Opportunistic WiFi Offloading in Vehicular Environment: A Game-Theory Approach

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***Abstract*—In this paper, we study opportunistic traffic offloading in a vehicular environment, where the cellular traffic of vehicular users (VUs) is offloaded through carrier-WiFi networks deployed by the mobile network operator (MNO). By jointly considering users' satisfaction, the offloading performance, and the MNO's revenue, two WiFi offloading mechanisms are proposed: auction game-based offloading (AGO) and congestion game-based offloading (CGO). Moreover, we introduce an approach to predict WiFi offloading potential and access cost and incorporate it in the offloading mechanisms. Specifically, with the AGO mechanism, the MNO employs auctions to sell WiFi access opportunities; VUs decide whether to bid according to their utilities and are capable of using WiFi if the auction is won. With the CGO mechanism, a VU calculates utility considering other VUs' strategies and makes offloading decisions accordingly. We show that the AGO mechanism can maximize social welfare and increase the MNO's revenue, whereas the CGO mechanism can achieve a better performance of average VU utility and fairness. Additionally, both AGO and CGO mechanisms can improve the overall WiFi offloading performance. Through simulations, we demonstrate that both AGO and CGO mechanisms can achieve higher average utility of VUs and lower average service delay and offload much more cellular traffic compared with existing offloading mechanisms.**

***Index Terms*—Cellular traffic offloading, vehicular communication, delay tolerant, game theory, auction theory.**

I. INTRODUCTION

THE demand for high-speed mobile Internet services has increased dramatically. A recent survey reveals that Internet access is predicted to be a standard feature of future motor vehicles [1]. Passengers in vehicle want to be connected at home or office, and may require varied Internet services such as web surfing, email, online game, audio and video streaming, among others. Not surprisingly, cellular-based access technologies, such as 3G and Long Term Evolution (LTE), play a vital role in providing reliable and ubiquitous Internet access to vehicles, as the cellular infrastructure is well planned and widely available. However, the cellular network nowadays is straining to meet the current mobile data demand, and on the other hand, the unprecedented growth of mobile data traffic is no end in sight, resulting in an increasingly severe overload problem. It is reported that the number of interconnected mobile devices will exceed 25 billion in 2020, and the global mobile data will increase by 13 times in 2017, which will exceed one hundred exabytes [2]. Therefore, simply using cellular networks for vehicular Internet access may worsen the overload problem, and degrade the service performance of both non-vehicular and vehicular users (VUs).

With millions of hotspots deployed around the world, WiFi can be a complementary cost-effective solution to vehicular Internet access [3]. The built-in WiFi radio or WiFi-enabled mobile devices on board can access the Internet when vehicles are moving in the coverage of WiFi hotspots, which is often referred to as the *drive-thru Internet* [4]. High vehicle speed and limited coverage area of WiFi hotspot are the challenging issues in vehicular WiFi offloading scenario. The connection time between a vehicle and a WiFi AP might be short, and therefore the volume of transferred data might be limited. Many research works have demonstrated the efficiency of such a short-range communication paradigm. In [4], the performance of drive-thru Internet is first investigated using IEEE 802.11b in a planed scenario. The authors showed that even with the low-rate 802.11b WiFi, the volume of content downloading could be up to 8.8 MBytes (80 kmph, UDP throughput) in one drive-thru, which is adequate for downloading a music file or a small video clip. Later on, several works studied the performance of drive-thru Internet with different WiFi technologies under varied scenarios. For example, in [5], large-scale urban experimental evaluations of the drive-thru Internet with multiple vehicles are conducted. It is shown that with mobility in urban area and IEEE 802.11g, the volume of data downloaded within one drive-thur could be 32 MBytes. One of the problems in providing WiFi access to vehicles is the authentication and association process, which takes up a considerable amount of the short connection time. The problem can be addressed by some advance WiFi technologies and recent Passpoint/Hotspot 2.0. In [5], a scheme called Quick WiFi is proposed. Through tight integration and parallelism of authentication and association steps, Quick WiFi can greatly reduce the connection establishment time from several seconds to 366 ms. Passpoint/ Hotspot 2.0 can provide WiFi with secure connectivity and seamless roaming [6]. In Hotspot 2.0, a pre-association protocol is designed to allow mobile users to obtained the information about the reachable services and service providers

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before it associates. According to the information, the mobile devices can identify suitable access points, and authenticate to a remote service provider (e.g., a mobile network operator), making it much faster than requiring authentication before learning such information. Assisted by Hotspot 2.0, pioneering mobile network operators (MNOs) have rolled out **carrier-WiFi networks** and integrated them with the cellular network. Carrier-WiFi network is a cost-effective and manageable tool for MNOs to increase the network capacity, with the support of easy access, security and roaming, guaranteed quality of service (QoS), and new business models and services. However, due to the equipment size, target venues, and the reliability requirements of carrier-WiFi networks, the deployment and maintenance cost of carrier-WiFi infrastructure is substantially higher than free and individually deployed WiFi networks. Therefore, the MNO expects to not only offload the cellular traffic through, but also profit from the carrier-WiFi network.

For stationary or slow moving users, WiFi serves as one of the primary offloading technologies [7]–[10]. By delivering data originally targeted for cellular networks by WiFi, termed *WiFi offloading*, the congestion of cellular networks can be alleviated. It has been shown that around 65% of the cellular traffic can be offloaded by merely switching from the cellular network to WiFi when the WiFi connectivity is available (*on-the-spot offloading*). Although users prefer to be served immediately, if the MNO can provide more incentives, they may be willing to delay non-real-time traffics [11], e.g., software update, file backup, down-and-play audio/video, etc. If data services can be deferred for some time (e.g., up to one hour) until WiFi connectivity becomes available, above 80% of the cellular traffic can be offloaded (*delayed offloading*) [7], [12], [13]. Obviously, the offloading performance is outstanding in stationary/low-mobility scenarios. In a vehicular environment, data offloading through WiFi is opportunistic due to limited coverage of WiFi and high mobility of vehicles. Such an opportunistic WiFi offloading has the following unique features:

- *A relatively small volume of data can be delivered to a vehicle in each drive-thru, due to the short connection time with WiFi APs.*
- *The offloading performance can be significantly improved if the data service can tolerate a certain delay, as vehicles with a high speed can have multiple drive-thru opportunities in a short future.*

A basic delayed offloading mechanism for cellular traffic offloading in the vehicular environment has been studied in [14], where VUs constantly delay their applications to wait for WiFi transmission opportunities. However, in reality, considering the satisfaction of VUs in terms of service delay, such a mechanism can hardly satisfy VUs. On the other hand, the MNO deploys the carrier-WiFi and expects to offload as much mobile data traffic as possible and increase its revenue from the carrier-WiFi network. Thus, effective and efficient offloading mechanisms are required to intelligently offload cellular traffic in the vehicular environment considering these issues, which, to the best of our knowledge, have not been well studied.

In this paper, we propose two WiFi offloading mechanisms to offload cellular traffic of VUs through carrier-WiFi networks based on game-theory approaches, jointly considering the utilities of VUs and the MNO, and the overall offloading performance. Specifically, in the auction game-based offloading (`AGO`) mechanism, periodic auctions are employed for the MNO to sell WiFi access opportunities. VUs calculate their utilities and submit bids if the utility is positive. In congestion game-based offloading (`CGO`) mechanism, WiFi access is available to all VUs. Each VU makes an offloading decision based on the strategies of other VUs and its own satisfaction function to maximize his/her own utility. In addition, a method to predict WiFi offloading potential and access cost is introduced and incorporated in the proposed offloading mechanisms to make offloading decisions efficiently.

