Spatial Coordinated Medium Sharing: Optimal Access Control Management in Drive-Thru Internet

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Abstract*—Driven by the ever-growing expectation of ubiquitous connectivity and the widespread adoption of IEEE 802.11 networks, it is not only highly demanded but also entirely possible for in-motion vehicles to establish convenient Internet access to roadside WiFi access points (APs) than ever before, which is referred to as Drive-Thru Internet. The performance of Drive-Thru Internet, however, would suffer from the high vehicle mobility, severe channel contentions, and instinct issues of the IEEE 802.11 MAC as it was originally designed for static scenarios. As an effort to address these problems, in this paper, we develop a unified analytical framework to evaluate the performance of Drive-Thru Internet, which can accommodate various vehicular traffic flow states, and to be compatible with IEEE 802.11a/b/g networks with a distributed coordination function (DCF). We first develop the mathematical analysis to evaluate the mean saturated throughput of vehicles and the transmitted data volume of a vehicle per drive-thru. We show that the throughput performance of Drive-Thru Internet can be enhanced by selecting an optimal transmission region within an AP's coverage for the coordinated medium sharing of all vehicles. We then develop a spatial access control management approach accordingly, which ensures the airtime fairness for medium sharing and boosts the throughput performance of Drive-Thru Internet in a practical, efficient, and distributed manner. Simulation results show that our optimal access control management approach can efficiently work in IEEE 802.11b and 802.11g networks. The maximal transmitted data volume per drive-thru can be enhanced by 113.1% and 59.5% for IEEE 802.11b and IEEE 802.11g networks with a DCF, respectively, compared with the normal IEEE 802.11 medium access with a DCF.

***Index Terms*—Drive-thru Internet, IEEE 802.11, DCF, saturated throughput, spatial coordination.**

I. Introduction

THE advance of wireless communications and pervasive use of mobile electronics in the recent years have driven the ever-increasing user demands of ubiquitous Internet access [1], [2]. This is particularly evident for in-vehicle Internet access with people now spending much time in cars [3]. As a result, an extensive body of research has been devoted to enabling vehicular communications with diverse applications ranging from the road safety, trip entertainment to driving efficiency and traffic management [4], [5].

Motivated by widespread deployment of wireless local area networks (WLANs) and great success of IEEE 802.11 standard, a dominant approach of vehicular communications is to transplant the WLAN prototype into the vehicular environments [6]. By deploying a multitude of IEEE 802.11 radio access points (APs) along the roadside and opening them to vehicles, vehicles are possible to acquire temporary and opportunistic wireless connections for Internet access when they drive through the coverage of APs, which is referred to as the Drive-Thru Internet [6]. By using the grass root WLAN APs in the urban or suburban areas, the Drive-Thru Internet is appealing due to the low connection cost and high transmission rate [7], [8], which can work as a useful complement to cellular networks for transmitting delay tolerable contents [9], [10].

Despite that the IEEE 802.11 DCF has been proven to be efficient to self-organize a mass of wireless nodes for dynamic medium access and sharing fairly in both theory and real-world deployment [11]–[13], its performance in the outdoor vehicular environment is still unclear when a large number of fast-motion nodes contend for transmissions at the same time [14]. One of the major concerns is the performance anomaly phenomenon in multi-rate 802.11 WLANs. As shown in Fig. 1, the transmission rate from roadside unit (RSU) to a vehicle depends on the distance between the vehicle and RSU. When a number of vehicles contend the medium using the carrier sense multiple access with collision avoidance (CSMA/CA) and a vehicle located at the zone 4 obtains the current frame

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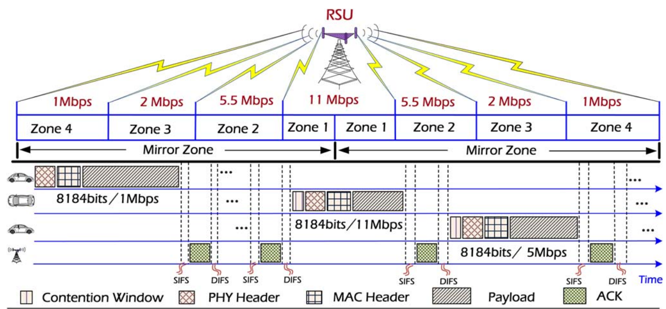

Fig. 1. The illustration of performance anomaly phenomenon in multi-rate 802.11b WLANs for vehicular medium access control.

transmission opportunity, the transmission rate is 1 Mbps. With this low transmission rate, the time duration to transmit a frame by RSU will be longer than that for a vehicle located at the zone 1, which has a higher transmission rate. Therefore, the low transmission rate will greatly reduce the average throughput over all vehicles in the RSU's coverage. This phenomenon is referred as the performance anomaly.

Due to the performance anomaly phenomenon in multi-rate 802.11 WLAN, the throughput of all nodes transmitting at the higher rate is degraded below the level of the lower rate, which penalizes high-rate nodes and privileges the slow-rate ones [11], [15]. To cope with this issue, the proposed solutions address the issue of fairness constraint and throughput optimization tradeoff for static wireless users in WLANs [16], [17]. However, in the mobile vehicular environment, the throughput of Drive-Thru Internet can be jointly determined by the following three perspectives: 1) vehicular related traffic flow state (e.g., vehicular density, driving speed); 2) IEEE 802.11 Physical layer related fault parameters [18] (e.g., bit rate, coverage range); 3) IEEE 802.11 MAC layer related fault parameters (e.g., MAC frame size, contention window size). To address the performance anomaly in large-scale deployment of Drive-thru Internet and efficiently adapt the IEEE 802.11 protocol according to the real-time road traffic with light computation cost and simple operations, we are motivated to address the following questions: 1) *How to theoretically and accurately evaluate the IEEE 802.11 DCF throughput considering different traffic flow states and different versions of 802.11 products?* 2) *How to achieve the optimal IEEE 802.11 DCF throughput under different traffic flow states by overcoming the performance anomaly phenomenon in vehicular environment?* 3) *How to ensure the airtime fairness for medium sharing and boost the throughput performance of Drive-Thru Internet?*

To seek for the answers to above questions, in this paper, we propose a unified analytical framework for Drive-Thru Internet performance evaluation, which can be applied to the widely deployed multi-rate IEEE 802.11a/b/g WLANs and adapt to different traffic flow states scaled from the free flow state to congested flow state. Towards this end, we first apply the Fluid Traffic Motion (FTM) model which is widely used in the traffic engineering analysis and some empirical data collected from the traffic flow report [19] to analyze the contending vehicle number and residence time within distinguished length of spatial zones of AP's coverage mathematically. By accurately modeling and formulating the relationship between the coverage range and data rate, which is abstracted from the real-world measurement data of IEEE 802.11a/b/g WLANs, we present the mathematical expression of mean vehicular saturated throughput and transmitted data volume per drive-thru in IEEE 802.11 networks with DCF. Particularly, observed from the unique mobility feature of vehicles in VANET, i.e., the relatively fair medium access opportunity during the AP's sojourn time, almost similar velocity, and the same mobility direction on each driving lane, we can schedule the vehicles to transmit in the optimally selected spatial region of coverage range that can achieve maximal mean saturated throughput and transmitted data volume, which are validated using numerical analysis. The main contributions of the paper are two-fold:

- Unified Drive-Thru Internet analytical framework: existing literature largely adopt one of the IEEE 802.11 protocols (i.e., IEEE 802.11a/b/g) for the Drive-Thru Internet performance analysis and evaluation. In this paper, we derive the mathematical expression of the mean saturated throughput of Drive-Thru Internet and the mean transmitted data volume per drive-thru, based on the widely deployed three types of network models (IEEE 802.11a/b/g networks) and fluid traffic motion model. Using empirical data, the proposed analytical framework is much closer to real vehicular environments and can be applied to analyze the Drive-Thru Internet performance under various vehicular traffic flow states.
- Optimal access control: based on the collected empirical data from real-world WiFi networks and traffic transport environments, we develop an optimal access control scheme. The proposal optimally determines the best spatial region in which vehicles should start medium access and sharing to achieve the maximal system throughput. The proposed access control scheme is directly applicable to off-the-shelf IEEE 802.11a/b/g APs and has the advantage of simple and flexible operability. Moreover, through both analysis and extensive simulation results, we show that our proposal can ensure the airtime fairness for medium sharing and boost the throughput performance of Drive-Thru Internet.

The remainder of this paper is organized as follows. Section II gives the related literature. Section III describes the network model. Section IV presents the performance and optimal access analysis in Drive-Thru Internet. Section V describes the optimal access control management realization. Section VI validates the analysis accuracy with simulations, and Section VII closes the paper with conclusions.

II. Related Work

In spite of the increasing research popularity of VANET oriented applications using WiFi as a wireless access approach, the extensive researches focusing on the performance evaluation and related enhancement strategies in IEEE 802.11 networks with DCF do not consider the specific vehicular environment, and only few literature investigate the Drive-Thru Internet most

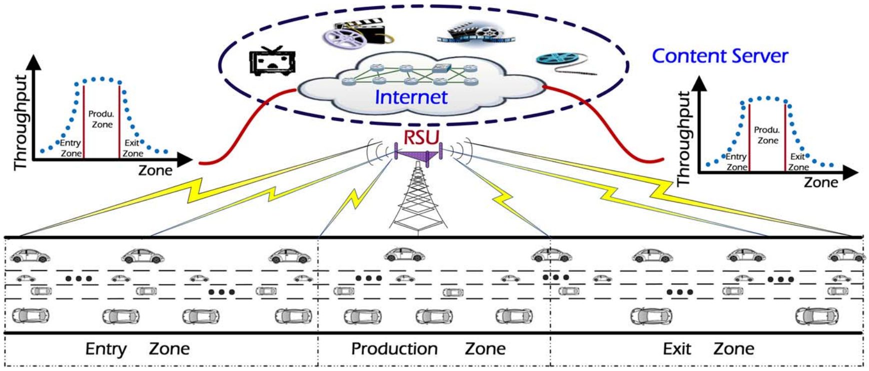

Fig. 2. A widely deployed Drive-Thru Internet scenario for Internet service provisioning.

recently. In this section, the related work presentation includes two parts: 1) IEEE 802.11 DCF related performance evaluation and enhancement strategies in general wireless networks; 2) Drive-Thru Internet oriented performance analysis and improvement strategies.

