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Dependable Content Distribution in D2D-Based Cooperative Vehicular Networks: A Big Data-Integrated Coalition Game Approach

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***Abstract*—Driven by the evolutionary development of automobile industry and cellular technologies, dependable vehicular connectivity has become essential to realize future intelligent transportation systems (ITS). In this paper, we investigate how to achieve dependable content distribution in device-to-device (D2D)-based cooperative vehicular networks by combining big data-based vehicle trajectory prediction with coalition formation game-based resource allocation. First, vehicle trajectory is predicted based on global positioning system and geographic information system data, which is critical for finding reliable and long-lasting vehicle connections. Then, the determination of content distribution groups with different lifetimes is formulated as a coalition formation game. We model the utility function based on the minimization of average network delay, which is transferable to the individual payoff of each coalition member according to its contribution. The merge and split process is implemented iteratively based on preference relations, and the final partition is proved to converge to a Nash-stable equilibrium. Finally, we evaluate the proposed algorithm based on real-world map and realistic vehicular traffic. Numerical results demonstrate that the proposed algorithm can achieve superior performance in terms of average network delay and content distribution efficiency compared with the other heuristic schemes.**

***Index Terms*—D2D-V2V communication, dependable content distribution, cooperative vehicular networks, vehicle trajectory prediction, coalition formation game, big data.**

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I. Introduction

A. Background and Motivation

THE exponential growth of vehicle volumes and densities over the past decades has caused a series of critical problems to human lives such as increased energy consumption, traffic accident, and air pollution. In the United States, the transportation sector accounts for 32% of the overall CO_2 emission, and traffic congestions cause approximate 2 billion gallons of waste fuel [1]. To solve these problems, environment harmonic intelligent transportation systems (ITS), which can not only leverage up-to-date advances of automobile industry with novel information and communication technologies but also manage the computational resources to provide better service in dynamic vehicular environment [2], are urgently required. Among various core technologies, dependable vehicular connectivity, which enables ubiquitous information exchange and content sharing among vehicles with little or no human intervention, is essential to realize the ITS framework. It also provides unprecedented opportunities for applications in the domains of road safety, travel efficiency, driving assistance, and in-vehicle infotainment.

A major line of works in the field of vehicle-to-vehicle (V2V) communication were developed based on the ad-hoc fashioned protocols such as IEEE 802.11p, in which the legacy carrier sense multiple access with collision avoidance (CSMA/CA) scheme is adopted for medium access control [3]. Since the contention based CSMA/CA scheme was not originally designed for vehicular networks with fast mobility, ad-hoc fashioned V2V communication may lead to unpredictable transmission latency and cannot satisfy the dependable timeliness requirements of ITS applications [4]. On the other hand, device-to-device (D2D) communication, which allows direct content sharing over proximate peer-to-peer links [5], provides a promising solution for realizing dependable vehicular connectivity [4]. Compared to ad-hoc V2V solutions, D2D based V2V (D2D-V2V) communication can easily achieve dependable service delivery and coordinated resource utilization by exploring the ubiquitous presence of cellular infrastructures with centralized intelligence [6].

Considering hot spots with extremely high vehicle density, a situation encountered frequently is that the same popular content such as traffic congestion and road condition information is simultaneously required by a large number of vehicular users [7]. A critical problem is how to obtain a popular content in a dependable way with possible minimum delay [3]. In the conventional cellular model, the high volumes of vehicular data traffic put an additional heavy burden on the capacity and delay constrained backhaul links [8]. The cell overload problem may get even worse considering the emergence of multimedia-rich applications, e.g., augmented reality, video on demands, on-line games, etc [9], [10]. Hence, D2D-V2V communication can be applied to realize effective data offloading by distributing the popular content from a local content holder to its neighboring vehicles via either single-hop or multi-hop transmissions.

However, the successful implementation of D2D based vehicular content distribution imposes new challenges. First of all, it is difficult to determine how to form a content distribution group because of the fast-varying channel conditions and network topologies caused by high vehicle mobility. The key research issue is how to achieve dependable content distribution through highly dynamic and unreliable D2D-V2V links. Second, co-channel interference caused by cellular spectrum reusing should be carefully managed in order to satisfy the dependable timeliness requirements of D2D-V2V communication. Thirdly, the multi-hop content distribution process involves a more sophisticated route selection problem, which has to be jointly optimized with peer discovery and spectrum allocation from a delay minimization perspective. Last but not least, performance evaluation should be conducted in a trustworthy manner based on realistic macro-mobility (real-world road/street topologies, traffic signs, etc.) and micro-mobility (acceleration/deceleration, V2V interactions, vehicle-to-road interactions, overtaking, etc.) descriptions [11].

B. Contribution

The major contributions of this work are summarized as follows:

- We investigate how to achieve dependable content distribution in D2D based cooperative vehicular networks by combining big data based vehicle trajectory prediction with coalition formation game based resource allocation. Vehicle trajectory is predicted by combining the interacting multiple model (IMM) estimation with the multi-Kalman filter (MKF) approach based on global positioning system (GPS) and geographic information system (GIS) big data. Then, by exploring reliable and long-lasting D2D-V2V connections, the content distribution is formulated as a joint peer discovery, route selection, and spectrum allocation problem, which is NP-hard due to the combinatorial nature.
- To provide a tractable solution, the determination of how to form content distribution groups with different lifetimes is formulated as a coalition formation game. The utility function is developed based on the minimization of average network delay, which is transferable to the individual payoff of each coalition member according to its contribution. We develop a big data integrated coalition formation approach to solve the joint optimization problem from a delay minimization perspective, in which the coalition merge and split process is implemented in an iterative fashion based on preference relations. We also provide in-depth analysis for theoretical properties in terms of stability and convergence.
- We evaluate the delay performance based on real-world map and realistic vehicular traffic by connecting SUMO with MATLAB via predefined standard interfaces. We take into account both macro-mobility and micro-mobility features, and compare the proposed algorithm with a non-cooperative scheme and a random group formation scheme. Numerical results demonstrate that superior performance in terms of average network delay and content distribution efficiency can be achieved by the proposed algorithm.

The remaining parts of the work are organized as follows. Section II introduces related works. Section III provides an in-depth description of the vehicle trajectory prediction model, the channel model, and the vehicular content distribution model. The formulation of the content distribution problem with the objective of minimizing average network delay is presented in Section IV. The coalition game formulation and coalition formation game based content distribution process are described in Section V. Experiment setup and numerical results are presented in Section VI. The conclusions and further works are summarized in Section VII.

II. Related Works

The objective of this work is to investigate how to achieve dependable content distribution in D2D based cooperative vehicular networks by combining big data based vehicle trajectory prediction with coalition formation game based resource allocation. A number of works have already studied content distribution problems in conventional D2D networks [12]–[14]. In particularly, the typical resource allocation problem has been addressed under versatile content distribution scenarios including relay networks [13], social networks [14], as well as mmWave cellular networks [15]. These works mainly target on D2D links with constant network topology, and are not suitable for the highly dynamic and unreliable D2D-V2V links caused by fast mobility of vehicles.

