Engineering a Game Theoretic Access for Urban Vehicular Networks

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***Abstract*—Drive-thru Internet has emerged as a fundamental approach for information/content distribution to vehicles on the go. In the drive-thru Internet, one vehicle may connect to multiple roadside units (RSUs) along its trip, and in the meantime, multiple vehicles may compete one RSU at the same time for transmissions. Therefore, both vehicles and RSUs need to optimize their connections to achieve their best utilities. In the perspective of RSUs, it is important to select optimal vehicles to transmit so as to maximize the global RSU system's utilization. For individual vehicles, it needs to wisely select RSUs along its trip to connect so as to minimize its download cost, e.g., energy consumption and bandwidth cost. This paper targets to address the two design goals in one framework using a game theoretic model. Specifically, we model the two-dimensional drive-thru Internet as a second-price sealed-bid auction. In each RSU cell, an adaptive reserve price scheme is designed such that the RSU is allowed to selectively provide connections to vehicles based on the network size, vehicle's transmission rate, urgency of download, and content popularity; the RSU finally obtains the optimal utility on a Bayesian Nash equilibrium of the auction. For individual vehicles, a finite-horizon Markov decision process has been developed to guide vehicles to optimally select RSUs to connect along their road trips. Using extensive simulations, we demonstrate that the proposed framework can achieve the highest utility for the RSUs compared with existing proposals. It can also help vehicles keep a higher utility and transmission ratio when going through a single RSU or multiple RSUs than the conventional schemes.**

***Index Terms*—Access mechanism, auction, Nash equilibrium, optimal policy, V2I communication.**

I. Introduction

With dashboard touch screens and mobile operating systems (*e.g.*, Android Auto and Apple CarPlay) becoming a common practice in cars, to provide high-rate Internet connections and high-quality mobile service applications at anywhere to vehicles has received increasing demands and keen research attentions [1]–[5]. The traditional cellular networks, although stable and widely deployed, are however costly to be applied directly to support the media-rich vehicular mobile applications [6], [7]. This results in the drive-thru Internet as an effective alternative. By deploying the WiFi-like communications infrastructure along the roadside, namely roadside unit (RSU), the drive-thru Internet provides high-rate and low-cost wireless connections to vehicles when they are driving through the coverage of RSUs [8]–[11].

The large-scale deployment of drive-thru Internet in reality, *e.g.*, urban area, however, faces several fundamental challenges [12]. First, due to the high mobility of vehicles, the vehicles can only acquire intermittent and short-lived connections when they are within the coverage of RSUs [13], [14]. This directly poses threats to the quality of service (QoS) of vehicular mobile applications, *e.g.*, content distribution, social networking and traffic reporting. Second, an RSU typically has limited bandwidth, but needs to serve a multitude of vehicles at the same time [15]. The contentions among vehicles further deteriorate the network performance by lowering the RSU bandwidth utilization [16]. Third, in a real-world environment, like urban, a multitude of RSUs may need to be deployed to provide seamless connections to massive vehicles. In this case, not only the download performance of individual vehicles, but also the deployment cost and profits of service providers need to be considered [17]–[20]. Note that vehicles may have heterogeneous service requirements and travel through different RSUs along their trips, separate RSUs at different locations can collaborate on the data transmissions to a vehicle and optimally utilize RSU's bandwidth towards the best performance across the entire network. To summarize, the design of a drive-thru Internet is challenged by not only the significant channel variations and QoS requirements of individual vehicles, but also the need for an integrated network optimization towards the maximal system profit.

Drive-thru Internet has been widely investigated. The performance of medium access control (MAC) is studied in [13], [21] based on the contention nature among vehicles and the effects of the mobility of vehicles, respectively. In order to maximize the number of download content, studies [14], [22] focus on improving the transmission performance of vehicles to infrastructure (V2I) communications by exploring specific features of vehicles and service requests, *e.g.*, communication distance, content file size, *etc*. In addition, discussions in [23], [24] give the thought to download content from an RSU in a cooperative manner, where vehicles can cooperate with each

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other to download content. By taking the satisfaction and cost into account, Xing *et al.* [25] aims to maximize the total utility, using the utility model to map the satisfaction level. Moreover, with the random access of V2I connection process, Cheung *et al.* [26] proposes a dynamic optimal algorithm to let a vehicle find the decision sequence to minimize the cost when driving through multiple RSUs. Liu *et al.* [27] designs an RSU deployment algorithm for the purpose of satisfying the content download from RSU with the lowest RSU deployment cost. However, few of them focus on the selection of vehicles to make the connection to obtain more profits to RSUs. Furthermore, based on the different urgency of vehicles, the strategy for keeping a higher satisfaction by selecting different RSUs is also not mentioned.

In this paper, we advance the knowledge by proposing an integrated framework to attain both design goals at the same time: QoS guarantee of individual vehicles and optimal system performance. In particular, we address two fundamental issues of drive-thru Internet: (1) from the perspective of an RSU, how to select appropriate vehicles based on the characteristics of vehicles' transmission channels to obtain the maximal network utility within one RSU cell, and (2) from the perspective of a vehicle, how to appropriately select different RSUs to connect along its trip to optimize its download performance. To address the above issues, we establish a game theoretic analytical framework which captures the interactions among vehicles, RSUs, and the individual performance concerns of both RSUs (or service providers) and vehicles. The game is designed from the aspects of both RSUs and vehicle. On one hand, RSUs adopt an auction scheme to optimally select vehicles to serve; key impacting factors considered in the auction include the fading channel, network population and QoS requirements of vehicles. On the other hand, a vehicle decides whether to join in the auction of RSUs or not based on the service and connection status, *e.g.*, service urgency, number of competing nodes, channel status and distances to RSUs, *etc*. With the two mechanisms combined and executed in a fully distributed manner, we prove that the system can achieve the optimal performance from both vehicle's and RSU's perspective.

Our main contributions are three-fold.

1) *Modelling*: We propose a comprehensive model on two-dimensional drive-thru Internet which optimizes from both vehicle's perspective on individual download performance and cost, and RSU's/system's perspective on profits and system utilization.
2) *Algorithm*: Based on the developed model, we design an algorithm to formulate the interactions between an RSU and the vehicles within its coverage so that the vehicles can be optimally selected by the RSU to make the connection. Further, from the perspective of a vehicle which may go through multiple RSUs, we design an algorithm to help the vehicle find the optimal transmission policy to improve the utility and transmission ratio.
3) *Validations*: We evaluate the performance of the proposed framework using extensive simulations. We show that the proposed framework achieves the highest utility to RSUs. Moreover, with the adoption of the optimal policy, vehicles can obtain a higher utility and transmission ratio as compared with the conventional schemes in the cases of single RSU and multiple RSUs, respectively.

The remainder of this paper is as follows. Section II discusses on the the related literature and highlights our contributions. Section III presents the system model. Section IV formulates the process of V2I connection as an auction game, where the utilities of both RSUs and vehicles are analyzed. An optimal bidding strategy and decision policy for vehicles are also derived. Section V evaluates the performance of the proposal using simulations, and Section VI closes the paper with conclusions.

II. Related Work

The mobility of vehicles has been extensively studied in the context of V2I networks. Luan *et al.* [13] analyse the impact of mobility on the MAC in vehicular networks. A simple model which incorporates the mobility is proposed to evaluate the throughput. The enhancement schemes are presented to make the MAC to be adaptive according the mobility of vehicles. Khabbaz *et al.* [28] present a multiserver queuing model to capture the dynamics of V2I communication and evaluate its performance based on the essential behavioral characteristics such as the force termination. Different from [13], [28], our work focuses on how to select RSUs to make connection to improve the utility of vehicles based on the mobility.

In parallel to the mobility studies, a collection of works investigate the competition and cooperation among vehicles. Zhuang *et al.* [21] study on the MAC performance by taking the contention nature and the realistic traffic model into account. The authors show the relationships among parameters such as vehicle density and speed. Harigovindan *et al.* [29] present analytical expressions to optimize the values of contention window, which can solve the unfairness problem and improve the aggregate data transferred by using a resource allocation method named proportional fairness. Ota *et al.* [23] focus on the real-time applications and study a cooperative downloading algorithm which can maximize the download data packets while minimizing the delivery delay. Zhou *et al.* [24] propose a cooperative scheme by selecting appropriate vehicles to form a linear cluster to download the same file. In contrast to the above works, rather than analyzing the competition and cooperation to improve the performance, we target to utilize them to make more profits for both vehicles and RSUs in V2I networks.

