# Collaborative Content Delivery in Software-Defined Heterogeneous Vehicular Networks

Yilong Hui, Zhou Su, and Tom H. Luan

***Abstract*— The software defined heterogeneous vehicular networks (SD-HetVNETs), which consist of cellular base stations (CBSs) and roadside units (RSUs), have emerged as a promising solution to address the fundamental problems imposed by the surge increase of vehicular content demand. However, due to the ever increasing requirement of the vehicles' quality of experience (QoE) and the network vendors' utilities, there come new challenges to motivate CBS to cooperate with RSU for content delivery in order to maximize their utilities and improve the efficiency of the networks. Therefore, in this paper, we propose a collaborative content delivery scheme to improve the utilities of the participants (i.e., CBS, RSU and vehicles) in the SD-HeVNETs, where the CBS can cooperate with RSUs by serving a group of vehicles with multicast technology. We first define the utility models to map the profits of the participants in the networks and formulate the utilities of CBS and RSU as two optimization problems. Then, we exploit the double auction game to motivate CBS to cooperate with RSU for the multicast assisted content delivery to address the two maximization problems. Next, the optimal bidding strategies of CBS and RSU in the game are analyzed when the Bayesian Nash equilibrium is achieved. With the optimal bidding strategies, both CBS and RSU can bid for the multicast assisted content delivery services to maximize their utilities based on the network status. Finally, the performance of the proposed cooperative scheme is evaluated by using simulations. The simulation results demonstrate that the utilities of all the participants in the networks can be enhanced and the efficiency of the networks can be improved.**

***Index Terms*— Software defined networks, heterogeneous vehicular networks, content delivery, double auction game.**

## I. Introduction

THE software defined heterogeneous vehicular networks (SD-HetVNETs), which combine the software defined networks (SDN) and the heterogeneous vehicular networks (HetVNETs), are expected to enable flexible network resources management to support vehicles with ubiquitous content services [1]–[3]. In the SD-HetVNETs, the network is recognized as an operating system and the resources are managed by a logically centralized controller [4]–[6]. In this way, devices charged by various vendors can communicate with each other via a standardized interface (e.g., OpenFlow), which significantly simplifies the network management by providing a scalable and flexible network architecture [7]–[10]. In the SD-HetVNETs, vehicles can obtain their requested contents through the WiFi-like access point (e.g., roadside unit (RSU)) or 4G/5G (e.g., cellular base station (CBS)) [11]–[13]. Obviously, different access methods represent different content delivery performance. As shown in Fig. 1, the RSU, which has limited communication coverage, can provide vehicles with the occasional connections by using the dedicated short range communications (DSRC) technology [14]–[16]. On the contrary, the CBS typically can provide stable content download rate to vehicles at anywhere and anytime, but with a higher bandwidth cost than the RSU.

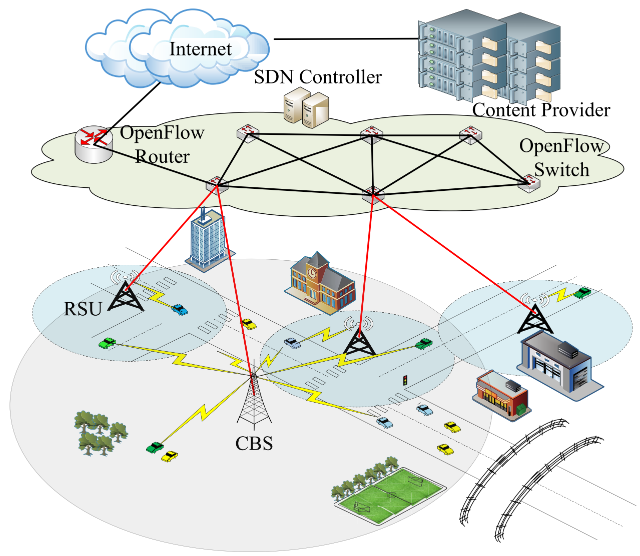


Fig. 1. Illustration of multicast assisted vehicular content delivery in SD-HetVNETs.

In the SD-HetVNETs, different vehicles may request the same content, such as advertisements, road conditions and traffic accidents. Motivated by this, some recent works have made effort for further improving the efficiency of the networks by using the multicast technology which has been incorporated in the third generation partnership project (3GPP) specifications [17]–[19]. With the multicast technology, both the CBS and RSU can serve the vehicles that request the same content via a single multicast transmission in the SD-HetVNETs. In this way, a group of vehicles that request the same content can

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be served concurrently, where the available bandwidth of the networks charged by different network vendors can be efficiently utilized and the quality of experience (QoE) of vehicles for the content delivery services can be enhanced [20].

Although vehicles can benefit from the multicast technology, each RSU may not serve all the vehicles in the coverage when the vehicle density is high. This is because that the vehicles in the SD-HetVNETs, in general, not only request the safety contents, but also request the rich multimedia contents (e.g., high resolution video) which typically have large size [21]–[23]. For the vehicles that have not succeeded in obtaining their requested contents from RSU, RSU can request CBS for cooperation to provide these vehicles with the requested contents to guarantee their QoE. The cooperation between CBS and RSU for multicast assisted vehicular content delivery is therefore becoming an instrumental component of the future communication network to provide contents to vehicles. The realization of the cooperation between RSU and CBS, however, is still facing several fundamental issues. 1) As selfish individual, CBS may refuse to help RSU to provide contents for the vehicles which have not succeeded in obtaining their requested contents from RSU, the corresponding incentive model to motivate CBS to cooperate with RSU is therefore needed to be considered. 2) When CBS intends to cooperate with RSU, the strategy of the profit distribution for the content delivery services to maximize their utilities poses threats to achieve the agreement between CBS and RSU. 3) With the cooperative network architecture, how to guarantee the QoE of vehicles which request contents from RSU and improve the efficiency of the networks to satisfy the massive demands of vehicles also need to be further studied.

The existing researches for the multicast assisted vehicular content delivery, however, pay much attention to the performance enhancement, such as multicast scheduling [18], spectrum utilization [19], application management [24], etc. Few of them consider the selfishness of network vendors which charge different access networks and focus on their own utilities. Additionally, there are few works which study the cooperation between CBS and RSU based on the utility model to distribute profits between them in the SD-HetVNETs. Besides, the existing works mainly consider the networks from the aspects of CBS and RSU, while the utility of vehicles has not been studied enough. As the cooperative networks are composed of three participants (i.e., CBS, RSU and vehicles), a novel scheme which jointly considers the utilities of all the participants in the SD-HetVNETs should be designed.

To this end, in this paper, we propose a scheme to motivate CBS to cooperate with RSU for multicast assisted vehicular content delivery in the SD-HetVNETs. Specifically, by considering that CBS may refuse to cooperate with RSU due to the resource costs, we define the utility functions to map the profits and costs of CBS, RSU and vehicles, respectively. The distributed profits can thus motivate CBS to take part in the multicast assisted content delivery process efficiently. In this way, the QoE of vehicles in the networks can be guaranteed. After that, a double auction game is formulated to model the interaction between CBS and RSU for achieving the agreement and distributing the profits, where the optimal bids of CBS and RSU are analyzed based on the network status. By finding the Bayesian Nash equilibrium of the double auction game, both CBS and RSU can obtain their maximum utilities and the efficiency of the networks can be improved at the same time. The contributions of this paper are three-fold.

- **Problem Formulation:** Considering the cooperative network architecture, we define the utility models to map the profits of the participants in the SD-HetVNETs and formulate the utilities of CBS and RSU as two optimization problems.
- **Game Analyzation:** The optimization problems are formulated as the double auction game to motivate CBS to cooperate with RSU for multicast assisted content delivery. With the analysis of the game, the optimal bidding strategies of both CBS and RSU can be obtained when the Bayesian Nash equilibrium of the game is achieved to maximize their utilities.
- **Simulation Evaluation:** The performance of the proposed cooperative scheme is evaluated in terms of the utilities of the participants and the efficiency of the networks. The simulation results show that the utilities of all the participants in the networks can be enhanced and the efficiency of the networks can be improved.

The remainder of this paper is organized as follows. Section II reviews the related works and highlights our contributions. Section III presents the system model, and Section IV formulates the optimization problems of the participants in detail. The double auction game is analyzed in Section V. Section VI evaluates the performance of the proposed scheme by simulations, and Section VII closes the paper with conclusions.