The contributions of this paper are listed as followed:

- WiFi offloading mechanisms are proposed to offload cellular traffic in the vehicular environment, jointly considering both VUs' and the MNO's utility. With `AGO` mechanism, the MNO can obtain a high utility (revenue) due to the auction-based mechanism, while with `CGO` mechanism, VUs make offloading decisions to maximize their own utilities.
- We design the offloading mechanisms in order to improve the overall offloading performance. By reducing the number of VUs contending for the channel and prioritizing high WiFi data rates, the contention and performance anomaly problem of WiFi can be alleviated, and thus the offloading performance can be improved.
- A prediction method is developed based on Markov chain, which is crucial for intelligent offloading decision making. With the future knowledge about WiFi offloading potential and access cost, VUs can calculate the expected utilities, and make offloading decision accordingly to maximize their utilities.

Implementation of the proposed offloading mechanisms: The proposed offloading mechanisms can be installed in VUs' devices, e.g., a software installed in Android phones, as an offloading engine to automatically and intelligently offload VUs' cellular traffic. VUs may need to set their satisfaction in the first place, and after that the offloading procedure is transparent to users. Through the implementation of the offloading mechanisms, the cellular network congestion can be also mitigated, creating a win-win situation for both VUs and the MNO.

The remainder of the paper is organized as follows. Section II studies the literature of network selection and offloading mechanisms. Section III describes the system model. Sections IV and V describe the details of `AGO` and `CGO` mechanisms, respectively. Section VI investigates the prediction of WiFi offloading potential and access cost. Section VII evaluates the proposed schemes through real road map based simulation. Section VIII concludes the paper.

II. Related Work

To deal with the unprecedented growth of mobile data challenges, heterogeneous access networks and technologies, e.g., cellular, WiFi, small cells, should be efficiently utilized. A mobile terminal equipped with multi-interface can access multiple networks. Therefore, selecting a desired access network is crucial for optimizing both user experience and network performance. Intelligent network selection strategies (NSSs) have been well studied in the literature [15], [16]. Most NSSs utilize multiple attribute decision-making (MADM) theory, in which attributes may include QoS and quality of experience (QoE), network and node conditions, service cost, user preference, etc. In [15], a cost-function-based NSS is proposed focusing on system performance, and satisfying a user's needs as well. The cost function of a user access network i is defined as $C_i = \omega_g G_i + \omega_s S_i + \omega_\phi \Phi_i$, where G_i, S_i and Φ_i indicate traffic load, signal strength, and access fee, respectively. Game-theory approaches have been widely used in the study of network selection to provide distributed, dynamic and automatic network selection decisions. In [16], the network selection problem in heterogeneous wireless networks is formulated as a Bayesian game. Each user makes decision given the incomplete information of other users' preference. The Bayesian best response dynamics and aggregate best response dynamics are used to study the dynamics of the network selection. It is shown that Bayesian Nash equilibrium can be reached with incomplete information.

Cellular traffic offloading mechanisms have been investigated in [11] and [17]. Motivated by the fact that WiFi radio wastes a lot of energy in scanning transmission opportunities and remaining idle, a prediction-based offloading scheme is proposed in [17] to save energy of user devices. The MNO collects its subscribers' user mobility profiles (UMPs) and deploys WiFi APs in the places which are mostly visited. The location information of APs and the UMP is sent to the users so that they can predict WiFi availability and turn on the WiFi radio only when the WiFi access is predicted to be available. In [11], an incentive framework to motivate users to offload their cellular traffics is proposed. A reverse auction is employed where users submit bids to the MNO due to their delay tolerance, and the MNO buy the delay tolerance from different users to achieve its offloading target. To minimize the incentive cost given to users, users with large offloading potential and delay tolerance are preferred. The aim is for the MNO to offload targeted traffic with minimal cost. However, these offloading schemes are designed for fixed users or in low mobility environment. Differently, in vehicular environment, the features of short WiFi connection time and multiple WiFi access opportunities in a short duration should be considered. In this paper, we proposed WiFi offloading mechanisms for VUs to maximize their utilities.

III. System Model

In this section, we present the system model. The communication model describes the communication details of cellular and WiFi network, the mobility model captures the mobility characteristics of VUs, and the application model shows the features of applications of VUs. A system diagram of the main functions of each sub-model is shown in Fig. 1. A summary of the mathematical notations is given in Table I.

A. Communication Model

VUs can transmit data and fulfill their data services through the always-on cellular networks or the opportunistic WiFi transmission. These two access options have different features, such as coverage, data rate, price, etc. We consider that the cellular network provides seamless coverage to the whole urban area. The channel spectral efficiency is denoted by θ (bits/s/Hz), which is considered to be uniformly distributed in the range $[\theta_{\min}, \theta_{\max}]$ [18]. A VU is allocated with W bandwidth for cellular access. Thus, the data rate of cellular transmission for a VU is $r_c = \theta W$, and the expected data rate is $\bar{r_c} = \bar{\theta} W = ((\theta_{\max} - \theta_{\min})/2)W$. Additionally, the price of using cellular to transmit unit size of data is χ_c.

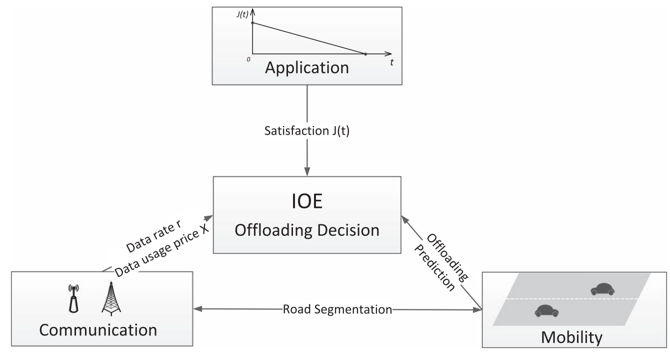

Fig. 1. An overview of the system model.

TABLE I
The Useful Notations

Symbol	Description
$\bar{r_c}$	expected cellular data rate
h_i	zone i in AP coverage
l_i	length of zone i
v	average vehicle speed
r_i^j	the instantaneous WiFi data rate of VU j in h_i
χ_c, χ_w	price of using cellular and WiFi, respectively
$J(t)$	the price that a user is willing to pay given current service delay t
U_i	the expected utility of VU i in T using AGO
T	auction interval in AGO; delaying interval in CGO
$U_i(t)$	the utility of VU i at t using CGO
$\mathbf{V}$	a set of VUs with cardinality $\vert\mathbf{V}\vert$
p_{ij}	the limiting probability of the transition from j to k
$\Upsilon_{jk}(t)$	the sojourn time distribution at state j when the next state is k
$Y_j^A(t)$	total data traffic offloaded within t given the initial state j using AGO
$Y_j^C(t)$	data traffic offloaded within t while the initial state is j using CGO
$P_j^C(t)$	WiFi access cost within t while the initial state is j using CGO

Denote χ_w the access price per unit time of the carrier-WiFi networks. Transmission rate adaption is utilized, where discrete WiFi data rates are received by vehicles depending on the distance to AP. Thus, the road within the radio coverage of an AP is divided into discrete zones h_i, $i = 1, 2, \ldots, L$, such that vehicles in each zone have distinct WiFi transmission rates which are denoted by r_i, as shown in Fig. 2. l_i denotes the lengths of each zone. Note that the WiFi network is deployed by the MNO, and thus each AP can be carefully deployed in the way that h_i and l_i are identical for all AP coverage areas. Moreover, zones outside WiFi coverage are donated by h_0 with average length l_0 and data rate $r_0 = 0$. We define the road section from h_0 to h_L as a WiFi coverage road section, which includes one complete WiFi coverage and one zone with only cellular coverage. The WiFi channel resource is shared by VUs in a contention-based manner. The instantaneous WiFi data rate of VU j in h_i can be calculated by

$$r_i^j = \frac{\rho r_i \xi(n)}{n} \tag{1}$$

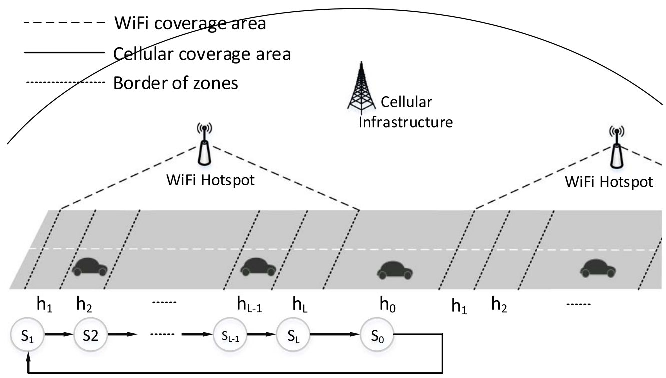

Fig. 2. System model.

