicles' Partitioning (PMVP)

- Input: M platoons, U clusters;
- Output: The clustering result of PM vehicles // assign each PM vehicle to one of the U clusters.

1. **For** $m = 1 : \mathscr{M}$ **do**
2. Let $\mathscr{PM}_m$ be the set of PM vehicles of platoon m.
3. **Repeat**
4. Randomly select a PM vehicle v of platoon m, $v \in \mathscr{PM}_m$
5. **For** $u = 1 : U$ **do**
6. **If** cluster u contains a PM vehicle of platoon m **then**
7. Go to Line 4;
8. **End if;**
9. Compute the increased intra-cluster interference by $\sum_{v' \in \mathscr{U}_u} (w_{v,v'} + w_{v',v})$
10. **End for;**
11. Assign PM vehicle v of platoon m to cluster u^* with $u^* = \mathrm{argmin} \sum_{v,v' \in U_{u^*}} (w_{v,v'} + w_{v',v})$
12. $\mathscr{PM}_m = \mathscr{P}\mathrm{M}_m v$ // remove the PM vehicle v from the set
13. **Until** $\mathscr{PM}_m = \emptyset$ // all PM vehicles of platoon m are assigned to the corresponding clusters.
14. **End For;**

The complexity of the JSPA-PLs algorithm is $O(M * K)$, where M is the amount of platoon, K subchannels.

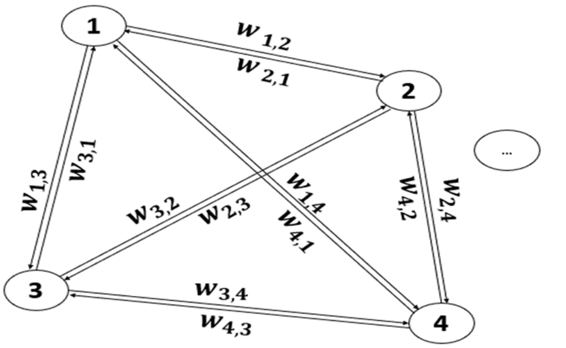

FIGURE 4. An exemplary weighted graph that represents the interference relationships in a cluster.

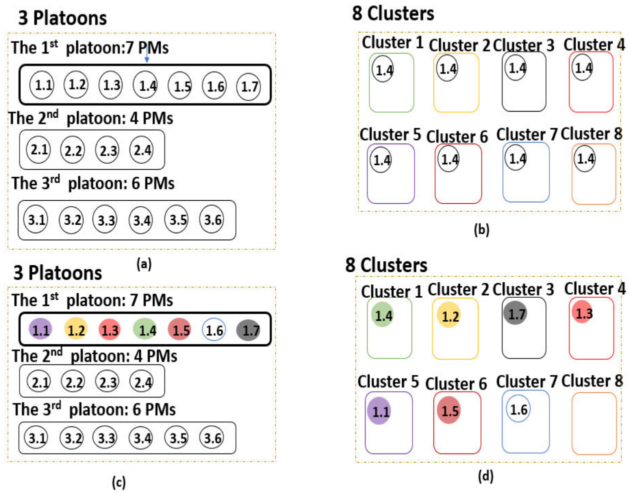

FIGURE 5. The exemplary execution for partitioning PM vehicles of the 1st platoon into the corresponding clusters.

B. THE 2ND STAGE: SUBCHANNEL ALLOCATION FOR PM VEHICLES

Three phases of the proposed algorithms for solving the problem of PM vehicles' subchannel allocation using the objective function depicted in Equation (14) are as follows:

1) PHASE 1: PM VEHICLES' PARTITIONING

In order to efficiently model the complicated interference scenario and to reduce the resource allocation complexity, PMs' vehicles are clustered at first based on their allocated subchannels, for which those PMs' vehicles are put into a cluster when they use the same subchannel.

Then, the channel interference among those PMs' vehicles using the same subchannel can be modeled as a weighted graph $G(V, W)$ for each cluster of PMs' vehicles. There is no more than one PM vehicle of the same platoon in a cluster. For convenient explanation, Fig. 4 depicts an exemplary weighted graph representing interference relationships in a cluster. Referring to Fig. 4, in a graph $G(V, W)$, each vertex denotes a PM vehicle of a platoon; a direct line, which connects two vertices v and v, is associated with number $w_{v,v'}$, which represents the channel gain of the interference from the transmitting PM vehicle v to the receiver PM vehicle v'.

The idea of the proposed heuristic algorithm, which is called Platoon Member Vehicles' Partitioning (PMVP), is based on the work of [20]. For the resource allocation scheme, it can use the graph partitioning algorithm to divide the V2V links into different spectrum-sharing clusters based on their mutual interferences before formulating the spectrum sharing problem. PMVP iteratively assigns PMs of each platoon to a cluster such that, at each step, the increased intra-cluster interference is minimized in each step.

Some requirements of PMVP are as follows. It is started by initializing U clusters, where (i) the amount of clusters equals the number of the remaining subchannels after the 1st stage was done, i.e., $U = K'$; (ii) the amount of cluster U should be equal to or greater than the largest platoon size N, i.e., $U \geq N$; (iii) the total number of PM vehicles of the M platoons is greater than the number of clusters, i.e., $\sum_{m=1}^{M} (N_m - 1) > U$. The partitioning problem becomes trivial when $\sum_{m=1}^{M} (N_m - 1) \leq U$ because it can just give each PM vehicle a subchannel when the number of subchannels that are available for allocation is greater than or equal to the resource needed by PM vehicles. PMVP attempts to dispatch all strongly interfering PMs' vehicles of M platoons to different clusters such that PMs' vehicles within the same cluster can share the same subchannel with the lower mutual interference. That is, the PMVP algorithm separates all strongly interfering PM vehicles of M platoons into U sets, i.e., $U_1, U_2, \ldots, U_U$, where the sum of intra-cluster interferences of all clusters is minimized, i.e., $\sum_{u=1}^{U} \left(\sum_{v,v' \in U_u} w_{v,v'}\right)$.

Line 1 of the PMVP algorithm iteratively selects each platoon in each step to assign its PM vehicles to U clusters. Line 4 randomly selects a PM vehicle v of the selected platoon. Lines 5-10 compute the intra-cluster interferences when PM vehicle v is put to each cluster. If the cluster contains a PM vehicle of the selected platoon, then this cluster is ignored, which is depicted in Lines 6-8. Line 9 computes the intra-cluster interference. Line 11 selects the cluster u^* that has the minimum intra-cluster interference, in which PM vehicle v is assigned to the selected cluster u^*. Lines 3-13 are repeated executed until all PM vehicles of the selected platoon are assigned to their corresponding clusters. Lines 1-14 are executed repeatedly until all PM vehicles of these M platoons have been assigned to U clusters.