## II. Related Work

### A. Vehicular Content Delivery in SD-HetVNETs

There have been a number of researches to study the vehicular content delivery in SD-HetVNETs. Sun *et al.* [1] propose an SDN-based intelligent model to improve system capacity and meet dynamic service demands, where the heterogeneous resources can be efficiently managed. He *et al.* [2] design an SDN-based wireless communication scheme, where the communication cost can be minimized by scheduling different network resources. To improve heterogeneous network management, Duan *et al.* [7] propose an SDN enabled 5G vehicular network framework. By using SDN's global information gathering and network control capabilities, neighboring vehicles are clustered adaptively according to road conditions. By exploiting SDN, Huang *et al.* [25] present a 5G-enabled software defined vehicular network architecture to simplify network management and improve resource utilization. He *et al.* [26] design an SDN-based scheme in vehicular networks to reduce the SDN management overhead caused by the highly dynamic mobility of vehicles.

Although vehicular content delivery in SD-HetVNETs has been efficiently studied in the above works, few of them consider the cooperation between CBS and RSU for multicast assisted vehicular content delivery. Unlike the above works, the aim of our work is to improve the utilities of both CBS and RSU and increase the number of vehicles which obtain their requested contents.

### *B. Multicast Assisted Content Delivery*

The performance of the multicast assisted content delivery has been extensively studied in recent years. Zhang *et al*. [17] propose a video multicast orchestration scheme to optimize the distribution of video content in 5G ultra-dense networks. The simulation results show that the proposed scheme can distribute video content efficiently. By exploiting the complete network knowledge of the SDN controller, Yang *et al*. [27] design a multimedia multicast streaming framework to enable scalable video transmission. By considering the inherent multicast capability of wireless medium, Zhou *et al*. [28] study the optimal content delivery in heterogeneous networks to satisfy dynamic user demands. Zhao *et al*. [29] propose a non-orthogonal multiple access-based multicast scheme to improve the spectrum efficiency. Using simulations, the analytical results are verified and the performance gains of the proposed scheme is demonstrated. To satisfy the massive demand for mobile data and minimize the energy expenditures, Poularakis *et al*. [20] present a network paradigm which builds on caching and multicast. The results show that the energy costs can be reduced by combining caching and multicast.

Unlike the above researches in multicast assisted content delivery, in our paper, we pay attention to the utility models of CBS and RSU for multicast assisted vehicular content delivery in SD-HetVNETs. In addition, we study the cooperation between CBS and RSU to deliver content, where the utilities of CBS and RSU can be improved and the efficiency of the networks can be enhanced.

### *C. Game Models for Content Delivery*

To model the interactions among the participants in vehicular networks, game models have received considerable attentions. By taking parked vehicles into account, Su *et al*. [30] propose a framework to facilitate content delivery in vehicular networks, where a pricing model to maximize the utilities of moving vehicles, RSU and parked vehicles is proposed based on a Stackelberg game. Wang *et al*. [31] propose a coalitional game approach to help vehicles complete the content delivery process. By forming coalitions, vehicles in the same coalition can exchange their pieces of the same content. In order to improve the efficiency of data collection, Hui *et al*. [32] propose a data computing scheme based on the utility. In the proposed scheme, the interactions among participants are modeled as a bargaining game. Based on hierarchical Stackelberg games, Groot *et al*. [33] investigate several road pricing schemes to reduce the congestion in traffic networks. With a coalition formation game, Xu *et al*. [34] propose a cloud-based network selection scheme in vehicular networks. The scheme can assist vehicles to select the best network during driving.

Different from the game models used in these works from different aspects, the double auction game in this paper is used to motivate CBS to help RSU with the multicast assisted vehicular content delivery. By formulating the interactions between CBS and RSU, both of them have the right to make the optimal bidding strategy and bid for the content delivery service to maximize their utilities.

## III. SYSTEM MODEL

In this section, we present the system model based on the scenario of SD-HetVNETs.

### *A. Network Model*

In the SD-HetVNETs, the RSU and CBS are only in charge of delivering contents to vehicles. The control decisions are made by the SDN controller which has the globe view of the networks. In this way, the controller in the control plane makes decisions and the RSU and CBS in the data plane deliver content based on the command published by the controller. If an RSU cannot serve all the vehicles in its coverage, the controller will start the double auction process. If the agreement between the RSU and CBS in the auction is achieved, the CBS and RSU will provide vehicles with contents based on the content delivery command determined by the SDN controller. According to this architecture, we then model the SD-HetVNETs with the following components.

1) Vehicular contents. The vehicle in the area can send request for obtaining the requested content from the CBS at anywhere or from an RSU when the vehicle is within the RSU's coverage. Let $\mathbb{Q} = \{1, ..., q, ..., Q\}$ be the set of contents that can be requested by vehicles in the networks, where $Q$ is the number of elements in the set. The size of content $q (q \in \mathbb{Q})$, denoted as $s_q$, follows a uniform distribution and lies in $[s_{\min}, s_{\max}]$. In general, different contents have different popularities in vehicular networks. Based on [35]–[37], the probability that content $q$ is requested by a vehicle can be determined by the Zipf-like distribution, we have

$$p_q = \left( \sum_{\iota=1}^{Q} \frac{1}{\iota^{\varpi}} \right)^{-1} / {\chi_q}^{\varpi}, \tag{1}$$

where $\chi_q$ is the ranking of content $q$ based on the request times. $\varpi$ is the parameter of the Zipf-like distribution.

2) CBSs. The set of CBSs in the networks is denoted as $\mathbb{K} = \{1, ..., k, ..., K\}$, where each CBS in the networks has broad coverage and can connect with RSUs and vehicles within its coverage in a multicast or unicast way. The aim of each CBS is to maximize the utility by providing the requested contents for vehicles at anywhere and anytime with a high bandwidth cost.

3) RSUs. The set of RSUs in the coverage of CBS $k (k \in \mathbb{K})$ is denoted as $\mathbb{J} = \{1, ..., j, ..., J\}$, where $J$ is the total number of RSUs. The coverage radius of RSU $j$ is denoted as $R_j$. As studied in [38], the transmission rate depends on the distance from the RSU to the receiving vehicle. In general, the coverage of the RSU is divided into several zones according to the 802.11p standard, where vehicles in different zones have different transmission rates. Therefore, if the RSU delivers content to a group of vehicles, the transmission rate between the RSU and these vehicles is constrained by the one which has the lowest rate. To guarantee the QoE of vehicles,

the RSU provides vehicles with the requested contents in a unicast way. In comparison, the CBS serves vehicles using the multicast technology. For a group of vehicles which request the same content and cannot be served by the RSU, they will be served by the CBS.

Based on the above analysis, the coverage of RSU $j$ is divided into $Z_j$ zones in this paper, where the set of zones is denoted as $\mathbb{Z}_j = \{1, ..., z_j, ..., Z_j\}$. For zone $z_j (z_j \in \mathbb{Z}_j)$, the transmission rate between a vehicle and its connected RSU is $r_{z_j}$. Let $\overline{r_j}$ denote the average transmission rate when a vehicle downloads the requested content from RSU $j$. It can be given by

$$\overline{r_j} = \sum_{z_j=1}^{Z_j} \frac{d_{z_j} r_{z_j}}{2R_j}, \tag{2}$$

where $d_{z_j}$ is the length of zone $z_j$.

### B. Traffic Model

As RSUs are deployed at different locations, the vehicle arrival rates within their communication coverage are therefore different. For RSU $j$, the arrival rate of vehicles to its coverage is denoted as $\omega_j$, which follows the Poisson distribution [39]–[41]. We have

$$\omega_j = \rho_j v_j l_j, \tag{3}$$

where $l_j$, $\rho_j$ and $v_j$ are the number of lanes, vehicle density, and vehicle velocity in the coverage of RSU $j$, respectively.

Let $N_{j,\max}$ be the maximum number of vehicles which can stay in the coverage of RSU $j$ concurrently, we have

$$N_{j,\max} = 2R_j \rho_{\max} l_j, \tag{4}$$

where $\rho_{\max}$ is the maximum density of vehicles in this area.