Recently, an extensive body of research has been devoted to using different schedule schemes/frameworks to improve the performance of V2I networks. Zhang *et al.* [14] present a service scheduling scheme which gives thought to the service deadline and data size. Xing *et al.* [25] investigate the scheduling of multimedia services based on a utility model which can map the throughput. In order to maximize the utility, the authors formulate it as a finite-state decision problem and solve it by a practical heuristic algorithm. Bi *et al.* [30] present a novel transport scheme to adjust the source transfer rate, avoid congestion, and improve fairness. The results show that the scheme can reduce packet losses and improve the utilization efficiency. Zhou *et al.* [31] present a unified framework to investigate the

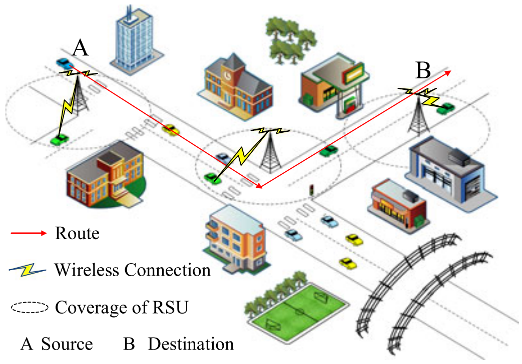

Fig. 1. Network scenario for V2I communications.

performance of drive-thru Internet. The framework can not only accommodate various traffic flow states but can also be compatible with IEEE 802.11a/b/g networks. Different from the above works, our scheme gives a thought to the QoS (*i.e.*, utility) of vehicles and the system performance (*i.e.*, profits) by formulating the access scheme as a bidirectional selection process. In our scheme, the RSU is the leader by carrying out the auction and charging the reserve price to maximize profits. Once the auction starts, vehicles become the decision-makers and can selectively bid for connecting the RSU to maximize their utilities.

Furthermore, there have been a lot of works focusing on the game model and costs in V2I networks. Ma *et al.* [32] propose an incentive mechanism to encourage vehicles to participate in the content forwarding to improve the performance based on game theory. Saad *et al.* [18] present a coalition formation game where the RSUs can cooperate with each other to improve the diversity of the information and exploit the underlying content-sharing. Akkarajitsakul *et al.* [33] propose a game-theoretic model to solve the bandwidth allocation problem in the V2I networks, where both cooperative and non-cooperative behaviors among vehicles are considered. Cheung *et al.* [26] study the scenario that vehicles want to upload content when driving through multiple RSUs on a high way. A dynamic optimal random access algorithm is designed by using the backward induction method to find the optimal transmission policy for vehicles to minimize the cost. By contrast to the existing schemes, our scheme is more realistic by considering the detailed demand of vehicles and the profits of RSUs to minimize each vehicle's download cost and maximize the profits of RSUs. As a result, vehicles can achieve higher utility and the RSUs can obtain higher profits than the conventional methods.

III. System Model

This section presents the system model including the traffic model and the communication model as shown in Fig. 1. Table I summarizes the notations used.

A. Traffic Model

We consider a number of RSUs deployed along road in a two-dimensional map. A number of vehicles are involved with each vehicle driving through at least one RSU along its road trip on the map. The traffic flow in the coverage of each RSU is assumed smooth and not interrupted by traffic jams [34]. The arrival of vehicles to an RSU follows the Possion distribution [35]. Let λ_j denote the mean number of vehicle arrivals per unit time to the coverage of RSU j. According to the results of traffic engineering [36], we have

$$\lambda_j = \rho_j v_j, \tag{1}$$

where ρ_j and v_j are the road density and velocity of vehicles, respectively, in the coverage of RSU j.

The relationship between the vehicle velocity and density as derived in [37], is

$$v_j = v_{\max}\left(1 - \frac{\rho_j}{\rho_{\max}}\right), \tag{2}$$

where $v_{\max}$ is the velocity of vehicles when the traffic is unimpeded and $\rho_{\max}$ is the density when the traffic jam occurs.

Let M denote the number of RSUs deployed in the city, and m ($m \leqslant M$) denote the number of RSUs that vehicle i will go through. N is denoted as the maximum number of vehicles in the coverage of each RSU. We then have $N = 2R\rho_{\max}$, where R is the radius of each RSU.

A vehicle may go through multiple RSUs from the source to the destination. In the coverage of different RSUs, the time that a vehicle stays in may be different due to the different density of vehicles. Let $\tau_{i,j}$ be the time that vehicle i stays in the coverage of RSU j. The total time that vehicle i stays in m RSUs can be expressed as

$$\tau_i = \sum_{j=1}^{m} \tau_{i,j} = \sum_{j=1}^{m} \frac{2R}{v_{i,j}}. \tag{3}$$

where $v_{i,j}$ is the velocity of vehicle i in the coverage of RSU j. When vehicle i is not in the coverage of any RSU, it takes time, denoted as $o_{i,e}$, to let vehicle i drive in the available coverage of an RSU. When there are m RSUs in the trip of vehicle i, the time that vehicle i is out of any RSU along its trip is given by $\sum_{e=1}^{m-1} o_{i,e}$. Then the total time from vehicle i entering in the first RSU to vehicle i leaving the last RSU is given by

$$\Gamma_i = \tau_i + \sum_{e=1}^{m-1} o_{i,e} = \sum_{j=1}^{m} \frac{2R}{v_{i,j}} + \sum_{e=1}^{m-1} o_{i,e}. \tag{4}$$

B. Communication Model

Vehicles can download/upload contents only when they are inside the RSU coverage. For a vehicle inside an RSU's coverage, let $y = 0$ and $y = 1$ denote if the vehicle intends to download or upload contents, respectively.

For ease of analysis, we apply a slotted time system with the unit time slot equal to Δt. Let $T_{i,j}$ be the number of time slots that vehicle i spends in the coverage of RSU j. It can be given by

$$T_{i,j} = \frac{2R}{v_{i,j}\Delta t} = \frac{\tau_{i,j}}{\Delta t}. \tag{5}$$

As vehicle i may go through multiple RSUs from the source to the destination, the total time slots for vehicle i from its entering

TABLE I
SUMMARY OF NOTATIONS

Notations	Description
$\mathbb{Z}$	Set of spatial zones in the coverage of an RSU.
$\mathbb{R}$	Set of the transmission rates.
$\prod$	Set of policies.
m	Number of RSUs that vehicle i will go through.
v_j	Speed of vehicles in the coverage of RSU j.
$v_{\max}$	Speed when the traffic is unimpeded.
ρ_j	Density of vehicles in the coverage of RSU j.
$\rho_{\max}$	Density when the traffic jam occurs.
$\tau_{i,j}$	Time that vehicle i is in the coverage of RSU j.
Γ_i	Time from vehicle i entering in the first RSU to vehicle i leaving the last RSU.
$T_{i,j}$	Number of time slots that vehicle i stays in RSU j.
$\overline{T}_i$	Number of time slots that vehicle i goes through from the source to the destination.
K_t	Number of vehicles that join in the game at time slot t.
n_t	Number of vehicles in the coverage at time slot t.
r_{Z_l}	Transmission rate when vehicle i is in zone Z_l.
T_j^*	Number of time slots in each zone of RSU j.
p_1	Probability that the content is in the buffer.
p_2	Probability that the content is not in the buffer.
F_N	Number of content in the networks.
p_t	Probability that the connection is successful at time slot t.
$b_{i,t}$	Bid of vehicle i at time slot t.
$\mathcal{C}_{i,t}^*$	Value of vehicle i at time slot t.
$b_{w,t}^*$	Price bid by vehicle w at time slot t.
$\mathcal{C}_{i,t}^p$	Private value of time slot t charged by vehicle i.
$\mathcal{U}_{i,t}$	Utility of vehicle i at time slot t.
$\mathcal{C}_{i,\overline{T}+1}^{\text{penalty}}$	Penalty price of vehicle i when the content is not finished.
$\mathcal{U}_{i,\pi}^{\text{total}}$	Utility of vehicle i when policy π is adopted.
$\mathcal{U}_{\text{RSU}}$	Utility of RSU in a period time.
π^*	Optimal policy of vehicle i.
$\mathcal{L}_{i,t}(s_t, p_t)$	The highest expected utility from the current time slot t to the last slot at destination.

in the first RSU to its leaving the last RSU can be expressed by

$$\overline{T}_i = \frac{\sum_{j=1}^{m} \tau_{i,j} + \sum_{e=1}^{m-1} o_{i,e}}{\Delta t} = \sum_{j=1}^{m} T_{i,j} + \sum_{e=1}^{m-1} o_{i,e}/\Delta t. \tag{6}$$

Based on [13], [31], [38], the transmission rate of the channel in each zone is set to be different and dynamically changed due to varying wireless channel conditions. The coverage of each RSU is divided into multiple zones based on the distance to the RSU to reflect the dynamical change of channels. The fading of the channel is also considered in our model. Let $\mathbb{Z} = \{Z_1, ..., Z_l, ..., Z_L\}$ denote the set of zones in the coverage and the set of transmission rates is $\mathbb{R} = \{r_{Z_1}, ..., r_{Z_l}, ..., r_{Z_L}\}$. The transmission rates are different when vehicles are at different zones, while they are the same when vehicles are at the same zone.