In term of IEEE 802.11 DCF related performance evaluation and enhancement in general wireless networks, the majority of literature investigated the performance anomaly impact on the IEEE multi-rate 802.11 networks and corresponding improving strategies. The performance anomaly phenomenon was first reported in [11], which is taken IEEE 802.11b networks for instance. Inspired from this report, in [15]–[17], [20], the analytical performance anomaly in IEEE 802.11 networks with multiple transmission rates is demonstrated and some possible remedies to improve the performance in IEEE 802.11 networks are developed, such as optimally selecting the initial contention window, frame size, maximal backoff stage etc., depending on the PHY-layer transmission rates and traffic states. Recently, in [13] and [21], the accurate and unified analytical framework for both saturated and unsaturated traffic load scenarios are proposed. In [22], under a mixture of traffic scenario, a service differentiation model without prioritization are specifically designed to improve the performance of delay and throughput sensitive traffic in multi-rate 802.11 network.

Different from general IEEE 802.11 networks, the introduced vehicular environment makes Drive-Thru Internet unique in term of some traffic features. In [14], the impact of vehicular mobility on the MAC of Drive-Thru Internet is investigated, and the corresponding MAC parameters adjustment in tune with the nodal mobility for throughput improvement of 802.11 DCF is proposed. In [23], [24], the impact of road traffic on the throughput performance of Drive-Thru Internet is discussed, and a MAC protocol to control the transmission probability of vehicles for maximizing system throughput is proposed. In [25], the uplink MAC performance of Drive-Thru Internet is evaluated. It is worthy of mention that this paper points out that the higher throughput can be achieved by determining the optimal admission control region by using simulations. However, how to reach the optimal drive-thru throughput for different traffic flow states and multi-rate 802.11 network models is lacked. In addition, similar with the cooperative relay approach proposed in [26], in which nodes located within high transmission rate region will repeat/relay the data to the node with low transmission rate to address the rate anomaly problem, in [27], a multi-vehicular maximum (MV-MAX) approach is introduced. However, those relay based approaches are less fair than the IEEE 802.11 DCF.

III. System Model

We consider Drive-Thru Internet to support various vehicle-oriented applications, such as multimedia content distribution, file downloading/uploading and web browsing etc. As shown in Fig. 2, a roadside unit (RSU) is installed on the roadside which serves as the gateway to provide Internet services to vehicles driving through the RSU's coverage. The RSU is also referred to as access point (AP). Therefore, we use RSU and AP interchangeably in the paper. As discussed in [12], the multi-rate spatial zones within AP coverage can be divided into three types according to the achieved drive-thru throughput: 1) entry zone; 2) production zone; 3) exit zone. Vehicles within the different zones will achieve different transmission bit rates.

In multi-rate spatial zones, the performance anomaly phenomenon highly degrades the performance of Drive-Thru Internet. To address this problem, we propose an optimal access control approach in this paper. By considering different traffic flow states and combining the empirical data collected from the real IEEE 802.11 networks test, the proposed approach regulates vehicles in optimal access control region to share the medium fairly and efficiently such that a higher drive-thru throughput can be achieved for all vehicles within the AP's coverage. Before analyzing and formulating the proposed approach, we describe the vehicle mobility model and vehicle to roadside unit (V2R) communication model as follows. To be clear, the many symbols used in this paper have been summarized in Table I.

A. Vehicle Mobility Model

We apply the fluid traffic motion (FTM) model to capture the macroscopic relationship between the average vehicular speed and traffic density on the road [28], which can be expressed as

$$\bar{\upsilon} = \max\left\{\upsilon_{\min}, \upsilon_{\max}\left(1 - \frac{\sigma}{\sigma_{jam}}\right)\right\} \quad (1)$$

where $\bar{\upsilon}$, $\upsilon_{\min}$ and $\upsilon_{\max}$ denote the vehicles' average, minimal and maximal speed, respectively. σ and σ_{jam} are the factual

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbols Associated with Network Model	
$\overline{\upsilon},\ \upsilon_{\max}$	The vehicular average driving speed and maximal speed constraint.
$\sigma,\ \sigma_{\max}$	The factual traffic density and jammed traffic density.
L, ℓ	The roadway segment length and mean length of vehicles.
ϑ_v	The mean vehicular arrival rate.
$f_\nu(\nu_i)$	The pdf of normal distribution of speed ν_i of arbitrary arriving vehicle i.
$f_\Gamma^{L_{s_i}}(\tau), F_\Gamma^{L_{s_i}}(\tau)$	The pdf/cdf of vehicle's residence time within L_{s_i}−length roadway segments.
$\overline{\Gamma}^{L_{s_i}}$	The mean vehicle's residence time within L_{s_i}−length roadway segments.
$\overline{N}^{r_{z_j}}$	The mean number of vehicles within c_{z_j}-long coverage range zone.
$\mathbb{S}$	The investigated IEEE 802.11 protocol set.
$\mathbb{R}$	The adaptive transmission rate set of IEEE 802.11 protocols.
$\mathcal{C}$	The transmission coverage set of different transmission rates.
$\mathcal{Q}_{ser}$	The traffic flow state set under different traffic densities.
Symbols Associated with MAC Protocol	
ξ	The conditional probability that any vehicle transmits in the randomly chosen slot-time.
p_k^{tr}	The probability that there is at least one transmission within transmission zones set $\mathbb{Z}_k$.
p_k^{su}	The probability that a successful transmission on the considered channel within $\mathbb{Z}_k$.
$E[T_{su,k}^{rts}]$	The mean time that the channel is sensed busy due to the successful transmission within $\mathbb{Z}_k$.
$E[T_{bu,k}^{rts}]$	The mean time that the channel is sensed busy due to a collision within $\mathbb{Z}_k$.
$E[T_{slot}]$	The mean time-slot using RTS/CTS mechanism in DCF.
$\Re_k$	The nodal throughput passing k continual transmission zones.
$\mathbb{F}_k(\cdot)$	The function of mean total amount of transmitted data from/to AP.
$x_{s_i}^*(\mathcal{Q}_{type})$	The optimal channel access range for vehicles within AP's coverage.

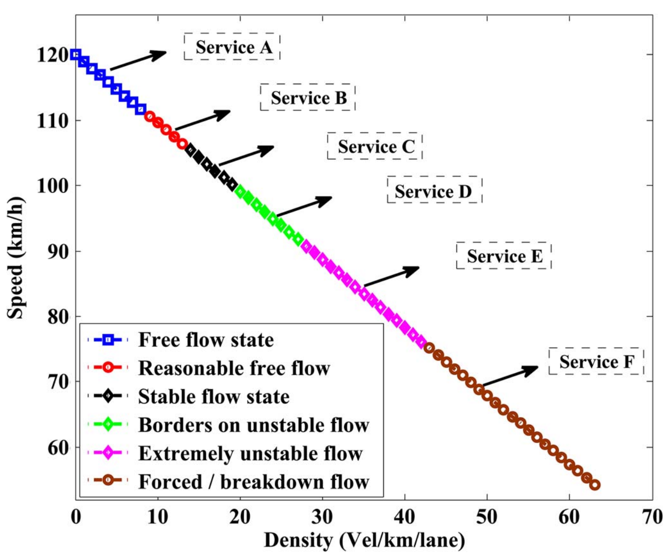

Fig. 3. The relationship between the vehicular density and driving speed.

TABLE II
TRAFFIC FLOW STATE PER LANE FOR DIFFERENT DENSITIES [19]

Density (veh/km)	Traffic flow state		
	TSL	Speed (km/h)	Flow operations
$0-8$	A	≥ 97	free
$9-13$	B	≥ 92	reasonable free
$14-19$	C	≥ 87	stable
$20-27$	D	≥ 74	borders on unstable
$28-42$	E	≥ 49	extremely unstable
$43-63$	F	< 49	forced or breakdown

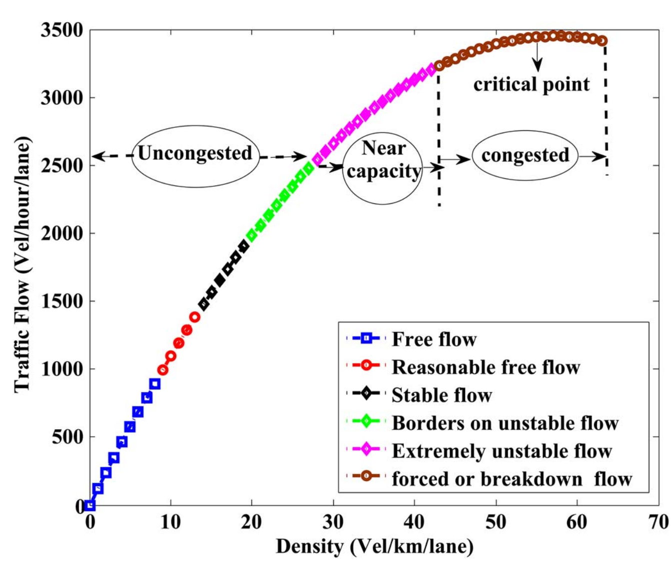

Fig. 4. The relationship between the vehicular density and traffic flow.

traffic density and jammed traffic density, respectively. σ_{jam} in unit of vehicular number per meter is determined by the capacity of roadway segment. Let ℓ be the mean length of vehicles, which is about 6 meters in general. We can have $\sigma_{jam} = 1/\ell$ at the extreme case. Considering the driving space between vehicles for safety issue, the typical value of σ_{jam} is set as 115/1000 [19].