We consider the traffic flow model to charge the velocity of vehicles in which vehicles have the same velocity in an RSU's coverage [42]–[44]. With this model, the relationship between vehicle velocity and density in the coverage of RSU $j$ can be expressed as

$$v_j = \max\left\{v_{\min}, v_{\max}\left(1 - \frac{\rho_j}{\rho_{\max}}\right)\right\}, \tag{5}$$

where $v_{\min}$ and $v_{\max}$ are the minimum and maximum vehicle speeds in the networks, respectively.

## IV. Problem Formulation

In this section, we first introduce the cooperation mechanism for multicast assisted vehicular content delivery in SD-HetVNETs. After that, the utilities of the participants including CBSs, RSUs and vehicles are analyzed, respectively.

### A. Cooperation Mechanism

The heterogeneous vehicular networks consist of the RSU and CBS [45]. To enhance the content delivery performance and make profits, these two technologies may cooperate with each other by using the SDN technology. The new architecture can simplify the network management by providing a scalable and flexible network architecture. For the vehicles which intend to download contents from the RSU with a low cost, it may not be served by the RSU due to the limited service ability. Thus, the CBS can sell the available bandwidth resources to the RSU by providing the vehicles with the requested contents to earn profits. In this way, the profits of both RSU and CBS can be increased, which further promotes the cooperation between the CBS and RSU. Based on this, the utility functions and maximization problems of RSU and CBS are formulated in our work.

In the SD-HetVNETs, the service capability of the RSU is limited due to the constraint of transmission power. The CBS, which has large communication power and rich resources, can sell the remaining available resources to RSUs in its coverage with the help of the SDN. In other words, if an RSU cannot serve all the vehicles in its coverage, it can ask the help from the CBS to cooperate. In this way, a part of vehicles which request contents from RSUs can be served by CBS to guarantee the QoE. Meanwhile, the utilities of both the CBS and RSU can be increased and the efficiency of the networks can be improved.

For RSUs, they intend to serve more vehicles to earn profits. Therefore, they need to decide whether to ask CBS for help or serve vehicles by themselves. We first analyze the time to serve all the vehicles in the coverage of RSU $j$. It can be expressed as

$$\mathrm{T}_j = \frac{\sum_{i=1}^{N_j} \sum_{q=1}^{Q} \gamma_{i,q} s_q}{\overline{r_j}}, \tag{6}$$

where $\gamma_{i,q}$ is a binary variable. Specifically, $\gamma_{i,q} = 1$ if content $q$ is requested by vehicle $i$ and $\gamma_{i,q} = 0$ otherwise. $N_j$ is the number of vehicles in the coverage of RSU $j$.

Then, we define $a_j$ to help RSU $j$ to decide whether to send a request to CBS $k$, where CBS $k$ is the base station that covers RSU $j$. If $\mathrm{T}_j > 2R_j/v_j$, the RSU then asks the help from CBS $k$, where $2R_j/v_j$ is the time from a vehicle enters in the RSU's coverage to the vehicle leaves the RSU's coverage. We have

$$a_j = \begin{cases} 1, & \mathrm{T}_j > 2R_j/v_j, \\ 0, & \mathrm{T}_j \leq 2R_j/v_j, \end{cases} \tag{7}$$

where $a_j = 1$ means that RSU $j$ cannot provide all the requested contents to the vehicles in its coverage. Consequently, RSU $j$ needs to require its connected CBS for the content delivery.

When RSU $j$ intends to ask CBS $k$ for help, the content that needs to be delivered to vehicles by CBS $k$ should be selected. By jointly considering the request times and the size of each content, the content that needs to be provided by CBS $k$ is chosen by

$$q^* = \arg\max_q \left\{\kappa_j \log\left(1 + \frac{s_q}{s_{\max}}\right) + (1 - \kappa_j) \log\left(1 + \frac{N_{j,q}}{N_j}\right)\right\}, \quad q \in \mathbb{Q}, \tag{8}$$

where $\kappa_j$ is the weighting parameter. $N_{j,q}$ is the number of vehicles which request content $q$ in the coverage of RSU $j$, we have $N_{j,q} \leqslant N_j \leqslant N_{j,\max}$. To guarantee vehicles with high QoE, the transmission rate that RSU $j$ requests from CBS $k$ for delivering content $q^*$, denoted as $r_{k,q^*}$, should be equal to $\overline{r_j}$ (i.e., $r_{k,q^*} = \overline{r_j}$).

### B. Utility of CBS

The utility of CBS $k$ is based on whether to cooperate with RSU $j$ to provide vehicles with the requested contents. If there is no request sent by RSU $j$ to CBS $k$ or the agreement is not reached, the utility of CBS $k$ is zero. In comparison, when RSU $j$ and CBS $k$ decide to cooperate, the utility of CBS $k$ can be defined as the price that RSU $j$ pays for the service subtracts the cost for delivering the requested content. Let $\mu = 1$ denote that the agreement between RSU $j$ and CBS $k$ is achieved. The utility of the CBS can be expressed as

$$\mathcal{U}_k = \begin{cases} \mathcal{J}_{j,q^*} - \mathcal{C}_{k,q^*}, & \mu = 1, \\ 0, & \mu = 0, \end{cases} \tag{9}$$

where $\mathcal{J}_{j,q^*}$ is the price that RSU $j$ pays for the service. $\mathcal{C}_{k,q^*}$ is the cost for delivering the requested content which is related to the content transmission time and the number of vehicles that request content $q^*$. It is defined by

$$\mathcal{C}_{k,q^*} = \frac{s_{q^*}}{r_{k,q^*}} \varsigma_k + \beta_k \log\left(1 + N_{j,q^*}\right), \tag{10}$$

where $\varsigma_k$ is the cost for delivering content per unit time. $\beta_k$ is the adjustment factor of CBS $k$.

### C. Utility of RSU

The utility of RSU $j$ can be defined as

$$\mathcal{U}_j = \begin{cases} \displaystyle\sum_{i=1}^{N_j - N_{j,q^*}} \sum_{q=1}^{Q} \gamma_{i,q}(\mathcal{L}_{j,q} - \mathcal{C}_{j,q}) \\ \quad + \displaystyle\sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \mathcal{J}_{j,q^*}, & \mu = 1, \\ \displaystyle\sum_{i=1}^{\overline{N_j}} \sum_{q=1}^{Q} \gamma_{i,q}(\mathcal{L}_{j,q} - \mathcal{C}_{j,q}), & \mu = 0, \end{cases} \tag{11}$$

where $\overline{N_j}$ is the number of vehicles that can be served by RSU $j$ without the help of CBS $k$. $\mathcal{L}_{j,q}$ is the price that the vehicle pays for downloading content $q$. We have

$$\mathcal{L}_{j,q} = p_j \frac{s_q}{\overline{r_j}}. \tag{12}$$

$\mathcal{C}_{j,q}$ in (11) is the average cost of RSU $j$ to deliver content $q$. We have

$$\mathcal{C}_{j,q} = \varsigma_j \frac{s_q}{\overline{r_j}}, \tag{13}$$

where $p_j$ and $\varsigma_j$ are the price and cost to deliver content per unit time, respectively.

### D. Utility of Vehicle

The utility of a vehicle is related to both the time to download the requested content and the price paid for the content. For vehicle $i$, let $\phi = 1$ denote that vehicle $i$ requests content $q$ from RSU $j$ and the content is completely downloaded. We have

$$\mathcal{U}_{i,j,q} = \begin{cases} \mathcal{S} - \Upsilon_{i,j,q} - \mathcal{L}_{j,q}, & \phi = 1, \\ 0, & \phi = 0. \end{cases} \tag{14}$$

Here, $\mathcal{S}$ is a positive integer. $\Upsilon_{i,j,q}$ is the transformation factor between time and price that vehicle $i$ obtains content $q$. It can be given by

$$\Upsilon_{i,j,q} = \varphi_i \log\left(1 + \frac{s_q}{\overline{r_j}}\right), \tag{15}$$

where $\varphi_i$ is the adjustment factor to describe the sensitivity of vehicle $i$ to time.

Combining (12), (14) and (15), the utility of vehicle $i$ to download content $q$ from RSU $j$ can be expressed as

$$\mathcal{U}_{i,j,q} = \begin{cases} \mathcal{S} - \varphi_i \log\left(1 + \dfrac{s_q}{\overline{r_j}}\right) - p_j \dfrac{s_q}{\overline{r_j}}, & \phi = 1, \\ 0, & \phi = 0. \end{cases} \tag{16}$$

## V. Game Analysis

In this section, we model the interaction between CBS and RSU as a double auction game. We first give the description of the game and then analyze the valuations of the content delivery service decided by both CBS $k$ and RSU $j$. After that, we study the optimal bidding strategies of CBS $k$ and RSU $j$ to achieve the Bayesian Nash equilibrium.