Vehicular content distribution problems have been studied in [8], [16], [17]. A social-aware on-road friend recommendation and content sharing system named Verse was developed in [8] based on mutual interests of vehicular users. In [16], a chain cluster based cooperative content distribution scheme was proposed to enhance the successful probability of content acquisition. In [17], the authors proposed a Stackelberg game based content delivery approach with the assistance of parked vehicles. However, most of previous works were mainly developed based on ad hoc or IEEE 802.11 serial standards, and have neglected specific characteristics of D2D based cooperative vehicular networks including spectrum reusing, co-channel interference management, quality of service (QoS) provisioning, etc. There exist some works which addressed the content distribution problem in D2D based vehicular networks [9], [18], [19]. A social big data based D2D-V2V content distribution scheme was developed in [9] by exploring both the physical layer and social layer information. In [18], a social-aware D2D based vehicular content distribution architecture named VeShare was proposed based on software defined networking. In [19], a D2D-V2V grouping, reuse channel selection, and power control framework was proposed to maximize the sum rate of vehicular networks. Nevertheless, the above mentioned works have not taken into account the sophisticated multi-hop transmission scenario and vehicle trajectory prediction. The system model and problem formulations are completely different from our work, and the derived solutions cannot be directly applied here.

Cooperative game theory, which provides a powerful tool for designing efficient and dependable cooperative content distribution strategies, has been widely adopted to solve the vehicular content distribution problem [20]–[23]. A coalition game based dynamic vehicular content sharing scheme was proposed in [20], and was extended to the scenario of cognitive vehicular networks in [22]. In [23], the authors proposed a cloud based vehicular content distribution scheme by combining Bayesian coalition game and learning automata. A bus trajectory based advertisement distribution approach was proposed in [21] by exploring coalition formation game. A load balancing (LB) scheme with the assistance of cooperative user relay to solve the SNR degradation problem was studied in [24]. However, most of the previous works have not provided a unified treatment of the joint peer discovery, spectrum allocation, and route selection optimization considered in this work, and have been mainly developed based on ideal theoretical models without considering real-world street topologies and big data based vehicle trajectory prediction.

Big data-assisted vehicular networks, which can extract the characteristics of GPS data, transportation data, etc., numerical iterations, can highly improve the reliability of the simulation result. In [25], the authors proposed an overlapping and hierarchical social clustering model (OHSC) with a social-based localization algorithm (SBL) to predict the location of vehicles even without the GPS data. In [26], the authors introduced the big data solutions to vehicular ad hoc network challenges. However, these works have not focused on the vehicular content distribution scenario, and the derived solutions cannot be applicable for the dealy minimization problem.

III. System Model

We focus on a general vehicular content distribution scenario, where the same popular content is required simultaneously by a number of distributed vehicles. Fig. 1 shows the system model of a D2D based cooperative vehicular network, which is composed of a base station (BS), K cellular user equipments (CUEs), M vehicular content providers (denoted as V-TXs), and N vehicular content requesters (denoted as V-RXs). In the conventional cellular mode, all of the content requests have to be served by the BS, which puts an additional heavy burden on the capacity and delay constrained backhaul links, and makes the cell overload problem even worse. An alternative solution is to enable V-TXs which have already

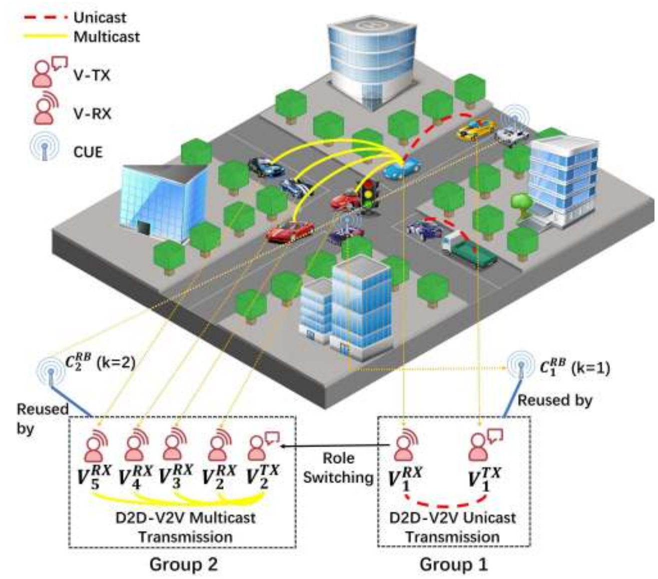

Fig. 1. The system model of D2D-V2V multihop content distribution.

obtained the content to act as transmitters, and to serve multiple neighboring V-RXs in the D2D-V2V multicast mode by reusing cellular spectrum. In particular, V-RXs which have obtained the content can also act as V-TXs and serve the content requests of their neighboring V-RXs. Thus, the content is actually delivered from the original M V-TXs to the N V-RXs in a multi-hop fashion. In the following subsections, we introduce the vehicle trajectory prediction model, the channel model, and the vehicular content distribution model in details.

A. Big Data Based Vehicle Trajectory Prediction Model

Vehicle mobility pattern and trajectory prediction have been thoroughly studied in several previous works [27]–[29]. We adopt a MKF based trajectory prediction approach proposed in [27] to estimate the connection time between two vehicles. The basic principle is briefly reviewed here, and interested readers can refer to [27] and references therein for more details.

Fig. 2 shows the GPS and GIS data based vehicle trajectory prediction by combining MKF and IMM. The three key steps are vehicle mobility modeling, data collection and preprocessing, and data processing and analysis.

1) Vehicle Mobility Modeling: To cover most of vehicle behaviors, four mobility patterns are incorporated to account for every possible on-road scenario: i) a vehicle with a constant location (CL); ii) a vehicle with a constant velocity (CV); iii) a vehicle with a constant acceleration (CA); iv) a vehicle with a constant jerk (CJ), which represents a constant change in acceleration. The mathematical expression of each mobility pattern as a function of vehicle position and velocity can be found in Section II of [27], which is omitted here due to space limitation. At each execution time of the MKF, it is assumed that the transition from one mobility pattern to another mobility pattern follows a Markov model, and the state

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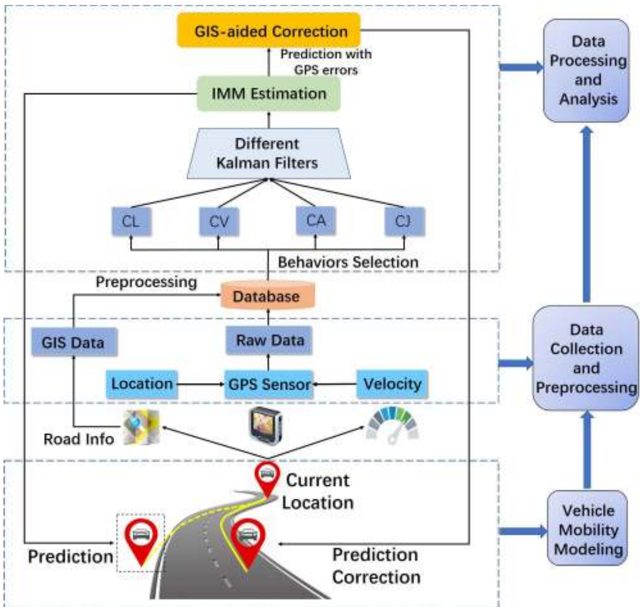

Fig. 2. The GPS and GIS data based vehicle trajectory prediction by combing MKF and IMM.

transition matrix is defined as

$$\pi_\theta = \begin{bmatrix} \theta_{CL}\to\theta_{CL} & \theta_{CL}\to\theta_{CV} & \theta_{CL}\to\theta_{CA} & \theta_{CL}\to\theta_{CJ} \\ \theta_{CV}\to\theta_{CL} & \theta_{CV}\to\theta_{CV} & \theta_{CV}\to\theta_{CA} & \theta_{CV}\to\theta_{CJ} \\ \theta_{CA}\to\theta_{CL} & \theta_{CA}\to\theta_{CV} & \theta_{CA}\to\theta_{CA} & \theta_{CA}\to\theta_{CJ} \\ \theta_{CJ}\to\theta_{CL} & \theta_{CJ}\to\theta_{CV} & \theta_{CJ}\to\theta_{CA} & \theta_{CJ}\to\theta_{CJ} \end{bmatrix}, \quad (1)$$

where θ_{CL}, θ_{CV}, θ_{CA}, and θ_{CJ} are the Markov states corresponding to CL, CV, CA, and CJ, respectively.