IV. Problem Formulation

A. System Description

Fig. 2 depicts the connection process of vehicles to RSUs. We model the drive-thru Internet as an auction game. In specific, in each RSU cell, the RSU leads the auction of connections; the RSU's connection is made to vehicles with the highest bid in the auction. At each time slot, the RSU determines a reserve price

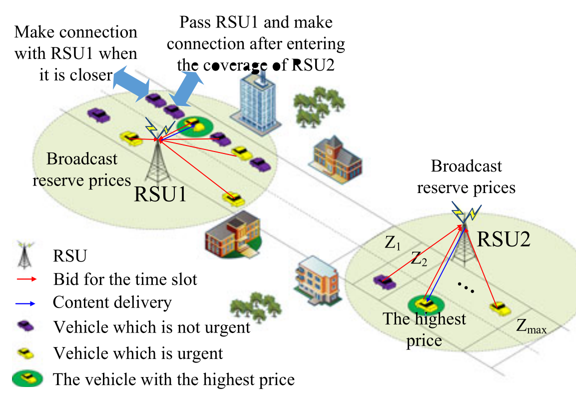

Fig. 2. The auction mechanism.

of connections and broadcasts the reserve price to vehicles. The vehicles then decide whether to take part in the auction based on their own status, including following items. (1) The number of vehicles in the coverage of the RSU: A vehicle is more likely to take part in the auction when the number of vehicles in the auction is small, as the probability that this vehicle wins the auction will be higher in this case. (2) The urgent degree of the demand on the requested content: A vehicle may join in the game directly if the content is urgent requested. (3) The zone that a vehicle stays in: A vehicle may join the auction when it is in the zones close to the nearby RSU, where the transmission rates are higher than the other zones. As a result, geo-distributed RSUs over the map lead distributed auctions based on their

Algorithm 1: Auction Mechanism at RSU.

1: $K_t = 0$
2: **while** $t > 0$ **do**
3: **Phase 1: Broadcast the reserve prices**
4: Record the number of vehicles in the coverage of RSU j: n_t
5: Calculate the reserve prices of vehicles, $\mathcal{C}_{k,t}^{r_x}$
6: Broadcast $\mathcal{C}_{k,t}^{r_x}$ to vehicles
7: **Phase 2: Provide the final prices**
8: **for** $k = 1; k \leq n_t$ **do**
9: Receive the reserve prices, $\mathcal{C}_{k,t}^{r_x}$
10: Decide whether to take part in the auction based on $\mathcal{C}_{k,t}^{r_x}$ and $\mathcal{C}_{k,t}^{p}$
11: **if** Join in the auction, **then**
12: Send the bid and information of the requested content to the RSU
13: $K_t = K_t + 1$
14: **end if**
15: **end for**
16: **Phase 3: Select the vehicle**
17: RSU receives the bids
18: **for** $k = 1; k \leq K_t$ **do**
19: Calculate $\mathcal{C}_{k,t}$
20: **end for**
21: Select the vehicle by

$$k^* = \arg\max_k \mathcal{C}_{k,t}$$

22: **end while**
23: $t = t + 1$
24: Update the number of vehicles: n_{t+1}

specific network environment; vehicles traverse different RSUs along their trips and selectively participate in auctions. The mobility of vehicles therefore triggers the collaboration among static and geo-distributed RSUs towards full network bandwidth utilization.

In what follows, we provide a theoretical modeling of the auction game. We first model and analyze the utilities of RSUs and vehicles. After that, we derive the equilibrium solution of the game to guide the bids of vehicles in the V2I communications. Lastly, an optimal policy is provided for a randomly target vehicle to maximize the utility.

B. Utility of Each RSU

In each drive-thru Internet cell, the RSU leads the auction game at each time slot following the operations in Algorithm 1. In specific, each RSU first determines the price of a time slot and sells the time slot for obtaining revenue (line 3-6). By taking the characteristics of V2I communications into consideration, the value of a vehicle (*e.g.*, k) at time slot t consists of two parts (line 7-15), which are the reserve prices required by the RSU and the private values charged to vehicles as follows,

$$\mathcal{C}_{k,t} = \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{k,t}^{r_x} + \mu \mathcal{C}_{k,t}^{p} \tag{7}$$

where ε_x $(x \in [1,3])$ and μ are weight coefficients. $\mathcal{C}_{k,t}^{p}$ is the private value bade by vehicle k at time slot t and the remaining items are the reserve price charged by RSU. As vehicles compete for making connection with the RSU to obtain content, the corresponding factors of the three players, *i.e.*, RSU, vehicles and contents, should be considered. The reserve price in this paper is determined by the three parts which represent above three players, respectively. The first part takes the feature of RSU into consideration. For example, the middle zone of the RSU has the highest price due to the best channel conditions. The second part is based on the feature of vehicles in the coverage of the RSU; the more vehicles in the coverage, the higher the reserve price will be. The third part is given by considering the aspect of content where a high priority is assigned to the content which is stored in the buffer as it is readily to be distributed.

1) The first part of the reserve price $\mathcal{C}_{k,t}^{r_1}$ is defined on the basis of the characteristics of V2I. Specifically, the middle zone has the highest price due to the better channel conditions to RSU. We consider the equal length of zone for its simplicity of computation. The model can be conveniently adapted to zones of different lengths. By dividing the coverage of RSU into several zones with an equal length, denoted as Z_l, the zone that a vehicle stays at time slot t can be shown as

$$Z_l = \left\lceil \frac{t}{T_j^*} \right\rceil, Z_l \in \mathbb{Z}, \tag{8}$$

where T_j^* is the number of time slots in each zone of RSU j and $\lceil \cdot \rceil$ is the ceiling function.
The price $\mathcal{C}_{k,t}^{r_1}$ can be defined as

$$\mathcal{C}_{k,t}^{r_1} = \left(\frac{(Z_L + 1 - Z_l) Z_l}{Z_L^2} \right)^2 \mathcal{Q}^{r_1}, Z_l \in \mathbb{Z}, \tag{9}$$

where Z_l is given in (8) and $\mathcal{Q}^{r_1}$ is the regulatory factor of the first part reserve price.

2) More vehicles in the coverage of the RSU will cause keener competition among vehicles to obtain time slots. Moreover, more time and power will need to collect and process vehicles information to select the highest price. Therefore, the second part of reserve price $\mathcal{C}_{k,t}^{r_2}$ is defined in an adaptive manner (*i.e.*, $\mathcal{C}_{k,t}^{r_2}$ increases with the increase of the number of vehicles), shown as,

$$\mathcal{C}_{k,t}^{r_2} = \log(1 + n_t) \mathcal{Q}^{r_2}. \tag{10}$$

Here, n_t is the number of vehicles in the coverage of the RSU at time slot t and $\mathcal{Q}^{r_2}$ is the regulatory factor of the second part reserve price.

3) The third part of the reserve price is the cost of power to fetch content from the remote server. For simplicity, the cost per time slot is set to be a constant value, *i.e.*,

$$\mathcal{C}_{k,t}^{r_3} = \varpi \mathcal{Q}^{r_3}, \tag{11}$$

where ϖ is a constant value and $\mathcal{Q}^{r_3}$ is the regulatory factor of the third part reserve price.