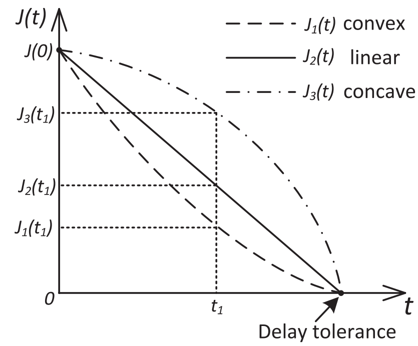

Fig. 3. Satisfaction function.

where ρ, n and $\xi(n)$ are WiFi throughput efficiency factor, the number of VUs communicating with the same AP simultaneously, and the WiFi channel utilization function, respectively. ρ is to account for the protocol and header overhead of MAC due to protocol layering, such as DIFS, SIFS, ACK and headers. For example, it is shown that for IEEE 802.11b 11 Mbps data rate, the maximum theoretical throughput is 5 Mbps ($\rho = 5/11$) [19]. $\xi(n)$ is a decreasing function with n, which accounts for the impact of contention on WiFi throughput performance in terms of the number of contending users. Such performance degradation due to contention has been extensively studied in the literature, e.g., in both RTS/CTS scenarios [20] and non-RTS/CTS scenarios [21].

B. Mobility Model

As the vehicle moves along the road, a VU sequentially passes zones $h_i, i = 0, 1, 2, \ldots, L$. Inspired by Luan *et al.* [22], we model the mobility of VUs as a continuous-time Markov chain (CTMC) $X(t)$, which describes the location (zone) of a VU at t. The discrete state space of $X(t)$ is $\mathbf{S} = \{S_0, S_1, S_2, \ldots, S_L\}$, where S_i corresponds to zones h_i. Since WiFi coverage areas are non-overlapping, $X(t)$ is a one-directional Markov chain, as shown in Fig. 2. The transition rates depend on the lengths l_i and the average vehicle speed v. The transition rates b_{ij} of $X(t)$ are thus given by

$$b_{ij} = \begin{cases} b_i, & j = i+1, \text{or } i = L,\ j = 0 \\ 0, & \text{otherwise} \end{cases}$$

where $b_i = v/l_i, i = 0, 1, 2, \ldots, L$ [22].

A relation between vehicle speed and density along the road is employed based on observations in [23]. Let v_i, v_f, k, and k_{jam} be the speed of VU i, the free-flow vehicle speed (often taken as speed limit of the road), vehicle density along the road, and vehicle jam density, respectively. Then, a relation can be given by $v_i = v_f(1 - (k/k_{\text{jam}}))$. Thus, if v_i, v_f and k_{jam} are given, we can estimate the number of vehicles within the coverage area of a WiFi AP as

$$n \approx k \sum_{j=1}^{L} l_j = \left(1 - \frac{v_i}{v_f}\right) k_{\text{jam}} \sum_{j=1}^{L} l_j \tag{2}$$

where $\sum_{j=1}^{L} l_j$ is the length of the road section covered by the AP.

C. Application Model

The proposed offloading mechanisms aim to intelligently offload cellular traffic considering the satisfaction of VUs. If delayed offloading strategy is considered, more traffic can be offloaded. However, the QoS of VUs is degraded with larger delay, and it is difficult to quantify the degree of QoS degradation. In this paper, we employ a satisfaction function to describe the QoS degradation in terms of delay [11]. The satisfaction function $J(t)$ reflects the price that the user is willing to pay for an application with delay t, which is a monotonously decreasing function of t, as shown in Fig. 3. Note that $J(t)$ varies with different VUs and applications, and is kept secret to VUs themselves. For an arbitrary VU i, when $t = 0$, the application is transmitted totally through cellular network immediately when it is requested, and thus $J_i(0) = \chi_c \mathcal{S}_i$, where $\mathcal{S}_i$ is the size of the application. If an application is delayed by t, VU i is willing to pay at most $J_i(t)$ for the application, i.e., the WiFi offloading within t should save at least $J_i(0) - J_i(t)$, otherwise VU i is not willing to delay the application.

D. Interworking Between WiFi and Cellular Networks

As mentioned above, the carrier-WiFi networks are deployed by MNOs who also operate the cellular networks, and therefore it is considered that the carrier-WiFi networks and the cellular networks can interwork with each other. Through Hotspot 2.0, with pre-association and remote authentication to the MNO, the association and authentication time of accessing WiFi APs can be greatly reduced. Moreover, recent works have also been done to reduce such times to improve the efficiency of drive-thru Internet. For example, QuickWiFi can speed up the WiFi connection establishment with mean time of 366 ms [5]. Consequently, we make a reasonable assumption that the VUs can seamlessly roam among carrier-WiFi networks and cellular networks.

In addition, we consider that an intelligent offloading engine (IOE) is installed in cellular base stations, which is responsible for exchanging information with VUs through both WiFi and cellular transmission, and is capable of assisting VUs to make offloading decisions.

IV. Auction Game Based Offloading Mechanism

In this section, we propose AGO mechanism in which the MNO sells WiFi access opportunity to VUs through auctions.

AGO mechanism is based on the auction theory, which is an applied branch of game theory [24]. An auction is a distributed mechanism to allocate resource, where there are one or more auctioneers and bidders. Generally in an auction, the auctioneer announces a price for selling the resources, and the bidders report their demands to the auctioneer. Then, the auctioneer adjusts the price until the total demand meets the supply. The basic idea of AGO mechanism is that the MNO conducts periodic auctions for each WiFi coverage road section to sell the WiFi access opportunities to VUs, in the way that in each auction there is only one VU winning; VUs calculate utilities according to satisfaction function and the prediction of WiFi offloading potentials, and decide whether to bid. VUs winning the auctions can use WiFi. The auction is repeated every time T which is called auction interval and can be adjusted to adapt to the dynamic vehicular environment. Auctions often introduce extra delay due to the auction procedure. However, we show that the extra delay can be neglectable in Section IV-B. Note that the procedures of the auctions for each WiFi coverage road section are identical, and thus we focus on an arbitrary auction. The set of VUs who participate in an auction is denoted by $\mathbf{V}$.

A. Utility Functions

The utility of the MNO within T, U_o, is defined as its revenue from WiFi service in one arbitrary auction, which can be expressed by

$$U_o = T \cdot \chi_{\text{win}} \tag{3}$$

where χ_{win} is the WiFi access price when the auction concludes.