As shown in Fig. 3, the vehicular speed is monotonically decreased with the increased traffic density, and finally lower bound to $\upsilon_{\min}$ when the traffic congestion reaches a critical state. Here, we define $\upsilon_{\min} = 0$ for the simplified analysis. Based on different traffic density, there are six-level traffic flow states [19], [29], which correspond to six traffic service levels (TSLs) and six flow operation scenarios shown in Table II. Meanwhile, Fig. 4 shows the relationship between the traffic density and the traffic flow state, ranging from the uncontested traffic state, near capacity traffic state to the congested traffic state. With the increase of traffic density, the traffic flow can be dramatically increased and finally reach a peak value.

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TABLE III
MEASUREMENT DATA IN AN OPEN INDOOR OFFICE ENVIRONMENT FOR 802.11a, 802.11b, AND 802.11g. (IN UNIT OF ft)

Protocol \ Date Rate (Mbps)	54	48	36	24	18	12	11	9	6	5.5	2	1
IEEE802.11a	45	50	65	85	110	130	-	150	165	-	-	-
IEEE802.11b	-	-	-	-	-	-	160	-	-	220	270	410
IEEE802.11g	90	95	100	140	180	210	160	250	300	220	270	410

For a roadway segment with a length L, let λ, $\overline{\Gamma}$ and $\overline{N}$ denote the average vehicle arrival rate, average vehicle residence time and average number of vehicles within the L roadway segment, respectively, where $\overline{\Gamma} = \mathrm{L}/\bar{\upsilon}$ and $0 \leqslant \overline{N} \leqslant L \cdot \sigma_{jam}$. Let σ_c denotes the critical traffic density which leads to the maximum vehicle arrival rate. We can have the relationship between σ_c and traffic density σ established in lemma 1:

Lemma 1: The critical density value σ_c is $\sigma_{jam}/2$, and the arrival rate λ is directly increasing with traffic density $\sigma \in [0, (\sigma_{jam}/2)]$ and inverse proportion with $\sigma \in [\sigma_{jam}/2, \sigma_{jam}]$. The range of traffic flow rate is $[0, \upsilon_{\max}\sigma_{jam}/4]$.

Proof: Using the Little's law, we can get that the mean vehicle arrival rate can formulated as

$$\lambda = \frac{\bar{N}}{\bar{\Gamma}} = \frac{\bar{N}}{(L\bar{\upsilon})}. \tag{2}$$

Combining the expression $\sigma = \overline{N}/L$ and (1), we can get

$$\lambda = \upsilon_{\max}\sigma - \frac{\upsilon_{\max}}{\sigma_{jam}}\sigma^2. \tag{3}$$

By setting first order derivative of (3), it is clear to find the critical density value σ_c, and the minimal and maximal traffic flow rate can also be obtained. The lemma is proved. ■

B. V2R Communication Model

We consider a unified multi-rate multi-protocol transmission model. In specific, the RSU's coverage is divided into different zones based on the applied transmission protocols (e.g., IEEE 802.11a, IEEE 802.11b, or IEEE 802.11g) and the distance from the RSU. Vehicles within different transmission zones have different transmission rates. Some notations are given in the following definitions to easily formulate this multi-rate multi-protocol transmission model.

Definition 1: Let $\mathbb{S} = \{\mathrm{s}_1, \mathrm{s}_2, \mathrm{s}_3\}$ denote the protocol set, where s_1, s_2 and s_3 represent the protocol IEEE 802.11a, 802.11b and 802.11g, respectively. Let $\mathbb{R} = \{r_{\mathrm{s}_i,\mathrm{z}_j} | \mathrm{s}_i \in \mathbb{S}, \mathrm{z}_j \in \mathbb{Z}\}$ be the adaptive transmission rate set, where z_j represents the j-th rate zone.

Definition 2: Let $\mathrm{C}_{\mathrm{s}_i}$ be the whole coverage range of the s_i-th 802.11 protocol, and $\mathcal{C}$ be the coverage set of different transmission rates, where $c_{\mathrm{s}_i,\mathrm{z}_j} = |x_{\mathrm{s}_i,\mathrm{z}_{j+1}} - x_{\mathrm{s}_i,\mathrm{z}_j}|$ is the coverage range of j-th transmission rate zone, $x_{\mathrm{s}_i,\mathrm{z}_j}$ denotes the coverage range point of j-mode transmission rate zone using s_i-th 802.11 protocol, and $\mathrm{C}_{\mathrm{s}_i} = 2 \cdot \sum_{\mathrm{z}_j \in \mathbb{Z}} c_{\mathrm{s}_i,\mathrm{z}_j}$.

Table III provides the measurement data for three types of IEEE 802.11 protocols under different communication settings,[1] which is from [30]. According to the Definitions 1-2 and Table III, the coverage set of different transmission rates with different transmission protocols can be expressed as

$$\begin{aligned}\mathcal{C} &= \begin{bmatrix} c_{s_1,z_1} & c_{s_1,z_2} & \cdots & c_{s_1,z_j} & \cdots & c_{s_1,z_{12}} \\ c_{s_2,z_1} & c_{s_2,z_2} & \cdots & c_{s_2,z_j} & \cdots & c_{s_2,z_{12}} \\ c_{s_3,z_1} & c_{s_3,z_2} & \cdots & c_{s_3,z_j} & \cdots & c_{s_3,z_{12}} \end{bmatrix} \\ &= \begin{bmatrix} 45 & 5 & 15 & 20 & 25 & 20 & - & 20 & 15 & - & - & - \\ - & - & - & - & - & - & 160 & - & - & 60 & 50 & 140 \\ 90 & 5 & 5 & 40 & 20 & 20 & 30 & 10 & 30 & 20 & 30 & 110 \end{bmatrix}\end{aligned} \tag{4}$$

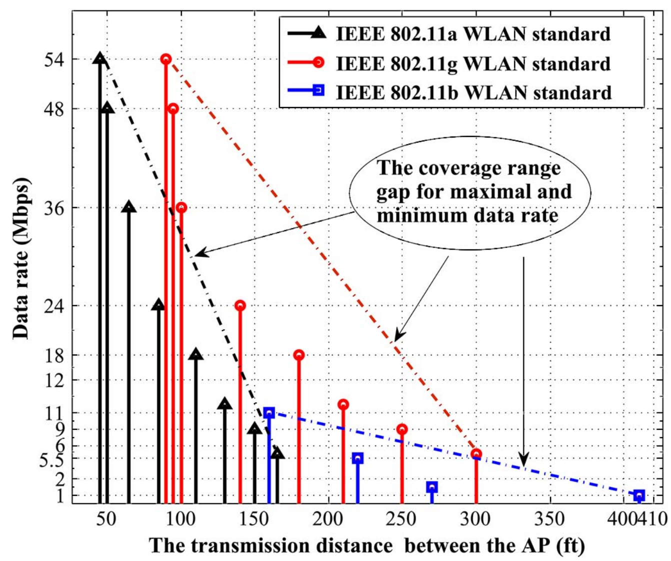

Fig. 5. The relationship between the transmitted data rate and the coverage range of AP.

Meanwhile, we show the relationship between the distance d_n and transmission rate in Fig. 5. It is observed that the transmission rate using all 802.11 protocols in $\mathbb{S}$ is directly proportional to the coverage range except several special points such as 160 ft, 220 ft and 270 ft for 802.11g networks,

Thus, for any vehicle n within the RSU's coverage, the transmission rate $r_{s_i}^n$ from the RSU to the vehicle when using

[1]The current communication settings in the measurement of 802.11a/b/g networks are 40 mW with 6 dBi, 100 mW with 2.2 dBi, and 30 mW with 2.2 dBi gain diversity patch antenna, respectively. Even though the measurement data is just for open indoor office environment, this is only available complete test data, and compared with the investigated 802.11b networks model in [12], there is few difference for the test data. In addition, this data is rational and feasible for the urban case with high buildings. Hence, we use this measurement data for the outdoor Drive-Thru Internet performance analysis.

s_i-th protocol is a function of distance from RSU to the vehicle. It can be expressed as

$$r^n_{s_i}(t) = \{r_{s_i,z_j} | x_{s_i,z_j} \leqslant \bar{v} \cdot \Gamma(t) < x_{s_i,z_{j+1}}\}, n \in \mathcal{N} \quad (5)$$

where $\Gamma(t)$ is the sojourn time within RSU's coverage and $\bar{v}$ denotes the average driving speed.

IV. Drive-Thru Throughput and Optimal Access Analysis

To analyze the drive-thru throughput performance, we first analyze the mean contending vehicular number and residence time within AP's coverage. Then, we analyze the drive-thru throughput of multi-rate WLANs with DCF. Finally, we formulate the optimal spatial coordinated channel access region in multi-rate WLANs to optimize the drive-thru throughput and whole transmitted data volume.