Next, we introduce the private values of vehicles based on their urgency of demand. Note that, when vehicle k is on its way, the urgency for connecting with RSU always changes no matter the vehicle is within the coverage of an RSU or not. Here, four typical functions are used to describe the urgency of vehicle k as follows:

$$f^1(t) = \begin{cases} \frac{t}{\overline{T}_k}, & 0 < t \le \overline{T}_k, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

$$f^2(t) = \begin{cases} 1 - \frac{t}{\overline{T}_k}, & 0 < t \le \overline{T}_k, \\ 0, & \text{otherwise}, \end{cases} \tag{13}$$

$$f^3(t) = \begin{cases} \frac{2t}{\overline{T}_k}, & 0 < t \le \overline{T}_k/2, \\ -\frac{2t}{\overline{T}_k} + 2, & \overline{T}_k/2 < t \le \overline{T}_k, \\ 0, & \text{otherwise}, \end{cases} \tag{14}$$

$$f^4(t) = \begin{cases} 1 - \frac{2t}{\overline{T}_k}, & 0 < t \le \overline{T}_k/2, \\ \frac{2t}{\overline{T}_k} - 1, & \overline{T}_k/2 < t \le \overline{T}_k, \\ 0, & \text{otherwise}. \end{cases} \tag{15}$$

As such, the private value of vehicle k is given by

$$\mathcal{C}^p_{k,t} = f^c(t)\mathcal{Q}^p, c \in [1, 4], \tag{16}$$

where $\mathcal{Q}^p$ is the regulatory factor of private value.

After vehicles within the coverage of the RSU offer their bids, the RSU selects the vehicle which bids the highest price to make connection (line 16-22), shown as,

$$k^* = \arg\max_k \mathcal{C}_{k,t} \tag{17}$$

Based on the final price for each time slot, we analyze the utility of the RSU (*e.g.*, j) in a fixed period time $T_{i,j}$ which is defined as the duration from the moment when a randomly tagged vehicle i comes into the coverage until the moment when it leaves. We consider all the RSUs deployed in the city use the same auction game to achieve maximum utility.

In order to make more profits, a buffer is installed in each RSU to store some popular content, such as digital map and traffic information. Let $d = 1$ denote the requested content is in the buffer; otherwise, $d = 0$. In our work, different contents in the buffer installed in each RSU have different popularities, which follows the Zipf-like distribution, a typically assumed popularity distribution in literature [39], [40]. Let p_q^{access} denote the probability that content q is requested, which can be expressed as

$$p_q^{\text{access}} = \frac{1}{{r_q}^{\theta} \sum_{\varrho=1}^{F_N} \frac{1}{\varrho^{\theta}}}, 0 \le \theta \le 1, \tag{18}$$

where r_q is the rank of content q and F_N is the total number of content in the V2I networks. Based on the popularity of content, the RSU can pre-store the top $b_{\max}$ content in the buffer. The probability that the requested content is available in the buffer can then be written as

$$p1 = \left(\sum_{q=1}^{b_{\max}} \frac{1}{{r_q}^{\theta} \sum_{\varrho=1}^{F_N} \frac{1}{\varrho^{\theta}}}\right) \left(\sum_{q=1}^{F_N} \frac{1}{{r_q}^{\theta} \sum_{\varrho=1}^{F_N} \frac{1}{\varrho^{\theta}}}\right)^{-1}. \tag{19}$$

Conversely, the probability that the requested content is not in the buffer is

$$\begin{aligned} p2 &= 1 - p1 \\ &= 1 - \left(\sum_{q=1}^{b_{\max}} \frac{1}{{r_q}^{\theta} \sum_{\varrho=1}^{F_N} \frac{1}{\varrho^{\theta}}}\right) \left(\sum_{q=1}^{F_N} \frac{1}{{r_q}^{\theta} \sum_{\varrho=1}^{F_N} \frac{1}{\varrho^{\theta}}}\right)^{-1}. \end{aligned} \tag{20}$$

By doing this, the third part of the reserve price can be seen as the potential benefits of the RSU if the following two conditions are satisfied:

1) $y = 0$;
2) $d = 1$.

In the situation described above, both the time and the cost of fetching content from the remote content server are avoided. However, when $y = 1$ or $d = 0$, the potential profits will become zero. Based on the second-price sealed-bid auction, the utility of the RSU in the period of time is

$$\mathcal{U}_{\text{RSU}} = \sum_{t=1}^{T_{i,j}} \left(\epsilon b^*_{w,t} + (1-\epsilon)(b^*_{w,t} - \varepsilon_3 \mathcal{C}^{r_3}_{w,t})\right), \tag{21}$$

where $b^*_{w,t} = f(\mathcal{C}_{w,t})$ is the second highest price bade by vehicle w. The value of ϵ is 1 if $y = 0$ and $d = 1$. Otherwise, $\epsilon = 0$.

C. Utility of Vehicle

The vehicle which sends a request to play the game needs to pay ψ to the RSU for which the power of both the vehicle and the RSU are consumed. Let a denote the decision whether a vehicle decides to take part in the auction. $a = 1$ means that the vehicle sends a request to the RSU; otherwise, $a = 0$.

For each time slot, the RSU broadcasts the reserve price in advance and then vehicles bid for the time slot. According to the second-price sealed-bid auction, the utility of vehicle i in a period time can be defined as

$$\mathcal{U}_i = \sum_{t=1}^{\overline{T}_i} \mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi), \tag{22}$$

where $\mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi)$ is the utility of vehicle i in time slot t. $b_{i,t}$ and $b_{-i,t}$ denote the bid by vehicle i and other vehicles, respectively. For each time slot, we consider two cases based on the number of vehicles in the coverage:

Case 1: n>1 According to the rules of the second-price sealed-bid auction, the vehicle which bids the highest price will get the time slot and eventually pay the amount of the second highest price. Therefore, when vehicle i is the highest bidder at time slot t, the utility of vehicle i can be defined as the highest price (*i.e.*, the bid of vehicle i) minus the second highest price which is bade by other vehicles. Conversely, if the bid of vehicle i is not the highest one, the vehicle will lose the chance to connect with the RSU at time slot t, mathematically,

$$\begin{aligned} &\mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi) \\ &= \begin{cases} b_{i,t} - b^*_{w,t} - \psi, & b_{i,t} > b^*_{w,t} \text{ and } a = 1, \\ 0, & a = 0, \\ -\psi, & \text{otherwise}. \end{cases} \end{aligned} \tag{23}$$

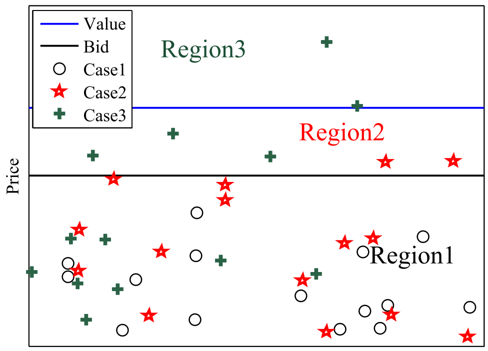

Fig. 3. The optimal strategy for vehicle i in the game.

Case 2: n=1 In this case, there is only the tagged vehicle i in the coverage of the RSU at time slot t, the utility of vehicle i is determined by its bid and the reserve price of the RSU. We have

$$\mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi) = \begin{cases} b_{i,t} - \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} - \psi, & b_{i,t} > \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} \text{ and } a = 1, \\ 0, & a = 0, \\ -\psi, & \text{otherwise.} \end{cases} \tag{24}$$

D. Equilibrium Solution of the Auction

For each time slot, the bid and the value may be different even for the same vehicle as the urgency of vehicles changes with time. Here, the value of the tagged vehicle i at time slot t is denoted as $\mathcal{C}_{i,t}^{*}$. As a rational individual, the bid and the value of vehicle i should be met:

$$b_{i,t} \leq \mathcal{C}_{i,t}^{*}. \tag{25}$$

Theorem 1: In the second-price sealed-bid auction, each vehicle has a weakly dominant strategy which is bade according to their true value. In particular, there exists a Bayesian Nash equilibrium of the auction if each vehicle follows the weakly dominant strategy.

Proof: Based on the bids of other vehicles in different regions which are shown in Fig. 3, the proof process can be divided into the following cases:

Case1: $b_{w,t}^{*} < b_{i,t} < \mathcal{C}_{i,t}^{*}$, vehicle i is the highest bidder.