2) Data Collection and Preprocessing: With the wide range application of GPS, real-time vehicle data in terms of location, velocity, and heading angles can be obtained from GPS sensors. On the other hand, GIS data are obtained by extracting road information from maps. Afterwards, data preprocessing is implemented to improve data quality. GPS measurement errors caused by signal multi-path, ionosphere and troposphere delays should be corrected to avoid confusion. Furthermore, a rolling window based smoothing approach can be adopted to remove inconsistencies. Data related to acceleration are obtained from the difference of two adjacent velocity logs. In a similar fashion, jerk is measured from the difference between two adjacent acceleration values.

3) Data Processing and Analysis: MKF is adopted to identify the future state of the four behaviors in a recursive manner. The functionalities of MKF are separated in two categories, i.e., prediction and correction. The prediction function provides an estimation of future vehicle positions and velocities based on current states and error-covariance measurements, while the correction function provides a feedback for how to adjust future state estimation.

However, it is inadequate to predict future location only based on independent state estimations, which have to be merged to produce a single prediction. To solve this problem, an IMM estimation algorithm is adopted, in which the probability of mobility pattern switching is recalculated after each iteration throughout the whole process by using a Markov model. The IMM algorithm consists of five main steps: i) mixing probability calculation based on state transition matrix; ii) mixing probabilities to compute initial conditions for each filter; iii) calculate output, covariance matrix, and probability density function for each filter; iv) update individual probability of each filter; v) evaluation and covariance combination. To further improve the accuracy of the IMM outcome, a GIS data based iterative error detection method is used to correct predicted locations which fall outside of the road accordingly.

B. Channel Model

The sets of M V-TXs, and N V-RXs are denoted as $\mathcal{V}_{TX} = \{V_1^{TX}, V_2^{TX}, \cdots, V_m^{TX}, \cdots, V_M^{TX}\}$, and $\mathcal{V}_{RX} = \{V_1^{RX}, V_2^{RX}, \cdots, V_n^{RX}, \cdots, V_N^{RX}\}$, respectively. In the multicast fashioned transmission where there are multiple D2D-V2V links and one resource block (RB) assigned to one group, or where there are multiple D2D-V2V links in one multicast transmission, multiple D2D-V2V links can reuse the same RB. To simplify the calculation, we assume that each CUE is allocated with one orthogonal uplink RB. We use $\mathcal{C}_V = \{C_1^V, C_2^V, \cdots, C_k^V, \cdots, C_K^V\}$, and $\mathcal{C}_{RB} = \{C_1^{RB}, C_2^{RB}, \cdots, C_k^{RB}, \cdots, C_K^{RB}\}$ to denote the sets of K CUEs and RBs, respectively.

In the channel model, we only consider the large-scale fading effects such as the free space propagation path-loss while ignoring the small-scale fading effects [4], [6], [30]. It is infeasible to acquire real-time channel state information (CSI) due to fast channel variations caused by high vehicle mobility. Simulation results in [4], [6], and [30] have demonstrated that the ignorance of small-scale fading effects results in little performance degradation. It is noted that the solution structure of the proposed algorithm is independent of the specific channel model, and thus, can be extended to more complex and practical models.

We consider an example that V-TX V_m^{TX} serves the content request of V-RX V_n^{RX} by reusing RB C_k^{RB}, i.e., $m = 1, 2, \cdots, M$, and $n = 1, 2, \cdots, N$. On account of uplink spectrum reusing, V_m^{TX} will create co-channel interference to the BS, while V_n^{RX} will suffer from the interference caused by CUE C_k^V. The signal to interference plus noise ratio (SINR) expressions for D2D-V2V link (V_m^{TX}, V_n^{RX}) and cellular link (C_k^V, BS) are given by

$$\gamma_{m,n}^k = \frac{P_{V_m^{TX}} d_{V_m^{TX},V_n^{RX}}^{-\alpha_v}}{P_{C_k^V} d_{C_k^V,V_n^{RX}}^{-\alpha_{cv}} + N_0}, \quad (2)$$

$$\gamma_k^m = \frac{P_{C_k^V} d_{C_k^V,B_0}^{-\alpha_c}}{P_{V_m^{TX}} d_{V_m^{TX},B_0}^{-\alpha_{vc}} + N_0}. \quad (3)$$

Here, $P_{V_m^{TX}}$ and $P_{C_k^V}$ indicate the transmit power of V_m^{TX} and C_k^V, respectively. $d_{V_m^{TX},V_n^{RX}}$, $d_{C_k^V,V_n^{RX}}$, $d_{C_k^V,B_0}$ and $d_{V_m^{TX},B_0}$ represent the distances of D2D-V2V link (V_m^{TX}, V_n^{RX}), interference link between C_k^V and V_n^{RX}, cellular link from C_k^V to

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the BS, and interference link from V_m^{TX} to the BS, respectively. α_v, α_{cv}, α_c, and α_{vc} refer to the path-loss exponents of V2V links, interference links between CUEs and V-RXs, cellular links, and interference links from V-TXs to the BS, respectively. N_0 represents the one-sided power spectral density of additive white Gaussian noise (AWGN). Moreover, in Fig. 1, for instance, the distance between V_2^{RX} and C_2^{RB} is larger than that between V_2^{RX} and C_1^{RB}. In such a case, the SINR $\gamma_{2,2}^2$ is better than $\gamma_{2,2}^1$, which represents that higher transmission rate can be achieved by reusing C_2^{RB} in group G_2 instead of C_1^{RB}.

To evaluate the content distribution performance, we take the network average delay as a key measurement, which can be expressed as a function of SINR and vehicle connection time. Given $\gamma_{m,n}^k$, the corresponding transmission rate is given by

$$r_{m,n}^k = B_k \log_2(1+\gamma_{m,n}^k) = B_k \log_2\Big(1+\frac{P_{V_m^{TX}} d_{V_m^{TX},V_n^{RX}}^{-\alpha_v}}{P_{C_k^V} d_{C_k^V,V_n^{RX}}^{-\alpha_{cv}} + N_0}\Big), \tag{4}$$

where B_k is the bandwidth of RB C_k^{RB} in *Hz*.