For a VU, consider that an auction begins at t_a, and the delay of the current application is t_d. Define $Z^i_{t_d}$ the total cost VU i should pay for the current application if VU i does not further delay the application. We can obtain that

$$Z^i_{t_d} = J_i(0) - \chi_c O_i(t_d) + P^i_w(t_d) \tag{4}$$

where $O_i(t_d)$ is the volume of data traffic already offloaded through WiFi, and $P^i_w(t_d)$ is the cost already paid to use WiFi. Given χ_w, the set of available strategies of each VU is $\mathbb{G} = \{\mathfrak{g}_0, \mathfrak{g}_1\}$, where $\mathfrak{g}_1$ indicates that the VU determines to bid at χ_w, and $\mathfrak{g}_0$ otherwise. Thus, the expected utility of VU i in T can be expressed by

$$U_i = \delta_i \left(\chi_c \min\left(Y^i_{t_a,T}, \mathcal{S}^i_l\right) - \chi_w T - \dot{J}_i(t_d, T) - \kappa_i\right) \tag{5}$$

where δ_i is an indicator of VU i's strategy, i.e., $\delta_i = 1$ if $\mathfrak{g}_1$, and $\delta_i = 0$ otherwise. $Y^i_{t_a,T}$ is the predicted WiFi offloading potential, i.e., the volume of data that can be offloaded from t_a to $t_a + T$, which is discussed in Section VI. $\mathcal{S}^i_l$ is the remaining data volume of the current application of VU i. Thus, $\min(Y^i_{t_a,T}, \mathcal{S}^i_l)$ represents the expected volume of data that can be transmitted through WiFi during $[t_a, t_a + T]$. $\dot{J}(t_d, T) = \max(Z^i_{t_d} - J_i(t_d + T), J_i(t_d) - J_i(t_d + T))$ denotes the least amount of cost VU i needs to save if the application is delayed from t_a to $t_a + T$. κ_i is a positive value to compensate the error in the prediction.

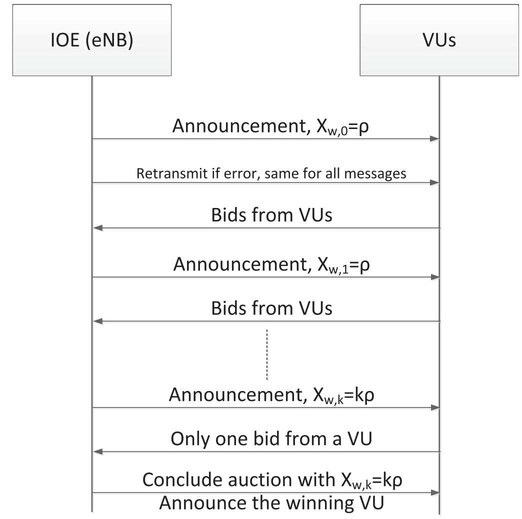

Fig. 4. AGO signaling.

Given χ_w, VU i bids to use WiFi if its utility is positive, and vice versa. From (5), we can calculate the maximum WiFi price $\chi^i_{w,m}$ at which VU i can bid by

$$\chi^i_{w,m} = \frac{\chi_c \min\left(Y^i_{t_a,T}, \mathcal{S}^i_l\right) - \dot{J}_i(t_d, T) - \kappa_i}{T}. \tag{6}$$

B. AGO Mechanism Design

Algorithm 1 shows the proposed AGO mechanism, which is based on the single object ascending clock auction, and WiFi resource is sold as a single object. Fig. 4 shows the interactions among the IOE and VUs.

Algorithm 1 AGO mechanism

1: // **Initialization**: Given step size $\varrho > 0$, and auction start time t_a, the IOE initializes the auction with clock index $k = 0$ and $\chi_{w,k} = 0$. The IOE announces $\chi_{w,k}$ to VUs.

2: VUs calculates their maximum prices to bid $\chi^i_{w,m}$ using (6). If $\chi_{w,k} < \chi^i_{w,m}$, VU i chooses $\mathfrak{g}_1$ and submits his bid. Otherwise, VU i chooses $\mathfrak{g}_0$.

3: If exactly one VU (e.g., VU i) submits his bid, the MNO concludes the auction, and announces VU i to use WiFi. Otherwise, set $\chi_{w,k+1} = \chi_{w,k} + \varrho$, $k = k + 1$, and repeat

- The IOE announces $\chi_{w,k}$ to all VUs
- Each VU compares $\chi_{w,k}$ and $\chi^i_{w,m}$. If $\chi_{w,k} < \chi^i_{w,m}$, VU i chooses $\mathfrak{g}_1$ and submits his bid. Otherwise, VU i chooses $\mathfrak{g}_0$.
- If exactly one VU (e.g., VU i) submits his bid, the MNO concludes the auction, and announces VU i to use WiFi. Otherwise, set $\chi_{w,k} = \chi_{w,k} + \varrho$, $k = k + 1$, and repeat the auction.

4: When the auction is concluded, VU j who wins the auction can achieve expected utility $U_j = \chi_c \min(Y^j_{t_a,T}, \mathcal{S}^j_l) - \chi_{w,k} T - \dot{J}_j(t_d, T) - \kappa_j$.

5: **return**

From Algorithm 1, IOE first sets up the step size $\varrho > 0$, and initializes the auction with $\chi_w = 0$. Each VU calculates the maximum WiFi price to bid using (6) at the auction start time t_a, and decides whether to bid. The auction repeats with $\chi_w = \chi_w + \varrho$ until only one VU bids. VU i can use WiFi if wins the auction, and other VUs fulfill their applications through the cellular network, until the subsequent auction starts.

C. Discussion

1) The *Overall Offloading Performance* is defined as the total amount of cellular traffic offloaded during a certain time. The MNO expects the overall offloading performance of the carrier-WiFi network as high as possible, in order to mitigate the congestion in the cellular network. However, several issues may degrade the performance of WiFi offloading, such as protocol overhead, performance anomaly [25], etc. One of the most important issues is contention, as discussed in Section III-A. AGO mechanism aims to improve the overall offloading performance of WiFi by mitigating the contention. Through auctions, only VUs winning the auctions can use WiFi, and thus the number of VUs contending for the channel is greatly reduced. Therefore, the WiFi offloading performance can be improved since $\xi(n)$ is a decreasing function. Additionally, it is possible that due to vehicle mobility, there is no winning VU in some WiFi coverage areas, under which circumstance the MNO can make such APs temporally available, e.g., for the VU who bided the second highest price, or for all VUs to access, in order to avoid waste of communication resources.

2) *Maximizing Social Welfare*. Social welfare (SW) is defined as the sum of the MNO's and VUs' utilities. We prove that AGO mechanism can maximize the social welfare under some conditions.

Theorem 1: If for each VU $j \in \mathbf{V}$, $\min(Y^j_{t_a,T}, \mathcal{S}^j_l) = Y^j_{t_a,T}$, AGO mechanism can maximize the social welfare, i.e., the outcome of the auction, VU i paying χ_w to use WiFi, is the solution to the following optimization problem:

$$\max_{\delta_i \forall i} \mathrm{SW} = \sum_{i\in\mathbf{V}} \delta_i \left(\chi_c \min\left(Y^i_{t_a,T}, \mathcal{S}^i_l\right) - \dot{J}_i(t_d, T) - \kappa_i\right). \quad (7)$$

Proof: Consider that with AGO mechanism, VU i wins the auction, and the social welfare is $\mathrm{SW}_1 = \chi_c Y^i_{t_a,T} - \dot{J}_i(t_a - t_s, T) - \kappa_i$. From (6), since VU i wins the auction,

$$\chi^i_{w,m} \geq \chi^j_{w,m}, \quad \forall j \neq i. \quad (8)$$

Thus, we have

$$\begin{aligned}\mathrm{SW}_1 &= \chi_c Y^i_{t_a,T} - \dot{J}_i(t_d, T) - \kappa_i \\ &\geq \chi_c Y^j_{t_a,T} - \dot{J}_j(t_d, T) - \kappa_j, \quad \forall j \neq i. \end{aligned} \quad (9)$$

For more than one VU using WiFi simultaneously, e.g., M arbitrary VUs use WiFi, $M \leq |\mathbf{V}|$ ($|\mathbf{V}|$ is the cardinality of $|\mathbf{V}|$), according to (9), the social welfare

$$\begin{aligned}\mathrm{SW} &= \sum_{j\in\mathbf{V}} \delta_j \left(\chi_c \min\left(Y^j_{t_a,T}, \mathcal{S}^j_l\right) - \dot{J}_j(t_d, T) - \kappa_i\right) \\ &= \sum_{j=1}^{M} \frac{\chi_c Y^j_{t_a,T}\xi(M)}{M} - \dot{J}_j(t_d, T) - \kappa_j \\ &< \sum_{j=1}^{M} \frac{\chi_c Y^j_{t_a,T}\xi(M) - \dot{J}_j(t_d, T) - \kappa_j}{M} \\ &\leq \sum_{j=1}^{M} \frac{\chi_c Y^i_{t_a,T} - \dot{J}_i(t_d, T) - \kappa_i}{M} \\ &= \chi_c Y^i_{t_a,T} - \dot{J}_i(t_d, T) - \kappa_i = \mathrm{SW}_1 \end{aligned} \quad (10)$$

where "$\leq$" is "$=$" if and only if $M = 1$. ■

Theorem 1 implies that when VUs have data-craving applications, AGO mechanism can maximize SW.