A. Contending Vehicle Number and Residence Time Within AP's Coverage Analysis

Note that the coverage range of AP along the road is symmetric, and let L_{s_i} be the first half (mirror) coverage range of the s_i-th 802.11 protocol and $c_{\mathrm{s}_i,\mathrm{z}_j}$ is the first half (mirror) coverage range of j-th transmission rate zone. For simplification, we neglect the notion s_i in the following rest space, i.e., we take one type of 802.11 protocol for example, which can be extended to the unified multi-rate transmission rate analytical model. According to investigation in [19], the speed ν_i of arbitrary arriving vehicle i follows the PDF of normal distribution, which is given by

$$f_\nu(\nu_i) = \frac{1}{\delta_\nu \sqrt{2\pi}} e^{-\left(\frac{\nu_i - \bar{\nu}}{\delta_\nu \sqrt{2}}\right)^2} \quad (6)$$

where $\bar{\nu} \in [\nu_{\min}, \nu_{\max}]$, $\delta_\nu = k\bar{\nu}$ and $\nu_{\min} = \bar{\nu} - m\delta_\nu$. As it's justified in [31], δ_ν and the two-tuple (k, m) can be found in the typical values of velocity distributions, which is based on the experimental data. To avoid generating the negative speeds or some values approaching to zero, a truncated version of vehicular speed distribution will replace (6). By defining the function $\mathrm{erf}(x) = (2/\pi)\int_0^x e^{-t^2} dt$, and the truncated vehicular speed distribution can be rewritten as

$$\begin{aligned}\widehat{f_\nu}(\nu_i) &= \frac{f_\nu(\nu_i)}{\int_{\nu_{\min}}^{\nu_{\max}} f_\nu(\nu_i) d\nu_i} \\ &= \frac{f_\nu(\nu_i)}{\frac{1}{2}\mathrm{erf}\left(\frac{\nu_{\max} - \bar{\nu}}{\delta_\nu \sqrt{2}}\right) - \frac{1}{2}\mathrm{erf}\left(\frac{\nu_{\min} - \bar{\nu}}{\delta_\nu \sqrt{2}}\right)}. \quad (7)\end{aligned}$$

Lemma 2: Given the coverage range L_{s_i} and the speed of arbitrary arriving vehicle follows the normal distribution, the PDF of vehicle's residence time $f_\Gamma^{L_{\mathrm{s}_i}}(\tau)$ is as follow,

$$f_\Gamma^{L_{\mathrm{s}_i}}(\tau) = \frac{\mathrm{M} \cdot L_{\mathrm{s}_i}}{\tau^2 \delta_\nu \sqrt{2\pi}} e^{-\left(\frac{\frac{L_{\mathrm{s}_i}}{\tau} - \bar{\nu}}{\delta_\nu \sqrt{2}}\right)^2}, \quad \tau \in \left[\frac{L_{\mathrm{s}_i}}{\nu_{\max}}, \frac{L_{\mathrm{s}_i}}{\nu_{\min}}\right] \quad (8)$$

Proof: The real-world road test indicates that the vehicle's speed can keep constantly for several hundred meters. Based on the reference [31], the cumulative distribution function (CDF) of vehicle's residence time $F_\Gamma^{L_{\mathrm{s}_i}}(\tau)$ can be derived by combining the CDF of vehicle's speed $\widehat{F_\nu}$, shown as

$$F_\Gamma^{L_{\mathrm{s}_i}}(\tau) = 1 - \widehat{F_\nu}\left(\frac{L_{\mathrm{s}_i}}{\tau}\right) = 1 - \frac{\mathrm{M}}{2}\left[1 + \mathrm{erf}\left(\frac{\frac{L_{\mathrm{s}_i}}{\tau} - \bar{\nu}}{\delta_\nu \sqrt{2}}\right)\right] \quad (9)$$

where $\mathrm{M} = 2/(\mathrm{erf}((\nu_{\max} - \bar{\nu})/\delta_\nu\sqrt{2}) - \mathrm{erf}((\nu_{\min} - \bar{\nu})/\delta_\nu\sqrt{2}))$. By setting the derivative of the CDF of vehicle's residence time $F_\Gamma^{L_{\mathrm{s}_i}}(\tau)$ and combining the expression $(d/dx)\mathrm{erf}(x) = (2/\sqrt{\pi})e^{-x^2}$, we can prove the lemma. ■

Based on the PDF of vehicle's residence time $f_\Gamma^{L_{\mathrm{s}_i}}(\tau)$, we can easily get the expression of mean vehicle's residence time within a fixed distance with a length L_{s_i}, shown as

$$\begin{aligned}\bar{\Gamma}^{L_{\mathrm{s}_i}} &= \int_{L_{\mathrm{s}_i}/\nu_{\max}}^{L_{\mathrm{s}_i}/\nu_{\min}} \tau f_\Gamma^{L_{\mathrm{s}_i}}(\tau) d\tau \\ &= \int_{L_{\mathrm{s}_i}/\nu_{\max}}^{L_{\mathrm{s}_i}/\nu_{\min}} \frac{\mathrm{M} \cdot L_{\mathrm{s}_i}}{\tau \delta_\nu \sqrt{2\pi}} e^{-\left(\frac{\frac{L_{\mathrm{s}_i}}{\tau} - \bar{\nu}}{\delta_\nu \sqrt{2}}\right)^2} d\tau \quad (10)\end{aligned}$$

Considering that multi-rate transmission zones have different individual coverage, the vehicles residence time $\bar{\Gamma}^{c_{\mathrm{z}_j}}$ within c_{z_j}-length road segment is

$$\bar{\Gamma}^{c_{\mathrm{z}_j}} = \bar{\Gamma}^{L_{\mathrm{s}_i}} \frac{c_{\mathrm{z}_j}}{\sum_{\mathrm{z}_j \in \mathbb{Z}} c_{\mathrm{z}_j}}, \qquad \mathrm{z}_j \in \mathbb{Z} \quad (11)$$

where $c_{\mathrm{z}_j} / \sum_{\mathrm{z}_j \in \mathbb{Z}} c_{\mathrm{z}_j}$ is the limiting probability that one vehicle locates within the zone z_j.

Theorem 1: The mean number of vehicles $\overline{N}^{c_{\mathrm{z}_j}}$ within c_{z_j}-long coverage range zone follows the Poisson Distribution, and the mean number of vehicles $\overline{N}^{c_{\mathrm{z}_j}}$ equals to

$$\bar{N}^{c_{\mathrm{z}_j}} = \frac{\bar{\Gamma}^{L_{\mathrm{s}_i}} \cdot c_{\mathrm{z}_j} \cdot \vartheta_v}{\sum_{\mathrm{z}_j \in \mathbb{Z}} c_{\mathrm{z}_j}} \quad (12)$$

Proof: According to the proof in [31], the probability of having n vehicles within a L_{s_i}-length coverage range zone is

$$P_n^{\bar{\Gamma}^{L_{\mathrm{s}_i}}} = \frac{(\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}})^n e^{-\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}}}}{n!}. \quad (13)$$

Hence, we can get the mean number of vehicles $\bar{N}^{L_{\mathrm{s}_i}}$ within a L_{s_i}-length coverage range zone, shown as,

$$\begin{aligned}\bar{N}^{L_{\mathrm{s}_i}} &= \sum_{n=0}^{\infty} n \cdot P_n^{L_{\mathrm{s}_i}} = \sum_{n=1}^{\infty} n \cdot P_n^{L_{\mathrm{s}_i}} \\ &= \sum_{n=1}^{\infty} \frac{(\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}})^{n-1} (\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}}) e^{-\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}}}}{(n-1)!}. \quad (14)\end{aligned}$$

By applying the Taylor Expansion, i.e., $e^m = \sum_{n=0}^{\infty}(m)^n / n!$, $\forall m$, we can get that $\sum_{n=1}^{\infty}(\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}})^{n-1}/(n-1)! = \sum_{m=0}^{\infty}(\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}})^m/(m)! = e^{\vartheta_\nu \bar{\Gamma}^{L_{\mathrm{s}_i}}}$. Hence, mathematically, we have the expression that the number of vehicles in L_{s_i}-length coverage zone. i.e., $\overline{N}^{L_{s_i}} = \bar{\Gamma}^{L_{s_i}} \cdot \vartheta_v$. Combining the limiting probability $c_{z_j} / \sum_{z_j \in \mathbb{Z}} c_{z_j}$ that the number of vehicles in the c_{z_j}-length transmission zone, we can prove the theorem. ■

B. Vehicular Drive-Thru Throughput Analysis

We consider a fundamental random medium access control scheme in IEEE 802.11 protocol [32], namely, collision avoidance carrier sense multiple access (CSMA/CA) based distrusted coordination function (DCF), to analyze the vehicular drive-thru throughput in Drive-Thru Internet. In addition, to eliminate the hidden terminal problem, we consider the IEEE 802.11 standard for WLAN medium access control in which the packets are transmitted by means of RTS/CTS mechanism. For generic analysis, the maximum backoff stage denoted by m and the contention window size CW are considered. We assume that the conditional probability ξ that any vehicle transmits in the randomly chosen slot-time is no relation with the vehicles' position. Under a constant and independent conditional collision probability p, ξ can be expressed as,

$$\xi = \frac{2}{1 + \mathrm{CW} + p\mathrm{CW} \sum_{j=0}^{m-1} (2p)^j}, \qquad p \in [0, 1] \tag{15}$$

when $p = 0$, we can get that $\xi = 2/(1 + \mathrm{CW})$, and $p = 1$, (15) is written as $\xi = 2/(1 + 2^m \mathrm{CW})$.

Within the z_j-th transmission zone, let $p_{z_j}^{tr}$ be the probability that there is at least one transmission within this zone during the considered time-slot. Given the number of vehicles within this transmission zone as $\overline{N}^{c_{z_j}}$, and mathematically, we have the probability $p_{z_j}^{tr}$ that is

$$p_{z_j}^{tr} = 1 - (1 - \xi)^{\overline{N}^{c_{z_j}}} \tag{16}$$

where for any IEEE 802.11 protocol, i.e., $\forall s_i$, $\overline{N}^{c_{z_j}}$ is related to the limiting probability, i.e., $c_{z_j} / \sum_{z_i \in \mathbb{Z}} c_{z_i}$, that one vehicle locates within the zone, and can be obtained using (12).