An exemplary clustering depicted in Fig. 5-7 is used for the explanation of Algorithm 2. Referring to Fig. 5, there are three platoons and their corresponding PM vehicles need to be allocated some resources. The 1st, 2nd and 3rd platoons have 7, 4, 6 PM vehicles, respectively. Referring to Fig. 5-(a), it randomly selects a PM vehicle of the 1st platoon, for which PM vehicle 1.4 is selected, and computes the intra-cluster interference of assigning the selected PM vehicle 1.4 to each cluster, which is depicted in Fig. 5-(b). In case there is no PM vehicle of the 1st platoon in a cluster, the intra-cluster interference in this cluster is zero. After all of the intra-cluster

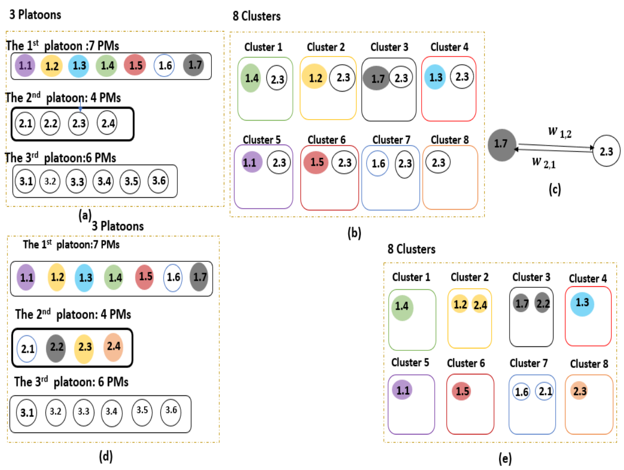

FIGURE 6. The exemplary execution for partitioning PM vehicles of the 2nd platoon into the corresponding clusters.

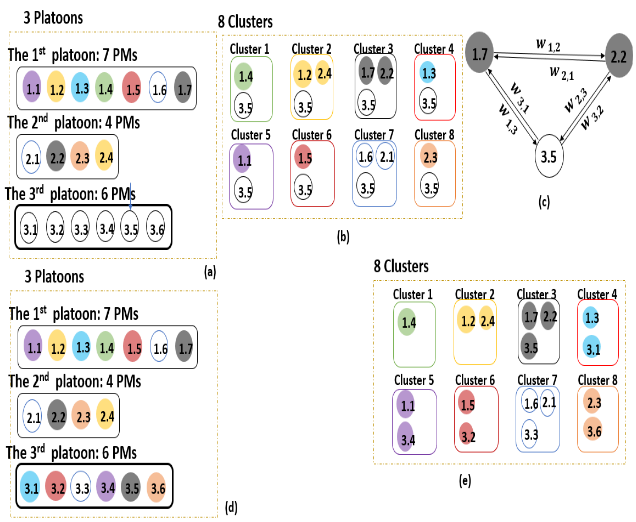

FIGURE 7. The exemplary execution for partitioning PM vehicles of the 3rd platoon into the corresponding clusters.

interferences of assigning the selected PM vehicle 1.4 to each cluster are computed, the selected PM vehicle 1.4 is assigned to the cluster that results in the minimum intra-cluster interference. It repeats this process until all of the PM vehicles of the 1st platoon have been assigned to different clusters. The exemplary configuration of all PM vehicles of the 1st platoon having been assigned to their corresponding clusters is depicted in Fig. 5-(d). After finishing partitioning the 1st platoon, it randomly selects a PM vehicle, which is PM vehicle 2.3 in Fig. 6-(a), of the 2nd platoon, and computes the intra-cluster interference, which is depicted in Fig. 6-(a) and Fig. 6-(b). Fig. 6-(c) depicts an example of the intra-cluster interference computation, for which the intra-cluster interference of cluster 3 is depicted. Cluster 3 has one PM vehicle of the 1st platoon when PM vehicle 2.3 of the 2nd platoon is selected. Therefore, the intra-cluster interference of cluster 3 is the sum of $w_{1,2} + w_{2,1}$ as depicted in Fig. 6-(c).

Algorithm 3 Tri-Partite Hypergraph Construction (TPHC)

- **Input**: (C, K', M, U) // C individual cellular network users, K′ unassigned subchannels after assigning subchannels to PL vehicles, M platoons and U clusters.
- **Output**: a tripartite hypergraph

1. Using **Algorithm 2** to divide PM vehicles of M platoons into U clusters.
2. **If** $C < U$ **then**: //create some virtual individual cellular network users;
3. $C = C + (U - C);$
4. **End if**;
5. **For** $c = 1 : C$ **do**
6. **For** $\Bbbk = 1 : K'$ **do**
7. **For** $u = 1 : U$ **do**
8. Compute the SINR of the PMs' vehicles in cluster u;
9. Compute the data transmission rate of individual cellular network user c;
10. **If** it satisfies Constraints (14b) and (14f) **then**
11. Compute the total latency of all PMs' vehicles communications in cluster u and set the weight $w(c, \Bbbk, u)$ to be equal to $\sum_{v\in\mathcal{U}_u} T_v$, where T_v denotes the transmission latency between the transmitting PM vehicle v and its receiver.
12. **End if**;
13. **End for**;
14. **End for**;
15. **End for**;

PMVP assigns the selected PM vehicle to the cluster u^*, $u = 1, 2, \ldots, 8$, with

$$u^* = \operatorname{argmin} \sum\nolimits_{v,v'\in \mathrm{U}_u} (w_{v,v'} + w_{v',v}).$$

The example in Fig. 6 shows that the selected PM vehicle 2.3 of the 2nd platoon is assigned to cluster 8 because it has the smallest intra-cluster interference comparing with other clusters. Repeating the above steps until the PM vehicles of the 2nd platoon are distributed into different clusters and then continue to do the same with the 3rd platoon. The exemplary configuration of all PM vehicles of the 2nd platoon having been assigned to their corresponding clusters as depicted in Fig. 6-(d) and Fig. 6-(e). Fig. 7 depicts partitioning PM vehicles of the 3rd platoon; the intra-cluster interference is computed and each PM vehicle is assigned to a cluster according to their mutual interferences. Similarly, the intra-cluster interference of cluster 3 is depicted in Fig. 7-(c). When PM vehicle 3.5 of the 3rd platoon is selected, the intra-cluster interference of cluster 3 is the sum of $w_{1,2} + w_{2,1} + w_{1,3} + w_{3,1} + w_{2,3} + w_{3,2}$. After computing and comparing intra-cluster interferences of all clusters, the example in Fig. 7 shows that the selected PM vehicle 3.5 is assigned to cluster 3. The above steps are executed repeatedly until all PM vehicles of the 3rd platoon are partitioned. Fig. 7-(c) and Fig. 7-(d) depict the exemplary configuration of all PM vehicles of the 3rd platoon having been assigned to their corresponding clusters.

The complexity of the PMPA algorithm is $O(M * N * U)$, where M is the amount of platoon, N is the maximum size of the platoon and U is the amount of cluster.

2) PHASE 2: TRI-PARTITE HYPERGRAPH'S CONSTRUCTION

The tripartite hypergraph matching is similar to the bipartite matching, except that the tripartite hypergraph matching matches three sets of vertices instead of two sets of vertices. A hypergraph $H = (V, E)$ consists of a set of vertices V and a set of hyperedges E, where each hyperedge connects an arbitrary number of vertices instead of only two. A matching in H is a subset R,$R \subseteq E$, of hyperedges such that for any distinct hyperedge $e_1 \cap e_2 = \emptyset, e_1 \in R$ *and* $e_2 \in R$. For C individual cellular network users, K' subchannels and U clusters, the resource allocation for PM vehicles can be formulated into a min-weight tripartite matching problem.