Thus, the transmission delay of D2D-V2V link (V_m^{TX}, V_n^{RX}) using RB C_k^{RB} can be approximately calculated as

$$\tau_{m,n}^k = \frac{\tilde{\tau}_{m,n}^k}{\Gamma(t_{m,n} \mid \tilde{\tau}_{m,n}^k)}, \tag{5}$$

where

$$\tilde{\tau}_{m,n}^k = \frac{D}{r_{m,n}^k} = \frac{D}{B_k \log_2\Big(1+\frac{P_{V_m^{TX}} d_{V_m^{TX},V_n^{RX}}^{-\alpha_v}}{P_{C_k^V} d_{C_k^V,V_n^{RX}}^{-\alpha_{cv}} + N_0}\Big)}. \tag{6}$$

Here, D represents the size of the required content in *bits*. $\Gamma(t_{m,n} \mid \tilde{\tau}_{m,n}^k)$ is an indicator function of $t_{m,n}$, which is given by

$$\Gamma(t_{m,n} \mid \tilde{\tau}_{m,n}^k) = \begin{cases} 1, & \text{if } t_{m,n} \geq \tilde{\tau}_{m,n}^k, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

$t_{m,n}$ represents the connection time of V_m^{TX} and V_n^{RX}, which can be calculated based on the trajectory prediction results obtained in Subsection III-A and the minimum D2D-V2V transmission distance. $\Gamma(t_{m,n} \mid \tilde{\tau}_{m,n}^k)$ makes sure that the connection time of two vehicles should be no less than the duration required to deliver the content.

C. Vehicular Content Distribution Model

In each content distribution group, the content is delivered simultaneously from a serving V-TX to multiple V-RXs co-located within the same group through D2D-V2V multicast links. During the modeling process of vehicular content distribution, there are two critical aspects that should be carefully considered:

- The numbers of V-TXs and V-RXs, i.e., M and N, vary over time rather than remain constant. The number of potential V-TXs increases gradually as more and more V-RXs obtain the content.

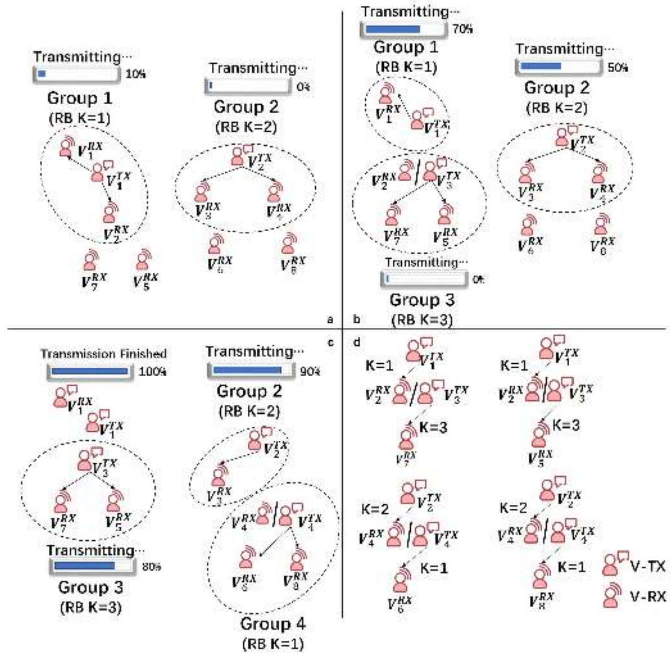

Fig. 3. Different starting and ending time of groups in content distribution process.

- The lifetime of each D2D-V2V content distribution group is different from one another due to the diverse channel conditions and interference levels.

Fig. 1 shows an example of the role switching process. We assume that V-TX V_1^{TX} and V-RX V_1^{RX} form group G_1 by reusing RB C_1^{RB}. After V_1^{RX} obtained the content, G_1 ends and C_1^{RB} is released. In the next time slot, V_1^{RX} switches to V-TX V_2^{TX}, and forms a new group G_2 with V-RXs V_2^{RX}, V_3^{RX}, V_4^{RX}, and V_5^{RX} by reusing RB C_2^{RB}. The multi-hop content distribution model becomes more sophisticated when combining role switching with different group lifetimes, and an example is provided in Fig. 3. In Fig. 3 (a), V-TX V_1^{TX} and V-RXs V_1^{RX}, V_2^{RX} form group G_1 by reusing RB C_1^{RB}, and V-TX V_2^{TX} and V-RXs V_3^{RX}, V_4^{RX} form group G_2 by reusing RB C_2^{RB}, respectively. The transmission starting time of group G_1 is not the same as that of group G_2. Meanwhile, V-RXs $V_5^{RX} \sim V_8^{RX}$ are not in any group since either the QoS or the connection time requirements cannot be satisfied. In Fig. 3 (b), V-RX V_2^{RX} which obtained the content switches its role to act as V-TX V_3^{TX}, and forms a new group G_3 with V-RXs V_5^{RX}, V_7^{RX} by reusing RB C_3^{RB}. In Fig. 3 (c), the content distribution process in G_1 is finished, and C_1^{RB} is released. V-RX V_4^{RX} which obtained the content switches its role to act as V-TX V_4^{TX}, and forms a new group G_4 with V-RXs V_6^{RX}, V_8^{RX} by reusing RB released by G_1, i.e., C_1^{RB}. It is noted that the ending time of each group is also different. Hence, for V-RXs $V_5^{RX} \sim V_8^{RX}$ which are not in the single-hop coverage of V-TXs V_1^{TX} and V_2^{TX}, data are actually delivered in a multi-hop fashion with the assistance of some intermediate relaying V-RXs. The equivalent multi-hop transmission routes are shown in Fig. 3 (d). Taking V-RXs V_5^{RX} as an example, data are firstly sent from V_1^{TX} to V_2^{RX}

in the first hop by reusing C_1^{RB}, and then is forwarded from V_2^{RX} to V_5^{RX} in the second hop by reusing C_3^{RB}.

Therefore, the delay for V_n^{RX} to obtain the content from V_m^{TX} is composed of two parts, i.e., the delay required for V_m^{TX} to obtain the content, and the transmission delay from V_m^{TX} to V_n^{RX}. The delay is calculated as

$$T_{m,n}^k = N_m T_s + \tau_{m,n}^k, \tag{8}$$

where N_m is the number of time slots required by V_m^{TX} to obtain the content, e.g., $N_m = 0$ if the content is initially located in V_m^{TX}. The value of N_m is determined by the resource allocation strategy. $N_m T_s$ demonstrates the delay required for V_m^{TX} to obtain the content. However, before the role switching that V_m^{TX} obtains the content, the content provider V_m^{TX} is a content requester V_n^{RX}. The time delay of the content requester V_n^{RX} to obtain the content has to be determined by the resource allocation strategy in the previous stage. In such a case, N_m cannot be explicitly represented in an analytical form. T_s is the time slot duration.

IV. Problem Formulation

This work aims at achieving rapid content distribution with possible minimum average network delay. Given the dynamic channel conditions and fast-varying network topologies, the main research challenge is how to jointly determine the formation of D2D-V2V content distribution groups, the utilization of cellular spectrum resources, and the selection of vehicular cooperative relays from a delay minimization perspective. We design a $M \times N \times K$ matrix $\mathbf{O}_{M\times N\times K}$ to represent the set of optimization variables. Each element $o_{m,n,k}$ of the matrix $\mathbf{O}_{M\times N\times K}$ is a binary variable, which denotes the relationship among V-TX V_m^{TX}, V-RX V_n^{RX}, and RB C_k^{RB}. More specifically, if V_m^{TX} and V_n^{RX} form a D2D-V2V pair by using C_k^{RB}, $o_{m,n,k} = 1$, and otherwise, $o_{m,n,k} = 0$. The formulated joint peer discovery, spectrum allocation, and route selection problem is given by