3) *Extra Delay*. We can see from Algorithm 1 that the extra delay introduced by the auction is the exchange of WiFi price among the IOE and VUs when an auction initializes. By properly setting ϱ, the rounds of exchanges can be controlled such that several tens of rounds are enough to conclude the auction. According to LTE-FDD standard, the transmission scheduling slot is 500 μs, and thus the whole exchange procedure may cost up to several tens of milliseconds. On the other hand, the auction interval T can be tens of seconds. In addition, the VUs who participate in the auction often have delay-tolerant services to transfer, and otherwise the VUs may use the cellular network directly. As a summary, it is considered that the extra delay introduced by auctions may have negligible impact on the performance of the offloading mechanism.

4) *Truthfulness and Individual Rationality*. AGO mechanism is based on the single object ascending clock auction, which is equivalent to the second price sealed-bid auction. In [26], the second price sealed-bid auction is proved to be truthful and individually rational. Therefore, AGO mechanism is truthful and individually rational.

V. Congestion Game Based Offloading Mechanism

AGO mechanism can maximize social welfare, improve the WiFi offloading performance and increase the MNO's revenue. However, from the perspective of users, the average utility of VUs may be low since they pay very high WiFi access price due to the auction-based mechanism. Besides, AGO mechanism may result in the issue of fairness among VUs, because only VUs winning the auctions can offload data traffic through WiFi, while other VUs directly use the cellular network. In this section, based on a contention game, we propose CGO mechanism that can increase VU's utility and improve fairness performance, while can also improve the overall offloading performance.

With CGO mechanism, offloading decision is made in a distributed manner, jointly considering the satisfaction function, instantaneous WiFi data rate, and the prediction of WiFi offloading potential and access cost. We prove that the designed CGO algorithm can achieve the Nash equilibrium (NE).

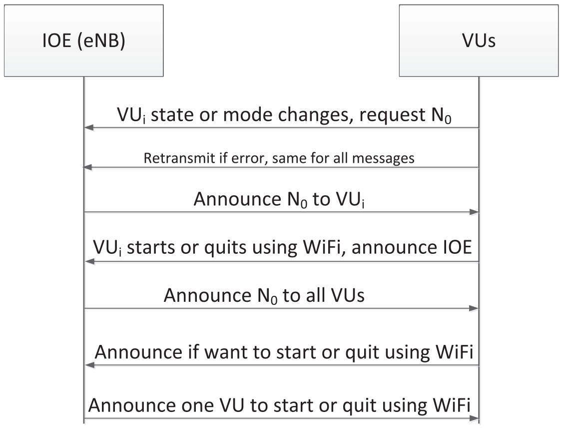

Fig. 5. CGO signaling.

Although the game is dynamic due to the mobility of vehicles, CGO mechanism is designed to quickly response to dynamics with low communication overhead.

A. Utility Function

With CGO mechanism, both χ_c and χ_w are fixed, and every VU knows the prices. All the VUs can access the WiFi AP simultaneously, and contend for the channel resource, which constitute a congestion game [24]. In the congestion game, VUs in an WiFi AP coverage area are players, and the WiFi channel resource is shared by players. The set of available strategies of a VU is $\mathbb{G} = \{\mathfrak{g}_0, \mathfrak{g}_1\}$, where $\mathfrak{g}_0$ and $\mathfrak{g}_1$ indicate that the VU uses or does not use the WiFi, respectively. Note that $\mathfrak{g}_0$ is in correspondence with two offloading decisions which are delaying the application and using cellular network directly, and we will discuss the offloading decision making in Section V-C. At an arbitrary time t, the utility of VU i using WiFi is defined as

$$U_i(t) = \max\left[0, r^i(t)\chi_c - \chi_w - \frac{\dot{J}_i(t_d, T)}{T} - \frac{\kappa_i}{T}\right]. \quad (11)$$

In utility function (11), $r^i(t)$ is the instantaneous WiFi data rate of VU i at t. $N_0 = \sum_{j \neq i} \delta_j + 1$ represents the total number of VUs currently using the same AP. t_d is the delay of VU i's current application at t. T is called delaying interval, which indicates that the offloading decision is made towards the next time duration T. The reason of using instantaneous data rate $r^i(t)$ in the utility function is that due to the mobility of VUs, $r^i(t)$ may vary with time, and the offloading decision should be adjusted.

The utility is a non-negative value since if WiFi access results in a negative utility, the VU will not use WiFi and then the utility of using WiFi is 0. A positive utility $U_i(t)$ indicates that transmission through WiFi at data rate $r^i(t)$ can save more cost than VU i aims to save if the application is delayed by T. With a non-positive $U_i(t)$, VU i does not use WiFi and makes a decision of either delaying the application or fulfilling it through the cellular network in the next T time duration. The decision making mechanism is discussed in Section V-C.

B. CGO Mechanism Design

The procedure of CGO Mechanism is described in Algorithm 2. With CGO mechanism, three offloading decisions can be made, i.e., using WiFi transmission, using cellular transmission or delaying the application. Three transmission modes of a VU are defined accordingly. With a positive utility, VU i uses mode $\mathbf{D_w}$ and transmits through WiFi; with a non positive utility, VU i uses delaying mode $\mathbf{D_d}$ or cellular mode $\mathbf{D_c}$, according to the decision making mechanism. With $\mathbf{D_w}$, if the instantaneous WiFi data rate $r^i(t)$ changed, VU i calculates $U_i(t)$ again using (11), and makes offloading decision correspondingly. Note that the main part of the algorithm is the update and announcement of N_0. The aim of step 4 in Algorithm 2 is to guarantee the game a sequential game with complete information, in which each move of a player constitutes an NE [24]. Fig. 5 shows the interactions among the IOE and VUs. We can see that CGO mechanism can response to the dynamics very fast with low communication overhead, involving only the exchange of announcement, acknowledgements, and N_0.

Algorithm 2 CGO mechanism

1: // **Initialization**: The IOE initializes χ_c and χ_w, and announces to all VUs.

2: If a VU i requests a new application, or the VU in mode $\mathbf{D_w}$ moves into a new zone, or the VU finishes mode $\mathbf{D_d}$ or $\mathbf{D_c}$, the VU requests N_0 from the IOE, determines r^i, and calculates U_i by (11). If $U_i > 0$, VU i uses mode $\mathbf{D_w}$, transmits using WiFi, and announces the IOE. The IOE executes step 3; otherwise, announces the IOE, and makes a decision of delaying $(\mathbf{D_d})$ or using cellular $(\mathbf{D_c})$.

3: A VU accesses WiFi AP $\#k$:

- The IOE updates N_0 of AP $\#k$. If the value of N_0 changes, the IOE announces N_0 to all VUs (denoted by a set $\mathbf{V}$) within the coverage area of AP $\#k$.
- Each VU in $\mathbf{V}$ calculates its utility using (11) and N_0. If the utility increases from zero to a positive value (resp. decreases from a positive value to zero), the VU announces to the IOE to start (resp. quit) using WiFi.
- If only one VU announces, the IOE responds to that VU with acknowledgement; If more than one VU announces, the IOE randomly chooses one VU and responds with acknowledgement;
- The VU who receives the acknowledgement starts (resp. stops) using WiFi and makes a decision of delaying $(\mathbf{D_d})$ or using cellular $(\mathbf{D_c})$.