### A. Game Description

If RSU $j$ in the coverage of CBS $k$ cannot serve all the vehicles, the RSU then selects content $q^*$ and sends a request to CBS $k$. After this, CBS $k$ and RSU $j$ start the double auction game by deciding their bids for the multicast assisted content delivery. Let $b_{k,q^*}(v_{k,q^*})$ and $b_{j,q^*}(v_{j,q^*})$ denote the bids of CBS $k$ and RSU $j$ for delivering content $q^*$ based on their valuations of the service (i.e., $v_{k,q^*}$ and $v_{j,q^*}$). The agreement is achieved if the bid of CBS $k$ is lower than that of RSU $j$, i.e., $b_{k,q^*}(v_{k,q^*}) < b_{j,q^*}(v_{j,q^*})$. The RSU $j$ then pays $\mathcal{J}_{j,q^*}$ to CBS $k$ for the service, where $\mathcal{J}_{j,q^*}$ is given by

$$\mathcal{J}_{j,q^*} = \lambda b_{j,q^*}(v_{j,q^*}) + (1-\lambda) b_{k,q^*}(v_{k,q^*}). \tag{17}$$

Here, $\lambda (0 < \lambda < 1)$ is the proportion for dividing the profits between RSU $j$ and CBS $k$. Along with this, CBS $k$ delivers content $q^*$ to the vehicles which request the content from RSU $j$ with the multicast technology.

To maximize the utility, both CBS $k$ and RSU $j$ need to estimate the valuation of the multicast assisted content delivery service provided by the CBS to obtain the optimal biding prices. In what follows, we analyze the valuations of CBS $k$ and RSU $j$ for the content delivery service in detail.

### B. Valuation of CBS for the Service

For CBS $k$, the valuation of the multicast assisted content delivery service can be defined by

$$v_{k,q^*} = \mathcal{C}_{k,q^*} + \mathcal{O}(k) \sum_{x=1}^{3} \varrho_{x,k} c_{x,k}, \tag{18}$$

where $\mathcal{O}(k)$ is the adjustment factor of CBS $k$. $\varrho_{x,k}$ is the weight value and $\sum_{x=1}^{3} c_{x,k}$ consists of the following parts.

1) The transmission rate

The CBS needs to deliver content $q^*$ with the transmission rate required by RSU $j$. Thus, a larger rate used to deliver the content results in a higher cost for the CBS. Accordingly, the CBS makes a higher valuation of the content delivery service. The importance of this part can be expressed as

$$c_{1,k} = \log\left(1 + r_{k,q^*}/r_{j,\max}\right), \tag{19}$$

where $r_{j,\max} = \max_{j} \left\{ r_{z_j} \right\}, \forall j \in \mathbb{J}$.

2) The time for delivering content $q^*$

Another factor which affects the cost of the CBS is the time spent on the content delivery service. For content $q^*$, we have

$$c_{2,k} = \log\left(1 + \frac{s_{q^*}/r_{k,q^*}}{s_{\max}/r_{j,\min}}\right), \tag{20}$$

where $r_{j,\min} = \min_{j} \left\{ r_{z_j} \right\}, \forall j \in \mathbb{J}$.

3) The available transmission resources

The CBS has more available transmission resources indicates that the CBS has enough bandwidth resources which can be used to provide vehicles with the requested contents. If the CBS has more available transmission resources, the CBS may have a lower valuation of the service so that its resources can be used to make profits. Conversely, the CBS may evaluate the service with a higher price if it has less available transmission resources. We model the importance of this part as

$$c_{3,k} = \log\left(1 + (d_{k,\max} - d_k)/d_{k,\max}\right), \tag{21}$$

where $d_k$ and $d_{k,\max}$ are the available transmission resources and total transmission resources of CBS $k$, respectively.

### C. Valuation of RSU for the Service

The valuation of RSU $j$ for the service can be defined as

$$v_{j,q^*} = \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \mathcal{O}(j) \sum_{x=1}^{3} \psi_{x,j} c_{x,j}, \tag{22}$$

where $\mathcal{O}(j)$ is the adjustment factor of RSU $j$. $\psi_{x,j}$ is the weight value and $\sum_{x=1}^{3} c_{x,j}$ consists of the following parts.

1) The size of content $q^*$

For RSU $j$, a larger content size of $q^*$ leads to a higher valuation of this part. This is because that the RSU has limited service capacity, where fewer vehicles will be served when the size of content $q^*$ is larger. We define this part as

$$c_{1,j} = \log\left(1 + s_{q^*}/s_{\max}\right). \tag{23}$$

2) The number of vehicles which request content $q^*$

When there are more vehicles which request content $q^*$ in the coverage of RSU $j$, a higher valuation of this part will be estimated by the RSU. We have

$$c_{2,j} = \log\left(1 + N_{j,q^*}/N_{j,\max}\right). \tag{24}$$

3) The number of RSUs which need the services

As there are several RSUs which need the help of CBS $k$, RSU $j$ may declare a higher price of this part if the number of RSUs which need the services is larger. We have

$$c_{3,j} = \log\left(1 + J^*/J\right), \tag{25}$$

where $J^*$ is the number of RSUs which need the services.

### D. Optimal Bidding Strategies

After estimating the valuation of the service, both CBS $k$ and RSU $j$ need to determine the optimal bidding strategies to maximize their utilities. Based on (9), the utlity of CBS $k$ can be rewritten as

$$\mathcal{U}_k = \mathcal{J}_{j,q^*} - \mathcal{C}_{k,q^*} = \mathcal{U}_k{}' + \mathcal{U}_k{}'', \tag{26}$$

where

$$\begin{cases} \mathcal{U}_k{}' = \mathcal{J}_{j,q^*} - v_{k,q^*}, \\ \mathcal{U}_k{}'' = v_{k,q^*} - \mathcal{C}_{k,q^*}. \end{cases} \tag{27}$$

In this way, the maximization problem of CBS $k$ can be formulated as

$$\begin{aligned} \textbf{Problem 1}: &\max_{b_{k,q^*}(v_{k,q^*})} \mathcal{U}_k{}' \\ &s.t. \quad b_{k,q^*}(v_{k,q^*}) > \mathcal{C}_{k,q^*} \end{aligned} \tag{28}$$

Similarly, the utility of RSU $j$ can be given by

$$\begin{aligned} \mathcal{U}_j = &\sum_{i=1}^{N_j - N_{j,q^*}} \sum_{q=1}^{Q} \gamma_{i,q} (\mathcal{L}_{j,q} - \mathcal{C}_{j,q}) \\ &+ \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \mathcal{J}_{j,q^*} \\ = &\,\mathcal{U}_j{}' + \mathcal{U}_j{}'', \end{aligned} \tag{29}$$

where

$$\begin{cases} \mathcal{U}_j{}' = \sum_{i=1}^{N_j - N_{j,q^*}} \sum_{q=1}^{Q} \gamma_{i,q} (\mathcal{L}_{j,q} - \mathcal{C}_{j,q}) \\ \qquad + \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - v_{j,q^*}, \\ \mathcal{U}_j{}'' = v_{j,q^*} - \mathcal{J}_{j,q^*}. \end{cases} \tag{30}$$

By doing this, the maximization problem of RSU $j$ can be expressed as

$$\begin{aligned} \textbf{Problem 2}: &\max_{b_{j,q^*}(v_{j,q^*})} \mathcal{U}_j{}'' \\ &s.t. \begin{cases} \mathrm{T}_j > 2R_j/v_j \\ b_{j,q^*}(v_{j,q^*}) > \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} \end{cases} \end{aligned} \tag{31}$$

According to the above analysis, if $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$, the problem of CBS $k$ can be changed by

$$\begin{aligned}&\max_{b_{k,q^*}(v_{k,q^*})} \mathcal{U}_k{}' \\ &= \max_{b_{k,q^*}(v_{k,q^*})} (\mathcal{J}_{j,q^*} - v_{k,q^*}) \\ &= \max_{b_{k,q^*}(v_{k,q^*})} \left\{\lambda b_{j,q^*}(v_{j,q^*}) + (1-\lambda) b_{k,q^*}(v_{k,q^*}) - v_{k,q^*}\right\}. \end{aligned} \tag{32}$$