$$\begin{aligned}
&\min_{\{o_{m,n,k}\}} \frac{1}{N} \sum_{V_n^{RX}\in\mathcal{V}_{RX}} \sum_{V_m^{TX}\in\mathcal{V}_{TX}} \sum_{C_k^{RB}\in\mathcal{C}_{RB}} o_{m,n,k} T_{m,n}^k \\
&\text{s.t. } C_1 : \gamma_{m,n}^k \geq \gamma_{min}^V, \\
&\qquad \forall V_m^{TX} \in \mathcal{V}_{TX}, \quad V_n^{RX} \in \mathcal{V}_{RX}, \ \forall C_k^{RB} \in \mathcal{C}_{RB}, \\
&\quad C_2 : \gamma_k^m \geq \gamma_{min}^C, \quad \forall C_k^V \in \mathcal{C}_V, \ \forall V_m^{TX} \in \mathcal{V}_{TX}. \\
&\quad C_3 : o_{m,n,k} \in \{0, 1\}, \\
&\qquad \forall V_m^{TX} \in \mathcal{V}_{TX}, V_n^{RX} \in \mathcal{V}_{RX}, \quad \forall C_k^{RB} \in \mathcal{C}_{RB}, \\
&\quad C_4 : \text{For any content distribution group,} \\
&\qquad \sum_{V_m^{TX}\in\mathcal{V}_{TX}, C_k^{RB}\in\mathcal{C}_{RB}} o_{m,n,k} \leq 1, \quad \forall V_n^{RX} \in \mathcal{V}_{RX}
\end{aligned} \tag{9}$$

where constraints C_1 and C_2 represent the QoS requirements for cellular links and D2D-V2V links, respectively. γ_{min}^V, and γ_{min}^C are defined as the SINR threshold for any D2D-V2V link and cellular link, respectively. C_3 and C_4 ensure that all of the V-RXs in the same group are related to the same V-TX and the same RB.

Remark 1: For the sake of simplicity, we denote $\mathcal{V}_{TX} \cup \mathcal{V}_{RX} \cup \mathcal{C}_{RB}$ as $\mathcal{T}$. In general, (9) is NP-hard since finding the optimal partition of the set $\mathcal{T}$ requires searching through all of the possible partitions, the number of which grows exponentially with the number of elements in $\mathcal{T}$, i.e., $| \mathcal{V}_{TX} \cup \mathcal{V}_{RX} \cup \mathcal{C}_{RB} |$.

V. Coalition Formation Game Based Dependable Content Distribution

Since the structure of content distribution group plays an important role, we employ a coalition formation game approach to solve the joint optimization problem formulated in (9). In this section, we firstly introduce how to formulate the original content distribution problem as a coalition formation game, and present the respective fundamental concepts. Then, the coalition formation game based dependable content distribution approach is derived. Finally, we provide in-depth analysis of theoretical properties in terms of convergence and stability.

A. Coalition Formation Game Formulation and Fundamentals

1) Game Formulation: As discussed in Section III, a D2D-V2V content distribution group consists of one V-TX, multiple V-RXs, and one RB reused for D2D-V2V multicast transmission, which can be regarded as a coalition. In a coalition formation game, a set of game players, i.e., V-TXs, V-RXs and RBs, denoted by $\mathcal{T}$, seek to form cooperative content distribution groups, i.e., coalitions, with the aim to reduce average network delay. The index m is used as the subscript to identify D2D-V2V coalitions. Hence, the game formulation is defined as:

Definition 1: A coalition formation game can be defined as a triplet $(\mathcal{T}, \mathcal{P}, U)$, where $\mathcal{T}$ is the *player set* defined as $\mathcal{V}_{TX} \cup \mathcal{V}_{RX} \cup \mathcal{C}_{RB}$, $\mathcal{P}$ is a *collection of coalitions*, and U denotes the *coalition utility*.

Definition 2: A collection of coalitions $\mathcal{P}$ is defined as any arbitrary set of disjoint coalitions $S_m \subset \mathcal{T}$, i.e., $\mathcal{P} = \{S_1, S_2, \cdots, S_m, \cdots, S_L\}$, such that $\forall m \neq m'$, $S_m \cap S_{m'} = \emptyset$. If $\mathcal{P}$ spans the player set $\mathcal{T}$, i.e., $\bigcup_{m=1}^{L} S_m = \mathcal{T}$, $\mathcal{P}$ can also be regarded as a *partition* of $\mathcal{T}$.

Remark 2: Although coalitions are formed to achieve dependable content distribution with possible minimum average network delay, there may exist some V-RXs which are not eligible to join any coalition if either the QoS or the connection time constraints cannot be satisfied. Thus, it is reasonable that some V-RXs are not included in $\mathcal{P}$. To make the definition of coalition consistent, we introduce the concept of solo coalition, which is given by

Definition 3: A solo coalition $\{V_n^{RX}\}$ contains only the unserved V-RX V_n^{RX}. The set of solo coalitions $\tilde{\mathcal{V}}_{\mathcal{P}}$ under $\mathcal{P}$ is defined as $\mathcal{V}_{RX} \backslash \{\mathcal{V}_{RX} \cap \mathcal{P}\}$. $\tilde{\mathcal{V}}_{\mathcal{P}}$ is a subset of $\mathcal{V}_{RX}$.

2) Utility Function Definition: The transferable utility of any coalition $S_m \in \mathcal{P}$, is denoted as $U(S_m)$, which can be distributed in a predefined manner among all of the coalition members. We define $U(S_m)$ as the reciprocal of average delay of V-RXs in coalition S_m, which is calculated as

$$U(S_m) = \begin{cases} \frac{|S_m|-2}{\sum_{V_n^{RX} \in S_m} \tau_{m,n}^k}, & \text{if } S_m \neq \emptyset, \\ 0, & \text{otherwise.} \end{cases} \quad (10)$$

A coalition S_m consists of one V-TX, one CUE and several V-RXs. Thus, $|S_m| - 2$ indicates the number of V-RXs. The work in [10] illustrates that the quality of user experience (QoE) can be greatly affected by the response time in the transmission and a reduction in transmission delay indicates a better QoE. Moreover, the utility function of end users (including V-RX) is usually inversely proportional to the transmission latency. Hence, for the purpose of simplicity, we assume the utility function and the transmission latency are reciprocally related.

$\tau_{m,n}^k$ indicates the transmission delay of a single-hop transmission between a content provider V_m^{TX} and a content requester V_n^{RX}. In our proposed coalition formation game based approach, the the content is actually delivered from the original M V-TXs to the N VRXs in a multi-hop fashion. Since the direct optimization of the multi-hop content distribution is intractable, the original NP-hard problem is separated into a sequence of single-hop content distribution problems, and the optimization is carried out in a hop by hop fashion. In the optimization of each hop, we only have to consider the content transmission delay from V-TXs to V-RXs, where the V-TXs have already obtained the content. For each V-TX, the time spent in obtaining the content has already been optimized in the previous hops, and should not be considered again in the current hop. Hence, for the optimization of transmission delay in each hop, $\tau_{m,n}^k$ is employed as the utility function rather than $T_{m,n}^k$.