Let T_v denote the transmission latency between the transmitting PM vehicle v and its receiver. The weight $w\,(\mathrm{c}, \Bbbk, \mathrm{u})$ of each hyperedge is denoted by the total transmission latency of all PMs' vehicles in the corresponding subchannel/cluster, $w\,(\mathrm{c}, \Bbbk, \mathrm{u}) = \sum_{v \in \mathrm{U}_u} T_v$. The objective is to find a subset of hyperedges such that any two distinct hyperedges in this subset is not intersected. To ensure that each vertex in set C and each vertex in set U can be matched with one subchannel, the number of vertices in set C, set K' and set U should be the same to ensure that the matching covered all of the vertices in each set. For example, let there be 2, 3 and 3 vertices in set C, set K' and set U, respectively. The matching is the subset of the hyperedges in which each hyperedge contains a vertex from each set. After the matching is done, there is still one vertex in K' and one vertex in U. Since $|C| < |K'|(= |U|)$, it needs to add one virtual vertex to set C such that the number of vertices in C can be equal to that of K and U.

A Tripartite Hypergraph Construction (TPHC) algorithm was proposed for constructing the tripartite hypergraph. Line 1 of the TPHC algorithm divides all PMs' vehicles into U clusters. If the amount of vertex of individual cellular network users is smaller than the number of clusters, Lines 2-4 of the TPHC algorithm add some virtual individual cellular network users to ensure that all of the three sets of the tripartite hypergraph contain the same number of vertices. Lines 8-9 of the TPHC algorithm compute the SINR of PM vehicles in cluster u and compute the transmission rate of individual cellular user c. Line 11 of the TPHC algorithm sets the hyperedge weight of the hypergraph.

Fig. 8 depicts an exemplary construction of the tripartite hypergraph. Fig. 8-(a) depicts the input of the TPHC algorithm, which is the number of individual cellular network users ($C = 2$), the number of unassigned subchannels ($K' = 3$) and the number of clusters ($U = 3$). Since the number of individual cellular network users C is smaller than the number of clusters U ($C<U$), a virtual cellular network user vertex c_3 is created. Fig. 8-(b) depicts an example of the weighted matrix when c_1 shares subchannel $\Bbbk_1$, $\Bbbk_2$ and $\Bbbk_3$ with PM vehicles in cluster u_1, u_2 and u_3, respectively. Similarly, Fig. 8-(c) (Fig. 8-(d)) depicts the example of the weighted matrix when c_2 (c_3) shares subchannel $\Bbbk_1$, $\Bbbk_2$ and $\Bbbk_3$ with PM vehicles in cluster u_1, u_2 and u_3, respectively.

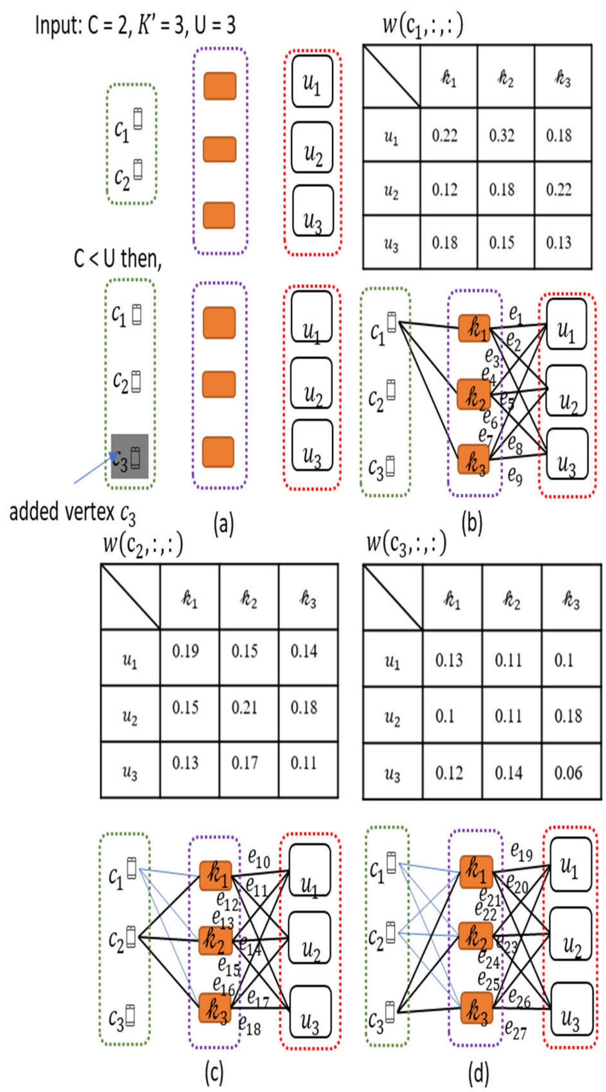

FIGURE 8. An example of the tripartite hypergraph construction.

Algorithm 4 Greedy Hypergraph-Based Subchannel Allocation for Platoon Members (GHSA-PMs)

- **Input**: $H = (E, V), w$
- **Output**: The min-weight tripartite matching;

1. **Initialization**: $R \leftarrow \emptyset$
2. E $\leftarrow sort(E, ascend)$ //Sorting all Hyperedges in the weight ascending list.
3. **For** $e \in E$ **do**
4. **If** $N[e] \cap R = \emptyset$ **then**
5. $R \leftarrow R \cup \{e\}$
6. **End if**
7. **End for**;

3) PHASE 3: GREEDY HYPERGRAPH-BASED SUBCHANNEL ALLOCATION

The problem of Equation (14) can be modeled as the min-weighted tripartite matching problem, which can be expressed as the integer program:

$$\textit{minimize} \quad \sum_{e \in E} w(e) * t(e) \tag{18}$$

$$\text{Subject to:} \quad \sum_{e \in \delta(v)} t(e) = 1, \forall v \in V \tag{18a}$$

$$t(e) \in \{0, 1\}, \forall e \in E \tag{18b}$$

where $w(e)$ denotes the weight of the hyperedge e, $t(e)$ denotes the matching situation of hyperedge e and $\delta(v)$ denotes the set of hyperedges that contain vertex v. The objective of the integer program (18) is to find the optimal $t(e)$. Constraint (18a) denotes that there is only one hyperedge for each vertex. Constraint (18b) is called integrality constraint, for which $t(e) = 1$ if the hyperedge e belongs to the matching, $t(e) = 0$ otherwise.

In this work, a Greedy Hypergraph-based Subchannel Allocation for Platoon Members (GHSA-PMs) algorithm was proposed to solve the problem of resource allocation for PM vehicles based on a tripartite hypergraph. Algorithm GHSA-PMs sorts all of the hyperedges in the ascending order according to their edge weights at first. For any hyperedge e, $e \in E$, the intersect of e_i and e is not empty, i.e., $e_i \cap e \neq \emptyset$, means that there is one or more vertices that e_i and e commonly have. Let $N[e]$ denote the set of hyperedges that intersect hyperedge e, i.e., if $e_i \in N[e]$ and $e_i \neq e$, then $e_i \cap e \neq \emptyset$, note that $e \in N[e]$. Line 2 of the GHSA-PMs algorithm sorts all of the hyperedges in the ascending order according to their weights. For vertices with only one hyperedge passing through, it will be selected first. Lines 3-7 of the GHSA-PMs algorithm select the hyperedge that has the minimum weight as part of matching sequentially. Lines 4-6 select the hyperedges that do not intersect the selected hyperedges as part of matching. The output of the GHSA-PMs algorithm is a matching R, which is the subset of hyperedges in E.