The tagged vehicle i will win the game and pay the price $b_{w,t}^{*}$ if the bid of vehicle i is $b_{i,t}$. This case is based on the situation that the bids of other vehicles are in the Region 1, including the second highest price bade by vehicle w. If vehicle i does not give the price $b_{i,t}$, $\mathcal{C}_{i,t}^{*}$ will be bade. The vehicle can still obtain the time slot to connect with the RSU and pay the same price. Therefore, $b_{i,t}$ is as good as $\mathcal{C}_{i,t}^{*}$ in this case.

Case2: $b_{i,t} < b_{w,t}^{*} < \mathcal{C}_{i,t}^{*}$, vehicle w is the highest bidder.

For this case, the highest price bade by vehicle w is in the Region 2. If the bid of vehicle i is $b_{i,t}$, the chance to connect with the RSU will be lost due to $b_{i,t} < b_{w,t}^{*}$. However, if the bid of vehicle i is $\mathcal{C}_{i,t}^{*}$, vehicle i could have won the game and gained the utility $\mathcal{U}_{i,t} = \mathcal{C}_{i,t}^{*} - b_{w,t}^{*} > 0$. Therefore, $\mathcal{C}_{i,t}^{*}$ is better than $b_{i,t}$ in this case.

Case3:$b_{i,t} < \mathcal{C}_{i,t}^{*} < b_{w,t}^{*}$, vehicle w is the highest bidder.

This case is based on the situation that vehicle w in the Region 3 wins the auction. As we can see, vehicle i loses the auction no matter the bid is $b_{i,t}$ or $\mathcal{C}_{i,t}^{*}$ for the reason that $b_{w,t}^{*}$ is higher than $\mathcal{C}_{i,t}^{*}$. Therefore, $b_{i,t}$ is as good as $\mathcal{C}_{i,t}^{*}$ in this case. From the above discussions, we can conclude that $\mathcal{C}_{i,t}^{*}$ is the best strategy for vehicle i to compete with other vehicles for the time slot. The theorem is proved.

Based on theorem 1, the optimal strategy of vehicle i at time slot t can be shown as

$$b_{i,t} = f(\mathcal{C}_{i,t}^{*}) = \mathcal{C}_{i,t}^{*}. \tag{26}$$

By substituting (26) into (23) and (24), the utility of vehicle i at time slot t can be rewritten as

$$\mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi \mid n > 1) = \begin{cases} \mathcal{C}_{i,t}^{*} - b_{w,t}^{*} - \psi, & \mathcal{C}_{i,t}^{*} > b_{w,t}^{*} \text{ and } a = 1, \\ 0, & a = 0, \\ -\psi, & \text{otherwise.} \end{cases} \tag{27}$$

$$\mathcal{U}_{i,t}(b_{i,t}, b_{-i,t}, \psi \mid n = 1) = \begin{cases} \mathcal{C}_{i,t}^{*} - \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} - \psi, & \mathcal{C}_{i,t}^{*} > \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} \text{ and } a=1, \\ 0, & a = 0, \\ -\psi, & \text{otherwise.} \end{cases} \tag{28}$$

E. Optimal Policy

Besides the optimal strategy for each time slot, we also need to consider all the time slots that vehicle i will go through from the source to the destination. We need to find an optimal policy for the vehicle because different policies adopted by the vehicle will lead to different utility.

Let s ($s \in \mathbb{S} = [S_{\min}, S_{\max}]$) denote the size of the content which is requested by vehicle i. Note that, the vehicle in zone Z_l only needs one time slot to successfully connect with RSU if $0 < s \leq r_{Z_l} \Delta t$. By contrast, if the size of content is larger than $r_{Z_l} \Delta t$, more time slots need to be provided by the same RSU or different RSUs. The remaining size of the content after vehicle i connect with the nearby RSU in one time slot is given by

$$s_{t+1} = [s_t - r_{Z_l} \Delta t]^{+}, r_{Z_l} \in \mathbb{R}, \tag{29}$$

where $[\cdot]^{+} = \max(0, \cdot)$.

Note that, each vehicle is on its own way (from different sources to different destinations) with the different urgency to connect with RSUs. For each time slot, the private values provided by vehicles are therefore various. In addition, vehicle i does not know the distribution of the private values of other vehicles before bidding for the time slot. This is because that all vehicles bid at the same time according to the second-price sealed-bid auction. Hence, in the coverage of each RSU, the probability that vehicle i successfully connects to the RSU at time slot t is corresponding to the number of vehicles in the coverage of the RSU. Let p_t and $\mathbb{P}$ be the probability that a vehicle successfully connects to the RSU at time slot t and the set of all the probabilities, respectively. We then have $p_t = 1/n_t$, where $p_t \in \mathbb{P}$.

According to [26], the state of vehicle i at time slot t can be presented by a two-dimensional Markov-chain $\{s_t, p_t\}$. s_t denotes the current size of the content to download/upload. The one-step transition probability from time slot t to $t+1$ is given by

$$\begin{aligned} p(s_{t+1}, p_{t+1}|s_t, p_t) &= p(s_{t+1}|s_t, p_t)p(p_{t+1}|p_t) \\ &= p(s_{t+1}|s_t, 1/n_t)p(1/n_{t+1}|1/n_t) \\ &= p(s_{t+1}|s_t, n_t)p(n_{t+1}|n_t). \end{aligned} \quad (30)$$

In each time slot of each RSU, the vehicle has the right to decide whether to connect with the RSU and download/upload content. However, if the content is not complete after the vehicle has arrived at the destination, the utility of the vehicle will be reduced. Therefore, we define a penalty function to incentive vehicle i as

$$\mathcal{C}_{i,\overline{T}_i+1}^{\text{penalty}} = \begin{cases} Q_i^{\text{penalty}} s, & s > 0, \\ 0, & \text{otherwise}, \end{cases} \quad (31)$$

where Q_i^{penalty} is the regulatory factor. Based on (31), the total utility of vehicle i when arriving at the destination can be expressed as

$$\mathcal{U}_i^{\text{total}} = \sum_{t=1}^{\overline{T}_i} \mathcal{U}_{i,t}(\mathcal{C}_{i,t}^*, b_{-i,t}, \psi) - \mathcal{C}_{i,\overline{T}_i+1}^{\text{penalty}} + \Upsilon, \quad (32)$$

where Υ is a positive integer.

When driving from the source to the destination, vehicle i will go through m RSUs. An optimal decision policy which can bring the highest utility to vehicle i needs to be found as different policies may bring different utilities to the vehicle. Let $\prod$ denote the set of all the policies that vehicle i may adopt from the source to the destination. $\mathcal{U}_{i,\pi}^{\text{total}}$ is denoted as the utility of vehicle i when policy π is adopted, where $\pi \in \prod$ is a randomized policy. In order to find the optimal decision policy $\pi^* = \{a_1^*, a_2^*, ..., a_{\overline{T}_i}^*\}$ when vehicle i goes through the $\overline{T}_i$ time slots to maximize the utility, the problem is formulated as

$$\mathcal{U}_{i,\pi^*}^{\text{total}} = \max_{\pi \in \prod} E\left\{\mathcal{U}_{i,\pi}^{\text{total}}\right\}. \quad (33)$$

Let $\mathcal{L}_{i,t}(s_t, p_t)$ denote the highest expected utility of vehicle i from time slot t to the destination. Based on [41], the optimal equation can be represented by

$$\begin{aligned} \mathcal{L}_{i,t}(s_t, p_t|a) = \max_{a \in \mathbb{A}} \Bigg\{ & \mathcal{U}_{i,t}(s_t, p_t) \\ & + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \Bigg\}. \end{aligned} \quad (34)$$

The right side of (34) means the utility of the current time slot t and the expected future utility in the remaining time slots. The boundary condition of (34) is the penalty function which is defined by (31), *i.e.*,

$$\mathcal{L}_{i,\overline{T}_i+1}(s_{\overline{T}_i+1}, p_{\overline{T}_i+1}) = \mathcal{C}_{i,\overline{T}_i+1}^{\text{penalty}}. \quad (35)$$

According to the value of a, the highest expected utility from time slot t to the destination can be divided into three cases:

Case 1: a=1, n>1

$$\begin{aligned} \mathcal{L}_{i,t}(s_t, p_t|a=1) &= \mathcal{U}_{i,t}(s_t, p_t|a=1) \\ &\quad + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \left((\mathcal{C}_{i,t}^* - b_{w,t}^* - \psi)p_t - \psi(1-p_t)\right) \\ &\quad + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \left((\mathcal{C}_{i,t}^* - b_{w,t}^* - \psi)p_t - \psi(1-p_t)\right) \\ &\quad + \sum_{n_{t+1}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, n_{t+1})|(s_t, n_t))\mathcal{L}_{i,t+1}(s_{t+1}, n_{t+1}). \end{aligned} \quad (36)$$