For the AP's coverage with multi-rate transmission zones, if multiple continual transmission zones are considered, the probability p_k^{tr} that there is at least one transmission within k continual transmission zones set $\mathbb{Z}_k$, i.e., $\mathbb{Z}_k = \{z_1, z_2, \ldots, z_k\}$, and $k \leqslant |\mathbb{Z}|$, can be expressed as,

$$p_k^{tr} = 1 - \prod_{j=1}^{k} (1 - \xi)^{\overline{N}^{c_{z_j}}} \tag{17}$$

where for $k = |\mathbb{Z}|$, which means that in a whole L_{s_i}-length transmission coverage of AP, (17) can be formulated as

$$p_k^{tr} = 1 - \prod_{j=1}^{|\mathbb{Z}|} (1 - \xi)^{\bar{N}^{c_{z_j}}} = 1 - (1 - \xi)^{\sum_{j=1}^{|\mathbb{Z}|} \frac{\bar{N}^{L_{s_i}} \cdot c_{z_j}}{\sum_{z_i \in \mathbb{Z}} c_{z_i}}}$$
$$= 1 - (1 - \xi)^{\bar{N}^{L_{s_i}} \sum_{j=1}^{|\mathbb{Z}|} \frac{c_{z_j}}{\sum_{z_i \in \mathbb{Z}} c_{z_i}}} = 1 - (1 - \xi)^{\bar{N}^{L_{s_i}}}. \tag{18}$$

Lemma 3: Within the specified z_j-th transmission zone, and given the number of vehicles is $\overline{N}^{c_{z_j}}$, the probability $p_{z_j}^{su}$ that a successful transmission on the considered channel equals to

$$p_{z_j}^{su} = \frac{\bar{N}^{c_{z_j}} \xi (1 - \xi)^{(\bar{N}^{c_{z_j}} - 1)}}{1 - (1 - \xi)^{\bar{N}^{c_{z_j}}}}. \tag{19}$$

Proof: $p_{z_j}^{su}$ can also be understood as the probability that only exactly one vehicle transmits within the specified z_j-th transmission zone, with the condition that at least one vehicle transmits factually. Hence, mathematically, we have

$$p_{z_j}^{su} = \frac{\bar{N}^{c_{z_j}} \xi (1 - \xi)^{(\bar{N}^{c_{z_j}} - 1)}}{p_{z_j}^{tr}} = \frac{\bar{N}^{c_{z_j}} \xi (1 - \xi)^{(\bar{N}^{c_{z_j}} - 1)}}{1 - (1 - \xi)^{\bar{N}^{c_{z_j}}}} \tag{20}$$

Using the (16), we can prove the lemma. ■

Lemma 4: Given the k continual transmission zones, i.e., $k = |\mathbb{Z}_k|$, the probability p_k^{su} that a successful transmission on the considered channel equals to

$$p_k^{su} = \frac{\left(\sum_{j=1}^{k} \overline{N}^{c_{z_j}}\right) \xi (1 - \xi)^{\left(\sum_{j=1}^{k} \bar{N}^{c_{z_j}} - 1\right)}}{1 - (1 - \xi)^{\sum_{j=1}^{k} \bar{N}^{c_{z_j}}}}, \quad k \leqslant |\mathbb{Z}| \tag{21}$$

Proof: Based on the Lemma 3 and combining the Eq. (17), we have the probability p_k^{su} that,

$$p_k^{su} = \frac{\left(\sum_{j=1}^{k} N^{c_{z_j}}\right) \xi (1 - \xi)^{\left(\sum_{j=1}^{k} \bar{N}^{c_{z_j}} - 1\right)}}{1 - \prod_{j=1}^{k} (1 - \xi)^{\bar{N}^{c_{z_j}}}}, \quad k \leqslant |\mathbb{Z}| \tag{22}$$

we can easily prove the lemma. Especially, if we consider a whole L_{s_i}-length AP's coverage, i.e., $k = |\mathbb{Z}|$, we can have the expression of $p_{|\mathbb{Z}|}^{su}$ as, $p_{|\mathbb{Z}|}^{su} = \bar{N}^{L_{s_i}} \xi (1 - \xi)^{(\bar{N}^{L_{s_i}} - 1)} / (1 - (1 - \xi)^{\bar{N}^{L_{s_i}}})$. ■

We consider the RTS/CTS medium access control mechanism, and the collision can only happen on RTS frames. For such a mechanism, let $E[T_{su,z_j}^{rts}]$ and $E[T_{bu,z_j}^{rts}]$ be the mean time that the channel is sensed busy within z_j-th transmission zone due to the successful transmission or a collision, respectively. Mathematically, $E[T_{su,z_j}^{rts}]$ and $E[T_{bu,z_j}^{rts}]$ can be expressed as,

$$\begin{cases} E\left[T_{su,z_j}^{rts}\right] = (RTS + \mathrm{CTS} + ACK + E[P])/\nu_{z_j} \\ \qquad\qquad + 3\mathrm{SIFS} + 4\sigma_{propa} + DIFS \\ E\left[T_{bu,z_j}^{rts}\right] = RTS/\nu_{z_j} + DIFS + \sigma_{propa} \end{cases} \tag{23}$$

where ν_{z_j} is the link transmission rates within z_j-zone, which can be obtained from the measurement data of Table III.

Easily, we can extend the derivation of mean time that a successful and collided transmission within one transmission zone to the case with k continual transmission zones. Among k continual transmission zones, let $c_{z_j} / \sum_{z_j \in \mathbb{Z}_k} c_{z_j}$ be the limiting probability that a vehicle is in the transmission zone z_j. The mean time that a successful channel transmission and the channel is sensed busy within k continual transmission zones are defined as $E[T^{rts}_{su,k}]$, and $E[T^{rts}_{bu,k}]$, respectively, which can be expressed as,

$$\begin{cases} E\left[T^{rts}_{su,k}\right] = \sum\limits_{j=1}^{k} E\left[T^{rts}_{su,z_j}\right] \frac{c_{s_i,z_j}}{\sum_{z_j\in\mathbb{Z}_k} c_{s_i,z_j}}, \\ E\left[T^{rts}_{bu,k}\right] = \sum\limits_{j=1}^{k} E\left[T^{rts}_{bu,z_j}\right] \frac{c_{s_i,z_j}}{\sum_{z_j\in\mathbb{Z}_k} c_{s_i,z_j}}, \end{cases} \quad k \leqslant |\mathbb{Z}| \tag{24}$$

We analyze the drive-thru throughput when vehicles pass k continual transmission zones. Based on the above analysis results, we can easily get that the mean time-slot $E[T_{slot}]$ using RTS/CTS mechanism in DCF is composed of three parts:

- The mean duration of empty slot-time $E[T^{em}_k]$ within k continual transmission zones with probability of $(1 - p^{tr}_k)$;
- The mean duration of successful transmission $E[T^{su}_k]$ within k continual transmission zones with probability of $p^{tr}_k \cdot p^{su}_k$;
- The mean duration $E[T^{bu}_k]$ that channel is busy within k continual transmission zones with probability of $p^{tr}_k(1 - p^{su}_k)$.

Mathematically, $E[T_{slot}]$ can be formulated as,

$$E[T_{slot}] = E[T^{em}_k] + E[T^{su}_k] + E[T^{bu}_k] \tag{25}$$

where we have $E[T_{em}]$, $E[T_{su}]$, and $E[T_{bu}]$, respectively,

$$\begin{cases} E\left[T^{em}_k\right] = (1 - p^{tr}_k)\sigma_{pro} \\ E\left[T^{su}_k\right] = p^{tr}_k p^{su}_k E\left[T^{rts}_{su,k}\right] \\ E\left[T^{bu}_k\right] = p^{tr}_k(1 - p^{su}_k)E\left[T^{rts}_{bu,k}\right]. \end{cases} \tag{26}$$

According to the normalized 802.11 system throughput definition in [32], the nodal throughput passing k continual transmission zones can be evaluated by defining the ratio of mean package payload size and the mean amount of payload package transmitted in a slot time successfully. Mathematically, we have,

$$\Re_k = \frac{E[X_{pl}]}{E[T_{slot}]} = \frac{p^{tr}_k p^{su}_k E[P]}{E\left[T^{em}_k\right] + E\left[T^{su}_k\right] + E\left[T^{bu}_k\right]} \tag{27}$$

In fact, the values of m and CW are hardwired in the PHY layer details [32]. Intuitively, different traffic flow states will generate different values of contending vehicular number and sojourn time within RSU's coverage, hence, the nodal throughput in (25) can be mainly determined by the traffic flow state and real transmission rates in multi-rate IEEE 802.11 networks if the DCF related parameters (m and CW) are fixed. According to the analysis, the more number of vehicles within a fixed road segment can lead to a higher contention overhead and less sharing capacity. The function of mean total amount of transmitted data $\mathbb{F}_k(\cdot)$ in the first mirror coverage range from/to AP by a vehicle is determined by the nodal throughput $\Re_k$ passing k continual transmission zones and the vehicular sojourn time $\sum_{j=1}^{k}\overline{\Gamma}^{c_{z_j}}$. Mathematically, we have $\mathbb{F}_k(\cdot)$ as,

$$\mathbb{F}_k(\cdot) \overset{def}{=} \Re_k \sum_{j=1}^{k} \bar{\Gamma}^{c_{z_j}}, \qquad z_j \in \mathbb{Z}, k \leqslant |\mathbb{Z}| \tag{28}$$

C. Optimal Spatial Coordinated Channel Access

As described in the performance anomaly phenomenon, the transmission within the low-rate transmission zones will degrade the performance of the Drive-thru Internet access in terms of the total transmitted data between RSU and vehicles within its coverage. To improve the performance and to keep the nice fairness among vehicles, we design a distributed spatial coordinated channel access scheduling method such that all vehicles within the RSU's coverage are regulated to utilize the high-rate transmission zones for channel access.