Fig. 9 depicts an example of the min-weight tripartite matching. First, the hyperedge is sorted as the weight ascending list, i.e., $w(c_3, k_3, u_3) < w(c_3, k_1, u_2) < \ldots < (c_1, k_2, u_1)$. The GHSA-PMs algorithm selects the hyperedges in the ascending order according to their weights sequentially and it skips the hyperedges that intersect the selected hyperedges. The hyperedge e, which connects vertex c_3, vertex k_3 and vertex u_3, has weight $w(c_3, k_3, u_3)$, is selected as part of the matching at first. Referring to Fig. 9, the matching is the set of the following hyperedges: (i) the hyperedge that connects three vertices c_3, k_3, u_3, (ii) the hyperedge that connects three vertices c_2, k_2, u_1, and (iii) the hyperedge that connects three vertices c_1, k_1, u_2.

An independent set of hyperedges with the lowest weight in tripartite hypergraph H are selected in a greedy manner using the GHSA-PMs algorithm. The essential idea behind the GHSA-PMs algorithm is to partition all PM vehicles using

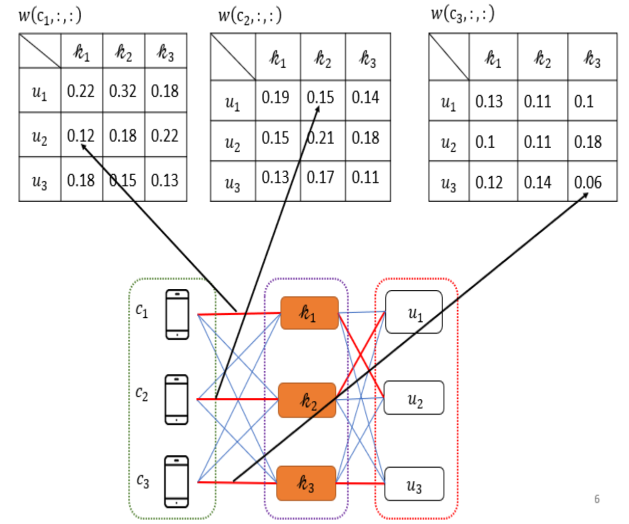

FIGURE 9. An exemplary the min-weight tripartite matching.

the PMPA algorithm at first. Then, the tripartite hypergraph is constructed using the THCA algorithm. Finally, the matching of the tripartite hypergraph is derived using the GHSA-PMs algorithm. The resource allocation problem depicted in Section IV-B. is evaluated using aforementioned algorithms, and the result is proved in the following Section.

VI. PERFORMANCE EVALUATION

This Section presents the performance evaluation of the proposed resource allocation method. The simulation environment and the performance metrics are explained first. Then, the simulation results are presented to validate the proposed resource allocation method.

A. THE SIMULATION ENVIRONMENT

In order to evaluate the performance of the proposed resource allocation method, a multi-lane highway that passes through a single cell, where the gNB is located at its center, is modeled. The simulation tool is MATLAB. The results are averaged over 1000 repeated experiments. The simulation parameters are depicted in Table 3. The simulated platoons use the same speed with different numbers of vehicles in these platoons. However, there are simulations set up with different speeds to compare transmission latency. The road segment is 2 KM and the gNB is placed in the middle with a radius of 1 KM.

Fig. 10 depicts the snapshot of the location distribution with 2 platoons ($M = 2$), 10 individual cellular network users ($C = 10$) and the maximum size of each platoon 10 ($N = 10$). The platoons and individual cellular network users are distributed on the roads according to the spatial Poison Distribution. The size of each platoon is randomly distributed and the intra-platoon distances of two neighboring PMs' distance are calculated using Equations (1), (2) and (3). The gNB is installed 35 meters perpendicularly away from the highway. The pathloss model used for individual cellular

TABLE 3. Parameters and their values used for the simulation.

Parameters	Values
Radius of gNB	1km
gNB antenna height	25m
gNB antenna gain	8 dBi
The distance from gNB to Highway	35 m
Vehicle antenna height	1.5 m
Highway lane	4
Lane width	4 m
SINR threshold for the receiver $SINR_{thr}$	5 dB
QoS requirement of individual cellular network users	0.5 bps/Hz
The maximum platoon size	10
PL vehicle's maximum transmitted power	30 dBm
PM vehicle's maximum transmitted power	17 dBm
Individual cellular network user's maximum transmitted power	30 dBm
Bandwidth	10 MHz
Carrier Frequency	2 GHz
Fading factor (α)	3
Noise power spectrum density (σ^2)	-114 dBm
Size of a data packet (λ)	300 Bytes
Pathloss model for individual cellular network users	128.1 + 37.6 $\log_{10}(d)$
Pathloss model for platoon vehicle's communications	$LOS\ WINNER + B1$ [31]

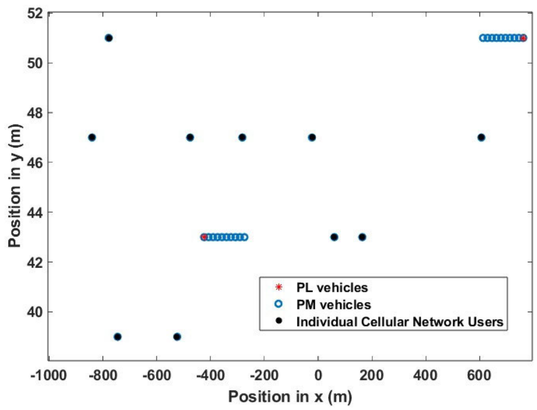

FIGURE 10. A Snapshot of the location distribution with M = 2, N = 10 and C = 10.

network users are as follows:

$$pl(\text{db}) = 128.1 + 37.6 * \log_{10}(d)$$

where $d(kilometer)$ is the distance between the individual cellular user and its receivers.

The Log-normal shadowing distribution and the Rayleigh fading model are applied for both individual cellular network users and platoon vehicles in the simulation. The standard deviation is 8 dB for individual cellular network users and 3 dB for platoon vehicles, respectively.