Case 2: a=1, n=1

$$\begin{aligned} \mathcal{L}_{i,t}(s_t, p_t|a=1) &= \mathcal{U}_{i,t}(s_t, p_t|a=1) \\ &\quad + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \left(\left(\mathcal{C}_{i,t}^* - \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} - \psi\right)p_t - \psi(1-p_t)\right) \\ &\quad + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \left(\left(\mathcal{C}_{i,t}^* - \sum_{x=1}^{3} \varepsilon_x \mathcal{C}_{i,t}^{r_x} - \psi\right)p_t - \psi(1-p_t)\right) \\ &\quad + \sum_{n_{t+1}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, n_{t+1})|(s_t, n_t))\mathcal{L}_{i,t+1}(s_{t+1}, n_{t+1}). \end{aligned} \quad (37)$$

Case 3: a=0

$$\begin{aligned} \mathcal{L}_{i,t}(s_t, p_t|a=0) &= \mathcal{U}_{i,t}(s_t, p_t|a=0) \\ &\quad + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t))\mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \\ &= \sum_{n_{t+1}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, n_{t+1})|(s_t, n_t))\mathcal{L}_{i,t+1}(s_{t+1}, n_{t+1}). \end{aligned} \quad (38)$$

The optimal policy π^* which can bring the highest utility to vehicle i can be obtained by using backward induction method to solve (34). In particular, the vehicle can get each $a_t^* \in \pi^*$ based on $\mathcal{L}_{i,t}(s_t, p_t)$, shown as,

$$a_t^* = \begin{cases} 1, & \mathcal{L}_{i,t}(s_t, p_t|a=1) > \mathcal{L}_{i,t}(s_t, p_t|a=0), \\ 0, & \text{otherwise}. \end{cases} \quad (39)$$

As shown in Algorithm 2, by using backward induction to recursively evaluate the expected utility from time slot $\overline{T}_i + 1$ to time

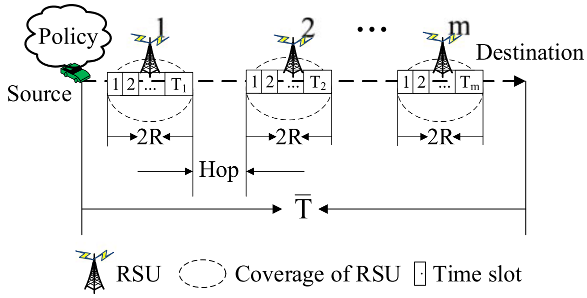

Fig. 4. The optimal policy of vehicle i.

slot 1, vehicle i can get the optimal policy $\pi^* = \{a_1^*, a_2^*, ..., a_{\overline{T}_i}^*\}$ in advance. As a result, vehicle i can achieve the highest utility by doing as follows: 1) get the optimal policy before the trip starts as shown in Fig. 4; and 2) follow the decisions of the optimal policy π^* to bid for connecting with RSUs.

Theorem 2: The policy π^*, which is obtained by Algorithm 2, is an optimal policy of the optimality equation (34) if the state space $\mathbb{S}$ is countable and the set of actions of vehicles $\mathbb{A}$ is finite for each $s \in \mathbb{S}$.

Proof: As $\mathbb{A}$ is finite of each time slot, there will be at least one action, denoted as a^*, $a^* \in \mathbb{A}$, which maximizes the right side of formula (34). In other words, for every $s \in \mathbb{S}$ and every time slot, there exists an action $a^* \in \mathbb{A}$ where

$$\mathcal{L}_{i,t}(s_t, p_t|a^*) = \sup_{a \in \mathbb{A}} \Bigg\{ \mathcal{U}_{i,t}(s_t, p_t) + \sum_{p_{t+1} \in \mathbb{P}} \sum_{s_{t+1} \in \mathbb{S}} p((s_{t+1}, p_{t+1})|(s_t, p_t)) \mathcal{L}_{i,t+1}(s_{t+1}, p_{t+1}) \Bigg\}. \tag{40}$$

Therefore, we have the optimal action a^* for each time slot shown as

$$a^* = \arg\max_{a \in \mathbb{A}} \mathcal{L}_{i,t}(s_t, p_t|a). \tag{41}$$

According to the principle of optimality [42], it implies that an optimal policy from time slot 1 to $\overline{T}_i$ is also optimal when the time slot from t to $\overline{T}_i$. We then can obtain the policy $\pi^* = \{a_1^*, a_2^*, ..., a_{\overline{T}_i}^*\}$ by using backward induction to recursively evaluate the expected utility of vehicle i from time slot $\overline{T}_i$+1 to time slot 1. The theorem is proved.

Algorithm 2: The Optimal Policy for Vehicles.

Initialization: Given the traffic parameters in urban area
Given the penalty function using (31)
Calculate the total time slots from the source to the destination using formula (6): $\overline{T}_i$
while $\overline{T}_i > 0$ **do**
  if vehicle i entering the coverage of an RSU, **then**
    $t = T_{i,m}$
    while $t > 0$ **do**
      Calculate a_t^* using (39)
      $t = t - 1$
      Update the state of vehicles in the coverage of RSU
    end while
    $\overline{T}_i = \overline{T}_i - T_{i,m} - o_{i,m-1}$
    $m = m - 1$
  end if
end while
Output: Optimal policy π^*
for $t = 1; t \leq \overline{T}_i$ **do**
  while $s > 0$ **do**
    if $\pi^*(t) = 1$ **then**
      Take part in the game and send a request content to the RSU
      if vehicle i wins the game, **then**
        Calculate s using (29)
      end if
    end if
  end while
  $t = t + 1$
end for

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Zone number	[1,2,3,4,5,6,7,8,9]
Transmission rate of each zone	[1,2,5,7,11,7,5,2,1]Mbps
R	100 m
$v_{\max}$	110 km/h
Δt	0.02 sec
$\rho_{\max}$	150 veh/km
ψ	0.1
Υ	200
m	[1,2,3]
ϖ	0.5
F_N	100
$b_{\max}$	10

V. Simulation Results

A. Simulation Setup

We study the performance of the proposal using simulations operated on Matlab. Our simulations are carried out based on the scenario as follows. There are 10 RSUs randomly deployed on a two-dimensional map along the roads. Based on different densities, the initial number of vehicles in the coverage of each RSU is randomly selected from the set $\{6, 10, 14, 18, 22\}$. The coverage diameter of each RSU is set to be 200 m and is divided into 9 zones as shown in Table II [13], [31]. Vehicles within the coverage of an RSU join in the auction game and bid for the time slot to make connection with the RSU. The traffic density on roads is different which finally leads to diverse vehicle velocities traversing the RSUs. In the coverage of an RSU, the velocity of vehicles is equal. At the initial time of the simulation (*i.e.*, $t = 1$), vehicles are randomly distributed in different zones. The value y of each vehicle is randomly selected from $\{0, 1\}$. We evaluate the performance of our proposal in two cases: 1) with a single RSU (*i.e.*, vehicle i goes through the coverage of RSU j);

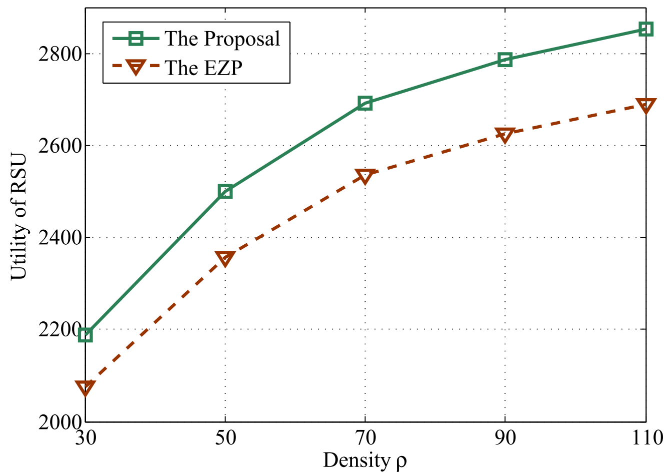

Fig. 5. Utility of RSU with different ρ.