Since the coverage range of AP along the road is symmetric, we consider the left half coverage range of the s_i-th 802.11 protocol (i.e., L_{s_i}). Let x_{s_i} be the length of channel access region that vehicles are regulated to communicate with AP within it. Firstly, we transform the length of road segment x_{s_i} to the position of transmission zones. The first k transmission zones covered by the road segment x_{s_i} can be derived by

$$k = \left\{ n \left| \sum_{j=1}^{n-1} c_{\mathrm{s}_i,\mathrm{z}_j} < x_{s_i} \leqslant \sum_{j=1}^{n} c_{\mathrm{s}_i,\mathrm{z}_j}, n \leqslant |\mathbb{Z}| \right. \right\} \tag{29}$$

where c_{s_i,z_j} is the coverage range of the j-th transmission rate zone with the s_i-th transmission protocol. Thus, the total amount of transmitted data $\mathbb{F}_{x_{s_i}}(\cdot)$ consists of two parts: 1) the transmitted data within the whole coverage of the first $k-1$ transmission zones, denoted as $\mathbb{F}_{k-1}(\cdot)$; 2) the transmitted data within the part of the coverage of the $k-$th transmission zone, denoted as $\mathbb{F}^p_{z_k}(\cdot)$. Mathematically, we have $\mathbb{F}_{x_{s_i}}(\cdot) = \mathbb{F}_{k-1}(\cdot) + \mathbb{F}^p_{z_k}(\cdot)$. Hence, we have $\mathbb{F}_{x_{s_i}}(\cdot)$ as,

$$\mathbb{F}_{x_{s_i}} = \mathbb{F}_{k-1} + \mathbb{F}_k \cdot \frac{x_{s_i} - \sum_{j=1}^{k-1} c_{\mathrm{s}_i,\mathrm{z}_j}}{\sum_{j=1}^{k} c_{\mathrm{s}_i,\mathrm{z}_j}} \tag{30}$$

where $(x_{s_i} - \sum_{j=1}^{k-1} c_{\mathrm{s}_i,\mathrm{z}_j})/\sum_{j=1}^{k} c_{\mathrm{s}_i,\mathrm{z}_j}$ is the proportion that the data is transmitted within the partial coverage of the $k-$th transmission zone.

The spatial coordinated medium sharing can be formulated as an optimal access region scheduling problem as follows.

$$\begin{aligned} x^*_{s_i}(\mathcal{Q}_{type}) &= \arg\max_{x_{s_i}\leqslant L_{s_i}} \{2 \cdot \mathbb{F}_{x_{s_i}}(\cdot)\} \\ \text{s.t.} \quad & s_i \in \mathbb{R}, z_j \in \mathbb{Z} \\ & \mathcal{Q}_{type} \in \mathcal{Q}_{ser} \end{aligned} \tag{31}$$

where $x^*_{s_i}(\mathcal{Q}_{type})$ is the optimal mirror channel access region for vehicles under the traffic flow state $\mathcal{Q}_{type}$, and $\mathcal{Q}_{ser}$ represents the set of traffic flow states. As shown in Table III, there are six traffic flow states corresponding to different service levels and traffic densities. That is, the set of the traffic flow states $\mathcal{Q}_{ser} = \{\mathcal{Q}_A, \mathcal{Q}_B, \mathcal{Q}_C, \mathcal{Q}_D, \mathcal{Q}_E, \mathcal{Q}_F\}$, where elements represent the service level A, B, C, D, E and F, respectively.

TABLE IV
SETTING OF DCF MECHANISM PARAMETERS

Parameters	Value	Parameters	Value
p	$0, 1/2, 1$	CW	$16, 32, 64$
m	$2, 3, 5$	$\nu_{\max}$	120 km/h
$E[P]$	8184 bits	MAC	272 bits
PHY	128 bits	ACK	112 bits+ PHY
RTS	160 bits + PHY	σ_{propa}	50 μs
CTS	112 bits + PHY	Lane number	6
SIFS	28 μs	$DIFS$	128 μs

V. OPTIMAL ACCESS CONTROL MANAGEMENT REALIZATION FOR REAL DRIVE-THRU INTERNET

In real applications, to determine the optimal channel access region and regulate all vehicles to do the channel access and data transmission within this region, we need external traffic density information to support the contending vehicular number and Drive-thru Internet performance analysis in the proposed unified analytical framework, which can be typically obtained from the vehicle density estimation in [33], [34]. In the implementation, vehicles can either locate the position within AP's coverage using the on-board GPS or through channel measurement. If the location of a vehicle n (denoted as loc_n) is not within the derived region $[-\mathcal{X}^*_{s_i}(\mathcal{Q}_{type}), \mathcal{X}^*_{s_i}(\mathcal{Q}_{type})]$, the vehicle n halts the transmission in a coordinated way. To avoid some dishonest nodes which continue to transmit when out of the optimal access control region, AP can block the transmissions by using the bit rate sensing technique as the access region can directly correspond to a transmission rate set. The algorithm of optimal access control management process is depicted in Algorithm 1.

Algorithm 1: Spatial Coordinated Access Control Management Approach

Input: $\mathcal{Q}_{type} \in \mathcal{Q}_{ser}, s_i \in \mathbb{S}, \upsilon_{\max}, \sigma_{jam}$
Output: $x^*_{s_i}$

```
Calculating N̄^{c_{s_i,z_j}} and Γ̄^{c_{s_i,z_j}} ;
Finding x*_{s_i}(Q_type) i.e.,
    x*_{s_i}(Q_type) = arg max_{x_{s_i} ≤ L_{s_i}} {2 · (F_{k-1}(·) + F^p_{z_k}(·))} ;
for n = 1; n ≤ |N| do
    while loc_n ∉ [−x*_{s_i}(Q_type), x*_{s_i}(Q_type)] do
        vehicle n stops the transmission;
        if vehicle n does not stop the transmission then
            Calculating C(x*_{s_i}) and Sensing ν_{s_i,z_j};
            while ν_{s_i,z_j} ∉ C(X*_{s_i}) do
                AP blocks the transmission of vehicle n;
```

VI. SIMULATION RESULTS

We evaluate the performance of the proposed optimal channel access approach using Matlab. Table IV lists the setting of simulation parameters, including the vehicular traffic parameters, V2R communication model parameters, and IEEE 802.11 DCF parameters, respectively.

A. The Demonstration for Vehicular Traffic Related Evaluation

Fig. 6 shows the distribution of vehicles residence time when the coverage range of AP is 165 ft, 330 ft, and 660 ft,

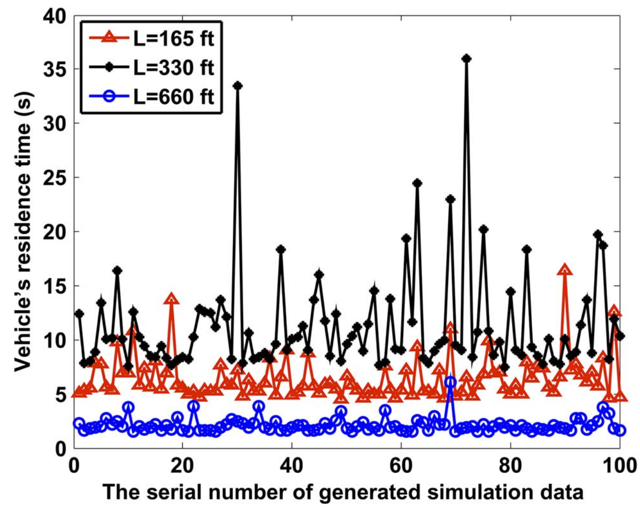

Fig. 6. The vehicle's residence time distribution under different coverage ranges.

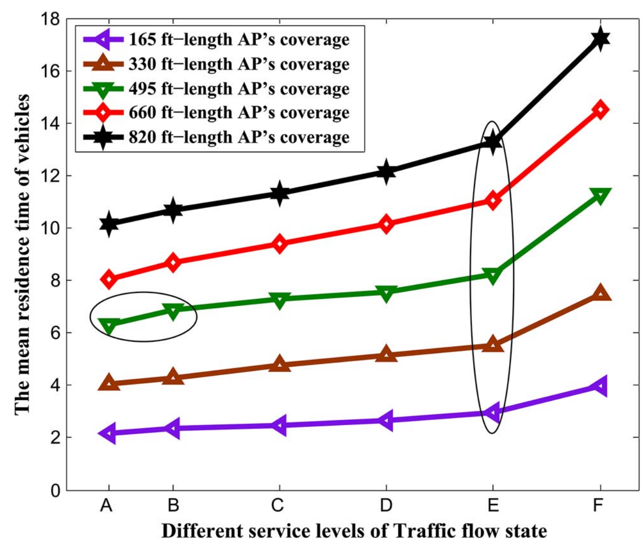

Fig. 7. The mean residence time of vehicles under different Traffic flow states.

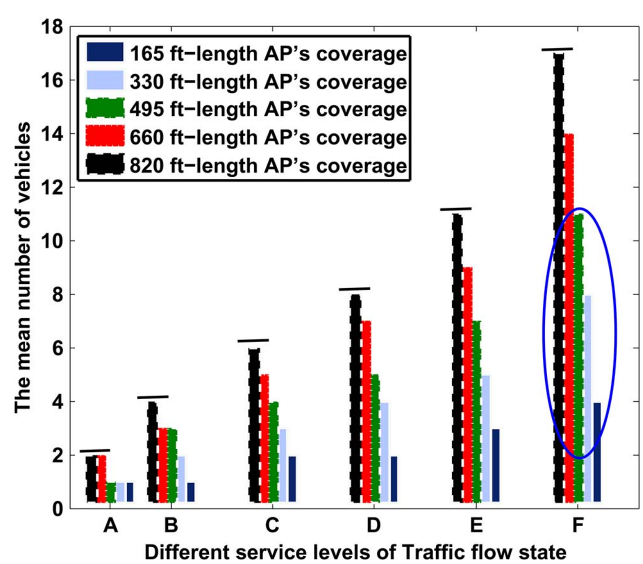

Fig. 8. The mean contending vehicular number under different Traffic flow states.