The compared methods are (i) the proposed 2-Stage Resource Allocation using Greedy Algorithm (2-STRA) control scheme, (ii) the Subchannel Allocation and Power Control (SAPC) for PL vehicles developed in [9], (iii) the Hypergraph-based Resource Allocation and Interference Management (HRAIM) scheme developed in [15], and (iv) the random subchannel assignment (RAA) method. SAPC allows the subchannels allocated to PM vehicles to be reused by other PM vehicles in different platoons, but does not allow the subchannel allocated to a PM vehicle to be reused by other intra-platoon PM vehicles. The communications of (i) PL vehicle's broadcasting messages to PM vehicles, (ii) PL vehicle's communication with BS and (iii) BS's communication with the PL vehicle use only one subchannel and can not be reused by other entities. The main difference between SAPC and the proposed method of this work is that the proposed method assigns a unique subchannel for the PL vehicle for broadcasting messages to its PM vehicles and it uses the other subchannel for the communication between PL and BS. HRAIM allows the subchannels allocated to PM vehicles to be reused by other PM vehicles belonging to the same platoon and/or different platoons; a subchannel assigned for an individual cellular network user is allowed to be shared with PM vehicles. For the RAA method, it randomly assigns subchannels to PM vehicles based on the constraint of the SINR requirement of the received PM vehicle in a platoon over an assigned subchannel using Equation (14a). When the individual cellular network user reuses a subchannel, the communication should satisfy the constraint of the QoS requirement denoted in Equations (14f). The SINR of a PM vehicle should be greater than the SINR requirement for successful transmission in HRAIM and SAPC methods.

The adopted performance metrics that are used for comparison are as follows:

(i) Platoon's Transmission latency (ms): It denotes the average transmission time that a PL vehicle transmits data to the tail PM vehicles.
(ii) Broadcast power of PL vehicles (mW): The PL vehicles' transmission power.
(iii) Spectral efficiency (bps/Hz): the data rate that can be transmitted over a given bandwidth in the system.
(iv) Sum rate (Mbits/s): The sum of the data transmission rates of platoon vehicles, including PM vehicles and PL vehicles.
(v) Number of assigned subchannels: The number of subchannels that can be assigned to platoon vehicles.

B. SIMULATION RESULTS

1) PLATOON'S TRANSMISSION LATENCY

Let the number of subchannels that can be assigned to platoons be 30 subchannels and the size of each platoon is

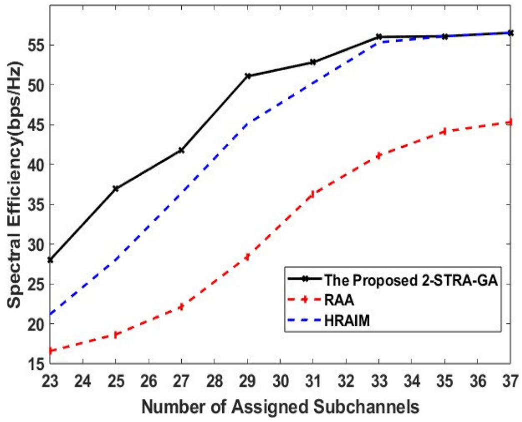

FIGURE 11. The transmission latency of a platoon for different numbers of platoons.

random and is in the range of [2], and [10] vehicles. Fig. 11 depicts the transmission latency of platoon vehicles using these compared methods for different numbers of platoons when the moving speed is 35 km/h. Referring to Fig. 11, the transmission latency of a platoon increases when the number of platoons increases. The reason is that when the number of platoons increases, the number of PM vehicles that use the same subchannel also increases, which means the interference among PM vehicles using the same subchannel becomes more complicated and thus SINR becomes lower. Consequently, the resulted bit rates become lower. In other words, one subchannel has fewer reusing PM vehicles when having fewer platoons. Therefore, with the fixed number of assigned subchannels, the transmission latency will be increased when the number of platoons increases. Referring to Fig. 11, the proposed 2-STRA control schemes achieve the best performance in terms of transmission latency. The reason is that RAA and HRAIM methods allow multiple intra-platoon PM vehicles to share one subchannel, which causes the interference to be higher. Due to the distance between a PM vehicle and its intra-platoon PM vehicles being short, the interferences caused by intra-platoon PM vehicles, i.e., the PM vehicles in the same platoon, may be higher than the interferences caused by inter-platoon PM vehicles, i.e., the PM vehicles in other platoons, that may be more far away.

Fig. 12 shows the transmission latency of a platoon for different platoon speeds, for which the number of platoons is 5 platoons ($M = 5$) and the size of each platoon is random and is in the range of [2], and [10], respectively. Referring to Fig. 12, when the speed becomes higher, the transmission latency becomes longer. The reason is that the increase of speed leads to the increase of intra-platoon PM vehicles' distance, which causes the increase of transmission latency using the Intelligent Driver car-following Model (IDM) [27]. Among these four compared methods, the proposed 2-STRA methods are always better on the whole, i.e., they have the lower transmission latency of a platoon in various speeds. The reason is that the proposed 2-STRA method does not

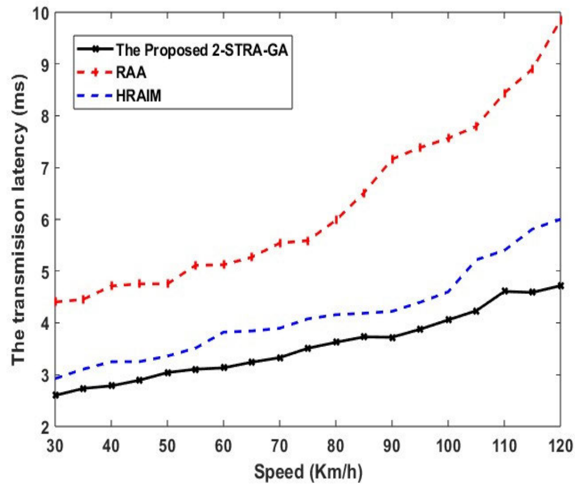

FIGURE 12. The transmission latency of a platoon for different platoon speeds.

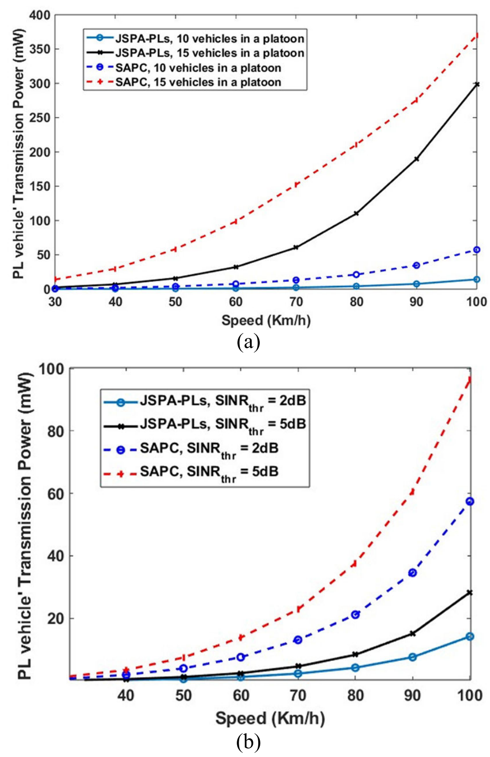

FIGURE 13. PL vehicle's transmission power verse different speeds with: (a) different platoon sizes (10 vehicles and 15 vehicles in a platoon); (b) different SINR thresholds.

allow subchannels to be reused by intra-platoon PM vehicles. Therefore, the interferences are only caused by the PM vehicles, in different platoons. For the other two methods, the subchannels can be reused by intra-platoon PM vehicles, i.e., PM vehicles in the same platoon, which causes higher interferences than those PM vehicles in different platoons.