4: **return**

C. Offloading Decision Making

As mentioned above, when $U_i \leq 0$, communication through WiFi at instantaneous data rate r^i cannot satisfy VU i. Thus, VU i needs to make a decision either to delay the application or fulfill it through the cellular network. Considering VU's satisfaction and prediction of WiFi offloading potential and access cost, if WiFi transmissions within the delaying interval T can be properly scheduled to achieve a positive utility over the next T time duration, the application is delayed ($\mathbf{D_d}$), and the optimal WiFi transmission scheduling is obtained by CGO; otherwise, VU i cannot obtain a positive utility, and thus the application is fulfilled through the cellular network ($\mathbf{D_c}$). The details of prediction are given in Section VI, and here we consider that the prediction results are known.

To utilize the prediction results, the delaying interval T is normalized by time slots with equal length Δt. Then, the delaying interval T is divided to T_Δ time slots, where $T_\Delta = \lceil T/\Delta t \rceil$. Denote $Y_{t,t'}$ the expected volume of data predicted to be offloaded from t to $t+t'$, and $P_{t,t'}$ the access cost predicted to be paid to use WiFi from t to $t+t'$. Thus, the predicted volume of data transmitted and cost paid in each time slot can be expressed by $Y_{t+m,1} = Y_{t,m+1} - Y_{t,m}$ and $P_{t+m,1} = P_{t,m+1} - P_{t,m}$, respectively.

The decision making mechanism is to find the optimal scheduling of WiFi transmissions in the next T time duration to maximize the utility, i.e., to decide δ_{t_w}, $t_w = 1, 2, \ldots, T_\Delta$ to maximize

$$U_i^T = -\dot{J}_i(t_d, T) - \kappa_i + \sum_{t_w=1}^{T_\Delta} \delta_{t_w} \left(\chi_c Y_{t_w,1} - P_{t_w,1}\right) \quad (12)$$

where δ_{t_w} is an indicator where $\delta_{t_w} = 1$ if VU i uses WiFi in slot t_w, and $\delta_{t_w} = 0$ otherwise. If $\max U_i^T > 0$, VU i delays the current application and transmits using WiFi according to δ_{t_w}. If $\max U_i^T \leq 0$, VU i cannot obtain a positive utility if delays the application, and thus uses the cellular network directly in the next T time duration.

D. Discussion

1) Offloading Performance: Similar to AGO mechanism, CGO mechanism can improve the overall WiFi offloading performance for the following reasons. Firstly, WiFi transmission opportunities with high data rate are preferred over those with low data rate when VUs make offloading decisions according to (11) and (12). Therefore, the performance anomaly problem of WiFi, i.e., the performance of WiFi is degraded by users with low data rates, can be alleviated. Secondly, a VU may not use WiFi even in the coverage area of WiFi, because the VU may be using mode $\mathbf{D_c}$ or cannot use WiFi due to the optimal WiFi transmission scheduling. Therefore, less VUs contend for the channel, and thus the degradation of WiFi performance due to contention can be mitigated.

2) Nash Equilibrium: In this part, we prove that Algorithm 2 can achieve NE among VUs. Consider that a set of VUs (denoted by $\mathbf{V}$) are within the coverage area of a WiFi AP the strategies of them constitute an NE. First, if $|\mathbf{V}| = 1$, it is clear that the strategy of VU i constitute an NE since if $U_i > 0$, change of the strategy from $\mathfrak{g}_1$ to $\mathfrak{g}_0$ results in the decrease of utility from a positive value to zero; if $U_i \leq 0$, change of the strategy from $\mathfrak{g}_0$ to $\mathfrak{g}_1$ results in the change of utility from zero to a non-positive value.

Now consider the situation $|\mathbf{V}| > 1$, and the strategies of all VUs in $\mathbf{V}$ constitute an NE. There are three cases that might change the NE.

Case 1 One VU (VU j) moves into a new zone in the coverage area and observes a different instantaneous data rate $r^j(t)$. VU j then calculates the utility U_j and there are two subcases.

Case 1.1 If $U_j > 0$, VU j will keep using WiFi, and other VUs utilities are not affected. Therefore, the NE remains the same.

Case 1.2 If $U_j \leq 0$, VU j will stop using WiFi, i.e., choose $\mathfrak{g}_0$, and make a decision on delaying the application or using the cellular network. According to Algorithm 2, there may or may not be on other VU starting to use WiFi. If no VU starts to use WiFi, according to (11), the utilities of VUs who are using WiFi will increase since less VUs are sharing the access opportunity. If one VU starts to use WiFi, that means the VU gets a positive utility, and other VUs' utilities will remain unchanged.

Case 2 One VU (VU j) leaves the coverage area of a WiFi AP. This case is the same as Case 1.2.

Case 3 One VU (VU j) moves into the coverage area of a WiFi AP, or requests a new application, or finishes mode $\mathbf{D_d}$ or $\mathbf{D_c}$. If $U_j \leq 0$, it is the same as Case 1.1. If $U_j \leq 0$, according to Algorithm 2, one VU may stop using WiFi, and thus other VUs are not affected since the number of VUs using the WiFi remains the same.

VI. Offloading Potential Prediction

In this section, we propose a prediction method for the WiFi offloading potential and access cost within a certain future time, based on the theory of semi-Markov process.

Recall that the mobility of a VU is modeled by a CTMC $\{X(t)\}$, where $X(t) \in \mathbf{S}$ indicates the location of the VU at t. Here we define a Markov renewal process $\{(X_n, T_n)\}$, where $X_n \in \mathbf{S}$ and T_n denote the state of the VU's n-th transition, and the time instance of this transition, respectively. Define

$$\begin{aligned} Q_{jk}(t) &= Pr(X_{n+1} = k, T_{n+1} - T_n \leq t | X_n = j) \\ &= p_{jk} \Upsilon_{jk}(t) \end{aligned} \quad (13)$$

where $p_{jk} = Pr(X_{n+1} = k | X_n = j) = \lim_{t\to\infty} Q_{jk}(t)$ is the limiting probability of the transition from j to k, and $\Upsilon_{jk}(t)$ is the sojourn time distribution at state j when the next state is k, which can be expressed by $\Upsilon_{jk}(t) = Pr(T_{n+1} - T_n \leq t | X_{n+1} = k, X_n = j)$. Based on the mobility model defined in Section III, the VU can only move to state S_{j+1} given the current state is S_j.[1] We can then obtain that $p_{j(j+1)} = 1$ and

[1] We consider that $S_{L+1} = S_0$ based on the mobility model.

$\Upsilon_{jk}(t) = 1 - e^{-b_j t}$ if $k = j+1$ and $\Upsilon_{jk}(t) = 0$ otherwise. Therefore, we have

$$Q_{jk}(t) = \begin{cases} \Upsilon_{j(j+1)}(t) = 1 - e^{-b_j t}, & k = j+1 \\ 0, & \text{otherwise.} \end{cases}$$

Denote $\Upsilon_j(t) = Pr(T_{n+1} - T_n \le t | X_n = j) = \sum_k Q_{jk}(t)$ the sojourn time distribution at state j. From above, we know that $\Upsilon_j(t) = \Upsilon_{j(j+1)}(t) = 1 - e^{-b_j t}$.