Similarly, if $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$, the problem of RSU $j$ is given by

$$\begin{aligned}&\max_{b_{j,q^*}(v_{j,q^*})} \mathcal{U}_j{}'' \\ &= \max_{b_{j,q^*}(v_{j,q^*})} (v_{j,q^*} - \mathcal{J}_{j,q^*}) \\ &= \max_{b_{j,q^*}(v_{j,q^*})} \left\{v_{j,q^*} - \lambda b_{j,q^*}(v_{j,q^*}) + (1-\lambda) b_{k,q^*}(v_{k,q^*})\right\}. \end{aligned} \tag{33}$$

Next, we find the optimal biding strategies based on the different valuations of CBS $k$ and RSU $j$ to address the above two problems. Let $\left\{b_{k,q^*}(v_{k,q^*})^*, b_{j,q^*}(v_{j,q^*})^*\right\}$ denote the Bayesian Nash equilibrium of the game, where $b_{k,q^*}(v_{k,q^*})^*$ is the optimal bidding price of CBS $k$ and $b_{j,q^*}(v_{j,q^*})^*$ is the optimal bidding price of RSU $j$.

In the double auction game, CBS $k$ intends to maximize its profits. Thus, the problem can be formulated as

$$\begin{aligned}&\max_{b_{k,q^*}(v_{k,q^*})} \mathbb{E}\{\mathcal{U}_k{}'\} \\ &= \max_{b_{k,q^*}(v_{k,q^*})} \Big\{\Big(\lambda \mathbb{E}\left[b_{j,q^*}(v_{j,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right] \\ &\quad + (1-\lambda) b_{k,q^*}(v_{k,q^*}) - v_{k,q^*}\Big) \\ &\quad \times \overline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}} \\ &\quad + 0 \times \overline{\Pr\{b_{j,q^*}(v_{j,q^*}) \le b_{k,q^*}(v_{k,q^*})\}}\Big\} \\ &= \max_{b_{k,q^*}(v_{k,q^*})} \Big\{\Big(\lambda \mathbb{E}\left[b_{j,q^*}(v_{j,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right] \\ &\quad + (1-\lambda) b_{k,q^*}(v_{k,q^*}) - v_{k,q^*}\Big) \\ &\quad \times \overline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}\Big\}. \end{aligned} \tag{34}$$

In (34), $\mathbb{E}\left[b_{j,q^*}(v_{j,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right]$ is the bidding price of RSU $j$ which is expected by CBS $k$ under the condition that $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$. $\overline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}$ is the probability that the bid of RSU $j$ is larger than the bid of CBS $k$ when the valuation of RSU $j$ for the multicast assisted content delivery service is $v_{j,q^*}$.

Similar to CBS $k$, RSU $j$ models the problem to maximize its utility as

$$\begin{aligned}&\max_{b_{j,q^*}(v_{j,q^*})} \mathbb{E}\{\mathcal{U}_j{}''\} \\ &= \max_{b_{j,q^*}(v_{j,q^*})} \Big\{\Big(\lambda b_{j,q*}(v_{j,q^*}) \\ &\quad + (1-\lambda)\mathbb{E}\left[b_{k,q^*}(v_{k,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right]\Big) \\ &\quad \times \underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}} \\ &\quad + 0 \times \underline{\Pr\{b_{j,q^*}(v_{j,q^*}) \le b_{k,q^*}(v_{k,q^*})\}}\Big\} \\ &= \max_{b_{j,q^*}(v_{j,q^*})} \Big\{\Big(\lambda b_{j,q*}(v_{j,q^*}) \\ &\quad + (1-\lambda)\mathbb{E}\left[b_{k,q^*}(v_{k,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right]\Big) \\ &\quad \times \underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}\Big\}. \end{aligned} \tag{35}$$

In (35), $\mathbb{E}\left[b_{k,q^*}(v_{k,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right]$ is the bidding price of CBS $k$ which is expected by RSU $j$ under the condition that $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$. $\underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}$ is the probability that the bid of CBS $k$ is smaller than the bid of RSU $j$ when the valuation of CBS $k$ is $v_{k,q^*}$.

For the ease of analysis, the bid strategies of CBS and RSU are linear functions of their valuations. The functions are used to reflect the feature that the bids of CBS and RSU increase with their valuations. For CBS $k$ and RSU $j$, we have

$$\begin{cases} b_{k,q^*}(v_{k,q^*}) = \delta_k + \ell_k v_{k,q^*}, \\ b_{j,q^*}(v_{j,q^*}) = \delta_j + \ell_j v_{j,q^*}, \end{cases} \tag{36}$$

where $v_{k,q^*}$ and $v_{j,q^*}$ follow the even distribution and range from $[\mathcal{C}_{k,q^*}, \Gamma_{\max}]$ and $\left[\Gamma_{\min,} \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j.q^*}\right]$. The $b_{k,q^*}(v_{k,q^*})$ and $b_{j,q^*}(v_{j,q^*})$ therefore follow the even distribution and lie in $[\delta_k + \ell_k \mathcal{C}_{k,q^*}, \delta_k + \ell_k \Gamma_{\max}]$ and $\left[\delta_j + \ell_j \Gamma_{\min,}\, \delta_j + \ell_j \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}\right]$, respectively. Under this condition, we first find the optimal bidding price of CBS $k$.

*Theorem 1:* In the double auction game, the optimal bidding price of CBS $k$ for the multicast assisted content delivery service is

$$b_{k,q^*}(v_{k,q^*})^* = \frac{(1-\lambda)\left(\delta_j + \ell_j \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}\right) + v_{k,q^*}}{2-\lambda}. \tag{37}$$

*Proof:* Refer to appendix A. ■

Then, we find the optimal bidding price of RSU $j$.

*Theorem 2:* In the double auction game, the optimal bidding price of RSU $j$ for the multicast assisted content delivery service is

$$b_{j,q^*}(v_{j,q^*})^* = \frac{\lambda\left(\delta_k + \ell_k \mathcal{C}_{k,q^*}\right) + v_{j,q^*}}{1+\lambda}. \tag{38}$$

*Proof:* Refer to appendix B. ■

Based on (36)-(38), the parameters of (36) are given by

$$\begin{cases} \delta_k = \dfrac{\lambda(1-\lambda)\mathcal{C}_{k,q^*}}{2(2-\lambda)} + \dfrac{(1-\lambda)}{2} \displaystyle\sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}, \\ \ell_k = \dfrac{1}{2-\lambda}, \\ \delta_j = \dfrac{\lambda \mathcal{C}_{k,q^*}}{2} + \dfrac{\lambda(1-\lambda)}{2(1+\lambda)} \displaystyle\sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}, \\ \ell_j = \dfrac{1}{1+\lambda}. \end{cases} \tag{39}$$

By substituting (39) into (37), the optimal bidding price of CBS $k$ can be rewritten as

$$\begin{aligned} & b_{k,q^*}(v_{k,q^*})^* \\ & = \frac{1-\lambda}{2}\left(\frac{\lambda \mathcal{C}_{k,q^*}}{2-\lambda} + \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}\right) \\ & \quad + \frac{1}{2-\lambda}\left(\mathcal{C}_{k,q^*} + \mathcal{O}(k^*)\right. \\ & \quad \times \left(\left.\begin{bmatrix} \varrho_{1,k} \\ \varrho_{2,k} \\ \varrho_{3,k} \end{bmatrix} \begin{bmatrix} \log\left(1 + r_{k,q^*}/r_{j,\max}\right) \\ \log\left(1 + \frac{s_{q^*}}{r_{k,q^*}} / \frac{s_{\max}}{r_{j,\min}}\right) \\ \log\left(1 + \frac{d_{k,\max} - d_k}{d_{k,\max}}\right) \end{bmatrix}^{\mathrm{T}} \right)\right). \end{aligned} \tag{40}$$

Similar to CBS $k$, by substituting (39) into (38), the optimal bidding price of RSU $j$ can be expressed as

$$\begin{aligned} & b_{j,q^*}(v_{j,q^*})^* \\ & = \frac{\lambda}{2}\left(\mathcal{C}_{k,q^*} + \frac{1-\lambda}{1+\lambda}\sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}\right) \\ & \quad + \frac{1}{1+\lambda}\left(\sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \mathcal{O}(j)\right. \\ & \quad \times \left(\left.\begin{bmatrix} \psi_{1,j} \\ \psi_{2,j} \\ \psi_{3,j} \end{bmatrix} \begin{bmatrix} \log(1 + s_{q^*}/s_{\max}) \\ \log\left(1 + \frac{N_{j,q^*}}{N_{j,\max}}\right) \\ \log(1 + J^*/J) \end{bmatrix}^{\mathrm{T}} \right)\right). \end{aligned} \tag{41}$$

## VI. Simulation Results

In this section, the performance of the proposed scheme is evaluated. We first introduce the simulation scenario of the multicast assisted vehicular content delivery in the SD-HetVNETs, and then present the simulation results and discussions in detail.