2) BROADCASTED POWER OF PL VEHICLES

Fig. 13 depicts the transmission powers of PL vehicles using the proposed JSPA-PLs method, which was described in the proposed Algorithm 1, and the SAPC method of [9] for different speeds. Let the number of platoons be 5 ($M = 5$). Fig. 13-(a) are for different platoon's sizes, i.e., the numbers of vehicles in the platoon are 10 and 15, respectively. Fig. 13-(b) are for different SINR thresholds, for which $SINR_{thr}$ is set to 2dB and 5dB, respectively. Let the $SINR_{thr}$ be fixed to 2dB in Fig. 13-(a). Referring to Fig. 13-(a), the transmission power of PL vehicles increases when the speed of vehicles increases, i.e., the speed of vehicles is changed from 30 km/h to 100km/h. When the SINR threshold is fixed, i.e., $SINR_{thr} = 2dB$, the PL vehicle' transmission power increases when the speed of platoon vehicles increases. The reason is that the intra-platoon distance becomes longer when the speed of vehicles increases. Thus, the distance from the PL vehicle to the tail PM vehicle becomes longer, which results in the increase of PL vehicle's transmission power. Comparing with the SAPC method, the proposed JSPA-PLs method used less power than the SAPC method. It is because our proposed JSPA-PLs method only assigns the orthogonal subchannel, which is not reused by others, for PL vehicles. However, since it only uses one subchannel for PL vehicle's broadcasted messages to PM vehicles and BS's communication with the PL vehicle, it results in the interference between PL vehicle and BS. Therefore, PL vehicles need to use more power to transmit their messages to PM vehicles using the SAPC method. Referring to Fig. 13-(b), PL vehicle's transmission power also needs to increase to satisfy the transmission requirements when the SINR threshold increases (from 2dB to 5dB). That is, PL vehicles increase their transmission power to send messages to more PM vehicles to meet the minimum SINR requirement.

3) SPECTRAL EFFICIENCY AND THE NUMBER OF ASSIGNED SUBCHANNELS

Let the number of platoons be 3 (M = 3), the maximum size of each platoon be 10 vehicles and the moving speed of vehicles be 35km/h. Fig. 14 shows the spectral efficiency of these compared methods for different numbers of assigned subchannels. Referring to Fig. 14-(a), the spectral efficiency is increased when the number of assigned subchannels is increased. The reason is that the number of PM vehicles allocated to the same subchannel is decreased with the increased number of assigned subchannels, which means the interference among PM vehicles that use the same subchannel become less. Therefore, the interference is lower, and thus SINR becomes higher, which results in the higher bitrate Thus the spectral efficiency is increased when the number of assigned subchannel is increased. When number of assigned subchannels is bigger than 33, the spectral efficiency of the proposed 2-STRA and HRAIM is quite the same; however, the RAA method is lower. The proposed 2-STRA outperformed the other two methods when the number of assigned subchannels is increased from 23 to 33. This reason is that the interference caused by PM vehicles in the same platoon is higher than that caused by the PM vehicles of other platoons.

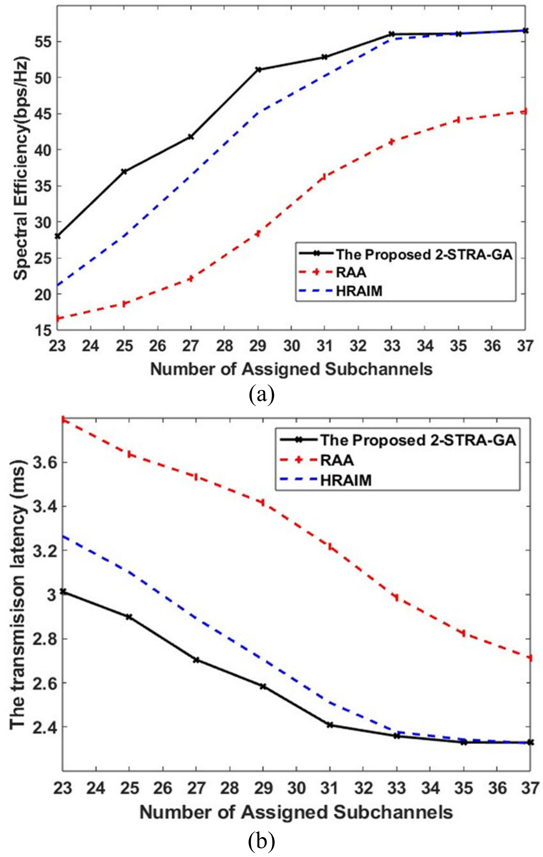

FIGURE 14. (a) The spectral efficiency for different numbers of assigned subchannels; (b) The transmission latency for different numbers of assigned subchannels.

Fig. 14-(b) depicts the effects of the number of assigned subchannels to the transmission latency of all platoon vehicles. Referring to Fig. 14-(b), the transmission latency changes when the number of subchannels increases. The reason is that the increased number of assigned subchannels leads to less interferences between PM vehicles using the same subchannel. That is, when the number of PM vehicles that shared one subchannel is decreased, the interference becomes lower, which results in the SINR becoming higher, and thus it can have the higher bitrate. Because of the increased bitrate, the transmission latency becomes lower. The proposed 2-STRA outperformed the other two methods in terms of the number of assigned subchannels allocation. The reason is that the number of PM vehicles that reuse the same subchannels is decreased, which results in the decreasing of the co-channel interference and the decreasing of the transmission latency. When the number of subchannels varies from 23 to 33, the transmission latency and spectral efficiency of the proposed 2-STRA method are better than that of HRAIM and RAA methods. However, when the number of subchannels is bigger than 33, i.e., from 33 to 37, HRAIM and the proposed 2-STRA method have the similar in transmission latency and spectral efficiency. The reason is that each PM vehicle

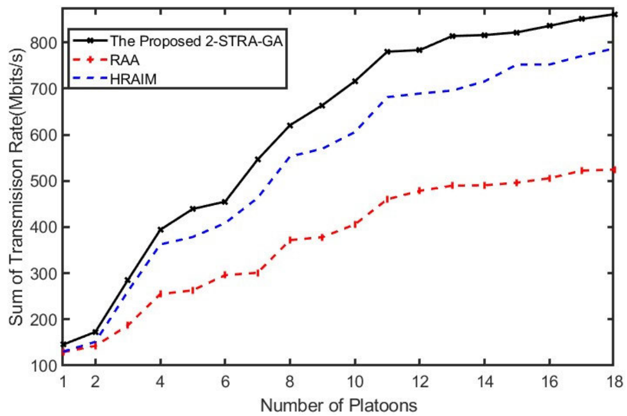

FIGURE 15. Transmission rate for different numbers of platoons.