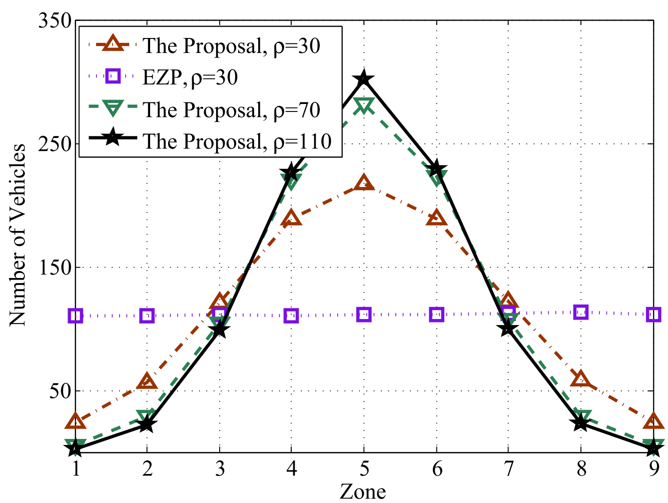

Fig. 6. The number of vehicles served in each zone.

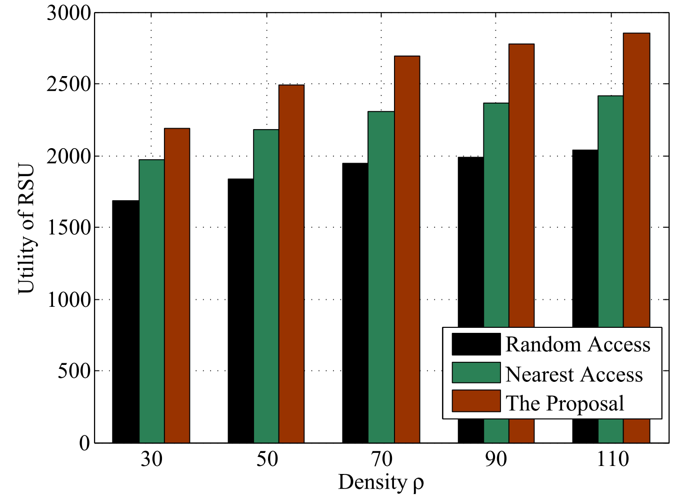

Fig. 7. Utility of RSU with different access schemes.

and 2) with multiple RSUs (*i.e.*, vehicle i drives from the source to the destination). Parameters used in simulation are given in Table II [43]–[45].

B. Simulation Results

In the first experiment, we study the utility of an RSU by comparing with the equal zone price (EZP) scheme. Here, in EZP each zone shares the same price.

As shown in Fig. 5, the utility of the RSU gradually increases with the increase of ρ. The reason is two-fold. First, the increasing number of vehicles intensifies the competition among vehicles which improves the utility of RSU. Second, the probability that vehicles have higher urgency in the middle zone may increase due to the higher road density. Furthermore, it can be shown that our proposal outperforms the EZP and brings a higher utility to the RSU by taking the different prices of zones into consideration.

Fig. 6 shows the number of vehicles served by the RSU in each zone. It can be seen that when using the EZP, the number of vehicles served by the RSU is almost evenly distribution. Different from the EZP, our proposal shows a normal like distribution. In particular, the vehicle in the middle zone where the transmission rate is high will more likely to be selected to get the time slot. Moreover, when the density of vehicles increases, the number of vehicles served in the middle zone also increases, for which the probability that more urgent vehicles are in the coverage of the RSU including the middle zone becomes higher.

Secondly, we evaluate the utility of an RSU with different density of vehicles by comparing our proposal with other access schemes (*i.e.*, the random access and the nearest access). As shown in Fig. 7, when the RSU uses the random access scheme, each vehicle will have the same opportunity to obtain the current time slot. Particularly, the vehicle which is in the farthest zone and has the lowest urgency will get the same chance to communicate with the RSU. It does not only reduce the utility of the RSU, but also reduces the throughput of the vehicular networks. When the RSU uses the nearest access scheme, the urgency of vehicles, however, is ignored. On the contrary, our proposal is in an adaptive manner, which can result in the highest utility to the RSU no matter the vehicle density is low or high, by considering both the different transmission rates in the coverage of RSU and the various urgency of demand of vehicles.

Thirdly, we carry out simulation experiments to compare the performance in terms of the utility of vehicles and transmission ratio by comparing our scheme with the greedy scheme and the r Rounds Backoff (rRB) scheme. Here, the rRB scheme means that a vehicle sends a request every r rounds, where r is randomly selected from [0, 3]. In the greedy scheme, a vehicle sends a request to join in the auction until the content is finished. In particular, we adopt different urgent degree functions to evaluate the utility of the tagged vehicle. For convenience of description and discussion, the four urgent degree functions are denoted by $F1$, $F2$, $F3$ and $F4$, respectively.

In terms of vehicle, both the $F1$ and $F2$ can lead to the higher utility when the proposal is employed as shown in Fig. 8. This is because when the vehicle density increases, the competition among vehicles will be keener. The greedy scheme makes the

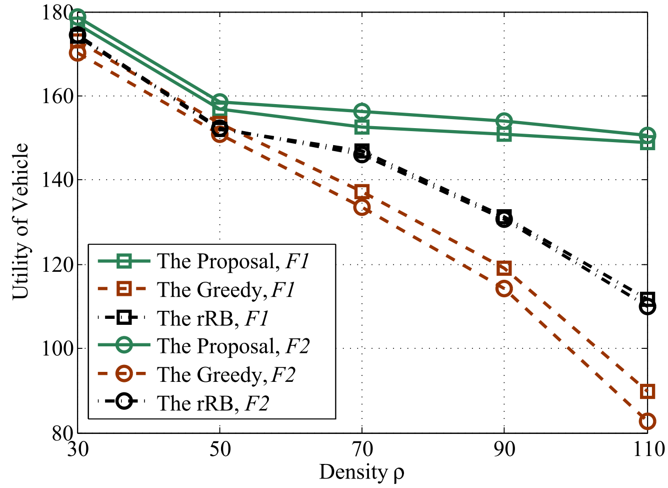

Fig. 8. Utility of vehicle by using $F1$ and $F2$.

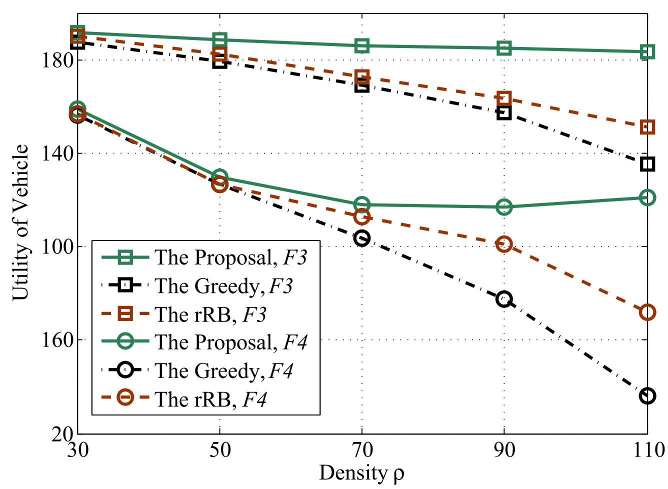

Fig. 9. Utility of vehicle by using $F3$ and $F4$.

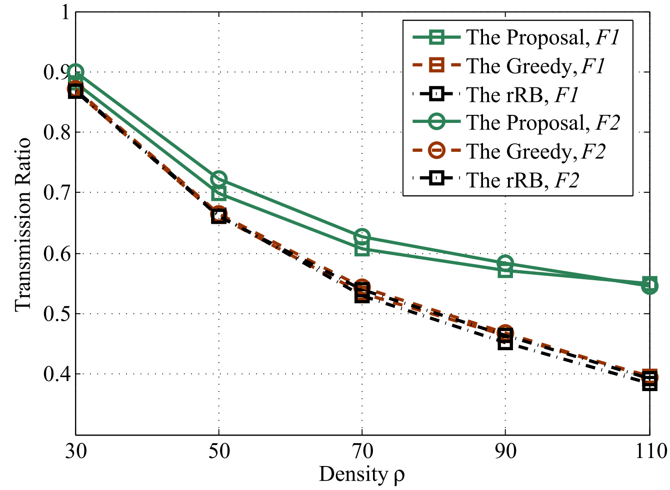

Fig. 10. Transmission ratio by using $F1$ and $F2$.