During a coalition game, each V-RX tends to join an ideal coalition to maximize its individual payoff. The RB occupied by the coalition can be released for new coalition formation if and only if all of the V-RXs within that coalition have received the requested content. Hence, the objective of a coalition is to minimize the average delay of all the coalition members rather than that of an individual member. As a result, a V-RX may be refused by a coalition if it dramatically decreases the coalition utility. To minimize the average delay of V-RXs in S_m, the payoff for any V-RX $V_n^{RX} \in \mathcal{V}_{RX}$ to join coalition S_m is defined as the contribution to the coalition utility, which is calculated as

$$\phi_n^m = \begin{cases} U(S_m \cup \{V_n^{RX}\}) - U(S_m), & \text{if } \gamma_{m,n}^k \geq \gamma_{min}^V \\ -\infty, & \text{otherwise.} \end{cases} \quad (11)$$

where $S_m \cup \{V_n^{RX}\}$ indicates the newly formed coalition after V_n^{RX} joining S_m. In other words, solo coalition $\{V_n^{RX}\}$ and coalition S_m merge into a new coalition $S_m \cup \{V_n^{RX}\}$.

Remark 3: Based on the transmission delay defined in (5), V-RX V_n^{RX} which tends to join coalition S_m but cannot satisfy the connection time requirement will result in infinite transmission delay, and thus will be eventually rejected by S_m.

After obtaining the requested content, a V-RX can act as V-TX and join a new coalition to serve other V-RXs in the next hop. A new D2D-V2V coalition can only be formed if a RB is willing to join this coalition. We define the individual payoff of RB C_k^{RB} as

$$\phi_k^m = \begin{cases} U(S_m \cup \{C_k^{RB}\}), & \text{if } \gamma_k^m \geq \gamma_{min}^C \\ -\infty, & \text{otherwise.} \end{cases} \quad (12)$$

A conflict arises when multiple RBs tend to join the same coalition. In this case, only the RB with the highest payoff is allowed to join the coalition.

3) Coalition Formation Concepts: In this subsection, we introduce the coalition preference relation, and the split and merge rule.

Definition 4: For two collections $\mathcal{P}$ and $\mathcal{P}'$ that are different partitions of the same subset $\mathcal{A} \subseteq \mathcal{T}$, we define the preference relation as $\succ$. In such a case, $\mathcal{P} \succ \mathcal{P}'$ indicates that the way $\mathcal{P}$ partitions $\mathcal{A}$ is superior to the way $\mathcal{P}'$ partitions $\mathcal{A}$. In the same way, for two coalitions S_m and $S_{m'}$ in the same $\mathcal{P}$, $S_m \succ S_{m'}$ represents that V_n^{RX} prefers S_m to $S_{m'}$.

Definition 5 (Split and Merge Rule): For any V-RX $V_n^{RX} \in S_m$, if the payoff of V_n^{RX} can be improved by splitting from S_m as a solo coalition $\{V_n^{RX}\}$ and merging with another coalition $S_{m'}$, i.e.,

$$\{S_{m'} \cup \{V_n^{RX}\}\} \succ S_m, \quad (13)$$

then, $\{S_m, S_{m'}\} \to \{S_m \backslash \{V_n^{RX}\}, S_{m'} \cup \{V_n^{RX}\}\}$

Remark 4: Some of the individual performance of transmission delay will increase inevitably. Nevertheless, our proposed method restricts the split and merge process concerning the effect of individual behavior to the whole network, which greatly improves transmission delay performance of the network. Compared with the non-cooperative method, in which individual vehicles ignore the relatively high transmission delay compared to the average delay of the coalition they prefer, the average transmission delay performance of cooperative vehicular network is much more superior.

B. Coalition Formation Game Based Vehicular Content Distribution

Based on the concepts of preference relation and the split and merge rule, the coalition formation game based vehicular content distribution is implemented as follows and the implementation process is described in Fig. 4.

Phase 1 (Coalition Formation Initialization):

- Initialize $\mathcal{V}_{TX}$, $\mathcal{V}_{RX}$, and $\mathcal{C}_{RB}$.
- Update vehicle location and trajectory prediction information for each $V_m^{TX} \in \mathcal{V}_{TX}$ and $V_n^{RX} \in \mathcal{V}_{RX}$.
- Calculate the initial preference of each $V_n^{RX} \in \mathcal{V}_{RX}$ towards any V-TX, which is defined as signal to noise ratio (SNR). Defining B_{ave} as the average bandwidth corresponding to the set $\mathcal{C}_{RB}$, the initial preference of V_n^{RX} towards V_m^{TX} is calculated as

$$\gamma_{m,n} = \begin{cases} \frac{P_{V_m^{TX}} d_{V_m^{TX}, V_n^{RX}}^{-\alpha_v}}{N_0}, & \text{if } \Gamma(t_{m,n} \mid \tilde{\tau}_{m,n}^0) = 1 \\ -\infty, & \text{otherwise,} \end{cases} \quad (14)$$

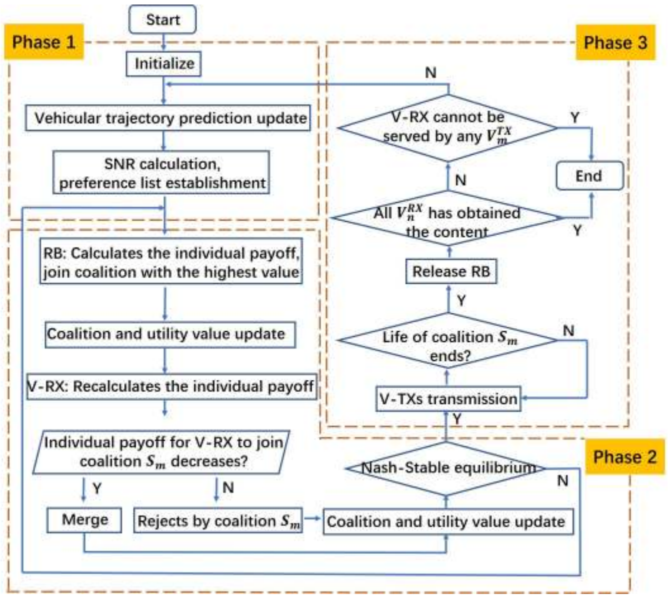

Fig. 4. The implementation process of the system.

where $\tilde{\tau}^0_{m,n}$ is the transmission delay calculated as

$$\tilde{\tau}^0_{m,n} = \frac{D}{B_{ave}\log_2(1+\frac{P_{V_m^{TX}} d^{-\alpha_v}_{V_m^{TX},V_n^{RX}}}{N_0})}. \quad (15)$$

That is, V_m^{TX} will not be included in the preference list of V_n^{RX} if the connection time requirement cannot be satisfied.

- The preference list of V_n^{RX} is established by sorting all of V-TXs in a descending order based on initial preferences.
- Each V-RX proposes to its most preferred V-TX in the preference list for coalition formation, and $\mathcal{P}$ is updated accordingly.

Phase 2 (Iterative Coalition Formation):

Repeat the following processes iteratively.

- Split and Merge Process for RBs
  - Each $C_k^{RB} \in \mathcal{C}_{RB}$ calculates the individual payoff towards any coalition $S_m \in \mathcal{P}$ based on (12), and joins the coalition with the highest payoff.
  - Update $\mathcal{P}$ and $U(S_m), \forall S_m \in \mathcal{P}$.
- Split and Merge Process for V-RXs
  - Each $V_n^{RX} \in \mathcal{V}_{RX}$ recalculates its payoff towards any coalition based on (11), and updates the preference lists.
  - Each V-RX proposes to join its most preferred coalition.
  - Update $\mathcal{P}$ and $U(S_m), \forall S_m \in \mathcal{P}$.

Until $\mathcal{P}$ converges to a Nash-Stable equilibrium $\mathcal{P}^*$.