### A. Simulation Setup

In the simulation, there are 1 CBS and 10 RSUs covered by the CBS in the SD-HetVNETs, where the RSUs are randomly deployed in the area. Both the CBS and RSUs are managed by the SDN. In the coverage of each RSU, the number of arriving vehicles into its coverage is determined by the Poisson distribution. We focus on the vehicles which request contents from RSUs. To be specific, if an RSU can serve all the vehicles in its coverage, there is no cooperation between the RSU and CBS. In comparison, if an RSU cannot serve the vehicles in its coverage, the RSU then asks the CBS which covers the RSU for cooperation. If the agreement between the CBS and the RSU is achieved, the CBS will provide the requested content for the vehicles selected by the RSU. The number of contents in the networks is set to be 100, where the size of each content follows a uniform distribution within [0.1, 0.5] Mbytes. Parameters in simulation are given by Table I.

TABLE I
SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| $K$ | 1 |
| $J$ | 10 |
| $\rho_j$ | {10, 30, 50, 70, 90}veh/km |
| $\rho_{\max}$ | 150veh/km |
| $v_{\min}, v_{\max}$ | 10km/h, 110km/h |
| $Q$ | 100 |
| $s_{\min}, s_{\max}$ | 0.1MBytes, 0.5MBytes |
| $\varsigma_j, \varsigma_k$ | 2, 5 |
| $\beta_k$ | 0.5 |
| $p_j$ | 10 |
| $\mathcal{S}$ | 20 |
| $\varpi$ | 1 |
| $Z_j$ | 7 |
| $r_{z_j}$ | {1, 2, 5.5, 11, 5.5, 2, 1}Mbps |

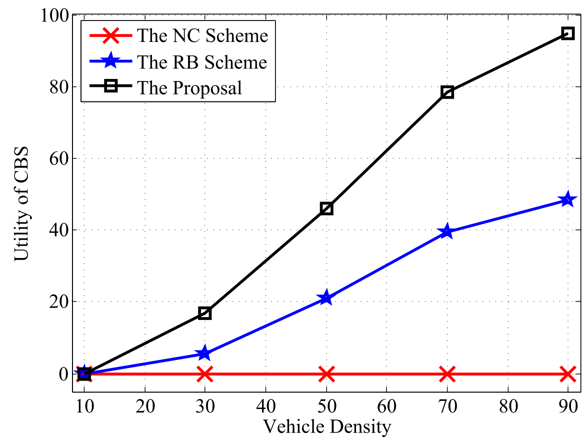


Fig. 2. Utility of the CBS with different values of vehicle density.

With different parameters (i.e., vehicle density and radius of RSU's coverage), we evaluate the utilities of the participants (i.e., CBS, RSU and vehicles) and the efficiency of the networks (i.e., number of vehicles which obtain the requested contents) by comparing our proposal with the following conventional schemes.

- The NC scheme: There is no cooperation between the CBS and RSUs. The requests of vehicles are served by RSUs in this area only.
- The RB scheme: The CBS cooperates with RSUs for vehicular content delivery, while both the CBS and RSUs decide their bidding strategies for the multicast assisted content delivery service randomly.

### B. Simulation Results

We first evaluate the utilities of the participants by changing vehicle density from 10veh/km to 90veh/km. Fig. 2 shows the results of the utility of the CBS in the above three schemes. It can be seen that the CBS obtains the highest utility when the CBS follows the proposal and cooperates with the RSU compared with the other schemes. In the NC scheme, the utility of the CBS is zero as it does not provide any contents for vehicles. As for the RB scheme, the probability that the agreement is achieved becomes lower than that in

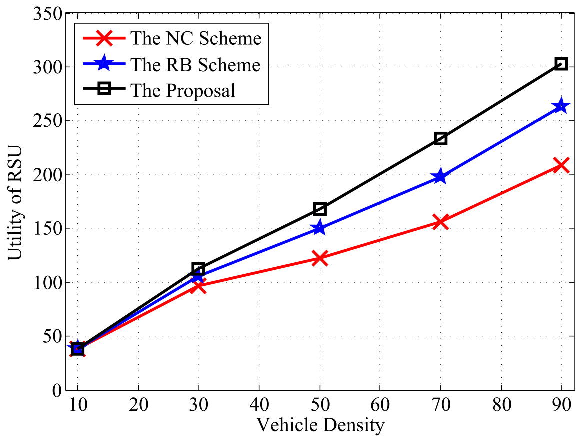


Fig. 3. Utility of the RSU with different values of vehicle density.

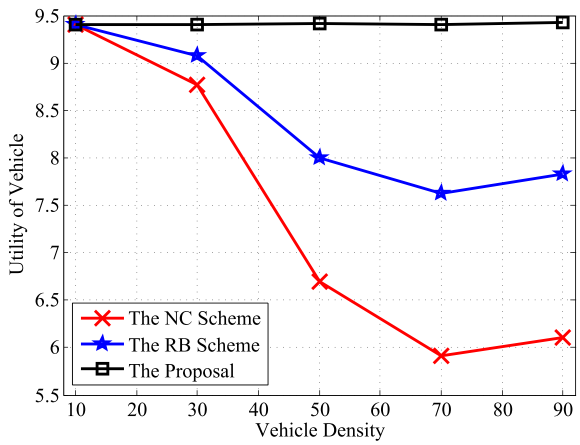


Fig. 4. Utility of the vehicle with different values of vehicle density.

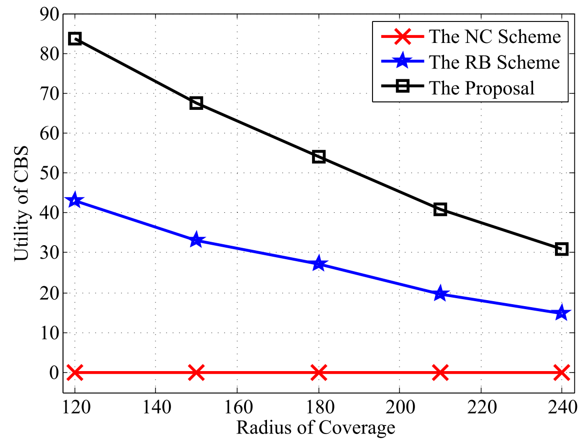


Fig. 5. Utility of the CBS with different radiuses of RSU's coverage.

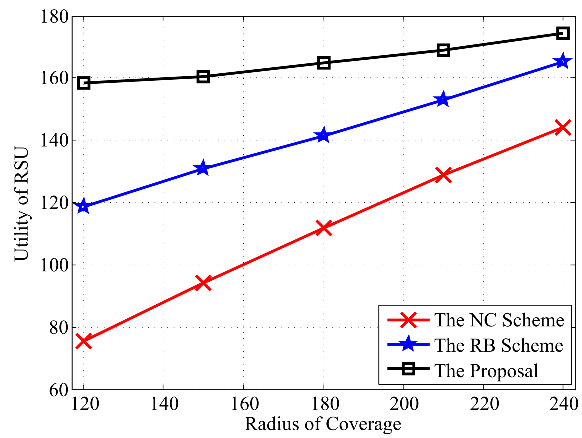


Fig. 6. Utility of the RSU with different radiuses of RSU's coverage.

our proposal for the reason that both the CBS and the RSU bid randomly. On the other hand, with the increase of vehicle density, the utility of the CBS is increased in both the RB scheme and the proposal. The reason for this is that the CBS will serve more vehicles to improve the utility when the vehicle density in the RSU's coverage is higher.