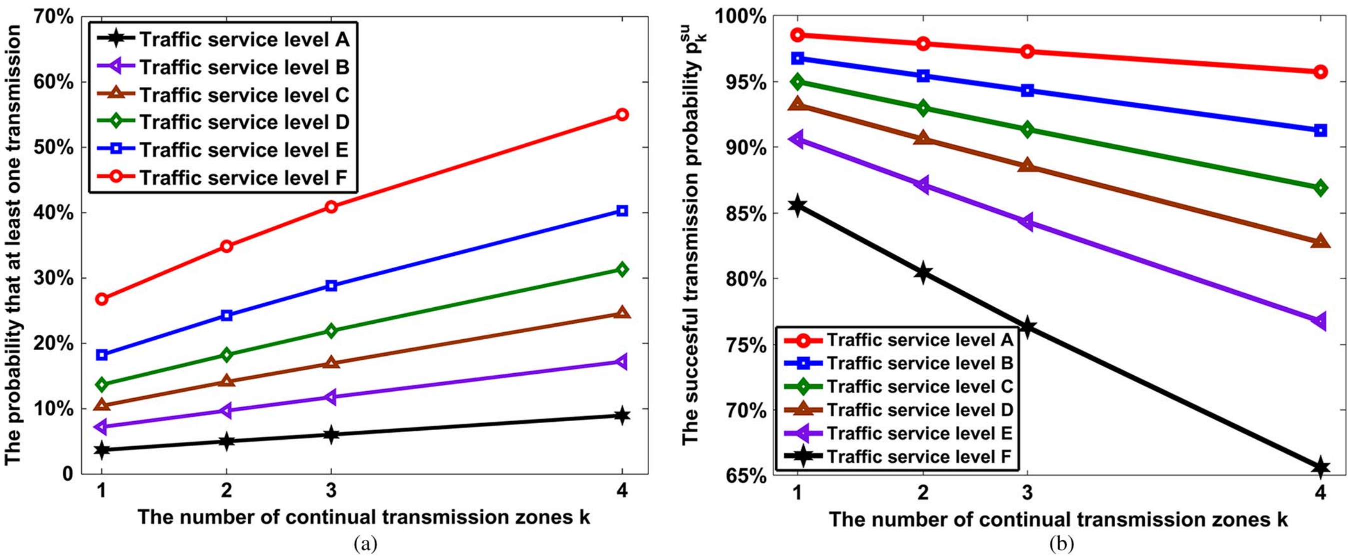

Fig. 9. The MAC performance of 802.11b. (a) The relationship between the zone number k and probability p_k^{tr}. (b) The relationship between the zone number k and probability p_k^{su}.

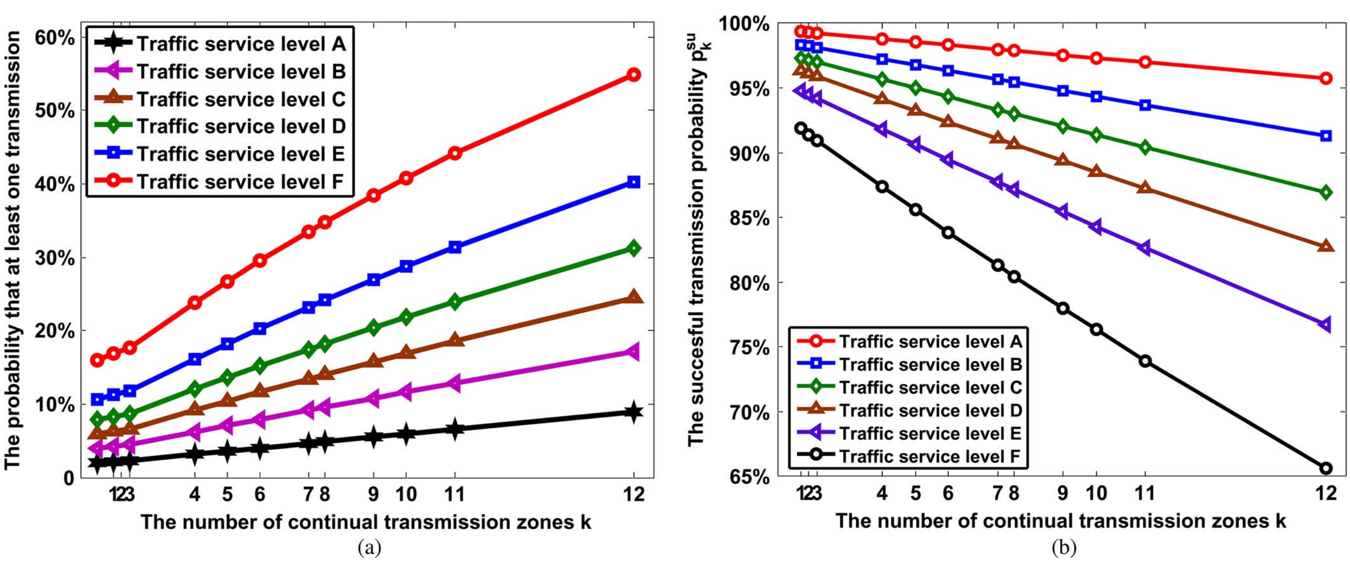

Fig. 10. The MAC performance of 802.11g. (a) The relationship between the zone number k and probability p_k^{tr}. (b) The relationship between the zone number k and probability p_k^{su}.

respectively. Using our analysis shown in (10), we could evaluate the average residence time within different coverage ranges. However, due to the complexity of calculating integral in (10), we evaluate the average vehicular residence time within a fixed coverage range by the statistical analysis. By generating 200 times $f_\Gamma^L(\tau)$ value, we can obtain the average residence time considering the 6 TSLs and different coverage ranges, shown in Fig. 8. For example, within $165 * 2$ ft and $410 * 2$ ft of AP's coverage, and under service level case E, the average vehicular residence time is 8.20 s, 13.82 s, respectively. In addition, the vehicular mean residence time is in direct proportion to the traffic flow state (see Fig. 7). The main reason is that the reduced mean vehicular driving speed prolongs the residence time within a fixed region when the traffic flow state is scaled from the free flow to the congested state. In Fig. 8, we can get the mean contending vehicular number under different TSLs within the AP's coverage. For example, under the traffic service level C, for the length of AP's coverage with 165 ft, 330 ft, 495 ft, 660 ft, and 820 ft, the average contending vehicular number is 4, 8, 11, 14, 17.

B. *The Demonstration for Saturated Throughput of IEEE 802.11a/b/g Networks*

The saturated throughput of Drive-Thru Internet is closely related to the probability parameters such as p_k^{tr} and p_k^{su}. Figs. 9 and 10 show that p_k^{tr} is in direct proportion to the length of AP's coverage. With the increase of zone number k, the number of contending vehicles within these zones will increase, and the probability that at least one transmission

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

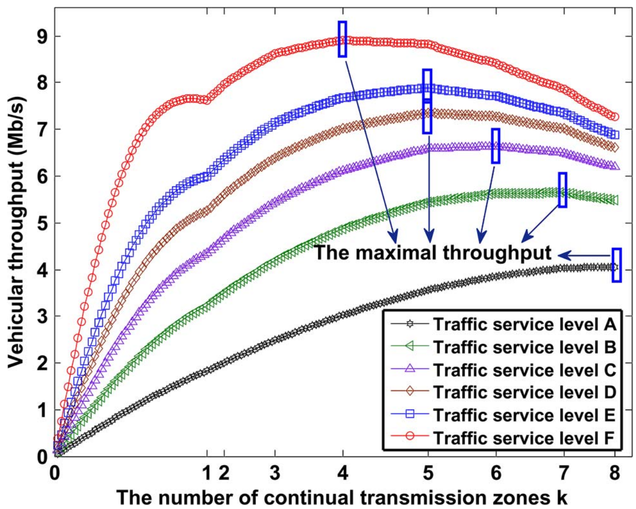

Fig. 11. The average vehicular throughput of 802.11a networks under different number of continual transmission zones.

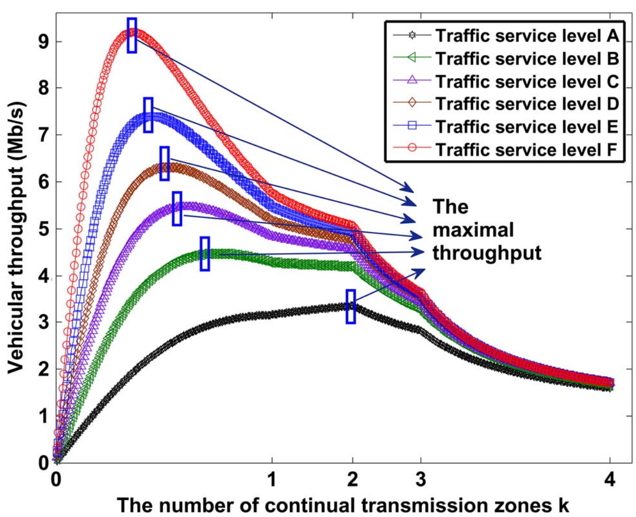

Fig. 12. The average vehicular throughput of 802.11b networks under different number of continual transmission zones.

occurs becomes higher. Therefore, the successful transmission probability (i.e., p_k^{su}) decreases due to the increased contending vehicles.

Figs. 11–13 show that the maximal vehicular throughput in IEEE 802.11a/b/g networks can be achieved by selecting an optimal access control region. For instance, Fig. 11 shows that the optimal number of medium access control zones is 5 with the traffic service level D in IEEE 802.11a network. That is, the optimal access control range is $2 * \sum_{j=1}^{5} c_{s_1,z_j}$), where c_{s_1,z_j} is the coverage range of the $j-$th transmission rate zone in IEEE 802.11a network.