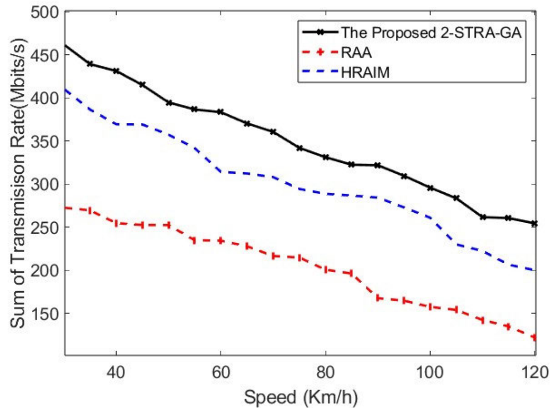

FIGURE 16. Sum of PM vehicles' transmission rates for different vehicle's speeds.

can be assigned its own subchannel and thus there is no interference among them. When the number of subchannels is 33 or higher, there are 3 subchannels assigned to PL vehicles and it still has 30 unassigned subchannels that can be assigned for PM vehicles. For the HRAIM and the proposed 2-STRA method, each vehicle is assigned a subchannel to maximize the transmission rate. As a result, the transmission latency and the transmission rate become similar.

4) SUM OF TRANSMISSION RATE

Let the speed of vehicles be 35km/h and the number of assigned subchannels be 30. Fig. 15 depicts the data transmission rates of all platoon vehicles for different numbers of platoons when the platoon size is random and is in range of [2], and [10] vehicles. Referring to Fig. 15, it can be observed that the sum of the data transmission rates of platoon vehicles is increased monotonically with the increase of the number of platoons from 1 to 18. Generally speaking, the number of platoons is increased, the sum of data transmission rates of all platoon vehicles increases. The gap of platoon vehicles' sum of data transmission rates between (i) the proposed 2-STRA method and (ii) RAA and HRAIM methods becomes bigger when the number of platoons increases from 3 to 18 platoons. The reason is that the co-channel interferences of the two other methods is higher than that of the proposed 2-STRA method. It shows that the proposed methods can result in the higher data transmission rate comparing with the other two methods.

Let the number of platoons be 5, the size of each platoon be in the range of [2], [3], [4], [5], [6], [7], [8], [9], and [10] and the number of assigned subchannels be 15, respectively. Fig. 16 depicts the impact of the vehicle's speed on the PM vehicle's data transmission rate. Referring to Fig. 16, it can be observed that the data transmission rate of platoon vehicles is decreased when the speed is increased. The reason is that when vehicles' speeds increase, the intra-platoon distance needs to be increased, which results in the SINR becoming smaller and thus the data transmission rate becoming lower. However, the performance of our proposed 2-STRA method is significantly better than that of the others even in the high mobility cases.

C. DISCUSSION

Overall, the HRAIM [15] and RAA methods allow subchannels to be reused by PM vehicles of the same platoon; our proposed methods do not allow subchannels to be reused by PM vehicles of the same platoon. The proposed 2-STRA method is validated in the simulation by increasing the number of platoons and their moving speeds. With the constraint of having the number of available subchannels being more than the maximum number of vehicles in the platoon, the transmission latency and spectrum efficiency of the platoons using the proposed 2-STRA method are better than the other compared methods.

In addition, in term of the transmitted powers of PLs, the proposed JSPA-PLs method uses the smaller power than the SAPC method [9]. The reason is that the proposed JSPA-PLs method only assigns the orthogonal subchannels, which are not reused by others, for PL vehicles. However, since it only uses one subchannel for (i) PL vehicle's broadcasting messages to PM vehicles and (ii) PL vehicle's communication with BS, it results in the interference between PL vehicle and BS. Therefore, PL vehicles need to use more power to transmit their messages to PM vehicles using the SAPC method.

In terms of the spectral efficiency and assigned subchannels, when the number of assigned subchannels is bigger than 33, the spectral efficiency of the proposed 2-STRA and HRAIM is quite similar; however, the RAA method is lower. When the number of assigned subchannels is increased from 23 to 33, the proposed 2- STRA outperforms the other two methods. This reason is that the interference caused by PM vehicles in the same platoon is higher than that caused by the PM vehicles of other platoons.

VII. CONCLUSION

In this work, the resource allocation for multi-platoon communications based on the graph theory approach has been studied. The 2-STage Resource Allocation (2-STRA) method, including (i) the resource allocation for PL vehicles that is resolved the 1st stage and (ii) the resource allocation for PM vehicles that is resolved in the 2nd stage, has been proposed to improve spectrum efficiency. In the 1st stage, a JSPA-PLs algorithm has been designed to maximize PL vehicle's broadcasted range using the minimum transmitted power of PL vehicles. In the 2nd stage, PMs' vehicles are clustered using the proposed PMVP algorithm, for which those PMs' vehicles that use the same subchannel are put into a cluster. After that, a tripartite hypergraph is formulated using the proposed TPHC algorithm. Then, the GHSA-PMs algorithm was proposed to solve the problem of resource allocation for PM vehicles based on the constructed tripartite hypergraph. The simulation results have shown that the proposed 2-STRA method has the better performance on (i) the transmission latency of platoon vehicles, (ii) the power control for PL vehicles and (iii) the transmission rates of platoon vehicles in the conditions of various speeds and various numbers of subchannels.

Several approaches along which this work may be further extended are as follows. i) It can consider the groupcast communication mechanism for relaying PL vehicle's information, for which the power control and transmission reliability need to be considered. (ii) This work investigates the resource allocation problem in the single-cell scenario. It can investigate the resource allocation for multi-cell multi-platoon communications by taking both intra-cell/inter-cell interferences and platoon's handoff into consideration. (iii) It can explore the subchannel resource allocation for electrical platoons, for which the remaining battery power of vehicles needs to be considered.

REFERENCES

[1] S. J. Taylor, F. Ahmad, H. N. Nguyen, and S. A. Shaikh, "Vehicular platoon communication: Architecture, security threats and open challenges," *Sensors*, vol. 23, no. 1, p. 134, Dec. 2022.

[2] J. Zhan, Z. Ma, and L. Zhang, "Data-driven modeling and distributed predictive control of mixed vehicle platoons," *IEEE Trans. Intell. Vehicles*, vol. 8, no. 1, pp. 572–582, Jan. 2023.

[3] H. Zhu, Y. Zhou, X. Luo, and H. Zhou, "Joint control of power, beamwidth, and spacing for platoon-based vehicular cyber-physical systems," *IEEE Trans. Veh. Technol.*, vol. 71, no. 8, pp. 8615–8629, Aug. 2022.

[4] P. Zhang, D. Tian, J. Zhou, X. Duan, Z. Sheng, D. Zhao, and D. Cao, "Joint optimization of platoon control and resource scheduling in cooperative vehicle-infrastructure system," *IEEE Trans. Intell. Vehicles*, vol. 8, no. 6, pp. 3629–3646, Jun. 2023.

[5] A. Balador, A. Bazzi, U. Hernandez-Jayo, I. de la Iglesia, and H. Ahmadvand, "A survey on vehicular communication for cooperative truck platooning application," *Veh. Commun.*, vol. 35, Jun. 2022, Art. no. 100460. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214209622000079

[6] M. Parvini, M. R. Javan, N. Mokari, B. Abbasi, and E. A. Jorswieck, "AoI-aware resource allocation for platoon-based C-V2X networks via multi-agent multi-task reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 72, no. 8, pp. 9880–9896, Aug. 2023, doi: 10.1109/TVT.2023.3259688.