Fig. 3 plots the utility of the RSU with different values of vehicle density. As we can see from this figure, the proposal can bring the highest utility to the RSU when the vehicle density in the coverage of the RSU is high (i.e., 30veh/km-90veh/km). In contrast, when the vehicle density is 10veh/km, the RSU can serve all the vehicles in its coverage by itself with the result that the three schemes bring the same utility to the RSU. As the number of vehicles served by the CBS increases with the increase of vehicle density, more profits then can be distributed between the CBS and the RSU. Therefore, in Fig. 3, the utility of RSU is gradually increased by changing vehicle density from 10veh/km-90veh/km.

Fig. 4 shows the average utility of each vehicle in the coverage of the RSU with different values of vehicle density. In Fig. 4, it can be seen that the proposal can keep a higher utility than the two conventional schemes no matter the vehicle density is high or low. In the NC scheme, each vehicle can obtain the highest utility when vehicle density is 10veh/km compared with other values. This is because that all the vehicles in the coverage of the RSU will be served when the vehicle density is 10veh/km. With the increase of vehicle density, a part of vehicles cannot obtain their requested contents in the two conventional schemes, which results in a low average utility for each vehicle.

Then, we study the utilities of the participants by changing the radius of the RSU's coverage from 120m to 240m. Fig. 5 depicts the utility of the CBS with different radiuses of RSU's coverage. From this figure, we can see that the proposal performs the best performance among all the schemes. With the increase of the coverage radius, the utility of the CBS gradually decreases in the RB scheme and the proposal. When the radius of the coverage is larger, more vehicles will be served by the RSU as the time that vehicles stay in the coverage becomes longer. Accordingly, fewer vehicles are served by the CBS, which leads a lower utility to the CBS.

Fig. 6 plots the utility of the RSU with different values of the RSU's coverage radius. As we can see, the proposal outperforms the other schemes and brings the highest utility to the RSU. By changing the radius of the RSU from 120m to 240m, the utility of the RSU keeps increasing in both the RB scheme and the proposal. As more vehicles can be served by the RSU itself to obtain profits, the utility of the

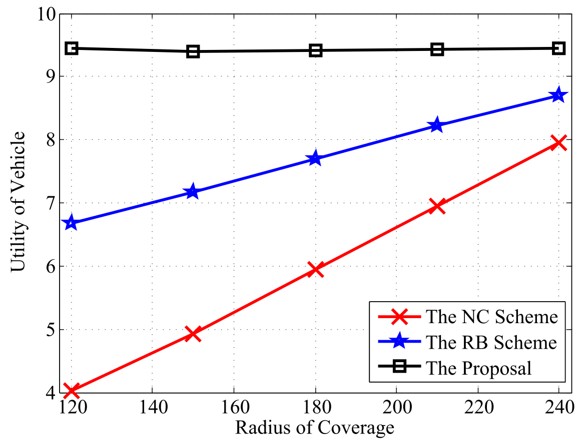


Fig. 7. Utility of the vehicle with different radiuses of RSU's coverage.

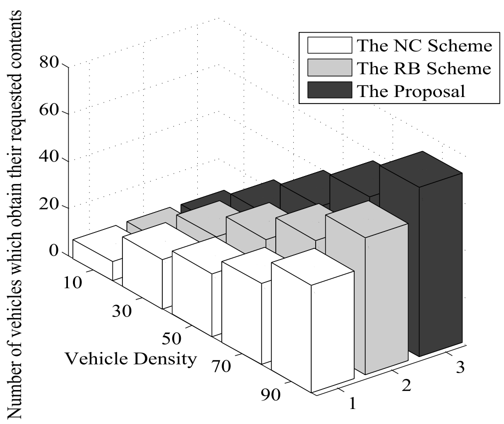


Fig. 8. Number of vehicles which obtain their requested contents with different values of vehicle density.

RSU is increased with the increase of coverage radius and the differences between our proposal and the other schemes become smaller.

Fig. 7 shows the average utility of each vehicle in the coverage of the RSU by changing the radius of the RSU. In Fig. 7, it can be seen that the utility of each vehicle in the proposal rarely changes with the increase of the coverage radius and the proposal can keep a higher utility than the NC scheme and the RB scheme. It is because that the CBS and the RSU work together to provide vehicles with the requested contents, where the utility of each vehicle can be guaranteed. In contrast, for the two conventional schemes, when the radius of the coverage is small, the time that these vehicles stay in the coverage becomes short. Along with this, more vehicles cannot be served by the RSU with a result of low utility for these vehicles.

Next, we evaluate the efficiency of the networks represented by the number of vehicles which obtain their requested contents. Fig. 8 shows the number of vehicles which obtain their requested contents with different vehicle densities. When the vehicle density is 10veh/km, three schemes can serve the same number of vehicles. With the increase of the vehicle density, more vehicles cannot obtain the requested contents in the two conventional schemes. By cooperating with the CBS, the RSU in our proposal can lead to a better performance to provide more vehicles with their requested contents than the other schemes.

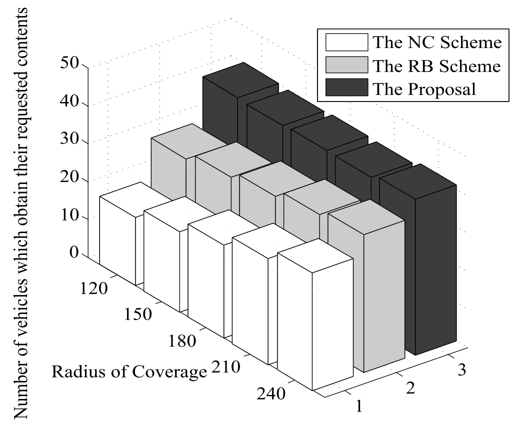


Fig. 9. Number of vehicles which obtain their requested contents with different radiuses of the RSU's coverage.

Fig. 9 depicts the number of vehicles which obtain their requested contents by changing the radius of the RSU's coverage from 120m to 240m. From Fig. 9, we can see that the proposal can serve the largest number of vehicles no matter the coverage radius of the RSU is small or large. The number of vehicles which obtain their requested contents increases with the increase of the radius in both the NC scheme and the RB scheme. The reason is that more vehicles are served when the time that these vehicles stay in the coverage becomes longer. In addition, with the decrease of the radius, fewer vehicles can be served by the RSU itself, and the differences between the proposal and the other schemes become larger.

## VII. Conclusion

In this paper, a utility based collaborative vehicular content delivery scheme has been proposed to motivate the CBS to cooperate with RSU in the SD-HetVNETs. With this scheme, the CBS can help the RSUs in its coverage provide contents requested by a group of vehicles with multicast technology. To maximize the utilities of the CBS and RSU, two optimization problems have been formulated by using the utility models to map the profits of the participants in the networks. Then, we have formulated the two maximization problems as the double auction game to motivate the CBS to join in the multicast assisted content delivery process. After that, we have obtained the optimal bidding strategies for both CBS and RSU by achieving the Bayesian Nash equilibrium of the game. Finally, the proposed scheme has been evaluated by simulations, where the results have demonstrated that the utilities of all the participants can be enhanced and the efficiency of the networks can be improved.

For the future work, we plan to study the cooperation among RSUs to provide vehicles with the requested contents in the SD-HetVNETs. In addition, we intend to design the bandwidth allocation scheme by considering the cooperation between CBS and RSUs to further improve the utilities of the participants in the networks.