Phase 3 (Resource Allocation and Content Dissemination):

V-TX in each coalition starts to transmit the content based on the results obtained in **Phase 2**. Any V-RX belonging to S_m that has obtained the content can act as a V-TX and serve other V-RXs by forming new coalitions. If the life of any coalition $S_m \in \mathcal{P}$ ends, i.e., all the V-RXs located in S_m have obtained the requested content, then the RB occupied by S_m will be released. The content distribution process will return back to **Phase 1**.

The algorithm terminates if either one of the following conditions is satisfied.

- Any $V_n^{RX} \in \mathcal{V}_{RX}$ has obtained the requested content.
- Any V-RX that has not obtained the content yet cannot be served by any $V_m^{TX} \in \mathcal{V}_{TX}$.

C. Convergence and Stability Property Analysis

By employing the concept from the hedonic coalition formation games [31], in which the formation of coalitions depends on the individual preference of each player, we can prove the convergence and stability property as follows.

Definition 6: A partition $\mathcal{P}^*$ is Nash-stable, if for any $V_n^{RX} \in S_m \in \mathcal{P}^*$, the preference relation. $S_m \succ \{S_{m'} \cup \{V_n^{RX}\}\}$ holds for all $S_{m'} \in \mathcal{P}^*$, $m' \neq m$.

Theorem 1: The partition produced by the coalition formation game converges to a Nash-stable equilibrium within finite iterations.

Proof: Since the total number of partitions for a given set with finite elements is also finite and is known as the Bell number [32], it is demonstrated in [32] that a dynamic coalition formation algorithm based on the split and merge rule always converges to a final partition $\hat{\mathcal{P}}$ within finite iterations.

Assuming that the final partition $\hat{\mathcal{P}}$ is not Nash-stable, there must exist a V-TX $V_n^{RX} \in S_m \in \hat{\mathcal{P}}$ such that $\{S_{m'} \cup \{V_n^{RX}\}\} \succ S_m$, $S_{m'} \in \hat{\mathcal{P}}$, $m' \neq m$. According to the split and merge rule, it is beneficial for V_n^{RX} to be split from S_m as a solo coalition, and merged with $S_{m'}$ to form a new coalition $S_{m'} \cup \{V_n^{RX}\}$. Then, a new partition $\tilde{\mathcal{P}}$ is produced, which contradicts with the assumption that $\hat{\mathcal{P}}$ is the final partition. Therefore, it is proved that the final partition $\hat{\mathcal{P}}$ produced by the coalition formation game must be Nash-stable. ∎

VI. Performance Evaluation

In this section, the proposed algorithm is evaluated based on real-world road topology and realistic vehicular traffic. Firstly, we introduce the experimental setting, in which both macro-mobility and micro-mobility features are taken into consideration. Then, numerical results are provided.

A. Experiment Setup

The microscopic road traffic simulation software, i.e., SUMO, is adopted to evaluate vehicle traffics in real-world road topologies without having to deploy an expensive physical transportation measurement system. SUMO treats each vehicle as an independent element and provides powerful control tools for separate adjustment of various mobility parameters such as acceleration, deceleration, velocity, and route.

The Xizhimen Overpass area in Beijing, China, is selected as the performance evaluation scenario, which is shown in Fig. 5. Xizhimen Overpass is widely known as the most complicated overpass in Beijing, and supports more than 300, 000 automobiles as well as buses from 50 routes every day. The GIS data required for trajectory prediction are

Fig. 5. The real-world map of the Xizhimen Overpass in Beijing, China.

Fig. 6. A snapshot of the microscopic simulation scenario based on the real-world map of the Xizhimen Overpass, in which vehicles generated by SUMO are represented as small yellow triangles.

obtained by using the road network importing tool NETCONVERT. We extract the characteristic data from OpenStreetMap and save the descriptions of road graph in terms of nodes, edges, connection links, and so on, as several XML files. Then, we generate vehicles based on specified road situations like vehicle headway distance, traffic congestion, and traffic signals by using the RANDOMTRIPS tool with a step of 10^{-1} second. The total duration of the time-discrete space-continuous simulation is set as 3.6×10^3 seconds in order to generate enough volume of data. Vehicle location and velocity data are read every one second as GPS logs. Hence, a total of 3.6×10^3 different snapshots are available for trajectory prediction and performance evaluation. A snapshot of the microscopic simulation scenario based on the real-world map of the Xizhiman Overpass is shown in Fig. 6, where vehicles generated by SUMO are represented as small yellow triangles.

The code of trajectory prediction, which is available in [33], is implemented in Microsoft Visual Basic V6.0 and Microsoft MapPoint 2013. The estimated vehicle positions are saved as an Excel file. Afterwards, the simulation of content distribution is conducted by connecting SUMO with MATLAB through the standard traffic control interface (TraCI) protocol. In this way, key parameters and attributes such as vehicle coordinate and velocity can be obtained during the simulation

TABLE I
SIMULATION PARAMETERS

Simulation Parameter	**Value**
Cell radius	500 m
Path-loss exponent $\alpha_c, \alpha_v, \alpha_{cv}, \alpha_{vc}$	3, 3.5, 4, 3
Transmit power of V-TX $P_{V_m^{TX}}$	23 dBm
Transmit power of CUE $P_{C_k^V}$	23 dBm
Noise power N_0	-114 dBm
Number of V-RXs N	8 $\sim$ 20
Number of CUEs/RBs K	8 $\sim$ 16
Number of V-TXs M	5 $\sim$ 15
Time slot duration T_s	1 ms
Content size D	30 Mb
SINR threshold of D2D-V2V pairs γ_{min}^V	20 dB
SINR threshold of cellular links γ_{min}^C	20 dB
Trajectory prediction interval	1 s
Total simulation duration	3.6×10^3 s
SUMO time step	1 s

TABLE II
AVERAGE ESTIMATION ERROR

Estimated position	1 *sec* ahead [meters]	3 *sec* ahead [meters]
single Kalman filter	3.72	10.86
MKF-IMM	1.54	5.68
MKF-IMM-GIS	1.02	3.24

via predefined interfaces. We compare the proposed algorithm with two heuristic schemes, i.e., a non-cooperative content distribution scheme [34] and a random group formation based content distribution scheme [34]. Simulation parameters are summarized in Table I.

The average estimation error, which is calculated as the distance between the predicted location and the actual location, is summarized in Table II. The prediction interval is one second because the inter-vehicle distance will not change dramatically within one second for most of the cases. Table II demonstrates that the estimation error of longer duration prediction can be dramatically reduced by the GIS-aided iterative error correction method. More details can be referred to [27].