[7] B. Wang and R. Su, "A distributed platoon control framework for connected automated vehicles in an urban traffic network," *IEEE Trans. Control Netw. Syst.*, vol. 9, no. 4, pp. 1717–1730, Dec. 2022.

[8] R. Wang, J. Wu, and J. Yan, "Resource allocation for D2D-enabled communications in vehicle platooning," *IEEE Access*, vol. 6, pp. 50526–50537, 2018, doi: 10.1109/ACCESS.2018.2868839.

[9] H. Peng, D. Li, Q. Ye, K. Abboud, H. Zhao, W. Zhuang, and X. Shen, "Resource allocation for cellular-based inter-vehicle communications in autonomous multiplatoons," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11249–11263, Dec. 2017.

[10] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, "Platoon cooperation in cellular V2X networks for 5G and beyond," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 3919–3932, Aug. 2019.

[11] C. Hong, H. Shan, M. Song, W. Zhuang, Z. Xiang, Y. Wu, and X. Yu, "A joint design of platoon communication and control based on LTE-V2V," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 15893–15907, Dec. 2020.

[12] Z. Dong, X. Zhu, Y. Jiang, H. Zeng, Z. Wei, F.-C. Zheng, and K.-C. Leung, "Dynamic manager selection assisted resource allocation in URLLC with finite block length for 5G-V2X platoons," *IEEE Trans. Veh. Technol.*, vol. 71, no. 11, pp. 11336–11350, Nov. 2022.

[13] J. Mei, K. Zheng, L. Zhao, L. Lei, and X. Wang, "Joint radio resource allocation and control for vehicle platooning in LTE-V2V network," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 12218–12230, Dec. 2018, doi: 10.1109/TVT.2018.2874722.

[14] H. Ding and K.-C. Leung, "Resource allocation for low-latency NOMA-enabled vehicle platoon-based V2X system," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2021, pp. 1–6, doi: 10.1109/GLOBECOM46510.2021.9685664.

[15] H. Cui, L. Xu, Q. Wei, and L. Wang, "Hypergraph based resource allocation and interference management for multi-platoon in vehicular networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Aug. 2020, pp. 853–857.

[16] R. Geng, H. Ren, and J. Yan, "User satisfaction-aware resource allocation for 5G green vehicle platooning," in *Proc. Int. Conf. Internet Things (iThings), IEEE Green Comput. Commun. (GreenCom), IEEE Cyber, Phys. Social Comput. (CPSCom), IEEE Smart Data (SmartData)*, Jul. 2019, pp. 868–873, doi: 10.1109/iThings/GreenCom/CPSCom/SmartData.2019.00156.

[17] P. Sroka, A. Kliks, M. Sybis, and P. Kryszkiewicz, "Dynamic power and frequency allocation scheme for autonomous platooning," in *Proc. IEEE 93rd Veh. Technol. Conf. (VTC-Spring)*, Apr. 2021, pp. 1–6, doi: 10.1109/VTC2021-Spring51267.2021.9449077.

[18] *Management and Orchestration; Architecture Framework (Release 17)*, document TS 28.533, V17.2.0, 3GPP, Mar. 2022.

[19] R. Y. Chang, Z. Tao, J. Zhang, and C.-C.-J. Kuo, "Multicell OFDMA downlink resource allocation using a graphic framework," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3494–3507, Sep. 2009, doi: 10.1109/TVT.2009.2014384.

[20] L. Liang, S. Xie, G. Y. Li, Z. Ding, and X. Yu, "Graph-based resource sharing in vehicular communication," *IEEE Trans. Wireless Commun.*, vol. 17, no. 7, pp. 4579–4592, Jul. 2018.

[21] S. Gupta, R. Patel, R. Gupta, S. Tanwar, and N. Patel, "A survey on resource allocation schemes in device-to-device communication," in *Proc. 12th Int. Conf. Cloud Comput., Data Sci. Eng. (Confluence)*, Jan. 2022, pp. 140–145.

[22] Z. Dong, X. Zhu, and Y. Jiang, "CoMP-based seamless handover and resource allocation for 5G-V2X platoon systems," in *Proc. IEEE Int. Conf. Commun.*, May 2022, pp. 2010–2015.

[23] G. Chai, W. Wu, Q. Yang, M. Qin, Y. Wu, and F. R. Yu, "Platoon partition and resource allocation for ultra-reliable V2X networks," *IEEE Trans. Veh. Technol.*, early access, 2023, doi: 10.1109/TVT.2023.3303195.

[24] X. Peng, H. Zhou, B. Qian, K. Yu, N. Cheng, and X. Shen, "Security-aware resource sharing for D2D enabled multiplatooning vehicular communications," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–6.

[25] *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures (3GPP TS 36.213 Version 16.4.0 Release 16)*. Accessed: Feb. 2012. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/136200_136299/136213/16.04.00_60/ts_136213v160400p.pdf

[26] M. Harounabadi, D. M. Soleymani, S. Bhadauria, M. Leyh, and E. Roth-Mandutz, "V2X in 3GPP standardization: NR sidelink in release-16 and beyond," *IEEE Commun. Standards Mag.*, vol. 5, no. 1, pp. 12–21, Mar. 2021.

[27] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 62, no. 2, pp. 1805–1824, Aug. 2000.

[28] E. Telatar, "Capacity of multi-antenna Gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, no. 6, pp. 585–595, 1999.
[29] Y. J. Bultitude and T. Rautiainen, "IST-4–027756 WINNER II D1. 1.2 V1. 2 WINNER II channel models," EBITG, TUI, UOULU, CU/CRC, NOKIA, Finland, Tech. Rep. Version 1.1, 2007.

CHUNG-MING HUANG (Senior Member, IEEE) received the B.S. degree in electrical engineering from National Taiwan University, in 1984, and the M.S. and Ph.D. degrees in computer and information science from The Ohio State University, in 1988 and 1991, respectively. He was the Chair of the Department of Computer Science and Information Engineering (CSIE), National Cheng Kung University (NCKU), Tainan, Taiwan, and the Director of the Institute of Medical Informatics, NCKU. He is currently a Distinguished Professor with the Department of CSIE, NCKU. He has published more than 300 refereed journals and conference papers in wireless and mobile communication protocols, interactive multimedia systems, audio and video streaming, and formal modeling of communication protocols. His research interests include wireless and mobile network protocol design and analysis, green computing and communication, media processing and streaming, and innovative network applications and services. He is a Senior Member of ACM. He has served as the Chair for the IEEE Vehicular Technology Society Tainan Chapter.

DAN-NGUYEN LAM received the M.S. degree in computer science and information engineering from National Cheng Kung University, Tainan, Taiwan, in 2022. His research interests include wireless and mobile networks, cloud computing, and software-defined networking.

DUY-TUAN DAO received the B.Sc. degree in electronics and telecommunications engineering from the Danang University of Technology, Vietnam, in 2008, and the M.S. and Ph.D. degrees in computer science and information engineering from National Cheng Kung University, in 2013 and 2019, respectively. He is currently a Ph.D. Lecturer with the Division of Computer Engineering, Faculty of Electronics and Telecommunications Engineering, The University of Danang-University of Science and Technology, Vietnam. His research interests include IP mobility, network intelligence, and wireless communication and its applications in vehicles.