## APPENDIX A
## PROOF OF THEOREM 1

Based on (34), the maximization problem of CBS $k$ can be rewritten as

$$\begin{aligned}&\max_{b_{k,q^*}(v_{k,q^*})} \mathbb{E}\{\mathcal{U}_k{}'\}\\&= \max_{b_{k,q^*}(v_{k,q^*})} \Big\{ \Big( \lambda\mathbb{E}\left[b_{j,q^*}(v_{j,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right] \\&\quad + (1-\lambda) b_{k,q^*}(v_{k,q^*}) - v_{k,q^*} \Big) \\&\quad \times \overline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}} \Big\}. \end{aligned} \tag{42}$$

Given the price of CBS $k$, $b_{k,q^*}(v_{k,q^*})$, the probability that the bid of RSU $j$ is higher than $b_{k,q^*}(v_{k,q^*})$ can be given by

$$\begin{aligned}&\overline{\Pr\left\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right\}}\\&= \Pr\left\{\delta_j + \ell_j v_{j,q^*} > b_{k,q^*}(v_{k,q^*})\right\}\\&= \frac{\delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - b_{k,q^*}(v_{k,q^*})}{\ell_j \left( \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right)}. \end{aligned} \tag{43}$$

If the probability is smaller than 0, it is set to 0. Then, the bidding price of RSU $j$ which is expected by the CBS $k$ under the condition that $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$ can be given by

$$\begin{aligned}&\mathbb{E}\left[b_{j,q^*}(v_{j,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right]\\&= 1 \Big/ \left( \ell_j \left( \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right) \right)\\&\quad \times \int_{b_{k,q^*}(v_{k,q^*})}^{\delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*}} x dx \Big/ \overline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}\\&= \Bigg\{ 1 \Big/ \left( \ell_j \left( \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right) \right)\\&\quad \times \frac{1}{2} \left( \delta_j + \ell_j \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} + b_{k,q^*}(v_{k,q^*}) \right)\\&\quad \times \left( \delta_j + \ell_j \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - b_{k,q^*}(v_{k,q^*}) \right) \Bigg\}\\&\quad \Big/ \frac{\delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - b_{k,q^*}(v_{k,q^*})}{\ell_j \left( \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right)}\\&= \frac{1}{2} \left( \delta_j + \ell_j \sum_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} + b_{k,q^*}(v_{k,q^*}) \right). \end{aligned} \tag{44}$$

By substituting (43) and (44) into (34), the maximization problem of CBS $k$ becomes

$$\begin{aligned}&\max_{b_{k,q^*}(v_{k,q^*})} \mathbb{E}\left\{\mathcal{U}_k{}'\right\}\\&= \max_{b_{k,q^*}(v_{k,q^*})} \Bigg\{ \lambda \frac{\delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} + b_{k,q^*}(v_{k,q^*})}{2}\\&\quad + (1-\lambda) b_{k,q^*}(v_{k,q^*}) - v_{k,q^*}(v_{k,q^*}) \Bigg\}\\&\quad \times \frac{\delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - b_{k,q^*}(v_{k,q^*})}{\ell_j \left( \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right)}. \end{aligned} \tag{45}$$

We take the first derivative of $\mathbb{E}\left\{\mathcal{U}_k{}'\right\}$ with respect to $b_{k,q^*}(v_{k,q^*})$, shown as

$$\begin{aligned}&\frac{d\mathbb{E}\left\{\mathcal{U}_k{}'\right\}}{db_{k,q^*}(v_{k,q^*})}\\&= \frac{(1-\lambda)\left( \delta_j + \ell_j \sum\limits_{i=1}^{N_{i,q^*}} \mathcal{L}_{j,q^*} \right) (2-\lambda)\, b_{k,q^*}(v_{k,q^*}) + v_{k,q^*}}{\ell_j \left( \sum\limits_{i=1}^{N_{i,q^*}} \mathcal{L}_{j,q^*} - \Gamma_{\min} \right)}. \end{aligned} \tag{46}$$

By solving (46), we can obtain the optimal bidding price of CBS $k$, shown as

$$b_{k,q^*}(v_{k,q^*})^* = \frac{(1-\lambda)\left( \delta_j + \ell_j \sum\limits_{i=1}^{N_{j,q^*}} \mathcal{L}_{j,q^*} \right) + v_{k,q^*}}{2-\lambda}. \tag{47}$$

The theorem is proved. ■

## APPENDIX B
## PROOF OF THEOREM 2

According to (35), the maximization problem of RSU $j$ can be rewritten as

$$\begin{aligned}&\max_{b_{j,q^*}(v_{j,q^*})} \mathbb{E}\{\mathcal{U}_j{}''\}\\&= \max_{b_{j,q^*}(v_{j,q^*})} \Big\{ \Big( \lambda b_{j,q*}(v_{j,q^*})\\&\quad + (1-\lambda)\mathbb{E}\left[b_{k,q^*}(v_{k,q^*}) | b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\right] \Big)\\&\quad \times \underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}} \Big\}. \end{aligned} \tag{48}$$

Given the price of RSU $j$, $b_{j,q^*}(v_{j,q^*})$, the probability that the bid of CBS $k$ is lower than $b_{j,q^*}(v_{j,q^*})$ can be expressed as

$$\begin{aligned}&\underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})\}}\\&= \Pr\{b_{j,q^*}(v_{j,q^*}) > \delta_k + \ell_k v_{k,q^*}\}\\&= \frac{b_{j,q^*}(v_{j,q^*}) - \delta_k - \ell_k \mathcal{C}_{k,q^*}}{\ell_k \left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)}. \end{aligned} \tag{49}$$

If the probability is smaller than 0, it is set to 0. Then, the bidding price of CBS $k$ which is expected by RSU $j$ under the condition that $b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}(v_{k,q^*})$ is given by

$$\begin{aligned}
&\mathbb{E}\left[b_{k,q^*}\left(v_{k,q^*}\right)|b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}\left(v_{k,q^*}\right)\right] \\
&\quad= \frac{1}{\ell_k\left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)} \\
&\qquad\times \int_{\delta_k+\ell_k\mathcal{C}_{k,q^*}}^{b_{j,q^*}(v_{j,q^*})} x dx / \underline{\Pr\{b_{j,q^*}(v_{j,q^*}) > b_{k,q^*}\left(v_{k,q^*}\right)\}} \\
&\quad= \left\{\frac{1}{\ell_k\left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)} \times \frac{1}{2}\left(b_{j,q^*}(v_{j,q^*}) + \delta_k + \ell_k\mathcal{C}_{k,q^*}\right)\right. \\
&\qquad\qquad \left.\times \left(b_{j,q^*}(v_{j,q^*}) - \delta_k - \ell_k\mathcal{C}_{k,q^*}\right)\right\} \\
&\qquad\qquad\qquad / \frac{b_{j,q^*}(v_{j,q^*}) - \delta_k - \ell_k\mathcal{C}_{k,q^*}}{\ell_k\left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)} \\
&\quad= \frac{1}{2}\left(b_{j,q^*}(v_{j,q^*}) + \delta_k + \ell_k\mathcal{C}_{k,q^*}\right).
\end{aligned} \tag{50}$$

By substituting (49) and (50) into (35), the maximization problem becomes

$$\begin{aligned}
&\max_{b_{j,q^*}(v_{j,q^*})} \mathbb{E}\{\mathcal{U}_j{''}\} \\
&\quad= \max_{b_{j,q^*}(v_{j,q^*})} \left\{v_{j,q^*} - \lambda b_{j,q^*}(v_{j,q^*})\right. \\
&\qquad\qquad \left. + (1-\lambda)\frac{b_{j,q^*}(v_{j,q^*}) + \delta_k + \ell_k\mathcal{C}_{k,q^*}}{2}\right\} \\
&\qquad\qquad\qquad \times \frac{b_{j,q^*}(v_{j,q^*}) - \delta_k - \ell_k\mathcal{C}_{k,q^*}}{\ell_k\left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)}.
\end{aligned} \tag{51}$$

We take the first derivative of $\mathbb{E}\{\mathcal{U}_j{''}\}$ with respect to $b_{j,q^*}(v_{j,q^*})$, shown as

$$\begin{aligned}
&\frac{d\mathbb{E}\{\mathcal{U}_j{''}\}}{db_{j,q^*}(v_{j,q^*})} \\
&\quad= \frac{v_{j,q^*} + \lambda\left(\delta_k + \ell_k\mathcal{C}_{k,q^*}\right)\left(1+\lambda\right)b_{j,q^*}(v_{j,q^*})}{\ell_k\left(\Gamma_{\max} - \mathcal{C}_{k,q^*}\right)}.
\end{aligned} \tag{52}$$

Let (52) be equal to zero, the optimal bidding price of RSU $j$ then can be expressed as

$$b_{j,q^*}(v_{j,q^*})^* = \frac{\lambda\left(\delta_k + \ell_k\mathcal{C}_{k,q^*}\right) + v_{j,q^*}}{1+\lambda}. \tag{53}$$

The theorem is proved. ■

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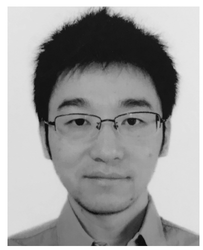

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