In the prediction, we assume the time is discrete and normalized by ϵ, and the initial state of the VU when prediction begins is j. Define the homogeneous semi-Markov process $\mathbf{X} = \{X_t, t \in \mathbb{N}^*\}$, which describes the state of the VU at time $t\epsilon$. The transition probability of $\mathbf{X}$ is defined by $\omega_{j,k}(t) = Pr(X_t = k | X_0 = j)$, which is calculated by

$$\omega_{j,k}(t) = (1 - \Upsilon_j(t))\,\delta_{jk} + \sum_{\iota=1}^{t} \dot{Q}_{j(j+1)}(\iota)\omega_{j+1,k}(t-\iota) \quad (14)$$

where δ_{jk} is an indicator with $\delta_{jk} = 1$ if $j = k$, and $\delta_{jk} = 0$ otherwise. $(1 - \Upsilon_j(t))\delta_{jk}$ is the probability that the state of VU stays unchanged within t. $\dot{Q}_{j(j+1)}(\iota) = Q_{j(j+1)}(\iota) - Q_{j(j+1)}(\iota - 1)$ is the probability that the state of VU transits from j to $j+1$ in time ι.

A. Prediction for AGO

With AGO mechanism, VUs predict the WiFi offloading potential in T when the auction initializes. Assume that the VU is currently in state S_j, and denote $Y^A_{j,k}(t)$ the expected data traffic offloaded within t while the initial state is j and the final state is k. Since with AGO mechanism, the VU expects WiFi to be exclusively used, the expected WiFi data rate of VU i in zone m can be expressed by $r^i_m = r_m$. Thus, the total data traffic offloaded within t given the initial state j can be obtained by $Y^A_j(t) = \sum_{k=j}^{\infty} Y^A_{j,k}(t)$, given in (15), shown at the bottom of the page.

B. Prediction for CGO

With CGO mechanism, VUs predict the WiFi offloading potential and access cost when necessary. WiFi channel resource is shared by VUs, and thus we predict the minimum expected WiFi offloading potential considering that all VUs are using WiFi simultaneously. According to (2), the number of vehicles in an AP coverage can be approximated by $n \approx (1 - v_i k_{\text{jam}}/v_f)\sum_{j=1}^{L} l_j$. Thus, the WiFi data rate of VU i in zone m can be approximated by $r^i_m = (\rho r_m \xi(n))/n$. Denote $Y^C_{j,k}(t)$ and $P^C_{j,k}(t)$ the data traffic offloaded and the WiFi access cost within t while the initial state is j and the final state is k, respectively. The total data traffic offloaded and the expected cost paid to use WiFi within t given the initial state j can be obtained, respectively, by $Y^C_j(t) = \sum_{k=j}^{\infty} Y^C_{j,k}(t)$ in (16), shown at the bottom of the page, and $P^C_j(t) = \sum_{k=j}^{\infty} P^C_{j,k}(t)$ in (17), shown at the bottom of the page. $\chi_{w,j}$ is the WiFi access price when a VU is in zone j, which can be expressed by

$$\chi_{w,j} = \begin{cases} 0, & j \bmod (L+1) = 0 \\ \chi_w, & \text{otherwise.} \end{cases}$$

In fact, based on the communication and mobility model defined in Section III, the prediction results only depend on the initial state of the VU and the prediction time t. Therefore, in realistic implementation of the proposed mechanisms, the prediction results can be pre-calculated and stored in APs or servers on the Internet. VUs can query for the prediction results with the current state and the prediction time, rather than predicting by him/herself which might be time-consuming. Note that the prediction results are given in an average sense, considering the state of a VU other than the real location. However, for carrier-WiFi network, it is possible that the locations and the information about coverage size and zones are known. In this case, the prediction can be done in a different way that considers the locations of VUs, and therefore the prediction results can be more accurate. We consider this as one of the future works.

VII. Performance Evaluation

In this section, we evaluate the performance of the proposed offloading mechanisms through simulation. The simulation is carried out in a 2.0 km × 2.0 km region road map in the downtown area of Washinton D.C., USA. LTE is considered to provide full coverage to the area, while the WiFi APs are deployed within the area by the MNO, whose coverage is limited. The IEEE 802.11n standard is employed, which can provide data rates up to 65 Mbps at 2.4 GHz. Also we assume that VUs are subscribers of the MNO network and pre-authorized when accessing WiFi, which means VUs can access the WiFi without the time-consuming authorization procedure. The street layout and AP locations are shown in Fig. 6, where each street segment has two lanes with the bidirectional vehicle traffic. We use VANETMobisim [27] to generate the mobility traces of vehicles. Speed limit is set to 50 km/h. The vehicle

$$Y^A_j(t) = \sum_{k=j}^{\infty} \omega_{j,k}(t) Y^A_{j,k}(t) = \sum_{k=j}^{\infty} \left[(1 - \Upsilon_j(t))\,\delta_{jk} t r^i_j + \sum_{\iota=1}^{t} \left[\iota r^i_j + Y^A_{j+1,k}(t-\iota)\right] \dot{Q}_{j(j+1)}(\iota)\omega_{j+1,k}(t-\iota) \right] \quad (15)$$

$$Y^C_j(t) = \sum_{k=j}^{\infty} \omega_{j,k}(t) Y^C_{j,k}(t) = \sum_{k=j}^{\infty} \left[(1 - \Upsilon_j(t))\,\delta_{jk} t r^i_j + \sum_{\iota=1}^{t} \left[\iota r^i_j + Y^C_{j+1,k}(t-\iota)\right] \dot{Q}_{j(j+1)}(\iota)\omega_{j+1,k}(t-\iota) \right] \quad (16)$$

$$P^C_j(t) = \sum_{k=j}^{\infty} \omega_{j,k}(t) P^C_{j,k}(t) = \sum_{k=j}^{\infty} \left[(1 - \Upsilon_j(t))\,\delta_{jk} t \chi^i_{w,j} + \sum_{\iota=1}^{t} \left[\iota \chi^i_{w,j} + P^C_{j+1,k}(t-\iota)\right] \dot{Q}_{j(j+1)}(\iota)\omega_{j+1,k}(t-\iota) \right] \quad (17)$$

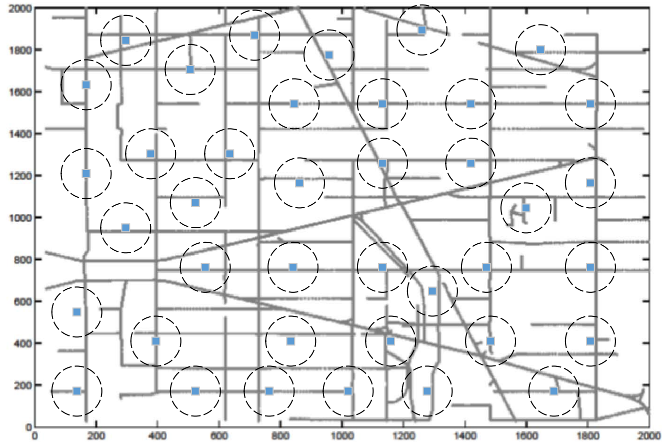

Fig. 6. Simulation scenario.

mobility is controlled by Intelligent Driver Model with Lane Changes model, in which vehicle speed is based on movements of vehicles in neighborhood.

In the simulation, the price to use cellular network is set to $\chi_c = \$1/\text{Mb}$. We consider $W = 2$ MHz, and $[\theta_{\min}, \theta_{\min}] = [0, 8]$ [28]. The application size $\mathcal{S}$ is randomly chosen from 200 Mb to 500 Mb, and we set the satisfaction function as $J(t) = \chi_c \mathcal{S} - \alpha t^{\beta}$. α determines the scale of $J(t)$, where a larger α leads to a smaller delay tolerance. $\beta > 1$, $\beta = 1$ and $\beta < 1$ indicate that $J(t)$ is concave, linear and convex, respectively, as shown in Fig. 3. Both auction interval and delaying interval are set to 10 seconds. We use two existing offloading mechanisms for comparison. With basic delayed offloading (BDO) mechanism, VUs constantly delay their applications to wait for WiFi transmission until the tolerated delay. The other one is on-the-spot offloading (OSO) mechanism with which VUs use WiFi when WiFi is available, otherwise use cellular network. The simulation runs for 10 hours, and the results are averaged over 5 runs.