B. Numerical Results

Fig. 7 shows the content distribution efficiency versus time. The percentage of served V-RXs is defined as the number of V-RXs that have obtained the content divided by the initial number of unserved V-RXs. Numerical results demonstrate that the proposed algorithm achieves the best content distribution efficiency, and outperforms the other two heuristic algorithms in two perspectives. On one hand, more rapid content distribution can be achieved by the proposed algorithm during the beginning phases. For an instance, 85.12% of V-RXs can obtain the content within 3×10^3 ms by using the proposed algorithm. In comparison, the percentages of served V-RXs corresponding to the non-cooperative approach and the random group formation approach are only 58.60% and 54.47%, respectively. On the other hand, the proposed algorithm achieves better coverage performance when the content distribution process is finished. After 8×10^3 ms, the percentage of served V-RXs achieved by the proposed algorithm outperforms the non-cooperative approach and the random group formation approach by 24.23% and 27.55%, respectively. The reason lies behind is that route selection, peer

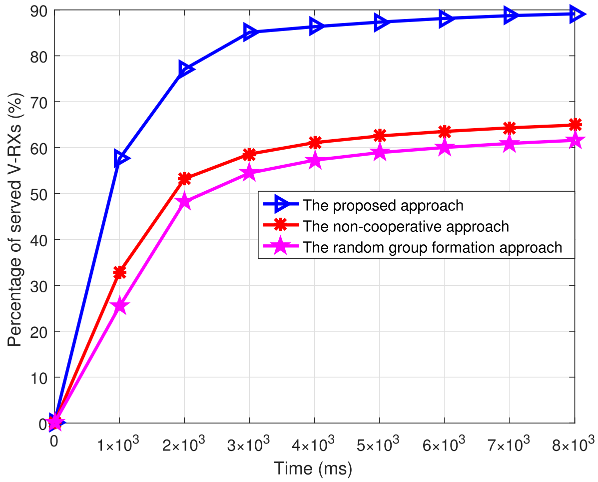

Fig. 7. The Percentage of served V-RXs versus time ($K = 8$, $N = 20$, $M = 8$).

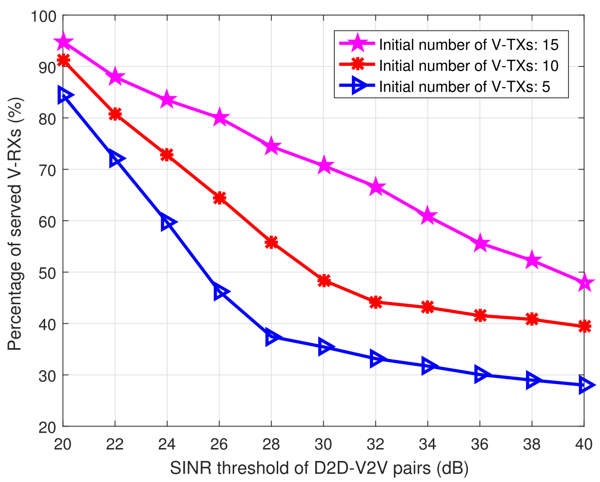

Fig. 8. The Percentage of served V-RXs versus SINR threshold ($K = 8$, $N = 20$, $M = 5, 10, 15$).

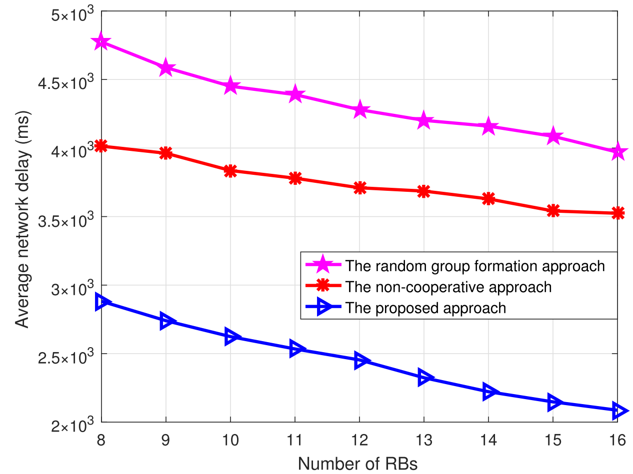

Fig. 9. Average network delay performance versus the number of RBs ($K = 8 \sim 16$, $N = 14$, $M = 8$).

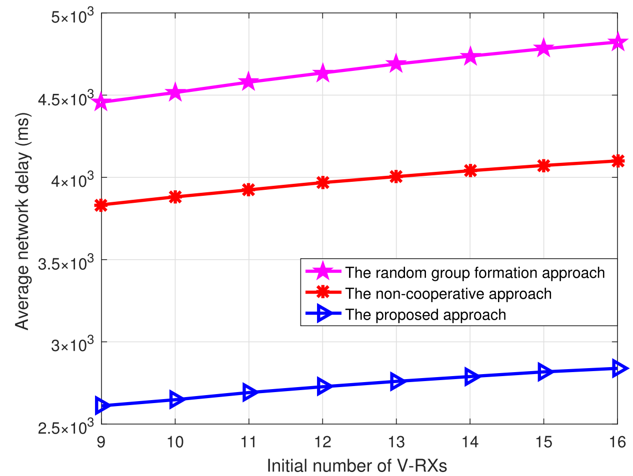

Fig. 10. Average network delay performance versus the initial number of V-RXs ($K = 8$, $N = 9 \sim 16$, $M = 8$).

discovery, and spectrum allocation are not jointly optimized from a delay minimization perspective in the two heuristic algorithms.

Fig. 8 shows the percentage of served V-RXs versus the SINR threshold of D2D-V2V link. Three cases with different initial numbers of V-TXs are compared. Numerical results show that the percentages of served V-RXs in all of the three cases decrease monotonically with the increment of the SINR threshold, and the falling rate, i.e., curve slope, is largely determined by the initial number of V-TXs. The reason behind is that the possibility to find a eligible V-TX is greatly lowered as SINR threshold increases. In particularly, for the cases with lower initial numbers of V-TXs such as 5 and 10, there are too few V-TXs available in the network, which are sparsely distributed and far away from V-RXs. An unit increment of SINR threshold will significantly reduce the number of eligible D2D-V2V pairs and leave many V-RXs unserved. Hence, there is a tradeoff between the percentage of served V-RXs and average transmission rate per D2D-V2V link.

Fig. 9 shows that the average network delay performance decreases monotonically with the number of RBs. There are two main reasons. First, a larger number of content distribution groups can be supported simultaneously as the number of RBs increases. Second, adding more RBs also introduces additional diversity gain since there will be an increased opportunity for each group to select a better RB from the delay minimization perspective. Hence, the performance gap demonstrates that the benefits brought by increasing the number of RBs can be better explored by the proposed algorithm compared to the heuristic schemes.

Fig. 10 shows that the average network delay performance increases monotonically with the initial number of V-RXs. The reason is that a larger value of N results in higher chances of multi-hop transmission because the absolute number of V-RXs with inferior channel conditions is also increased. Nevertheless, the proposed algorithm still achieves the best performance under all possible scenarios. The reason is that cooperation among V-RXs are encouraged in order to minimize the average network delay, which is not considered in the other two algorithms.

VII. Conclusion

In this paper, we investigated the content distribution problem in D2D-based cooperative vehicular networks, and proposed a big data integrated coalition formation game approach to jointly optimize peer discovery, route selection, and spectrum allocation from a delay minimization perspective. The proposed content distribution algorithm was compared with two heuristic schemes based on real-world map and realistic vehicular traffic by employing both SUMO and MATLAB. The following conclusions are summarized according to numerical results. First, the proposed algorithm achieves the best content distribution efficiency in terms of the percentage of served V-RXs. Second, we find that the percentage of served V-RXs is in negative relationship with the SINR threshold, and the falling rate is largely determined by the initial number of V-TXs. Third, the benefits brought by adding more RBs can be better explored by the proposed algorithm compared to the other two heuristic schemes. Finally, the proposed algorithm is shown to be more robust to the adverse impacts caused by multi-hop transmission. In future works, we will focus on how to jointly optimize content caching and distribution in a unified framework by employing up-to-date technologies including big data analytics and mobile edge computing.

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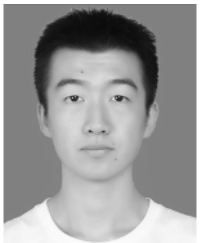

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