The detailed data for optimal medium access control range with different TSLs is shown in Table V. It can be seen in Table V that the length of optimal medium access control region reduces with the increase of traffic density. From the service level A to F (i.e., low traffic density to high traffic density) in IEEE 802.11a network, the optimal access control range is from 330 ft to 170 ft. The main reason is that the increased medium

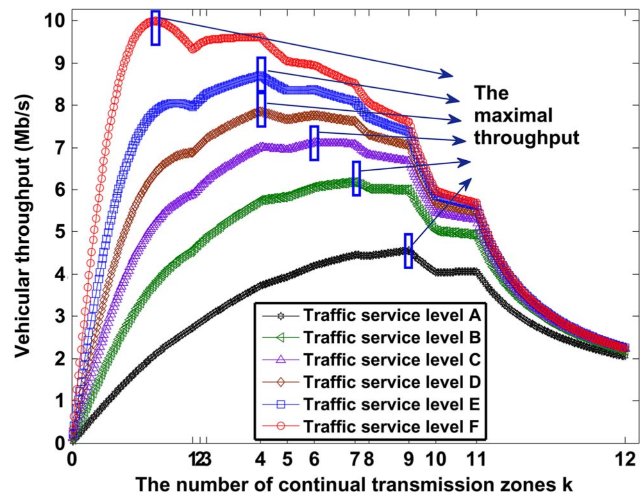

Fig. 13. The average vehicular throughput of 802.11g networks under different number of continual transmission zones.

access control range can enhance the successful transmission probability and increase the contending vehicular number as well. The contending vehicular number is the dominated factor for determining the optimal vehicular throughput. Therefore, we can control the contending vehicular number by reducing the medium access control region.

C. The Demonstration for the Performance Enhancement

To demonstrate the performance improvement of the proposed channel access approach, we further compare the proposed approach (denoted as "optimal" in Table VI) with the method without the use of the channel access region control (denoted as "normal" in Table VI). We evaluate the average transmitted data volume per vehicle with different transmission protocols and service levels. As shown in Figs. 14–16, the maximal transmitted data volume can be achieved by optimally choosing the medium access control region for IEEE 802.11b/g networks. Table VI gives the detailed performance enhancement of data download volume. It can be seen that the maximal data download volume improves by 113.1% and 59.5% with the traffic service level F for IEEE 802.11b and 802.11g networks, respectively.

In addition, Figs. 15 and 16 show that: 1) for traffic service level A, the optimal access control range in the mirror coverage zone of IEEE 802.11b and IEEE 802.11g networks is [0, 270] ft and [0, 300] ft, respectively; 2) for traffic service level $B, C, D, E,$ and F, the optimal access control range in the mirror coverage zone of IEEE 802.11b and IEEE 802.11g networks is [0, 220] ft and [0, 250] ft, respectively. Some further conclusions are as follows.

- The achieved average transmitted data volume is related not only to the TSL (i.e., traffic flow states or traffic densities), but also to the transmission protocols. The proposed optimal access control approach works effectively in IEEE multi-rate 802.11b/g networks. Meanwhile, due to the short coverage of AP in IEEE 802.11a network, the

TABLE V
OPTIMAL ACCESS CONTROL REGION FOR THE THROUGHPUT ENHANCEMENT OF IEEE 802.11a/b/g NETWORKS. (IN UNIT OF ft)

Protocol \ TSL	A	B	C	D	E	F
802.11a	[-175,175]	[-150,150]	[-130,130]	[-110,110]	[-110,110]	[-85,85]
802.11b	[-220,220]	[-119,119]	[-97,97]	[-84,84]	[-72,72]	[-72,72]
802.11g	[-250,250]	[-210,210]	[-180,180]	[-140,140]	[-140,140]	[-62,62]

TABLE VI
PERFORMANCE COMPARISON OF THE TRANSMITTED DATA VOLUME FOR 802.11b/g NETWORKS. (IN UNIT OF Mb)

Protocol \ TSL	A	B	C	D	E	F
802.11b (normal)	75.1	82.5	87.1	90.2	97.75	128.9
802.11b (optimal)	118.3	145.3	157.9	183.1	203.3	274.8
802.11g (normal)	32.5	35.9	38.6	41.6	45.6	58.7
802.11g (optimal)	37.7	48.0	55.4	62.1	70.3	93.6

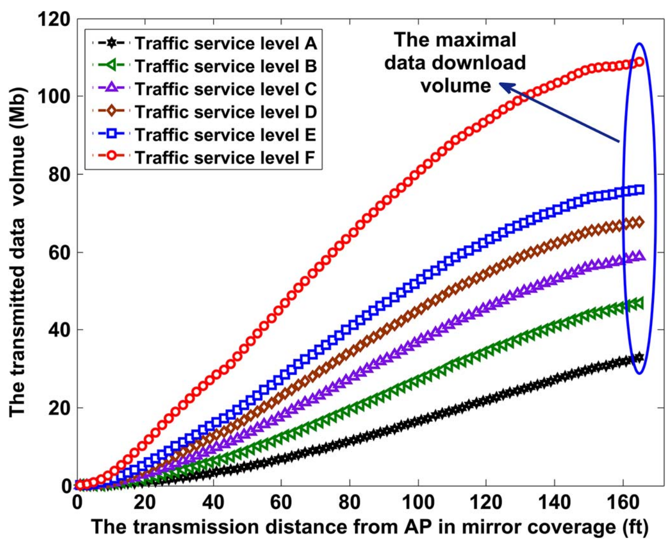

Fig. 14. The average transmitted data volume of 802.11a networks under different access control regions.

optimal access control region covers the whole coverage of the AP (i.e., $165 * 2$ ft shown in Fig. 14), which provides the meaningful guideline that it is unnecessary to regulate the access region in IEEE 802.11a networks.

- A uniform access control region can be set to optimize the performance of IEEE 802.11b/g networks for different TSLs (i.e., different traffic densities). As shown in Figs. 15–16, the length of uniform access control region is 440 ft and 500 ft (i.e., transmission zone $1 \sim 2$ and transmission zone $1 \sim 9$), respectively.[2]
- The optimal access control approach plays a significantly important role in improving the performance of IEEE 802.11b/g networks, especially as the increase of the traffic density. As shown in Table VI, for IEEE 802.11b network, the performance improvement of the proposed approach is 57.5% at the traffic service level of A (i.e., low traffic density) while 113.1% at the traffic service level of F (i.e., heavy traffic density); For IEEE 802.11g network, the performance improvement of the proposed approach is 16% at the traffic service level of A (i.e., low traffic density) while 59.5% at the traffic service level of F (i.e., heavy traffic density).

[2]These results are based on the parameter setting from the collected empirical data in [19]. Different parameter settings may have different access control regions.

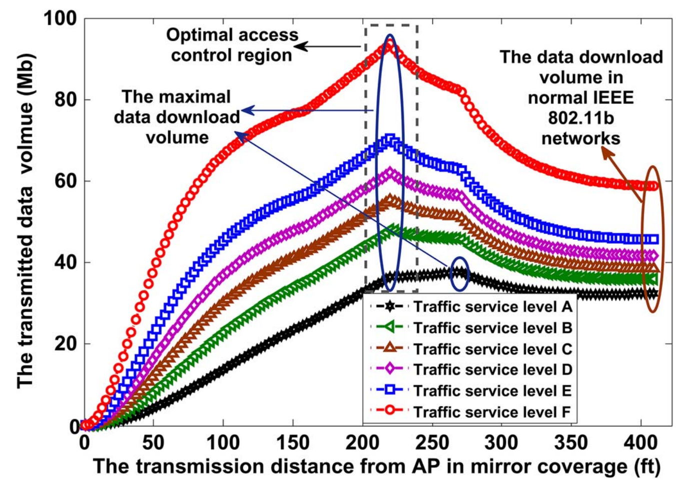

Fig. 15. The average transmitted data volume of 802.11b networks under different access control regions.

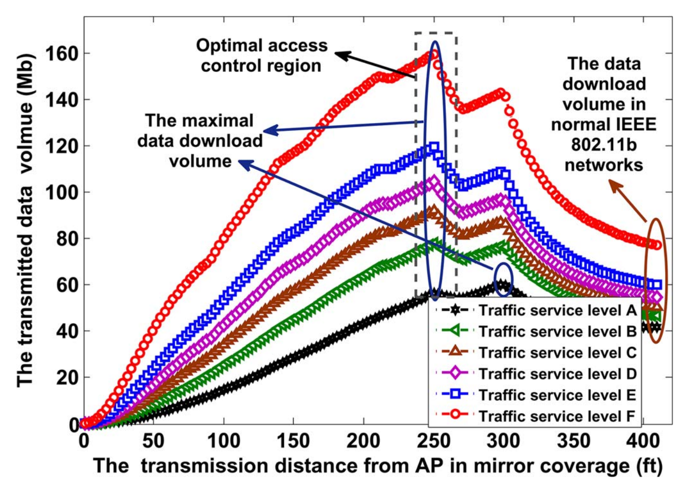

Fig. 16. The average transmitted data volume of 802.11g networks under different access control regions.

VII. CONCLUSION

In this paper, using the empirical measurement data from both the IEEE 802.11a/b/g networks and typical traffic scenarios, we have analyzed the average saturated throughput of IEEE 802.11a/b/g networks per drive-thru in our proposed

Drive-Thru Internet analytical framework. The proposed analytical framework can adapt to diverse multi-rate IEEE 802.11 networks and especially different real vehicular traffic states. To overcome the widely existing performance anomaly problem in the Drive-Thru Internet, we have proposed an optimal access control approach, which provides a fundamental solution to the performance enhancement. Specifically, by regulating all vehicles to do the channel access and data transmission within the optimal access region, the proposed approach can achieve significant performance improvement in terms of saturated throughput and transmitted data volume, which has been demonstrated in both the numerical analysis and the performance evaluation. Furthermore, by fully utilizing VANET feature such as the directed mobility behavior with fair sojourn time within the APs coverage, the proposed optimal access control approach can guarantee the airtime fairness among vehicles and be easily implemented, which are greatly beneficial to the Drive-Thru Internet.

For the future work, we will investigate the cooperative networking and content distribution approach in our proposed optimal Drive-Thru Internet framework.

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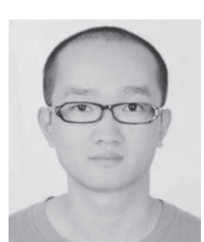

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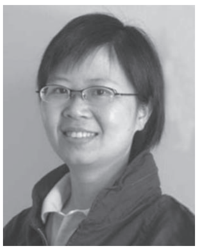

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