The performance of the proposed offloading mechanisms in terms of WiFi access price χ_w is shown in Fig. 7. Note that with AGO mechanism, the WiFi access price is determined by auctions. Fig. 7(a) shows the overall WiFi offloading performance. It can be seen that both AGO and CGO mechanisms can offload much more cellular traffic than BDO and OSO, the reasons for which are discussed in Sections IV-C and V-D. The slight fluctuation in the curve of AGO is due to the randomness in the simulation. When χ_w increases, the total traffic offloaded also increases with CGO employed. This is because when χ_w increases, more VUs use cellular network rather than WiFi, and higher WiFi data rates are preferred to achieve a positive utility. Therefore, contention and performance anomaly problem are further alleviated. Fig. 7(b) shows the total revenue of the MNO from the WiFi access service it provides, which is the total cost VUs pay to use WiFi. It can be seen that a higher χ_w leads to a higher revenue. With AGO, the revenue of the MNO is higher than that with CGO because the WiFi access price with AGO mechanism is determined by auctions and is relatively high (on average \$17.2/sec). Fig. 7(c) and (d) shows the average service delay. It can be seen that BDO leads to the highest service delay since it constantly delays the application until delay

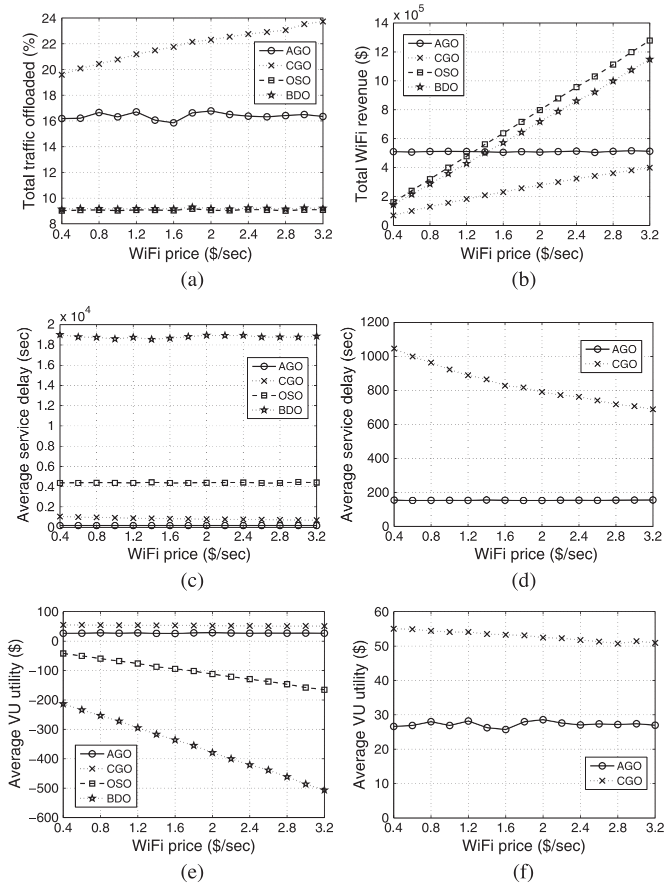

Fig. 7. Simulation results in terms of WiFi price. (a) Total traffic offloaded. (b) Total WiFi revenue. (c) Average service delay. (d) Average service delay (AGO versus CGO). (e) Average VU utility. (f) Average VU utility (AGO versus CGO).

tolerance or the application is completely fulfilled by WiFi. Both AGO and CGO mechanisms can achieve very low service delay. AGO mechanism can lead to lower service delay than CGO mechanism because only those VUs who win the auction delay the application, and other VUs directly use the cellular network. With the increase of χ_w, the average service delay of CGO mechanism decreases because VUs are more likely to use the cellular network since the utility to use WiFi becomes lower due to high χ_w. In Fig. 7(e) and (f), the average utility of VU obtained from each fulfilled application is shown. The utility that a VU obtains from an arbitrary application j is defined as the cost that is saved considering satisfaction function, i.e., $U_j = J_j(t_d) - P_j$, where t_d is the service delay of application j when it is fulfilled, and P_j is the total cost paid for application j. It can be seen that OSO and BDO cannot achieve positive average utility since user satisfaction is not considered, while both AGO and CGO mechanisms can achieve positive average utility. With the increase of χ_w, the average utility of VUs with CGO only decreases slightly, as shown in Fig. 7(f). The reason is that although χ_w is high, more traffic can be offloaded through WiFi in unit time (as shown in Fig. 7(a)), i.e., the average WiFi data rate with CGO increases with χ_w. According to (11), the utility increases with WiFi data rate and decreases with WiFi access price, which leads to the slight decrease of the average VU utility.

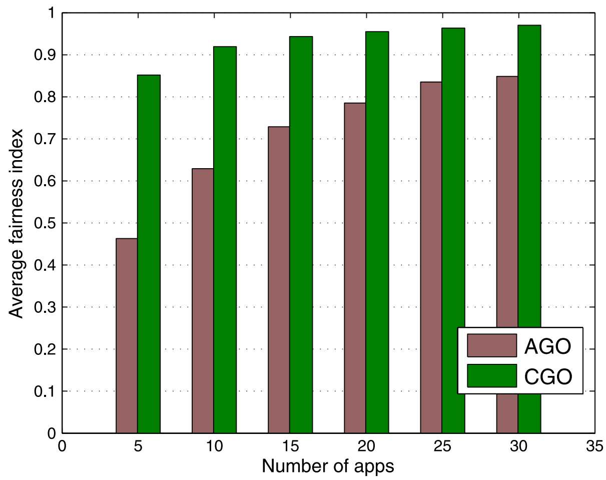

Fig. 8. Fairness performance.

Fig. 8 shows the fairness performance of the proposed offloading mechanisms. The number of applications N_a indicates that the fairness index is calculated considering N_a applications, where small N_a and large N_a correspond to short-term and long-term fairness, respectively. The fairness index F is calculated by $F = (\sum_j^N U_j)^2/(N \sum_j^N U_j^2)$, where N is the total number of VUs, and U_j is the total utility of VU j obtaining from N_a applications. It can be seen that CGO mechanism can achieve higher average fairness index since all VUs can access WiFi network while with AGO mechanism WiFi network is available only to VUs who win the auctions. It is shown that the average fairness index of AGO increases with N_a, which indicates that AGO can achieve higher long-term average fairness index. The reason is that with a shorter time, some VUs win the auctions and offload traffic through WiFi while others cannot; with a longer time, more VUs are likely to win the auctions, and thus the fairness performance becomes better.

VIII. Conclusion

In this paper, we have proposed an approach to predict WiFi offloading potential and access cost in vehicular environments, based on which we have introduced two intelligent offloading mechanisms, namely auction game-based and congestion game-based offloading mechanism, for vehicular users to effectively and efficiently offload the cellular traffic through the carrier-WiFi network. With the proposed offloading mechanisms implemented, the cellular traffic can be automatically and intelligently offloaded for vehicular users in a transparent manner, so that the cellular network congestion can be mitigated, while a win-win situation is created for both vehicular users and the MNO. Simulation results have shown that the proposed offloading mechanisms outperform existing offloading mechanisms in terms of total traffic offloaded, average user delay and utility.

For our future work, we will develop prediction approach that considers the locations of VUs, and offloading mechanisms in the scenario of unplanned WiFi environment. In addition, the features of application sessions will be considered during interworking between WiFi and cellular networks, since whether the application session can be kept during handover can greatly impact the design of the offloading mechanism.

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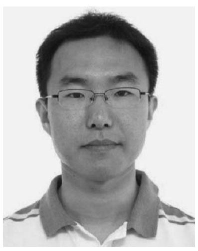

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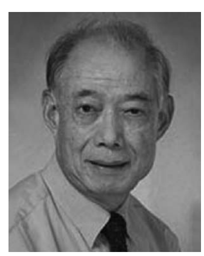

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