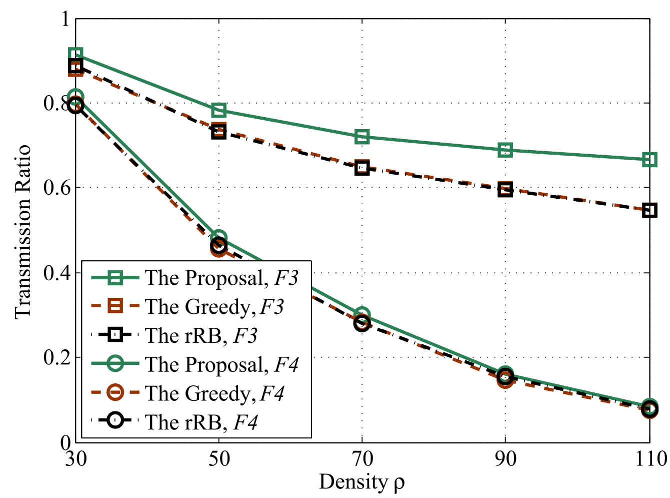

Fig. 11. Transmission ratio by using $F3$ and $F4$.

vehicle send requests to the RSU all the time if the content is not completed even there are many vehicles competing for the time slot. As for the rRB scheme, the competition among vehicles is ignored. In contrast, by following the decisions of the optimal policy, the vehicle can give the best response to make decisions. Specifically, when the number of vehicles is small and the transmission rate is high, vehicle will send the request to be involved in the game. However, when the density of vehicles is higher and the transmission rate is lower, vehicle will give up. By doing so, the proposal can still bring high utility to vehicle no matter the urgent degree function is $F1$ or $F2$.

Fig. 9 shows the utility of vehicle by using $F3$ and $F4$, respectively. With the adoption of $F3$, a higher utility than other functions can be obtained. Compared with the greedy scheme and the rRB scheme, the proposal leads to a higher utility as vehicle only sends requests in the high transmission rate zones, where both the urgency and the zone prices are high. As a result, vehicle will be more likely to successfully connect with the RSU. In Fig. 9 the greedy scheme obtains the lowest utility when the urgent degree function is $F4$ as the initial urgency to connect with the RSU is high while the zone price is low. When vehicle is in the middle zone, although the zone price is high, the urgency is low. In the greedy scheme, requests are always sent to the RSU even when the probability of successful connect with the RSU is low. While the proposal can still keep the high utility due to the requests to the RSU are not sent any more when the bad transmission condition is noticed.

Next, we study the transmission ratio (*i.e.*, total transmitted content size/total payment to the RSU) of vehicle. As shown in Figs. 10 and 11, with four different urgent degree functions, the proposal can keep a higher transmission ratio than that of the greedy scheme and the rRB scheme. Moreover, with the increase of the vehicle density, the transmission ratios of the three schemes decrease. In Fig. 10, due to the zone prices are symmetrically distributed, the transmission ratios of vehicle for the three schemes are almost the same even with the different urgent degree functions (*i.e.*, $F1$ and $F2$). In Fig. 11, with the adoption of $F3$, the highest transmission ratio can be obtained in the three schemes compared with other urgent degree functions. In contrast, the three schemes obtain the lowest transmission ratio when the urgent degree function is $F4$.

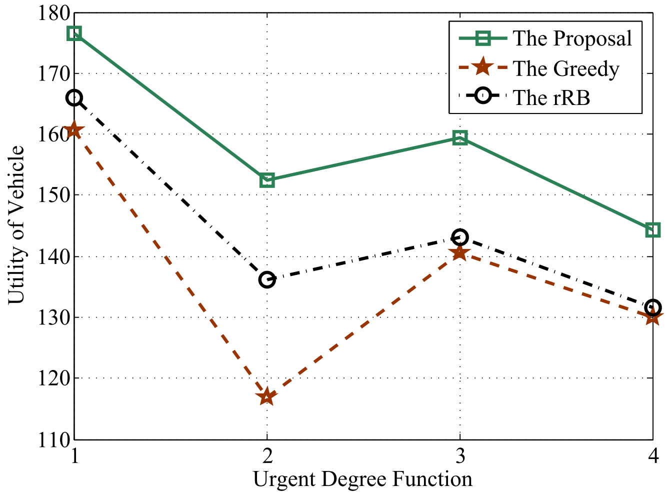

Fig. 12. Utility of vehicle with multiple RSUs.

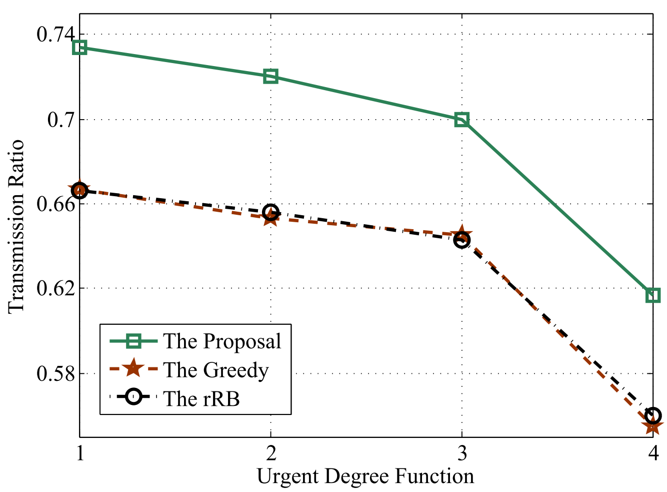

Fig. 13. Transmission ratio with multiple RSUs.

Finally, we study the utility and transmission ratio of the tagged vehicle going through multiple RSUs, where the density of each RSU is randomly selected from $\{30, 50, 70, 90, 110\}$ veh/Km. Note that the vehicle's urgency of demand changes no matter vehicle is inside or outside the coverage of any RSU. The distance between the two coverage of RSUs follows the uniform distribution in the range of [100, 350] m. Here, we continue to consider the utility and transmission ratio of vehicle with the four urgent degree functions. In Fig. 12, we can see that the utility of vehicle keeps higher than that in the greedy scheme and the rRB scheme when the optimal policy is used. The reason for this is that the greedy scheme always sends requests until the content is completed or out of the coverage of all RSUs. And the rRB scheme does not pay attention to the reserve price charged by the RSU and its private price. In contrast, the proposal makes an optimal policy in advance. When entering in the coverage of each RSU, the vehicle sends requests based on the policy to achieve the highest utility. Fig. 13 plots the transmission ratio when vehicle goes through multiple RSUs, where the transmission ratio of the proposal is higher than that of the other two schemes. This is because that both the greedy scheme and the rRB scheme do not take the cost and the number of competitive vehicles into consideration. While the proposal is more realistic, which aims to make optimal decisions and participate in the auction game by evaluating the transmission condition.

VI. Conclusion

In this paper, we have proposed a game theoretic access framework for urban vehicular networks. To enable vehicles and RSUs to achieve the highest utility, we model the V2I connection process as a second-price sealed-bid auction and optimize the network from both RSU and vehicles perspective. For RSUs, an adaptive reserve price scheme is designed which allows RSUs to selectively provide connections to vehicles according to the bids of vehicles. By doing this, RSUs can obtain the optimal utility on a Bayesian Nash equilibrium of the auction. From the perspective of vehicles, a finite-horizon Markov decision process is developed to guide vehicles to optimally select RSUs to connect, where vehicles can achieve the highest utility by using the back induction method to solve the decision problem. Simulation results have proved that the auction scheme can obtain the highest utility to RSUs compared with other schemes. Furthermore, with different urgent degree functions, the framework can keep a higher utility and transmission ratio than the conventional schemes with a single RSU or multiple RSUs for vehicles.

About the future work, we plan to extend the proposal by considering the content delivery applications over the drive-thru Internet, which is fundamental to traffic-related applications, *e.g.*, road report, carpool advertising. From the perspective of RSUs, we will study the content dispatch among RSUs by considering the features of the content. From the perspective of vehicles, the content sharing based on the cooperation among V2V will be studied.

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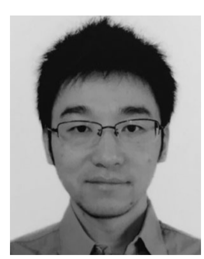

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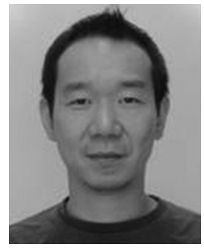

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